Review of Test Methods Used to Determine the Corrosion Rate of Metals in Contact With Treated Wood

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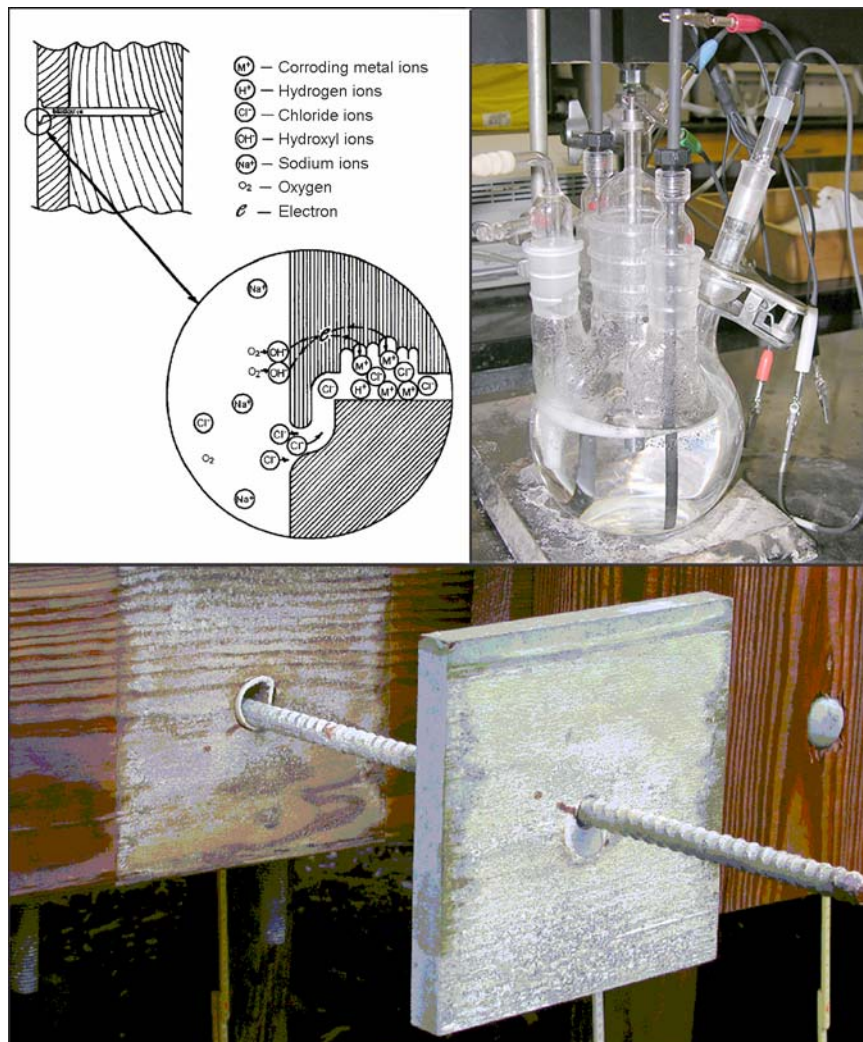
Abstract

Although preservative treatments prolong the life of wood, they can also accelerate the corrosion of fasteners. This is an issue that needs to be studied because corrosion of building materials and fasteners can negatively affect system performance. In this study, the test methods of twenty publications and one standard that examine the corrosion of metals in contact with wood are summarized and reviewed so that a comparison of their effectiveness can be made. While the focus is on the test methods, some qualitative results from these different methods are discussed to show nuances of the test method. Also, this literature review is intended to focus future research towards the use of the most promising test methods and eliminate overlap in research efforts.

Keywords: corrosion, fasteners, wood preservative, accelerated test, corrosion rate, metals, fire retardants

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Introduction

Metals are used in a wide variety of applications because of their high strength and ductility. However, metals in most environments are thermodynamically unstable and corrode (oxidize) to a more stable state. While not generally considered an aggressive environment, wood has the possibility of severely corroding metal, especially when preservative or fire treatments are utilized.

In almost every timber engineering application, wood is in intimate contact with metal. Metallic fasteners embedded in wood are subject to corrosion by the presence of water and oxygen in the cellular structure of wood. The corrosion of fasteners in wood is a coupled phenomenon; the corrosion products of the metal locally accelerate the degradation of the wood around the fastener (Richolson 1959, Baker 1978). Both the corrosion and the resulting decomposition of the wood significantly weaken the holding power of the fastener and can lead to failures in service (Zollo and Heyer 1982, Rossiter and others 1992, Bohnhoff 2002).

Historically, creosote, pentachlorophenol (penta), and other oil-based preservatives have been used to treat wood in bridges (Ritter and Morrell 1992). Oil-based preservatives have little, if any, accelerating affect on the corrosion of fasteners in wood (Nelson 1950, Marian and Wissing 1960, Jain and others 1970, Barnes and others 1984).

Waterborne preservatives, such as chromated copper arsenate (CCA) and ammoniacal copper arsenate (ACA), have also been used to treat bridges. While some of the preservative bonds to the wood and becomes "fixed," a small percentage of the CCA or ACA remains in ionic form in the wood. These ionic components serve to protect the wood; however, they also increase the corrosiveness of the wood environment, especially if the wood has not been given ample time to fixate before being put into service.

Recently, many designers are choosing to use alternatives to CCA, including ammoniacal copper quat (ACQ-B) and ammoniacal copper zinc arsenate (ACZA). There is very little published research on the effect of these ammonia-based preservatives on the corrosion rate, although there is a belief that ACQ and other new preservatives are much more corrosive that CCA. CCA contains hexavalent chromium, which typically acts as a corrosion inhibitor. On the other hand, some formulations of ACQ contain chlorides, which can increase the conductivity of the wood, as well as increase the corrosion rate and cause pitting corrosion in both carbon and stainless steels. Also, in most cases, these newer preservatives have more copper than CCA, which can cause increased galvanic corrosion. Unfortunately, there is not a readily available procedure to quantitatively evaluate the change of corrosion rate with these alternative preservatives.

Many papers on the corrosion of metals in contact with wood, including several previous literature reviews, have been published. Chronologically, the first literature review was published by Graham and others (1976). It briefly summarizes more than 125 references including sources on general corrosion, the corrosion of metal by wood and wood vapors, and the affects of preservative treatments on corrosion. Because of the number of references, neither the details of the test procedures nor any of the results were reported. The next literature review was by Bailey and Schofield (1984). Their literature review had an emphasis on roofing applications and discussed the effects of metals in contact with wood treated with CCA. Bailey and Schofield (1984) split the literature surveyed into three groups based on the exposure conditions of the metal in contact with wood: outdoor conditions, underground conditions, and laboratory conditions. Only 10 studies were reviewed by Bailey and Schofield (1984), and only a brief summary of the testing methods and results were given for each study. The most current literature review was by Ruddick (1987). The purpose of Ruddick's (1987) review was, "to summarize the data which is currently available on the corrosion of metal in contact with preservative treated wood." The 1987 review focuses on comparing the results of the 34 sources surveyed.

In addition to these literature reviews, additional, shorter papers give a general review of wood–metal corrosion, but in general, these papers are qualitative and do not critique test methods or numerical results (Campbell and Packman 1944, Farmer 1962, Smith 1982, BRE Digest 1985, Duncan 1988, Kubler 1992, Falk and Baker 1993).

Objective

The purpose of this literature review is to give a comprehensive overview of all test methods previously used to evaluate the corrosion of metals in contact with wood, so that a comparison of their effectiveness can be made. Moreover, the literature review is intended to focus future research towards the use of the most promising test methods and eliminate overlap with previously published research.

The research of the reviewed papers is summarized in Tables 1 and 2. Table 1 lists the metals tested in each publication, and Table 2 lists the wood species tested in each publication. It is impossible to list the wood preservatives in a summary table because there are too many different variations to make an effective comparison across different publications.

This paper reviews the test methods used to evaluate the corrosion of metals in contact with wood by breaking the experiments into three groups: exposure tests, accelerated exposure tests, and electrochemical tests. Exposure tests included outdoor exposure tests, underground exposure tests, and simulated exposure tests. Simulated exposure was used to describe tests that were run in a chamber with a controlled

Table 1—Summary of the metals tested in each experiment

Group	Experiment	Mild steel	Copper	Zinc	Monel	Silicon bronze	Aluminum alloys	Brass	Stainless steel	Hot-dipped galvanized	Electroplated galvanized nail	Mechanically galvanized	Plastic coated	Nickel-plated steel	Chrome-plated brass	Chrome-plated zinc	Cement coated	Cadmium-coated steel
Exposure	Baechler 1949	X						X		X								
Exposure	Farmer and Porter 1962						X											
Exposure	Scholten 1965																X	
Exposure	Wallin 1971	X	X				X	X	X	X	X		X					
Exposure	Johnson 1976	X			X					X			X					
Exposure	Baker and Gjovick 1977	X								X	X							
Exposure	Baker 1992		X		X	X	X		X	X	X	X						X
Exposure	Laidlaw and Cox 1983									X			X					
Exposure	Simm and Button 1985a	X					X		X		X							
Exposure	Davis and Allen 1993	X	X		X	X			X	X	X			X				
Accelerated	Wright and others 1957			X			X											
Accelerated	Doyle 1964	X					X			X								
Accelerated	Richolson 1959	X			X			X		X						X		
Accelerated	Bartel-Kornacka 1967	X																
Accelerated	Bengelsdorf 1983	X	X		X	X	X		X	X	X	X					X	X
Accelerated	Barnes and others 1984	X	X				X	X		X								
Electrochemical	Simm and Button 1985b	X		X			X		X								X	
Electrochemical	Jack and Smedley 1987	X	X	X														
Electrochemical	Cross 1990	X					X		X	X	X							
Electrochemical	Dennis and others 1995	X								X	X						X	
Electrochemical	Short and Dennis 1997	X								X	X							
Electrochemical	Wójtowicz and Piwowarczyk 2002									X	X						X	

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Table 2—Summary of the wood species tested in each experiment

Category	Experiment	Bald cypress	Balsa	British Columbia fir	Canadian rock elm	Douglas-fir	English elm	European beech	European oak	European redwood	European spruce	Greenheart	Gum wood	Mahogany	Obeche	Ponderosa pine	Radiata pine	Slash pine	Southern Pine	Teak	Western redcedar	White oak
Exposure	Baechler 1949															X						
Exposure	Farmer and Porter 1962		X			X	X	X	X		X	X		X	X						X	
Exposure	Scholten 1965															X						
Exposure	Wallin 1971									X												
Exposure	Johnson 1976					X																
Exposure	Baker and Gjovick 1977	Unknown																				
Exposure	Baker 1992																		X			
Exposure	Laidlaw and Cox 1983									X												
Exposure	Simm and Button 1985a									X												
Exposure	Davis and Allen 1993																		X			
Accelerated	Wright and others 1957			X	X								X	X								
Accelerated	Doyle 1964																		X			
Accelerated	Richolson 1959	X				X								X						X		X
Accelerated	Bartel-Kornacka 1967	Various Tropical Species																				
Accelerated	Bengelsdorf 1983					X																
Accelerated	Barnes and others 1984																		X			
Electrochemical	Simm and Button 1985b									X												
Electrochemical	Jack and Smedley 1987																X					
Electrochemical	Cross 1990									X	X											
Electrochemical	Dennis and others 1995									X												
Electrochemical	Short and Dennis 1997									X												
	Wójtowicz and Piwowarczyk 2002	Unknown																				

temperature and humidity to simulate in-service conditions. Accelerated exposure tests included tests that changed the moisture content or the temperature of the wood, or both, tests that used damp sawdust to accelerate corrosion, and salt-spray tests. Electrochemical tests accelerated the corrosion mechanism by sending an electrical current through the wood.

To the authors' knowledge, only one standard exists, AWPA E-12, that attempts to assess the corrosion of metal in wood. This standard, developed by the American Wood Preservers' Association (AWPA 2004a), is discussed in the moisture content and temperature section in Part 2—Accelerated Exposure Tests, since it uses these factors to accelerate results.

Most previous studies have focused on either how the wood affects the corrosion rate or how the corrosion products cause local degradation of the wood. Because the majority of experiments have attempted to measure the corrosion of metals in contact with wood, papers that solely discuss the degradation of wood in contact with metal are not included.

Many studies used the common name to identify the wood species evaluated. In clear cases where the genesis could be easily determined, the scientific name was given. If a specific genesis was unclear, the scientific name was omitted. Similarly, for the preservative or fire-retardant treatments, if a standard name or formulization could be determined from the information presented in the report, it was listed; otherwise, the general or commercial name was utilized. The unified numbering system (UNS) designation is included with alloys wherever possible (ASTM 2003e).

