WOOD PRESERVATION AND ITS CORROSIVE EFFECTS ON METAL FASTENERS

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ABSTRACT

Wood is one of the most commonly used building materials, especially in British Columbia. Ironically, our buildings are susceptible to moisture related deterioration for the same climatic reasons that forestry is a major industry in BC: high levels of rain within a relatively small range of temperatures, allowing sustained humidity levels and an inability for any incident moisture to dry out if building envelopes are not carefully designed and built.

Over the past two centuries, there have been numerous advances in wood preservation chemicals, processes, and applications. Wood treatments have been around for over 70 years; however, there are little to no practical guidelines for designers and builders as to how a wide variety of treatments interact with a wide variety of metallic fasteners.

This research paper will include a brief chronology of wood preservation materials, processes and techniques, then focus on the effects of corrosion between the more common wood treatment chemicals (CCA, ACQ, CA) and the most common fastener materials (steel, aluminum, copper, bronze, stainless steel) as well as some of their more common coatings.

This paper uses earlier papers focussing on wood-metal corrosion as a starting point, and subsequent papers that cited the earlier papers were added. Interconnected publications, related articles and relevant papers were further used as additional information in order to fully document and conclude how the evolution of wood preservation has affected the use of embedded metal fasteners in wood frame construction. As a practical summary, the author has tabulated the most common types of wood preservatives and fastener types into a matrix and ranked their suitability of use together

HISTORY OF WOOD PRESERVATION (FREEMAN ET AL. 2003, SCHULTZ ET AL. 2007)

Wood preservation was carried out by the early settlers in the "New World" as far back as the 17th century. Its use expanded significantly during the industrial revolution, especially within the application of railroads, cross ties and switch ties. These heavy timbers needed long term, reliable resistance to biological attack. The earliest related patent, known as "Spirit of Tarr", belonged to Dr. Wm. Crook in 1716. Although zinc chloride was used in 1815, coal-tar creosote was employed in most heavy timber applications during the 18th century. Creosote originated from a patent granted to Franz Moll in 1836 and its process of being

pressure treated was patented by John Bethell two years later. Bethell's patent remains the basis for modern pressure treating methods. In 1847, a similar process was used with zinc chloride, called the Burnett treatment. As the price of oil increased, an empty cell process was patented in 1902 (Ruping Process) and a second empty cell process was patented in 1906 (Lowry Process). Both processes initially compress air inside the wood so that when this air pushes excess preservative out, the preservative only coats the cell walls rather than saturating the cell voids. Creosote is still used today for railroad ties and marine piling.

Other chemical wood preservatives include the following: Copper naphthenate was commercially used in Germany in 1911; pentachlorophenol (oil-based) was patented in Britain in 1928; and Fluor Chrome Arsenate Phenol (FCAP) was used in Germany in the 1930s by diffusing it into green wood.

Chromated Copper Arsenate (CCA) was patented in 1938 and standardized by the AWPA (American Wood Preservation Association) in 1949. Up to 2004, it was the most widely used wood preservative. Three types of chemical formulations were developed using varying ratios of copper, chromium and arsenate (Type A – 1953, Type B – 1964 and Type C - 1969):

Table 1: AWPA Standardized Formulations of CCA.

CCA	**Copper (wt% as CuO)**	**Chromium (wt% as CrO3)**	**Arsenate (wt% as As2O5)**
A	18.1	65.5	16.4
B	19.6	35.3	45.1
C	18.5	47.5	34

The later Type C strikes a balance between the earlier two formulations. Other preservatives with similar active ingredients such as ACA (Ammoniacal Copper Arsenate) and ACZA (Ammoniacal Cooper Zinc Arsenate) were also developed – the latter is still being used primarily for industrial applications.

