Forest
Products
Laboratory

General
Technical
Report
FPL–GTR–227

In cooperation
with the

United States
Department of
Transportation

Federal
Highway
Administration

United States Department of Agriculture
Forest Service

Guide for Materials Selection and Design for Metals Used in Contact with Copper-Treated Wood

Samuel L. Zelinka

Abstract

This design guide summarizes recent research on the corrosion of metals in treated wood, presents design strategies to minimize corrosion of metals in contact with treated wood, and is targeted toward engineers, architects, builders, and homeowners. The guide is organized as a "question and answer" document. While the questions are arranged in a logical order, each question and answer are self-contained. Special efforts have been made to provide a comprehensive bibliography to direct the reader to further information on each question. The document was created to give practical "hands-on" information for corrosion in treated wood.

Keywords: corrosion, fasteners, galvanized steel, carbon steel, preservative-treated wood, alkaline copper quaternary (ACQ), chromated copper arsenate (CCA), copper azole

August 2013

Zelinka, Samuel L. 2013. Guide for materials selection and design for metals used in contact with copper-treated wood. General Technical Report FPL-GTR-227. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 12 p.

A limited number of free copies of this publication are available to the public from the Forest Products Laboratory, One Gifford Pinchot Drive, Madison, WI 53726–2398. This publication is also available online at www.fpl.fs.fed.us. Laboratory publications are sent to hundreds of libraries in the United States and elsewhere.

The Forest Products Laboratory is maintained in cooperation with the University of Wisconsin.

The use of trade or firm names in this publication is for reader information and does not imply endorsement by the United States Department of Agriculture (USDA) of any product or service.

The USDA prohibits discrimination in all its programs and activities on the basis of race, color, national origin, age, disability, and where applicable, sex, marital status, familial status, parental status, religion, sexual orientation, genetic information, political beliefs, reprisal, or because all or a part of an individual's income is derived from any public assistance program. (Not all prohibited bases apply to all programs.) Persons with disabilities who require alternative means for communication of program information (Braille, large print, audiotape, etc.) should contact USDA's TARGET Center at (202) 720–2600 (voice and TDD). To file a complaint of discrimination, write to USDA, Director, Office of Civil Rights, 1400 Independence Avenue, S.W., Washington, D.C. 20250–9410, or call (800) 795–3272 (voice) or (202) 720–6382 (TDD). USDA is an equal opportunity provider and employer.

Contents

This study is part of the Research, Technology and Education portion of the **National Historic Covered Bridge Preservation** (NHCBP) Program administered by the Federal Highway Administration. The NHCBP program includes preservation, rehabilitation and restoration of covered bridges that are listed or are eligible for listing on the National Register of Historic Places; research for better means of restoring, and protecting these bridges; development of educational aids; and technology transfer to disseminate information on covered bridges in order to preserve the Nation's cultural heritage.

This study is conducted under a joint agreement between the Federal Highway Administration–Turner Fairbank Highway Research Center, and the Forest Service – Forest Products Laboratory.

Federal Highway Administration Program Manager–
Sheila Rimal Duwadi, P.E.

Forest Products Laboratory Program Manager–
Michael A. Ritter, P.E.

Guide for Materials Selection and Design for Metals Used in Contact with Copper-Treated Wood

Samuel L. Zelinka, General Engineer
Forest Products Laboratory, Madison, Wisconsin

Introduction

The corrosion of metals in contact with wood has been studied for over 80 years, and in most situations wood is not corrosive. Recently, however, concerns have been raised about the durability of fasteners in preservative-treated wood. These concerns are a result of changes in regulation and certification of certain wood preservatives in the United States, the European Union, and Australasia. These regulation changes brought new copper-based wood preservatives into the market, following which was anecdotal evidence suggesting that newer wood preservatives were more corrosive (Mittendorf 2009), but little testing or scientific understanding to make informed decisions. Since this regulation change, there has been much research in this area.

This paper represents a compilation of research on the corrosion of metals in treated wood and is intended to explain why metals corrode in treated wood and give practical design recommendations. While the paper is targeted for a non-scientific audience, it is based upon experimental evidence. These experiments are cited throughout the document and further scientific details can be found in the references in the bibliography. The paper is arranged topically by questions. Although each question builds upon the previous question, the content within each question is independent, so the paper does not need to be read from cover to cover if only a specific question needs to be answered.

What Is Corrosion?

Corrosion is an oxidation/reduction reaction where a metal is oxidized (loses electrons) and a nearby chemical species is reduced (gains electrons). Once oxidized, the metal ion quickly reacts with the environment to form an inorganic compound (i.e., “rust”) (Fig. 1). Except for a few precious metals, such as gold and platinum, corrosion is nearly always thermodynamically favorable and will spontaneously happen. Therefore, materials selection is not about selecting materials that will not corrode (which is nearly impossible), but rather about selecting materials that will corrode so slowly that that the metal remains functional throughout its service life.

Figure 1. The omnipresence of corrosion: these corroded objects were found during a short walk. The rust, which appears reddish-brown, is an inorganic ceramic compound formed as part of the oxidation process.

Frequently when a metal corrodes, it forms a protective oxide or hydroxide layer that greatly reduces the corrosion rate of the remaining metal. This phenomenon is called passivation. Certain metals, such as aluminum and stainless steels, have extremely stable oxide layers that account for their corrosion resistance. In general, the stability of the passive layer depends upon the environment and is one of the controlling factors of the reaction kinetics, and therefore the useful service life of materials in a given environment.

Common metals used in combination with wood are carbon steel, galvanized steel, and stainless steel. Depending on how the metals are used, the metals are susceptible to several different types of corrosive attack. For example, Figure 2 shows the corrosion of a galvanized joist hanger held with galvanized nails and illustrates the different types of corrosion that can occur. The head of a nail or the outer side of a joist hanger is susceptible to atmospheric corrosion. The corrosion of the nail shank embedded in the wood depends upon the wood moisture content and chemistry. The inner face of the wood is similar to the embedded fastener but also may exhibit galvanic corrosion if the joist hanger and the fastener are made from different materials. Galvanic corrosion is described further in the section “How Can I Design To Minimize Corrosion in Treated Wood?”

Figure 2. Corrosion of a galvanized joist hanger and galvanized nails supporting a wood deck treated with a copper-containing wood preservative.

What Is Treated Wood? What Types of Wood Preservatives Are Used?

Wood preservatives are chemicals that are injected into the wood to help the wood resist attack by decay fungi, mold, and/or termites. Waterborne wood preservatives are used in most cases where the wood may be in contact with humans or will be painted. While many different formulations of waterborne preservative treatments have been developed, only a few of these have been used commercially. Most of the commercial treatments contain cupric ions, which give treated wood its characteristic greenish-brown coloration (Fig. 3).

Figure 3. (From left to right) Wood treated with MCQ, DDAC, and ACQ. Cupric ions from the wood preservative causes the dark coloration of the wood. Excess copper has deposited on the MCQ (green splotches) and the ACQ (along the end grain).