Corrosion Background and Terminology

The corrosion of metals in an aqueous environment is an electrochemical process. Corrosion involves two steps: (1) the reactants, mainly water and oxygen, must diffuse to the metal surface, and (2) upon reaching the surface, the reactants must have enough energy to complete the reaction. Because these steps are in series, the slower of these two steps dominates the rate of corrosion. When the diffusion to

the surface is the rate-determining step of corrosion, the reaction is said to be "concentration controlled" or "diffusion controlled". If there is an abundance of the reactants at the surface, the reaction rate is controlled by the number of atoms with enough energy to cross the energy barrier to complete the reaction. Because the number of atoms with this energy is a thermally activated process (that is, it follows the Arrhenius law), this situation is said to be "activation controlled". When reviewing previous research, it is important to consider that accelerating tests may change corrosion mechanisms from a diffusion-controlled process to an activation-controlled process or vice versa. In wood near its fiber saturation point, there is enough water that the corrosion reaction is activation controlled; however, at equilibrium moisture contents below about 20%, the reaction appears to be diffusion controlled (Jack and Smedley 1987, Bailey and Schofield 1984).

The defining characteristic of the corrosion rate is the mass loss (from metal to oxide) per unit time. If all the oxide is removed from the metal after corrosion has occurred, corrosion can be measured by the mass loss per unit time. However, simple mass loss measurements fail to describe the damage of the corrosion because they are not normalized by the size of the test specimen. By normalizing mass loss to specimen size, it is possible to compare the corrosion rates of two specimens of different size. Normally, corrosion is measured in depth of penetration per unit time, which is calculated from the mass loss data divided by the product of the density and the surface area of the corroded metal. The most common unit of corrosion, in both the United States and abroad, is mils of penetration per year (MPY), where a mil is one-thousandth of an inch (Jones 1996). However, millimeters per year (mm/y) and micrometers per year (μm/y) are also used. For reference, 1 MPY is equivalent to 0.0254 mm/y or 25.4 μm/y.

Because corrosion is an electrochemical process, the mass loss is directly related to a loss of electrons. In general, movement of charged particles, such as electrons, per unit time is the definition of electrical current, measured in amperes. Therefore, the electrical current produced from the corrosion reaction, if measured, can be related back to mass loss per unit time through unit analysis. Like mass loss per unit time, electrical current does not allow for comparisons between samples of different size. Therefore, electrical current density, measured in amperes per square centimeter, is the preferred unit to measure corrosion for electrochemical tests. Current density and depth of penetration are equivalent units and can be converted by unit analysis.

Part 1—Exposure Tests
Overview

The simplest way to measure the corrosion of metals in contact with wood is to expose metal in contact with wood

to the environment of interest. After a certain length of time, the metal can be removed from the wood, and both the metal and the wood can be visually examined for signs of corrosion. In addition to visual examination, the metal can be cleaned and weighed to measure the corrosion rate. In addition to being simple, the exposure method also allows the researcher to measure the actual corrosion rate for a given test set up. Careful choice of metal arrangement and environment allows the researcher to exactly replicate a given set of conditions that a wood–metal combination will see in service. However, this can also be a disadvantage. Because the local environment in the United States changes radically from a temperate rainforest in the Pacific Northwest to a desert environment in Arizona and New Mexico, corrosion data gathered in one specific environment cannot easily be applied to another environment. Even the same city could have two different corrosion environments if part of the city is near the seashore or contains large industrial facilities. In addition, there can be changes in the local environment during the duration of the test. Exposure tests also have the disadvantage that they take more time to complete than accelerated tests. Indeed, this is a potential problem with changes in preservative treatments; in the time it takes to run an exposure test, preservative treatments could change and the data that were collected might be of little value to evaluate the corrosiveness of the new preservative treatment.

Outdoor Exposure

To the authors' knowledge, there have been four papers that have studied the corrosion of metals in contact with wood by exposing them to outdoor conditions. These papers will be discussed chronologically, starting with Baechler (1949), followed by Farmer and Porter (1962), Scholten (1965), and finishing with Wallin (1971).

In 1949, R.H. Baechler of the USDA Forest Service, Forest Products Laboratory (FPL), published the results of a 20-year investigation into the corrosion of metal fastenings. This publication included results of outdoor exposure tests, as well as indoor natural exposure tests. The indoor natural exposure tests will be discussed under the appropriate subject headings later in the paper.

The purpose of Baechler's (1949) 20-year investigation was to determine how zinc-chloride preservative treatments affect the corrosion of metals in contact with treated wood. Most of the experimental details were published in a 10-year progress report (Baechler 1939). Baechler (1939, 1949) measured the corrosion of three different types of metals in contact with one species of wood with five different levels of zinc-chloride preservative treatment for various exposure times up to 20 years. No. 4 common wire nails, No. 6 brass screws, and 38-mm (1.5-in.) galvanized iron nails were driven into the sapwood of air-dried ponderosa pine. To see if paint protected the fasteners from corrosion, Baechler
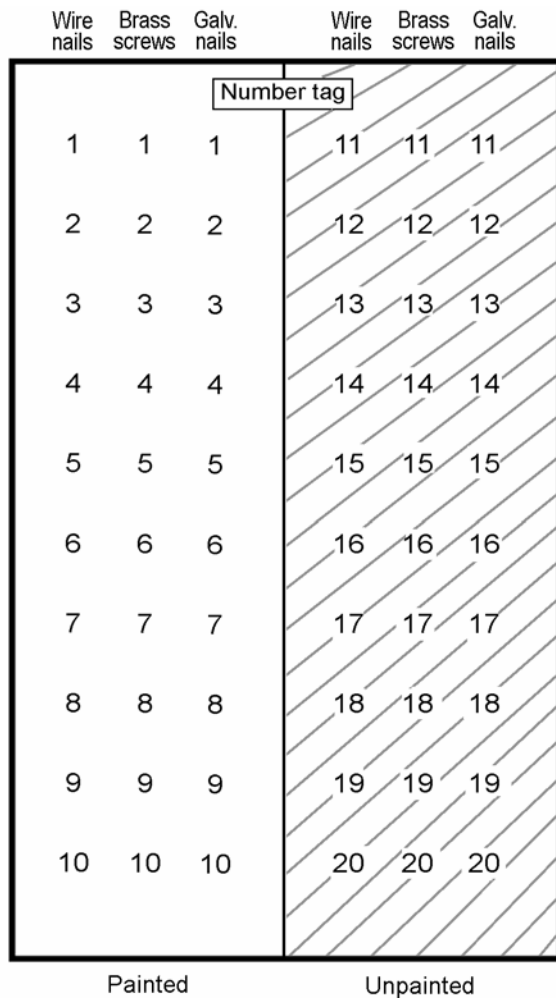
Figure 1—Fastener arrangement and test setup of the 20-year exposure test of Baechler (1939).

Wire nails	Brass screws	Galv. nails	Wire nails	Brass screws	Galv. nails
		Number tag			
1	1	1	11	11	11
2	2	2	12	12	12
3	3	3	13	13	13
4	4	4	14	14	14
5	5	5	15	15	15
6	6	6	16	16	16
7	7	7	17	17	17
8	8	8	18	18	18
9	9	9	19	19	19
10	10	10	20	20	20
Painted			Unpainted		

Table 3—Matrix of preservative treatments and moisture contents used by Baechler (1949)[a]

Moisture content	Preservative treatment
Original air-dried moisture content	Untreated
	1.41 lb/ft^3 zinc chloride
	0.74 lb/ft^3 zinc chloride
Damp from treatment	1.51 lb/ft^3 zinc chloride
	1.51 lb/ft^3 2:1 zinc chloride to sodium dichromate by weight

[a] 1 lb/ft^3 = 16.02 kg/m^3

painted half of the board after the fasteners were driven. Figure 1 shows an example test piece.

Zinc-chloride preservative treatments of several different loadings were analyzed. Two treatments, one with a net retention of 22.59 kg/m^3 (1.41 lb/ft^3) of dry zinc-chloride and the other with a net retention of 11.85 kg/m^3 (0.74 lb/ft^3) were applied, and the specimens were then allowed to return to their original moisture content prior to the corrosion tests. It took approximately 6 months for the specimens to return to original moisture content. Two other treatments were applied shortly before the corrosion test and were not allowed to dry. The first of these treatments had a net retention of 24.19 kg/m^3 (1.51 lb/ft^3), and the second treatment was a mixture of two parts zinc chloride to one part sodium dichromate by weight, with a net retention of 24.19 kg/m^3 (1.51 lb/ft^3) of total salt. For comparison, untreated ponderosa pine was tested. The different treatments are summarized in Table 3.

Baechler (1939, 1949) exposed 10 specimens (Fig. 1) "out of doors on a fence at Madison Wisconsin." It is unclear whether the test pieces were exposed parallel or perpendicular to the ground. At intervals throughout the 20-year test period, test pieces were removed and the fasteners were measured for corrosion. If the fastener was damaged upon removal, it was excluded from the results. The fasteners were examined by destroying the wood around the fasteners and removing the corrosion products with a rubber eraser. If the eraser was unable to remove the corrosion products, sandpaper was used. Fasteners that were removed 10 years or more from the start of the test were cleaned with a 10% solution of ammonium citrate for an hour. For those nails that were painted over, chloroform was used to remove the paint. The difference of the final and initial weights was recorded and the mass loss reported.

Baechler's (1949) report remains to this day one of the longest running and most comprehensive exposure tests. Although zinc-chloride is no longer used as a preservative treatment, the corrosion data from the untreated replicates could be used as baseline numbers for corrosion of metals in contact with wood in a midwestern, nonurban, nonindustrial environment. The weight loss data reported cannot be directly compared across fastener types or applied to general situations since weight loss depends on the sample size and density. However, because all fasteners were similar in size, similar amounts of weight loss approximate similar amounts of corrosion. Another barrier to using the weight loss data is that Baechler (1949) did not use standard procedures (ASTM 2003d, NACE 2000) to remove the corrosion products. Therefore, the reported weight loss numbers may be incorrect and cannot be compared directly to other corrosion data. Moreover, Baechler (1949) did not account for galvanic corrosion that could have occurred between different metal types placed in the same piece of wood. While this would not normally be a problem if the metals were not electrically connected, during 20 years of exposure, it is very possible that the fastener heads became electrically
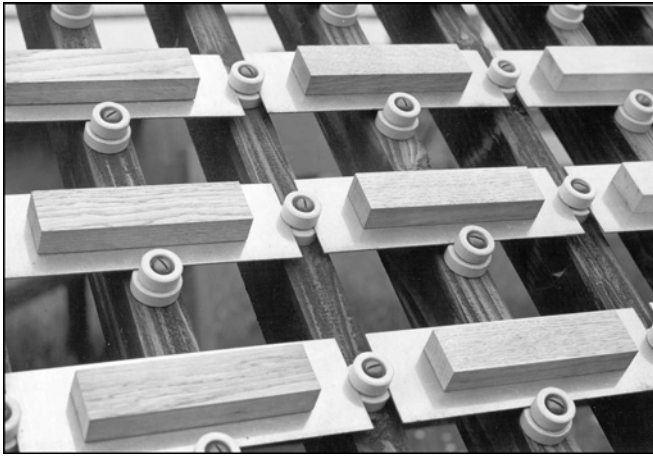
Figure 2—Corrosion test of Farmer and Porter (1962). (Used with permission of Timber Trades Journal, formerly "Wood").

connected by rainwater or melting snow and that galvanic corrosion occurred, which could have skewed the results.

Farmer and Porter (1962) conducted a 10-year investigation into the corrosion of aluminum in contact with wood. Commercial purity aluminum was put in contact with 10 different species of wood. The wood species tested were European spruce (*Picea abies*), Douglas-fir (*Pseudotsuga menziesii*), western redcedar (*Thuja plicata*), obeche (*Triplochiton scleroxylon*), European beech (*Fagus sylvatica*), European oak (*Quercus* spp.), English elm (*Ulmus procera*), African mahogany (*Khaya* spp.), balsa, and greenheart. Commercial purity aluminum was also put in contact with obeche and European beech treated with creosote, fluoride chrome arsenate, CCA, copper chrome, and copper napthenate. In addition to commercial purity aluminum, two different aluminum alloys were placed in contact with obeche, European beech, and European oak.

The test apparatus of Farmer and Porter (1962) is shown in Figure 2. The wood blocks are attached to the aluminum sheets with stainless steel screws insulated from the aluminum by rubber washers. The wood–aluminum couple was exposed at a 45° angle facing south at two locations in the United Kingdom—Princes Risborough, a rural environment, and Hayling Island, a marine environment. There were enough replicate tests so that a wood–metal couple of each of the metals, wood species, and preservative treatments could be removed at 1, 2, 5, and 10 years. Upon removal from the outdoor test site, the aluminum was cleaned in an ultrasonic bath of nitric acid with 5% chromic acid. After being cleaned, the mass loss was measured and if pitting corrosion occurred, the pit depth was measured with a pin micrometer.

One problem of the test procedure is that some of the mass loss of the plates might be caused by contact of the aluminum with the atmosphere, especially in the marine

environment. It is impossible to distinguish the mass loss caused by the atmosphere and that caused by the wood.

