Corrosion Rates of Fasteners in Treated Wood Exposed to 100% Relative Humidity

Samuel L. Zelinka, S.M.ASCE[1]; and Douglas R. Rammer, P.E., M.ASCE[2]

Abstract: In the past, gravimetric corrosion data for fasteners exposed to treated wood has been reported as a percent weight loss. Although percent weight loss is a valid measure of corrosion for comparing identical fasteners, it can distort the corrosion performance of fasteners with different geometries and densities. This report reevaluates a key report on the corrosiveness of wood treated with chromated copper arsenate (CCA) and ammoniacal copper arsenate (ACA) and converts the previous data into corrosion rates. In addition, similar experiments were run in wood treated with alkaline copper quaternary (ACQ). Comparison of the corrosion rates reveals ACQ treated wood is more corrosive than CCA treated wood for every metal. The corrosion rate of aluminum was found to be lower than both hot-dip galvanized steel and electroplated galvanized steel in ACQ, ACA, and CCA treated wood. In ACA and ACQ treated wood, the electroplated galvanized fastener had a lower corrosion rate than the hot-dip galvanized fastener.

DOI: 10.1061/(ASCE)0899-1561(2009)21:12(758)

CE Database subject headings: Corrosion; Wood; Wood preservatives; Fastening.

Introduction

With the voluntary withdrawal of chromated copper arsenate (CCA) for residential construction, questions have been raised about the durability of metallic fasteners in wood treated with alternative preservatives, such as alkaline copper quaternary (ACQ) and copper azole (CuAz). There is very little peer-reviewed research on the effect of these alkaline preservatives on the corrosion rate, although Simpson Strong Tie has published a technical bulletin indicating that both ACQ and CuAz are roughly twice as corrosive as CCA (Simpson Strong Tie 2008). It is believed that ACQ and CuAz are more corrosive than CCA due to the higher percentage of copper in these preservatives, and removal of chromium and arsenic; both known as corrosion inhibitors (Pourbaix 1973).

Quantifying the difference in corrosiveness between different wood preservatives has proven difficult. The only standard to address the corrosiveness of treated wood, American Wood Preservers' Association (AWPA) Standard E-12, accelerates corrosion by placing a metal coupon between two pieces of preservative treated wood in an extreme environment (AWPA 2007a). While this test gives rapid results, it is unclear how the measured corrosion rate relates to performance at ambient temperatures and environments encountered in service (Zelinka and Rammer 2005).

The 27°C, 100% relative humidity condition has been used by several researchers to evaluate the corrosion of metals in treated wood in the past (Baker 1992; Simm and Button 1985). Furthermore, Baker (1992) has shown that the percent weight loss of hot-dip galvanized fasteners in CCA treated wood varies linearly with time, for exposure times between 1 and 14 years in this environment, which implies a constant corrosion rate.

Although several corrosion studies have been run in CCA treated wood by different researchers, it has been impossible to compare data across studies because the researchers only reported percent weight loss, instead of a corrosion rate. This was most likely done because the surface area of the fasteners is difficult to determine and is necessary in a corrosion rate calculation. Examining corrosion in terms of percent weight loss distorts the actual corrosion performance, by penalizing smaller fasteners with higher densities. Because previous corrosion data did not report surface areas (Baker 1992; Simm and Button 1985) no comparison could be made between corrosion studies.

Recently, we have written an algorithm to calculate the surface area of fasteners from a photograph (Rammer and Zelinka 2008). For unthreaded (cylindrically symmetric) fasteners, the algorithm uses edge detection software to measure the diameter of the fastener at many points along the fastener body, which it then uses to calculate the circumference and the surface area. Full details of the algorithm can be found in Rammer and Zelinka (2008) and "Optical method for measuring the surface area of a threaded fastener," *Experimental Techniques* (unpublished).

Using this surface area algorithm, the writers were able to use photographs taken by Baker (1992) to calculate surface areas of the fasteners used in that study. Coupled with Baker's laboratory notebook, which contained the initial and final masses of the fasteners, the writers were able to calculate corrosion rates for fasteners in CCA and ACA (ammoniacal copper arsenate) treated wood. Tabulated alloy densities (Jones 1996) were used in the corrosion rate calculation [Eq. (1)]. To examine the effects of new wood preservatives, exposure tests were conducted on fasteners embedded in ACQ treated wood at the same conditions used in Baker's (1992) experiment (27°C, 100% relative humidity).