In 2004, EPA regulation changes in the United States restricted the use of chromated copper arsenate (CCA), which had previously dominated the preservative market for many years. Similar regulation changes happened in the European Union and Australasia. CCA can still be used in certain situations, specifically wood used in highway construction (excluding pedestrian bridges or hand railings). Since the regulation change, alternatives to CCA have been introduced to and now dominate the market. Lebow (2004, 2010) has summarized alternatives to CCA. A brief summary of the commercially important alternative wood preservatives is provided below. Although the formulations of the following wood preservatives are different from each other, they all have a higher percentage of copper than does CCA. This is important, as the corrosion mechanism involves the reduction of cupric ions from the preservative. Furthermore, the chromates and arsenates in CCA act as corrosion inhibitors (Zelinka and others 2007).

Alkaline copper quaternary (ACQ) is composed of copper oxide (67%) and 33% of a quaternary ammonium compound (DDAC—didecyldimethylammonium chloride or carbonate). When it was first commercially available, the quaternary ammonium compound was made with a chloride formulation but was later almost exclusively replaced with carbonate. Several formulations of ACQ have been commercialized and it can be treated with an amine or ammonia carrier.

Copper azole (CA) type-B and C are composed of ammine copper (96%) and an azole (4%). In CA type B, the azole is entirely comprised of tebuconazole. In type C, the azole is 50/50 mixture of tebuconazole and propiconazole. Although copper azole contains a higher percentage of copper than ACQ, the retention required for above-ground use (Category U3; Anon 2007a) is lower, and therefore, the total amount of copper in the treated wood is less.

In addition to these preservatives standardized by the American Wood Protection Association, several commercially important preservatives have been introduced to the market by ICC-ES evaluation reports. These preservatives include "micronized" formulations of ACQ and CA, which have various trade names. In these formulations, soluble copper is not injected into the wood; rather solid copper, copper oxide, or copper carbonate is ground into submicron particles or "micronized" and suspended in solution prior to injec-

Table 1. Summary of some waterborne wood preservatives and above ground retentions highlighting the difference in copper concentration between preservatives. Data are combined from Anon (2007b) and Lebow (2010).

Preservative	Composition	Above ground retention (kg of preservative per m^3 of wood)	Copper concentration (g of copper per m^3 of wood)
CCA	47.5% chromium trioxide 34.0% chromium trioxide 18.5% copper as copper oxide	4	591
ACQ	67% copper as copper oxide 33% DDAC	4	2,141
CA-B	96.1% amine copper as Cu 3.9% tebuconazole	1.7	1,634
CA-C	96.1% amine copper as Cu 1.95% tebuconazole 1.95% propiconazole	1.0	961
ESR-1721 (MCA-B)	96.1% amine copper as Cu 3.9% tebuconazole	1.0	961
ESR-1721 (MCA-C)	96.1% amine copper as Cu 1.95% tebuconazole 1.95% propiconazole	0.8	769
ESR-1980	67% copper as copper oxide 33% DDAC	2.4	1,285
ESR-2240	25/26 copper particles 1/26 tebuconazole	1.0	961

tion. Several different formulations of these preservatives are covered by different ICC-ES evaluation reports. These formulations differ in the listed uses and required retentions, and have slight differences in the formulations, but in general require less copper than the nonmicronized counterparts.

A summary of the wood preservatives highlighting copper concentration is given in Table 1. The preservative composition is given in the second column and the above-ground retention needed to meet Use Category 3b for above-ground use according to AWPA U1 is given in column 3 (Anon 2007c). The fourth column, calculated from the second and third columns, lists the amount of copper metal per volume of wood. Several studies have shown that as the copper concentration in the wood is increased, the corrosion of metal fasteners increases (Kear and others 2009; Zelinka and Rammer 2011).

Why and How Do Metals Corrode in Treated Wood?

The waterborne wood preservatives listed in Table 1 contain cupric ions, which are thermodynamically unstable in the presence of steel or zinc galvanized fasteners. The mechanism of corrosion in treated wood involves the transport of cupric ions through the wood to the fastener surface, where the cupric ions are reduced and the fastener (zinc or iron) is oxidized (Baker 1980, 1988; Zelinka and Stone 2011a). We illustrate this mechanism of corrosion in Figure 4.

For carbon steel and zinc-galvanized fasteners, the reduction of cupric ions is thermodynamically favorable and will occur, but how rapidly they corrode (the corrosion rate) needs to be determined empirically. The corrosion rate is determined by the slowest reaction step. In theory, the corrosion of embedded metals could be limited by the diffusion of ions to the metal surface (diffusion control), or conversely it could be limited by the electron transfer reaction at the metal surface (activation control). Several independent experiments have suggested that at high wood moisture contents, the reaction is activation controlled.

The corrosion of embedded metals is strongly dependent upon moisture content. When the wood is dry, embedded metals do not corrode (Baker 1980; Dennis and others 1995; Short and Dennis 1997). Short and Dennis (1997) characterized the dependence of the corrosion rate on the wood moisture content using electrochemical techniques. They found that the corrosion rate increased with moisture content until hitting a maximum corrosion rate near the fiber saturation point. Zelinka and others (2011) have used the data of Short and Dennis (1997) to predict the corrosion rate of galvanized steel in ACQ-treated wood as a function of moisture content, and this curve is given in Figure 5. The data show the importance of controlling the wood moisture content to reduce corrosion; the corrosion rate climbs from less than 1 $\mu m\ y^{-1}$ at 16% moisture content to more than 40 $\mu m\ y^{-1}$ at 26% MC.

The corrosion of metals in treated wood involves the reduction of cupric ions in the preservative and is strongly related to the wood moisture content. The mechanism is quite different from atmospheric corrosion, where the amount of

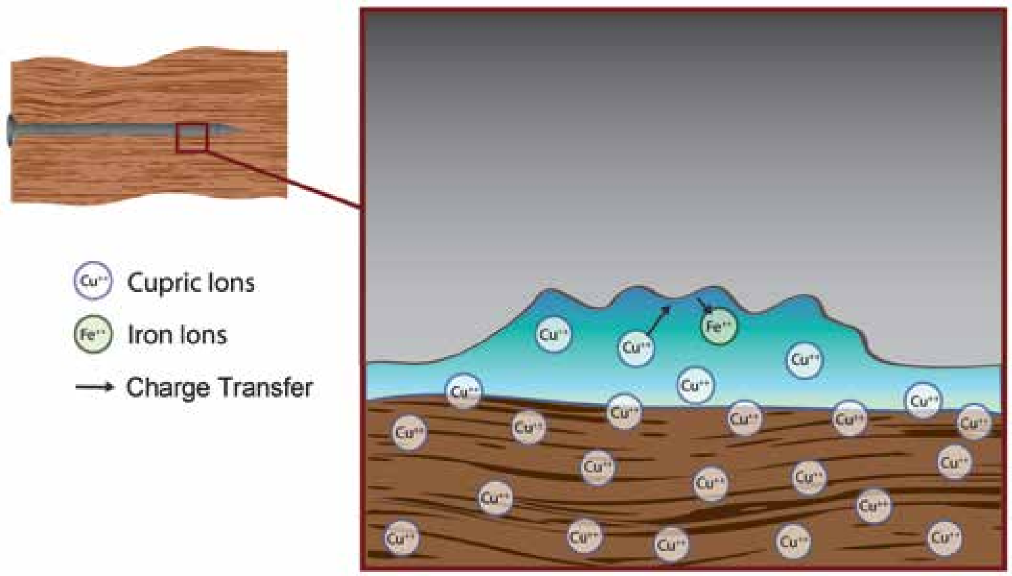

Figure 4. Mechanism of corrosion in treated wood. Cupric ions migrate through the wood to the metal surface where they are reduced as the fastener is oxidized.

