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The use of fumigants for controlling decay of wood: a review of their efficacy and safety

Jeffrey J. Morrell
Assistant Professor
Department of Forest Products
Oregon State University
Corvallis, OR 97331

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The use of fumigants for controlling decay of wood products: a review of their efficacy and safety. Jeffrey J. Morrell, Assistant Professor, Department of Forest Products, Oregon State University, Corvallis, Oregon, U.S.A.

ABSTRACT

Volatile agricultural chemicals (fumigants) such as chloropicrin (trichloronitromethane) and sodium n-methyldithiocarbamate have been used in the United States for controlling internal decay of large dimension wood products for over 20 years. This usage has been concentrated in the electric utility industry, but fumigants are increasingly applied to protect bridge timbers, marine piling, and even living trees.

This document will review the characteristics of fumigants in relation to other available chemicals, particularly the water-soluble pastes that are commonly employed in Europe. Studies to improve the handling safety of fumigants and future research needs will also be addressed.

KEY WORDS: Wood decay, fumigants, utility poles, piling, timbers, chloropicrin, methylisothiocyanate, Vapam.

INTRODUCTION

Many wood species have a moderately or non-decay resistant heartwood which resists penetration by conventional wood preservatives. As a result, preservative treatment produces a thin envelope of protection which remains effective only as long as the chemical barrier is not compromised. In service, round or boxed heartwood timbers check beyond the depth of preservative penetration or cuts made during installation permit the entry of moisture and fungal spores which eventually decay the internal, untreated portion of the wood. In the late 1960's, the incidence of internal decay in Douglas-fir poles in the western United States was so great that many utilities considered the replacement of wood with steel (Graham, 1973a,b; Hand et al., 1970).

Externally applied preservative pastes, which were commonly used to arrest surface decay (DeGroot, 1981, Panek et al., 1961), lacked the ability to migrate deep into the wood and were ineffective against internal decay. To overcome this problem, research programs evaluated two approaches. In many countries, the application of water soluble preservative salts under pressure or the addition of solid rods containing these same chemicals into holes drilled in the pole were evaluated (Murphy and Dickinson, 1986; Vinden, 1984). In North America; however, research emphasized the application of highly volatile compounds which could migrate through the wood to rapidly control internal decay (Hand et al., 1970, Ricard et al., 1967; Graham, 1973a, Graham et al., 1976). In general, the chemicals chosen were agricultural fumigants normally used to sterilize soil.

The development, application and safety aspects of water soluble preservatives will be the subject of a separate review. This document will review the history, chemistry, and application of fumigants to control wood decay.

FUMIGANTS

The word fumigant, used in conjunction with wood conjures images of the high volatile chemicals used for short-term structural pest fumigation. These chemicals, notably sulfuryl fluoride and methyl bromide, are highly volatile, odorless, and toxic, making them extremely difficult to handle. In practice, fumigation of wood with these chemicals is a temporary treatment which can eliminate established insect pests. Little or no trace of the chemical is left in the wood following treatment, and the organisms causing the problem can reinfest the wood. This type of fumigation is neither practical or useful for large poles in the field, since utilities normally inspect poles on a ten year cycle and can not risk substantial fungal decay between these inspections.

The difficulty of penetrating normally refractory wood with liquid chemical posed a major challenge to utilities with internally decaying poles. While diffusible chemicals might eventually control the decay, the utilities feared that strength losses occurring between the time of detection and eventual control of the fungus would reduce pole strength below acceptable levels. Fungicides capable of rapidly moving through refractory heartwood were unknown until Partridge (1961) demonstrated that methyl bromide and chloropicrin (trichloronitromethane) vapors could diffuse through oak. Later, fumigants were shown to be a practical method for eliminating the oak wilt fungus, Ceratocystis fagacearum from logs (Schmidt, 1983, Schmidt et al., 1982; Liese and Rütze, 1984; Liese et al., 1981; Jones, 1963). At about the same time, sodium n-methyldithiocarbamate (32.1 percent aqueous), Vorlex (20 % methylisothiocyanate in chlorinated C_3 hydrocarbons) and chloropicrin were found to migrate through sound or decayed Douglas-fir heartwood and eliminate established decay fungi (Graham, 1973a; Hand et al., 1970). These treatments were applied at the ground line through steep angled holes drilled into the pole. These holes were then plugged with tight fitting wood dowels (Graham and Helsing, 1979).

As a result of the initial success, over 80 % of electric utilities in the United States employ fumigants in their wood maintenance programs (Goodell and Graham, 1983). The widespread acceptance of fumigants reflects the tremendous investment savings realized by extending pole service life; however, the currently used fumigants have several drawbacks which limit their application. As a result, electric utilities and pole producers have sponsored extensive research programs at Oregon State University, SUNY College of Environmental Science and Forestry at Syracuse, NY, the University of Maine and Forintek, Canada to improve the handling characteristics of existing fumigants or identify safer formulations (Morrell and Corden, 1986).

PRESENT USES OF FUMIGANTS

Fumigants are primarily used for decay control, although they have some effects on insect and marine borer attack.

