Paper No.
09172

NACE INTERNATIONAL CORROSION 2009 CONFERENCE & EXPO

EVALUATING THE CORROSIVENESS OF SOUTHERN PINE TREATED WITH SEVERAL WOOD PRESERVATIVES USING ELECTROCHEMICAL TECHNIQUES

S.L. Zelinka and D.R. Rammer
USDA Forest Products Laboratory
One Gifford Pinchot Dr.
Madison, WI 53726

D.S. Stone
University of Wisconsin-Madison
1509 University Avenue
Madison, WI 53706

ABSTRACT

Chromated copper arsenate (CCA), the most widely used wood preservative of the past 50 years, has been replaced for most uses with alkaline-copper systems such as alkaline copper quaternary (ACQ), copper azole (CuAz) and micronized copper quaternary (MCQ). Preliminary research using high-temperature, high-humidity environments have shown that some of these wood preservatives are more corrosive than CCA, although it is unclear how the results of these extreme tests correlate to performance at temperatures and humidities seen in-service. Recently, the authors developed an electrochemical method for rapid determination of the corrosion rate for fasteners in water extracts of treated wood. The authors have previously demonstrated good correlation between the electrochemical-extract test and exposure tests of fasteners in ACQ treated Southern pine. This work uses the electrochemical-extract method to examine corrosion of carbon steel and galvanized steel on untreated southern pine, as well as southern pine treated with five different wood preservatives.

Keywords: wood, fastener, polarization resistance, steel, galvanized steel, alkaline copper quaternary (ACQ), chromated copper arsenate (CCA)

INTRODUCTION

Wood preservatives are used to extend the service life of wood by protecting wood against insect attack and decay fungi. Recently, changes in legislation and certification in the United States, the European Union, and Australia have restricted the use of chromated copper arsenate (CCA)[1], which was the most extensively used waterborne wood preservative. Currently, there are several commercially available alternatives to CCA including alkaline

copper quaternary (ACQ), micronized copper quaternary (MCQ), and copper azole (CuAz). Preliminary studies[2,3] have shown that ACQ and CuAz treated wood are more corrosive than CCA treated wood[4].

Although many methods have been used to quantify the corrosion of fasteners in contact with wood, a rapid test method with correlation to in-service performance has not yet been found[5]. Exposure tests of fasteners embedded in treated wood have taken up to twenty years[6]. The standard accelerated method for measuring corrosion in treated wood[7] places wood/metal assemblies in a high temperature, high humidity environment and has been shown not to correlate with in-service performance[8].

The fact that accelerated test methods are not able to predict the corrosion performance of fasteners in treated wood is most likely because the accelerated tests do not address the actual mechanism(s) of corrosion for fasteners embedded in wood which themselves are not well understood. It is believed [9-11] that corrosion of metals in wood is an aqueous process occurring in unbound water within the cellular structure of the wood. This aqueous mechanism is supported by observations that there is a threshold wood moisture content between 15% and 18% below which embedded metals do not corrode[12-16]. It is also believed that the corrosion is influenced by the cupric ions in the wood preservatives. Baker[9] has argued that cupric ions in treated wood will be reduced at the expense of the less noble fasteners. While this theory is plausible, it has not yet been confirmed by failure analysis of fasteners in treated wood.

Despite the lack of knowledge of the mechanism of corrosion for fasteners embedded in wood, the authors have recently had some success with electrochemical testing in water-extracts of the treated wood[17,4]. Specifically, fasteners were machined so that they fit in a standard[18] test flask, covered with a water extract of treated wood, and tested using a polarization resistance method similar to ASTM G59[19]. The results of the polarization resistance tests had good correlation with 1 year exposure tests for metals embedded in solid ACQ treated wood[2] for steel and galvanized steel (Figure 1).

