In-Place Preservative Treatments for Covered Bridges

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Abstract

Covered bridges can be vulnerable to damage from fungal decay and insect attack. This paper describes procedures for selecting and applying in-place treatments to prevent or arrest biodegradation, and summarizes recent research evaluating some of these treatments. Wood moisture is the key to decay and termite attack, and the first line of defense against biodeterioration is to minimize moisture intrusion through prompt maintenance and repair. Biodeterioration will tend to be more prevalent wherever members contact abutments, are near the ends of bridges subject to wetting from splashing, or are below windows or other openings that allow entry of wind-blown precipitation. In-place preservative applications can help limit deterioration when moisture cannot be eliminated. The goal of in-place treatment is to distribute preservative into areas of a structure that are vulnerable to moisture accumulation. In-place treatments include surface coatings, pastes, rods, gels and fumigants. Some preservative treatments may cause a color change in the treated wood and/or present safety and handling concerns. One limitation of all these treatments is that they cannot be forced deeply into the wood as is done in pressure-treatment processes. However, some can be applied into the center of large members via treatment holes and can move through the wood by vaporization or diffusion. Laboratory research compared the movement of 7 water diffusible treatments and 3 fumigant treatments as a function of moisture content, wood species and dosage. Field research evaluated the mobility of two water diffusible treatments and two fumigants placed into timbers in 5 covered bridges. The wood in many covered bridge timbers was too dry to promote diffusion. Water diffusible treatments must be applied in locations where moisture accumulation is suspected. Fumigants have greater potential for movement in dry bridge timbers and refractory wood species.

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Introduction

Wood, the primary building material of covered bridges, is vulnerable to biodeterioration if exposed to moisture. Decay fungi are the most common causes of deterioration, although insects, and especially subterranean termites, can also be important cause of deterioration in warmer climates. With few exceptions, degradation by both decay fungi and termites can be prevented if wood is protected from moisture. Covered bridges were designed to prevent such biodeterioration by keeping the wood dry. However, protecting all bridge members from moisture is difficult, even in well-designed and well-maintained covered bridges. Significant decay can occur in any untreated portion of a bridge where oxygen is present and the wood moisture content is above 20-25% for sustained periods. Sufficient oxygen and moisture are almost always present in members placed in contact with the ground or waterline area of members placed in water. In most climates there is also sufficient moisture for decay in members that are not directly in contact with soil or water and are not protected by a covering. In general, larger members are most prone to developing decay because water becomes trapped inside the wood during precipitation events and leaves more slowly during subsequent dry weather. Liquid water is rapidly absorbed in end-grain during rain events, and subsequent drying can be slowed if air movement is restricted in that area. These conditions commonly exist at connections where members are joined by fasteners or other means.

One of the most common, and critical areas of deterioration in covered bridges is where the support members (bottom chord or bedding timbers) contact some form of an abutment (Lebow, et al., 2012). Although the abutment area may be largely protected by the bridge roof, several factors combine to increase the risk of moisture accumulation: 1) the stone or masonry used to construct abutments can wick and hold moisture, 2) the location near the end of the bridge increases the likelihood that water will enter through the bridge deck above, and 3) high humidity and lack of air movement in this area retards drying. Similarly, all large members near the end of the bridge may be vulnerable to wind-blown or splashed precipitation. The deck members, the lower portions of the end posts, the ends of the bottom chords, and the ends of the diagonal bracing may all be exposed to wetting, depending on construction and site conditions. Wetting of deck members near the ends of bridges is especially likely in bridges with vehicular traffic. Areas below windows or other designed openings in the side of a bridge provide additional potential avenues for moisture intrusion. Although these openings are typically placed relatively high on the side of a bridge, the overhang length is not always sufficient to exclude moisture.

Other areas of covered bridges become vulnerable to moisture as a result of leaks or vandalism. Sources of moisture from openings in the roof or cladding can occur almost anywhere in a bridge and are not always easily detected. However, water stains or general discoloration may be visible. The area where decay develops may not be immediately adjacent to the where water enters the structure. As with other sources of moisture, problems are most likely to develop in larger members or at connections where moisture is slow to dry. Vandalism is a frequent cause of water intrusion. Cladding may be repeatedly removed to allow access for fishing or swimming, exposing the bottom chords to precipitation. Any portion of a bridge where the cladding has been lost for an extended period, or even for several shorter periods, may be vulnerable to decay.

Protecting wood from moisture is the most effective means of preventing biodeterioration in covered bridges, and moisture exclusion should be the first option. However, when protection from moisture is not practical, appropriately applied preservative treatments can provide additional protection against biodeterioration. This paper summarizes the properties and application of in-place preservative treatments, and discusses recent research evaluating the ability of some of these treatments to move through and protect covered bridge timbers.

Characteristics of In-Place Treatments

In-place or remedial preservative treatment refers to a broad range of preservatives and application methods. Examples include finishes, boron rods and fumigants. The objective of all these treatments is to protect areas of a structure that are vulnerable to moisture accumulation. Decay in covered bridges typically results from occasional wetting by wind-blown rain, from leaks, or from splashing by vehicles. Because the moisture supply is intermittent, decay is most likely to occur in the center of large timbers where water enters through checks or end-grain and drying occurs more slowly. Unfortunately, preservative treatment of the interior of large timbers is challenging because the majority of many of these timbers consists of less permeable heartwood. Surface treatments often penetrate only a few millimeters into dry wood, and treatment choices are often limited because of environmental concerns about the risk of spills over water. Internal treatments that are applied as solids, such as fumigants and rods have the potential to overcome these problems.

Diffusible preservatives

Diffusible preservatives, or diffusible components of preservatives, move slowly through water within the wood structure. Diffusible preservatives do not react with or “fix” in the wood, and thus are able to diffuse through wood as long as sufficient moisture is present. The distance or extent of diffusion is a function of preservative concentration, wood moisture content, and grain direction. A concentration gradient is needed to drive diffusion, and concentration can become a limiting factor with surface (spray) applied surface treatments because the volume of actives applied to the surface is limited. The most commonly available diffusible preservatives are based on some form of boron (Table 1), although sodium fluoride is also sometimes used as a diffusible treatment. This chemical is effective against decay fungi, but less commonly used to protect against insects.

Boron-based supplemental treatments have several advantages. Boron has efficacy against both decay fungi and insects, but has relatively low toxicity to humans. The sodium borate formulations used as field treatments are also relatively simple to dilute with water prior to application. Borates are also odorless and colorless and, when diluted, typically do not interfere with subsequent application of finishes.

Borate field treatments are available in a range of forms including powders, gels, thickened glycol solutions, solid rods and as one component of preservative pastes. The concentration of actives is usually expressed as percent disodium octaborate tetrahydrate (DOT), although concentration is sometimes expressed as boric acid equivalents (BAE) or boron oxide (B_2O_3) equivalents. Typically, wood moisture contents of at least 20% are thought to be necessary for boron diffusion to occur. While this moisture level is often surpassed for wood exposed outdoors, wood members more protected from moisture may be below this moisture content. Diffusion appears to be substantially more rapid at wood moisture contents in excess of 40%. Diffusion at higher moisture contents is much greater along than across the wood grain, but this effect may be less apparent at lower moisture contents.

Powdered borates typically contain 98% DOT, and are often the least expensive on the basis of active ingredient purchased. The powder is mixed (by weight) with water for use in spray or brush applications. Solution concentrations in the range of 15% DOT can be achieved with the combination of warm water and vigorous agitation. Powdered borates can also be poured or packed into holes for internal treatments but this method of application can be labor intensive and increases the risk of spillage.

Thickened glycol-borate solutions typically contain 40% DOT, although one product contains 50% DOT. The syrupy liquid is then diluted 1:1 or 1:2 with water, yielding a solution containing approximately 22% or 15% DOT. Lower concentrations can also be prepared if desired. Glycol formulations allow a greater borate solution concentration than the powders and dilution by volume rather than weight can also be advantageous in some situations. The more viscous and more concentrated glycol-borate solutions are also thought to allow deposition of higher concentrations of boron on the wood surface during spray applications.

Glycol-borates solutions can be applied by spray or brush, or used to flood cut-ends or holes. Water in the solution allows some diffusion to occur, even in dry wood. This effect is greatest for applications that provide a reservoir of solution, such as in filling treatment holes. Foaming agents and specialized equipment can also allow these formulations to be applied as foams. This approach has been used by the National Park Service for treatment of difficult to access areas in historic wooden vessels.

Table 1. Summary of supplemental preservative treatments properties and applications (*continued on next page*)

Applied As:	Actives	Supplied As:	Dilution	EPA Hazard Category	Uses	Mobility in Wood	Examples of Trade Name (s)
Liquid	98% DOT	Powder	Dilute to 10-15% in water (by weight)	Caution	Surface spray, brush, or foam, Internal injection, poured in holes	High	Board Defense, Borasol, Timbor, TimberSaver, Armour-guard
Liquid	25 - 40% DOT	water/glycol based	Dilute 1:1 with water	Caution	Surface spray or brush, poured into holes	High	Bora care, Bor-Ram, BoraThor, Shell-guard
Liquid	Copper Naphthenate,1-2% as Cu	Oil or water based	RTU[a]	Warning	Surface spray or brush, poured into holes, pads for bandages	Low	QNAP1, QNAP2, QNAP1w, QNAP2w
Liquid	9.1% DOT, 0.51% boric acid, 0.96% copper hydroxide (0.6% copper)	Water based	RTU[a]	Caution	Surface spray, brush, or foam, Internal injection,	B high, Cu Low	Genics CuB
Liquid	Copper Naphthenate, 5% as Cu	Water based	Dilute 1:4 or 1:1.5 with water	Danger	Surface spray or brush, poured into holes	Low	QNAP5w
Liquid	Copper Naphthenate, 8% as Cu	Oil based	Dilute 1:3.0-3.8 or 1:7.5-8 with oil	Warning	Surface spray or brush, poured into holes	Low	QNAP8
Liquid	Copper-8-quinolinolate (0.675%)	Oil based	RTU[a]	Caution	Surface spray or brush, poured into holes,	Low	Outlast Q8 Log Oil
Liquid	33% Sodium N-methyldithiocarbamate	Liquid fumigant	RTU[a]	Danger	Internal fumigant treatment. Poured into holes	Gas, Very High	WoodFume, SMDC-Fume, Pol Fume
Rod	100% Anhydrous Disodium Octaborate	Rod	RTU[a]	Caution	Placed into holes	High	Impel Rod
Rod	93% Sodium fluoride	Rod	RTU[a]	Warning	Placed into holes	High	FluRod
Rod	90.6% DOT, 4.7% Boric acid, 2.6% Cu	Rod	RTU[a]	Caution	Placed into holes	B high, Cu Low	Cobra Rod