Utility Poles: Controlling fungal deterioration in wood poles represents the single largest application of fumigants. As previously stated, most utilities use one of the four registered fumigants in their wood maintenance programs (Table 1) (Goodell and Graham, 1983). At present, NaMDC and chloropicrin are the two most commonly used fumigants, with NaMDC being used for poles in urban settings and chloropicrin being applied to poles in more rural settings. The latter chemical is more difficult to handle and many utilities use only NaMDC. In field tests on Douglas-fir, the protective effect of NaMDC begins to fail within 6 years after application, while chloropicrin remains effective for at least 18 years (Figure 1). Similar trials using southern pine, a more permeable species, suggest considerably shorter protective periods for this species group (Zabel and Wang, 1988; Zabel et al., 1982). In addition to these two chemicals, two more recently registered formulations, Vorlex and methylisothiocyanate (MITC) are applied to poles on a limited basis. Vorlex has performed as well as chloropicrin in field tests, while MITC, the pure active ingredient of Vorlex, has only been in test for 10 years. The results of MITC field trials suggest that this chemical will perform comparably to Vorlex. Based upon the current utility inspection practices, retreatment with fumigants at 10 year intervals is recommended. This time period conforms to the time period that most utilities use for inspections for other maintenance practices which insure that electric transmission lines comply with the U.S. National Electric Safety Code. In addition, the cost of chemical represents a small fraction of the total cost of travel to and inspection of a pole.

Table 1. Fumigants used for remedial control of wood decay fungi

Trade name	Active Ingredient	Sources
chloropicrin, Timber-Fume	trichloronitromethane (96%)	Angus Chemical Co. Great Lakes Chemical Co. Osmose Wood Preserving, Inc.
Vapam, Wood-fume Metham sodium	32.1% sodium, n-methyldithiocarbamate	Kop-Coat, Inc; Osmose Wood Preserving, Inc.; Buckman Laboratories, Int'l.
Vorlex	20% methylisothiocyanate 80% chlorinated C_3 hydrocarbons	NorAm Chemical Co.
MITC-Fume	96% methylisothiocyanate	Osmose Wood Preserving, Inc.

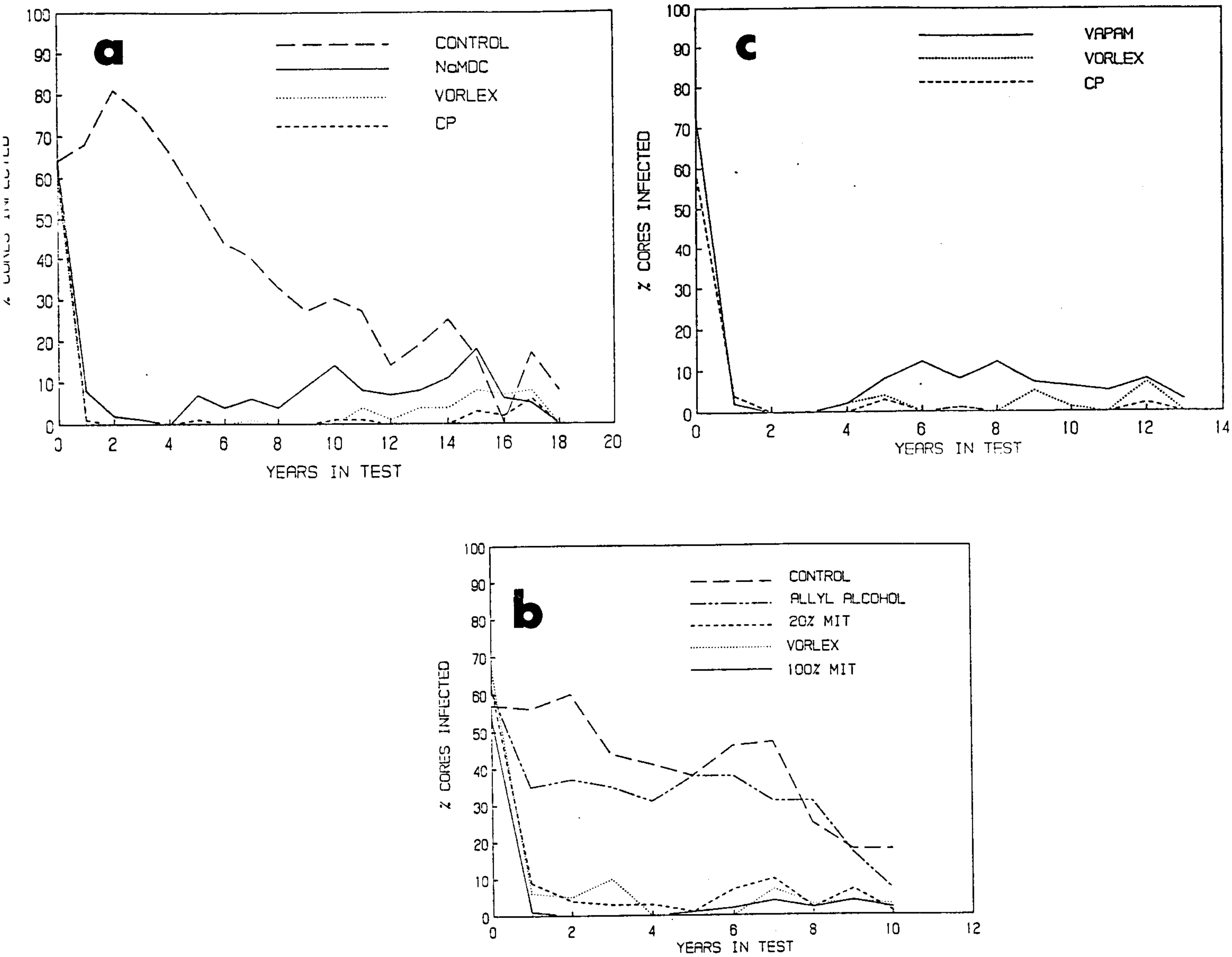

Figure 1. Ability of wood fumigants to arrest and prevent fungal colonization of preservative treated Douglas-fir as measured by culturing increment cores removed from the wood on an annual basis. A) Utility poles treated with NaMDC, Vorlex or chloropicrin or left untreated B) Utility poles treated with Vorlex or methylisothiocyanate, or C) Marine piling treated with NaMDC, Vorlex or chloropicrin.