CCA is relatively inexpensive, highly effective, and poses negligible risk when used for residential and garden construction, outdoor furniture, and playground equipment (Freeman et al. 2003). Regardless of its outstanding performance and environmental record, public perceptions of leached arsenic led to the US Environmental Protection Agency (EPA) announcing eventual phase out of CCA from most residential applications after December 31, 2003. In 2004, the voluntary withdrawal led to a market share loss of 68% and similar changes have occurred in over 26 countries (Freeman et al. 2003). An amendment in the European Union Commission Directive 76/769/EEC stated that arsenic compounds could only be used for industrial applications. The Austrailian Pesticides and Veterinary Medicines authority (APVMA) ceased the use of CCA for timber applications that have human impact in March 2006. However, arsenic is naturally found in soil, and research in *Wood and Fibre Science* (Vol 36, pp 119-128, 2004) shows that soil contamination due to the presence of CCA-treated wood after 45 years was minimal. Subsequent studies have found that CCA does not pose a risk to children as was publicly perceived (Barraj et al. 2007, Lew et al. 2010). In North America, CCA is still used in a wide range of industrial and farm applications such as utility poles, guardrail posts, bridge timbers, and farm fence posts. It is also approved and used for some residential applications such as shingles and shakes, permanent wood foundations and other uses for treated wood.

This controversial withdrawal of CCA, from most residential applications, led to the use of other wood preservatives such as ACQ (Alkaline Copper Quarternary), and CA (Copper Azole) and in the USA, the less widely used CuHDO (Copper bis-N-cyclohexyldiazeniumdioxy) or copper xuligen. Most recently, Micronized Copper Azole (MCA) has been commercialized, first in the USA, then later in Canada.

Pressure treatment with boron compounds such as Sodium Borate (SBX) was introduced in the late 1990s. These are effective as preservatives, versatile in use, less corrosive to metals, and lower in mammalian toxicity than most other preservatives. However, these leach easily and should be limited to uses where they will not be continually exposed to rain.

The science of wood preservation is comprehensive and its potential is abundant given the fact that significant growth has been seen in every decade since Bethell originally impregnated timber with creosote in the 1830s. Promising research for the future includes non-biocidal preservation methods (polymerizing *in situ* – although this does not stop decay), chemically modified wood (acetylating), physically modified wood (heat treating), wood-plastic composites (hybrid of natural wood and plastic fibres) and bringing back the basics by returning to mankind's historical use of naturally durable heartwood (genetically developing plantation-grown trees, which would develop heartwood quicker) that could have durability characteristics similar to wood treated with second or third generation biocides.

GENERAL CORROSION OF METAL FASTENERS IN WOOD

Corrosion of metals in wood can be viewed similarly to a dry cell that generates voltage (e.g. alkaline battery), simply because materials at a higher energy state tend to revert to materials of a lower energy state. The zinc electrode in the dry cell (anode) gives up electrons, making it the negative electrode. During a similar process within a metal fastener (e.g. steel), an excess of electrons occurs at the anode (embedded fastener shank) and a lack of electrons is created at the cathode (fastener head).

Chemical reaction at the anode: $Fe \longrightarrow Fe^{2+} + 2e^-$

Chemical reaction at the cathode: $O_2 + 2H_2O + 4e^- \longrightarrow 4OH^-$

Because of this voltage difference between anode (shank) and cathode (head), electrons flow through the fastener, completing the electrical circuit, and corrosion proceeds. Distances between the anode and cathode can range from extremely small (microscopic) to several feet (Graham et al. 1976). Corrosion in fasteners embedded in wood is generally located in the shank, directly below the fastener head (Simm et al. 1985) – mainly confined to the first centimetre, with the largest amount of corrosion occurring between 1 mm to 5 mm from the wood surface (Zelinka et al. 2011a).

A majority of wood preservatives are copper based. Therefore, the primary cathodic reaction in these preservatives is the reduction of cupric ions. Three year tests of eleven fastener types, embedded in wood treated with copper-containing waterborne salt preservatives, show that metals anodic to copper are more susceptible to corrosion and therefore fastener materials that are cathodic to copper should be chosen (Baker 1980). These results were later confirmed by Baker (1992).

