

Review of Oxine Copper Efficacy in Field Trials and Implications for Use in Military Wood Packaging Applications

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Abstract

Oxine copper is listed in the United States as a wood preservative for exterior aboveground use, with active Environmental Protection Agency registrations for both oil- and water-based formulations. While it has limited use in many markets, water-based oxine copper is widely used by the US military to protect wood packing materials for munitions because of its low risk to human health and demonstrated activity against certain insects, decay, and sapstain fungi. Thus, it will likely persist as a wood treatment while other preservatives may face greater restrictions or elimination due to increased concerns regarding health and safety. Here, we summarize results from decades of field trials conducted by the Forest Products Laboratory, which incorporated various formulations of oxine copper on a variety of wood species, and present compiled data on the durability and expected service life of oxine copper-treated wood. Results showed the efficacy of oxine copper to be highly dependent on formulation and concentration and, to a lesser extent, wood species. In general, wood products treated with oil-based oxine copper formulations had substantially longer service lives than water-based formulations. However, not all oil-based treatments were the same; oxine copper in Stoddard solvent was not as effective as formulations in other petroleum-based solvents. Water-based formulations provided approximately 5 to 8 years of protection in ground contact or ground proximity. While this is sufficient based on current military specifications that require protection for 2 years under outdoor exposure, alternative formulations may be required in areas with higher termite or decay pressure.

Oxine copper ($C_9H_6ON-Cu-NOH_6C_9$; also known as copper 8-quinolinolate [Cu8]) is an organometallic compound that is formed by a chemical reaction between inorganic copper (Cu II) and organic 8-hydroxyquinoline (oxine) into an odorless, olive-green crystalline powder (Environmental Protection Agency [EPA] 2010). It has a different chemical makeup than the more commonly used copper salts of carboxylic acids, with different bonding modes and mechanisms of action. Oxine copper is essentially a non-ionizable chelate of copper and 8-hydroxyquinoline, with the latter acting as a strong chelating agent by virtue of the N,O donors that form a stable coordination complex with copper. In comparison, carboxylic acids react with copper solely by virtue of their acidity, and the less stable O,O' ligand is susceptible to hydrolysis at low pH (Benignus 1948, Bayley 1956).

Quinoline has been shown to serve as a highly effective scaffold for the design and development of antifungal compounds due to its structural versatility and low inherent toxicity (Musiol et al. 2010), although activity against certain insects and fungi can be relatively high (Schultz and Nicholas 2010). The addition of a hydroxyl group to the quinoline

structure at C-8 increases antifungal activity by orders of magnitude compared to non-hydroxylated quinoline (Gershon et al. 1971, 1991; Nicoletti et al. 1999). The 8-hydroxyquinoline structure forms saturated and unsaturated complexes with metals (such as copper). The fully saturated

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chelates are neutral and lipid-soluble, allowing them to cross cell membranes. Once inside, they dissociate into highly toxic, unsaturated half-chelates (e.g., copper mono-oxinate; Block 1955, 1956a; Nicoletti et al. 1999; O'Connor and Rubino 1991). The suggested antifungal mode of action of oxine copper involves inhibition of normal metabolic processes in cells, either by competing with coenzymes for metal-binding sites or by inserting copper at metal-binding sites on proteins, enzymes, or other cellular components where other metals normally function (EPA 2010, Freeman and McIntyre 2008, Liu et al. 1994, Vicklund et al. 1954). The fungicidal activity of oxine copper can be reversed, however, in the presence of excess metal ions and excess oxine (Block 1956b).

The antifungal activity of oxine copper has been demonstrated repeatedly in various laboratory studies. Silva et al. (1999) showed good leach resistance and protection against the decay fungus *Gloeophyllum trabeum* using oil-based Cu8 in toluene (0.5% as Cu), applied by dip to red oak, yellow poplar, Douglas-fir, and loblolly pine. Gershon et al. (1989) demonstrated antifungal activity of 8-quinolinols mixed with different metal chelates against five of six mold species tested (i.e., *Aspergillus niger*, *Aspergillus oryzae*, *Trichoderma viride*, *Myrothecium verrucaria*, *Trichophyton mentagrophytes*). The exception was *Mucor circinelloides*, which was not inhibited by any of the treatment formulations. They concluded that there was synergism between 8-quinolinols and their metal chelates and that the fungitoxicity with different metals appeared to be additive. Petrush et al. (2019) determined oil- and water-based formulations (with and without pH adjustments) were effective in preventing decay by two brown-rot fungi (i.e., *Rhodonina placenta* and *G. trabeum*) in laboratory soil block tests. Their results also suggested little difference between oil- and water-based systems. Similarly, Lebow et al. (2017) showed promising decay resistance of water-based oxine copper (1.2% and 1.8% as Cu8) applied as a dip treatment on southern pine against *G. trabeum* and *R. placenta* in laboratory tests. They suggested that the results for decay resistance of oxine copper against *R. placenta* in their study indicated activity against copper-tolerant fungi. This is supported by Block (1955), who showed greater efficacy of oxine copper against copper-tolerant fungi than copper carboxylates, which Clausen and Green (2003) later attributed to its ability to prevent oxalic acid production by decay fungi.

Oxine copper is approved for a diversity of applications as a fungicide/anti-sapstain. It is recommended for prevention of wood decay, protection of adhesives and glues, and preservation of paper-based materials (Stokes et al. 1991). It can also be incorporated into various products to control mold and mildew, such as paints, cement, and pulp/paper (Hatfield et al. 1944, EPA 2010). It is one of a few preservatives that can be used to control sapstain in freshly cut or debarked lumber or on other unfinished wood materials (EPA 2010). Oxine copper is also approved by the US Food and Drug Administration (FDA) as an indirect food additive or as a component in materials in direct contact with foodstuffs (e.g., fruit, vegetables, mushrooms; EPA 2010, Schultz and Nicholas 2010, Giordano et al. 2021). As a result, it is ideal for treating truck beds (wooden decks or slats) of refrigerated trucks and produce haulers (Thomason et al. 2006). Presently, the end use of oxine copper-

treated wood is primarily exterior aboveground applications as well as certain interior structural components (EPA 2010).

The American Wood Protection Association (AWPA) developed standards for oxine copper use as a commercial/industrial wood preservative for nonpressure and pressure treatments and as a protective wood coating/water repellent. It was originally added to AWPA standards in 1962 (as standard P8-62). This standard was later withdrawn in 2014, and information regarding its use was merged into the current standard P37-23 (AWPA P37-23; AWPA 2025a). A 1994 AWPA committee report asserted that a major obstacle to oxine copper is one of economics, specifically, its treated wood cost relative to competitive preservatives (Rei and McEntee 1994). The system was initially registered with the EPA as a pesticide in 1956 and reaffirmed in 2007 (EPA-HQ-OPP-2007-0556). In 2010, EPA initiated a Registration Review process for oxine copper with the Interim Registration Review Decision published in 2024 (EPA 2024).

A key development in the use of oxine copper as a stable wood preservative was solubilization of oil-based formulations in nickel 2-ethylhexanoate, which served as a basic carrier via the Kalberg process (Kalberg 1951, 1956). This enabled the compound to be dissolved in organic solvents rather than used as a less effective suspension, as was the case with earlier formulations (Goldfarb 1962, Stokes et al. 1991). Similarly, water-soluble forms of oxine copper can also be made using dodecylbenzene sulfonic acid (Barnes 2001). The main formulation of oxine copper, first listed in the 1964 *AWPA Book of Standards*, specified use of a 10 percent solution of nickel 2-ethylhexanoate as a solubilizing agent (Stokes et al. 1991, US Department of Agriculture [USDA] 2010). However, the standard was amended in 2011 to remove nickel 2-ethylhexanoate as the required solubilizing agent; instead, other proprietary emulsifiers are used to increase the solubility of oxine copper in oil-based formulations. Solubility criteria are defined in the current standard P37-23, which also prohibits use of dispersed formulations (AWPA 2025a). Cosolvents used in commercial oil-based products are typically highly acidic and polar, which have the potential to increase water solubility in the final oxine copper formulation. This could conceivably result in concerns regarding the role of moisture in solution stability. However, while an oil-based concentrate (~10% oxine copper) might have slightly greater water solubility, the actual wood-treating solutions will have been diluted fifty times or more with hydrophobic diesel oil, negating any increase in water solubility in the actual treating solution (Jim Brient, personal communication, July 2026).

Oil-based oxine copper has some advantages over water-based formulations. For example, water-based oxine copper is known to corrode metals (e.g., carbon steel and galvanized steel), while oil-based oxine copper does not cause increased corrosion compared to untreated wood (Barnes et al. 1984, Groenier and Lebow 2006, Kirker and Lebow 2021). Also, water-based formulations generally require pH adjustments to achieve solubility. However, advantages of water-based oxine copper formulations include reduced odor, lessened environmental impact, improved paintability, and reduced cost (Groenier and Lebow 2006, Freeman and McIntyre 2008). Currently, only the oil-solubilized formulation of oxine copper is listed in the *AWPA Book of Standards* (AWPA 2025a). It is specified for use as a wood preservative for treating several

softwood species in exterior, aboveground exposure (i.e., UC1, UC2 [interior dry or damp], UC3A [partially protected], and UC3B [unprotected]) at a minimum specified retention of 0.02 pounds per cubic foot [pcf] (0.32 kg/m³) (AWPA 2025a). It is not approved for soil or freshwater contact.