Scholten (1965), also of FPL, indirectly measured the corrosion of metals in contact with wood by measuring the nail withdrawal strength of wood exposed outdoors for 5 years in Madison, Wisconsin. The purpose of the study was to examine how different preservative treatments affected the withdrawal resistance of nails used to hold together field boxes. Sixpenny cement-coated box nails were used to assemble the field box out of ponderosa pine (*pinus* spp.). Seventeen preservative treatments were tested (Table 4). The nail withdrawal test follows the methodology of ASTM D 1761–88 (ASTM 2003b) with the exception of pilot holes and delay time. While the standard (ASTM 2003b) calls for the nails to be withdrawn immediately after being driven, the tests were run 5 years after insertion so that the time and corrosion effects could be measured.

Scholten (1965) makes several notes about the level of corrosion of the fasteners and even includes a photograph (Fig. 3). It is obvious from Figure 3 that the corrosion of the nail is an important factor in the lower withdrawal strength. Scholten (1965) speculates that, "A small amount of corrosion tends to increase the withdrawal loads; however, in some boxes, the corrosion had progressed to the stage where the nail broke off during the test."

While Scholten does not quantify corrosion, his test methods do give some insight to the corrosion of metals in contact with wood exposed to outdoor conditions. Because metal in contact with wood is often used as a fastener, the goal of any corrosion test should ultimately be to relate the corrosion back to the mechanical properties of the fastener. Although measuring the withdrawal strength of the fastener after exposure to the outdoors does relate the corrosion back to the mechanical properties, it does have some disadvantages. Firstly, the withdrawal values for nails driven into the side and end grain of wood decline with time even if no corrosion takes place (Ehlbeck 1979). Therefore, it is hard to separate the effects of corrosion and time delay from a simple withdrawal test. Secondly, the experiment took 5 years to run, which makes it inappropriate for rapid testing and evaluation of a new preservative treatment. In addition to these factors, like all other outdoor exposure tests, the results of this experiment are only valid for the climate in which the experiment was run, in this case, Madison, Wisconsin.

Wallin (1971), of the Scandinavian Lead Zinc Association, also examined the corrosion of metals in contact with wood by exposing them to the environment. The purpose was to determine the corrosive effect of preservative treatments, including CCA-B (Boliden K 33, Osmose Utilities Services, Buffalo, New York) and acid copper chromate (ACC) (Celcure) of Table 5 (AWPA 1971a) on fasteners embedded in wood.

Table 4—Different preservative treatments used by Scholten (1965). The water repellent used in several treatments consisted of 6.5 wt% ester gum, 6.5 wt% raw linseed oil, and 2 wt% paraffin wax

Treatment	Preservative	Solvent	Retention (kg/m^3)
Dip	0.5% salicylanilide	Commercial aromatic solvent	28.8
Dip	15% water repellent	Commercial aromatic solvent	24.0
Dip	5% orthophenylphenol	Commercial aromatic solvent	27.2
Dip	5% orthophenylphenol and 15% water repellent	Commercial aromatic solvent	27.2
Dip	5% pentachlorophenol and 15% water repellent	Commercial aromatic solvent	25.6
Dip	5% pentachlorophenol and 5% ester gum	Commercial aromatic solvent	38.4
Dip	5% rosin amine D-pentachlorophenate	Commercial aromatic solvent	32.0
Dip	5% zinc alkyl sulfate	Commercial aromatic solvent	32.0
Dip	Copper napthanate with 1% metalic copper	Commercial aromatic solvent	30.4
Dip	0.1% copper-8-quinolinolate	Stoddard solvent and proprietary	27.2
Dip	5% copper 3 phenol salicylate	Coal tar naptha	24.0
Dip	0.94% cocoamine salt of tetrachlorophenol and 25% water repellent	Mineral spirits	28.8
Dip	2% sodium pentachlorophenate and 3% borax	Water	30.4
Dip	3.17% ammoniacal copper arsenate	Water	36.8
Dip	5% sodium orthophenylphenate	Water	35.2
Pressure	ACA	Water	4.3
Pressure	Nickel sulfate Sodium arsenate Arsenic acid Sodium dichromate	Water	3.4

A unique aspect of Wallin's (1971) test is that he set out to test theories on nail coatings. He speculated that electroplated galvanized fasteners do not adequately protect fasteners against corrosion in wood because the coating is too thin, in some cases less than 5 μm (0.0002 in.). Hot-dipped galvanized fasteners on the other hand have coatings that range between 40 and 80 μm (0.0016 and 0.0031 in.). Therefore, Wallin (1971) expected that the hot-dipped galvanized fasteners would perform better than the electroplated fasteners. Furthermore, Wallin (1971) suspected that nails coated with poly(vinylchloride) (PVC) would perform poorly because the PVC coating would shear off during insertion. In addition to testing PVC-coated nails, electroplated zinc nails, and hot-dipped galvanized nails, Wallin also tested nails made out of mild steel, copper, brass (63wt%Cu, 37wt%Zn), stainless steel (17wt%Cr, 12wt%Ni, 3wt%Mo), and an unspecified aluminum alloy.

Fasteners were driven into pieces of European redwood (*Pinus sylvestris*) treated with four different preservative treatments. The brand names of the preservative treatments used, as well as their composition, are given in Table 5. In addition to the four preservative treatments, Wallin (1971) tested fasteners driven into untreated wood as a control. The wood–fastener couples were exposed on top of the roof of a sulfuric acid plant for 1 year. Although the location of the plant is not specified, it is assumed to be near Stockholm where the paper was published. Weight loss data is reported, although the procedure for removing the corrosion products is not mentioned.

Wallin's (1971) experiment has several factors that make it different from the work of Scholten (1965) and Baechler (1949). Data cannot be compared across the work of Wallin and the researchers from FPL because of the different climates in Wisconsin and Sweden. Furthermore, the industrial environment of the sulfuric acid plant also makes the data set more complicated. It is impossible to say what chemicals were in the local atmosphere around this plant in 1971 and how they changed the corrosion rate. However, since all of the fasteners that Wallin tested were exposed at the same industrial plant in Sweden, Wallin's data can be used to make relative statements about how different alloys perform in an industrial environment. The most important result was
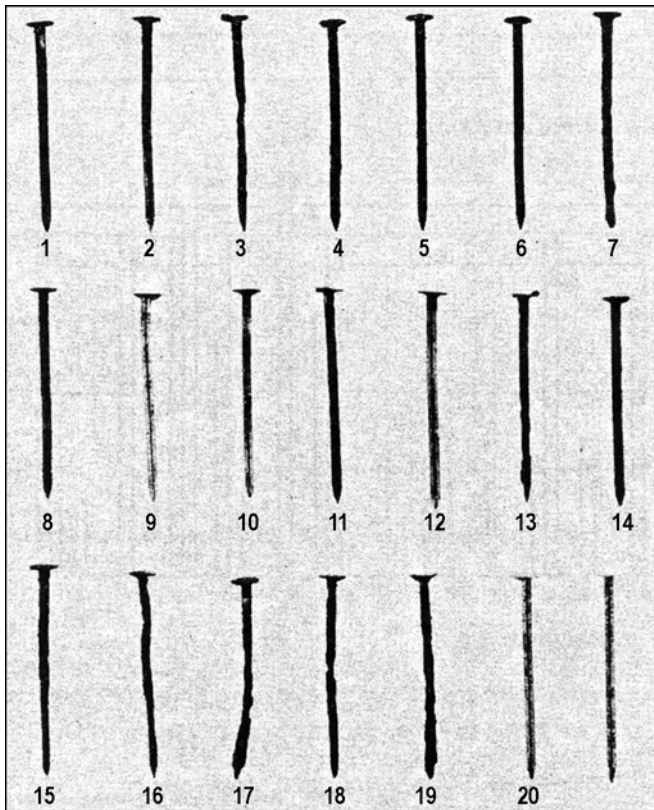
Figure 3—Corrosion of fasteners exposed near Madison, Wisconsin, for 5 years. The unnumbered nail is a new, clean, cement-coated nail (Scholten 1965).

in Virginia and Minnesota; the other, a 17-year exposure of nails in treated wood buried underground.

Baker and Gjovick (1977) presented the results of a condition assessment of fasteners used in wood foundations in Virginia and Minnesota in an unpublished FPL report. The goal was to observe the condition of fasteners in preservative-treated wood foundations and to measure the moisture content because the moisture content is a major factor of corrosion in any environment. Baker and Gjovik (1977) focused on galvanized steel fasteners because galvanized steel fasteners were recommended for use with preservative-treated lumber by the National Forest Products Association (now called the American Forest and Paper Association). In addition, there were concerns about the durability of galvanized fasteners in preservative-treated wood. A secondary objective was to evaluate the effectiveness of X-ray radiography as a method to nondestructively evaluate the corrosion of fasteners in wood foundations.

The foundations of sixteen houses were examined. Nine of the sixteen house foundations were built with CCA-treated wood and were located in Virginia. The remaining seven houses were located in Minnesota, and the foundations were made of wood treated with ACA. The age of the foundations treated with CCA ranged from 9 to 38 months, and the foundations treated with ACA ranged from 22 to 50 months. At each location, the dirt around the foundation of the house was removed to a depth of 0.6 m (2 ft) so that fasteners could be removed and moisture measurements taken with an electronic moisture meter. A core of wood surrounding the fastener was removed, and then from that core, the fastener was extracted and visually examined. Radiographs were taken at several locations. Baker and Gjovik (1977) reported that the moisture content ranged from 10% to 30% in the foundations and also noted that several fasteners, including hot-dipped galvanized fasteners, had red rust.

No quantitative measure was made of the corrosion of fasteners in preservative-treated wood foundations by Baker and Gjovik (1977). However, their findings give "real-life" proof for the need to understand and quantify the corrosion of fasteners in preservative-treated timber.

that hot-dipped galvanized outperformed electrodeposited galvanized in every situation just as Wallin had predicted.

Underground Exposure

Baker (1992) and Baker and Gjovick (1977) ran two experiments to estimate the amount of corrosion that could be expected in wood foundations for housing. One was a condition assessment of the fasteners used in wood foundations

Table 5—Different preservative treatments used by Wallin (1965)

| | Composition (wt%) | | | | | | | | | | | |
| | Cu | | Cr | | As$_2$O$_5$ | | SO$_4$ | | Na | | Cl | |
Trade name	min	max	min	max	min	max	min	max	min	max	min	max
Bliden K 33	0.31	0.26	0.58	0.51	1.26	0.91	—	—	—	—	—	—
Celcure	0.18	0.18	0.46	0.43	0.64	0.54	0.4	0.4	0.8	0.2	—	—
KP-Cuprinol[a]	0.4	0.06	—	—	—	—	—	—	—	—	—	0.01
BP-Hylosan	—	—	—	—	—	—	—	—	—	—	0.08	0.08

[a]Sherwin-Williams Co., Cleveland, Ohio.

Baker (1992) published the results of a 17-year study into the investigation of fastener corrosion in preservative-treated wood exposed underground to simulate the conditions of permanent wood foundations. Like Baker and Gjovik (1977), the purpose of the 1992 report by Baker was to gain information into the performance of fasteners exposed to preservative-treated wood used in wood foundations. In addition to the outdoor exposure, Baker (1992) ran simulated exposure tests by exposing fasteners embedded in preservative-treated wood to high moisture contents. The results of the simulated exposure test will be discussed in a later portion of the paper.

Baker (1992) tested the sapwood of Southern Pine (*Pinus* spp.) treated with CCA Type A, CCA Type B, and ACA (AWPA 2004b). All preservatives were applied to a loading of 9.5 kg/m^3 (0.6 lb/ft^3) and the wood was kiln-dried to a maximum 19% MC after the preservative treatment was applied but before fastener insertion. Eleven different types of nails were tested; monel (UNS N04400), stainless steel (American Iron and Steel Institute (AISI) 304 and AISI 316 (UNS S30400 and UNS S31600)), copper, hot-dipped galvanized steel, mechanically coated galvanized steel, electroplated galvanized steel, cadmium-coated steel, tin-cadmium alloy coated steel, and aluminum (aluminum alloy (AA) 5056 (UNS A95056)). The nails were driven in predrilled holes into the preservative-treated lumber. An interesting aspect of Baker's test setup was that the nails were driven through two pieces of preservative-treated wood to simulate how nails are used in service. There was a 0.8-mm (1/32-in.) spacer between the two pieces of wood so that all test replicates had the same availability of water and oxygen. Specimens were buried underground at a test site near Madison, Wisconsin, and replicates were removed at 1, 3, and 17 years. Upon removal, the fasteners were washed with water and solvent, and if necessary, a rubber stopper was used to rub the corrosion product off. Baker (1992) reports the corrosion rate as weight loss.

Like other exposure tests, Baker's results are specific to the environment and climate in which they were run. The data collected on the different alloys used can be used to get a relative ranking of alloy performance in treated wood, assuming that the mechanism of corrosion does not change significantly between underground and aboveground exposure.