While fumigants perform well as remedial treatments to preservative treated wood, they do not appear to be capable of protecting untreated wood in ground contact (Corden et al., 1988; Morrell et al., 1986).

Marine Piling and Timbers: Preservative treated marine piling and timbers are often cut during or after the construction process (Helsing et al., 1986). Exposure of an untreated pile top above the waterline can result in substantial internal decay in as little as 4 years. The problems experienced above the waterline with large timbers or roundwood in marine environments are similar to those found in utility poles, and it is not surprising that fumigants perform well in marine timber and piling.

Field trials indicate that NaMDC, Vorlex, chloropicrin, ammonium bifluoride, and MITC are all capable of eliminating existing infestations and preventing renewed colonization by decay fungi from marine piling for as long as 10 years (Helsing et al., 1984b; 1986, Morrell, 1988). As a result of this effectiveness, fumigants are increasingly used along the West Coast of the United States to provide supplemental protection to piling and large timbers (Morrell et al., 1984).

Building Timbers: Architects are notorious for designing wood structures which illustrate a basic lack of understanding of wood properties. In many cases, these designs involve the exposure of untreated end-grain to weathering (Graham, 1979). The resulting decay mars building appearance and creates structural instability. Both NaMDC and chloropicrin have been applied to the external portions of exposed building timbers with great success (Morrell and Corden, 1986; Goodell et al., 1980). Holes are drilled down into the wood at 0.9 to 1.2 m intervals along the length of the timber. Portions of the wood inside the building are not treated, since the chemical can volatilize from the wood to create a potential health hazard (Morrell and Lebow, in press). Once applied, the chemical migrates from the point of application along the grain, eliminating any decay fungi present. Preliminary trials suggest that fumigants are lost more rapidly from sawn timbers, possibly due to the exposure of more cell lumens on the wood surface. Thus, more frequent retreatments may be advisable if the wood can not be kept dry.

Living Trees and Stumps: While the primary use of fumigants has been remedial application to wood products, several studies suggest that fumigants may also be useful for eliminating certain root pathogens from living trees and freshly cut stumps (Filip and Roth, 1977; Houston and Eno, 1964, Thies, 1984; Thies and Nelson 1987a). This particular root pathogen decreases forest productivity by over 4.4 million cubic meters in the Pacific Northwest (Nelson et al., 1981). MITC, chloropicrin, or Vorlex can eliminate laminated root rot, caused by *Phellinus weirii*, from Douglas-fir stumps (Thies and Nelson, 1987a). This pathogen normally moves from infected trees and stumps to younger trees in the stand. Application of fumigants to infested trees or stumps could help break the cycle of infection in timber stands. Similar results might be achieved with *Armillaria mellea*, a worldwide problem in conifer stands.

Field tests also indicate that fumigants can be safely applied at lower dosages to living trees (Goodell et al., 1984; Thies and Nelson, 1987b). The tree produces a core of reaction wood above each treatment hole (Goodell et al., 1984), but the high sapwood moisture content appears to limit the amount of chemical reaching the cambium, thus minimizing the effects on tree health (Morrell and Newbill, in review). Fumigants might be applied to living trees to prevent heartrots and root diseases. Application to all trees in a stand is not feasible; however, treatment of special high value trees might be useful. Chloropicrin is currently the only fumigant registered for this purpose.

Recent studies suggest that application of sublethal dosages of fumigant may stimulate the growth of antagonistic fungi (Munnecke, 1984; Nelson et al., 1987), potentially effecting control of root diseases at lower chemical levels . This approach has been used for fumigation of avocado, but its effectiveness in the control of forest diseases remains unknown.

Marine borer and insect control: Controlling marine borer and insect infestations with fumigants poses more of a challenge because these organisms can move away from the point of chemical application. In addition, many of these organisms do not actually digest the wood, decreasing the probability that high dosages will be ingested. Nevertheless, fumigants have been reported to control termite infestations in utility poles when the colonies were near the point of application (Hand et al., 1970). More recent application of Vorlex to Douglas-fir poles containing carpenter ant infestations suggests that the chemical levels typically applied to utility poles were insufficient to control this insect (Morrell, 1988).

Fumigants have been shown to inhibit Limnoria or shipworm attack of Douglas-fir panels for up to 3 years (Helsing et al., 1984a). These panels were treated to very high fumigant retentions and subsequent tests using more realistic chemical levels suggest that fumigants can only provide short-term protection against marine borers (Newbill and Morrell, in review). These treatments could provide temporary protection to damaged piling, provided routine maintenance practices repaired the damage within one year.

FUMIGANT PROPERTIES

Until recently, much of our knowledge about fumigants was derived from studies in soil (Gersti et al., 1977), but research on the movement of chloropicrin and MITC through Douglas-fir heartwood have improved our knowledge of chemical/wood interactions (Goodell, 1979, 1981, 1983, Zahora, 1983; 1987). MITC is the major volatile fungitoxic product produced by decomposition of NaMDC and a major component of Vorlex. More recently, MITC has been registered as a 96 % concentrate of the active chemical (Morrell, 1989). In addition, one promising solid fumigant, Mylone, also decomposes to produce MITC as one of its fungitoxic products.