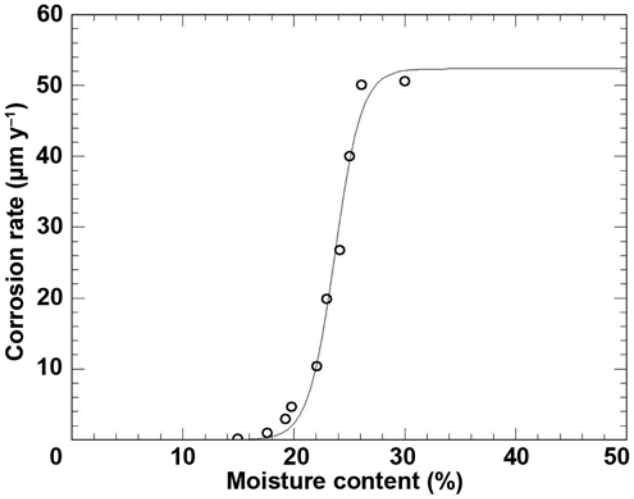

Figure 5. Corrosion rate of galvanized steel in ACQ-treated wood as a function of moisture content constructed from the data of Short and Dennis (1997) and Zelinka and Rammer (2009). From Zelinka and others (2011).

corrosion depends upon the amount of humidity, chlorides, and sulphides in the local environment. Not surprisingly, these differences in corrosion mechanism result in different behavior of metals in treated wood as opposed to those exposed to atmospheric condition. Since many of the methods for protecting steel from atmospheric corrosion are often applied to wood fasteners by default, we highlight the two major differences between the two environments: (1) relative corrosion rates of different metals and (2) variation of corrosion rate with time.

It is common knowledge that galvanized steel has a longer life than uncoated steel when undergoing atmospheric corrosion. Zhang (2003) summarized the literature and found steel exposed to outdoor atmospheric conditions, on average, corroded 20 times faster than zinc. In atmospheric corrosion, galvanized steel forms smithsonite ($ZnCO_3$), a protective, passivating corrosion product that slows further corrosion. Likewise in atmospheric corrosion, carbon steel forms goethite (α-FeOOH), also called “red-rust.” Zinc corrodes more slowly in atmospheric corrosion than steel because smithsonite is better at protecting zinc from further corrosion than goethite is at protecting steel (Zhang 2003). In environments where smithsonite is not stable, such as immersion in saltwater or in environments with volatile acetic and formic acids, zinc corrodes more rapidly than steel (Knotkova-Cermakova and Vlckova 1971; Zhang and others 1998). Zelinka and others (2010) examined the corrosion products that formed on fasteners exposed to treated and untreated wood using X-ray diffraction and did not find smithonsite. In the same study, they observed that zinc-galvanized fasteners corroded more rapidly than uncoated steel fasteners.

During atmospheric corrosion, in many cases the corrosion rate decreases with time because of passivation. Empirically, the kinetics are described by

$$\Delta W = Kt^n \tag{1}$$

where ΔW is the change in weight, K is a constant (the 1-y corrosion rate), t is the time in years, and n is an exponent that controls the kinetics and describes passivation (Legault and Preban 1975). Observed values of n range from 0.35 to 1 (Legault and Preban 1975; Legault and Pearson 1978).

Corrosion of metals in wood is activation controlled ($n = 1$) and therefore exhibits a constant corrosion rate with time. This observation is supported by Baker (1992), who conducted a 17-y exposure test and observed that the mass loss increased linearly with time. Electrochemical corrosion testing performed by Zelinka and others (2008) also supports that the corrosion mechanism is activation controlled. They observed that the corrosion rate in water extracts of treated wood was the same as those measured in solid wood, which suggests that diffusion is not the rate limiting mechanism. Finally, comparison of measured diffusion rates of cupric ions in wood (1.3 cm y^{-1}, Simons and others 1998) to the diffusion rate needed to maintain the measured corrosion rate of 60 $\mu m\ y^{-1}$ (diffusion rate of <1 cm y^{-1}), suggests that diffusion should not be the limiting factor.

In short, the corrosion mechanism involves the reduction of cupric ions, depends upon the wood moisture content, and is different from atmospheric corrosion. By understanding the corrosion mechanism, it is possible to develop strategies for maximizing the life of embedded fasteners. For example, by using a metal noble to copper (e.g., stainless steel), the fasteners are immune to the major corrosion mechanism. Likewise, if the wood can be kept dry, corrosion should not be a concern. A deeper examination of methods to protect wood from corrosion is given at the end of this document.

How Rapidly Do Metals Corrode in Wood?

Since the 2004 change in wood preservative regulation, there have been several investigations of the corrosiveness of metals in contact with treated wood. The studies cover a wide range of preservatives, preservative retentions, wood moisture contents, and metals tested. Not surprisingly, a wide variation in corrosion rates has been reported (e.g., from 2–113 $\mu m\ y^{-1}$ for galvanized steel in ACQ-treated wood). Because of the wide variations of test conditions used, it is best to only compare results within a single study or across different studies with very similar conditions.

Many of the design recommendations for materials selection in wood are based off of the recommendations of Baker (1992), who conducted a 17-y investigation of corrosion of metal fasteners embedded into chromated copper arsenate (CCA) and ammoniacal copper arsenate- (ACA-) treated wood exposed either underground or in a room maintained near 100% relative humidity. From these data, Baker concluded that at a minimum, hot-dip galvanized fasteners should be used in treated wood and cautioned against the use of aluminum fasteners. Importantly, Baker presented the corrosion data as a percentage of weight loss instead of a true corrosion rate because he could not calculate the surface area of threaded fasteners. Zelinka and Rammer reanalyzed Baker's data using data in Baker's laboratory notebook and an algorithm they had developed to measure the surface area of threaded fasteners (Rammer and Zelinka 2008; Zelinka and Rammer 2009; Rammer and Zelinka 2010). They found that when the corrosion rate was adjusted to a true corrosion rate, the corrosion rate of aluminum was in fact less than hot-dip galvanized steel. Baker also reported that pitting was observed on the aluminum fasteners; however, Zelinka and Rammer could not determine any evidence of pitting corrosion in similar exposure tests conducted for one year, nor could they find any evidence of pitting corrosion in photographs in Baker's laboratory notebook (Zelinka and Rammer 2009).