[1]Materials Engineer, USDA Forest Service, Forest Products Laboratory, 1 Gifford Pinchot Dr., Madison, WI 53726 (corresponding author). E-mail: szelinka@fs.fed.us

[2]Research General Engineer, USDA Forest Service, Forest Products Laboratory, 1 Gifford Pinchot Dr., Madison, WI 53726. E-mail: drammer@fs.fed.us

Note. This manuscript was submitted on May 1, 2007; approved on June 12, 2009; published online on November 13, 2009. Discussion period open until May 1, 2010; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Materials in Civil Engineering***, Vol. 21, No. 12, December 1, 2009. ©ASCE, ISSN 0899-1561/2009/12-758–763/$25.00.

Table 1. Retention and Composition of the Wood Preservatives Compared in This Study

	Retention ($kg\ m^{-3}$)	Copper as CuO (%)	Chromium as CrO_3 (%)	Arsenic as As_2O_5 (%)	DDAC[a] (%)
ACQ	2.4[b]	67	—	—	33
CCA-I	2.9[c]	18	65	16	—
CCA-II	2.9[c]	20	35	45	—
ACA	2.9[c]	50	—	50	—

[a]Didecyldimethyl ammonium chloride.

[b]Measured retention.

[c]Specified retention.

Experimental Setup

Lumber

Select structural grade Southern pine boards, nominally 50×100 mm treated with ACQ were purchased from a commercial supplier. The ACQ treated lumber was intended for use above ground according to AWPA use category UC3-B (2007c) and had a specified nominal retention of 4 $kg\ m^{-3}$. The exact type and formulation of the ACQ was not specified on the commercially purchased lumber. The copper retention was assayed using an inductively coupled plasma mass spectrometer (ICP) from several locations on all boards tested. From the copper concentrations, the actual retention of the lumber (standard error) was determined to be 2.44 $kg\ m^{-3}$ (0.03), lower than the specified nominal retention. The compositions of the wood preservatives compared in this paper are given in Table 1 (AWPA 2007b). Before the test began, the wood was equilibrated in a room at 27°C, 90% relative humidity.

Fasteners

Five different types of fasteners were tested: an 8d carbon steel nail (diameter of 3.3 mm, length of 63.5 mm), an 8d hot-dip galvanized common nail (diameter of 3.0 mm, length of 63.5 mm), a 4d aluminum alloy nail (unified numbering system alloy A5056, diameter of 2.5 mm, length of 38.1 mm), a 64 mm electroplated galvanized screw, and a 64-mm stainless steel screw. The aluminum alloy fastener was the same alloy (UNS A5056) that was tested in Baker's (1992) study. The coating thickness of the electroplated galvanized screw was 8 μm and the thickness of the hot-dip galvanized fastener was 66 μm. The compositions of the different galvanized coatings are listed in Table 2.

Preexposure Procedure

Prior to insertion into the wood, the fasteners were cleaned, degreased, and weighed. The fasteners were then allowed to dry, weighed to the nearest 0.0001 g, and driven on the 50 mm face of the wood into predrilled holes with a diameter of 2.26 mm. The predrilled hole corresponds to approximately 90% of the diameter of the smallest fastener and was used to prevent wood splitting and ensure uniform contact between the nail surface and the wood. The predrilling should give a conservative estimate of the corrosion rate as splits would allow rapid moisture movement to the fastener. The fasteners were each driven into their own piece of wood, nominally $50 \times 100 \times 100$ mm to prevent cross contamination between fasteners, and ensure that each fastener was equidistant from the edge of the wood.

Table 2. Composition of Coatings of the Two Types of Galvanized Fasteners Exposed to ACQ Treated Wood

	Hot-dip (wt%)	Electroplated (wt%)
Aluminum	0.0030	0.370
Bismuth	0.0009	—
Boron	—	0.015
Calcium	—	0.031
Chromium	—	0.074
Copper	—	0.016
Iron	0.1400	—
Magnesium	0.0010	0.008
Manganese	0.0020	—
Silicon	0.0140	—
Zinc	99.8000	99.300

To see if shorter exposure times could accurately predict the corrosion rate, corrosion tests were run for times of 4, 8, 12, 24, 36, and 48 weeks. Three replicates were run for each metal and time period.