<u>Chloropicrin</u>: This highly volatile chemical is one of the most difficult to contain during application, and its chemistry in the wood has been addressed by Cooper et al. (1974) and Goodell (1981, 1983). In the United States, applicators must wear a gas mask with the appropriate filter, along with gloves and goggles. Inhalation of even small quantities can incapacitate the applicator, but olefactory sensitivity is so great that the applicator can normally move away from any leaks or spills before any damage occurs. The high volatility of chloropicrin has lead many utilities to use NaMDC to improve applicator safety.

Chloropicrin has been shown to bind more effectively to sound than brown-rotted wood, suggesting that the binding sites were affected by fungal attack. Goodell et al., (1986) found covalent binding between chloropicrin and vanillin, suggesting that lignin was a possible site for binding in wood. Aeration of chloropicrin treated wood rapidly reduced the levels of chemical present, although a small residual level remained (Goodell et al., 1985). This residual chloropicrin may account for the long term protection provided by this chemical.

More recent studies of western redcedar heartwood indicate that up to 56 mg of chemical per cc of wood remained in the wood 5 years after treatment (Morrell and Scheffer, 1985), while southern yellow pine retained 12 mg of chloropicrin per cc of wood 1 year after treatment (Zabel et al., 1982). These variations in chemical level suggest that fumigant movement varies with the degree of permeability, with more permeable species losing chemical more rapidly. Similar effects have been noted in several laboratory and field studies (Ruddick, 1984, 1986; Morrell et al., 1986a, 1988).

<u>NaMDC</u>: This chemical is the most frequently applied fumigant for utility poles. NaMDC is not highly volatile and must decompose to produce fungitoxic MITC. NaMDC is usually applied as a 32.1 % aqueous solution which decomposes to produce approximately 14 different breakdown products (Turner and Corden, 1963; Miller and Morrell, in press; Elson, 1966). Of these, carbon disulfide, carbonyl sulfide, hydrogen sulfide, methylamine, and MITC are volatile chemicals which can move long distances through the wood. In most cases, MITC is considered to be the primary volatile fungitoxic component of NaMDC; however, recent studies suggest that the rate of MITC production from NaMDC yields only 12 percent by weight of MITC per weight of NaMDC applied. Thus, other volatile chemicals may also influence the effectiveness of this compound. In addition to the volatile chemicals released during NaMDC decomposition, several studies suggest that solid components such as elemental sulfur or dimethylthiuram disulfide may be deposited some distance from the point of application where they can provide long-term protection against renewed fungal colonization (Hand et al., 1970, Miller and Morrell, in press).

NaMDC can also be formulated as a pure salt, which can be applied in that form or compressed into more easily handled pellets. Although the rate of decomposition is slightly slower in the absence of the water, the dosage can be maximized, potentially improving the protection period provided by the treatment (Morrell, 1988).

Vorlex and MITC: Vorlex has only recently been registered for wood use and its chemistry in wood remains unexplored; however, MITC is presumed to be the primary fungitoxic component of this formulation. The remaining chlorinated C_3 hydrocarbons in Vorlex are believed to provide insecticidal protection.

MITC, which is a major fungitoxic component of most of the commonly used wood fumigants, has received more extensive study. Early studies indicated that MITC could move up to 0.6 m through Douglas-fir heartwood after 14 to 30 weeks of incubation (Zahora, 1983). Further studies reveal that MITC is sorbed in high quantities to wood blocks, particularly when the wood moisture content falls below 20 percent. Most of the sorbed chemical can be removed by aeration, but a small "bound" fraction is consistently present. This fraction could be released by wetting the wood. This action suggests that a "bound" MITC fraction in dry wood would be ideally poised to protect wood that becomes wet and, thus, susceptible to decay.

While MITC is a highly effective fungicide, it apparently slowly decomposes in the wood (Zahora and Morrell, 1988b). This effect is more pronounced in wet wood (decomposition rate of 1.6 % per week at 60 percent moisture content). MITC decomposition products are only slightly fungitoxic, but they may provide long-term protection against germination of fungal spores.

The recent identification of the diffusion and sorption relationships between MITC and Douglas-fir (Zahora and Morrell, 1989) has permitted the development of a model which predicts MITC movement through Douglas-fir heartwood. This model indicates that movement through the heartwood increases with increased MC, that the presence of an oil-treated shell retards fumigant loss from the wood surface, but does not affect chemical levels within the wood, and that an entire cross section is protected within 6 months after application (Zahora et al., 1988). Although the rate of movement was slightly faster than that seen in the field, the levels and effects were similar to previous field reports of MITC distribution in treated wood poles.

The high affinity of MITC for wood and its relative stability suggest that treatments which incorporate this chemical should provide excellent long-term protection against fungal attack. Further studies are underway to extend the MITC movement model to a three-dimensional pole to optimize treatment patterns and dosages.