Zelinka has published results of several different corrosion tests that were conducted at 27 °C (80 °F) and 100% relative humidity (Zelinka 2007; Zelinka and Rammer 2009; Zelinka and others 2010; Zelinka and Stone 2011a). In one study, Zelinka and Rammer (2009) examined the corrosion of five different metal fasteners (carbon steel, hot-dip galvanized steel, electroplated galvanized steel, aluminum, and stainless steel) embedded in wood treated with ACQ-D to a retention of 4 kg m^{-3}. They found that the corrosion rate of hot-dip galvanized steel (in $\mu m\ y^{-1}$) was the highest (62) followed by carbon steel (34), aluminum (22), and electroplated galvanized steel (21).The corrosion rate of stainless steel was statistically indistinguishable from zero. In another study, Zelinka and others (2010) exposed steel and hot-dip galvanized steel fasteners to six different wood treatments: chromated copper arsenate (CCA-C), alkaline copper quaternary (ACQ-D), copper azole (CA-B), micronized copper quaternary (MCQ), didecyldimethylammonium carbonate (DDAC, or the "quat" in ACQ) and MCQ. For galvanized steel ACQ was the most corrosive (32 $\mu m\ y^{-1}$), followed by CA (29), MCQ (19), CCA (16), DDAC (5.5), and untreated (4.4). For carbon steel, the order was slightly different: ACQ (17), MCQ (13), CA (11), CCA (10), DDAC (1.9), and untreated (0.7).

Kear and others (2009) examined the corrosion of three different metals (316 stainless steel, hot-dip galvanized steel, and plain carbon steel) in three different preservatives (CCA, ACQ, CA), treated to three different retention levels with four different test methodologies. The retention levels were specified in a New Zealand standard that specifies a mass basis (i.e., kg/kg) instead of a density basis and therefore cannot be directly compared to traditional U.S. retentions (in lb/ft^3 or kg m^{-3}). Differences in the corrosiveness of the preservatives were most apparent in a constant exposure to 90% RH. Corrosion rates were (CCA:CA:ACQ) 4:14:45 $\mu m\ y^{-1}$ for mild steel fasteners and 5:16:26 $\mu m\ y^{-1}$ for hot-dip galvanized steel fasteners. Average corrosion rates as high as 113 $\mu m\ y^{-1}$ were observed for galvanized steel in ACQ-treated wood in a "moisture saturated air" condition.

Simpson Strong Tie Company (Pleasanton, California) published a technical bulletin on the results of in-house

AWPA E12 (Anon 2007a) corrosion tests they had conducted (Anon 2008). In this test method, a metal plate is sandwiched between two blocks of wood and exposed to a high temperature (50 °C), high humidity (90% RH) environment. They found that the corrosiveness of ACQ-D (carbonate) was roughly equivalent to that of CA, and both of these were more than twice as corrosive as CCA-C. They also found that ACZA was more than three times more corrosive than CCA and that borates were less corrosive than CCA. A footnote in the table mentioned that for micronized formulations like MCQ, the "relative corrosiveness is somewhat lower than ACQ-D."

Copper napthenate is sometimes used as a preservative in timber bridges. Although there are no peer-reviewed data on the corrosiveness of copper napthenate, Anthony Forest Products Company (El Dorado, Arkansas) published a technical bulletin with the results of AWPA E12 tests that compares both the waterborne and oilborne formulations of copper napthenate against ACQ-D and CCA-C for mild steel, hot-dip galvanized steel, aluminum, and red brass (Anon n.d.). No data are given on the variability between replicates; however, the data clearly suggest that either formulation of copper napthenate is much less corrosive than ACQ and possibly less corrosive than CCA. For mild steel, the corrosion rates (in microns per year) were 124 for ACQ, 25.4 for CCA, 4.3 for waterborne copper napthenate, and 0.8 for the oilborne formulation. An even larger difference was observed for aluminum where the corrosion rates were 185 for ACQ, 7.6 for CCA, 1.8 for waterborne copper napthenate, and 0 for the oilborne formulation. While it should be noted that this bulletin was published by a company that supplies products treated with copper napthenate, the data suggest that copper napthenate is much less corrosive than ACQ and less than or equal in corrosiveness to CCA.

Freeman and McIntyre (2008) summarized the results of several unpublished corrosion tests of pressure-treated wood in contact with different metals that compared traditional (ACQ and CA) against their micronized formulations (MCQ and mCA). Most of the data shown were from AWPA E12 tests. The results are inconclusive. In one test, the micronized formulation of CA is less corrosive than the standard formulation for galvanized steel but more corrosive for plain carbon steel and the micronized formulation is much more corrosive to aluminum. The remainder of the E-12 data have similar trends; in some cases the micronized formulations show lower corrosiveness, in other cases, the traditional formulations appear less corrosive. The only results that consistently show that the micronized formulations are less corrosive than the traditional formulations are from a test conducted using a protocol from the International Staple and Nail Tool Association (ISANTA). In this test, the micronized formulations appear slightly (approximately 30%–40%) less corrosive, with the notable exception of aluminum, in which case the micronized formulations are more corrosive.

Table 2 summarizes corrosion rates measured in a variety of test methods over a range of wood preservatives and metals. Each row in the table represents a paper or report and the test method is briefly summarized in the leftmost column. Corrosion rates for each metal are contained in columns followed by the type of wood preservative. The data can be used for observing general trends or relative comparison of a preservative or a metal type; however, it is dangerous to compare across rows as different test methods were used.

Do Wood Extractives Affect Corrosion?

In addition to structural polymers (cellulose, hemicellulose, and lignin) wood contains a variety of additional chemical components. Because these chemicals can be extracted by rinsing with various solvents, they are referred to as extractives. The type and amount of extractives vary widely among wood species. In some species, called naturally durable species, the extractives can protect the wood from decay.

Although a single piece of wood can contain over 700 different extractives (Hazelwood and others 2006), only three types of extractives have been thought to affect the corrosion of metals in contact with wood or the black liquors of wood pulp: small organic acids (acetic and formic acid), tannins (or more broadly polyphenols), and phenols with two or three adjacent hydroxyl groups (e.g., catechol and pyrogallol). For solid wood, only organic acids and tannins have been mentioned in the literature; catechol (1,2-dihydroxybenzene) and pyrogallol (1,2,3-trihydroxybenze) are formed as the lignin is destroyed in the pulping process (Clark and Green 1968; Niemelä 1989).