Despite being a known preservative for decades, there was renewed interest in oxine copper in the 1980s to 1990s driven, in part, by changes in registered applications for pentachlorophenol. In 1986, pentachlorophenol was reclassified as a restricted-use pesticide (RUP), which meant it was no longer suitable for residential usage or for wood-based packaging (EPA 1984; see also EPA 2021). At that time, oil-based, water-repellent preservatives were commonly used for nonpressure dip treatments of precut lumber, as they were known to be effective in protecting wood from decay in aboveground applications associated with intermittent wetting (Verrall and Teitell 1954, Verrall 1965, Verrall and Scheffer 1969, Scheffer et al. 1971). However, increasing costs of imported petroleum prompted evaluations of water-based preservatives as alternatives to oil-based systems that could be used as dip treatments (DeGroot and Stroukoff 1986). As a result, water-based oxine copper was targeted for use as a possible alternative to pentachlorophenol. In a study to address this, De Groot and Stroukoff (1986) examined a diversity of preservatives for protection of wood packing materials (WPMs) under severe field exposure conditions and found dip treatment with 1.2 percent water-based copper 8-quinolinolate to perform as well as the standard reference treatment (i.e., 5% oil-based pentachlorophenol) in resisting decay. This work, as well as subsequent efforts by Lebow et al. (2015, 2017), helped to support US military efforts aimed at selecting preservative systems for protecting WPMs.

Currently, dip treatment with a 1.8 percent water-based oxine copper formulation is approved for use with military ammunition wood packaging (US Army 2017a, 2017b). US military specification allow the use of either buffered (with borates) or unbuffered water-based oxine copper, depending on extent of corrosion concern. Because oxine copper completely precipitates from solution above pH 3.3 (Jeffery et al. 1989), maintaining the acidic conditions required for solubility may increase corrosivity (Petruch et al. 2019). Generally, buffered formulations are used to treat WPM assemblies with significant metal hardware exposure, such as wire-bound boxes (specification MIL-DTL-46506E Amd 3 and PPP-B-585D; US Army 2016, 1992). Conversely, unbuffered formulations are used to treat other WPM assemblies with minimal metal hardware exposure such as artillery projectile pallets (specification MIL-DTL-45449C Amd 2; US Army 2017c), four-way entry hardwood pallets (specification MIL-DTL-15011K Amd 2; US Army 2025), dunnage and gates used to square off conventional ammunition unit loads (AMC Basic Procedures 19-48-4116-20PA1002 Rev 14; US Army 2019), and nailed or hinged wooden boxes (specification MIL-DTL-2427J Amd 1; US Army 2024).

While there is a long history of research on the use of oxine copper as a wood preservative, much of the work initiated by Forest Products Laboratory (FPL) researchers or in association with collaborators has only been published as summary tables without detailed results or discussions of differences in formulations or service life, for example. The goal of this article was to compile and summarize the oxine copper field testing research conducted by the FPL between 1952 and 2020 and add to the body of literature on the durability of oxine copper

as a wood preservative. Furthermore, this article aims to present insights into the expected service life of oil- and water-based oxine copper with the intention of determining their utility for the protection of military WPMs.

Materials and Methods

This study examined decay and termite-resistance data of oxine copper-treated specimens installed in nine separate field plots in Mississippi, Wisconsin, and Indonesia. Field studies of oxine copper discussed in this article incorporated a diversity of treatment methods, sample sizes, and wood-based materials, which are summarized in Table 1. Further details on the methodology associated with these test plots are provided below.

Wood preservation treatment methods

Wood specimens were impregnated with treatment chemical in one of three ways (see Table 1 for the method used for each test plot). Two of the methods used were pressure treatments, which used vacuum and pressure to drive the preservative treatment into the wood. The “empty cell pressure treatment” method was designed for deep preservative penetration, but less overall retention, and is commonly used with oil-based treatments. For this method, an initial pressure of up to 35 to 40 psi is applied to compress air into wood lumens, the water-conducting section of the wood cells. The tank is then filled with the treatment chemical while the initial pressure is held. Pressure is then increased to 140 to 150 psi and held for several hours and then relieved before a final vacuum is applied. This type of treatment method saturates the wood cell walls with the preservative but leaves the wood lumens empty. The “full cell pressure treatment” (also known as the Bethell process) is a method used for maximum preservative retention. During this process, wood is placed in a closed cylinder and subjected to controlled vacuum and pressure cycles (i.e., initial 30 minute vacuum followed by 120 minutes at 150 psi). This type of treatment method saturates both the wood cell walls and wood lumens with preservative. For a more detailed explanation of the wood pressure treatment process, see Kirker and Lebow (2021). The third method used was a “dip treatment,” in which specimens are submerged in a treatment solution for a set period of time (usually 1 to 3 minutes). As this method does not use pressure or vacuum, the preservative is mainly confined to the outer surface of the sample, offering minimal to no penetration into the wood cell wall or lumens.

While a few of the test formulations examined water-based oxine copper, most early studies utilized oil-based formulations in three main types of solvents: Stoddard solvent—a synthetic, organic solvent made from crude oil distillates, considered a type of mineral spirit (Type C hydrocarbon solvents; AWPA HSC-17; AWPA 2025b); heavy petroleum solvent—AWPA P9 (AWPA HSA-23; AWPA 2025c); or diesel diluted with toluene—30 percent solvent consisting of local No. 2 diesel fuel and toluene (hydrite). The specific solvent used for each test plot is provided in Table 1.

Field test sites

The data presented here are from field exposure evaluations conducted at three main test locations. As the data in

Table 1.—Summary of Forest Products Laboratory field studies incorporating oxine copper as a wood preservative.

Location ^a	Plot no.	Installation year	Wood species ^b	Specimen size(s)	Treatment method	Oxine copper formulation tested	AWPA ^c field test method
HEF	54	1959	SP	1.5 by 3.5 by 18 in.	Empty cell	Copper 8-quinolinolate Stoddard solvent	E7
HEF	62	1963	SP	1.5 by 3.5 by 18 in.	Empty cell	Copper 8-quinolinolate in heavy petroleum solvent	E7
HEF	75	1976	SP	1.5 by 3.5 by 18 in. and $\frac{3}{4}$ by $\frac{3}{4}$ by 18 in.	Full cell	Water-soluble copper 8-quinolinolate	E7
HEF	84	1981	SP	1.5 by 3.5 by 18 in.	Full cell	Copper 8-quinolinolate in toluene	E7
HEF	95-01	1995	SP, RO, YP, CW	$\frac{3}{4}$ by $\frac{3}{4}$ by 18 in.	Full cell	Oxine copper in diesel toluene mix ^d	E7
Indo.	96-01	1995	SP, YB (heartwood), HM (sapwood and heartwood)	$\frac{3}{4}$ by $\frac{3}{4}$ by 18 in.	Full cell	Oxine copper in diesel toluene mix ^d	E7
HEF	96-01	1996	SP, YB (heartwood), HM (sapwood and heartwood)	$\frac{3}{4}$ by $\frac{3}{4}$ by 18 in.	Full cell	Oxine copper in diesel toluene mix ^d	E7
VV	96-04	1996	SP, YB (heartwood), HM (sapwood and heartwood)	$\frac{3}{4}$ by $\frac{3}{4}$ by 18 in.	Full cell	Oxine copper in diesel toluene mix ^d	E7
HEF	14-02	2014	SP, YP	5 by 1 by 1.5 in.	Dip (1 to 3 minutes)	Water-soluble copper 8-quinolinolate	E18 & E26

^a HEF = Harrison Experimental Forest; Indo. = Indonesia; VV = Forest Products Laboratory Valley View test site.

^b SP = southern pine; YP = yellow poplar; YB = yellow birch; HM = hard maple; CW = cottonwood; RO = red oak.

^c AWPA = American Wood Protection Association.

^d Treating solutions with oxine copper were mixed with toluene so that the amount of No. 2 diesel fuel was only 30 percent by weight of the total solution.

this report are based on historical field plots, information on annual precipitation and temperature provided here is from De Groot et al. (1996) and Woodward et al. (2011) to best represent the environmental conditions at these test sites during the major periods of exposure (Table 2). The primary test site is within the Harrison Experimental Forest (HEF), which is a Forest Service-owned property located in Saucier, Mississippi. This site is considered a severe deterioration zone (AWPA U1-23, fig. 1; AWPA 2025d). The Valley View (VV) test site, located in Verona, Wisconsin, is also a Forest Service-owned property maintained by the FPL. This site is considered a low deterioration zone in part because of the lack of termite presence at this site compared to other locations (AWPA U1-23, fig. 1; AWPA 2025d). The Cikampek, Indonesia (Indo.), test site was used in one test plot that had comparable test samples in field tests at the HEF and VV. This site is located in the northern coastal region of Western Java, Indonesia. This site can be considered a severe deterioration zone with high levels of decay and termite activity.