Simulated Natural Exposure

The outdoor environment is constantly changing. While many wood products are exposed to outdoor conditions, running a test outdoors has the disadvantage that it cannot be duplicated or verified by another researcher because of the variance in outdoor conditions. Researches such as Baechler (1949), Johnson (1976), Laidlaw and Cox (1983), Simm and Button (1985a), Han and Chung (1986), Baker (1988, 1992), and Davis and Allen (1993) have tried to eliminate this variability by running experiments in controlled conditions. However, there is a fine line between simulating the outdoor conditions and accelerating the corrosion by placing the specimen in too harsh of a controlled environment.

For the purpose of comparison in this paper, experiments that have run controlled exposure tests for more than a year are grouped into the simulated natural exposure tests; even though some of the conditions slightly accelerate the corrosion. This classification was chosen because in most cases, the authors who ran experiments in accelerating conditions for more than a year were using it as an upper bound for other exposure tests. On the other hand, most tests that were less than a year in length were focused on accelerating the corrosion rate for rapid evaluation.

In addition to running outdoor exposure experiments, Baechler (1939, 1949) also ran 20-year tests in humidity rooms to simulate different environments. Sets of similar specimens were exposed to a constant temperature of 27°C, (80°F) and a constant relative humidity of 30%, 60%, or 90% for 20 years. The equilibrium moisture contents associated with those conditions are 6.1%, 11.7%, and 20.2% (Forest Products Laboratory 1999). The 27°C, 90% RH (relative humidity) represents a severe exposure condition, and the 27°C, 30% RH represents a lower bound for corrosion in wood used for construction. Beyond exposure conditions, the same procedure was used in both the outdoor exposure tests that were discussed earlier and the humidity room tests (Fig. 1). Baechler (1939, 1949) concluded from his data that the amount of corrosion on fasteners exposed to the outdoors was about the same as the that on fasteners exposed to the constant 27°C, 65% RH environment.

Johnson (1976) ran experiments to determine the mechanical properties of fasteners in contact with wood treated with fire retardants. At that time, all mechanical fasteners were given a 10% reduction in design capacity when used in fire-retardant-treated wood because there was little long-term durability information and many engineers recognized that hydrolytic fire-retardant treatments would accelerate corrosion.

Johnson ran lateral nail tests in Douglas-fir treated with three different types of commercially available fire retardants: NON-COM[1] (Arch Wood Protection, Smyrna, Georgia), Pyresote (Protexol Corp., Kenilworth, New Jersey) (AWPA 1971a,b), and FR-28[2], a borax–boric acid solution.

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[1] NonCom is a four-part system that contains Ammonium sulfate, ammonium phosphate, boric acid–borax, and dicyandiamide.

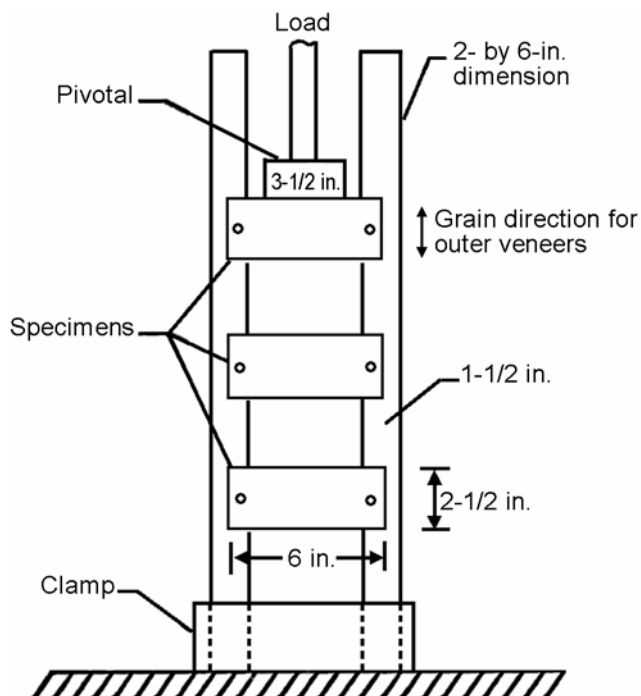[2] FR 28 is a three-part system that contains boron, calcium, and sodium.

**Figure 4—Lateral nail test of Johnson (1976)
(1 in. = 25.4 mm) (Used with permission of
Oregon State University).**

No information was given on the composition or retention on the wood treated with NON-COM or Pyresote. A nail or staple was driven through plywood into a piece of solid sawn lumber. Johnson (1976) tested assemblies where both the solid sawn wood and the plywood were treated or untreated, as well as running tests where either the solid sawn or the plywood was treated and the other piece was not. Eight types of fasteners were used: 6d common nail, 6d box nail, 6d galvanized nail, 6d galvanized-T nail, 6d nickel alloy 400 (monel (UNS N04400)) nail, 14 gauge galvanized staple, 16 gauge galvanized staple, and 16 gauge nylon-coated staple. The wood–metal couple was then exposed for either 2 or 7 years in one of three conditions: cold, 2°C (35°F) and 80% RH; standard, 21°C (70°F) and 65% RH; or hot, humid, 32°C (90°F) and 90% RH.

In total, with eight types of fasteners, three treatments, three exposure conditions, two exposure lengths, and four methods to apply the treatments, there were 4,704 different combinations tested. The lateral nail test is shown in Figure 4. Unlike the ASTM (2003b) standard for determining the lateral load capacity of fasteners, which tests only one fastener at a time, Johnson's assessment tested two fasteners at once.

Johnson (1976) was the only researcher to determine the corrosion of metals in contact with wood by measuring the lateral bearing strength of the assembly. This makes it very difficult to compare his research with other researchers who

have studied corrosion. Furthermore, neither the composition nor the retention of the proprietary treatments are given, which makes it impossible to replicate the experiment.

Laidlaw and Cox (1983) also tried to simulate environments to which wood–metal connections are frequently exposed. The purpose of the study was to quantify any long-term risk of the corrosion of nail plates used in conjunction with preservative-treated trusses used in roof spaces. Pieces of European redwood with varying amounts of heartwood and sapwood and free of any splits or checks were held together by zinc-coated nail plates. The wood had been treated with either CCA or a proprietary organic solvent. The salt form of CCA was applied to a retention of between 9.5 and 18 kg/m^3 (0.60 and 1.1 lb/ft^3) and was kiln-dried before testing. The organic solvent consisted of pentachlorophenol as well as tributyltin oxide and a water repellant. Auxiliary tests were run on radiata pine that had been treated with borates. In addition to the standard zinc-coated nail plates, those that had been coated a second time with a nonmetallic coating were also tested. The nonmetallic coatings tested were bitsumatic paint, hot-dipped nylon, and sintered epoxy.

The wood joints were then exposed to one of three conditions—"damp", "natural exposure", or "dry"—for times ranging from 1 to 8 years. The damp condition corresponded to a humidity chamber conditioned at 27°C (81°F) and 87% RH. The wood–metal joints that were put in the natural exposure condition were placed directly under a roof in a nonheated building in Britain. This placement sheltered the joints from rain, but still exposed them to the changes of temperature and humidity. Those specimens subjected to a dry condition were placed in a heated, nonhumidified building.

Laidlaw and Cox (1983) measured the amount of corrosion by running mechanical tests. Static and fatigue tests were run on joints to see if the corrosion affected the fatigue strength more than the static strength. After the strength of the joint was measured, several additional tests were run on both the wood and the nail plate. The density, hardness, pH, and conductivity of the wood were measured. The conductivity was measured indirectly by measuring the resistance with an ohmmeter. The weight of the zinc coating of the nail plate was measured and the nail plate was examined with a microscope and X-ray diffraction.

The work of Laidlaw and Cox (1983) was unique in that it studied the corrosion of joints connected with nail plates. However, they did not directly measure the corrosion rate, which makes it very hard to compare the data to those of other researchers. Additionally, it is hard to separate the reduction in mechanical capacity caused by time from the affects of corrosion.

Simm and Button (1985a) classified the corrosiveness of CCA preservative treatments. In their introduction, Simm and Button (1985a) question the validity of outdoor exposure tests because wood degrades when cycled through changes in temperature and moisture content that occur in the outdoor environment; therefore "This [degradation] can lead to cracking and splitting of wood samples which will expose fasteners to corrosive conditions which may be completely different from those produced in the wood." While this cracking and splitting may be seen in service, it is undesirable during testing because it adds variance to the test and also makes the results harder to interpret.

To test the corrosiveness of CCA, Simm and Button (1985a) inserted fasteners into blocks of CCA-treated European redwood (*Pinus sylvestris*) with salt retentions ranging from 3.0 to 9.1 kg/m^3 (0.19 to 0.56 lb/ft^3) and placed them in a humidity chamber for 30 months. The humidity chamber was kept at 25°C ± 1°C (77 ± 1.8°F) with a RH that ranged between 95% and 100%. Four different types of metal fasteners: mild steel, electroplated galvanized steel, stainless steel (AISI 302 (UNS S30200)), and an aluminum alloy (AA 2024 (UNS A92024)), were tested (Table 6). After the exposure, the fasteners were placed in a steam bath, brushed off to remove dirt, and then placed in a chemical bath to remove the corrosion products. Simm and Button (1985a) reported the corrosion as the change in weight.

Even though the exposure methodology of Simm and Button (1985a) is similar to other previous research, their paper is filled with original ideas. Simm and Button (1985a) were the first researchers to apply corrosion science techniques to the corrosion of metals in wood. After the exposure tests, Simm and Button (1985a) used scanning electron microscopy and X-ray diffraction to analyze the fastener and the wood. By using these instruments, they were able to determine the composition of the corrosion products and monitor how far they traveled in the wood. With information about the corrosion products, Simm and Button (1985a) were able to speculate about the corrosion reactions that occurred at the

wood–fastener interface and predict the behavior of fasteners in CCA-treated wood in other environments. Not surprisingly, Simm and Button (1985b) were also the first researchers to apply electrochemical methods used in corrosion science to wood. Details of this work will be discussed later.

Han and Chung (1986) simulated the in-service corrosion performance by placing test blocks, containing a nail, into desiccators filled with K_2SO_4 on the bottom. Test blocks were treated with 2% solution of CCA-Type A, CCA-Type B, CCA-Type C, ACC (AWPA 2004b), and phenol flourid, nailed, and placed in the desiccators for 5, 10, and 20 days. Results showed that rate of weight loss of nail was strongly correlated with the type of wood preservative used to treat the wood. Test periods did not show any significant difference, and there was no significance between the interaction of test period and preservative type.

In addition to running exposure tests in the soil, Baker (1988, 1992) also exposed specimens to a controlled humidity room to simulate conditions that "would have a corrosion rate higher than that expected in wood foundations." The specimens were identical to those specimens exposed to the ground; they were made from preservative-treated Southern Pine with one of eleven different metals used to fasten the wood together (Table 1). The specimens were exposed to a humidity chamber at 27°C (80°F) and 98% ± 2% RH for 14 years. At the end of the 14 years, the fasteners were removed, the corrosion products cleaned, by rubbing the fasteners with a rubber stopper, and weight loss data reported.

Even though the corrosion data at 27°C (80°F) and 98% ± 2% RH cannot be extrapolated to normal conditions, they are still of value. Baker's results represent a significant database on the corrosion of metals embedded in CCA-treated wood. Even though the utilization of CCA-treated wood is decreasing, the experiment could be replicated in wood treated with newer waterborne preservatives. Parallel experiments with new preservatives could give insight into their relative corrosiveness compared with CCA.

Table 6—Aluminum alloys tested by Wright and others (1957)

Alloy	U.S. equivalent	Form	Alloying elements (weight %)							
			Cu	Fe	Mg	Mn	Si	Ti	Cr	Al
65S-T6	6061-T6	Sheet	0.36	0.37	1.06	—	0.64	0.05	0.22	97.3
65S-T7	6061-T7	Rod	0.25	0.34	0.95	—	0.55	0.01	0.24	97.66
65S-T8	6061-T8	Bolts	0.23	0.34	1.01	—	0.49	0.01	0.13	97.79
65S-T9	6061-T9	Coupons	0.29	0.4	0.94	—	0.57	—	0.2	97.6
24S-T3	2024-T3	Sheet	4.52	0.34	1.44	0.63	0.25	0.01	—	92.81
24S-T4	2024-T4	Rod	4.64	0.27	1.52	0.64	0.2	0.01	—	92.72

Davis and Allen (1993) altered outdoor conditions to obtain a more reproducible corrosion test. The purpose of their experiments were to measure how the corrosiveness of wood treated with CCA varies with time after treatment. Davis and Allen (1993) hypothesized that since freshly treated wood has a higher moisture content and higher conductivity because of the unfixated preservatives, it is more corrosive. To test this hypothesis, fasteners were inserted into slash pine (*Pinus elliottii*) treated with the salt formulation CCA at various times after the treatment was applied. The retention of CCA in the slash pine was not reported. Several different fastener materials were used so that a relative comparison could be made. The fasteners used were stainless steel (AISI 304 (UNS S30400)), monel (UNS N04400), brass, copper, silicon bronze, nickel-plated steel, hot-dipped galvanized steel, and mild steel. Holes were predrilled in the wood for the fasteners to minimize splitting damage to the fastener. The fasteners were driven into preservative-treated wood in intervals after the wood had been treated. During this time, the wood was placed under a cover outdoors. No outdoor location is specified, but it is assumed to be in or near Queensland, Australia, where the report was published. The specimens were exposed either 6 or 12 months. After the exposure, the corrosion product was removed in accordance with ASTM (2003d) standard G1-81. Mass loss data were reported.