Table 1. Summary of supplemental preservative treatments properties and applications, *concluded from previous page*

Applied As	Actives	Supplied As:	Dilution	EPA Hazard Category	Uses	Mobility in Wood	Examples of Trade Name (s)
Granules	98% Dazomet (decomposes to MITC)	Granule	RTU	Danger	Internal fumigant treatment. Placed into holes	Gas,Very High	Dura-fume
Granules	98% Dazomet (decomposes to MITC)	Granule	RTU	Danger	Internal fumigant treatment. Placed into holes	Gas,Very High	Super-Fume
Capsule (paper tube)	98% Dazomet (decomposes to MITC)	Capsule	RTU	Danger	Internal fumigant treatment. Placed into holes	Gas,Very High	Super-Fume
Capsule	97% Methylisothiocyanate (MITC)	Capsule	RTU	Danger, Poison, Restricted	Internal fumigant treatment. Placed into holes	Gas,Very High	MITC-FUME
Paste	43.5% Borax, 3.1% Copper hydroxide (2% Cu)	Paste	RTU	Warning	With exterior wrap for groundline area, spread under pile caps, injected into holes (caulking gun)	Cu Low, B high	Cu-Bor
Paste	40% Borax, 18% Copper Naphthenate (2% Cu)	Paste	RTU[a]	Warning	With exterior wrap for groundline area, spread under pile caps, injected into holes (caulking gun)	Cu Low, B high	CuRap 20
Paste	43.7% borax, 0.2% tebuconazole, 0.04% bifenthrin, 0.3 % copper quinolinolate (0.05% Cu)	Paste	RTU[a]	Caution	With exterior wrap for groundline area, spread under pile caps, injected into holes (caulking gun)	B high, others low,	MP400-EXT
Gel	40% DOT	Gel	RTU[a]	Caution	Internal, injected into holes	High	Jecta

[a]Ready To Use (no dilution or mixing is required prior to application)

Borate gels are currently less widely available than other forms of borates, but are provided by at least one manufacturer. The gel contains 40% DOT and is provided in tubes for application with standard caulking guns. An advantage of gel formulations is that that they can be applied to voids, cracks and treatment holes that are oriented horizontally or downward and would not contain liquid borates. They are also convenient to apply, but are typically the most costly form of borates on the basis of active ingredient purchased.

Rods contain active diffusible preservatives compressed or fused into a solid for ready application into treatment holes. The most common active ingredient is boron (with or without copper), although one product is composed of sodium fluoride. The advantages of rod formulations are their ease of application, low risk of spillage, and their ability to be applied to holes drilled upward from under a member. One disadvantage of the rods is that their application does not include water to assist the initial diffusion process. Some applicators address this limitation by drilling slightly over-size treatment holes and filling the void space around the rod with a borate solution.

Paste formulations typically contain at least one component that diffuses into the wood and at least one other component that is expected to provide long term protection near the surface. The most common diffusible component is some form of borate, although one formulation utilizes fluoride. The less mobile component is commonly some form of copper. Pastes tend to be more complex mixtures of actives than other types of supplemental treatments. The paste treatments are most commonly applied to the ground line area of terrestrial support timbers or piles. Copper-containing pastes have a blue or green color and may not be appropriate for areas where maintenance of a natural or historic appearance is important. Pastes also leave a residue on the wood surface in the application area.

In some instances, water based external treatments that contain both non-diffusible and diffusible components may be injected under low pressure. These products are most effective for treatment of voids. They are typically viscous in nature and will not run out of the wood as quickly or easily as non-diffusible liquids.

Non-diffusible liquids

The oldest and simplest method for field treatment involves brushing or spraying a preservative onto the surface of the suspected problem area. These solutions do not penetrate more than a few millimeters (a few 10^{ths} of an inch) across the grain of the wood, although greater penetration is possible parallel to the wood grain of the wood. In general, however, these treatments do not move great distances from their point of application. The preservatives in this category are applied as liquids, but have some ability to resist leaching once applied to the wood. Oil-based preservatives, for example, resist leaching because of their low water-solubility. For decades, pentachlorophenol and creosote solutions were used for this purpose but their use is now restricted to pressure-treatment facilities. Most liquid treatments now utilize some form of copper (i.e. copper-8-quinolinolate or copper naphthenate).

Oil-based copper naphthenate is available in copper concentrations ranging from 1 – 8% (as elemental copper). The solution is typically applied at 1 – 2% copper concentration, and more concentrated solutions are diluted with mineral spirits, diesel, or a similar solvent. These solutions impart an obvious green color to the wood although some of the 1% copper solutions are tinted to dark brown or black. Naphthenates also have noticeable odor.

Water-based copper naphthenate is currently less widely used than the oil-based formulations. It is available as a concentrate containing 5% copper, and can be diluted with water. The water-based formulation has a somewhat less noticeable odor, and the color is more blue than green. The water-based formulation is slightly more expensive than the oil-based form, and may not penetrate as deeply into the wood as the oil-based form.

Oil-based copper-8-quinolinolate was recently standardized by the American Wood Protection Association for field-treatment of cuts, holes or other areas of untreated wood exposed during construction. It is available as a Ready-to-Use solution containing 0.675% copper-8-quinolinolate (0.12% as copper metal) as well as incorporated water repellents. It has a light greenish color, although it can be tinted to some extent. It can be applied by immersion, brushing or spraying.

Fumigants

Fumigants are used to internally treat large logs or timbers. Like some diffusible formulations, fumigants are applied in liquid or solid form in predrilled holes. However, they then volatilize into gasses that move much greater distances through the wood than do the diffusible treatments. One type of fumigant has been shown to move over 2.4 m (8 ft) along the grain from point of application in poles. To be most effective, a fumigant should be applied at locations where it will not readily volatilize out of the wood to the atmosphere. Fumigants should not be applied into voids or when application holes intersect voids or checks in order to prevent accidental release of the product into the environment. Care and caution should be taken in the removal of wood structures that have been treated with fumigants to prevent exposure. All but one the commercial fumigants (chloropicrin) eventually decompose to produce the active ingredient methylisothiocyanate (MITC). Fumigant treatments are generally more toxic and more difficult to handle than the diffusible treatments. Some are classified as Restricted Use Pesticides by the US. EPA, requiring extra precautions. Fumigants are usually applied by specially trained personnel.

Liquid fumigants are poured into pre-drilled treatment holes, necessitating that they be applied from above. A fumigant commonly applied in liquid form is metam sodium (33% Sodium N-methyldithiocarbamate). This liquid formulation tends to be less expensive than other sources of MITC, but also contains a lower proportion of active ingredient. Chloropicrin is only available in liquid form. It is a very effective fumigant, but also difficult to handle safely because of its volatility. Its use is generally confined to critical structures in rural areas.

Granular fumigants are poured into pre-drilled treatment holes in a manner similar to liquids. The current formulations utilize granular dazomet (98% tetrahydro-3, 5-dimethyl-2-H-1,3,5, thiodazine-6-thione), that decomposes to produce MITC. The granular fumigant formulations offer relatively easy handling compared to the liquid metham sodium, and also contain a higher percentage of the active ingredient. However, they decompose to produce MITC more slowly than the liquids, and in some cases liquid additives are also poured into the treatment hole to promote decomposition.

Encapsulated fumigants are pre-packaged for convenient application, and have the added advantage of allowing holes to be drilled from below. In addition to convenience, these encapsulated fumigants minimize the risk of spillage when applications are made over water or any other sensitive environments. One encapsulated product contains the same granular dazomet that is poured into holes. It is encased in a tube-shaped air-permeable membrane that contains the granules while allowing MIT gas to escape. Another encapsulated product is comprised of an aluminum tube filled with solid 97% MITC. At the time of application, a special tool is used to remove the air-tight cap from the tube, and MITC vapors are released through this opening. A disadvantage of the encapsulated fumigants is their higher costs, and that they require a minimum treatment-hole diameter and depth for application.

Application Guidelines for In-place Treatments

Internal treatments

Decay may become established in large timbers because once moisture penetrates deeply into the wood it is slow to dry. Large timbers are typically too thick to effectively treat the interior with surface application of preservatives. Internal treatments are typically applied by drilling holes into the wood, but there are many variations on this approach.

Diffusible internal treatments

Diffusible internal treatments generally do not move as far through the wood as do fumigants, and so their location and spacing is critical. Although they could be used to treat the length of timbers or beams, they may be better suited to protection of specific vulnerable areas such as near connections as well as areas around fasteners. The extent of movement of these diffusible treatments has been shown to vary with wood moisture content and wood species, although wood moisture content is probably the most important factor. Wood moisture content is typically lower for wood above ground than wood used in ground contact, and studies of boron movement from internal treatments have indicated somewhat limited mobility in above-ground timbers with low moisture content.