Postexposure Procedure

The fasteners were removed in such a way to minimize the damage to the fastener. Initially, two grooves were cut in the wood surrounding the fastener with a band-saw. The wood was then placed in a vise. As pressure was applied, the wood split along the sawn grooves and the fastener was removed without damaging the corrosion products.

Because the cleaning methods can affect the measured corrosion rate, several small experiments were carried out to measure the effect of different cleaning methods on the measured corrosion rate for these specific fasteners. ASTM standard G1-03 (2007) as a guideline, different solvents were tested for various times, with and without ultrasonic agitation, on corroded and uncorroded fasteners. In addition, ASTM G1-03 gives a second methodology where the corroded specimen undergoes many cleaning "cycles" and the weight loss is given by the change in the slope of mass loss plotted as a function of cycles. This methodology was also tested for its effectiveness on fasteners, but it was not used because it was labor intensive and chemicals were found that were relatively benign to the base metal.

The cleaning methods that were decided upon are summarized in Table 3. The weight loss due to cleaning (m_c) was calculated by using the same cleaning process on uncorroded fasteners. These methods were found to be the most effective at removing corrosion products, while also leaving the base metal in good condition.

Results

The corrosion rate, R, is calculated from the familiar equation

$$R = K\frac{m_i - m_f + m_c}{A\rho(t_f - t_i)} \tag{1}$$

where m_i and m_f=initial and final masses (g); t_i and t_f=initial and final times (h); A=surface area (cm^2); ρ=density ($g \times cm^{-3}$) as tabulated in ASTM G1-03; and K=constant (87,600,000 $\mu m\ cm^{-1}\ h\ year^{-1}$). The term m_c (g) was added by the writers to represent the additional loss of base metal that results from re-

Table 3. Cleaning Methods and Corresponding Weight Changes due to Cleaning for the Fasteners Exposed to ACQ Treated Wood

Material	Solution	Cleaning time (minutes)[a]	m_c weight change due to cleaning (mg)
Steel and stainless steel	50:50 mixture of distilled water and Evapo-Rust[b]	60	−1.2
Aluminum	Concentrated nitric acid	5	+0.1
Galvanized (white rust only)	Saturated ammonium acetate	60	−1.6
Galvanized (white and red rust)	(Step 1) Saturated ammonium acetate	60	−1.6
	(Step 2) 50:50 mixture of distilled water and Evapo-Rust	60	−1.2

[a]Cleaning was performed with ultrasonic agitation.
[b]Evapo-Rust, Orison Marketing, Abilene, Tex.

moving the corrosion products. Assuming uniform corrosion and a constant corrosion rate, which was observed by Baker (1992), the corrosion rate should be the same regardless of the exposure time.

The corrosion rates for metals in ACQ are shown in Figs. 1(a–d) as a function of time. Along with the measured corrosion rates, are the mean value (solid line) as well as the mean value at times greater than 24 weeks (dashed line) are shown. Each data