Field testing methods

The majority of field tests in these studies followed the AWPA E7-21 (AWPA 2025e) standard test for evaluation of wood preservatives to be used in ground contact (Fig. 1).

Each preservative type/concentration consisted of 10 replicate specimens with dimensions of $\frac{3}{4}$ by $\frac{3}{4}$ by 18 in. or 1.5 by 3.5 by 18 in. A ground proximity test was conducted in one of the studies, which included components of both AWPA aboveground and ground proximity testing standards (AWPA E18-24 and E26-21, respectively; AWPA 2025f, 2025g). Here, groups of bricks or cinder blocks were placed flat on the ground, five replicate wood test specimens (5 by 1 by 1.5 in.) were placed randomly on top, and then the entire assembly was covered with a shade cloth frame (AWPA E18-24; AWPA 2025f) (Fig. 1). Untreated wood was placed on the ground around the cinder blocks to encourage termite foraging.

Field inspections

Specimens were inspected at specific intervals depending on years of exposure. In general, inspections were conducted every year for 5 years, every other year for the next 6 years, every 5 years for 9 more years, and then every 5 years until plot closure. During these inspections, specimens were removed individually, gently scraped to remove debris, examined, rated, and returned to their original position if failure had not occurred. Failed specimens were noted and discarded. During the inspection, the specimens were visually rated based on the amount of decay and termite attack visually present.

Table 2.—Site-specific conditions for each of the field test plots.

	Harrison Experimental Forest (HEF)	Valley View (VV)	Cikampek, Indonesia (Indo.)
Geographic location	Saucier, Mississippi, USA	Verona, Wisconsin, USA	Cikampek, Western Java, Indonesia
Mean annual precipitation (mm)	1,574–1,580	780–787	1,891
Average annual temperature (°C)	19.6	7.4	32–34
Soil type	Well-drained Poarch sandy loam ^a	Clay loam	Red and brown latosol, reddish laterite; parent material intermediate tuffaceous volcanic soil

^a Schultz et al. (2005).



Figure 1.—Field exposure of test specimens in ground contact (left) and ground proximity (right) tests (photo credits: Stan Lebow and Rachel Arango).

Prior to 1985, a numerical and letter rating system was used, which was converted to the numeric–numeric rating system that has been used since 1991 (for more details, see Woodward et al. 2011). Data presented in this report are based on the later system, which uses the rating scale shown in Table 3 (see also AWP A E7-21, AWP A 2025e).

Data analysis

In the results shown here, decay and termite damage were not analyzed separately as oxine copper did not appear to be more susceptible to one or the other. Instead, the average minimum visual ratings were determined by taking the lower of the two visual ratings (decay or termite) at an inspection period and then averaging these for each treatment group. For example, if a specimen was given a rating of 6 (decay) and 9 (termite), then the 6 would be used as the overall rating for that specimen.

To determine potential service life, the year specimen failure occurred (i.e., received a decay and/or termite rating of 0) was recorded and averaged for each treatment group and presented as the average years to failure. Values are based on 100 percent specimen failure unless otherwise noted. Total preservative solution absorption and Cu8 retention data for specimens in each field plot were calculated as shown below. If raw data could not be located, service life estimates and preservative retentions were taken from the 2011 progress report (Woodward et al. 2011).

Preservative uptake

Preservative uptake in pressure-treated specimens was determined by the difference between the pretreatment weight (T1) and the posttreatment weight of the specimen immediately after treatment (i.e., wet weight; T2). Specimen size and percent of primary active ingredients in the preservative were then used to determine active ingredient uptake. These were calculated as shown in Equations 1 and 2 below in plots where raw data could be found. Preservative

uptake in dip-treated specimens was determined based solely on total uptake and does not account for specimen size because chemical uptake was limited to the outer sections of the wood block.

$$\text{Gross solution uptake} \left(\frac{\text{lbs}}{\text{ft}^3} \right) = \frac{G (\text{lbs})}{V (\text{ft}^3)} \quad (1)$$

$$\text{Oxine Cu retention} \left(\frac{\text{lbs}}{\text{ft}^3} \right) = \left(\frac{G (\text{lbs})}{V (\text{ft}^3)} \right) \times \left(\frac{C}{100} \right) \quad (2)$$

where V = volume of wood specimen (ft^3) (V = length [ft] $\times$ width [ft] $\times$ height [ft]); G = total uptake (lbs) (G = T2 [lbs] – T1 [lbs]); and C = percent oxine copper (Cu8%) in treatment solution.

Organization of results

Results for the field plots presented below are reported under two different categories, the 02 and non-02 plots. The 02 research plots, which include HEF plots 54, 62, 75, and 84, are part of a larger study that was compiled into a progress report published approximately every 10 years, summarizing field data for a diversity of preservative formulations (e.g., Gjovik and Gutzmer 1989, Woodward et al. 2011). The non-02 research plots are those that were installed after 1990 and have not yet been included in a larger progress report. These include four related in-ground field tests (HEF plots 95-01, 96-01; VV plot 96-04; Indo. plot 96-01) and one ground proximity test (HEF plot 14-02). While oxine copper and copper 8-quinolinolate can be used interchangeably, the terminology provided in the results here included both, based on the terminology used in the original study.

Table 3.—Visual rating scale based on condition of wood specimens according to AWP A E7-21 (AWP A 2025e).

Visual rating	Decay damage	Termite damage
10	Sound. Suspicion of decay permitted.	Sound. 1 to 2 small nibbles permitted.
9	Trace decay to 3% of cross section.	Slight evidence of feeding to 3% of cross section.
8	Decay from 3% to 10% of cross section.	Attack from 3% to 10% of cross section.
7	Decay from 10% to 30% of cross section.	Attack from 10% to 30% of cross section.
6	Decay from 30% to 50% of cross section.	Attack from 30% to 50% of cross section.
4	Decay from 50% to 75% of cross section.	Attack from 50% to 75% of cross section.
0	Failure	Failure

Table 4.—Preservative retention and average years to failure of copper 8-quinolinolate-treated stakes exposed in ground contact at the Harrison Experimental Forest (HEF): 02 plots. Note: Specimens remaining are not included in determining years to failure.

HEF plot no. (02 report table no.) ^a	Wood specimen size and species	Preservative ^b	Cu8 (%)	Average solution uptake (lbs/ft ³)	Average retention Cu8 ^c (lbs/ft ³)	Average years until failure (SD)	Remarks ^e
54 (38)	2 by 4 by 18-in. nominal SP	Copper 8-quinolinolate in Stoddard solvent	0.1	9.9	0.01	5.3 ^d	10% remaining at year 9 10% remaining at year 9
			0.2	9.9	0.02	4.2 ^d	
			0.6	10	0.06	5.6 ^d	
		Untreated SP	—	—	—	2.2 ^d	
62 (43)	2 by 4 by 18-in. nominal SP	Copper 8-quinolinolate in AWP A P9 heavy petroleum	0.15	9.35	0.01	27.1 (7.7)	40% remaining at year 55
			0.3	10.14	0.03	28.4 (5.9)	
			0.6	9.89	0.06	31.6 (5.3)	
		Untreated SP	—	—	—	50.8 (3.8)	
75 (54)	2 by 4 by 18-in. nominal SP	Petroleum solvent control	—	—	—	20.9 (5.3)	60% remaining at year 17
		Untreated SP	—	—	—	1.9 (0.3)	
	3/4 by 3/4 by 18-in. SP	Copper 8-quinolinolate in water	5.4 ^f	1.12	0.06	13.25 (3.6)	
			—	—	—	2.5 (0.5)	
			5.4 ^f	0.34	0.02	3.3 (0.5)	
			5.4 ^f	0.38	0.02	3.8 (0.9)	
			5.4 ^f	0.5	0.03	4.6 (0.7)	
			5.4 ^f	0.94	0.05	6.3 (1.3)	
			5.4 ^f	1.16	0.06	8 (3.1)	
			5.4 ^f	1.3	0.07	7.3 (2.1)	
			5.4 ^f	1.84	0.10	8.6 (2.7)	
		Untreated SP	—	—	—	2.3 (0.5)	
84 (61)	2 by 4 by 18-in. nominal SP	Copper-8-quinolinolate in toluene	0.675 ^f	1.5	0.01	6.3 (2.3)	30% remaining (1 missing) at year 42 No complete failures (4 missing) at year 42
			0.675 ^f	2.96	0.02	12.4 (4.9)	
			0.675 ^f	8.75	0.06	29.5 (7.3)	
			0.675 ^f	17.5	0.12	—	
		Untreated SP	—	—	—	2.6 (0.6)	

^a Number in parentheses references the table number for that plot in Woodward et al. (2011; FPL-RN-02) for reference.

