# Review of test methods used to determine the corrosion rate of metals in contact with treated wood

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## Editor's Note

*Some in the post-frame and wood deck industries are beginning to consider whether or not the few corrosion tests related to treated wood currently available through the American Society for Testing and Materials (ASTM) are adequate in accurately predicting corrosion resistance and product longevity. This article sets the stage for that discussion by reviewing tests that have been performed related to corrosion and treated wood.*

*This article is an abbreviated version of a paper published in January 2005 by the same authors. Some figures, tables, and details have been omitted in this version in the interest of space. The original paper was published as General Technical Report number FPL-GTR-156 published by the USDA Forest Products Laboratory with the same title. Readers looking for a more information on the subject should refer to the original article, which is available at www.fpl.fs.fed.us/documnts/fplgtr/fpl_gtr156.pdf.*

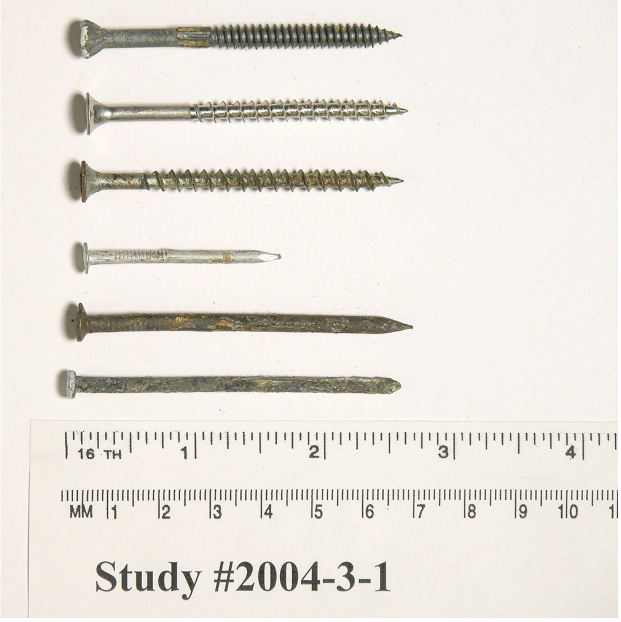
## Introduction

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 [1]. 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 [2].

Historically, creosote, pentachlorophenol (penta), and other oil-based preservatives have been used to treat wood in bridges [3]. Oil-based preservatives have been shown to have little, if any, accelerating affect on the corrosion of fasteners in wood [4].

Waterborne preservatives, such as chromated copper arsenate (CCA) and ammoniacal copper arsenate (ACA) also have been used to treat bridges and other outdoor structures. 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 are what 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.




*Nails and screws in contact with ACQ-D treated wood for six months. The treated wood was put in a conditioning room with 100 percent relative humidity at 80 degrees Fahrenheit. The fasteners are (top to bottom): a proprietary coated fastener, stainless steel, electroplated galvanized, aluminum, plain carbon steel, and hot dipped galvanized.*

Due to the voluntary phase out of CCA, designers are now faced with using alternative preservative treatments. 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 than 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. Unfortunately, there is not a readily available procedure to quantitatively evaluate the change of corrosion rate with this switch of preservative.

The purpose of this literature review is to give an overview of test methods previously used to evaluate the corrosion of metals in contact with wood.

This article 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.

Two tables summarizing the types of wood species and metals tested in each experiment are included in the original article upon which this summary is based (see Web site for more information).

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 [5], is discussed in the moisture content and temperature section in Part 2—Accelerated Exposure Tests, since it uses these factors to accelerate results.

## 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 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.

The defining characteristic of the corrosion rate is the mass loss (from metal to oxide) per unit time. By normalizing mass loss to specimen size, it is possible to compare the corrosion rates of two different sized specimens. Normally, corrosion is measured in units of depth of penetration per unit time. 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 [6]

Because corrosion is an electrochemical process, the mass loss is directly related to a loss of electrons. The electrical current produced from the corrosion reaction, if measured, can be related back to mass loss per unit time through unit analysis.

## Part 1 — 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 environment. 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 the change to new 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

In 1949, R.H. Baechler [7] of the USDA Forest Service, Forest Products Laboratory (FPL), published the results of a 20-year investigation into the corrosion of metal fastenings.

The purpose of the investigation was to determine how zinc-chloride preservative treatments affect the corrosion of metals in contact with treated wood. Baechler 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.

At intervals throughout the 20-year test period, test pieces were removed and the fasteners were measured for corrosion. The fasteners were examined by destroying the wood around the fasteners and removing the corrosion products with a rubber eraser. The difference of the final and initial weights was recorded and the mass loss reported.

Baechler's [7] 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, non-urban, non-industrial environment.