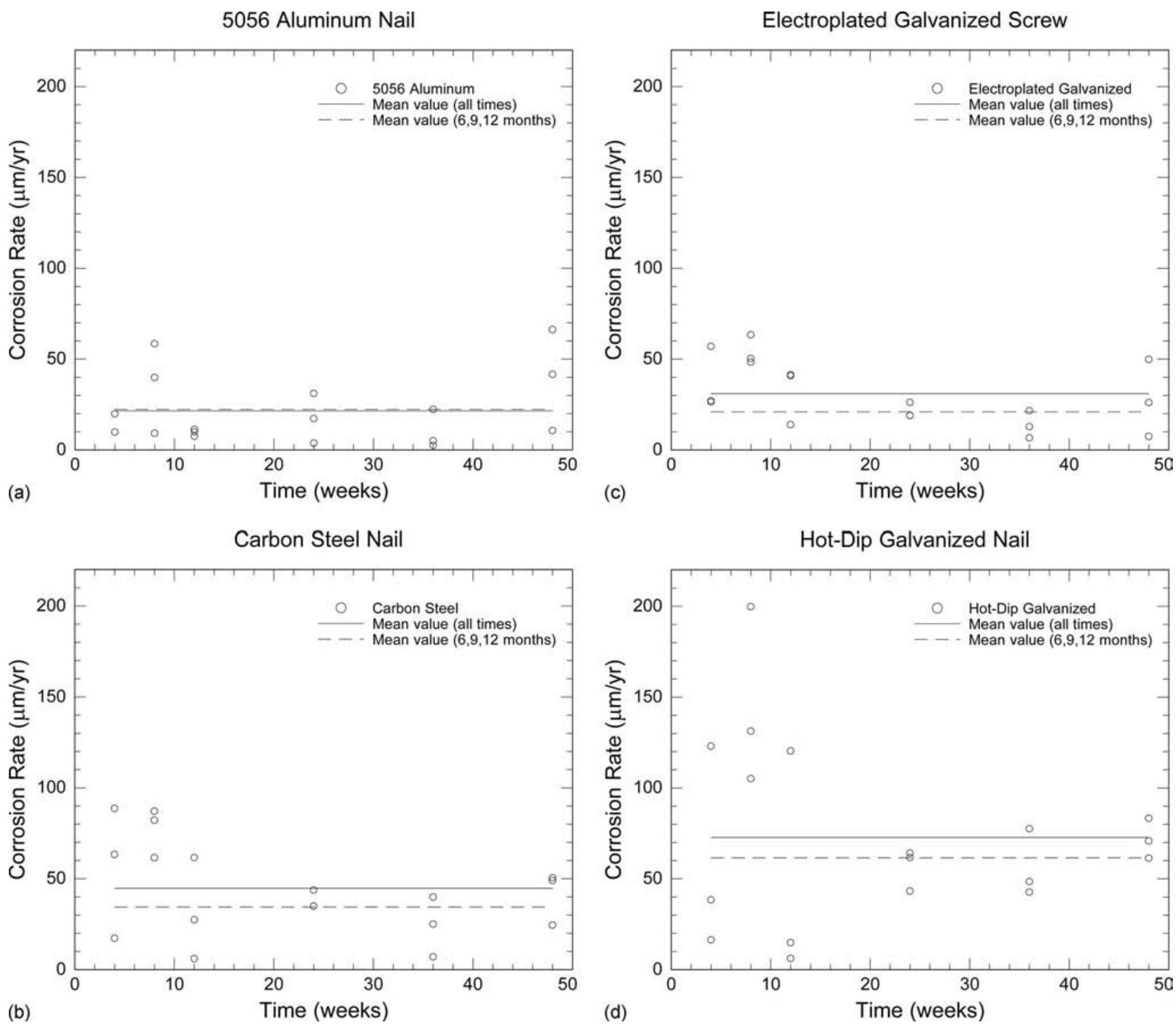

Fig. 1. Corrosion rate (in μm/year) for fasteners exposed to ACQ treated wood for various times: (a) 5056 aluminum nail; (b) carbon steel nail; (c) electroplated galvanized screw; and (d) hot-dip galvanized nail. Solid line represents the mean value over all times, the dashed line represents the mean corrosion rate collected from times after 6 months (48 weeks).

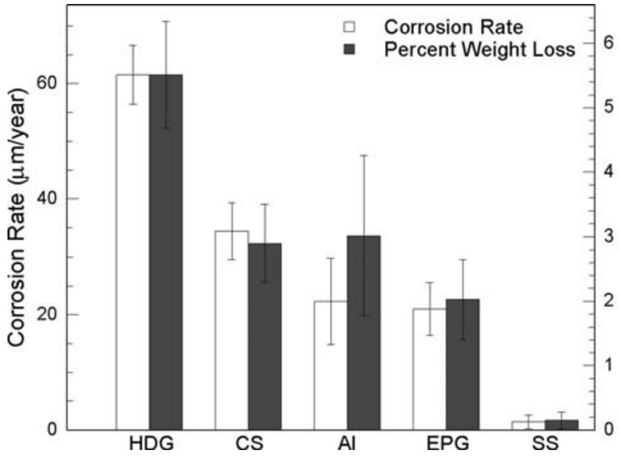

Fig. 2. Results of the corrosion tests conducted in a 27°C, 100% relative humidity environment in ACQ treated wood for a hot-dip galvanized nail (HDG), carbon steel nail (CS), electroplated galvanized screw (EPG), aluminum nail (Al) and a stainless steel nail (SS). The values represent the average of nine replicates, which were exposed from times between 36 and 48 weeks. The error bars represent the uncertainty in the mean.

set is plotted on the same axis so that quick comparisons can be made across fastener types. The data for stainless steel is not plotted because the corrosion rates are much lower, and therefore cannot be seen on these axes. Uniform attack (no pitting) was observed on all fasteners, although red-rust was observed on the electroplated galvanized fasteners. Microscopy was not performed on the corrosion products.