^b SP = southern pine.

^c As oxine copper (a.i.).

^d Raw data not found, so values for average years until failure were taken from Woodward et al. (2011; FPL-RN-02).

^e Based on 100 percent failure of all stakes unless otherwise noted.

^f Dilution concentrations could not be found; values are based on concentration of stock solution reported.

Results

FPL 02 research plots

The 02 test plots incorporated specimens pressure treated with oxine copper diluted in different solvents (i.e., water, diesel/toluene, heavy petroleum, Stoddard solvent). Wood specimens consisted of solid southern pine, and most plots included 10 replicates per treatment concentration. Preservative retentions and average years to specimen failure are shown in Table 4 for all 02 HEF plots. As preservative uptake values for individual specimens in the majority of these plots could not be found, retention information presented in Table 4 relied heavily on values from Woodward et al. (2011), which is the most recent edition of the FPL 02 progress report. Average minimum visual rating data are presented in Figures 2, 3, and 4 for plots 62, 75, and 84, respectively. Minimum visual ratings for plot 52 were not determined as raw data could not be found.

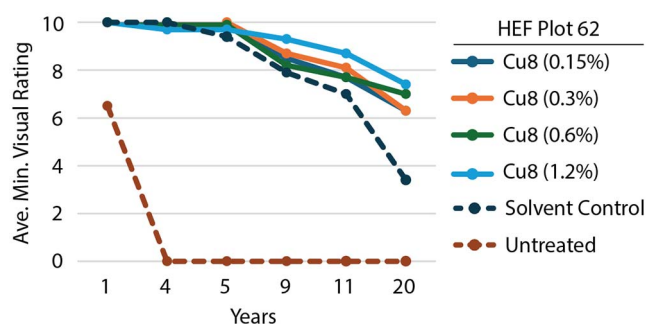


Figure 2.—Average of the minimum visual ratings given to oil-based (P9 heavy petroleum) Cu8-treated southern pine specimens for either decay or termites (i.e., whichever was the lowest) at years 1, 4, 5, 9, 11, and 20 installed in plot 62 at the Harrison Experimental Forest (HEF) test site.

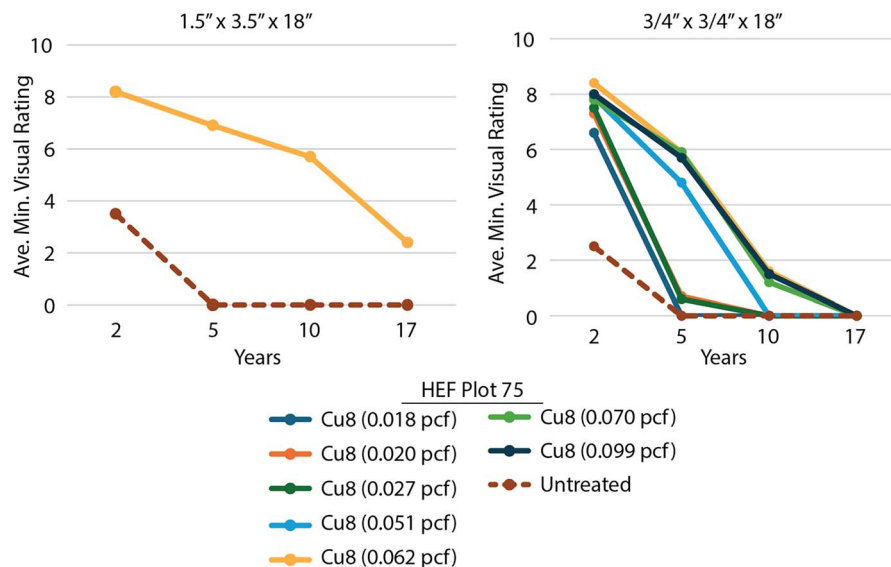


Figure 3.—Average of the minimum visual rating given to water-based Cu8-treated southern pine specimens (nominal 2 by 4-in. specimens [left]/3/4-in. specimens [right]) for either decay or termites (i.e., whichever was the lowest) at years 2, 5, 10, and 17 installed in plot 75 at the Harrison Experimental Forest (HEF) test site.

Field plot 54

In this plot four concentrations of oil-based Cu8 (soluble concentrate) were evaluated. Raw data for this plot could not be found; however, 9 year data were presented in the 2011 02 report and used here. Results show the average service life of Cu8-treated stakes in Stoddard solvents was 5.3, 4.2, 5.6, and 7.8 years for 0.1 (0.01 pcf), 0.2 (0.02 pcf), 0.6 (0.06 pcf), and 1.2 percent (0.12 pcf) Cu8, respectively (Table 4). Thus, Cu8 in Stoddard solution does not appear to be as effective as Cu8 in other petroleum-based solvents with an average service life of 5 to 8 years.

Field plot 62

Four concentrations of Cu8 (soluble concentrate) in heavy petroleum solvent were evaluated in this plot. Average minimum rating data are shown in Figure 2. Results suggest all concentrations tested had nearly complete protection for 5 years; however, there was almost no difference in performance between Cu8 treatments and the solvent

controls until year 9. At year 20, Cu8-treated specimens were better protected compared to those treated with petroleum solvent alone. The percent of failures (rating of 0) at year 20 were 100 percent for southern pine (SP) controls, 50 percent for petroleum solvent controls, 10 percent for 0.15 percent (0.01 pcf) and 0.3 percent (0.03 pcf) Cu8, and 0 percent for the remaining Cu8 formulation concentrations. At 20 years, the average minimum ratings were 3.4 (± 3.6), 6.3 (± 2.2), 6.3 (± 2.2), 7 (± 0), and 7.4 (± 0.7) for solvent controls, 0.15 percent, 0.3 percent, 0.6 percent, and 1.2 percent Cu8, respectively. After 55 years of field exposure, 40 percent of specimens treated with 1.2 percent (0.12 pcf) Cu8 remained with an average minimum visual rating of 4. Thus, while the petroleum solvent alone provided substantial wood protection, the addition of Cu8 provided increased protection over a longer period of time (i.e., over 20 years).

Field plot 75

Among the 02 plots, plot 75 included the only water-soluble form of copper 8-quinolinolate (soluble concentrate) tested. Evaluations were mainly conducted on smaller $\frac{3}{4}$ by $\frac{3}{4}$ by 18-in. stakes, with one solution concentration (0.06 pcf Cu8) tested on larger specimens (i.e., 2 by 4 in. nominal by 18 in.). Results for the 2 by 4-in. nominal specimens at 0.06 pcf Cu8 showed an average of 13.3 years until failure with 60 percent of specimens remaining after 17 years in field exposure (Table 4). However, the average minimum visual ratings were 8.2, 6.9, 5.7, and 2.4 at years 2, 5, 10, and 17 years, respectively, suggesting a useful service life to be between 5 and 10 years under conditions similar to that of Saucier, Mississippi (HEF, Fig. 3, left). The smaller, $\frac{3}{4}$ by $\frac{3}{4}$ -in. stakes at retentions of 0.02, 0.02, 0.03, 0.05, 0.06, 0.07, and 0.10 pcf Cu8 had average years until failure of 3.3, 3.8, 4.6, 6.3, 8.0, 7.3, and 8.6 years, respectively (Table 4). For the four higher retentions (0.05, 0.06, 0.07, and 0.10 pcf Cu8), the average minimum visual ratings

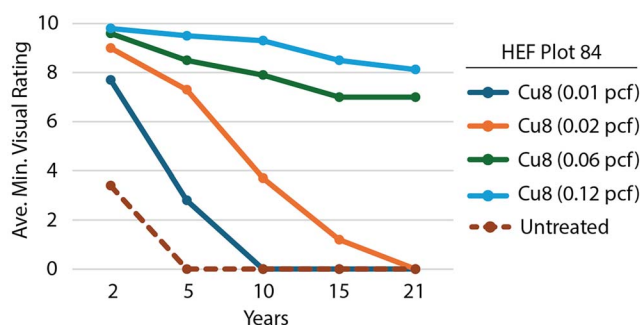


Figure 4.—Average of the minimum visual rating given to oil-based (toluene) Cu8-treated southern pine specimens for either decay or termites (i.e., whichever was the lowest) at years 2, 5, 10, 15, and 21 installed in plot 84 at the Harrison Experimental Forest (HEF) test site. (Note: toluene alone was not tested.)

Table 5.—Summary of wood species evaluated at each of the four test sites.

Field site ^a	Plot no.	Wood species tested						
		Southern pine	Hard maple (sap)	Hard maple (heart)	Yellow birch (heart)	Cotton-wood	Red oak	Yellow poplar
HEF (Mississippi)	95-01	x	—	—	—	x	x	x
HEF (Mississippi)	96-01	x	x	x	x	—	—	—
VV (Wisconsin)	96-04	x	x	x	x			
Indo. (Indonesia)	96-01	x	x	x	x			

^a HEF = Harrison Experimental Forest; Indo. = Indonesia; VV = Forest Products Laboratory Valley View test site.

were between 5.9 to 6.2 at year 5, suggesting the useful service life of these specimens to be approximately 5 years or less in ground contact (Fig. 3, right).