Although the pH of wood, a solid material, is not well defined, the water extracts of nearly all wood species are acidic (Packman 1960; Bootle 1983; Balban and Uçar 2003). The reason for this acidity is that in the presence of water, acetyl and formyl groups in the hemicelluloses are hydrolyzed to form acetic and formic acid (Packman 1960). Research has shown that this process is chemical, rather than biological (Packman 1960) and that over 90% of the acid produced is acetic (Balban and Uçar 2003).

Zelinka and Stone (2011) have shown that the tannins in solid wood act as a corrosion inhibitor to the embedded fasteners. Previous research on sawblade corrosion suggested that wood tannins accelerated the corrosion of sawblades; however, in general, tannins are known as a corrosion inhibitor (Nasrazadani 1997; Matamala and others 2000; Mabrour and others 2004; Rahim and others 2008; Radojcic and others 2008). In addition to the corrosion rate data, Zelinka and Stone (2011b) observed a blue-black patina forming on the steel, indicative of the formation of iron-tannate (Fig. 6). Iron-tannate is known as a passivating corrosion product; as it is formed, it slows the corrosion of the underlying metal (Pelikán 1966).

Table 2. Summary of published corrosion rates (in µm y^{-1}) in treated wood. The table represents a wide variety of test methodologies. Comparisons should only be made within a single row.

	Plain steel	Hot dip galvanized steel	Stainless steel	Aluminum
17 years, 27 °C (80 °F), 100% RH (Baker 1992; Zelinka and Rammer 2009)		9|CCA I	<1|CCA I	3|CCA I
		6|CCA II	<1|CCA II	4|CCA II
1 year, 27 °C (80 °F), 100% RH (Zelinka and Rammer 2009)	34|ACQ	61|ACQ	1|ACQ	22|ACQ
1 year, 27 °C (80 °F), 100% RH (Zelinka and others 2010)	9.4|CCA	16.1|CCA		
	16.8|ACQ	32.5|ACQ		
	12.5|mCQ	19.4|mCQ		
	11.1|CA-B	28.9|CA-B		
	1.9|DDAC	5.5|DDAC		
	0.7|Untreated	4.4|Untreated		
1 year, 27 °C (80 °F), “moisture saturated air” (Kear and others 2009)	62|CCA	26|CCA	≤1|CCA	
	176|ACQ-B	113|ACQ-B	≤1|ACQ-B	
	84|CA-B	87|CA-B	≤1|CA-B	
1 year, 27 °C (80 °F), 90% RH (Kear and others 2009)	4|CCA	5|CCA	≤1|CCA	
	45|ACQ-B	26|ACQ-B	≤1|ACQ-B	
	14|CA-B	16|CA-B	≤1|CA-B	
1 year, 27 °C (80 °F), 75% RH (Kear and others 2009)	1|CCA	1|CCA	<1|CCA	
	3|ACQ-B	2|ACQ-B	<1|ACQ-B	
	2|CA-B	2|CA-B	<1|CA-B	
AWPA E12 (Anon. n.d.)	4|CuN-W	11|CuN-W		(–1)|CuN-W
	1|CuN-O	2|CuN-O		2|CuN-O
	124|ACQ-D	23|ACQ-D		185|ACQ-D
	27|CCA-C	10|CCA-C		7|CCA-C
AWPA E12 (Freeman and McIntyre 2008)	140| mCA	23|mCA		18|mCA
	107|CA	51|CA		(–3)|CA
AWPA E12 (Freeman and McIntyre 2008)	66|mCA	69|mCA		3|mCA
	180|CA	76|CA		0|CA
	41|mCQ	41|mCQ		0|mCQ
	196|ACQ-D	81|ACQ-D		3|ACQ-D
	41|CCA-C	53|CCA-C		3|CCA-C
AWPA E12 (Freeman and McIntyre 2008)	89|mCQ	25|mCQ		10|mCQ
	307|ACQ-D	28|ACQ-D		10|ACQ-D
	76|CCA-C	20|CCA-C		5|CCA-C

Using simple kinetic models of the corrosion rate dependence of metals on pH and on inhibitor efficiency, Zelinka and Stone developed the following relation to describe the dependence of corrosion on the pH and tannin concentration

$$r = r_0'\left(1+k'c\right)^{-1}\left(e^{m(5-\mathrm{pH})}+1\right) \qquad (2)$$

where c is the concentration of tannins (mg L^{-1}), r_0', k', and m are fitting parameters, and $m > 0$ (Zelinka and Stone 2011b). From this equation, and from corrosion data measured in extracts of pine (low pH, low tannins) white oak (low pH, high tannins), American elm (high pH, low tannins), and black locust (high pH, high tannins) they developed an isocorrosion map (Fig. 7). While the numbers are higher than would be expected in solid wood, the same general trends are expected to apply in solid wood.

How Does the Corrosion of Fasteners Affect the Strength of the Connection?

Up until this point, we have talked about corrosion rates in units of depth of metal loss per unit of time. However, what is ultimately important for metal fasteners used in construction is how this corrosion affects the strength of the connection. Recently, Zelinka and Rammer (2012) have used yield theory to examine how corrosion damage reduces the joint capacity. The yield theory selects the minimum of several failure modes that depend upon the dowel (nail) diameter and depth of penetration, the dowel-bearing stress of the wood members, the bending yield stress of the dowel, and the thickness of the wood members. For a given joint geometry, wood species and fastener bending yield stress, the equations depend only on the fastener diameter, which is

Figure 6. Iron-tannate precipitating in a solution with the same pH and tannin concentration as white oak. See Zelinka and Stone (2011b) for more information.

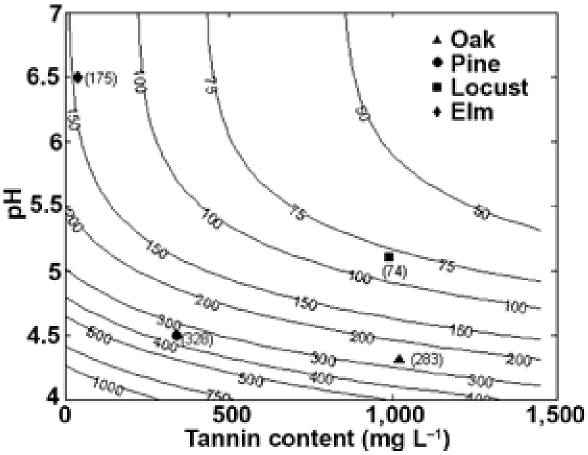

Figure 7. Isocorrosion map showing the interplay between tannins (abscissa) and pH (ordinate). Contours represent combinations of tannins and pH that result in the same corrosion rate. From Zelinka and Stone (2011b).

a function of the corrosion rate. The reduction of capacity in time is a straightforward calculation based upon the amount of the original diameter that remains.