Mylone: Although it is not currently registered for wood use, Mylone (3.5 dimethyl tetrahydro- 1,3,5,2H-Thiadiazone -2-Thione), has great promise for wood protection. A crystalline solid at room temperature, this compound slowly decomposes to produce a multitude of products, including MITC. The slow rate of natural decomposition has limited the application of this chemical, although Mylone has shown some promise in one field trial (Highley and Eslyn, 1982; Eslyn and Highley, 1985). The rate of Mylone decomposition can be altered by increasing the pH, and a recent study indicates that effective fungal control can be achieved when an aqueous buffer at pH 12 is poured into the treatment hole containing the powdered Mylone (Morrell et al., 1988b). Although the use of buffers may not be practical for field use, studies are underway to develop pellets containing mixtures of Mylone and the appropriate buffer. The pellets could then be activated by addition of water to the treatment hole, or by moisture present in the wood.

Ultimately, solid crystalline formulations offer vastly improved safety for wood application and should become an important tool for remedial wood treatment.

DETECTING FUMIGANTS IN WOOD

While conventional wood preservatives can be detected in wood either visually or using chemical indicators, detecting colorless fumigants in wood poses a challenge. Initially, fumigants in wood were detected using bioassays, where small pieces of wood were removed and placed in petri dishes or tubes containing a test fungus. Growth of the test fungus in the presence of treated wood was compared with growth of fungi exposed to similar, but untreated wood. This method developed into the closed-tube bioassay (Scheffer and Graham, 1975). A recent evaluation of this method indicated that this assay operated at the limits of gas chromatographic sensitivity, but was somewhat variable (Zahora and Morrell, 1988a). The bioassay can be used in the field to determine if chemical retreatment is necessary.

More recently, gas chromatography (GC) has emerged as a useful tool for quantifying chemical levels in the wood. In practice, a small wood sample is removed, extracted in the appropriate solvent (hexane for chloropicrin or ethyl acetate for MITC) and the extract is analyzed on a GC equipped with the appropriate column and detector (electron capture for chloropicrin or flame photometric for MITC) (Morrell and Scheffer, 1985; Zahora and Morrell, 1988a). This technique permits quantification of chemical level on a wood volume or weight basis. GC analyses are presently not practical for assessing chemical levels in the field.

The presence of chloropicrin can also be detected using acridine dye under ultra violet light or Drager gas detector tubes (Eslyn and Highley, 1985; Highley and Eslyn, 1982).

In general, it is not necessary to determine the precise level of chemical present in the wood, and many utilities simply replenish the fumigant at 10 year intervals to reduce the risk of reinvasion by decay fungi.

SAFETY AND ENVIRONMENTAL RISKS

In the United States, the four registered wood fumigants are restricted-use pesticides, which requires that the applicator be licensed by the State where the treatment occurs. In addition, 3 of the 4 chemicals are highly volatile and require that respirators, goggles, and protective gloves be used during application. The fourth fumigant, NaMDC, is not as volatile, but contact with the skin can cause burns. The volatility and handling difficulties can be minimized by following the label instructions.

These handling properties, nevertheless, appear to be a major hurdle for expanded worldwide us of these chemicals.

Once applied to the wood, fumigants migrate throughout the cross section and, in the process, small amounts are emitted from the wood into the surrounding soil and air. The release of fumigants into soil should pose little difficulty, since soil rapidly mineralizes the fumigant. This process is clearly illustrated by the absence of residual fumigant in agricultural fields within 7 days after treatment. Thus, emission into the surrounding soil should pose no hazard. Similarly, emission from wood in open areas with ample air exchange should pose no hazard. Emissions may pose a hazard, however, when applied to wood in weatherized buildings where air exchange is low. Fumigant concentrations could build up in these spaces, creating a potential hazard (Morrell and Lebow, in press). For this reason, fumigant application is not recommended inside inhabited buildings or in spaces with poor ventilation. Studies are underway to better quantify the potential emission levels from wood under poor aeration conditions.

FUTURE RESEARCH

Fumigants have been used to arrest decay in wood structures for over 20 years, but we still lack basic information on the chemistry and efficacy of the chemicals. Obtaining this information could help in the development of the next generation of fumigants. While the currently registered formulations have performed well, it is readily apparent that they have drawbacks and that shifting in environmental policies could eliminate the registrations of one or more formulations with relative ease. Thus, we must continue to evaluate new formulations for their potential as wood fumigants, with a particular emphasis on solid formulations that can be more easily handled. A wide array of potential chemicals have been screened (Corden and Morrell, 1988), but many other agricultural chemicals may prove useful. A second approach is to slow or contain the existing chemicals prior to treatment. Gelatin or glass encapsulation, pelletizing, and gelling have all been evaluated with varying degrees of success (Zahora and Corden, 1985a, Goodell, 1989). In general, these approaches have been limited by the increased cost of the encapsulated or gelled formulation.

Fumigants are currently employed in the United States and Canada (Ruddick, 1986, Cooper, 1986; Morrell and Corden, 1986), but they could potentially be used in many tropical countries where limited wood resources are further strained by the high decay hazards to which construction timber is exposed. Fumigant application could extend the service life of timber in these environments. Preliminary studies indicate that fumigants can protect most wood species, but the levels required for protection vary (Morrell et al., 1986, 1988).

The performance of several fumigants, particularly NaMDC, often exceed the levels which would be expected by chemical analysis. A number of microfungi have been isolated from fumigant treated poles (Giron and Morrell, in review). These fungi exhibit fumigant tolerance, but also appear to inhibit the growth of Basidiomycetes normally found in the pole species examined (Giron and Morrell, in press). These results would suggest that fumigant treatment alters the normal wood microflora, favoring antagonistic fungi. This approach might permit the use of reduced chemical dosages that enhance antagonistic fungi. To better understand this process, we need information on the fumigant levels necessary to inhibit fungal colonization of wood. Laboratory studies indicate that active cultures can overcome the protective effect of fumigants (Goodell, et al., 1985; Zahora and Morrell; in review; Zahora and Corden, 1985b), but this bears little resemblance to a single spore or hyphal fragment invading through a check in the wood.