Field plot 84

This plot evaluated the condition of southern pine stakes (2 by 4 in. nominal by 18 in.) treated with nine different wood preservatives, one of which was copper 8-quinolino-late (ready-to-use formulation) in toluene. Solvent controls were not included, and untreated controls showed an average service life of approximately 2.5 years. Results showed specimens treated with Cu8 retentions of 0.01, 0.02, and 0.06 pcf to have average years until failure of 6.3, 12.4, and 29.5 (Table 4). Two highest treatment retentions continued to show average minimum visual ratings of over 7 at 21 years, suggesting the useful service life to be around 5 years at lower concentrations and >20 years at higher concentrations (Fig. 4).

Non-02 field plots

Four field plots (i.e., HEF: 95-01, 96-01, Indo: 96-01, and VV: 96-04) incorporated the same or similar sets of materials with the goal of evaluating preservatives that could be used as pressure treatments to protect temperate and tropical hardwoods (see De Groot et al. 1996); see Table 5 for results. In these studies, oil-based oxine copper in diesel/toluene (soluble concentrate) was evaluated at slightly different treatment solutions ranging from 0.04 percent to 4.8 percent oxine copper, depending on wood species and exposure location. These studies were more extensive due to the number of wood species tested; therefore, tables detailing average service life are presented for each plot individually (not combined like the 02 data presented above).

Field plot 95-01 (HEF)

Results from field plot 95-01 are shown in Figure 5 and Table 6. Oxine copper retentions were found to be lower in

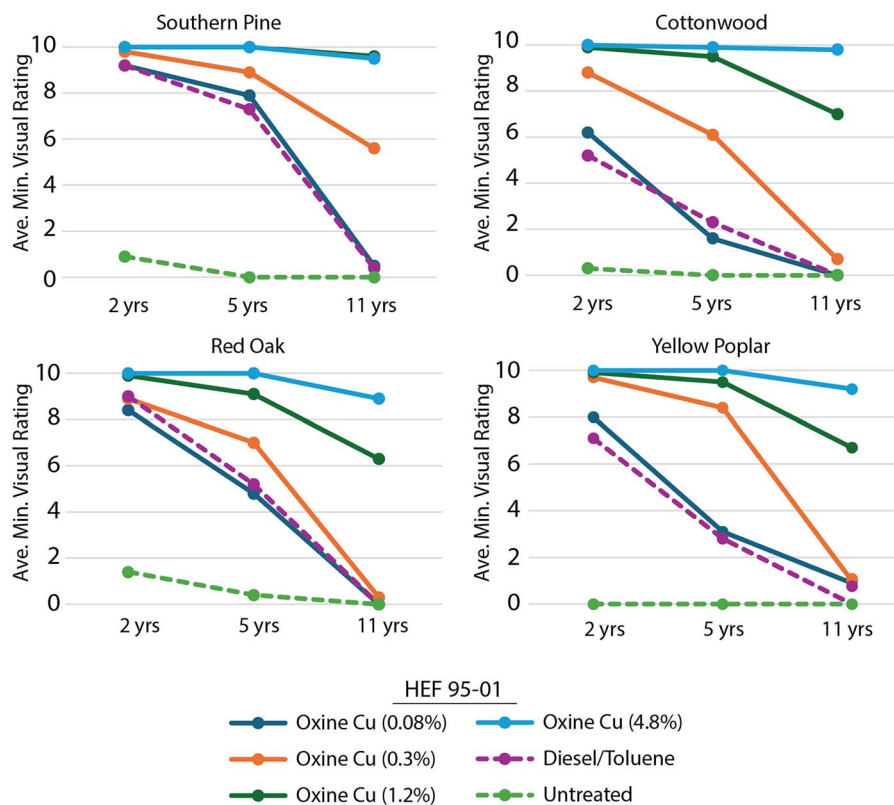


Figure 5.—Average of the minimum visual rating given to specimens for either decay or termites (i.e., whichever was the lowest) at years 2, 5, and 11 in plot 95-01 at the Harrison Experimental Forest (HEF) test site.

Table 6.—Preservative retention and average years to failure of $\frac{3}{4}$ by $\frac{3}{4}$ by 18-in. oxine copper-treated stakes exposed in ground contact at the Harrison Experimental Forest (HEF) plot 95-01. Note: Specimens remaining are not included in determining years to failure.

Preservative	Oxine copper (%)	Wood species ^a	Average gross solution uptake ^b (lbs/ft ³)	Average retention of oxine copper ^{b,c} (lbs/ft ³)	Average years to failure ^b	Stakes remaining (%) at year 11
Oxine copper in diesel/toluene	0.08	SP	28.36 (3.01)	0.02 (0.00)	8.7 (1.4)	5
		CW	34.41 (2.50)	0.03 (0.00)	4.5 (2.5)	0
		RO	20.35 (1.15)	0.02 (0.00)	6.5 (1.6)	0
		YP	31.00 (3.81)	0.02 (0.00)	5.5 (1.9)	10
	0.3	SP	28.41 (2.77)	0.09 (0.01)	9.3 (1.4)	65
		CW	32.46 (3.34)	0.10 (0.01)	7.6 (2.0)	10
		RO	19.09 (2.07)	0.06 (0.01)	8.6 (1.8)	5
		YP	31.19 (2.89)	0.09 (0.01)	9.1 (1.1)	15
	1.2	SP	28.22 (2.92)	0.34 (0.04)	—	100
		CW	33.51 (3.25)	0.40 (0.04)	11 (0)	85 (one missing)
		RO	19.93 (1.41)	0.24 (0.02)	11 (0)	85
		YP	30.95 (4.65)	0.37 (0.06)	11 (0)	85
	4.8	SP	29.14 (2.70)	1.40 (0.13)	—	95 (one under log)
		CW	31.05 (3.67)	1.49 (0.18)	—	100
		RO	16.20 (1.96)	0.78 (0.09)	—	100
		YP	31.10 (3.56)	1.49 (0.17)	—	95 (one missing)
Diesel and toluene (solvent control)	—	SP	27.50 (2.44)	—	8.2 (1.7)	5
		CW	34.35 (2.40)	—	4.4 (3.0)	0
		RO	19.97 (2.09)	—	6.9 (1.9)	0
		YP	30.33 (3.99)	—	5.4 (2.4)	0
Untreated	—	SP	—	—	1.6 (0.7)	None
		CW	—	—	1.4 (0.6)	
		RO	—	—	2.4 (1.5)	
		YP	—	—	1.1 (0.2)	

^a SP = southern pine; YP = yellow poplar; HM = hard maple; CW = cottonwood; RO = red oak.

^b Standard deviation values are in parentheses.

^c As oxine copper (a.i.).

red oak specimens at the three higher preservative concentrations (i.e., 0.3%, 1.2%, and 4.8%) compared to the other wood species tested, suggesting some treatability challenges with this species. Retention levels were comparable among the other three wood species within each treatment concentration (Table 6). Average minimum visual rating data showed stakes treated with 0.08 percent oxine copper did not perform any better than the solvent control (i.e., diesel and toluene)-treated stakes. All hardwoods treated with 0.3 percent oxine copper were close to failing or had failed by year 11. Protection of southern pine was achieved at an oxine copper concentration of 1.2 percent, while the higher concentration (4.8%) was required to achieve the same protection in the three hardwood species. After 11 years, 4.8 percent oxine copper showed good protection of all wood species evaluated at the HEF test site, indicating higher concentrations may be needed to provide adequate protection in hardwoods.

Field plots 96-04 (VV) and 96-01 (HEF)

Average minimum visual rating data are shown in Figures 6 and 7 for plots 96-04 and 96-01, respectively. Average years until failure and preservative retention values for both plots are shown in Tables 7 and 8. Untreated control specimens of all wood species failed between 2.5 and 2.7 years at the HEF test site and mostly failed around 2.8 to 4.5 years at the VV test site.

Results from the VV site (96-04) showed that protection of southern pine, yellow birch, and hard maple sapwood, at oxine copper concentrations of 0.04 percent and 0.08 percent, was

not different from those treated with the solvent control alone. However, these wood species were well protected (i.e., visual decay ratings between 8 and 10 for 12 years) at oxine copper concentrations of 0.3 percent or higher (Fig. 6). Hard maple heartwood samples treated with concentrations of 1.2 percent and 4.8 percent oxine copper were similarly protected from decay over the 12-year rating period. In these samples, increasing the concentration of oxine copper did not show any improvement in durability. Therefore, under climate conditions similar to those in Wisconsin (and without termite pressure), southern pine, hard maple sapwood, and yellow birch heartwood should be reasonably protected for 10 or more years by pressure treatment with oxine copper in diesel/toluene at a concentration of 0.3 percent or higher (Table 7). Hard maple heartwood was not evaluated at the lower concentrations of oxine copper but was well protected at the 1.2 percent concentration.