Scholten [8], also of FPL, indirectly measured the corrosion of metals in contact with wood by measuring the nail withdrawal strength of wood exposed outdoors for five years in Madison, Wis. 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. The nail withdrawal test is similar to the methodology of ASTM D 1761–88 [9].

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. It should be noted that the withdrawal values for nails driven into the side and end grain of wood decline with time even if no corrosion takes place [10]. Therefore, it is hard to separate the effects of corrosion and time delay from a simple withdrawal test.

Wallin [11] examined the corrosion of metals in contact with wood. The purpose was to determine the corrosive effect of preservative treatments.

A unique aspect of Wallin's 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 $\mu$m (0.0002 in.). Hot-dipped galvanized fasteners on the other hand have coatings that range between 40 and 80 $\mu$m (0.0016 and 0.0031 in.). Therefore, Wallin expected that the hot-dipped galvanized fasteners would perform better than the electroplated fasteners. Furthermore, Wallin 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, stainless steel, and an aluminum alloy.  The most important result was that hot-dipped galvanized outperformed electrodeposited galvanized in every situation just as Wallin had predicted.

## Underground Exposure

Baker and Gjovick [12] 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. The report focused on galvanized steel fasteners.

The foundations of 16 houses were examined. Nine of the 16 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, dirt around the foundation of the house was removed 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. Baker and Gjovick reported that the moisture content ranged from 10 percent to 30 percent in the foundations and noted that several fasteners, including hot-dipped galvanized fasteners, had red rust.

Baker [13] 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.

Baker [13] tested the sapwood of Southern Pine (Pinus spp.) treated with CCA Type A, CCA Type B, and ACA. Eleven different types of nails were tested. Specimens were buried underground at a test site near Madison, Wis., and replicates were removed at one, three, and 17 years. Upon removal, the fasteners were washed with water and solvent. Baker 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.

## Simulated Natural Exposure Methods

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.

In addition to running outdoor exposure experiments, Baechler [7] also ran 20-year tests in humidity rooms to simulate different environments. Sets of similar specimens were exposed to a constant temperature of 27 degrees Celsius, (80 degrees Fahrenheit) and a constant relative humidity of 30 percent, 60 percent, or 90 percent for 20 years. The 27 degrees Celsius, 90 percent RH represents a severe exposure condition, and the 27 degrees Celsius, 30 percent RH represents a lower bound for corrosion in wood used for construction. Baechler [7] 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 degrees Celsius, 65 percent RH environment.

Johnson [14] ran experiments to determine the mechanical properties of fasteners in contact with wood treated with fire retardants. Johnson ran lateral nail and staple tests in Douglas-fir treated with three different types of commercially available fire retardants. In total, with eight types of fasteners, three treatments, three exposure conditions, two exposure lengths, and four methods to apply the preservative, there were 4,704 different combinations tested. Johnson was the only researcher to determine the corrosion of metals in contact with wood by measuring the lateral bearing strength of the assembly.

Laidlaw and Cox [15] 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 were held together by zinc-coated nail plates. The wood joints were then exposed to one of three conditions — "damp," "natural exposure," or "dry"— for times ranging from one to eight years. Laidlaw and Cox measured the amount of corrosion by running mechanical tests. Static and fatigue tests were run on joints.

The work of Laidlaw and Cox was unique in that it studied the corrosion of joints connected with nail plates. Furthermore, they tested several more conditions that may be encountered by wood–metal joints in service.

Simm and Button [16] classified the corrosiveness of CCA preservative treatments. In their introduction, Simm and Button 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 makes the results harder to interpret.

To test the corrosiveness of CCA, Simm and Button inserted fasteners into blocks of CCA-treated European redwood and placed them in a humidity chamber for 30 months. Four different types of metal fasteners were tested. Simm and Button reported the corrosion as the change in weight.

Simm and Button were the first researchers to apply corrosion science techniques to the corrosion of metals in wood. After the exposure tests, Simm and Button used scanning electron microscopy and X-ray diffraction to analyze the fastener and the wood. By using these new 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 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.

Davis and Allen [17] altered outdoor conditions to obtain a more reproducible corrosion test. The purpose of their experiment was to measure how the corrosiveness of wood treated with CCA varies with time after treatment. The fasteners were driven into preservative-treated wood in intervals after the wood had been treated. The specimens were exposed either six or 12 months. After the exposure, the corrosion product was removed in accordance with ASTM standard G1-81 [18]. Mass loss data were reported.

While the work of Davis and Allen [17] is interesting, it is important to note that their data may be slightly misleading. Although the wood was exposed for either six 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 effects of cure time.

## Part 2—Accelerated Exposure Tests

### Overview

Outdoor and 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. 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.