While the work of Davis and Allen (1993) is interesting, it is important to note that their data may be slightly misleading. Although the wood was exposed for either 6 or 12 months, the actual time that the fasteners were in contact with the wood varied because the effects of cure time were studied by placing fasteners in contact with the wood at different time intervals after treatment. Because the fasteners that were driven into freshly treated wood are also the fasteners that were exposed the longest to the wood, the data may overemphasize the affects of cure time.

Part 2—Accelerated Exposure Tests

Overview

Outdoor and simulated natural exposure tests have the disadvantage that they take a long time to run. In fact, in the time it takes for results to be gathered, the formulation of the preservative treatment may have changed. Moreover, if a company wanted to test a preservative treatment for corrosion before marketing it, it would have to delay market intervention several years, which would be prohibitively expensive. Outdoor exposure tests also have the disadvantage of low reproducibility because the conditions the wood is exposed to are constantly changing and unpredictable. Because of these disadvantages, many researchers have tried to accelerate the corrosion process by making the environment around the wood more conducive to corrosion. Three

different methods have been used to increase the corrosiveness of the environment. The first method is increasing the moisture content and temperature of the wood. The second is placing the metals in contact with moist sawdust. The third accelerated environment is a salt-spray cabinet, which is commonly used outside of the wood industry to measure corrosion in marine environments.

Moisture Content and Temperature

At higher moisture contents, wood conducts electricity and ions better, and therefore, the corrosion reaction occurs at a faster rate. Because the equilibrium moisture content of wood is dependent on the temperature and the RH, the effects of these two variables must be examined together.

The kinetics of corrosion (oxidation) are faster at higher temperatures because diffusion and other processes of corrosion are thermally activated. However, at higher temperatures, there is less thermodynamic tendency for corrosion (oxidation) to occur because it is an exothermic reaction. Near room temperature, the change in the reaction rate caused by the kinetic component dominates. Therefore, increasing the temperature increases the reaction rate in this regime.

Several papers have tried to accelerate corrosion by increasing RH or temperature, or both. The equilibrium moisture content is a function of both temperature and RH. Also for a given moisture content, the RH itself is a function of temperature. Therefore, these factors will be discussed together.

There have been five reports, as well as a standard test method, that accelerate the corrosion of metals in wood by changing the moisture content and temperature of the wood. In chronological order, they are Wright and others (1957), Doyle (1964), Wallin (1971), Barnes and others (1984), and the AWPA standard (AWPA 2004a), which was originally adopted in 1994.

Wright and others (1957) were funded by the Canadian Navy to investigate the corrosion performance of aluminum alloys (Table 6) used in conjunction with woods commonly used in shipbuilding: mahogany, Canadian rock elm (*Ulmus thomasii*), British Colombia Douglas-fir (*Pseudotsuga menziesii*), and gum wood. Wright and others (1957) tested the corrosiveness of these species with several different methods including exposing the wood–aluminum to high temperature and moisture content as well as exposing the aluminum to damp sawdust. The damp sawdust experiments are discussed in the next section. In addition to the damp sawdust and high moisture content tests, Wright and others (1957) also ran some ancillary tests placing blocks of wood with aluminum dowels in the ocean for extended lengths of time. These ancillary tests are not discussed but can be found in the original publication and are not pertinent to our discussion.
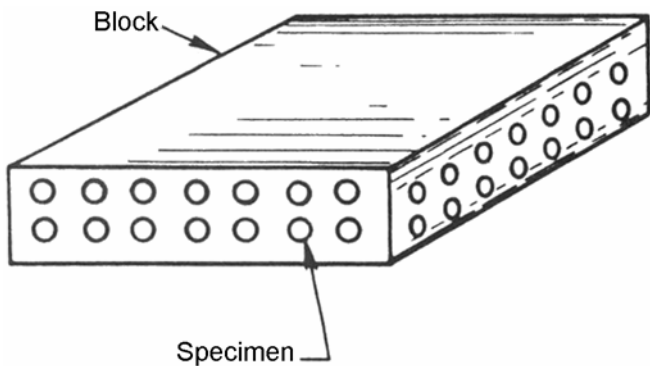
Figure 5—Design of the high temperature and humidity wood–metal exposure test of Wright and others (1957) (Used with permission of NACE International).

In addition to testing the aluminum alloys, Wright and others (1957) also tested commercially pure zinc as a reference. Dowels constructed of all alloys were placed inside holes in a specially machined block of wood shown in Figure 5. To simulate shipbuilding practice, after the metallic dowel was inserted, wood plugs were placed over the dowel to cover it from the outside environment. Wood plugs were used to cover half of the dowels; the other dowels were left open as a control. After construction, the wood block with metal dowels was placed in a controlled humidity chamber at 49°C (120°F) and 100% RH for either 2, 6, or 8 months. After the exposure, the dowels were removed and the corrosion products were removed. No details were reported on the methods used to remove the corrosion products. After the corrosion products were removed, the dowels were weighed and the corrosion was reported for weight loss per total surface area as mils per year (MPY). Pitting corrosion was noted on several of the specimens.

The conditions chosen by Wright and others (1957) were very severe and would be expected to highly accelerate the corrosion rate. Interestingly, humidity cabinet corrosion rates reported by Wright and others (1957) are extremely low. Therefore, even in severe conditions, the corrosion of aluminum in contact with untreated wood can be ignored. However, other reports have shown that corrosion of aluminum in contact with preservative-treated wood is much higher than untreated wood (Bengelsdorf 1983, Simm and Button 1985b, Cross 1990, Baker 1992). Furthermore, the use of aluminum fasteners is not recommended for use with preservative-treated wood (Cook 2003, WTCA 2004).

Doyle (1964) investigated the corrosion of nails and bolts in glue-laminated Southern Pine treated with commercial fire preservatives. Before lamination, a proprietary fire preservative (NON-COM) was applied to Southern Pine treated to a retention of 80.10 kg/m^3 (5 lb/ft^3). Unlike other studies, Doyle (1964) tested the mechanical response of both nails and bolts. Doyle (1964) measured the change in withdrawal strength of five types of eight-penny nails; common, zinc-coated, aluminum, ring-shank, and hardened ring shank as well as sixteen-penny nails. The dowel bearing strength was also tested on steel bolts with diameters of 12.7 mm (0.5 in.) and 19.0 mm (0.75 in.). The corrosion process was accelerated by placing the specimens in an environment of 27°C (80°F) and 97% RH for intervals of 3, 6, 12, 24, and 48 weeks. After these intervals, the nail withdrawal strength, according to D 1761-88 (ASTM 2003b) was measured as well as the dowel bearing strength of the bolts. Additionally, nails were driven immediately into the exposed wood and withdrawn as a baseline. Dowel bearing strength was measured in a manner similar to the recently published ASTM (2003c) standard D 5764-97a for testing the dowel bearing strength of the full hole. Doyle also measured the weight loss of the nails after they had been withdrawn to measure the corrosion rate. The exact method for removing corrosion products is unclear, but it is noted in the report that the "rust scale" was removed.

The work of Doyle (1964) is unique in that both nails and bolts were tested. Like the results of Scholten (1965) and Davis and Allen (1993), it is hard to separate the effects of corrosion and time delay from a simple withdrawal test even though Doyle ran immediate withdrawal tests in the exposed wood as a control. Doyle was the only researcher to directly measure the effect of treated wood on the dowel bearing strength. In addition, the weight loss measurements do give a measure of corrosion, but it is impossible to relate the corrosion measured in the experiment to the corrosion in service because of the accelerating techniques used, which probably changed the mechanism of the corrosion reaction.

In addition to outdoor exposure tests, Wallin (1971) also ran accelerated tests at elevated temperature and moisture content. The same test parameters as the outdoor exposure test were used; seven types of nails were driven into CCA-treated European redwood (*Pinus slyvestrus*) and weight loss data were reported. The wood–metal couple was exposed in a greenhouse at 20°C (68°F) and 100% RH for 1 year.

Barnes and others (1984) used heat and humidity to accelerate the corrosion of metals in preservative-treated wood. They tested metal coupons sandwiched between blocks of treated wood. According to Barnes and others, this "sandwich" test method was first used by Preston and van Poppel in 1978 (Preston, A.F.; van Poppel, C.M. Corrosion studies with copper chrome arsenate and quaternary ammonium preservative treatments in wood. FRI Rep. FP/WP 25. New Zealand Forest Service.). However, the work of Preston and van Poppel was never published and the authors of this paper were unable to procure it. Therefore, this paper is omitted from the literature review.

Barnes and others (1984) tested wood treated with CCA (both the salt and oxide formulations), ACA, and penta.

Table 7—Different preservative treatments used by Barnes and others (1984)

	Chemical	Retention (kg/m^3)
Inorganics	CCA- type C (oxide)	5.77
	CCA- type C (oxide)	7.53
	CCA- type C (oxide)	10.89
	CCA- type C (oxide)	14.10
	CCA- type C (salt)	5.93
	CCA- type C (salt)	9.61
	CCA- type C (salt)	14.42
	ACA (oxide)	7.21
	ACA (oxide)	8.49
	ACA (oxide)	13.14
	Boric acid	11.53
	CCA (oxide) and boric acid	21.62
Organics	Pentachlorophenol	7.21
	Didecyldimethyl ammonium chloride	4.32
	3-Iodo-2-propynyl butyl carbamate	2.72
Organo-metallics	Water-dispersible pentachlorophenol	6.57
	Copper-8-quinolinolate (acid)	0.37
	Copper-8-quinolinolate (neutral)	1.28
	Copper napthenate	1.60
	Zinc napthenate	1.12

In addition to these treatments, some organic and organometallic treatments were tested (Table 7). The metal coupons were constructed out of carbon steel (SAE 1018 (UNS G10180)), aluminum (AA 6061 (UNS A96061)), galvanized steel (20 gauge), brass (85wt%Cu, 15wt%Zn), and copper. The metal coupon was held between the wooden blocks by clamping the wood and metal together with twine. The metal coupons were about 1 mm (0.4 in.) thick, and the wood blocks were 89 mm (3.5 in.) thick. The assemblies were placed in a room at 38°C (100°F). Half of the specimens were exposed to 90% RH, and the other half were placed partially in water in a closed beaker to simulate complete water saturation. It is explicitly noted that the coupons were not in direct contact with the water for the saturated samples. The exposure period was 10 to 12 weeks. After the wood–metal couple was exposed, the corrosion products were removed according to NACE (2000) standard TM-01-69 and the corrosion rate was reported in MPY.

Barnes and others (1984) is an important paper because it uses a similar methodology to the only standard that addresses nail corrosion (AWPA 2004a). The E12 standard originated in a military specification (Department of Defense 1984) used to screen fire-retardant treatments for use in wood construction. In the E12-94 standard, a metal coupon is sandwiched between two pieces of preservative-treated wood. Nylon bolts are inserted through the wood to hold the

metal coupon in place. These wood–metal assemblies are then placed in a conditioning chamber of 49°C ± 1°C (120°F ± 2°F) with RH of 90% ± 1%. The standard specifies a minimum of 240 h of accelerated exposure, although it states that 366 h of exposure is more commonly used. The standard also specifies that the corrosion products are to be cleaned in accordance with ASTM (2003d) standard G-1 and that the corrosion rate should be reported in MPY.

While the sandwich method used by Barnes and others (1984) and AWPA (2004a) is currently standardized, the results of the test must be interpreted carefully. Even the AWPA (2004a) standard cautions, "The [corrosion] rate can not be extrapolated to all possible scenarios." It is unsafe to extrapolate the corrosion rate from these sandwich tests because currently, there is no way to relate the corrosion of metals in wood exposed to high temperature and humidity environments to the corrosion rate in normal service conditions. Therefore, the results can only be used as a comparison method.

Recently, Jin and Preston (2000) compared modified E-12 test results for nails and screws to field tests in Harrisburg, North Carolina. They concluded that laboratory test procedures might not provide optimal results.

Furthermore, the sandwich method can be very sensitive to how tightly the assembly is held together (Personal communication, Crawford, 2003). The more tightly the assembly is held together, the harder it is for water and oxygen to reach the metal, which lowers the corrosion rate. The variability of results from the AWPA (2004a) standard could be greatly improved by specifying a torque rating on the bolts. Also, nylon swells when in contact with water. Therefore, the AWPA test can be further improved by specifying nonwater-soluble polymer bolts.

In conclusion, test methods that vary moisture content or temperature to accelerate the corrosion rate should not be used as the exclusive determination of the corrosion rate—especially for in-service conditions. These accelerated test methods can give rapid results. However, it is very hard to relate these results to in-service life. At their best, test methods that change the moisture content or temperature can give relative results of fastener performance. At their worst, if these test results are misinterpreted, they can lead to incorrect design or improper materials selection. The implication of critical test conditions are still as yet unknown, such as clamping pressure and the interaction of temperature and moisture content. Significant work would be needed to correlate real world performance to lab results.