Baker (1992) has shown that the corrosion rate of fasteners in treated wood is constant for times between 1 and 14 years. However, the data for ACQ treated wood at times of 4, 8, and 12 weeks visually seem, on average, to have a higher corrosion rate than those collected at 24, 36, and 48 weeks. These higher corrosion rates at early times may indicate that a steady state has not yet been reached in the corrosion reaction, physically corresponding to the formation of protective corrosion product. Because only three data were taken at each time period, it is also impossible to reject the null hypothesis that there is no variation in corrosion rate with time. For the remainder of the report, the "average corrosion rate" for any metal in ACQ treated wood, is taken as the average of the data collected at 24, 36, and 48 weeks. If the difference is indeed caused by a higher initial corrosion rate, this chosen average gives the most accurate representation of the corrosion rate. If on the other hand, this difference is caused by observing a small sample size, this average will give a lower bound on the corrosion rate; that is, the measured corrosion in another experiment should be greater than or equal to the reported corrosion rate (within experimental error).

Given this method for averaging the corrosion rates, we can now more clearly compare the corrosion rates among different fastener types. Fig. 2 presents the average corrosion rate and percent weight loss for all metals tested in ACQ treated wood along with the uncertainty in the mean (the standard error). Fig. 2 illustrates how percent weight loss magnifies the apparent corrosion of smaller fasteners, in this case the 4d aluminum nail.

At first glance, there are two unexpected features. The first, that the electroplated galvanized fastener out performed the hot-dip galvanized fastener, is surprising because both Wallin (1971) and Baker (1992) recommend the use of hot-dip galvanized fasteners over electroplated galvanized fasteners, the former stating that the electroplated galvanized coatings are too thin to be effective. The second unexpected feature is the aluminum fastener performed relatively well, better than both the hot dip galvanized fastener and the common steel nail. This is surprising because Baker (1992,1980) concluded that aluminum does "not appear suitable for use in moist ACA- and CCA-treated wood where long service life is required."

Table 4. Data of Baker (1992) Presented as Corrosion Rates

	Corrosion rate[a] (COV[b])		
	CCA I	CCA II	ACA
Monel	<1	<1	<1
316 stainless steel[c]	<1	<1	<1
304 stainless steel[c]	<1	<1	<1
ETP copper[c]	<1	<1	<1
Hot-dip galvanized steel[c]	9 (17%)	6 (23%)	44 (63%)
Mechanically coated zinc on steel[d]	17 (37%)	18 (49%)	43 (13%)
Electroplated zinc on steel[d]	16 (106%)	11 (43%)	36 (69%)
5056 aluminum[d]	3 (52%)	4 (130%)	8 (90%)

[a]Corrosion rate in µm/year.

[b]COV-coefficient of variation (standard deviation)/mean.

[c]Based upon measurements at 1, 3, and 14 years.

[d]Based upon measurements at 1 and 3 years only.

Upon closer evaluation, these results are indeed consistent with the previous literature. Baker's statement on aluminum fasteners was most likely based on his observations that the aluminum fasteners were susceptible to pitting corrosion. In fact, if we look at Baker's (1992) weight loss data for fasteners exposed to CCA and ACA treated wood in an 27°C, 100% relative humidity environment, we'd find that the aluminum fasteners always had a lower percent weight loss than any of the galvanized fasteners-exactly what was found in this study. Furthermore, Baker found that in ACA treated wood, the percent weight loss of hot-dip galvanized fasteners was equal to or greater than the percent weight loss of electroplated galvanized fasteners. The differences between different types of galvanizing are most easily quantified in terms of corrosion rates.

Table 4 gives the calculated corrosion rates from Baker's (1992) 14-year corrosion study for fasteners exposed to a 27°C, 100% relative humidity environment. Corrosion rates for mechanically coated zinc on steel, electroplated zinc on steel, and 5,056 aluminum are based on the average of weight loss measurements at taken at 1 and 3 years, the rest of the entries are based on the average of measurements taken at 1, 3, and 14 years. Silicon bronze, cadmium coated steel, and tin cadmium coated steel are excluded from this table because these fasteners were not photographed with the others and therefore surface areas could not be calculated. Included with the corrosion rate is the coefficient of variation (COV) the standard deviation in the corrosion rate divided by the mean corrosion rate.