Research indicates that solid boron rods applied to above-ground timbers generally need to be placed no more than 51 mm (2 in.) apart across the grain and 305 mm (12 in.) apart along the grain. Tighter spacing may be needed for some less permeable species, as there is substantial variability in boron mobility in timbers treated with combinations of liquid and solid internal treatments. In more permeable pine timbers, spacing of approximately 76 mm (3 in.) across the grain and between 76 and 125 mm (3 – 5 in.) along the grain may be sufficient to achieve overlapping boron penetration. The manufacturer of one of the boron rod products recommends parallel to the grain spacing of between 152 – 381 mm (6 – 15 in.) depending on the size of the timber and the size of the rod installed. They also recommend that the across the grain distance between treatment holes not exceed 152 mm (6 in.). It should be noted that parallel to the grain diffusion of boron away from the rods may not be symmetrical in vertical members. Highley et al. (1996) noted that downward boron diffusion was much greater than upward boron diffusion when rods were placed into Douglas-fir transmission poles.

Liquid borates may be applied in a similar manner as rods, except that their use is generally limited to holes oriented downward. The concentration of boron in the liquid treatments is not as great as that in the rods, but the potential for diffusion is greater at lower wood moisture contents. The liquid borates also provide protection more rapidly than the rods, but the duration of protection is more limited. Liquid borates also allow more flexibility in the size of the treatment hole, and in some cases, it may be desirable to drill many small holes instead of a few large holes. The liquids can be readily applied to smaller treatment holes with squeeze or squirt bottles. In situations where the treatment holes are protected from precipitation and public access, the holes can be temporarily left un-plugged to allow re-filling as the liquid moves out of the treatment hole and into the wood. Alternatively, a rod can be placed into the treatment hole after the liquid has drained into the wood. It is worth noting however, that movement of liquid is slow through the heartwood of many wood species, and that the time required for the hole to empty may be longer than anticipated. Rods and liquid borates can also be simultaneously added to treatment holes by drilling holes slightly larger than needed to accommodate the rod. This approach can provide both an immediate boost of liquid boron as well as the longer-term slow-release from the rod, but it does require drilling a larger treatment hole than would otherwise be necessary.

Liquid borates have also been injected into small treatment holes in horizontal timbers using a low-pressure sprayer, with the nozzle pressed tightly against the treatment hole to prevent leakage. Under these conditions, a diamond pattern has been recommended, with 305 mm (12 in.) between holes along the grain and 102 to 152 mm (4 - 6 in.) across the grain. It is likely that penetration achieved using this approach would depend greatly on wood permeability. Risk of spillage into the area below the structure is likely to be higher with this approach than with non-pressure applications.

Gels and paste products may also be applied as diffusible internal treatments in a manner similar as liquids and rods. Depending on the properties of the individual product, they may be applied to holes that are horizontal or even oriented upward. Application to treatment holes is typically accomplished with use of a caulking tube and caulking gun. In theory these formulations provide somewhat of a compromise between the liquid formulations and the solid rods, with slower distribution than the liquids but more rapid distribution than rods. However, there is little published research comparing the penetration or longevity of these formulations to that of the other formulations.

There is also limited information on the mobility of internal diffusible preservatives other than boron. Both fluoride and copper have been incorporated into internal treatments, and fluoride has been used as a stand-alone preservative in a rod form. The mobility of copper when applied in this manner appears very limited, probably as a result of lower water solubility and its tendency to react with and "fix" to the wood structure. Fluoride is thought to have diffusion properties similar to boron, although this assumption is not well-documented by research.

Fumigants

To be most effective, a fumigant should be applied at locations where it will not leak away or be lost by diffusion to the atmosphere. When fumigants are applied, the member should be inspected thoroughly to determine an optimal drilling pattern that avoids metal fasteners, seasoning checks, and severely rotted wood (Highley and Scheffer, 1989). Manufacturers have developed specific guidance for application of their products to round vertical members such as posts, poles and piles. Although these application instructions vary somewhat between products, they generally specify drilling holes of 19 - 22 mm (0.75 – 0.825 in.) diameter downward at angle of 45° to 60° through the center of the round member. The length of the hole is approximately 2.5 times the radius of the member. A minimum hole length of 305 mm (12 in.) is required for the use of the MITC-FUME tube, necessitating the use of a steeper drilling angle in smaller diameter members. In ground-contact applications the first hole is drilled at or slightly below the ground line. Subsequent holes are drilled higher on the member, moving up and around in a spiral pattern. Depending on the product and diameter of the member, the holes should be spaced at either 90° or 120° around the circumference. The recommended vertical distance between treatment holes varies from 152 to 305 mm (6 - 12 in.) near the groundline, with 305 mm (12 in.) spacing used higher on the member. Fumigants are not specifically labeled for application to aquatic structures, but at a minimum the lowest part of a treatment hole should be above the normal high water mark.

There is much less information on application of fumigants to large timbers. Holes are typically drilled into a narrow face of the member (usually either the top or bottom). Holes can be drilled straight down or slanted; slanting may be preferable because it provides a larger surface area in the holes for escape of fumigant. As a rule, the holes should be extended to within about 51 mm (2 in.) of the bottom of the timber and should be no more than 1.22 m (4 ft) apart. Treatment holes can be drilled upward in a similar manner with the encapsulated solid fumigants. Solid fumigants provide a substantial advantage in treatment of timbers and beams because often only the bottom face is readily accessible. A disadvantage of the pre-encapsulated fumigants is that they require a minimum size of treatment hole, and thus, cannot be used on smaller members. The applicator should also consider the potential effect of drilling a relatively large treatment hole or holes on the strength properties of the member.

When treating with fumigants, the treatment hole should be plugged with a tight-fitting treated wood dowel or removable plastic plug immediately after application. Sufficient room must remain in the treating hole so the plug can be driven without squirting the chemical out of the hole or impacting the solid fumigant. The amount of fumigant needed and the size and number of treating holes required depend on timber size. Fumigants will eventually diffuse out of the wood, allowing decay fungi to re-colonize. Fumigant can be applied at a later date to the same treatment hole, a process that is made easier with the use of removable plugs.

Non-diffusible liquids

Non-diffusible liquid treatments, typically containing copper, are sometimes used for internal treatments. Although these treatments do not diffuse in water within the wood, they can wick for several cm parallel to the wood grain. Movement across the grain is minimal. The advantage of these liquids relative to the diffusible treatments is their resistance to leaching. Thus, they may have applications where duration of efficacy is of greater importance than volume of wood protected. An example is the treatment of connector holes when substantial untreated wood is exposed during fabrication. Treatment holes can also be drilled above existing connectors, filled with preservative, and plugged. Again, this type of treatment may be desirable if subsequent fabrication or construction activities will make that area difficult to access in the future. In large members these preservative liquids may be used to flood internal voids such as decay pockets, but the risk of spillage makes this type of application less suitable for some applications.

External treatments

External treatments generally have the greatest applicability for members that have not been pressure-treated, but also have value in protecting pressure-treated wood when untreated wood is exposed by fabrication during construction. Many of the same formulation used for internal treatments can also be used for external treatment. Protection is generally limited to within a few millimeters of the wood surface, although greater movement does occur when solutions are applied to the end-grain of wood. Surface-applied diffusible treatments can also achieve deeper penetration under some conditions. However, broad scale surface sprays can be problematic from the viewpoint of environmental contamination, and potential benefit from this approach must be weighed against this risk. In many cases it may be more practical to limit surface applications to localized areas.

Diffusible liquid preservatives (borates) are typically applied with low-pressure sprayers or by brushing in smaller areas. The greatest benefit is achieved by flooding checks, cracks and other openings, potentially allowing diffusion into decay-prone areas where water precipitation has become trapped within the wood. Because of this it is often desirable to apply the solution after a prolonged dry interval, when checking in the wood is at a maximum. Borates applied to the wood surface can be rapidly depleted if the wood is exposed to precipitation or other forms of liquid water. Borate depletion from exposed members can be slowed (but not completely prevented) with application of a water-repellent formulation after the borate treatment has dried. This may necessitate tarping or otherwise protecting the treated members until they have dried sufficiently to allow application of the water-repellent. Use of preservative-based water repellents (for example containing copper naphthenate) can provide further protection to the wood surface. This process can be repeated after the wood surface loses its water repellency. Surface application of non-diffusible liquid treatments is typically limited to exposed situations where their resistance to leaching is a key attribute. As mentioned above, the oil-type non-diffusible liquids can also be applied after a diffusible treatment to slow leaching of the diffusible preservative and to provide long term protection.

The most common external use of gels and pastes is in the protection of the ground-line area of support poles, posts or timbers as part of a wrap system. Soil is excavated from around the support to a depth of approximately 0.46 m (18 in.) and the formulation is brushed or troweled onto the exposed wood to form a thick layer that extends 51 – 76 mm (2 – 3 in.) above the ground line. The layer of preservative is then covered with a water-impervious wrap to hold the chemical against the wood, and the excavated area is refilled. In some products the paste is incorporated directly into a wrap for ease of application. The diffusible components of the formulation (for example boron) gradually diffuse into the wood while the less mobile components remain near the wood surface. When these pastes are applied to pine sapwood, boron or fluoride may penetrate as much as 76 mm (3 in) into the wood and copper may penetrate up to up to 13 mm (0.5 in.). These treatments have been shown to offer substantial protection to the groundline area of untreated wood. This type of application must not be used in areas where standing water is expected. The same principal can also be used to protect wood above-ground that is covered with metal or a simple barrier. For example, these products can be spread on to the timbers that are subsequently wrapped with metal flashing. Metal flashing can cause moisture to condense between the metal and the wood, so treatment in this area is desirable. However, many of these formulations are not colorless, and preservative that wicks along the grain and extends beyond the cover could slightly discolor untreated wood. Similarly, pastes can be spread on the tops of cut piles before application of pile caps. Labeling also allows most of the paste products to be used for internal treatment of holes by application with a caulking gun. The paste would need to be loaded into refillable caulking tubes for application in this manner, and some users may not want to undertake this additional handling.

Summary of In-place Treatment Application Concepts

Liquid surface treatments

Surface-applied liquid treatments should not be expected to penetrate more than a few millimeters across the grain of the wood, although those containing boron can diffuse more deeply under certain moisture conditions. They will not effectively protect the interior of large piles or timbers unless applied to drill holes.

Liquid surface treatments are most efficiently used to flood checks, exposed end-grain, bolt holes, etc. They may move several centimeters parallel to the grain of the wood if the member is allowed to soak in the solution.