Damp Sawdust

As stated many times throughout this paper, the corrosion rate for metals embedded in wood is partially dependent on the ability for water and oxygen to reach the fastener.

To accelerate the rate of corrosion, researchers have tried to increase the moisture content of the wood to allow more water to reach the fastener. However, a limit exists to the amount of water that the wood can physically hold. To accelerate the corrosion rate even further, some researchers have tried placing metals in contact with sawdust suspended in water. Because of the similarity of the methods used by these researchers, all of the sawdust methods will be discussed together at the end of the section.

In addition to exposing untreated wood–aluminum specimens to high temperature and humidity, Wright and others (1957) also tried to accelerate the corrosion of aluminum in contact with shipbuilding woods by exposing the aluminum to water and sawdust of the woods used to build ships. Sheets of zinc and aluminum alloys were placed in contact with 750 cm^3 (46 in^3) of sawdust for 30 days at room temperature. The exact ratio of sawdust to water is not reported, but according to Wright and others (1957), "The sawdust was kept moistened with distilled water and evaporation was minimized by covering each dish with heavy aluminum foil." After exposure to the damp sawdust, the zinc and aluminum sheets were cleaned and weighed. The corrosion was reported in MPY.

Bartel–Kornacka (1967) investigated the corrosiveness to plain steel of several species of trees that are native to Ghana by using a sawdust method. Sawdust from several of these species (Table 8) was saturated with water and placed in a glass vile. A steel nail was then placed in contact with the saturated sawdust and a stopper was placed over the vial. The sealed vials were then placed in a chamber that was kept at 28°C (82°F) and 100% RH for either 28 or 62 days. Corrosion was determined by removing the corrosion product, igniting it, and using chemical methods to isolate and measure the iron using colorimetry.

Bengelsdorf (1983) ran extensive sawdust tests to determine the corrosion of fasteners in preservative-treated wood. A unique aspect of Bengelsdorf's (1983) tests compared with other researchers who used sawdust methods was that he also increased the temperature to increase the reaction rate. According to Bengelsdorf (1983), "Based on the accepted theory of doubling of the rate of a chemical reaction for each 10°C (18°F) rise in temperature, it was anticipated that the elevated temperature would increase the rate of corrosion many [times]." While this temperature relation may be roughly true for biological processes around room temperature, it does not hold true for corrosion. As explained in the section on moisture content and temperature, the kinetics of corrosion under activation polarization is limited by the number of atoms with sufficient energy to overcome the energy barrier of the reaction. Therefore, the temperature dependence of the corrosion rate is much more complicated than a doubling per 10°C increase and in fact may be erroneous, as stated in the beginning of the section Moisture Content and Temperature.

Table 8—Different tree species tested by Bartel–Kornacka (1956)

Latin name	Ghana name
Afrormosia elata	Kokrodua
Alstonia boonei	Sindru nyamedua
Chlorophora excelsa	Odum
Cynometra avanta	Ananta
Entandrophragma angolense	Edinum
Entandrophragma candollei	Omu candollei
Entandrophragma cylindricum	Penkwa
Entandrophragma utile	Efrobrodigwo
Funtumia elastica	Funtum
Guarea cedrata	Kwabohoro
Khaya anthotheca	Akwantanuro
Khaya ivorensis	Dubini mahogany
Lannea welwitschii	Kumenini
Lova trichilioides	Dubini-biri
Mansonia altissima	Pruno
Mimusops heckelii	Baku
Nauclea diderrichii	Kusia
Piptadeniastrum africanum	Dahoma
Tarrietia utilis	Nyankom
Terminalia liorensis	Emeri
Terminalia superba	Ofram
Triptochiton scleroxylon	Wawa
Turreanthus vignei	Opeya

Bengelsdorf (1983) ran sawdust corrosion tests for a whole year at 52°C (125°F). Thirty-one different types of both power and hand-driven fasteners were tested including fasteners that used several different galvanizing techniques (Table 9). To simulate the way fasteners are used in service, the fasteners were driven into the wood and removed before being placed in the sawdust environment. The fasteners were removed from the environment, cleaned, weighed, and reinserted into the sawdust at regular intervals throughout the year. This process of removing, cleaning, and reinserting increased the measured corrosion rate because, in most cases, the corrosion products partially protect the metal from further oxidation. The fasteners were then inserted into the sawdust of Douglas-fir treated to a level 10% greater than was required by the standards. It is hard for preservative treatments to penetrate Douglas-fir, although ACA is more able to penetrate it than CCA (Ritter and Morrell 1992). This inability to penetrate typically results in a nonuniform zone of treatment near the outer edge of the member. A unique aspect of Bengelsdorf's (1983) test is that instead of using the sawdust of treated wood, Bengelsdorf treated the sawdust. By treating sawdust, Bengelsdorf (1983) probably had the greatest success for a full and uniform penetration of the preservative in the wood. It is unclear how corrosion results from this uniform treatment relate to corrosion in nonuniformly treated wood.

Table 9—Fasteners tested by Bengelsdorf (1983)

Fastener alloy/coating	Type	Application method	Replicates
S30400 stainless steel	Nail	Hand	1
S31600 stainless steel	Nail	Hand	1
Aluminum	Nail	Hand	1
Bright steel	Nail	Hand	1
Commercial bronze	Nail	Hand	1
Copper	Nail	Hand	1
Double hot-dipped galvanized steel	Nail	Hand	1
Hot-tumbled galvanized steel	Nail	Hand	1
Mechanical tin-cadmium-plated steel	Nail	Hand	2
Mechanical zinc-plated and chromated steel	Nail	Hand	1
Monel (UNS N04400)	Nail	Hand	1
Silicon bronze	Nail	Hand	1
Double-coated bright steel	Nail	Power	1
Electro-galvanized and chromated steel	Nail	Power	1
Galvanized steel	Nail	Power	1
Hot-dipped galvanized steel	Nail	Power	1
Mechanical tin-cadmium-plated steel	Nail	Power	3
Mechanical zinc-plated and chromated steel	Nail	Power	4
S30400 stainless steel	Staple	Power	2
Aluminum (steel core)	Staple	Power	1
Bronze	Staple	Power	1
Electro-galvanized steel	Staple	Power	1
Galvanized steel	Staple	Power	2

Indeed, Bengelsdorf (1983) found that his initial results for corrosion of fasteners in preservative-treated lumber were different than he anticipated; he found that CCA was more corrosive than ACA, which was a misleading result more biased by treating higher absorbent sawdust than representative of many other lab results.

It is unclear how much the damp sawdust methods used by Wright and others (1957), Bartel–Kornacka (1967), and Bengelsdorf (1983) accelerated the corrosion of metals in contact with wood. While the previously mentioned publications acknowledged that the corrosion rate of metals in contact with damp sawdust was accelerated in comparison to metals in contact with wood, there is no physical way to extrapolate this data back to normal, in-service conditions. Moreover, it is nearly impossible to compare results between the three damp sawdust methods because each test was slightly different. For instance, Bartel–Kornacka (1967)

sealed the test vials, reducing the amount of oxygen available for the corrosion reaction and also had an unorthodox method to measure corrosion. Contrastingly, Bengelsdorf (1983) did not cover the dampened sawdust test specimens but increased the temperature to increase the corrosion rate. Similar to the accelerated tests, which increase moisture and humidity, damp sawdust tests are only able to give relative and qualitative results of corrosiveness. However, the current change in preservative treatments requires an accelerated test that can give quantitative results of the corrosion of fasteners in wood.

Salt-Spray Tests

Salt-spray or salt fog tests are a commonly used and standardized method to test metal parts that will be exposed to marine conditions. Richolson (1959), who worked for the U.S. Navy's materials laboratory, was the only published researcher to apply these tests to measure the corrosion of metals in contact with wood. Richolson (1959) ran tests to determine the corrosive effects of five types of wood used in shipbuilding on metal fasteners by placing wood–metal assemblies in a salt-spray chamber that conformed to ASTM (2003a) standard B-117. Richolson (1959) made assemblies with every combination of five woods: white oak (*Quercus abla*), teak, mahogany, bald cypress (*Taxodium distichum*), and Douglas-fir (*Pseudotsuga menziesii*), and five types of 38-mm (1.5-in.) No. 12 screws: bright steel, galvanized steel, brass, chrome-plated brass, and silicon bronze. In addition to these combinations, Richolson (1959) also tested the affect on corrosion of lubricating the screws prior to insertion. Before placement into the salt-spray chamber, the heads of the screws were covered with a wooden block in a similar manner to the work of Wright and others (1957). These wood–metal assemblies were then placed in a salt-spray cabinet that was kept at 35°C ± 1°C (95°F ± 2°F) and 95% ± 2% RH (Fig. 6). After exposure, the corrosion products were cleaned (Table 10) and the weight loss values were measured and reported.

Figure 6—Salt-spray cabinet and specimens of Richolson (1959).

Table 10—Methods of cleaning the corrosion products used by Richolson (1959)

Metals	Solution
Bright steel	3.5% $SbCl_3$ dissolved in 36% HCl
Brass Chrome-plated brass Silcone bronze	5% $(NH_4)_3 C_6H_5O_7$ dissolved in distilled H_2O
Galvanized steel	None, mechanical cleaning only

Richolson (1959) is the only researcher known to the authors to use salt-spray methods to determine the corrosion of metals in contact with wood. These salt-spray methods can be valuable if the wood and metal will be exposed to ocean conditions. However; performance in a salt-spray test cannot be related to the corrosion performance in inland conditions because the addition of the chloride ion can change corrosion mechanisms. In short, care should be taken when evaluating the results of a salt-spray test to accelerate the corrosion of metals in contact with wood, and such tests methods should never be used to evaluate corrosion performance for wood that is not in contact with salt water.

Part 3—Electrochemical Tests

Because corrosion is an electrochemical process, applying an electrical current to the corrosion cell can either accelerate or decelerate the corrosion reaction. Through this acceleration and deceleration, the corrosion rate at a specific condition can be determined. Electrochemical methods are attractive because they allow for rapid testing to be done in situ; that is, they can be run at a temperature and moisture content of interest, in any desired geometry. The goal of electrochemical test methods is to measure the current density at which the corrosion takes place. Current density can then be converted to mass loss or depth of penetration through unit analysis. The corrosion current density, i_{corr}, cannot be measured directly. However, several well-established techniques have been developed to measure the corrosion current density indirectly. Further explanation of the science and theory of electrochemical corrosion testing can be found in the third chapter of Jones (1996).

Simm and Button (1985b) were the first researchers to use electrochemical methods to measure the corrosion of metals in contact with wood by running experiments in European redwood (*Pinus sylvestris*) treated with CCA. The treated wood that was used had been stored for 2 years before it was tested.

Polarization resistance tests were run to measure the corrosion rate for several different metals: mild steel, stainless steel, pure zinc, and an aluminum alloy. In addition, several tests were run on zinc that had been given a chromium (VI)
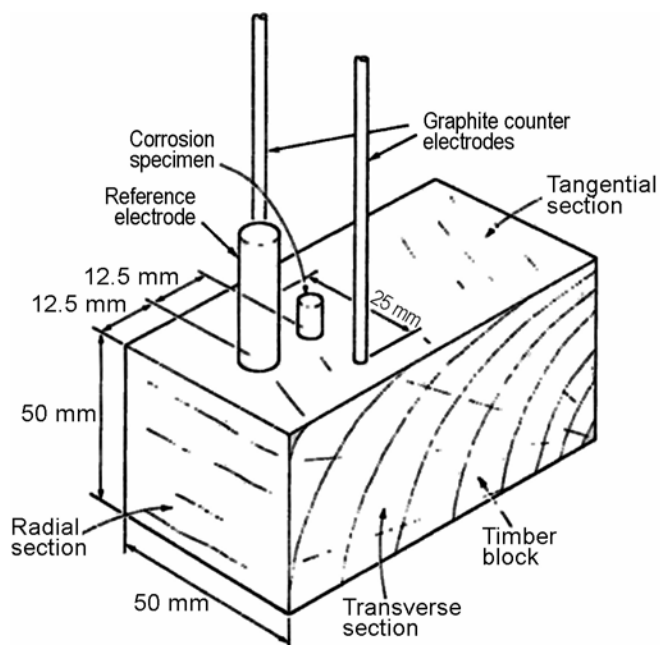

Figure 7—Corrosion cell of Simm and Button (1985b) (Used with permission of Corrosion Prevention & Control).

coating for passivation. Before the polarization test was run, the wood was soaked in a water bath at 20°C ± 2°C (68 ± 4°F) for 2 hours to saturate the wood with water and increase the conductivity of the wood. Holes were drilled into the wood for the electrodes. The counter electrodes were placed 12.5 mm (0.5 in.) away from the working electrode. A visual representation of the corrosion cell used by Simm and Button (1985b) is shown in Figure 7.