Discussion

Results of two separate experiments by two different researchers on the corrosion of metals in wood treated with four different preservatives has been presented. In all cases, the corrosion rate of aluminum was found to be lower than galvanized steel, although Baker (1980) observed pitting corrosion for aluminum fasteners exposed to ACA and CCA treated wood after 1–3 years

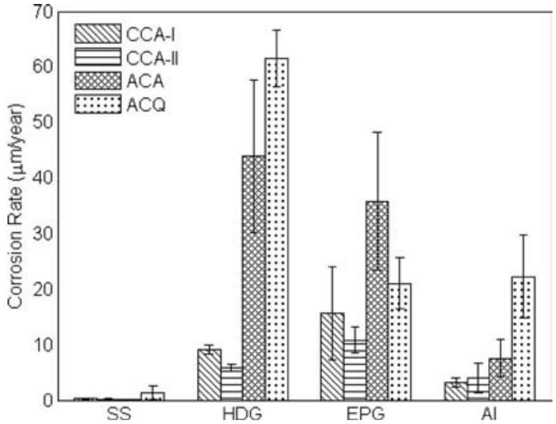

Fig. 3. Corrosion rates of metals exposed to treated wood. The error bars represent the uncertainty in the mean.

of exposure. This pitting corrosion was not observed for aluminum fasteners embedded in ACQ treated wood for 1 year. For fasteners exposed to ACQ treated wood, the corrosion rate appears higher in the first three months. Electroplated galvanized fasteners show lower corrosion rates in wood treated with ACA and ACQ vis-à-vis hot-dip galvanized fasteners, but the converse is true in wood treated with CCA (both I and II).

Fig. 3 shows the corrosion rates of the metals tested in both experiments and the error bars represent the uncertainty in the mean (the standard error). For all metals, ACQ is more corrosive than either CCA I or II. For hot-dip galvanized fasteners, ACQ is more than six times more corrosive than CCA I and more than 10 times more corrosive than CCA II. For aluminum fasteners, ACQ is more than seven times more corrosive than CCA I and more than five times more corrosive than CCA II.

Unfortunately, all of the data in Fig. 3 come from small sample sizes, with high variances. As stated earlier, the ACQ data are based on nine measurements, and the data on CCA and ACA is based on at most 10 measurements, and in some cases, as few as five because in many cases Baker (1992) was forced to cull specimens because they broke upon removal, making accurate gravimetric measurements impossible. The writers have shown that inherent uncertainties in the corrosion rate measurement due to this technique in a 27°C, 100% relative humidity are negligible for exposure times longer than 6 months (Zelinka 2007). Furthermore, the (somewhat limited) data seem to indicate that the corrosion rate reaches a steady state around this time. It would seem then, from this information, that effective corrosion rate tests could be run in times less than one year. Because the relative cost of running a 1-year (or less) exposure test is much less than that of a 14-year test, the savings from running a test shorter in duration could be put into running more replicates of each fastener type so that a meaningful confidence interval of the corrosion rate could be generated.

For ACA and ACQ, electroplated galvanized fasteners exhibited a lower corrosion rate than hot-dip galvanized fasteners. This contradicts the current paradigm on fastener use in treated wood. It should be noted however, that there is not one single type of hot-dip galvanized fastener, nor is there one single type of electroplated fastener. Each manufacturer may have a different process, with different alloying elements, or conversion coatings. For instance, in the case of the galvanized fasteners exposed to ACQ treated wood, there was a large difference in the coating compositions. It is likely that the coating composition may be just as important as the method used to apply the galvanized coating.

In all cases, aluminum fasteners had a lower corrosion rate than either type of galvanizing. Baker (1992) reported pitting corrosion on the fasteners exposed to CCA and ACA treated wood, and no pitting corrosion was observed in fasteners exposed to ACQ treated wood. However, the fasteners exposed to ACQ treated wood were exposed for a shorter amount of time than the fasteners in CCA or ACA treated wood. While pits may have nucleated in this experiment, they may not have grown large enough to be seen in the post exposure visual examination. An accelerated test may be effective in determining whether aluminum fasteners experience pitting corrosion in ACQ treated wood.