Surface treatments with diffusible components will be washed-away by precipitation if used in exposed members. However, their loss can be slowed if a water repellent finish is applied after the diffusible treatment has dried.

Paste surface treatments

Paste surface treatments can provide a greater reservoir of active ingredients than liquids. When used in conjunction with a wrap or similar surface barrier, these treatments can result in several centimeters of diffusion across the grain into moist wood over time. They are typically used for the groundline area of posts or timber that are not usually exposed to standing water, but can also be applied to end-grain of connections or under flashing. Some formulations can be applied under low pressure as a void treatment.

Internal treatments

These treatments are typically applied to the interior of larger members where trapped moisture is thought to be a current or future concern. They can be applied to smaller members in some situations.

Diffusible treatments move with moisture in the wood. They are generally easy to handle, but do not move for as great a distance as fumigants and do not move in dry wood. The diffusion distance in moist wood is approximately 51 – 102 mm (2 – 4 in.) across the grain and 152 – 305 mm (6 – 12 in.) along the grain. Diffusible treatments may be best suited for focusing on specific problem areas such as near exposed end-grain, connections, or fasteners.

Rod diffusible treatments provide a longer, slower release of chemical while liquid diffusible treatments provide a more rapid, but less long-lasting dose of preservative. Paste and gel internal treatments fall somewhere between rods and liquids in regards to speed of release.

Fumigant treatments move as a gas through the wood. They have the potential to move up to a meter along the grain of the wood, but have increased handling safety and application concerns compared to other internal treatments.

Research Results on In-place Preservative Treatments for Covered Bridges

The majority of research on efficacy of in-place preservative-treatments has focused on the protection of pressure-treated industrial products such as utility poles or modern highway bridges (Barnes, et al., 2011; Freitag et al., 2011; Graham, 1973; Highley et al., 1996; Morrell and Corden, 1986.; Morrell, et al. 1992, 1996, 2011; Ziobro et al., 2004). However, the conditions for such traditional uses for internal treatments differ substantially from conditions in covered bridge applications, and protecting wooden members in covered bridges can present unique challenges. In the majority of traditional applications, and particularly for fumigants, the internal treatments are applied to wood that has been pressure treated with preservative. The pressure treatment creates an outer shell that may help retain the fumigant within the inner portions of the timber. Traditional uses of internal treatments also typically involve members that are more fully exposed to the precipitation than are covered bridge timbers. This is particularly relevant for water diffusible treatments because they require moisture to move through the wood. Past research on use of internal treatments also focused on southern pine and Douglas-fir, which are the primary wood species pressure treated for use in outdoor construction projects. In contrast, covered bridges across North America were built with a range of wood species, typically utilizing species native to the area. In addition, wood used in historic covered bridges was rarely preservative treated prior to installation. To address the lack of information on use of in-pace treatments for covered bridges the FHWA funded a study titled “Identification of Preservative Treatments and Fumigants for Treating Historic Covered Bridges” (project DTFH61-01-C-005). This FHWA funded research, which is summarized in this paper, included both laboratory and field assessments of the ability of the preservatives to move through the wood structure.

Laboratory Evaluation

The laboratory research summarized in this paper compared the ability of numerous types of internal treatments to move through wood as a function of moisture content, wood species and dosage (Table 2). Laboratory evaluations were divided into small and large scale tests (Morrell, et al., 2013). Small scale tests used 25 by 25 by 100 mm (1 by 1 by 4 in.) long test blocks and were used to assess fumigants, while the larger scale tests used 100 by 100 by 400 mm (4 by 4 by 16 in.) long blocks and were used to assess liquid and solid diffusible preservatives. The species evaluated in these tests were Douglas-fir, southern pine, eastern white pine, eastern hemlock, red oak and white oak. The blocks were pressure soaked with water, and then air dried to set moisture contents (30, 60, and 100 % by weight). Once a block reached a target moisture content, the cross sections were covered with tape prior to dipping the block in molten paraffin to retain moisture. The treatments (Table 2) were added to a hole drilled into the block, and the hole was then plugged with a tight fitting rubber plug. Each treatment was replicated on a minimum of 5 blocks per wood species per time point sampled. Small blocks were incubated for 4 to 12 weeks following chemical treatment while large blocks were incubated at room temperature for up to 24 weeks. Chemical levels were assessed by cutting a series of mm (0.2 in.) thick sections beginning at each end of the block. The two outermost sections were discarded, the next section inward was cut into 16, five mm (0.2 in.) cubes and the inner 4 cubes were immediately placed into 5 ml of either ethyl acetate or hexane for the fumigant treatments or were ground and hot water extracted for the boron or fluoride treatments.

Table 2. Preservatives included in laboratory evaluation of in-place treatments in covered bridge timbers.

Preservative	Active ingredients	Block Size[a]	Treatment Levels (mg per block)
BoraCare	DOT/glycol	Large	100, 250, 500
ShellGuard	DOT/glycol	Large	100, 250, 500
TimBor	DOT	Large	100, 250, 500
CuRap 20	Sodium Tetraborate decahydrate/copper naphthenate	Both	100, 250, 500
Impel Rods	Boron	Small	100, 250, 500
FluRod	Sodium fluoride	Small	100, 250, 500
CobraRod	Boron/Copper	Small	100, 250, 500
MITC	Methylisothiocyanate	Small	25, 50, 100, 250
Dazomet	Tetrahydro-3,5-dimethyl-2H- 1, 3, 5-thiodiazine-2-thione	Small	25, 50, 100, 250
Chloropicrin	Trichloronitromethane	Small	25, 50, 100, 250

[a]Large blocks 100 by 100 by 400 mm (4 by 4 by 16 in.), small blocks 25 by 25 by 100 mm (1 by 1 by 4 in.)

Results of Small Block Tests

Chemical levels in small blocks at 100% moisture content among the various wood species tended to be more consistent and these data were used as the primary assessment tool for these treatments. Boron levels tended to be low 1 week after treatment, but rose considerably between 1 and 4 weeks (Table 3). Boron levels were lowest in white oak, reflecting the refractory nature of this species. In most cases, boron levels were above the 0.11% boric acid equivalents (BAE) threshold for protection against internal fungal attack. Boron levels tended to be much lower with the copper naphthenate/boron paste, reflecting the less concentrated boron in this system. Fluoride levels tended to be lower than those found with boron, again reflecting the fact that the fluoride rods contained less chemical than either the boron or boron/copper rods. Fluoride levels did begin to approach the threshold for protection 4 weeks after treatment.

Table 3. Boron or fluoride levels in small blocks of various wood species conditioned to 100 % moisture content prior to treatment and then incubated for 1 or 4 weeks after treatment.

Wood Species	Dosage (mg)	Boron or Fluoride Content (% wt/wt)[a]							
		Impel Rods		Cobra Rods		CuRap20		FluRods	
		1 wk	4 wk	1 wk	4 wk	1 wk	4 wk	1 wk	4 wk
Douglas-fir	0	0.011	-	0.000	0.005	0.000	0.005	0.000	-
	100	0.064	**0.408**	0.059	**0.419**	0.040	0.090	0.001	-
	250	**0.236**	**0.285**	**0.167**	**0.745**	0.101	**0.160**	0.003	-
	500	**0.239**	**0.144**	**0.168**	**1.100**	0.109	**0.300**	0.003	-
Southern pine	0	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.002
	100	0.001	0.010	0.003	0.008	0.001	0.002	0.001	0.005
	250	0.002	0.016	0.019	0.013	0.001	0.004	0.001	0.018
	500	0.002	0.025	0.010	0.026	0.002	0.008	0.004	0.024
Eastern white pine	0	0.013	0.011	0.013	0.007	0.008	0.000	-	0.001
	100	0.099	**0.350**	**0.160**	**0.309**	0.106	0.085	0.007	0.036
	250	0.066	**0.704**	**0.197**	**0.687**	**0.135**	**0.205**	0.008	0.061
	500	**0.117**	**1.190**	**0.225**	**0.954**	**0.129**	**0.231**	0.009	0.079
Eastern hemlock	0	0.002	0.012	0.013	0.016	0.013	0.016	0.001	0.001
	100	0.068	**0.302**	0.082	**0.288**	0.089	0.099	0.001	0.017
	250	**0.126**	**0.635**	0.074	**0.525**	0.039	**0.133**	0.002	0.042
	500	**0.163**	**0.501**	**0.192**	0.096	0.065	**0.166**	0.002	0.041
Red oak	0	0.028	0.048	0.015	0.018	0.015	0.018	0.001	0.001
	100	0.044	**0.228**	**0.133**	**0.237**	0.042	0.036	0.001	0.014
	250	0.089	**0.425**	**0.141**	**0.422**	-	**1.001**	0.001	0.017
	500	0.100	**0.754**	0.017	**0.818**	-	-	0.002	0.015
White oak	0	0.029	0.035	0.030	0.036	0.030	0.036	-	0.001
	100	0.025	0.067	0.026	0.059	0.036	0.029	-	0.001
	250	0.036	**0.123**	0.032	0.071	0.031	0.034	-	0.001
	500	0.027	**0.246**	0.031	0.031	0.031	0.025	-	0.001

[a]Values represent means of 5 analyses per wood species/treatment dosage. Values in bold represent chemical levels above the threshold for protection against internal fungal attack (0.11% boric acid equivalent (BAE)).

Chemical distribution in blocks at lower moisture contents (30%) differed markedly from blocks at 60% MC. Free moisture is essential for movement of boron and fluoride in wood. While 30% is at or near the fiber saturation point for most of the species tested, there is little free moisture present at this moisture content, sharply reducing the potential for chemical movement through the wood. Moisture appeared to have the least effect on chemical movement in white oak. This may reflect the inherent resistance of this species to fluid movement, which overwhelmed relatively small changes in water availability. The two sets of data strongly suggest that water diffusible treatments of white oak are less likely to be effective in the short term, although prolonged exposure may result in the development of effective chemical levels where moisture is present at suitable levels.