Wright and others [19] were funded by the Canadian Navy to investigate the corrosion performance of aluminum alloys used in conjunction with woods commonly used in shipbuilding. Aluminum dowels were placed inside holes in a specially machined block of wood. To simulate shipbuilding practice, after the metallic dowel was inserted, wood plugs were placed over the dowel to cover it from the outside environment. After construction, the wood block with metal dowels was placed in a controlled humidity chamber at 49 degrees Celsius (120 degrees Fahrenheit) and 100 percent RH for two, six, or eight months. 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 were very severe and would be expected to highly accelerate the corrosion rate. Interestingly, humidity cabinet corrosion rates reported by Wright and others 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 [12, 20, 21, 22]. Furthermore, the use of aluminum fasteners is not recommended for use with preservative-treated wood.

Doyle [23] investigated the corrosion of nails and bolts in glue-laminated Southern Pine treated with commercial fire preservatives. Doyle measured the change in withdrawal strength of eight-penny nails and the dowel bearing strength was tested on steel bolts. The corrosion process was accelerated by placing the specimens in an environment of 27 degrees Celsius (80 degrees Fahrenheit) and 97 percent RH for intervals of three, six, 12, 24, and 48 weeks. After these intervals, the nail withdrawal strength and the dowel bearing strength of the bolts was measured. Doyle also measured the weight loss of the nails after they had been withdrawn to measure the corrosion rate.

Barnes and others [4] used heat and humidity to accelerate the corrosion of metals in preservative-treated wood. They tested metal coupons sandwiched between blocks of treated wood.

Metal coupons were constructed out of five different metals and held between the wooden blocks by clamping the wood and metal together with twine. After the wood–metal couple was exposed the corrosion products were removed and the corrosion rate was reported in MPY.

Barnes and others is an important paper because it uses a similar methodology to the only standard that addresses nail corrosion. 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 degrees Celsius ± 1 degree (120 degrees Fahrenheit ± 2 degrees) with RH of 90 percent ± 1 percent. The standard specifies a minimum of 240 hours of accelerated exposure. The standard also specifies that the corrosion products are to be cleaned in accordance with [18] and that the corrosion rate should be reported in MPY.

While the sandwich method used by [4] and [5] is currently standardized, the results of the test must be interpreted carefully. It may be 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.

Recently, Jin and Preston [24] compared modified E-12 tests results for nails and screws to field tests in Harrisburg, N.C.

They concluded that laboratory tests procedures might not provide optimal results.

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 have the advantage that they 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 and significant work would be needed to correlate real world performance to lab results.

## Damp Sawdust

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.

In addition to exposing untreated wood–aluminum specimens to high temperature and humidity, [19] 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 sawdust for 30 days at room temperature. After exposure to the damp sawdust, the zinc and aluminum sheets were cleaned and weighed. The corrosion was reported in MPY.

Bengelsdorf [20] ran sawdust corrosion tests for a whole year at 52 degrees Celsius (125 degrees Fahrenheit). Thirty-one different types of both power and hand-driven fasteners were tested. The fasteners were removed from the environment, cleaned, weighed, and reinserted into the sawdust at regular intervals throughout the year. The fasteners were then inserted into the sawdust of Douglas-fir treated to a level 10 percent greater than was required by the standards

It is unclear how much the damp sawdust methods used by [19] and [20] 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 damp sawdust methods because each test was slightly different. 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 [25], 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 ran tests to determine the corrosive of wood used on metal fasteners by placing wood–metal assemblies in a salt spray chamber. Richolson made assemblies with every combination of five woods and five types No. 12 screws. 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 [19]. These wood–metal assemblies were then placed in a salt-spray cabinet. After exposure, the corrosion products were cleaned and the weight loss values were measured and reported.

Richolson is the only published 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.

## Part 3 — Electrochemical Tests

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. Further explanation of the science and theory of electrochemical corrosion testing can be found in the third chapter of [6].

Simm and Button [21] 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. Polarization resistance tests were run to measure the corrosion rate for several different metals. Holes were drilled into the wood for the electrodes. The counter electrode was placed 12.5 mm (0.5 in.) away from the working electrode.

Jack and Smedley [26] 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. 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.

Cross [22] used EIS and direct current methods to investigate the corrosion of metals in contact with CCA-treated wood in roof environments. After the wood had reached equilibrium moisture content, metals were inserted into the wood and corrosion measurements were taken using EIS. 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.

Dennis and others [27] ran experiments to test different types of zinc coatings in the presences of preservative-treated wood. Sixteen types of zinc-coated steel were tested. The metals were tested by direct current polarization methods. Dennis and others 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 percent. However, Dennis and others 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 presented in the paper as a function of moisture content is subject to debate.

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. 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.

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 preservative environment. Second, EIS applies an alternating current, which eliminates any permanent polarization of the wood electrolyte or the preservative. 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 ones 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.

## 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. 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. ■

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