These calculations assume that corrosion occurs uniformly across the length of the fastener, and that at failure, the wood moisture content is greater than 19%. The first assumption was necessary as the yield theory equations assume a constant fastener diameter; however, the maximum corrosion depth gives a conservative estimate. The second assumption was necessary as the dowel-bearing strength is independent of moisture content above 19% (Rammer 2001). This is likely a valid assumption if fastener corrosion is occurring (see Fig. 5).

Figures 8 and 9 show how these equations can be used to calculate the reduction in lateral capacity of an 8d (3.4-mm diameter) galvanized nail. This is a common nail size for decking applications where the expected side member thickness is greater than 21 mm and the resulting failure mode is Mode IV. For Mode IV failures, the yield strength is inversely related to the square of the diameter, which results in the lateral capacity decreasing rapidly with time as corrosion rate increases (Fig. 8). Figure 8 includes corrosion rates measured for galvanized steel embedded in untreated wood (5 µm y^{-1}), and a hypothetical copper treatment with a corrosion rate of 60 µm y^{-1} exposed to 100% relative humidity (Zelinka and Rammer 2009). If an arbitrary failure criterion were applied (for instance, 50% of the original capacity), then a “time to failure” $t_{(\text{fail})}$ can be calculated by

$$t_{\text{fail}} = \frac{d_{\text{o}}\left(2-\sqrt{2}\right)}{4R}$$

where d_{o} is the original diameter of the fastener and R is the corrosion rate. Figure 9 graphically shows how changes in the corrosion rate, which may arise from fluctuations in moisture content or different treatment chemicals, affect this time to failure. It is important to note that measured corrosion rates in wood are on the steepest part of this curve. Therefore, even small changes in the wood moisture content have can have potentially large effects in the service life of fasteners embedded in wood.

How Can I Design To Minimize Corrosion in Treated Wood?

Metal fasteners are an essential part of wood construction and their use in preservative-treated wood cannot be avoided. Therefore, it is important to design and utilize metals in wood so that they will exhibit the least amount of corrosion. Here we discuss three design considerations that will help prolong the service life of metals in wood: proper moisture management, understanding non-metallic coatings and barriers, and avoiding mixed metals in construction.

Moisture Management

Proper moisture management is the most important thing one can do to reduce corrosion of metals in treated wood. If

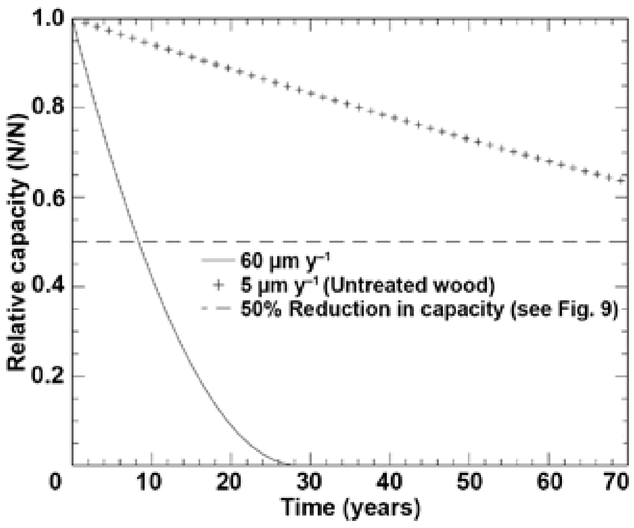

Figure 8. Reduction in capacity of an 8d galvanized decking nail exhibiting a Mode IV failure (wood bearing failure with two plastic hinges) for two different corrosion rates. From Zelinka and Rammer 2012.

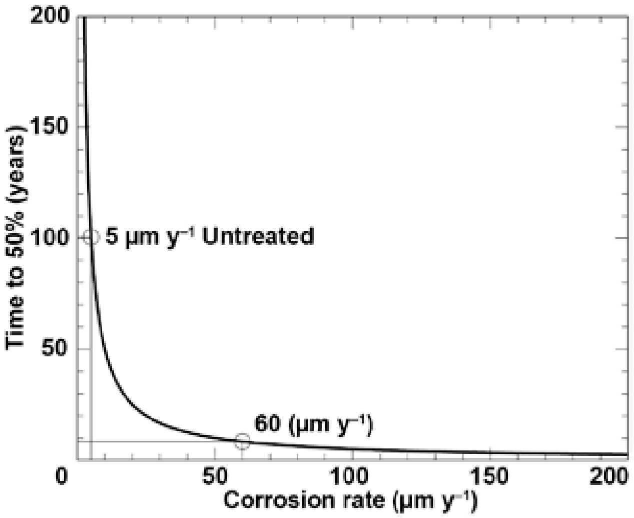

Figure 9. Illustration of how the "time to failure", in this case arbitrarily set to 50% of the original strength of the joint, changes with corrosion rate for the 8d galvanized decking nail shown in Figure 8.

wood is kept dry, both the wood and the fasteners can last for centuries (Clausen and Glass 2012). In most cases, preservative-treated wood is specified because the wood will be exposed in an outdoor environment where it will be exposed to rain and will get wet. However, sound design principles can maximize the drainage of rainwater and minimize the amount of moisture that is absorbed by the wood.

Clausen and Glass (2012) recently published a design guide for minimizing wood decay in residential construction by keeping the wood dry. Pertinent strategies that also apply to exterior structures and covered timber bridges involve (1) keeping rainwater from seeping in through the end grain and (2) designing roofs and overhangs so they do not drain onto lower structures.

End Grain

Moisture transport in the longitudinal direction (along the grain) is more than 10 times faster than in the radial or tangential directions. Therefore, if the end grain of the wood member is allowed to come into contact with liquid water, the entire member will absorb significant amounts of moisture. It is important to design the structure so that the end grain is not exposed to water. This frequently happens at joints between two members if the connection is improperly designed or installed and the joint traps water. Vertical members (e.g., posts) are especially prone to water uptake along the end grain. For these members, impermeable coatings or end caps could be used to reduce or prevent water uptake through the end grain.

Roof

For outdoor wooden structures with a roof, such as covered bridges, proper roof design and detailing can shield much of the structure from water, and keep the wood moisture content low. The larger the overhangs of the roof are, the less likely it is that drainage from the roof will strike the walls below it (Fig. 10).

Coated Metals

Paints and other nonmetallic coatings are frequently used to protect metals from corrosion by isolating the metal from the corrosive environment. The cost of coatings used to prevent corrosion is estimated at US$100 billion, which is 36% of the total cost of corrosion in the United States, and 1.1% GDP of the entire United States (Tator 2003). Whereas many different formulations of organic coatings are available, the goal of nearly all coatings is to isolate the metal from the environment.

Coatings fail when the corrosive environment can reach the metal substrate. This can happen if the coating is mechanically damaged during installation (Fig. 11). Zelinka and others (2009) observed that screws with a nonmetallic coating had a much worse corrosion performance after they had been driven into the wood or driven through a joist hanger into the wood and attributed this decrease in performance to damage in the coating caused by inserting the fastener into wood. Extreme care should be taken if using coated metals in construction with wood so that the coating does not get damaged before or during installation.