The role of moisture in water diffusible treatments is often over-looked, but failure to place these treatments in wood that will eventually wet above the fiber saturation point will result in failure of the preservative to move away from the treatment hole.

Residual chemical levels in blocks treated with the fumigants MITC or chloropicrin tended to be the reverse of those found with the water diffusible rods. In most cases, chemical levels in the small blocks were higher 1 week after treatment and declined precipitously with an additional 3 weeks of incubation (Table 4). The reduced chemical levels reflect the volatility of these treatments which move though the wood as gases and exit into the surrounding atmosphere. Fumigant levels above the threshold for fungal protection were generally found in blocks treated with either pure MITC or chloropicrin. Protective levels for chloropicrin were found 1 week after treatment for Douglas-fir, eastern white pine, eastern hemlock and white oak blocks. Protective levels of MITC were found for all of the species tested. Chemicals levels also tended to vary with wood species. For example, chemical levels tended to be higher 1 week after treatment in Douglas-fir than southern pine. Both MITC and chloropicrin are believed to have weak chemical interactions with the wood that slow their volatilization. The affinity appears to vary with species. This effect has been noted in field trials in utility poles and would be accentuated in the small blocks where the high surface to volume ratio of the blocks increases losses to the surrounding air. We suspect that chemical losses were much more rapid in southern pine, given the high gas permeability of this species.

MITC levels in dazomet treated blocks tended to be very low 1 week after treatment and then increased with an additional 3 weeks of incubation with some species (for example Douglas-fir, white pine and white oak). Dazomet must decompose to produce MITC and this decomposition rate is highly dependent on moisture content. The rate is typically accelerated by addition of copper based compounds such as copper naphthenate or copper sulfate.

Table 4. Residual concentrations of methylisothiocyanate (for dazomet or MITC) or chloropicrin in small blocks of various wood species 1 or 4 weeks after treatment with 25 to

Wood Species	Dosage (mg/block)	Fumigant Concentration (ug/g wood)[a]					
		Dazomet		Methylisothiocyanate(MITC)		Chloropicrin	
		1 wk	4 wk	1 wk	4 wk	1 wk	4 wk
Douglas-fir	25	-	-	-	-	**68.7**	6.8
	50	0.0	9.9	**772.6**	5.8	**160.3**	**31.6**
	100	0.4	2.6	**726.0**	5.8	**177.7**	12.0
	250	3.0	0.0	**2466.2**	9.7	-	-
Southern pine	25	-	-	-	-	0.0	0.0
	50	0.0	0.0	18.6	0.0	0.9	0.1
	100	0.0	0.0	**52.8**	0.0	9.9	0.2
	250	0.0	0.0	**71.7**	0.0	-	-
Eastern White pine	25	-	-	-	-	**138.6**	2.6
	50	0.0	3.5	309.4	0.0	**166.0**	12.4
	100	5.6	3.5	237.1	0.0	**216.6**	**72.2**
	250	13.6	4.7	425.4	0.0	-	-
Eastern hemlock	25	-	-	-	-	**128.2**	5.4
	50	12.6	8.6	16.9	0.0	**227.8**	13.5
	100	5.7	11.1	31.3	0.0	**451.8**	**70.3**
	250	5.3	16.5	62.8	0.0	-	-
Red oak	25	-	-	-	-	6.6	0.2
	50	-	0.0	**255.9**	0.0	11.5	0.1
	100	-	0.0	**533.4**	4.2	19.1	1.0
	250	-	0.0	**860.2**	7.0	-	-
White oak	25	-	-	-	-	19.4	**38.2**
	50	0.0	0.1	**258.1**	**106.5**	**38.9**	**62.5**
	100	0.0	0.1	**653.5**	**157.9**	**189.1**	**94.5**
	250	0.0	0.5	**1270.0**	**989.4**		

[a]Values represent means of 5 analyses per wood species/chemical treatment. Values in bold represent concentrations above the threshold for fungal growth.

The small block trials clearly show that boron or fluoride in water diffusible rods can move through the various wood species although protective levels developed in a limited number of wood species/treatment combinations. These trials are useful for rapid assessment of movement, but they may be a poor predictor of movement in larger materials, particularly with more dilute treatments. For this reason, the larger blocks were evaluated over a longer time period.

Results of Large Block Tests

The large blocks provided a more stable environment in which to evaluate the water diffusible chemicals; however, they provide a poor measure of fumigants because, despite their larger size, they still contain a high surface to volume ratio that results in rapid volatilization of the fumigant from the wood. Although the blocks were sampled after 4, 16 and 24 weeks, in the interest of brevity only the 24 week data will be discussed.

The four treatments evaluated in the large block test were all boron-based. One system also contained an amine based copper naphthenate component in a paste. Copper levels around the holes in blocks treated with this paste were sometimes elevated, but never approached levels that would be considered to be protective (data not shown). The levels declined sharply 6 to 12 mm (0.25 to 0.5 in.) away from the treatment site, indicating that any protective effect of the copper naphthenate component would be limited to an area immediately adjacent to the treatment site. This is consistent with previous trials of this system in external preservative bandages.

Boron levels in Douglas-fir blocks treated with the various boron treatments tended to decline with distance from the treatment hole and increase with moisture content (Table 5). Boron distribution was very limited in blocks conditioned to 30 % moisture content, then increased as moisture content increased. Boron levels were often similar in blocks at 60 or 100 % moisture content

Table 5. Residual boron 24 weeks after treatment in large Douglas-fir blocks conditioned to 30, 60 or 100% moisture content and then treated with low, medium or high dosages of 4 remedial treatment chemicals.

	Distance from Treatment	Residual Boron Level (% BAE)[a]								
		Low Dosage by Moisture Content			Medium Dosage by Moisture Content			High Dosage by Moisture Content		
Preservative	(mm)[b]	30%	60%	100%	30%	60%	100%	30%	60%	100%
BoraCare	0-6	**0.885**	**0.887**	**0.679**	**2.045**	**0.725**	**0.474**	**3.389**	**1.940**	**0.310**
	6-12	**0.375**	**0.479**	**0.766**	**0.482**	**0.558**	**0.319**	**0.802**	**0.873**	**0.181**
	12-18	0.097	**0.282**	**0.551**	**0.246**	**0.482**	**0.404**	**0.542**	**0.656**	**0.233**
	18-33	0.024	**0.134**	**0.481**	0.088	**0.401**	**0.431**	**0.295**	**0.342**	**0.205**
CuRap 20	0-6	**0.834**	**0.738**	**0.762**	0.020	**1.813**	**0.855**	**1.272**	**1.876**	**1.256**
	6-12	0.048	**0.281**	**0.207**	**1.186**	**0.705**	**0.357**	0.086	**0.863**	**0.570**
	12-18	0.005	**0.170**	0.100	0.011	**0.319**	**0.128**	0.014	**0.444**	**0.125**
	18-33	0.002	0.082	0.135	0.042	**0.118**	**0.417**	0.007	**0.192**	**0.271**
Shell Guard	0-6	**0.758**	**0.402**	**0.547**	**1.635**	**0.952**	**0.208**			
	6-12	**0.424**	**0.233**	**0.196**	**0.886**	**0.811**	**0.358**			
	12-18	**0.258**	**0.221**	**0.358**	**0.303**	**0.476**	**0.153**			
	18-33	0.091	**0.182**	**0.295**	0.083	**0.488**	**0.164**			
Timbor	0-6	**1.030**	**0.348**	**0.394**	**1.591**	**1.330**	**0.152**			
	6-12	**0.361**	**0.220**	**0.278**	**0.472**	**0.412**	**0.159**			
	12-18	0.094	**0.191**	**0.193**	**0.198**	**0.171**	**0.176**			
	18-33	0.038	**0.114**	**0.381**	0.034	**0.127**	0.072			

[a]Values represent means of 5 analyses per treatment. Values in bold are above the threshold for fungal protection (0.11% Boric acid equivalent (BAE)).
[b]Corresponds to 0-0.25, 0.25-0.5,0.5-0.75 and 0.75-1.3 in.

Boron levels were typically lower in CuRap 20 treated blocks, reflecting the lower levels of available boron in this treatment. Levels of chemical tended to increase with depth over time in the wetter blocks, while they tended to remain relatively shallowly distributed in the 30% MC blocks.

Boron levels in southern pine blocks treated with the various compounds tended to be much higher than those found with Douglas-fir (Tables 5, 6). These differences probably reflect the more permeable nature of southern pine, however, it also means that pine will tend to lose chemical more rapidly, providing a shorter overall protective period. Boron levels tended to be highest with Boracare. In addition to the higher levels near the treatment site, boron levels further away tended to be elevated in comparison with Douglas-fir. As with Douglas-fir, chemical levels tended to increase with moisture level as did the boron levels further way from the treatment hole.

Prolonged incubation of southern pine blocks tended to produce fairly flat chemical gradients away from the original treatment site, except for CuRap 20, which retained a steeper distribution gradient on this species (Table 6).

Table 6. Residual boron 24 weeks after treatment in large southern pine blocks conditioned to 30, 60 or 100% moisture content and then treated with low, medium or high dosages of 4 remedial treatment chemicals.