One final area which remains largely unexplored is the use of volatile chemicals which react in the wood to produce insoluble, fungitoxic precipitates. Each gas would be applied to the wood separately and as the second gas migrated into contact with the first, an insoluble precipitate would form in the wood. This process creates the potential for complete treatment of normally refractory species. Preliminary trials using ethylene diamine and carbon disulfide to produce ethylene bis-dithiocarbamate indicate that the reaction proceeds too slowly in wood, possibly due to low pH. As a result, the level of chemical deposited in the wood was insufficient to protect against decay fungi (Morrell and Lebow, unpublished). Alteration of pH might overcome this limitation, creating the potential for complete protection of the wood cross section.

CONCLUSIONS

Fumigants, like the water soluble pastes, have definite advantages and disadvantages. They can rapidly arrest decay and have the ability to migrate several meters from the point of application through normally refractive heartwood. In addition, they do not appear to pose a hazard once applied to the wood. On the negative side, the currently registered fumigants are volatile and difficult to handle; however, these problems can be minimized by proper handling practices.

Water soluble pastes are more slow acting and do not appear to migrate for as great a distance through the wood, particular above the point of application. This slower rate of action may permit fungal decay to expand for a period of years before complete control is effected. Conversely, the pastes are non-volatile, reducing the risk of worker exposure. One potential problem with pastes is the risk of chemical leaching from the pole into the surrounding soil. Although the levels which leach into to surrounding soil may be quite small, there are increasing concerns about soil contamination.

In summary, each approach to remedial decay control has benefits, and each has a role in pole maintenance. Fumigants can provide a method for rapidly arresting existing fungal infestations, while pastes and rods could be applied at the time of pole installation to provide additional protection to the pole. Diffusible chemicals in rod form could also be used to arrest decay above the groundline, where fumigants are not currently recommended because of the risk of spills.

LITERATURE CITED

Cooper, P.A. 1986. Selecting fumigants for treatment of internal decay in wood. IRG/WP/3370.

Cooper, P.A., R.D. Graham, and R.T. Lin. 1974. Factors affecting the movement of chloropicrin vapor in wood to control decay. Wood and Fiber 6(1):81-90.

Corden, M.E. and J.J. Morrell. 1988. Evaluation of potential decay control agents using a small-block test. Wood and Fiber Science 20:477-486.

Corden, M.E., J.J. Morrell, M.A. Newbill, and R.D. Graham, 1988. Fumigant protection of untreated Douglas-fir. Holzforschung 42(2):127-130.

DeGroot, R.C. 1981. Groundline treatments of southern pine posts. USDA Forest Serv. Res. Pap. FPL-409.

Elson, J.E. 1966. Fungitoxicity of sodium N-methyldithiocarbamate (Vapam) and its decomposition products. M.A. thesis. Oregon State University, Corvallis, Oreg. 35 pp.

Eslyn, W.E., and T.L. Highley. 1985. Efficacy of various fumigants in the eradication of decay fungi implanted in Douglas-fir timbers. Phytopathology 75:588-592.

Filip, G.M., and L.F. Roth. 1977. Stump injections with soil fumigants to eradicate Armillariella mellea from young-growth ponderosa pine killed by root-rot. Canadian Journal of Forest Research 7:226-231.

Gersti, R., U. Milgelgrin, and B. Yaron. 1977. Behavior of Vapam and methylisothiocyanate in soils. Soil Sci. Soc. Am. J. 41:545-548.

Giron, M.Y. and J.J. Morrell. Fungi colonizing preservative-treated Douglas-fir poles after remedial treatment with fumigant. Canadian Journal of Microbiology (in press).

Giron, M.Y. and J.J. Morrell. Interactions between microfungi isolated from fumigant-treated Douglas-fir heartwood and Poria placenta or Poria carbonica. Wood and Fiber Science (in review).

Goodell, B.S. 1989. Evaluation of encapsulated and gelled chloropicrin formulations for use in wood poles. Wood and Fiber Science 21:37-44.

Goodell, B.S. 1983. Microdistribution and retention of chloropicrin in Douglas-fir [Pseudotsuga menziesii (Mirb.) Franco] heartwood. Ph.D. thesis. Oregon State Univ., Corvallis, Oreg. 93 pp.

Goodell, B.S. 1981. A note on the toxicity of chloropicrin vapors to Gloephyllum saepiarium and Poria sp. in wood. Wood and Fiber 13:138-143.

Goodell, B.S. 1979. Chloropicrin movement and fungitoxicity in decaying southern pine laminated timbers. M.S. thesis. Oregon State Univ., Corvallis, Oreg. 92 pp.

Goodell, B.S., G.G. Helsing, and R.D. Graham. 1984. Responses of Douglas-fir trees to injection of chloropicrin. Canadian Journal of Forest Research 14:623-627.

Goodell, B.S. and R.D. Graham. 1983. A survey of methods used to detect and control fungal decay of wood poles in service. International Journal of Wood Preservation 3(2):61-63.

Goodell, B.S., R.D. Graham and R.L. Krahmer. 1980. Chloropicrin movement and fungitoxicity in a decaying southern pine laminated timber. Forest Products Journal 30(12):39-43.