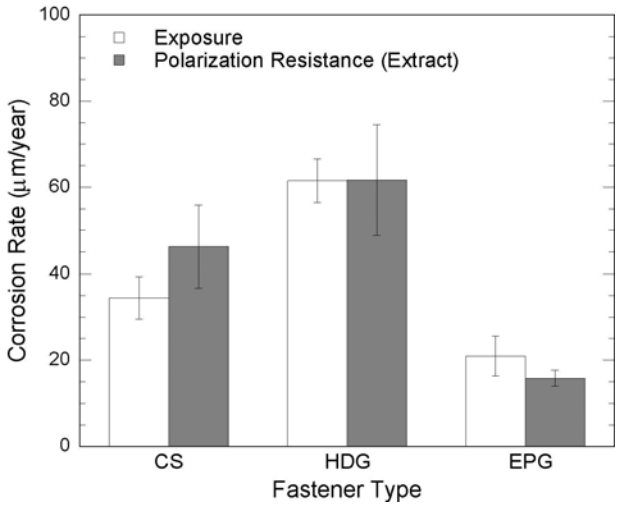

Figure 1: Corrosion rates from exposure tests[2] and electrochemical tests[4] ran in the extract for carbon steel (CS), hot-dip galvanized (HDG) and electroplated galvanized (EPG) fasteners

Because of the good correlation with exposure tests, it was decided to investigate this method further, with the goals of understanding the limitations of the method and whether it could be used as a possible acceptance criteria to screen new fasteners or new wood preservatives. The current paper is part of a larger, systematic exploration of the corrosion behavior of steel and galvanized steel fasteners in treated wood. In addition to the electrochemical results presented in this paper, matched exposure tests are being conducted but are not finished at this time.

MATERIALS AND METHODS

Table 1: Compositions and nominal retentions of the preservatives tested.

Treatment	Nominal Composition[1]	Nominal Retention (kg m^{-3})
Chromated Copper Arsenate (CCA)	47.5% CrO_3 18.5% CuO 34.0% As_2O_5	4
Alkaline Copper Quaternary (ACQ)	66.7% CuO 33.3% DDAC[2]	4
Copper Azole type C (CuAz)	96.8% CuO 1.6% Tebuconazole 1.6% Propiconazole	1
Micronized Copper Quaternary (MCQ)	66.7% CuO 33.3% DDAC	4
Alkyl ammonium Compound (DDAC)	100.0% DDAC	1.3

[1]Nominal compositions from AWPA standard P5[20], with the exception of MCQ, which comes from ICC-ES evaluation report ESR-1980.
[2]DDAC: didecyldimethylammonium carbonate

Southern pine (*Pinus spp.)* boards, nominally 50mm×150mm×2.5m from the same plantation were split into five groups, and treated with four different wood preservative treatments. The fifth group was left untreated as a control. The composition and nominal retention of the treatments is listed in Table 1. A sixth group, southern pine boards treated with CuAz had nominal dimensions of 50mm×100mm×1.2m and their history prior to treatment is unknown. The choice of these treatments was based on their commercial availability as well as their experimental value. Although each treatment is chemically different, there are similarities between several treatments so individual factors can be evaluated to better understand the mechanism of corrosion. For instance, ACQ, MCQ, and DDAC (didecyldimethylammonium carbonate) treated wood contain DDAC, and the difference comes from the amount and chemistry of the copper. MCQ contains nearly insoluble copper and it is likely to have a different corrosion mechanism than ACQ since Baker's theory of galvanic corrosion in wood is based on the reduction of free cupric ions[9]. As well as being a historic baseline, CCA is the only acidic preservative, which allows us to investigate the effects of pH.

The extraction procedure was the same as the one used in previous studies[4]. Sawdust was combined with distilled water in a 1:10 weight ratio for one week at room temperature, after which the sawdust was filtered off using a Büchner funnel. To prevent mold from growing in the extracts, the extracts were stored in a refrigerator kept near 0°C and rapidly brought to laboratory temperature via microwave heating just before testing. The physical properties for each extract are summarized in Table 2. The concentration of copper, chromium, and arsenic were measured with inductively coupled plasma mass spectrometer (ICP). The pH was measured with a double junction glass bulb electrode (Cole Parmer) in conjunction with a 5-star meter (Orion). The conductivity was measured with the same meter and a 2-cell epoxy/platinum electrode (Orion).

Table 2: Physical properties of the extracts.