	Distance from Treatment	Residual Boron Level (% BAE)[a]								
		Low Dosage by Moisture Content			Medium Dosage by Moisture Content			High Dosage by Moisture Content		
Preservative	(mm)[b]	30%	60%	100%	30%	60%	100%	30%	60%	100%
BoraCare	0-6	**1.38**	**0.72**	**0.49**	**1.84**	**0.83**	**0.92**	**3.18**	**2.21**	**0.71**
	6-12	**0.89**	**0.53**	**0.37**	**1.02**	**0.70**	**0.73**	**0.88**	**1.32**	**0.62**
	12-18	**0.44**	**0.33**	**0.30**	**0.37**	**0.64**	**0.63**	**1.40**	**1.46**	**0.54**
	18-33	0.04	**0.20**	**0.21**	0.11	0.06	**0.48**	**1.13**	**0.26**	**0.48**
CuRap 20	0-6	**0.97**	**0.70**	**0.68**	**1.07**	**1.66**	**1.23**	**0.65**	**2.03**	**0.26**
	6-12	**0.13**	**0.34**	**0.45**	**0.18**	**0.92**	**0.85**	**0.12**	**0.46**	**1.14**
	12-18	0.01	0.04	**0.38**	0.02	**0.61**	**0.64**	0.02	**0.19**	**0.73**
	18-33	0.00	0.05	**0.29**	0.00	**0.28**	**0.46**	0.00	**0.12**	**0.61**
Shell Guard	0-6	**0.58**	**0.34**	**0.25**	**0.72**	**0.17**	**0.75**			
	6-12	**0.36**	**0.30**	**0.21**	**0.47**	**0.51**	**0.63**			
	12-18	**0.19**	**0.22**	**0.18**	**0.36**	**0.43**	**0.54**			
	18-33	0.08	**0.16**	**0.18**	**0.22**	**0.20**	**0.54**			
Timbor	0-6	**0.33**	**0.27**	**0.25**	**0.41**	**0.26**	**0.42**			
	6-12	**0.29**	**0.20**	**0.19**	**0.38**	**0.40**	**0.35**			
	12-18	**0.33**	**0.15**	**0.16**	**0.26**	**0.36**	**0.30**			
	18-33	0.07	**0.13**	**0.15**	**0.36**	**0.31**	**0.25**			

[a]Values represent means of 5 analyses per treatment. Values in bold are above the threshold for fungal protection (0.11% boric acid equivalent (BAE)).
[b]Corresponds to 0-0.25, 0.25-0.5,0.5-0.75 and 0.75-1.3 in.

Boron levels in eastern white pine blocks 4 weeks after treatment tended to be elevated near the treatment zone regardless of chemical (Table 7). The highest boron levels were again found with BoraCare and CuRap 20. Boron levels declined rapidly further away from the treatment site with CuRap 20, but had a more gradual decline with the other boron treatments. Boron based systems were clearly capable of movement in this wood species.

Table 7. Residual boron 24 weeks after treatment in large eastern white pine blocks conditioned to 30, 60 or 100% moisture content and then treated with low, medium or high dosages of 4 remedial treatment chemicals.

Preservative	Distance from Treatment (mm)[b]	Residual Boron Level (% BAE)[a]								
		Low Dosage by Moisture Content			Medium Dosage by Moisture Content			High Dosage by Moisture Content		
		30%	60%	100%	30%	60%	100%	30%	60%	100%
BoraCare	0-6	**0.158**	**1.291**	**1.030**	**1.762**	**1.444**	**1.353**	**1.301**	**2.512**	**2.399**
	6-12	**0.974**	**0.742**	**0.659**	**1.196**	**1.001**	**0.968**	**1.186**	**1.682**	**1.354**
	12-18	**0.281**	**0.391**	**0.369**	**0.808**	**0.494**	**0.494**	**0.605**	**1.265**	**1.055**
	18-33	0.075	**0.127**	**0.140**	**0.275**	**0.243**	**0.373**	**0.132**	**0.812**	**0.563**
CuRap 20	0-6	**0.413**	**1.429**	0.087	**0.646**	**0.414**	**1.618**	**0.825**	**2.380**	**3.115**
	6-12	0.020	**0.389**	**0.264**	0.009	**0.954**	**0.506**	0.052	**0.770**	**0.789**
	12-18	0.005	**0.144**	**0.573**	0.007	0.068	**0.261**	0.005	**0.283**	**0.248**
	18-33	0.000	0.031	**2.106**	0.002	0.013	0.093	0.000	0.086	0.081
Shell Guard	0-6	**0.935**	**0.691**	**0.811**	**1.431**	**1.646**	**1.195**			
	6-12	**0.307**	**0.454**	**0.446**	**0.208**	**0.852**	**0.552**			
	12-18	0.074	**0.290**	**0.304**	0.026	**0.516**	**0.290**			
	18-33	0.004	**0.149**	**0.178**	0.007	**0.246**	**0.160**			
Timbor	0-6	**0.786**	**0.450**	**0.395**	**1.485**	**0.516**	**0.661**			
	6-12	0.094	**0.273**	**0.282**	**0.212**	**1.182**	**0.545**			
	12-18	0.003	**0.197**	**0.192**	0.022	**0.302**	**0.415**			
	18-33	0.002	0.074	**0.123**	0.005	**0.181**	**0.299**			

[a]Values represent means of 5 analyses per treatment. Values in bold are above the threshold for fungal protection (0.11% boric acid equivalent (BAE)).
[b]Corresponds to 0-0.25, 0.25-0.5,0.5-0.75 and 0.75-1.3 in.

Prolonged diffusion of the boron treatments produced increased levels of boron away from the treatment site in all treatments except the CuRap 20. Boron levels increased to the greatest extent at higher moisture contents.

Boron levels in red oak blocks appeared to be more greatly dependent on dosage and moisture content than those of Douglas-fir blocks (Table 8). After 4 weeks boron levels tended to be lower than those found with Douglas-fir, a seeming contradiction since red oak is far more permeable than Douglas-fir (data not shown). In addition, boron levels were highest in CuRap 20 treated blocks, again the opposite of that found with Douglas-fir. Boron levels increased sharply with an additional 12 weeks of incubation, suggesting that the 4 week results may have been an anomaly.

Boron levels in white oak blocks tended to be slightly lower than those found with Douglas-fir, again reflecting the limited permeability of white oak (Table 9). Because of difficulty in uniformly pressure-treating the larger white-oak blocks with water, white oak was not evaluated at 100% moisture content. Boron levels near the treatment site were highest with the BoraCare and CuRap 20 treatments; however, the boron levels further away from the treatment site tended to be much greater with the BoraCare treatment. This most probably reflects the amount of chemical available although the glycol in the Boracare may have aided in movement.

Table 8. Residual boron 24 weeks after treatment in large red oak blocks conditioned to 30, 60 or 100% moisture content and then treated with low, medium or high dosages of 4 remedial treatment chemicals.

	Distance from Treatment	Residual Boron Level (% BAE)[a]								
		Low Dosage by Moisture Content			Medium Dosage by Moisture Content			High Dosage by Moisture Content		
Preservative	(mm)[b]	30%	60%	100%	30%	60%	100%	30%	60%	100%
BoraCare	0-6	**0.443**	**0.405**	**0.552**	**0.595**	**0.620**	**0.669**	**0.925**	**0.789**	**1.111**
	6-12	**0.230**	**0.348**	**0.369**	**0.290**	**0.517**	**0.410**	**0.460**	**0.806**	**0.857**
	12-18	0.097	**0.232**	**0.238**	0.123	**0.356**	**0.327**	**0.310**	**0.701**	**0.661**
	18-33	0.038	0.171	**0.123**	0.082	**0.324**	**0.183**	**0.249**	**0.570**	**0.408**
CuRap 20	0-6	**1.550**	**0.923**	**0.733**	**1.480**	**2.117**	**1.360**	**2.248**	**2.217**	**3.457**
	6-12	**0.140**	**0.429**	**0.425**	**0.119**	**0.768**	**0.822**	**0.234**	**0.703**	**1.202**
	12-18	0.016	0.072	**0.208**	0.013	**0.339**	**0.335**	0.036	**0.286**	**0.574**
	18-33	0.007	**0.326**	**0.120**	0.010	**0.135**	**0.170**	0.012	0.098	**0.213**
Shell Guard	0-6	**0.254**	**0.373**	**0.313**	**0.734**	**0.590**	**0.525**			
	6-12	**0.249**	**0.283**	**0.247**	**0.290**	**0.332**	**0.447**			
	12-18	**0.118**	**0.178**	**0.169**	**0.117**	**0.428**	**0.268**			
	18-33	0.031	**0.114**	0.091	0.075	**0.362**	**0.142**			
Timbor	0-6	**0.444**	**0.442**	**0.328**	**0.620**	**0.579**	**0.379**			
	6-12	**0.212**	**0.280**	**0.196**	**0.207**	**0.361**	**0.491**			
	12-18	0.057	**0.214**	**0.138**	**0.118**	**0.231**	**0.226**			
	18-33	0.023	**0.130**	0.081	0.068	**0.131**	**0.143**			

[a]Values represent means of 5 analyses per treatment. Values in bold are above the threshold for fungal protection (0.11% boric acid equivalent ((BAE)).
[b]Corresponds to 0-0.25, 0.25-0.5,0.5-0.75 and 0.75-1.3 in.

Boron levels in blocks incubated for 16 weeks tended to differ little from those found 4 weeks after treatment. Boron levels were much higher in CuRap 20 treated blocks, but again, this effect as limited to the area around the original treatment site. Boron levels were lowest in Shellguard treated blocks. Incubation for an additional 8 weeks (24 weeks total) produced little or no change in boron levels and suggests that boron based treatment will move for only short distances in this species. This may be a major drawback to the use of boron based systems in covered bridges constructed with white oak.

As shown in Tables 5 – 9, the concentration of boron in the large blocks was often well above that needed to prevent fungal decay. However, in some parts of the U.S. termites may also pose a threat to covered bridges. The minimum protective threshold for termite protection with borates has not been precisely established. Previous researchers have reported effective borate (as B_2O_3) concentrations ranging from below 0.7 to over 7.0 kg/m^3 (0.04 to 0.44 lb/ft^3) (Drysdale, 1994; Peters and Fitzgerald, 2006). This wide range of retentions equates to approximately 0.23 to 2.3% boric acid equivalents (BAE), depending on the density of the wood. Much of the variability reported for boron protective thresholds for termites arises from differences in test methods, wood species, and termite species. Laboratory tests generally indicate efficacy at retentions of around 1.4 kg/m^3 (0.09 lb/ft^3, or approximately 0.5% BAE), while some field tests indicate that higher retentions are needed to ensure protection (Peters and Fitzgerald, 2006). A recent study in which treated specimens were weathered (leached) down to range of boron concentrations before exposure to termites concluded that the threshold of effectiveness was about 1.12 kg/m^3 (approximately 0.4% BAE) (Lake and McIntyre, 2006). Current pressure treatment standards specify boron retention of 2.7 kg/m^3 (0.17 lb/ft^3, as B_2O_3) for most applications and a higher retention (4.5 kg/m^3, or 0.28 lb/ft^3) for locations with Formosan subterranean termites (AWPA, 2012). These retentions equate to approximately 0.9 and 1.5% BAE, depending on the density of the wood species. With the exception of white oak, boron levels adjacent to the treatment site often exceeded the 0.5% BAE termite threshold indicated by laboratory tests. However, the proportion of samples meeting this level dropped substantially as little as 18 mm from the treatment site.