Jack and Smedley (1987) ran experiments to determine how the corrosion rate of iron and zinc varied with moisture content and exposure time. They were the first researchers to use another corrosion science technique, electrical impedance spectroscopy (EIS) to analyze corrosion in wood. In EIS, a small alternating current is applied to a test cell similar to those used in direct current corrosion measurements (Fig. 7 and 8). The frequency of the current is changed and the response of the impedance is measured, which can be related to the corrosion rate through an equivalent circuit model whose impedance is the same as the corrosion cell.

Jack and Smedley (1987) ran experiments in untreated and CCA-treated radiata pine (*Pinus radiata*). Three different metals were tested: copper, zinc, and iron. The wood sat for 8 weeks after the preservative treatment was applied to ensure copper fixation. The wood was then ovendried at 100°C (212°F) before being cut into slices for use in a sandwich test cell similar to that of Dennis and others (1995) (Fig. 8). The sandwich cell was then placed in a humidity chamber to achieve the desired moisture content before testing. The range of moisture contents tested varied from
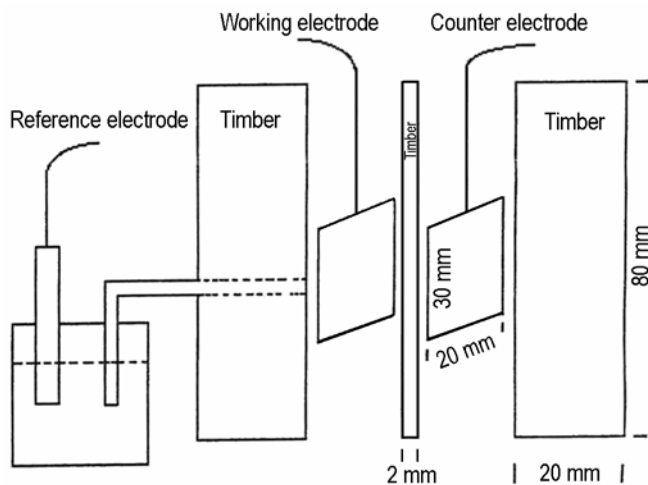
Figure 8—Corrosion cell of Dennis and others (1995) (Used with permission of The Institute of Metal Finishing).

Figure 9—Unique working electrode of Cross (1990) (Used with permission of E & FN Spon).

12% to 28%. Experiments were also run in wood saturated with water.

In addition to running EIS experiments, Jack and Smedley (1987) also used other methods to measure the corrosion in wood including DC steady state, DC polarization, and weight loss methods. Insufficient details were given to comment on the other methods.

Cross (1990) used EIS and direct current methods to investigate the corrosion of metals in contact with CCA-treated wood in roof environments. Experiments were run on two different species of wood, European redwood (*Pinus sylvestris*) and European spruce (*Picea abies*), treated with either the salt or the oxide formulation of CCA. These pieces of wood were exposed to temperatures ranging from 10°C to 35°C (50°F to 95°F) with RH ranging from 87% to 100%. These conditions caused the moisture content of the wood to range between 17% and 26%. In addition to these laboratory conditions, specimens were also placed in four roof spaces in England.

After the wood had reached equilibrium moisture content, metals (mild steel, hot-dipped galvanized steel, zinc electroplated steel, AISI 304 (UNS S30400) stainless steel, and AA 6063 (UNS A96063) aluminum) were inserted into the wood and corrosion measurements were taken using EIS. A unique geometry for the working electrode was developed to simulate nail plates (Fig. 9). The data, which are reported in micrometers per year, can be used to estimate the relative life of the metals because there were no extraneous additions to the wood to accelerate corrosion.

Unfortunately, Cross (1990) is a summary paper; not all of the experimental procedures are given, nor are all of the results listed. However, the data that are contained in Cross (1990) are worth a further review. Even though the
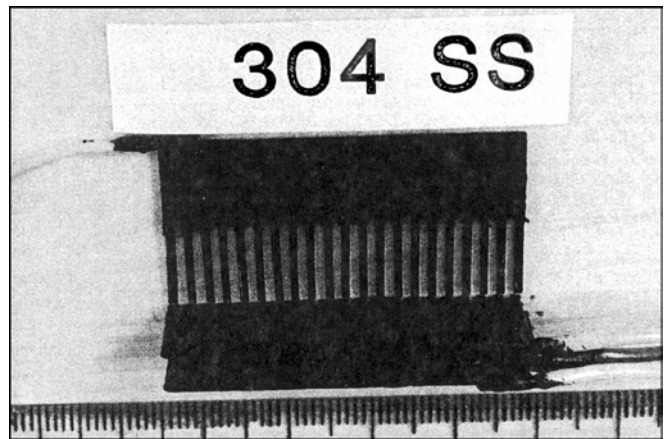
publication is short on experimental details and results, Cross (1990) describes a very clear understanding of the factors that affect the corrosion of metals in contact with wood, and correspondingly, the experiment of Cross (1990) is very well designed.

Dennis and others (1995) ran experiments to test different types of zinc coatings in the presences of preservative-treated wood. Although Dennis and others (1995) wanted to test the corrosive effect of CCA, they were unable to obtain the arsenic compounds, and therefore, they treated the specimens of European redwood with solutions of copper and chrome. This solution should be similar in corrosiveness to CCA because the arsenic does not seem to play a large role in the corrosion of metals in contact with CCA-treated wood (Simm and Button 1985a).

Sixteen types of zinc-coated steel were tested by Dennis and others (1995), as well as mild steel, to determine which coating was superior. Details of the zinc coatings are given in Table 11. The metals were tested by direct current polarization methods, similar to Simm and Button (1985b). However, unlike Simm and Button (1985b), Dennis and others (1995) used a sandwich cell to measure the corrosion of metals in contact with wood (Fig. 8). Dennis and others (1995) were able to successfully measure the change in corrosion rate with moisture content. They noted that the corrosion rate approaches zero in copper-chrome-treated wood when the moisture content nears 15%. However, Dennis and others (1995) used direct current methods, which need to be corrected for the resistance of the solution. Because the resistance of the solution was changing as the moisture content was changing, the corrosion data plotted as a function of moisture content are hard to interpret. Another complication is that direct current methods give incorrect results when the corrosion reaction becomes diffusion controlled. As the moisture content falls below saturation, there is a higher likelihood that the reaction becomes diffusion controlled and the numbers may be misleading.

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Table 11—Zinc coatings tested by Dennis and others (1995) and Short and Dennis (1997)

Type	Coating composition (wt%)	Conversion coating
Galvanized	Zn 100	Chromated (0.05% Cr)
	Zn 100	Chromated (0.2% Cr)
	Zn 92, Fe 8	None
	Zn 43.5, Al 55, Si 1.5	Chromated
	Zn 43.5, Al 55, Si 1.5	None
	Zn 95, Al 5	None
Electroplated	Zn 100	None
	Zn 100	Blue passivated (Cr)
	Zn 100	Full passivated (Cr)
	Zn 99, Co 1	None
	Zn 99, Co 1	Chromated
	Zn 87.5, Ni 12.5	None
	Zn 87.5, Ni 12.5	Chromated
	Zn 99.4, Fe 0.6	None
	Zn 99.4, Fe 0.6	Yellow passivated (Cr)
	Zn 99.4, Fe 0.6	Black passivated (Cr)

Wójtowicz and Piwowarczyk (2002) ran experiments to model the corrosion of galvanized metals in contact with fire-retardant-treated wood. Hot-dipped galvanized, electroplated zinc with a chromium (VI) coating, and electrodeposited zinc with a chromium (III) coating were tested. The thickness of the hot-dipped galvanized coating was 20 μm, (0.0008 in.) and the thickness of the electrodeposited coatings was 12 μm (0.0005 in.). Two types of treatments were used, which were discussed as A and B throughout the paper. Treatment A contained ammonium phosphate, ammonium sulfate, boric acid, and urea. Treatment B contained ammonium phosphate, ammonium sulfate, boric acid, and borax (hydrated sodium borate).

To measure the corrosiveness of these wood fire retardants, Wójtowicz and Piwowarczyk (2002) ran direct current polarization measurements as well as EIS measurements. Unlike other electrochemical experiments, which ran the electrochemical tests in wood, Wójtowicz and Piwowarczyk (2002) ran the experiments in an aqueous preservative in which sawdust was suspended. This test setup did not allow for the direct measurement of the corrosion rate, but the purpose of the experiment was to model the performance of the zinc coatings, not the corrosion rate.

Wójtowicz and Piwowarczyk (2002) found that the electrochemical tests worked very well. They were able to classify and model the passivation of zinc coatings in contact with the fire-retardant treatment and sawdust. They concluded that electrochemical methods are far superior to weight loss methods because the electrochemical methods allow the

researcher to model the behavior and classify surface characteristics of the metal.

Both the direct current polarization and the EIS method have been shown to be a viable option for measuring the instantaneous corrosion rate of metal in treated wood (Simm and Button 1985b, Jack and Smedley 1987, Cross 1990, Dennis and others 1995, Wójtowicz and Piwowarczyk 2002). However, more work is needed to further develop the methods. There needs to be a better understanding of ionic conduction and resistivity of the wood, as well as the corrosion process, before a meaningful EIS model can be fully developed.

For direct current polarization methods, a direct current is applied to the test cell and the current density is measured. Because direct current is used and salt-based wood treatment is made up of ionic components, the direct current will drive the unfixated treatment chemical through the wood and permanently polarize it. Therefore, after direct current is driven through the wood one time, it is no longer possible to derive any useful information from it.

An additional limitation of direct current polarization methods comes from how the corrosion process changes from activation to diffusion controlled in wood materials. A direct current polarization resistance experiment is only valid if the corrosion reaction is activation controlled and the resistance loss caused by the medium can be neglected. At fiber saturation, these assumptions probably hold, but as the moisture content is lowered, these assumptions become more questionable.

In direct current polarization experiments, the resistivity of the wood fiber and multilayer cell wall structure will be important and should be strongly considered when designing the test. In a high resistivity medium like wood, the resistance loss caused by the current having to travel 12.5 mm (0.5 in.), as it did in the experiment of Simm and Button (1985b), could be quite large and dominate the measured resistance, which is inversely proportional to the corrosion current density, i_{corr}. Grain angle also plays an important role because conductivity is greater along the grain than across it; it also differs between the radial and tangential directions (Forest Products Laboratory 1999).

In our opinion, it would be experimentally desirable to run the experiment such that the current flows parallel to the grain because this represents a worst-case scenario and this is how most fasteners are in contact with wood. Most fasteners are inserted perpendicular to the grain so that the diffusion of water and ions to the metal surface will occur parallel to the wood grain.

The EIS models derived from the experiments should be tied to reality. Jack and Smedley (1987) found that the equivalent circuit in Figure 10 fit their data very well. However, the paper does not discuss whether the equivalent circuit had
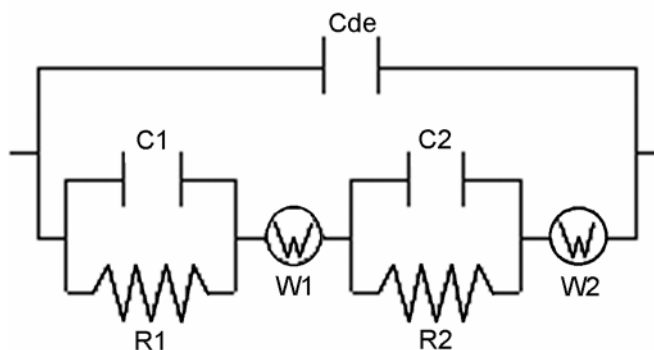
Figure 10—Equivalent circuit model of Jack and Smedley (1987).

any physical significance, nor does it try to explain any of the components. It is unlikely, however, that the equivalent circuit in Figure 10 had any physical significance. Wood is a highly resistive media, and in theory, any model involving wood should have a resistor in series to account for this. Considering that the thickness between the working and counter electrodes in Jack and Smedley's (1987) experiment is 5 mm (0.2 in.), the solution resistance term should be somewhere between 10 Ω and 10^{13} Ω. Also, to calculate the corrosion current density, i_{corr}, it is necessary to know the polarization resistance (R_p). Neither of the resistors in the diagram is labeled R_p, nor do they have the resistances of R_p that were listed in another section of the paper.

In summary, for EIS models to be appropriate and representative, they must be developed with an understanding of the given corrosion process for the given environment and geometric parameters. Thus, while more work is needed to develop EIS-based methods, EIS is recognized as having several advantages. First, the corrosion cell can be made to reflect the in-service treatment environment. Second, EIS applies an alternating current, which eliminates any permanent polarization of the wood electrolyte or the treatment. Third, EIS can be used if the corrosion reaction is diffusion or activation controlled. In wood with moisture content below the fiber saturation point, the corrosion rate is controlled by diffusion and direct current measurements are no longer effective. Finally, it is possible to model the corrosion cell by an equivalent circuit whose impedance is the same as the corrosion cell. Components of this equivalent circuit can then be given physical significance such as the resistance of the wood or the dielectric constant of the wood. The corrosion rate in EIS is found through the polarization resistor component of the equivalent circuit, which is inversely proportional to the corrosion rate. Using the equivalent circuit analysis method, it is possible to correct for the resistance losses caused by the electrolyte, which in this case, is very important because wood conducts electricity poorly. There is a possibility that these models could be used to model the corrosion rate in different environments to predict the relative corrosion life of different fasteners.