Conclusions

Fasteners were embedded in ACQ treated wood at a 27°C, 100% relative humidity environment to simulate Baker's studies of CCA and ACA treated wood. Uniform corrosion was observed on all fasteners, and the corrosion rate was calculated. Corrosion rates measured at times less than 24 weeks seem to have a higher corrosion rate than corrosion rates measured at times greater than 24 weeks.

The data from Baker's study was converted from percent mass loss, which can distort the relative performance between different geometries and densities of fasteners, to a corrosion rate using an algorithm written by the writers. This CCA corrosion rate data can be used as a benchmark to compare current and future wood preservatives.

In this study, 1 year exposure data in ACQ treated wood was compared against Baker's CCA benchmark data. Comparison of the corrosion rates revealed that in all cases, ACQ was more corrosive than CCA. It also revealed that in ACQ and ACA, electroplated galvanized fasteners had a lower corrosion rate hot-dip galvanized fasteners.

This comparison between preservatives was based on the assumption of a constant corrosion rate, which Baker for galvanized fasteners in CCA treated wood. Furthermore, the data reported herein is based on small sample sizes with high variance. In order to get a better statistical comparison, the writers are examining several preservative treatments, including ACQ and CCA, with fasteners from the same manufacturer and batch.

Notation:

The following symbols are used in this paper:

A = surface area of corrosion specimen;
K = unit constant for corrosion rate calculation;
m_c = change in mass of corrosion specimen due to cleaning;
m_f = final mass of corrosion specimen;
m_i = initial mass of corrosion specimen;
R = corrosion rate;
t_f = final time;
t_i = initial time; and
ρ = mass density of corrosion specimen.

References

American Wood Preservers' Association (AWPA). (2007a). "Standard method of determining corrosion of metal in contact with treated

wood." *AWPA E-12*, Granbury, Tex.
American Wood Preservers' Association (AWPA). (2007b). "Use category system." *AWPA P5-06*, Granbury, Tex.
American Wood Preservers' Association (AWPA). (2007c). "Use category system." *AWPA U1-06*, Granbury, Tex.
ASTM. (2007). "Standard Practice for preparing, cleaning, and evaluating corrosion test specimens." *ASTM G1-03*, West Conshohocken, Pa.
Baker, A. J. (1980). "Corrosion of metal in wood products." *Durability of building materials and components ASTM STP 691*, P. J. Sereda and G. G. Litvan, eds., ASTM, West Conshohocken, Pa., 981–993.
Baker, A. J. (1992). "Corrosion of nails in CCA- and ACA-treated wood in two environments." *For. Prod. J.*, 42(9), 39–41.
Jones, D. A. (1996). *Principles and prevention of corrosion*, 2nd Ed., Prentice-Hall, Upper Saddle River, N.J.
Pourbaix, M. (1973). *Lectures on electrochemical corrosion*, Plenum, New York.
Rammer, D. R., and Zelinka, S. L. (2008). "Determination of the surface area of a threaded fastener." *J. Test. Eval.*, 36(1), 80–88.
Simm, D. W., and Button, H. E. (1985). "Corrosion behaviour of certain materials in CCA-treated timber. Environmental tests at 100% relative humidity." *Corros. Prev. Control*, 32(2), 25–35.
Simpson Strong Tie. (2008). "Corrosion fact sheet." S*impson Strong Tie technical bulletin TPTWOOD08*, ⟨http://www.strongtie.com/ftp/bulletins/T-PTWOOD08.pdf⟩ (May 21, 2008).
Wallin, T. (1971). "Corrosion of fasteners in treated wood." *Proc., 6th Scandinavian Corrosion Congress*, Scandinavian Lead Zinc Association, Stockholm, Sweden.
Zelinka, S. L. (2007). "Uncertainties in corrosion rate measurements of fasteners exposed to treated wood at 100% relative humidity." *J. Test. Eval.*, 35(1), 106–109.
Zelinka, S. L., and Rammer, D. R. (2005). "Review of test method used to determine the corrosion rate of metals in contact with treated wood." *Technical Rep. No. FPL-GTR-156*, U.S. Department of Agriculture, Madison, Wis.