	Moisture Content (%)[1]	pH	Conductivity (μS cm^{-1})	Copper (mg L^{-1})	Chromium (mg L^{-1})	Arsenic (mg L^{-1})
CCA	11.5	4.9	195	33.4	6.20	9.30
ACQ	10.6	6.6	596	51.0	[2]	[2]
CuAz	8.6	6.5	446	23.9	0.06	0.22
MCQ	11.3	5.1	220	32.5	[3]	0.09
DDAC	11.5	4.6	173	0.2	[3]	0.33
Untreated	10.2	4.5	190	0.3	[2]	[2]

[1]Moisture content of the sawdust before extraction
[2]Not assayed
[3]Assayed, but not detected

Two types of fasteners were tested, a carbon steel fastener, and a hot-dip galvanized fastener. The fasteners came from the same batch; the carbon steel fasteners were removed from the process line prior to galvanizing. The fasteners were nominally 64mm (2.5 in.) in length, commonly referred to as 8d. The fasteners were machined so that they fit into the standard test flask, and the machined surface was covered with a polytetrafluoroethylene gasket. To measure the surface areas, the fasteners were digitally imaged, and the surface areas were calculated by an algorithm developed by the authors[21,22]. Immediately prior to testing, the fasteners were cleaned in a soap solution with ultrasonic agitation for 5 minutes, rinsed with distilled water, placed in distilled water bath with ultrasonic agitation for an additional 5 minutes, rinsed with acetone, and finally rinsed again with distilled water.

The electrochemical testing was performed in a similar manner to ASTM G59[19]. Measurements were taken with a PCI4-300 potentiostat (Gamry). After the fastener was placed in the extract, the open circuit potential (OCP) was measured for 60 minutes, after which, the fastener was polarized from -30mV vs. OCP to +30mV vs. OCP at a scan rate of 0.166 mV/s, with potentiostat's automatic IR-compensation applied. The Tafel slopes and instantaneous corrosion rate for each polarization resistance tests were calculated from the nonlinearities in the data using Mansfeld's method[23,24]. For each extract and fastener type, 10 replicates were run with no purge gas or other perturbation to the solution. Additional tests were run in solutions that had been purged with either nitrogen (5) or compressed air (5) for an hour prior to the beginning of the test. The gas purge continued through the completion of the polarization test.

The data from the tests purged with gas contained a lot of noise in the current density but not the potential (Figure 2). We attributed this to intermittent changes in the area caused by gas bubbles landing on the surface then leaving. This change in surface area was appreciable since the fasteners have a much longer aspect ratio than the sample suggested in the standard[19]. Because of this noise, the Tafel slopes could not be measured on these curves because the nonlinear fitting routine would not converge. To measure the Tafel slopes, the data were smoothed by taking a moving average of the current density (Figure 2). Paired sample equivalence testing[25] showed the smoothing did not significantly (95% confidence) change the polarization resistance within a bias of ±15%.

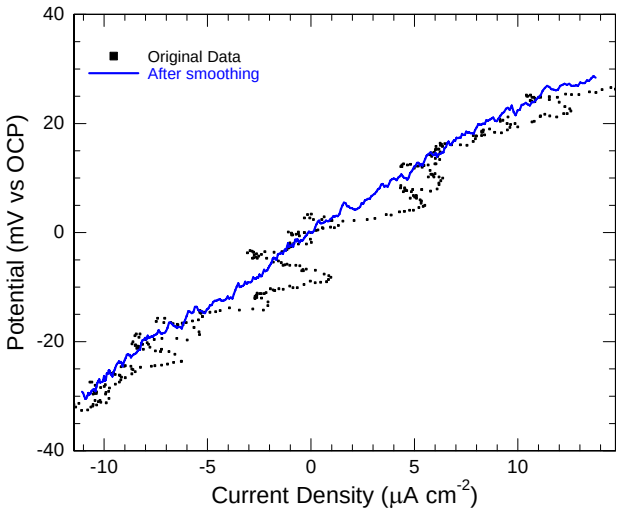

Figure 2: Example of a polarization curve taken during a gas purge. Taking a running average of the x-data resulted in the 'after smoothing' curve. This smoothed curve could then be analyzed to determine Tafel slopes.

RESULTS

The instantaneous corrosion rates in the unpurged extracts calculated from Mansfeld's method[23,24] are given in Figure 3. For all treatments, the corrosion rates of galvanized steel was higher than carbon steel. This was also observed in the original measurements in ACQ treated extract (Figure 1). The MCQ steel data had a negligible corrosion rate. Even though there were no cupric ions in the DDAC treated wood and the untreated wood, the corrosion of fasteners in these solutions was much higher than the other treatments.