Goodell, B.S., R.L. Krahmer, and R.D. Graham. 1986. Bound chlorinated residue in chloropicrin-treated Douglas-fir. Wood and Fiber Science 18(1):127-133.

Goodell, B.S., R.L. Krahmer, and R.D. Graham. 1985. Residue retention and fungal invasion of chloropicrin-treated Douglas-fir. Forest Products Journal 35(2)45-49.

Graham, R.D. 1979. In large timbers fumigants stop rot that good design could have prevented. Forest Products Journal 29(9):21-27.

Graham, R.D. 1973a. Preventing and stopping internal decay of Douglas-fir poles. Holzforschung 27(5):168-173.

Graham, R.D. 1973b. Fumigants can stop internal decay of wood products. Forest Products Journal 23(2)35-38.

Graham, R.D. and G.G. Helsing. 1979. Wood pole maintenance manual: inspection and supplemental treatment of Douglas-fir and western redcedar poles. Research Bulletin 24. Forest Research Laboratory, Oregon State University, Corvallis, Oreg.

Graham, R.D., T.C. Scheffer, G.G. Helsing, and J.D. Lew. 1976. Fumigants can stop internal decay of Douglas-fir poles for at least 5 years. Forest Products Journal 26(7):38-41.

Hand, O.F., P.A. Lindgren, and A.F. Wetsch. 1970. The control of fungal decay and insects in transmission poles by gas phase treatment. Branch Lab., Bonneville Power Adm., Vancouver, Wash. 28 pp.

Helsing G.G., R.D. Graham, and M.A. Newbill. 1984a. Effectiveness of fumigants against marine wood-borers. Forest Products Journal 34(6):61-64.

Helsing, G.G, J.J. Morrell, and R.D. Graham. 1986. Service life of Douglas-fir piles: methods for protecting cut-off tops from decay. Forest Products Journal 36(2):21-24.

Helsing, G.G., J. Morrell, and R.D. Graham. 1984b. Evaluations of fumigants for control of internal decay in pressure-treated Douglas-fir poles and piles. Holzforschung 38(5):277-280.

Highley, T.L., and W.E. Eslyn. 1982. Using fumigants to control interior decay of waterfront timbers. Forest Products Journal 32(2):32-34.

Houston, D.R., and H.G. Eno. 1969. Use of soil fumigants to control spread of Fomes annosus. USDA Forest Serv. Res. Pap. NE-123. 3pp.

Jones, T.W. 1963. Fumigation may end oak embargos. Forest Products Journal 13(12):564.

Liese, W., and M. Rütze. 1984. Development of a disinfection treatment for oak logs to be imported from the USA. International Research Group on Wood Preservation IRG/WP/3283. Stockholm, Sweden.

Liese, W., H. Knigge, and M. Rütze. 1981. Fumigation experiments with methyl bromide on oak wood. Material und Organismen 16(4):265-280.

Miller, D.B. and J.J. Morrell. Interactions between sodium n-methyldithiocarbamate and Douglas-fir heartwood. Wood and Fiber Science (in review).

Morrell, J.J. 1989. Fumigant treatments for prolonging utility pole service life: recent developments. Transmission and Distribution (in press).

Morrell, J.J. 1988. Conserving energy by safe and environmentally acceptable practices in maintaining and procuring transmission poles. Eighth Annual Report, Cooperative Pole Research Program, Oregon State University, Corvallis, Oregon. 118 p.

Morrell, J.J. and M.E. Corden. 1986. Controlling wood deterioration with fumigants: a review. Forest Products Journal 36(10):26-34.

Morrell, J.J., M.E. Corden, A.R. Zahora, and M.Y. Giron. 1986a. Application of fumigants to control decay fungi colonizing Apitong, Tangile, Eucalyptus, and Scots Pine. Material und Organismen 21(4):265-271.

Morrell, J.J., G.G. Helsing and R.D. Graham. 1984. Marine wood maintenance manual: a guide for proper use of Douglas-fir in marine exposures. Research Bulletin 48. Forest Research Laboratory, Oregon State Univ., Corvallis, Oreg.

Morrell, J.J., S. Kumar, C.M. Sexton, and M.A. Newbill. 1988. Fumigant treatment of Eucalyptus. Journal, Timber Development Association (India) 34(2):35-39.

Morrell, J.J. and S.T. Lebow. Volatile emissions from Douglas-fir heartwood treated with Vapam or methylisothiocyanate. Forest Products Journal (in press).

Morrell, J.J. and M.A. Newbill. Distribution of chloropicrin or methylisothiocyanate in Douglas-fir trees treated with wood fumigants. Forest Science (in review).

Morrell, J.J., and T.C. Scheffer. 1985. Persistence of chloropicrin in western redcedar poles. Forest Products Journal 35(6):63-67.

Morrell, J.J., C.A. Sexton, and S. Lebow. 1988. The effect of pH on decomposition of Mylone (Dazomet) and tridipam to fungitoxic methylisothiocyanate in wood. Wood and Fiber Science 20(4):422-430.

Morrell, J.J., S.M. Smith, M.A. Newbill, and R.D. Graham. 1986b. Reducing internal and external decay of untreated Douglas-fir poles: a field test. Forest Products Journal 36(4):47-52.

Munnecke, D.E. 1984. Establishment of micro-organisms in fumigated avocado soil to attempt to prevent reinvasion of the soil by Phytophthora cinnamoni. Transactions British Mycolological Society 83(2):287-294.