Corrosion of embedded metal fasteners is very different from atmospheric corrosion. The former is much less dependent on atmospheric relative humidity and more dependent on moisture content in the wood. Another difference is that the rate of atmospheric corrosion decreases with time due to passivation ($\triangle W=Kt^n$), whereas corrosion in wood is linear with time. The latter is activation controlled, exhibiting a constant corrosion rate with time (Zelinka 2013b). This has been confirmed on multiple occasions by Baker (1992), Zelinka et al. (2008) and Zelinka and Rammer (2009).

EFFECTS OF MOISTURE IN WOOD ON METAL FASTENERS

Metal fasteners will not corrode without the presence of an electrolyte (water). Theoretically ionic transfer requires a medium, and this is quite apparent in literature as it is mentioned in almost every paper written on this topic. This paper will be no exception: the amount of moisture in the wood, as influenced by material factors (e.g. permeability, density, grain angle) and environmental factors (e.g. temperature, atmospheric relative humidity, amount and frequency of wetting), is the primary factor governing corrosion of metallic fasteners in wood. This has been understood and accepted by the scientific community as far back as 1949 (Baechler 1949), when the first major paper on this topic was published.

The critical moisture content in wood, above which corrosion starts to noticeably occur, will vary depending on a number of factors. The agreed upon range for this critical moisture content is between 15% to 20% (by mass of wood): Graham et al. in his annotated bibliography (Graham et al. 1976) and The Norwegian Institute of Wood Working and Wood Technology in 1973 indicated 15%; Farmer stated 16% to 18% (Farmer 1962); Dennis et al. suggested 18% (Dennis et al. 1994); Baker in 1980 implied 20% (Baker 1980) and approximates 18% in 1988 (Baker 1988); Dennis et al concludes 18% to 20% (Dennis et al. 1994); and Bailey and Schofield accepted 20% (Bailey et al. 1984). As moisture increases past this threshold, the corrosion rate increases significantly. The corrosion rate also plateaus at a certain moisture content and therefore varies in a sigmoidal fashion.

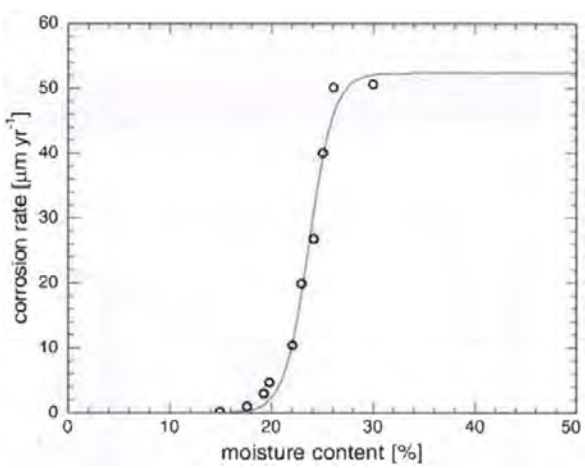


Figure 1: Corrosion Model used in hygrothermal simulations (Zelinka et al. 2012).

This graph is noteworthy because consultants concerned with mould growth and wood decay aren't typically alarmed with moisture contents in the high teens. This range is, however, when the corrosion rate of metals tend to increase significantly.

With respect to relative humidity, the agreed upon percentage under which corrosion will not occur is 60% to 75%: Wallin's investigation of past literature showed 60% to 65% (Wallin 1971); Graham's annotated bibliography stated 70% as the critical humidity at normal temperatures (Graham et al. 1976); and Smith stated a critical humidity of 75% (Smith 1982), which was later confirmed by Bailey and Schofield (Bailey et al. 1984) as well as Simm and Button (Simm et al. 1985). Of some interest is what happens to metal fasteners when the wood substrate is buried in soil. Obviously, these are not ideal conditions; however, it should be noted that embedded fasteners at conditions exposed to 100% RH, at 27°C (with an abundant amount of O_2) are worse off than if they were buried in soil where oxygen availability is limited (Baker 1980) – this was also confirmed by Baker in 1992, as can be seen in the graph below.