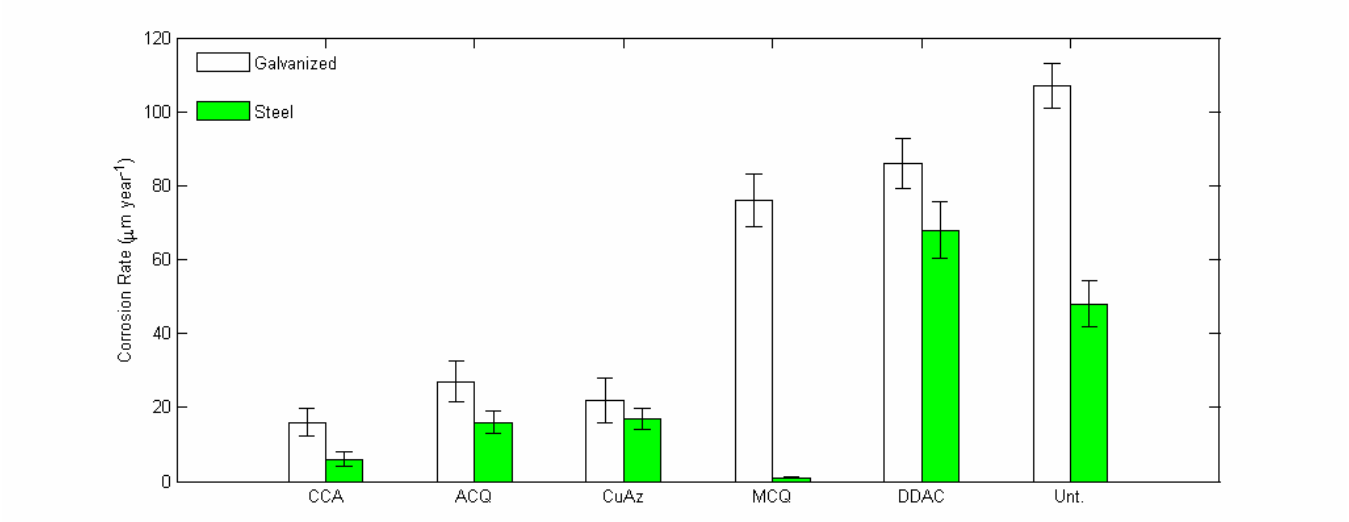

Figure 3: Results of the extract corrosion rate tests (unpurged). The error bars represent the standard error. It is not yet clear how these results correspond to in-service performance.

When the ACQ corrosion rate data from this study is compared with the original measurements, (Figure 1), it is found that the corrosion rates are much lower. While this difference is statistically significant, there are several differences between the current study

and the former one. Namely, the fasteners used in this study are from a different manufacturer. Also, it is possible that the formulation of the DDAC in ACQ has changed during this time[(1)]. Ultimately, the utility of this method will depend more on how the electrochemical data from the current study compares with the exposure data from the matched specimens.

Table 3: Average corrosion rates (µm/year) from polarization resistance measurements in the extract of steel and galvanized steel. The extracts were either not purged (-), purged with nitrogen gas (N_2) or purged with compressed air (Air).

	Steel			Galvanized		
	-	N_2	Air	-	N_2	Air
CCA	6	60	5	16	87	49
ACQ	16	4	5	27	23	76
CuAz	17	8	16	22	22	37
MCQ	1	1	1	76	323	114
DDAC	68	26	432	86	54	269
Unt.	48	19	201	107	49	176

(All rates given in µm/year)

The results obtained from extracts with air and nitrogen purges are summarized in Table 3. It was originally hypothesized that corrosion rates in the unpurged extracts would lie between the rates measured in the nitrogen and air purges. This was found to be true only in the solutions without metal ions (DDAC and untreated). In several cases (CCA-steel, CCA-galvanized, MCQ-galvanized), the corrosion rates were highest in the solutions purged with nitrogen.