Discussion

Exposure tests have the advantage that they give data on how fasteners perform in actual service conditions and the results are directly applicable to a specific application. However, exposure tests take a long time to complete and are very costly to run. A further disadvantage is that exposure tests are not repeatable because the weather and climate are always changing.

Accelerated tests can be repeated at any laboratory and give results much quicker than exposure tests. However, by accelerating the test, it is possible that the mechanism of the corrosion reaction has changed. Even if the same mechanism is still occurring, there are significant voids in our ability to understand the factors involved, and thus, there is no way to develop the model and then relate the results of an accelerated test back to the corrosion rate of service conditions.

Electrochemical methods show great promise in their ability to rapidly evaluate the corrosion of metals in contact with wood. Electrochemical tests have numerous advantages compared with weight loss methods: they can be run in situ, they can be run at any temperature or moisture content, they can be used to measure the corrosion rate directly. Moreover, several tests can be run in the same piece of wood eliminating variance between different replicates of the same species. Additionally, electrochemical tests allow for the construction of an equivalent circuit model that would be able to extrapolate the current database of corrosion data. However, electrochemical tests require expensive equipment and a detailed knowledge of electrochemistry. At this point in time, electrochemical test methods appear to be the best way to measure the corrosion of metals in contact with wood.

The corrosion-related service life of metals in contact with wood is not an easy problem to understand or even estimate. Caution should be taken in interpreting the results from even the most perfectly run corrosion tests. Corrosion is a stochastic process; that is, it depends on the occurrence of random events. While it is possible to classify many of the variables that have an effect on corrosion and it is possible to design tests to avoid these variances, in service, these variables cannot be controlled. For example, splits and checks on the wood surface can lead to an increase in the amount of water and oxygen that reach the fastener, which greatly increases the corrosion rate. Experimenters can avert this variable by making sure that the wood being tested does not split or check during the test. However, any corrosion data from that experiment does not apply once a split or check develops in service.

Conclusions

Although preservative and fire-retardant treatments prolong the life or serviceability of the treated wood, they can also accelerate the corrosion of fasteners. This represents a liability issue that needs to be further studied. This paper reviewed the test methods used by twenty different publications and one standard to determine the corrosion rate of metal in contact with wood. Currently, in our opinion, electrochemical methods appear to be the most promising method to study the uniform corrosion of metals in contact with wood because they can be run in situ, they can be run at all temperatures and moisture contents, and they directly measure the corrosion rate at the condition of interest.

Acknowledgments

Literature Cited

ASTM. 2003a. Standard practice for operating salt spray (fog) apparatus. ASTM B-117-03. West Conshohocken, PA: American Society for Testing and Materials.

ASTM. 2003b. Standard test methods for mechanical fasteners in wood. ASTM D1761-88. West Conshohocken, PA: American Society for Testing and Materials.

ASTM. 2003c. Standard test method for evaluating dowel-bearing strength of wood and wood-base products. ASTM D5764-97. West Conshohocken, PA: American Society for Testing and Materials.

ASTM. 2003d. Standard practice for preparing, cleaning, and evaluating corrosion test specimens. ASTM G-1-03. West Conshohocken, PA: American Society for Testing and Materials.

ASTM. 2003e. Standard practice for numbering metals and alloys. ASTM E527-83. West Conshohocken, PA: American Society for Testing and Materials.

AWPA. 1971a. Trade names of waterborne preservatives and fire-retardant formulations. AWPA M5-71. Bethesda, MD: American Wood-Preservers' Association.

AWPA. 1971b. Standards for fire-retardant formulations. AWPA P10-68. Bethesda, MD: American Wood-Preservers' Association.

AWPA. 2004a. Standard method of determining corrosion of metal in contact with treated wood. AWPA E12-94. Selma, AL: American Wood Preservers' Association.

AWPA. 2004b. Standard for waterborne preservatives. AWPA P5-01. Selma, AL: American Wood Preservers' Association.

Baechler, R.H. 1939. Corrosion of metal fastenings in zinc-chloride treated wood after ten years. In: Proceedings of the annual meeting of the American Wood-Preservers' Association; 1939; Washington, DC. Bethesda, MD: American Wood-Preservers' Association: 35: 56–63.

Baechler, R.H. 1949. Corrosion of metal fastenings in zinc chloride-treated-wood after 20 years. In: Proceedings of the annual meeting of the American Wood-Preservers' Association; 1949; St. Louis, MO. Bethesda, MD: American Wood-Preservers' Association: 45: 381–397.

Bailey, G.; Schofield, M.J. 1984. Corrosion of metal fastenings in CCA-treated timber—the corrosion science assessment. Journal of Institute of Wood Science. 10(1): 14–18.

Baker, A.J. 1978. Corrosion of metal in wood products. In: Durability of building materials and components. Proceedings, First International Conference; 1978 Aug. 21–23; Ottawa, Canada. West Conshohocken, PA: American Society for Testing and Materials.

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: Proceeding 47358; 1987 October 28–30; Memphis, TN. 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.

Baker, A.J.; Gjovick, L.R. 1977. Report on inspection of all weather wood foundations in Virginia and Minnesota. Unpublished rep. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Barnes, H.M.; Nicholas, D.D.; Landers, R.W. 1984. Corrosion of metals in contact with wood treated with water borne preservatives. In: Proceedings of the annual meeting of the American Wood Preservers' Association; 1984; Stevensville, MD. Selma AL: American Wood Preservers' Association: 80: 10–25.

Bartel–Kornacka, E.T. 1967. Corrosion of iron by Ghana timbers. Wood. 32(7): 39–42.

Bengelsdorf, M.F. 1983. Fastener corrosion in waterborne preservative-treated wood. Rep. PT80–1A. Tacoma, WA: American Plywood Association. 17 p.

Bohnhoff, D.R. 2002. Hidden danger. Wood Design Focus. 12(1): 19–25.

BRE Digest. 1985. Corrosion of metals by wood. Building Research Establishment Digest. 301. (September)

Campbell, W.G.; Packman, D.F. 1944. Wood as a causal factor in the corrosion of metals. Wood. 9(5): 99–101.

Cook, D.R. 2003. Making the connection; corrosive effects of new wood preservatives on steel fasteners and connections. Structural Engineer. 5(3): 28–31.

Cross, J.N. 1990. Evaluation of metal fastener performance in CCA treated timber. In: Baker, J.M. (eds.), Durability of building materials and components. London: E & FN Spon.

Davis, R.I.; Allen, P.J. 1993. Corrosive effect of CCA-timber treatment on various metal fasteners. Res. Note. Rep. 45. Queensland, Australia: Department of Primary Industries, Forest Service, 7 p.

Department of Defense. 1984. Lumber and plywood, fire retardant treated. Military Specification MIL-L-19140E. 14 p.

Dennis, J.K.; Zou, C.; Short, N.R. 1995. Corrosion behavior of zinc and zinc alloy coated steel in preservative treated timber. Trans. IMF. 73(3): 96–101.

Doyle, D.V. 1964. Performance of nails and bolts in fire-retardant-treated wood. Unpublished rep. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Duncan, J.R. 1988. Corrosion of metal fasteners in timber. Construction Building Materials. 2(4): 194–200.

Ehlbeck, J. 1979. Nailed joints in wood structures. Rep. 166. Blacksburg, VA: Virginia Polytechnic Institute and State University, Wood Research and Wood Construction Laboratory. 148 p.

Falk, R.H.; Baker, A.J. 1993. Fasteners for exposed wood structures. Wood Design Focus. 4(3): 14–17.

Farmer, R.H. 1962. Corrosion of metals in association with wood. Pt. 2: Corrosion of metals in contact with wood. Wood. 27(11): 443–446.

Farmer, R.H; Porter, R.C. 1962. The corrosion of metals in association with wood. Pt. 3: Corrosion of Aluminum in contact with wood. Wood. 28(12): 505–507.

Forest Products Laboratory. 1999. Wood handbook—Wood as an engineering material. Gen. Tech. Rep. FPL–GTR–113. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 463 p.

Graham, R.D.; Wilson, M.M.; Oteng–Amoako, A. 1976. Wood–metal corrosion. An annotated survey. Res. Bull. 21. Corvallis, OR: Forest Research Laboratory, Oregon State University. 34 p.

Han, M.W.; Chung, D.K. 1986. A study on test for corrosion of iron by wood preservative. Wood Science and Technology. 14(6): 14–19.

Jack, E.J.; Smedley S.I. 1987. Electrochemical study of the corrosion of metals in contact with preservative treated wood. National Association of Corrosion Engineers. 43(5): 266–275.

Jain, J.C.; Kamala, B.S.; Tewari, M.C. 1970. Studies on the effect of preservatives on the nail-holding power of timbers. Indian Forester. 96(3): 251–257.

Jin L.; Preston, A. 2000. Evaluation of the corrosivity of the treated wood—laboratory vs field test methodologies. In: Proceedings, 31st annual meeting of the International Group on Wood Preservation; 2000 May 14–19; Kona, Hawaii.

Johnson, J.W. 1976. Lateral bearing strength of eight fasteners in lumber–plywood joints treated with fire retardants. Res. Paper 28. Corvallis, OR: Oregon State University, Forest Research Laboratory, School of Forestry. 28 p.

Jones, D.A. 1996. Principles and prevention of corrosion, 2nd ed. Saddle River, NJ: Prentice Hall. 572 p.

Kubler, H. 1992. Corrosion of nails in wood construction interfaces. Forest Products Journal. 42(1): 47–49.

Laidlaw, R.A.; Cox, R.N. 1983. The effect of preservatives on the corrosion of galvanized metal plate fasteners in timber. Pt. 1: Effect of joint strength and the significance for trussed rafter roofs. The International Journal of Wood Preservation. 3(2): 51–60.

Marian, J.E.; Wissing, A. 1960. The chemical and mechanical deterioration of wood in contact with iron. Pt. 2. chemical decomposition. Svensk Papperstidning. 63(4): 98–106.

NACE. 2000. Laboratory corrosion testing of materials. NACE TM0169-2000. Houston, TX: National Association of Corrosion Engineers.

Nelson, G.A. 1950. Corrosion data survey. San Francisco CA: Shell Development Co. 15 p.

Richolson, J.M. 1959. Establishment of trend curves for the corrosivity of five common shipbuilding woods to five classes of metal wood screws. Lab Project 5090-3, Pt. 4; Final Rep. NS 032-001. Brooklyn, NY: Material Laboratory, New York Naval Shipyard. 46 p.

Ritter, M.A.; Morrell, J. 1992. Preservation and protection of timber bridges. Chap. 4. In: Timber bridges: design, construction, inspection, and maintenance. Washington, DC: U.S. Department of Agriculture, Forest Service. 944 p.

Rossiter, W.J.; Roberts, W.E.; Streicher, M.A. 1992. Corrosion of metallic fasteners in low-sloped roofs. Materials Performance. 31(2): 62–65.

Ruddick, J.N.R. 1987. Corrosion of metals in contact with preservative treated wood. In: Proceedings, American Wood-Preservers' Association Technical Committee Meeting. September 1987. Selma, AL: American Wood Preservers' Association. 23 p.

Scholten, J.A. 1965. Effect of various preservative treatments on field boxes on nail holding. Res. Paper FPL–42. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 8 p.

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

Simm, D.W.; Button, H.E. 1985a. Corrosion behaviour of certain materials in CCA-treated timber. Environmental tests at 100% relative humidity. Corrosion Prevention & Control. 32(2): 25–35.

Simm, D.W.; Button, H.E. 1985b. Electrochemical measurements on metals in CCA-treated wood. Corrosion Prevention & Control. 32(4): 67–74, 83.

Smith, C.A. 1982. The corrosion of metals by wood. Anti-Corrosion Methods and Materials. 19(3): 16–17.

Wallin, T. 1971. Corrosion of fasteners in treated wood. Sixth Scandinavian Corrosion Congress; 1949; Gothenburg, Sweden. 13 p.

Wójtowicz, M.; Piwowarczyk, W. 2002. Using of electro-chemical methods to the determination of activity of the protective agents of timber on the galvanized connector of the timber structures. Ochrona Przed Korozja. 12: 328–331.

Wright, T.E.; Goddard, H.P.; Jenks, I.H. 1957. The performance of Alcan 65S-T6 aluminum alloy embedded in certain woods under marine conditions. Corrosion-National Association of Corrosion Engineers. 13(4): 77–83.

WTCA. 2004. TPI/WTCA interim guidelines for use of alternative preservative treatments with metal connector plates. Wood Truss Council of America. Staff. Structural Building Components. 34–35 (March).

Zollo, R.F.; Heyer, E.F. 1982. Rx-treated lumber & metal + corrosion ailments. Civil Engineering—American Society of Civil Engineers. (8): 56–57.