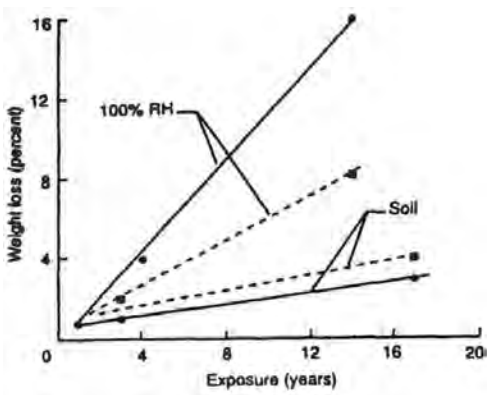


Figure 2: Weight loss of HDG nails in CCA treated wood over time for both exposure conditions. The difference between the solid and dashed line or simply formulations in the CCA (Baker 1992).

Note that after 10 years, embedded Hot Dipped Galvanized (HDG) nails will corrode five and half times more at 100% RH than if buried in soil.

Macro climates based on geography must also be taken into consideration. Based on a combined hygrothermal-corrosion model, corrosion depths range from 5 μm in Phoenix, Arizona, to 45 μm in Hilo, Hawaii (Zelinka et al. 2011a). However, not only should the total annual rainfall be considered, but so should the distribution of these rain events. To help demonstrate this point, see the table below summarizing maximum predicted corrosion depths for nine US cities. Seattle has the second highest maximum predicted corrosion depth, even though it has the third lowest amount of total annual rainfall. What is important here is that it ranks as the second highest in total number of rain hours. Therefore, the walls stay wetter longer and in the case of Seattle, the average temperatures and humidity levels do not allow for high drying potential.

Table 2: Summary of climatic data used in simulations (Zelinka et al. 2011a).

Zone	City	State	Year	Maximum predicted corrosion depth µm (mil)	Yearly Mean Temperature °C (°F)	Yearly Total Rainfall m (ft)	Total number of hours with T > 0°C (32°F)	Total number of hours with Rain
1	Hilo	HI	1990	45(1.8)	23.0 (73)	5.36 (17.5)	8760	2213
1	Miami	FL	1968	12(.47)	23.4 (74)	2.12 (6.96)	8760	588
2a	New Orleans	LA	1961	20(.79)	19.6 (67)	2.12 (6.96)	8715	593
2b	Phoenix	AZ	1978	5(.20)	23.3 (74)	0.39 (1.28)	8734	284
3a	Atlanta	GA	1975	17(.67)	15.9 (61)	1.68 (5.51)	8440	699
4a	Baltimore	MD	1989	16 (.63)	12.6 (55)	1.32 (4.33)	8127	794
4c	Seattle	WA	1971	26 (1.0)	10.1 (50)	1.10 (3.61)	8422	1205
5a	Chicago	IL	1983	11 (.43)	9.7 (49)	1.25 (4.10)	6691	739
6a	Minneapolis	MN	1983	12 (.47)	7.8 (46)	0.99 (3.25)	6217	731

Zelinka et al. (2011).

Another example of this can be seen when comparing Chicago and Minneapolis. Even though the former has about 25% more annual total rainfall, both cities have similar predicted corrosion depths, confirming that the total number of hours of rain is the more governing factor.

However, it should be noted that it's not just the total hours of rain but the distribution of rain events is also a factor. Comparing Miami and New Orleans will confirm this point. They both have similar total annual rainfalls and similar hours of precipitation, but predicted corrosion depths are higher in New Orleans. This is because rain events in New Orleans are spread more evenly throughout the year, whereas rain events in Miami are typically confined to only two thirds of the year leaving a dry season (Figure 3).