DISCUSSION

The most interesting results occurred in MCQ treated wood, where the galvanized fasteners exhibited a high corrosion rate and the steel fasteners exhibited practically no corrosion. It was also intriguing that the corrosion rates in the extracts without cupric ions (DDAC and untreated) were the two most corrosive treatments. On the other hand, the relative performance of CuAz, ACQ, and CCA treated wood is not surprising. Other accelerated test methods[3] have found that CuAz and ACQ are similar in corrosiveness and that they are more corrosive than CCA. Below, we examine the results from the MCQ and CCA solutions with regard to the thermodynamics of possible corrosion reactions and the solution chemistry.

In the MCQ extract, the galvanized fasteners exhibited a relatively high corrosion rate (76 µm/year) while the steel fasteners practically did not corrode (~1 µm/year). This disparity between steel and galvanized is in contrast to all of the other extracts where the corrosion rate of steel ranged between 30-80% of the corrosion rate of the galvanized fasteners. This large difference between corrosion rates of steel and galvanized steel in the MCQ solution suggests that it is not just a difference in kinetics on the metal surface, but possibly a thermodynamic difference.

[(1)] Personal conversation with Stan Lebow (USDA Forest Products Laboratory).

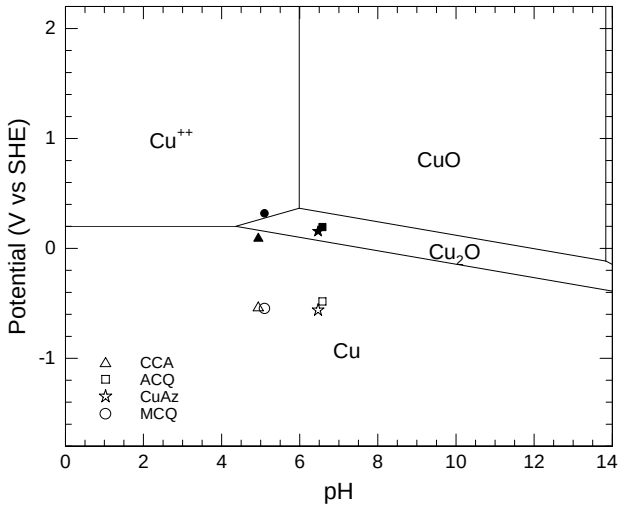

Figure 4: Potential-pH diagram of copper with an assumed ion solution activity of 10^{-4}. The average open-circuit potential data of steel (filled symbols) and galvanized steel (open symbols).

To investigate the thermodynamics, we invoke the potential-pH diagram (Pourbaix diagram) of copper[26] (Figure 4), drawn using an assumed copper ion solution activity of 10^{-4}; the actual copper concentrations are given in Table 2 and are of this order of magnitude. Data for each copper containing solution and metal combination are overlaid using the pH of the extract and the average open circuit potential prior to polarization (60 minutes after immersion). The error bars are excluded in this diagram as they are smaller than the markers on the graph.