Mixed Metals

Special design consideration is needed if two different metals are used in contact with each other. Galvanic corrosion happens when three conditions are satisfied: (1) two dissimilar metals (2) are placed in electrical contact (3) in the presence of an electrolyte. If any of the three

Figure 10. Illustration of the importance of roof overhangs for protecting wood from biodeterioration and corrosion. The right side of the beam is protected by the large roof overhang, whereas the left side is exposed to rain.

Figure 11. Corrosion underneath a coating failure. This lamp post was in service for less than 5 years before corrosion was visible at defects in the coating.

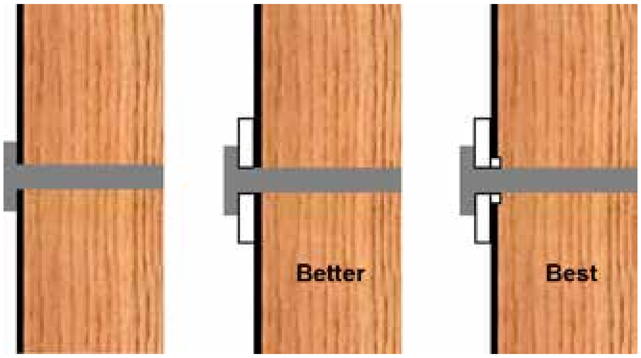

Figure12. Strategies to mitigate galvanic corrosion. A non-conductive washer between the head of the lag screw and the sign should eliminate electrical contact between the bolt and the sign (Better). If there is a tight clearance between the hole and the bolt, it might be necessary to coat the edge of the holes to prevent electrical contact (Best).

conditions are not met (e.g., metals are not in electrical contact, metals are not in an electrolyte), galvanic corrosion cannot occur. When the conditions for galvanic corrosion are met, the more active metal (called the anode) will corrode more rapidly than it would otherwise corrode, and the more noble metal (called the cathode) will corrode more slowly than it would otherwise corrode. Whether a metal is active or noble to another metal depends upon the thermodynamics of the oxidation reactions in that environment.

Galvanic corrosion is a design concern in wood when a joist hanger or sign is attached to wood with a fastener. If the fastener is a different metal than the sheet metal, the conditions for galvanic corrosion exist: wood acts as the electrolyte and they are in electrical contact between the head of the fastener and the sheet metal.

It is important to point out a couple of common misunderstandings of galvanic corrosion at this point. For instance, commonly it is assumed that only the anode (“sacrificial anode”) corrodes in a galvanic couple. This is not true, as both metals corrode, but the cathode may corrode slowly enough that it does not fail in a normal service life. The second common misperception is that there is a single “galvanic series” that one can use to tell if a given metal will be active in a given environment. While galvanic series have been tabulated for seawater and other electrolytes (Matsukawa and others 2011), the positions of metals can change dramatically depending on the environment (e.g., treated wood).

An example of galvanic corrosion with wood was observed by the Wisconsin Department of Transportation (WisDOT) (Wilson 2004). In this case, aluminum signs were attached to sign posts made of treated wood with galvanized lag screws. The aluminum signs exhibited excessive corrosion around the lag screw, causing the sign to fall off in some cases. In this case, aluminum was acting as the anode, the galvanized lag screw, the cathode, and wood the electrolyte. As it would be difficult to change the sign material, and aluminum lag screws do not exist, it is impossible from a design perspective to change one of the metals to avoid corrosion. A better design solution would be to electrically isolate the aluminum sign from the galvanized lag screw (Fig. 12).

References

Anon 2007a. AWPA E-12: Standard method of determining corrosion of metal in contact with treated wood. Birmingham, AL: American Wood Preservers' Association.

Anon 2007b. AWPA P5: Standard for waterborne preservatives. Birmingham, AL: American Wood Preservers' Association.

Anon 2007c. AWPA U1-06: Use category system. Birmingham, AL: American Wood Preservers' Association.

Anon 2008. Preservative treated wood. Simpson Strong-Tie Technical Bulletin No. T-PTWOOD08-R. Pleasanton, CA: Simpson Strong Tie.

Anon. n.d. Copper Naphthenate Corrosivity Data. Retrieved from http://www.anthonyforest.com/pdfs/cunap_corrosivity.pdf on April 1, 2013: El Dorado, AR: Anthony Forest Products.

Baker, A.J. 1980. Corrosion of metal in wood products. Durability of building materials and components. ASTM STP 691. West Conshohocken, PA: American Society for Testing and Materials. 981–993.

Baker, A.J. 1988. Corrosion of metals in preservative-treated wood. In: Hamel, M., ed. Wood protection techniques and the use of treated wood in construction. Madison, WI: Forest Products Society. 99–101.

Baker, A.J. 1992. Corrosion of nails in CCA- and ACA-treated wood in two environments. Forest Products Journal 42(9): 39–41.

Balban, M.; Uçar, G. 2003. Estimation of volatile acids in wood and bark. Holz als Roh- und Werkstoff. 61(6): 465–468.

Bootle, K.R. 1983. Corrosion aspects of wood use. In: Bootle, K.R., ed. Wood in Australia. Types, properties and uses. Sydney: McGraw-Hill Book Company. 62–67.

Clark, I.T.; Green, J. 1968. Production of phenols by cooking kraft lignin in alkaline solutions. Tappi Journal. 51(1): 44–48.

Clausen, Carol A.; Glass, Samuel V. 2012. Build green: wood can last for centuries. General Technical Report FPL–GTR–215. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 24 p.

Dennis, J.K.; Zou, C.; Short, N.R. 1995. Corrosion behaviour of zinc and zinc alloy coated steel in preservative treated timber. Transactions of the Institute of Metal Finishing. 75(3): 96–101.

Freeman, M.A.; McIntyre, C.R. 2008. A comprehensive review of copper-based wood preservatives with a focus on new micronized or dispersed copper systems. Forest Products Journal. 58(11): 6–27.

Hazlewood, P.E.; Singh, P.M.; Hsieh, J.S. 2006. Role of wood extractives in black liquor corrosiveness. Corrosion. 62(10): 911–917.

Kear, G.; Wu, H.-Z.; Jones, M.S. 2009. Weight loss studies of fastener materials corrosion in contact with timbers treated with copper azole and alkaline copper quaternary compounds. Corrosion Science. 51(2): 252–262.

Knotkova-Cermakova, D.; Vlckova, J. 1971. Corrosive effect of plastics, rubber and wood on metals in confined spaces. British Corrosion Journal. 6(1): 17–22.

Lebow, S. 2004. Alternatives to Chromated Copper Arsenate for Residential Construction. Res. Pap. FPL–RP–618. USDA Forest Service, Forest Products Laboratory, Madison, WI.