Table 9. Residual boron 24 weeks after treatment in large white oak blocks conditioned to 30 or 60% moisture content and then treated with low, medium or high dosages of 4 remedial treatment chemicals.

Preservative	Distance from Treatment (mm)[b]	Residual Boron Level (% BAE)[a] Low Dosage by Moisture Content 30%	60%	Medium Dosage by Moisture Content 30%	60%	High Dosage by Moisture Content 30%	60%
BoraCare	0-6	**0.151**	**0.227**	**0.598**	**0.396**	**0.649**	**0.498**
	6-12	**0.128**	**0.140**	**0.207**	**0.210**	**0.241**	**0.382**
	12-18	0.025	0.104	0.051	**0.203**	**0.164**	**0.291**
	18-33	-0.012	0.084	0.067	**0.173**	0.078	**0.302**
CuRap 20	0-6	0.466	**0.743**	**0.785**	**1.110**	**0.862**	**1.715**
	6-12	0.067	**0.321**	**0.129**	**0.321**	0.102	**0.478**
	12-18	0.015	**0.178**	0.015	**0.153**	0.004	**0.239**
	18-33	-0.002	0.050	0.008	0.040	-0.006	0.066
Shell Guard	0-6	**0.204**	**0.200**	**0.200**	**0.254**		
	6-12	0.046	**0.151**	0.101	**0.254**		
	12-18	0.037	0.100	0.092	**0.247**		
	18-33	0.043	0.108	**0.174**	**0.173**		
Timbor	0-6	**0.118**	**0.176**	**0.341**	**0.252**		
	6-12	0.095	**0.137**	**0.242**	**0.201**		
	12-18	0.064	0.105	**0.177**	**0.196**		
	18-33	0.074	0.095	**0.189**	**0.182**		

[a]Values represent means of 5 analyses per treatment. Figures in bold are above the threshold for fungal protection (0.11% boric acid equivalent (BAE)).
[b]Corresponds to 0-0.25, 0.25-0.5,0.5-0.75 and 0.75-1.3 in.

Copper levels in CuRap 20 treated blocks were elevated immediately adjacent to the treatment site, but fell off sharply regardless of moisture content or wood species (Table 10). The copper naphthenate in this system is an amine based system with limited water solubility. Although CuRap 20 is a highly effective external supplemental preservative treatment it is clear from our results that the primary effect of the CuRap 20 in internal applications is associated with the boron.

Table 10. Residual copper in large blocks of various species conditioned to 30, 60 or 100 % moisture content 24 weeks after treatment with low, medium or high dosages of CuRap 20.

Species	Distance from Treatment (mm)[b]	Residual Copper Level (%)[a]								
		Low Dosage by Moisture Content			Medium Dosage by Moisture Content			High Dosage by Moisture Content		
		30%	60%	100%	30%	60%	100%	30	60%	100%
Douglas-fir	0-6	0.126	0.280	0.327	0.241	0.476	0.492	0.131	0.259	0.001
	6-12	0.000	0.000	0.000	0.000	0.002	0.057	0.002	0.018	0.008
	12-18	0.000	0.000	0.000	0.000	0.000	0.012	0.000	0.012	0.003
Southern pine	0-6	0.177	0.085	0.094	0.390	0.216	0.203	0.242	0.261	0.282
	6-12	0.005	0.003	0.011	0.001	0.042	0.028	0.001	0.021	0.047
	12-18	0.000	0.000	0.001	0.000	0.006	0.006	0.000	0.004	0.007
Eastern white pine	0-6	0.001	0.000	0.004	0.001	0.001	0.001	0.001	0.010	0.002
	6-12	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.001
	12-18	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000
Red oak	0-6	0.014	0.000	0.091	0.000	0.100	0.091	0.156	0.120	0.194
	6-12	0.000	0.000	0.000	0.000	0.000	0.006	0.000	0.003	0.000
	12-18	0.000	0.094	0.000	0.093	0.000	0.004	0.000	0.001	0.000
White oak	0-6	0.004	0.030	-	0.006	0.061	-	0.050	0.094	-
	6-12	0.000	0.010	-	0.000	0.001	-	0.001	0.000	-
	12-18	0.000	0.006	-	0.000	0.005	-	0.000	0.000	-

[a]Values represent means of 5 analyses per treatment.
[b]Corresponds to 0-0.25, 0.25-0.5, and 0.5-0.75 in.

Field Evaluation

The supplemental treatments were evaluated in five historic covered bridges located in Wisconsin, Vermont, California and Illinois (Figure 1) (Morrell, et al., 2013). The bridges varied in construction design, wood species, and climate characteristics (Table 11). The approach used to evaluate the treatments varied slightly depending on the bridge design, but the overall methodology was similar for each bridge. To minimize concerns with spillage during applications over water, only internally placed solid treatments were considered. These included two fumigant treatments (MITC-FUME [96 % MITC in an aluminum tube] and granular dazomet) and two diffusible treatments (Impel® boron rods and FLURODS™ fluoride rods). Five (or in some cases 4) replicate doses of each type of treatment were applied to members of each bridge. The drill shavings removed from these treatment holes were sealed in plastic bags and returned to the laboratory for determination of moisture content and identification of wood species. Mobility of the treatments was determined by assaying the treated timbers at one and two years after treatment. Sampling holes were drilled into the treated members at distances of 300, 600 and 900 mm (12, 24 and 36 in.) for fumigant treatments or 100, 200 and 300 mm (4, 8 and 12 in.) for diffusible treatments, from each side of the treatment hole. These wood samples were analyzed for the respective active ingredient of the treatments (MITC for the fumigant treatments, boron for the boron rods, and fluoride for the sodium fluoride rods). The treatments were also weighed before and after treatment to determine mass loss presumably resulting from sublimation or diffusion.

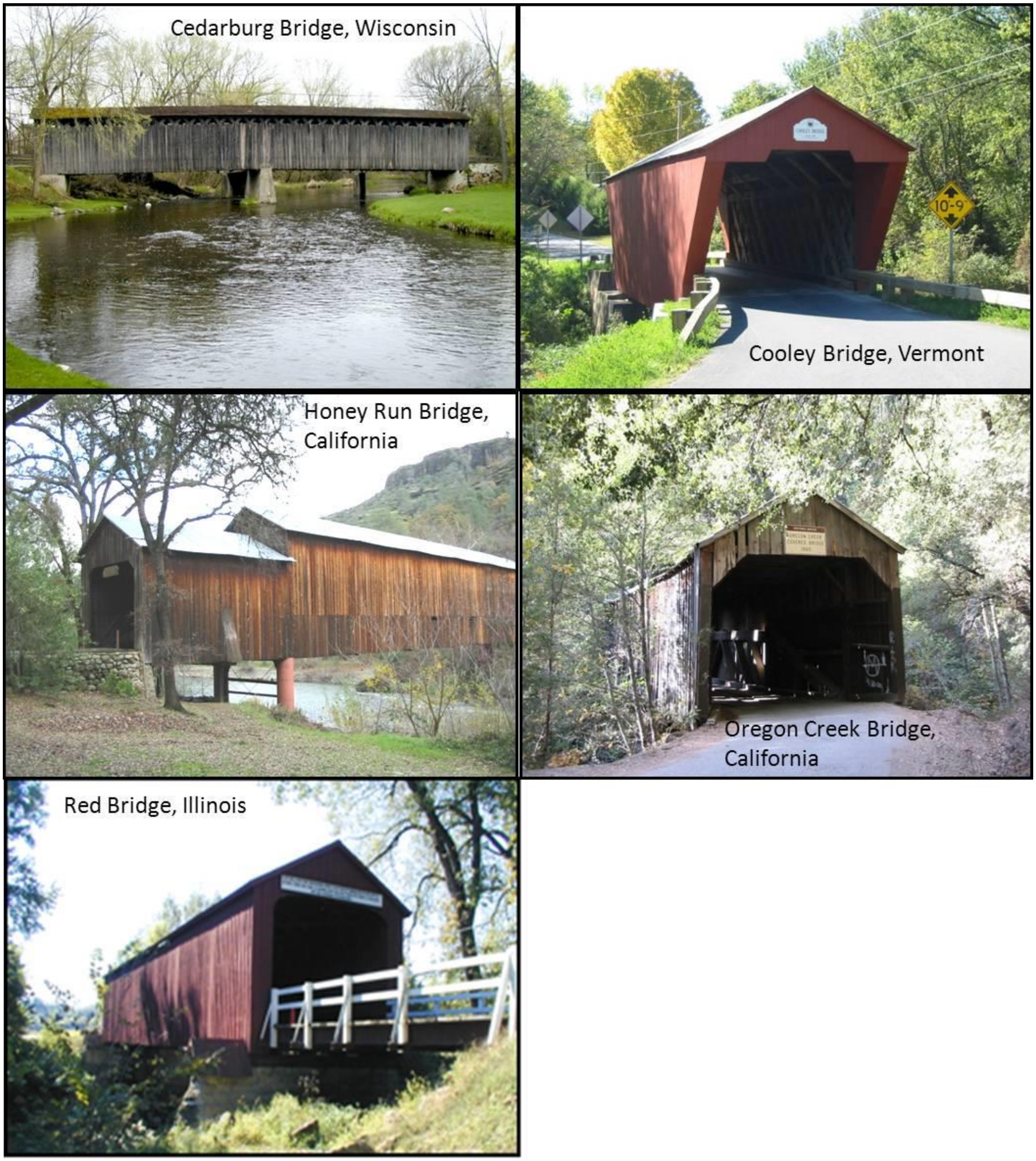

Figure 1. Covered bridges included in field evaluation of in-place treatments.