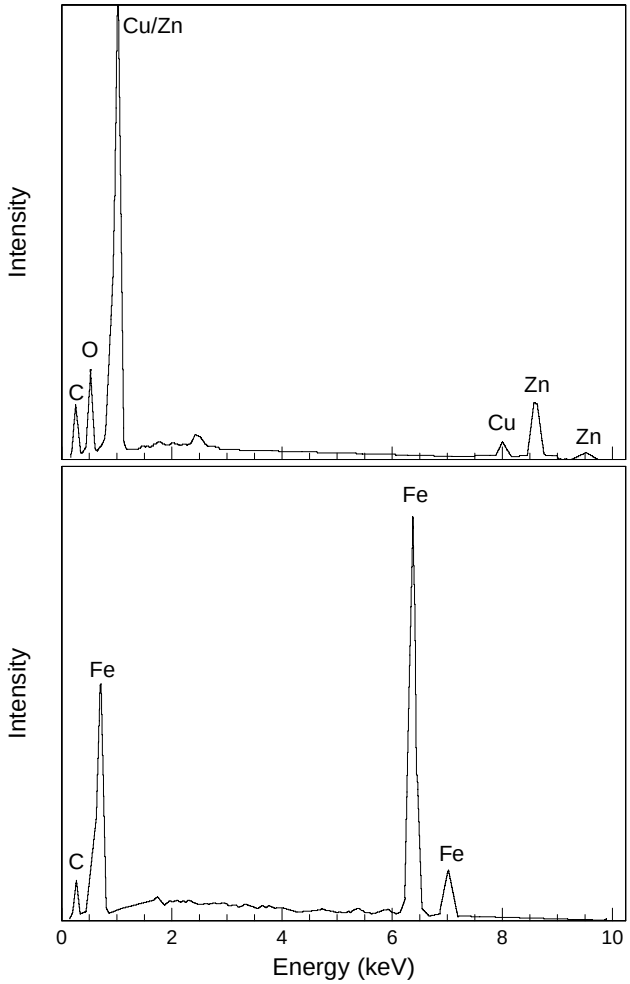

Figure 5: EDX (15 KeV excitation voltage) spectra of a galvanized fastener (top) and a carbon steel fastener (bottom) after a polarization resistance test.

For the MCQ solution, we see that the steel fasteners are in a region where cupric ions are stable, whereas the galvanized fasteners are in a region where copper metal is stable. Combined with the disparity in corrosion rates, the potential-pH diagram suggests two things (1) the reduction of copper is the major cathodic reaction and (2) there must be cupric ions in the extract. The second point is somewhat surprising since MCQ treating solution is supposedly comprised of small particles of nearly-insoluble copper[27,28].

To confirm the predictions of the potential-pH diagram in MCQ treated wood, EDX measurements with a 15 keV excitation voltage were taken on the surfaces of fasteners after they had been polarized Figure 5. The spectra for the galvanized fastener (Figure 5 top) exhibited copper, whereas the spectra for the carbon steel fastener did not (Figure 5 bottom).

Another notable observation from the potential-pH diagram is that the open-circuit potential of the steel fasteners is unusually high when compared to the galvanized fasteners. For example, in previous work[4] in ACQ extracts, the open circuit potential (standard error) for steel fasteners was -0.33 (0.07) V vs. SHE whereas in the current study it was 0.19 (0.02) V vs. SHE. The open circuit potential of the galvanized fasteners was -0.62 (0.01) V vs. SHE in the previous study whereas it was -0.48 (0.01) in the current study. The only difference between these studies was that the fasteners came from different manufacturers, although this should only cause a small difference, and indeed, this did not greatly affect the potential of the galvanized fasteners. While we are unable to explain why the carbon steel fasteners are more noble than expected, it clearly had a large effect on the MCQ data, since this high open circuit potential placed the steel fasteners in a region where cupric ions are stable.

The reason for the relatively high corrosiveness of the DDAC and untreated solutions is more subtle. It is well known that for solid wood, untreated wood is less corrosive than wood treated with waterborne wood preservatives- roughly 6 μm/year for carbon steel[6] compared with over 30 μm/year for ACQ treated wood in similar conditions[2]. However, previous work[17] found that an untreated wood extract was more corrosive than an ACQ treated wood extract. This was attributed to the production of acetic acid from acetyl ions in the sawdust, a mechanism which has been documented in the wood literature[29,30]. In the previous work it was believed that ACQ was less corrosive because the ACQ is alkaline and buffered the acetic acid that was produced during the extraction. While it is true that the untreated and DDAC treated extracts are the most acidic in the current study, and they have the highest corrosion rates, it is unlikely that the pH is the only factor affecting corrosion since two other extracts (CCA and MCQ) had a similar pH and in some cases had much lower corrosion rates.

At first glance, the corrosion data from the CCA and MCQ extracts appears contradictory to the previous hypothesis that the untreated and DDAC treated extracts were more corrosive because they were more acidic. However, in addition to having a pH similar to the untreated and DDAC treated extracts, the CCA and MCQ extracts contain metal ions that appear to influence corrosion. For instance, the CCA extract (pH 4.9) was the least corrosive of all the extracts but the MCQ extract (pH 5.1) was the most corrosive towards the galvanized fasteners. While both the CCA and MCQ extracts contain cupric ions, the CCA extract also contains chromate and arsenate ions, which are both regarded as corrosion inhibitors[26].

For galvanized fasteners, the corrosion rate in the MCQ extract was similar to the corrosion rate in the DDAC extract. Although both extracts are within a half pH unit of each other and have similar corrosion rates, the mechanism of corrosion is different in these extracts. For the MCQ extract, the cathodic reaction is clearly the reduction of cupric ions, as evidenced by the EDX (Figure 5), and there are no cupric ions to reduce in the DDAC extract (Table 1). When the solutions are purged with nitrogen the corrosion rate of fasteners in DDAC extract goes down, whereas in the MCQ extract, the corrosion rates go up. These facts suggest that the cathodic reaction in the DDAC extract is the reduction of dissolved oxygen and/or a reduction of protons, although it is not clear why deaerating the solution accelerates corrosion in the MCQ extract.