Lebow, S. 2010. Wood Preservation. In: Wood handbook—Wood as an engineering material. Chapter 15. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: 15-1–15-28.

Legault, R.A.; Pearson, V.P. 1978. Kinetics of the atmospheric corrosion of galvanized steel. In: Coburn, S.K., ed. Atmospheric factors affecting the corrosion of engineering metals, ASTM STP 646. West Conshohocken, PA: American Society for Testing and Materials. 83–96.

Legault, R.A.; Preban, A.G. 1975. Kinetics of the atmospheric corrosion of low-alloy steels in an industrial environment. Corrosion. 31(4): 117–122.

Mabrour, J.; Akssira, M.; Azzi, M.; Zertoubi, M.; Saib, N.; Messaoudi, A.; Albizane, A.; Tahiri, S. 2004. Effect of vegetal tannin on anodic copper dissolution in chloride solutions. Corrosion Science. 46(8): 1833–1847.

Matamala, G.; Smeltzer, W.; Droguett, G. 2000. Comparison of steel anticorrosive protection formulated with natural tannins extracted from acacia and from pine bark. Corrosion Science. 42(8): 1351–1362.

Matsukawa, Y.; Chuta, H.; Miyashita, M.; Yoshikawa, M.; Miyata, Y.; Asakura, S. 2011. Galvanic series of metals conventionally used in tap water with and without flow and its comparison to that in seawater. Corrosion. 67(12): 125004–7.

Mittendorf, S. 2009. Letter to the editor: Hardware corrosion from PT lumber: looking for answers. Journal of Light Construction. 27(10): 13–13.

Nasrazadani, S. 1997. The application of infrared spectroscopy to a study of phosphoric and tannic acids interactions with magnetite (Fe3O4), goethite ([alpha]-FEOOH) and lepidocrocite ([gamma]-FeOOH). Corrosion Science. 39(10–11): 1845–1859.

Niemelä, K. 1989. GLC-MS Studies on pine kraft black liquors Part V. identification of catechol compounds. Holzforschung. 43(2): 99–103.

Packman, D.F. 1960. The acidity of wood. Holzforschung. 14(6): 178–183.

Pelikán, J.B. 1966. Conservation of iron with tannin. Studies in Conservation. 11(3): 109–115.

Radojcic, I.; Berkovic, K.; Kovac, S.; Vorkapic-Furac, J. 2008. Natural honey and black radish juice as tin corrosion inhibitors. Corrosion Science. 50: 1498–1504.

Rahim, A.A.; Rocca, E.; Steinmetz, J.; Kassim, M.J. 2008. Inhibitive action of mangrove tannins and phosphoric acid on pre-rusted steel via electrochemical methods. Corrosion Science. 50(6): 1546–1550.

Rammer, D.R. 2001. Effect of moisture content on nail bearing strength. Res. Pap. FPL-RP-591. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 22 p.

Rammer, D.R.; Zelinka, S.L. 2008. Analytical determination of the surface area of a threaded fastener. ASTM Journal of Testing and Evaluation. 36(1): 80–88.

Rammer, D.R.; Zelinka, S.L. 2010. Optical method for measuring the surface area of a threaded fastener. Experimental Techniques. 34(4): 36–39.

Short, N.R.; Dennis, J.K. 1997. Corrosion resistance of zinc-alloy coated steel in construction industry environments. Transactions of the Institute of Metal Finishing. 75(2): 47–52.

Simons, P.J.; Levy, J.F.; Spiro, M. 1998. Electrical migration of exogenous mineral ions through green sapwood of *Pinus sylvestris* L. (Scots pine). Wood Science and Technology. 32(6): 411–419.

Tator, K.B. 2003. Introduction to coatings and linings. In: Cramer, S.D. and Covino, B.S., eds. Materials Park, OH: ASM International. 814–816.

Wilson, J. 2004. Aluminum sign corrosion investigation. Final Report #WI-06-04 WisDOT Highway Research Study #WI-04-02. Madison, WI: Wisconsin Department of Transportation.

Zelinka, S.L. 2007. Uncertainties in corrosion rate measurements of fasteners exposed to treated wood at 100% relative humidity. ASTM Journal of Testing and Evaluation. 35(1): 106–109.

Zelinka, S.L.; Derome, D.; Glass, S.V. 2011. Combining A Hygrothermal And Corrosion Model To Predict Corrosion Of Metal Fasteners Embedded In Wood. Building and Environment. 46(10): 2060–2068.

Zelinka, S.L.; Ortiz-Candelaria, L.; Stone, D.S.; Rammer, D.R. 2009. Electrochemical impedance spectroscopy (EIS) as a tool for measuring corrosion of polymer-coated fasteners used in treated wood. Forest Products Journal. 59(1/2): 77–82.

Zelinka, S.L.; Rammer, D.R. 2009. Corrosion rates of fasteners in treated wood exposed to 100% relative humidity. ASCE Journal of Materials in Civil Engineering. 21(12): 758–763.

Zelinka, S.L.; Rammer, D.R. 2011. Synthesis of published and unpublished corrosion data from long term tests of fasteners embedded in wood: calculation of corrosion rates and the effect of corrosion on lateral joint strength. In CORROSION 2011. Houston, TX: NACE International.

Zelinka, S.L.; Rammer, D.R. 2012. Modeling the effect of nail corrosion on the lateral strength of joints Forest Products Journal 62(3):160–166.

Zelinka, S.L.; Rammer, D.R.; Stone, D.S. 2008. Electrochemical corrosion testing of fasteners in wood extract. Corrosion Science. 50(5): 1251–1257.

Zelinka, S.L.; Rammer, D.R.; Stone, D.S.; Gilbertson, J.T. 2007. Direct current testing to measure corrosiveness of wood preservatives. Corrosion Science. 49(3): 1673–1685.

Zelinka, S.L.; Sichel, R.J.; Stone, D.S. 2010. Exposure testing of fasteners in preservative treated wood: gravimetric corrosion rates and corrosion product analyses. Corrosion Science. 52(12): 3943–3948.

Zelinka, S.L.; Stone, D.S. 2011a. Corrosion of metals in wood: Comparing the results of a rapid test method with long-term exposure tests across six wood treatments. Corrosion Science. 53(5): 1708–1714.

Zelinka, S.L.; Stone, D.S. 2011b. The effect of tannins and pH on the corrosion of steel in wood extracts. Materials and Corrosion. 62(8): 739–744.

Zhang, X.G. 2003. Corrosion of zinc and zinc alloys. In: Cramer, S.D.;Covino, B.S., eds. ASM Handbook Volume 13B, Corrosion: Materials. Materials Park, OH: ASM International. 402-417.

Zhang, X.G.; Hwang, J.; Wu, W.K. 1998. Corrosion testing of steel and zinc. In: Proceedings of the 4th International Conference on Zinc and Zinc Alloy Coated Steel Sheet (GALVATECH ‘98). Chiba, Japan.