Murphy, R.J. and D.J. Dickinson. 1986. Diffusion treatment of sawn Sitka Sprice. Annual Record, British Wood Preserver's Association 1986 (pp 46-54).

Nelson, E.E., B. Goldfarb, and W.G. Thies. 1987. Trichoderma species from fumigated Douglas-fir roots decayed by Phellinus weirii. Mycologia 79:370-374.

Nelson, E.E., N.E. Martin, and R.E. Williams. 1981. Laminated root rot of western conifers. USDA Forest Service, Forest Insect and Disease Leaflet 158. 6 p.

Newbill, M.A. and J.J. Morrell. Evaluation of methylisothiocyanate, chloropicrin, or Vorlex for preventing and controlling marine borer attack of Douglas-fir piling. Forest Products Journal (in review).

Panek, E., J.O. Blew, Jr., and R.H. Baechler. 1961. Study of groundline treatments applied to five pole species. USDA Forest Service, Forest Products Laboratory Report 2227. Madison, Wisconsin.

Partridge, A.D. 1961. Fumigants kill the oak wilt fungus in wood. Forest Products Journal 11(1):12-14.

Ricard, J.L., T.E. See, and W.B. Bolen. 1967. Control of incipient decay with gases in Douglas-fir poles. Forest Products Journal 18(4):45-51.

Ruddick, J.N.R. 1986. Fumigant movement in Canadian wood species. Proceedings (Pages 112-132), The Wood Pole Conference, Portland, OR.

Ruddick, J.N.R. 1984. Fumigant movement in Canadian wood species. International Research Group Wood Preserv. IRG/WP/3296. Stockholm, Sweden.

Scheffer, T.C. and R.D. Graham. 1975. Bioassay appraisal of Vapam and chloropicrin fumigant-treating for controlling internal decay of Douglas-fir poles. Forest Products Journal 25(6):50-56.

Schmidt, E.L. 1983. Laboratory fumigations to determine the minimum temperature for methyl bromide eradication of the oak wilt fungus in red oak. International Research Group on Wood Preservation. IRG/WP/3243. Stockholm, Sweden.

Schmidt, E.L., M.M. Ruetze, and D.W. French. 1982. Methyl bromide treatment of oak wilt infected logs: laboratory and preliminary field fumigations. Forest Products Journal. 32(3):46-49.

Thies, W. 1984. Laminated root-rot: the quest for control. Journal of Forestry 82(6):345-356.

Thies, W.G. and E.E. Nelson. 1987a. Reduction of Phellinus weirii inoculum in Douglas-fir stumps by the fumigants chloropicrin, Vorlex, or methylisothiocyanate. Forest Science 33(2):316-329.

Thies, W.G. and E.E. Nelson. 1987b. Survival of Douglas-fir injected with the fumigants chloropicrin, methylisothiocyanate or Vorlex. Northwest Science 61(1):60-64.

Turner, N.J. and M.E. Corden. 1963. Decomposition of sodium N-methyldithiocarbamate in soil. Phytopathology 53:1,388-1,394.

Vinden, P. 1984. Preservative treatment of green timber by diffusion. International Research Group on Wood Preservation IRG/WP/3291.

Zabel, R.A. and C.J. K. Wang. 1988. Utility pole problems in the Eastern United States: changing viewpoints. Proceedings (Pages 69-80), The Wood Pole Conference II, Portland, OR.

Zabel, R.A., C.J.K. Wang, and F.E. Terracina. 1982. The fungal associates, detection, and fumigant control of decay in treated southern pine poles. Report EL2768. Electric Power Research Institute, Palo Alto, Calif. 80 pp.

Zahora, A.R. 1983. Methylisothiocyanate as a wood fumigant: fungitoxicity to Poria carbonica in wood and gelatin encapsulation for use in wood products. M.S. thesis. Oregon State University, Corvallis, Oreg. 65 pp.

Zahora, A.R. 1987. Interactions of the fumigant methylisothiocyanate with Douglas-fir used and their influence on fumigant effectiveness. Ph.D. Dissertation Oregon State University, Corvallis, Oregon.

Zahora, A.R. and M.E. Corden. 1985a. Gelatin encapsulation of methylisothiocyanate for control of wood decay. Forest Products Journal 35(7):64-69.

Zahora, A.R. and M.E. Corden. 1985b. Methylisothiocyanate fungitoxicity to Poria carbonica in Douglas-fir heartwood. Material und Organismen 20:193-204.

Zahora, A.R., P.E. Humphrey, and J.J. Morrell. 1988. Preliminary modeling of methylisothiocyanate movement through Douglas-fir transmission poles. International Research Group on Wood Preservation IRG/WP/3466.

Zahora, A.R. and J.J. Morrell. 1989. Diffusion and sorption of the fumigant methylisothiocyanate in Douglas-fir wood. Wood and Fiber Science 21:55-66.

Zahora, A.R. and J.J. Morrell. 1988a. A note on the sensitivity of a closed-tube bioassay to volatile methylisothiocyanate residues in fumigant-treated wood. Wood and Fiber Science 20:91-96.

Zahora, A.R. and J.J. Morrell. 1988b. Decomposition of methylisothiocyanate in Douglas-fir heartwood. Forest Products Journal 38(10):46-52.

Zahora, A.R. and J.J. Morrell. The influence of wood moisture content on the fungitoxicity of methylisothiocyanate in Douglas-fir heartwood. Wood and Fiber Science (in review)