In short, there appear to be two types of behavior with respect to corrosion in the extracts. For the extracts containing cupric ions, the reduction of cupric ions appears to be the major cathodic reaction. Based upon the earlier correlation with exposure tests, we hypothesize that this reaction seems to proceed at the same rate in the extract as in solid wood. Future results

from the matched exposure tests will either confirm or alter this hypothesis. It also appears that for extracts that do not contain cupric ions, the mechanism of corrosion in solid wood is different than the corrosion in the extract. More research is needed to understand why extract corrosion rates are similar to solid wood corrosion rates only when the extracts contain cupric ions.

CONCLUSIONS AND FUTURE WORK

This work was part of a larger exploration of the corrosion behavior of metals in wood treated with waterborne wood preservatives. Previously, the extract test method presented in this paper showed good correlation with one year exposure tests in solid wood treated with ACQ for steel and galvanized steel. The data presented in this paper will be compared to matched exposure tests in solid wood. This comparison will lead to a better understanding of the mechanism of corrosion in both the extract and solid wood. Although the present work has focused on the corrosion of metals in contact with wood preservatives, the broader concepts can be applied to corrosion in solutions with both metal ions and organic compounds.

The current work focused on southern pine with different preservative treatments. The disparity between steel and galvanized steel in MCQ treated wood was explained in terms of the potential-pH diagram of copper. The corrosion rate, potential-pH diagram, and EDX data all suggested that the MCQ extract contained cupric ions. It was found that the corrosion of fasteners in untreated and DDAC treated wood was higher than corrosion in preservatives with cupric ions. It is believed that for these treatments, the fasteners corrode more rapidly in the extract than in the solid wood because of the production of acid during extraction. It is possible that for the extracts with similar pH to the untreated and DDAC extracts that the reduction of cupric ions occurs preferentially to the reduction of dissolved oxygen or protons, and this is why the corrosion rates are different.

Several additional experiments are planned involving electrochemical tests run in wood extracts. We are planning on testing different species of wood, with a wide variety of extractives. In addition to small organic acids, corrosion of metals in wood/wood pulp is believed to be influenced by polyphenols[31], although there is disagreement on whether the polyphenols accelerate corrosion[32] or inhibit corrosion[33,34]. The results of these tests will then be compared with tests run in “model extracts” made in the laboratory to have the same total acidity and polyphenolic content as the wood extracts to see if there may be other extractives affecting corrosion.

ACKNOWLEDGEMENTS

This work was funded by the U.S. Forest Service, Forest Products Laboratory (FPL). Jim Gilbertson of FPL assisted greatly with the experimental work, and Dave Eustice, also of FPL, machined the fasteners. Tom Kuster collected the SEM and EDX data. Dan Foster collected the ICP data.

References

1. G. Kear, H.Z. Wú, M.S. Jones, "Corrosion of ferrous- and zinc-based materials in CCA, ACQ, and CuAz timber preservative solutions," Materials and Structures, 41, 2008): pp. 1405-1417.

2. S.L. Zelinka, D.R. Rammer, Corrosion rates of fasteners in treated wood exposed to 100% relative

humidity ASCE Journal of Materials in Civil Engineering, (Submitted for Publication).

3. Simpson Strong Tie, Preservative treated wood, Technical Bulletin T-PTWOOD06, Simpson Strong Tie, 2006, available electronically at http://www.strongtie.com/literature/tech-bulletins.html

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

5. S.L. Zelinka, D.R. Rammer, "Review of test method used to determine the corrosion rate of metals in contact with treated wood. Gen. Tech. Rp. FPL-GTR-156", (Master's thesis, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 2005), 23 pp.

6. R.H. Baechler, "Corrosion of metal fastenings in zinc-chloride treated wood after 20 years.", Proceedings of the Forty-Fifth Annual Meeting of the American Wood Preservers' Association, St. Louis, MO,(Bethesda, MD: American Wood Preservers' Association, 1949), pp. 381-397.