Table 11. Characteristics of covered bridges evaluated.

Bridge Name	Location	Year Built	Design	Wood Species	Annual Climate Averages Temp. C (F)	Precip. mm (in.)
Cedarburg	Cedarburg, WI	1876	Town lattice	White pine	8 (46)	838 (33)
Cooley	Rutland, VT	1849	Town lattice	Eastern spruce	7 (45)	889 (35)
Honey Run	Chico, CA	1896	Pratt and kingpost trusses	Sugar pine and Douglas-fir	16 (60)	889 (35)
Oregon Creek	North San Juan, CA	1860	Howe pony truss	Ponderosa pine and Douglas-fir	12 (54)	1372 (54)
Red	Princeton, IL	1863	Howe truss	Red pine	10 (50)	914 (36)

Results of Field Evaluation

With few exceptions, no movement of boron and fluoride from the rods was detected in the field-treated bridges. Concentrations in assay samples were either not above background levels or not detected. The possible exceptions were low levels of fluoride detected in a few assay samples removed 100 mm (4 in.) from the treatment holes after 2 years exposure in the California bridges. The general absence of boron and fluoride in the assay samples is in agreement with the lack of weight loss observed in the rods after 2 years exposure (Table 12). The poor mobility observed in this study is probably attributable to the low moisture content of the bridge members. The highest moisture content detected in the members when the rods were placed in the bridge was 27%. Although the moisture content in the members likely fluctuates with precipitation events, it appears that moisture was never consistently elevated to the point here diffusion could occur from the rods.

In contrast to the diffusible treatments, MITC was detected in many of the samples removed from locations adjacent to the MITC treatments holes. Concentrations were generally greatest and most consistently elevated in samples removed at 300 mm from the treatment holes, but elevated concentrations were detected at distances of 600 (24 in.) and 900 mm (36 in.) as well (Figure 2). Concentrations detected in samples removed from 4 of the 5 bridges were relatively similar. The highest concentrations after 1 year were detected in a California bridge located in hot, dry climate, while concentrations detected after 2 years were higher in the northern bridges. Sublimation of solid MITC is faster at higher temperatures and the higher temperatures at the warm California location may have accelerated release of MITC from the tubes. Weight losses measured after 2 years suggest that nearly all the MITC has been released from tubes at that bridge. Interestingly, MITC concentrations detected at the other California bridge were notably lower than for the other bridges. The reason for this is unclear, as the MITC weight loss from the tubes at this bridge after was similar to the other bridges after 2 years.

Table 12. Average wood moisture content at time of application and average percent of original treatment depleted after two years of exposure.

Treatment and Characteristic	Covered Bridge				
	Cedarburg	Cooley	Honey Run	Oregon Creek	Red
Boron Rod					
Wood MC%	13	13	13	18	12
% Depleted	<1	<1	<1	<1	<1
Fluoride Rod					
Wood MC%	13	13	12	14	13
% Depleted	<1	<1	4	<1	<1
Granular Dazomet					
Wood MC%	14	13	12	12	13
% Depleted	<1	<1	<1	<1	<1
MITC Tube					
Wood MC%	14	13	11	14	12
% Depleted	64	59	99	76	53

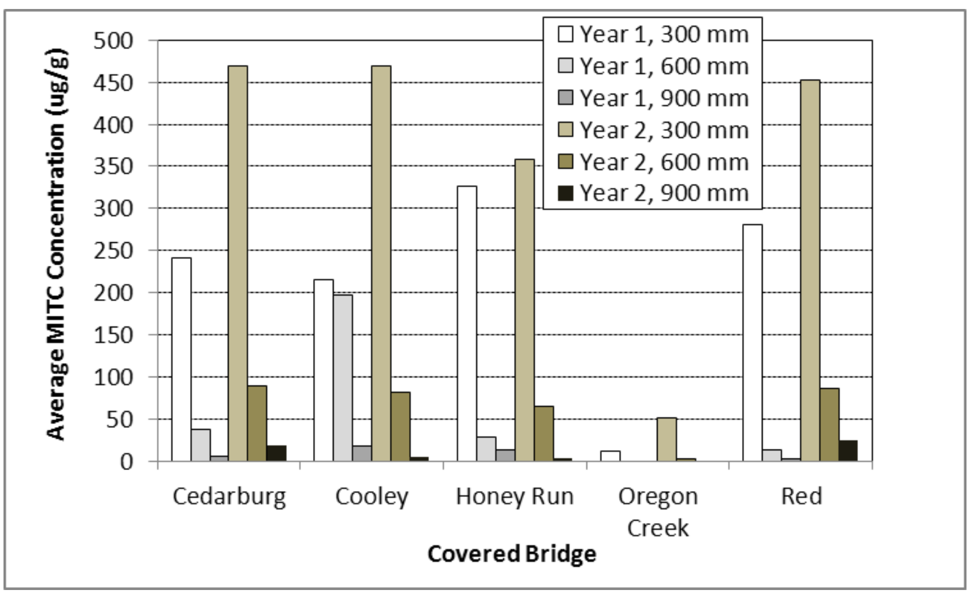

Figure 2. Average MITC concentration in wood samples removed at 300, 600 and 900 mm (12, 24 and 36 in.) from MITC-FUME applications.

None of the wood assay samples corresponding to the dazomet treatments contained detectable concentrations of MITC at any distance, bridge or time point. Weight loss from the dazomet treatments was also minimal, indicating that little decomposition and release of MITC had occurred after 2 years. Some suppliers recommend addition of accelerants to dazomet treatments to speed decomposition, which was not done in this study. It is possible that greater decomposition would have been observed with the use of these accelerants.

Summary of Research on In-place Preservative Treatments for Covered Bridges

Laboratory studies showed that boron and fluoride would diffuse through moist wood of most species at effective levels except for white oak which has a well know reputation for being impermeable. MITC and chloropicrin tended to move well through all species regardless of moisture level, while dazomet failed to decompose to produce MITC at effective levels under the conditions tested. Field tests indicated that most covered bridge timbers were relatively dry, limiting movement of preservative from solid diffusible treatments. The use of solid diffusible treatments in covered bridges may be seen as a type of insurance against future moisture problems. In theory, if these moisture problems do occur the preservative in the rods would become activated and spread into the moistened area. However, this scenario requires that the rods be placed at frequent intervals to ensure that a rod is near the location where wetting occurs. Movement from the rods could have also been given an initial boost by adding water or a liquid borate solution (in the case of the boron rod) to the treatment hole. Because fumigant treatments do not rely on moisture for their mobility, they have greater potential for movement in dry bridge timbers. MITC from the MITC-FUME treatments in this study routinely moved 600 mm from the treatment hole, suggesting that installation of this treatment with a spacing of 1.2 m spacing would provide for adequate protection of members. Average MITC concentrations increased during year 2 of the study, suggesting that the treatments will be effective for at least 3 years. Research on utility poles indicates that MITC levels in wood decline gradually over time and fall below effective concentrations 5 – 7 years after treatment (Morrell, et al, 1998). In covered bridges the longevity of the treatment will be less predictable because of the wide range of designs and member dimensions. No MITC was detected adjacent to dazomet treatments, possibly because no accelerant was used to enhance decomposition.

Conclusions

Covered bridges were designed to prevent biodeterioration by keeping the wood dry, and moisture exclusion should be the first option in preserving bridge members. However, protecting all bridge members from moisture is difficult, even in well-designed and well-maintained covered bridges. When protection from moisture is not practical, appropriately applied in-place preservative treatments can provide additional protection against biodeterioration.

The objective of an in-place treatment is to distribute preservative into areas of a structure that are vulnerable to moisture accumulation. Types of field treatments range from finishes, to boron rods, to fumigants. A major limitation of in-place treatments is that they cannot be forced deeply into the wood under pressure as is done in pressure-treatment processes. However, they can be applied into the center of large members via treatment holes.

Surface-applied liquid treatments should not be expected to penetrate more than a few millimeters across the grain of the wood, although those containing boron can diffuse more deeply under moist conditions. Liquid surface treatments are most efficiently used to flood checks, exposed end-grain, bolt holes, etc. They may move several centimeters parallel to the grain of the wood if the member is allowed to soak in the solution. Surface treatments with diffusible components will be washed-away by precipitation if used in exposed members. However, their loss can be slowed if a water repellent finish is applied after the diffusible treatment has dried. Surface treatments will not effectively protect the interior of large timbers.

Paste surface treatments can provide a greater reservoir of active ingredients than liquids. When used in conjunction with a wrap or similar surface barrier, these treatments can result in several centimeters of diffusion across the grain into moist wood over time. They are typically used for the groundline area of posts or piles that are not usually exposed to standing water, but can also be applied to end-grain of connections or pile tops.

Internal treatments are typically applied to the interior of larger members where trapped moisture is thought to be a current or future concern. Diffusible internal treatments move through moisture in the wood and are relatively easy to handle and apply. However, the volume of wood protected by a single diffusible treatment is relatively low, and internal diffusible treatments may be best suited for specific problem areas such as near exposed end-grain, connections, or fasteners. In contrast, fumigant internal treatments move as a gas through the wood. They have the potential to move several feet along the grain of the wood, but have greater handling and application concerns.

Research on use of in-place treatments in covered bridges is not extensive, but laboratory and field tests illustrate that movement of preservative away from diffusible preservative treatments, such as boron, is highly dependent on wood moisture content. Because the majority of covered bridge members are generally dry, the use of these diffusibles will be most efficient if they are closely targeted to locations where moisture is suspected. Because fumigants do not rely on moisture to move through wood, they appear to be able to move much greater distances through covered bridge timbers.

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