Unlike the VV site (96-04), which has no termite activity, data from the HEF site (96-01) incorporated visual ratings of damage from both termites and decay (Fig. 7). Results showed good protection of southern pine over the 12-year test period at concentrations of 0.3 percent or higher (i.e., visual ratings between 8 and 10). Yellow birch was well protected for 5 years and only moderately protected for 10 years at the highest concentration of oxine copper tested (1.2%), with average minimum ratings of 8.9, 7.0, and 5.5 at years 5, 10, and 12, respectively. Hard maple sapwood was well protected for 5 years at the two higher concentrations (1.2% and 4.8%), but only samples at the highest concentration (4.8%) were protected over 10 years. Both

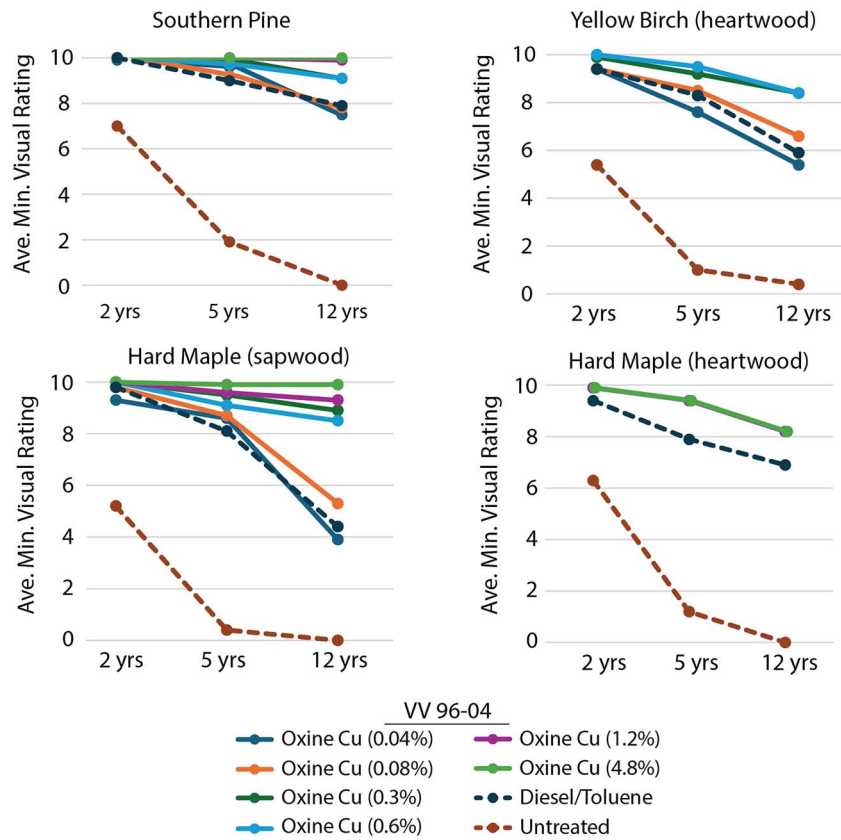


Figure 6.—Average minimum visual rating given to specimens for decay at years 2, 5, and 12 installed in plot 96-04 at the Valley View (VV) test site.

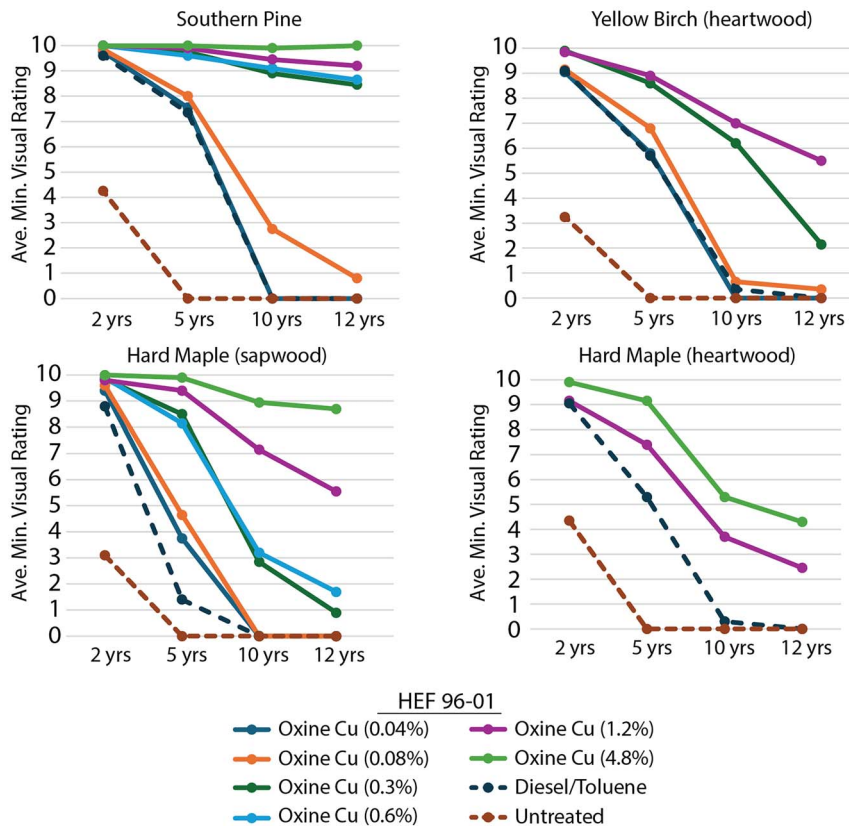


Figure 7.—Average of the minimum visual rating given to specimens for either decay or termites (i.e., whichever was the lowest) at years 2, 5, 10, and 12 installed in plot 96-01 at the Harrison Experimental Forest (HEF) test site.

Table 7.—Preservative retention and average years to failure of $\frac{3}{4}$ by $\frac{3}{4}$ by 18-in. oxine copper-treated stakes exposed in ground contact at the Valley View test site (VV) plot 96-04. Note: Specimens remaining are not included in determining years to failure.

VV 96-04					
Wood species	Oxine copper (%)	Average gross absorption ^a (lbs/ft ³)	Average retention of oxine copper ^{a,b} (lbs/ft ³)	Average years to failure ^a	Stakes remaining at year 12 (%)
Southern pine	0.04	27.3 (1.7)	0.01 (0.00)	10.5 (2.1)	90
	0.08	26.6 (1.8)	0.02 (0.00)	12 (0)	95
	0.30	27.2 (1.8)	0.08 (0.01)	6 (0)	95
	0.60	27.2 (1.5)	0.16 (0.01)	—	100
	1.20	27.9 (2.1)	0.34 (0.03)	—	100
	4.80	27.0 (2.0)	0.33 (0.02)	—	100
	30% diesel in toluene	27.5 (1.7)	—	12 (0)	95
	Untreated	—	—	4.5 (2.1)	0
Hard maple sapwood	0.04	23.3 (3.1)	0.01 (0.00)	11 (2.1)	50
	0.08	24.8 (1.7)	0.02 (0.00)	10.6 (2.7)	65
	0.30	23.9 (2.0)	0.07 (0.01)	—	100
	0.60	24.6 (1.8)	0.15 (0.01)	—	100
	1.20	23.1 (4.5)	0.28 (0.05)	—	100
	4.80	22.8 (4.9)	0.27 (0.06)	—	100
	30% diesel in toluene	23.8 (3.2)	—	10 (3.0)	55
	Untreated	—	—	2.8 (1.0)	0
Hard maple heartwood	1.20	16.7 (4.5)	0.20 (0.05)	—	100
	4.80	8.6 (3.6)	0.41 (0.17)	12 (0)	95
	30% diesel in toluene	17.5 (3.2)	—	8.5 (4.9)	90
	Untreated	—	—	3.6 (2.2)	0
	Untreated	—	—	3.6 (2.2)	0
Yellow birch heartwood	0.04	24.6 (2.1)	0.01 (0.00)	9.6 (3.3)	65
	0.08	24.4 (2.2)	0.02 (0.00)	11.3 (1.5)	80
	0.30	24.2 (2.7)	0.07 (0.01)	—	100
	1.20	24.4 (3.0)	0.29 (0.04)	12 (0)	95
	30% diesel in toluene	25.3 (2.3)	—	10.8 (1.6)	75
	Untreated	—	—	3.3 (1.9)	5

^a Standard deviation values are in parentheses.

^b As oxine copper (a.i.).

1.2 percent and 4.8 percent oxine copper concentrations provided better protection of hard maple heartwood than solvent-only treatments. However, all treatments had limited protective effects after 5 years, with 65 percent failure around 8.5 years for specimens treated at the 1.2 percent concentration and 45 percent failure around 9.6 years for specimens treated at the 4.8 percent concentration (Table 8). These results suggest that under conditions similar to Mississippi, lower concentrations of oxine copper in diesel/toluene (i.e., 0.3% or higher) can effectively protect easily treatable wood species (e.g., southern pine) for 10 or more years, but much higher concentrations are needed for protection of more difficult-to-treat hardwood species.