7. AWPA, AWPA E-12: Standard method of determining corrosion of metal in contact with treated wood., <15 Edition> ed, (Granbury, TX: American Wood Preservers' Association, 2007).

8. L. Jin, A. Preston, "Evaluation of the corrosivity of the treated wood. Laboratory vs field test methodologies", Proceedings of the 31st annual meeting of the International Group on Wood Preservation, Kona, Hawaii,(2000),

9. A.J. Baker, "Corrosion of metals in preservative-treated wood", Wood protection techniques and the use of treated wood in construction: Proceedings 47358, Memphis, TN,(Madison, WI: Forest Products Research Society, 1987), pp. 99-101.

10. R.H. Farmer, "Corrosion of metals in association with wood. Part 2. Corrosion of metals in contact with wood.," Wood, 27, 11 (1962): pp. 443-446.

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

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

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

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

15. C.A. Smith, "Corrosion of metals by wood," Anti-Corrosion Methods and Materials, 29, 3 (1982): pp. 16-17.

16. R. Davis, "Timber and metal- the connection", Pacific Timber Engineering Conference, Gold Coast, Australia,(Queensland University of Technology, 1994), pp. 439-448.

17. S.L. Zelinka, D.R. Rammer, D.S. Stone, "Corrosion of metals in contact with treated wood: developing test methods", CORROSION/2008, New Orleans, LA,(Houston, TX: NACE, 2008),

18. ASTM, ASTM G5 Standard reference test method for making potentiostatic and potentiodynamic anodic polarization measurements, <15 Edition> ed, (Wes Conshohocken, PA: American Society for Testing and Materials, 2005).

19. ASTM, ASTM G59: Standard test method for conducting potentiodynamic polarization resistance measurements, <15 Edition> ed, (West Conshohocken, PA: ASTM International, 2005).

20. AWPA, AWPA P5: Standard for waterborne preservatives, <15 Edition> ed, (Granbury, TX: American Wood

Preservers' Association, 2007).

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

22. D.R. Rammer,S.L. Zelinka, "Algorithm to calculate the surface area of a threaded fastener". United States as represented by the Secretary of Agriculture. 2008.

23. F. Mansfeld, "Tafel slopes and corrosion rates from polarization resistance measurements," Corrosion, 29, 10 (1973): pp. 397-402.

24. F. Mansfeld, "Simultaneous determination of instantaneous corrosion rates and Tafel slopes from polarization resistance measurements.," Journal of the Electrochemical Society, 120, 4 (1973): pp. 515-518.

25. S. Feng, Q. Liang, R. Kinser, K. Newland, R. Guilbaud, "Testing equivalence between two laboratories or two methods using paired-sample analysis and interval hypothesis testing," Analytical and Bioanalytical Chemistry, 385, 5 (2006): pp. 975-981.

26. M. Pourbaix. Lectures on Electrochemical Corrosion, (New York, NY: Plenum Press, 1973), 336 pp.

27. H. Matsunaga, M. Kiguchi, P. Evans, "Micro-distribution of metals in wood treated with a non-copper wood preservative. Paper No IRG/WP 07-40360", The 38th Annual Meeting of the International Research Group on Wood Protection, Wyoming,(Stockholm: International Research Group on Wood Protection, 2007),

28. J. Zhang,R.M. Leach, "Micronized wood preservative formulations in organic carriers". 2006.

29. D.F. Packman, "The acidity of wood," Holzforschung, 14, 6 (1960): pp. 178-183.

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

31. H. MacLean, J.A.F. Gardner, "Heartwood extractives in digester corrosion," Pulp and Paper Magazine of Canada, 54, 11 (1953): pp. 125-130.

32. A. Krilov, R. Gref, "Mechanism of sawblade corrosion by polyphenolic compounds," Wood Science and Technology, 20, 4 (1986): pp. 369-375.

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

34. P.M. Singh, A. Anaya, "Effect of wood species on corrosion behavior of carbon steel and stainless steels in black liquors," Corrosion Science, 49, 2007): pp. 497-509.

IN : Corrosion 2009 : NACE international corrosion 2009 conference & expo papers, March 22-26, 2009, Atlanta, Georgia, U.S.A. Houston, TX : NACE International ; [S.l.] : Omnipress (producers), c2009.
1 CD-ROM.