Field plot 96-01 (Indo.)

Raw data for stakes installed in plot 96-01 in Indonesia could not be located. However, several progress reports were found that summarized some of the data from this study (Table 9; Permadi et al. 1998). After 2 years, results for samples treated with oxine copper were indistinguishable from solvent-only controls in southern pine. Oxine copper treatments performed slightly better than solvent-only controls in yellow birch and hard maple heartwood. Hard maple sapwood showed the most improvement in durability with oxine copper treatment, with less variability in efficacy compared to solvent-only controls. Service life

could not be estimated, however, as we only had access to the 2-year visual ratings.

Field plot 14-02 (HEF)

This field plot is unique because it evaluated water-based Cu8 as a dip treatment for specimens that would be near, but not in direct contact with, the ground (i.e., ground proximity). This plot was established as part of a larger study aimed at examining potential preservatives for protection of military WPMs (see Lebow et al. 2015, 2017). Two concentrated solutions of Cu8 were used, Cu8-1 (concentrate with 9% to 11% copper 8-quinolinolate) and Cu8-2 (concentrate with 5.1% to 5.7% copper 8-quinolinolate). Both were diluted with water for final concentrations of 1.2 percent and 1.8 percent Cu8. Unlike the other field tests, these treatment solutions were buffered with a borate solution.

Results showed that most untreated specimens were undamaged with visual ratings between 8 and 10 after 2 years of field exposure. Initial failures of untreated control specimens were observed after approximately 3 and 5 years of field exposure at the HEF test site for southern pine and yellow poplar, respectively (Table 10). At year 5, only half of the untreated southern pine samples were remaining in the test, which showed no decay damage but had an average termite rating of 6.5 ± 4.2 . A higher percentage of untreated yellow poplar specimens remained at year 5 (77%), but these did show major damage with average

Table 8.—Preservative retention and average years to failure of $\frac{3}{4}$ by $\frac{3}{4}$ by 18-in. oxine copper-treated stakes exposed in ground contact at the Harrison Experimental Forest (HEF) plot 96-01. Note: Specimens remaining are not included in determining years to failure.

HEF 96-01					
Wood species	Oxine copper (%)	Average gross absorption ^a (lbs/ft ³)	Average retention of oxine copper ^{a,b} (lbs/ft ³)	Average years to failure ^a	Stakes remaining at year 12 (%)
Southern pine	0.04	26.8 (1.6)	0.01 (0.00)	7.9 (1.7)	0
	0.08	27.2 (2.0)	0.02 (0.00)	9.6 (2.1)	10
	0.30	27.8 (1.6)	0.08 (0.01)	10 (0)	95
	0.60	27.7 (1.8)	0.17 (0.01)	—	100
	1.20	27.3 (1.6)	0.33 (0.02)	—	100
	4.80	28 (2.1)	1.34 (0.10)	—	100
	30% diesel in toluene	27.2 (1.5)	—	7.4 (1.4)	0
	Untreated	—	—	2.6 (0.6)	0
	0.04	24.3 (2.0)	0.01 (0.00)	5.8 (1.7)	0
	0.08	25.4 (1.8)	0.02 (0.00)	6.2 (1.5)	0
Hard maple sapwood	0.30	23.2 (3.4)	0.07 (0.01)	9.8 (2.1)	15
	0.60	24.5 (2.0)	0.15 (0.01)	9.8 (2.1)	20
	1.20	24.3 (2.3)	0.29 (0.03)	11.2 (1.1)	75
	4.80	23.6 (5.3)	1.13 (0.25)	8 (0)	95
	30% diesel in toluene	22.1 (3.8)	—	4.7 (1.0)	0
	Untreated	—	—	2.5 (0.7)	0
	1.20	14.6 (4.5)	0.18 (0.05)	8.5 (2.9)	35
	4.80	10.6 (4.5)	0.51 (0.22)	9.6 (1.9)	55
Hard maple heartwood	30% diesel in toluene	18.5 (3.4)	—	6.9 (2.3)	0
	Untreated	—	—	2.7 (0.8)	0
	0.04	24.6 (2.1)	0.01 (0.00)	7.3 (1.4)	0
	0.08	24.8 (1.6)	0.02 (0.00)	8.1 (2.0)	5
Yellow birch heartwood	0.30	23.9 (2.9)	0.07 (0.01)	11.3 (1.7)	30
	1.20	15.4 (4.8)	0.19 (0.06)	11.5 (1.0)	75
	30% diesel in toluene	24.6 (2.5)	—	7.5 (2.6)	0
	Untreated	—	—	2.5 (0.6)	0

^a Standard deviation values are in parentheses.

^b As oxine copper (a.i.).

termite and decay ratings of 6.2 ± 3.9 and 6.2 ± 3.4 , respectively. By year 10, nearly all untreated southern pine (85%) and yellow poplar (92%) specimens had failed.

Preservative uptake in treated samples was between 4.7 and 6.1 g and between 3.2 and 3.9 g in southern pine and yellow poplar, respectively, as determined by total grams of solution uptake pre- and postdip. None of the Cu8-1-treated specimens failed in the first 2 years of field exposure. However, failures occurred between 4 and 5 years and between 5 and 8 years for southern pine and yellow poplar, respectively. The majority of specimens of all types failed by year 8 (Table 10; Fig. 8). As with Cu8-1 specimens, all Cu8-2 specimens showed relatively minimal termite/decay damage at year 2. Failures of southern pine Cu8-2-treated

specimens began around year 4 to 5, and failures of Cu8-2-treated yellow poplar occurred around year 8. Overall, both Cu8-1 and Cu8-2 performed similarly to untreated control specimens in this study, suggesting that these formulations, when applied as a dip treatment, are not very effective at preventing biological damage when placed in ground proximity outdoors at the HEF site.

Discussion

Oxine copper has been evaluated as a wood protectant for decades with varied results depending on concentration, formulation, and method of solubilization (DeGroot and Stroukoff 1986, Stokes et al. 1991). For oil-based formulations,

Table 9.—Summary of visual ratings after 2 years exposure in Indonesia (Indo. 96-01).

Oxine copper (%)	Southern pine ^a		Yellow birch ^a (heart)		Hard maple ^a (sap)		Hard maple ^a (heart)	
	Decay	Termite	Decay	Termite	Decay	Termite	Decay	Termite
0.3	8.8 (0.83)	8.2 (0.83)	7.9 (0.79)	8.3 (0.61)	6.9 (1.45)	7.1 (1.95)	NT ^b	NT ^b
0.6	8.6 (0.59)	8.4 (0.74)	8 (0.63)	8.3 (0.57)	8.1 (0.74)	8.5 (0.82)	NT ^b	NT ^b
1.2	9.1 (0.67)	9.1 (0.72)	8.3 (0.7)	8.8 (0.78)	8.5 (0.87)	9 (0.79)	7.7 (0.65)	8 (0.89)
2.4	9.6 (0.5)	9.4 (2.23)	8.8 (0.75)	8.9 (0.87)	9.1 (0.94)	9.3 (0.65)	8.4 (0.58)	8.2 (1.44)
4.8	8.3 (0.78)	7.6 (1.96)	9.1 (0.7)	9.8 (0.44)	9 (0.95)	9.7 (0.73)	8.7 (1.06)	8.3 (2.42)
Diesel/toluene	8.8 (0.6)	8.3 (1.33)	6.7 (2.06)	7.5 (1.96)	3.2 (3.96)	4.3 (4.02)	6.5 (2.8)	6.8 (2.73)
Untreated	1 (2.36)	0.2 (0.89)	1.8 (3.13)	0.5 (2.23)	0.4 (1.53)	0.7 (1.74)	2.2 (3.39)	0.5 (2.23)

^a Standard deviation values are in parentheses.

^b NT = not tested.

Table 10.—Year of first failure, average years to specimen failure, and percent of specimens remaining at year 10 in Harrison Experimental Forest (HEF) plot 14-02.

Preservative	Oxine copper ^a (%)	Southern pine			Yellow poplar		
		Year of first failure	Average years to failure (SD)	Specimens remaining at year 10 (%)	Year of first failure	Average years to failure (SD)	Specimens remaining at year 10 (%)
Water	None	3	5.5 (2.0)	15	5	7.25 (1.4)	8
Cu8-1	1.2% as Cu-8	4	7 (2.0)	20	5	6.8 (1.6)	0
	1.2% as Cu-8 (3-minute dip)	8	8 (0)	20	8	8 (0)	20
	1.8% as Cu-8	5	6.5 (1.7)	20	5	6.2 (1.6)	0
Cu8-2	1.2% as Cu-8	4	6.3 (2.1)	20	8	8 (0)	0
	1.8% as Cu-8	5	6 (1.7)	40	8	8 (0)	20

^a All treatments were applied as a 1-minute dip unless otherwise noted.

differences in efficacy are strongly affected by type of solvent. Lebow (2007) suggested that oxine copper dissolved in heavy oil provides longer protection than formulations using certain hydrocarbon solvents. This is supported by field results from plot 54 with oxine copper dissolved in Stoddard solution (hydrocarbon solvent) providing only 7.8 years of protection while plot 62 with oxine copper dissolved in petroleum provided 20+ years of protection. Additionally, Schultz et al. (2005) showed pressure treatment of southern pine with oil-based oxine copper (soluble concentrate) in mineral spirits had average decay and termite ratings of 0.8 and 0.4 for 0.13 percent (0.019 pcf) oxine copper, 3.8 and 2.9 for 0.3 percent (0.06 pcf) oxine copper, and 7.6 and 6.8 for 0.69 percent (0.12 pcf) oxine copper after 5.75 years of ground-contact exposure at the HEF test site. Verrall (1959) conducted field trials of dip treatments for M22 ammunition boxes, including an oil-based oxine copper formulation (10% concentrate diluted in aliphatic mineral spirits). Their results for boxes exposed in the Panama Canal zone showed those dipped with 0.3 percent oxine copper plus a water-repellent additive had 17 percent failure after 2.5 years and over 50 percent failure after 3.5 years. Boxes dipped in 0.6 percent oxine copper with a water-repellent additive had 33 percent and 80 percent failure after 3.5 and 4.5 years, respectively. However, this study was conducted on treated soil to remove termite pressure, which is severe in these locations, and therefore the actual useful service life is likely much shorter when termites are present. These studies highlight the limitations of oxine copper in certain hydrocarbon-based solvents.

Oxine copper in toluene demonstrated improved protection compared to other hydrocarbon solvents. This is shown in plot 84 with 6.3, 12.4, and 29.5 average years until failure with oxine copper retentions of 0.01, 0.02, and 0.06 pcf, respectively. Wood treated in this plot with 0.12 pcf oxine copper had no complete failures and average decay and termite visual ratings of 7.3 and 9 after 42 years in ground contact. However, there were no solvent-only controls in this study, so it cannot be determined what protection was provided by toluene alone. It should be noted that toluene alone likely provides little protection because it quickly volatilizes out of the wood (Stan Lebow, personal communication, April 2026). It can be inferred from plots 95-01 and 96-01 that the average service life of toluene when combined with diesel alone is approximately 4.4 to 7.5 years depending on wood species. Thus, much of the long-term durability in these specimens can be attributed to the addition of oxine copper.

Oxine copper dissolved in heavy petroleum solvents gave substantially more protection than other formulations, as shown in results from plot 62. Here, solvent controls alone provided around 9 to 11 years of protection (minimum visual rating between 7.0 and 8.0), while the addition of oxine copper at concentrations of 0.6 percent or higher provided an additional 9 to 11 years. Findings from plots 95-01, 96-01, and 96-04 pressure treated in solutions of diesel/toluene demonstrate better treatability of softwoods compared to hardwoods and suggest that concentrations above 1.2 percent oil-based oxine copper are needed to protect

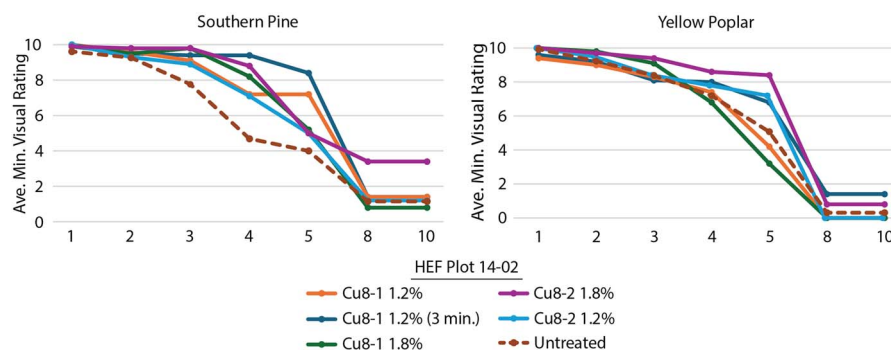


Figure 8.—Average of the minimum visual rating given to specimens for either decay or termites (i.e., whichever was the lowest) over 10 years in a ground proximity test in plot 14-02 at the Harrison Experimental Forest (HEF) test site for southern pine and yellow poplar specimens.

hardwoods past 5 years in ground-contact exposure conditions. However, as mentioned above, diesel/toluene solvent controls protected wood from 4.4 to 9.3 years without the addition of oxine copper. Overall, these results suggest that certain oil-based formulations of oxine copper may provide adequate protection of wood in ground-contact exposure. However, treatability should be a consideration, particularly when using hardwood materials.

Pressure treatment with water-soluble formulations of oxine copper evaluated in plot 75 averaged between 3.3 and 8.6 years until failure for $\frac{3}{4}$ by $\frac{3}{4}$ -in. stakes at retentions between 0.02 and 0.1 pcf oxine copper. However, minimum visual rating data suggest substantial damage to all specimens after only 5 years of in-ground exposure (i.e., rating ≤ 6). The larger 2 by 4-in. nominal stakes showed improved field performance at a retention of 0.06 pcf oxine copper with 13.3 average years until failure. Dip treatment with two different water-soluble concentrations of oxine copper was also not effective for protecting southern pine or yellow poplar from termites or decay, as shown in plot 14-02. These field results suggest that water-based oxine copper provides little to no protection of specimens in external ground proximity or ground-contact exposures after 3 to 5 years in environments with severe biodeterioration pressure. However, the concentrations of oxine copper that were evaluated in plot 75 were lower than those used in some of the oil-based treatments. Several studies have indicated that higher oxine copper concentrations are likely required for efficacy in water-based systems. For example, Mitchoff and Morrell (1988) found water-based Cu8 was effective for protection of red alder against decay, but they noted that higher concentrations were required compared to the other preservative systems tested. Their study identified thresholds of 0.03, 0.01, and 0.04 pcf (0.46, 0.22, and 0.60 kg/m³; as Cu) for protection against *R. placenta*, *G. trabeum*, and *Trametes versicolor*, respectively, and concluded that a loading of 0.37 pcf (6 kg/m³) or greater would be required for protection of nondurable species like red alder. Alternative formulations of water-based oxine copper could also be used to enhance durability. A “water-based” (water with 10% P9-A oil) formulation of oxine copper performed well at 0.2 percent to 0.6 percent solution concentration (0.05 to 0.17 pcf oxine copper) when exposed for 102 months in an aboveground miter joint test at a Mississippi test site (i.e., Dorman Lake; Stokes et al. 1991).

While water-based oxine copper has limited durability under field exposure conditions, it still has some advantages as a preservative for treating military WPMs over oil-based treatments (e.g., reduced odor, easy cleanup, nonflammable, lower cost). According to current specifications, military ammunition WPMs need to remain serviceable for a minimum of 20 years in storage and 2 years under external environmental exposure regardless of geographic location. Results shown here suggest water-based oxine copper-treated wood provides approximately 3 to 5 years of protection against decay and termites under external exposure conditions similar to the HEF. Perhaps more importantly, the efficacy of oxine copper as an anti-sapstain/mold inhibitor makes it ideal for protecting wood in storage for long periods of time under high relative humidity (Vicklund et al. 1954, Arango et al. 2023). For this use, preservative

application using a dip treatment is sufficient as damage by mold fungi is confined to the wood surface.

However, the service life under more severe conditions will necessitate use of higher preservative concentrations, alternative oxine copper formulations, or a change from dip to pressure treatment for certain materials. To address this, future studies should evaluate the treatability of different wood species with oxine copper and compare durability of pressure-treated versus dip-treated specimens. This is particularly important because there has been an increase in the use of more durable hardwood species by the military despite the relatively unknown service life of hardwoods treated with water-based preservatives. The use of non-biocidal water repellents (e.g., hydrocarbon waxes, thermoplastics) could also be considered as they have improved durability of wood preservatives by reducing the amount of decay and preventing leaching of biocides from the treated wood (Schultz et al. 2007). They would also likely help to prevent mold growth during storage. However, issues related to paintability may be an issue with wax emulsions (Verrall 1965) as well as increased flammability, which may impact suitability for use on military WPMs.

Conclusions

Field and laboratory studies have shown oxine copper can perform very well as a wood preservative, although its service life can vary widely and is strongly influenced by formulation. Certain oil-based systems, such as those in heavy petroleum, provide good protection in ground contact, while those in lighter, hydrocarbon solvents may be suitable for aboveground exposure. Water-based formulations have shown some promising results in laboratory studies; however, they provided very little protection under field exposure. While water-based oxine copper may have limited efficacy as a wood preservative in most markets, it remains one of the preferred preservative systems used for protection of military WPMs because of its regulatory acceptance, toxicity profile, adequate service life, and activity as an anti-sapstain. Continued work is needed to better define the effective retention levels for protection of various wood species/types using water-based oxine copper formulations. Additional field trials focusing on weather exposure and long-term performance should be conducted as these are currently limited for water-based oxine copper compared to other copper-based preservative systems. Potential improvements to the durability of water-based systems, such as the inclusion of a water repellent, should also be evaluated.

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