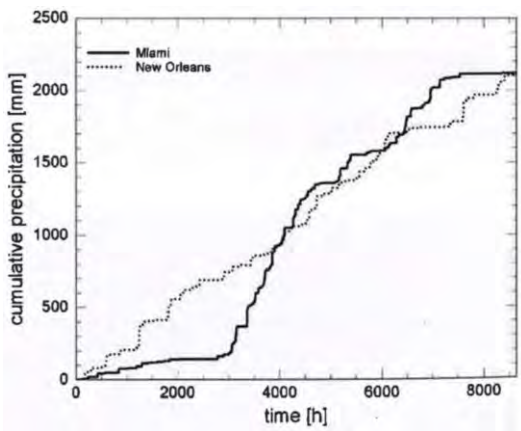


Figure 3: Cumulative precipitation as a function of time of the year for Miami and New Orleans (Zelinka et al. 2011a).

The group of relatively dry months in Miami allow the moisture content in the wood to remain below the corrosion range longer than in New Orleans, where the wood is more likely to stay wet due to the constant, more evenly dispersed rain events.

Zelinka et al. (2011a) further summarized the predicted corrosion depths compared to the fastener depths for all nine cities.

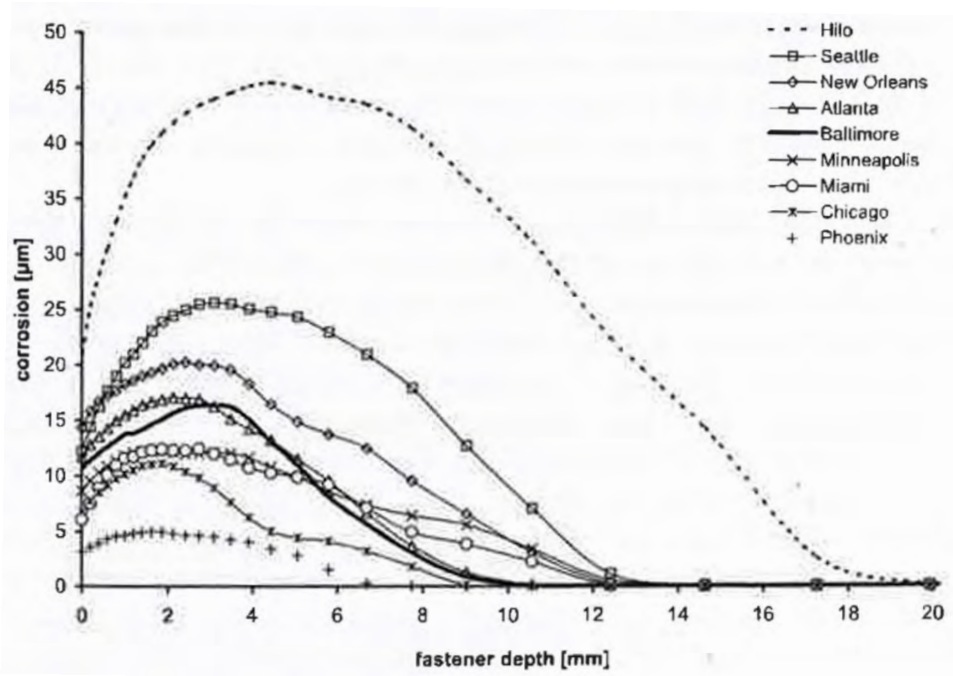


Figure 4: Amount of corrosion after one year as a function of depth below the wood surface for each of the climates simulated (Zelinka et al. 2011a).

The shapes of all the curves show that there is a maximum corrosion depth and this maximum occurs below the wood's surface. This can be explained by the hygrothermal aspects and sorption characteristics of the wood during and between rain events. During a period of rain, the wood surface is saturated above the corrosion threshold, corrosion occurs and its depth is related to the amount of rain during the rain event. The further along the fastener shank (distance from wood surface), the less moisture there is in the wood, and the electrolytic medium required for corrosion disappears. After the rain event, the wood begins to dry out at the surface, which drops quickly below the corrosion threshold. The first few millimetres of the wood are at the capillary saturation threshold moisture content, which is why the maximum amount of corrosion is not at the surface that gets wet by rain, but a short distance below it (Zelinka et al. 2011a).

EFFECTS OF WOOD PROPERTIES ON METAL FASTENERS

Without preservation treatments, embedded metals would eventually corrode in wood given sufficient moisture contents because most woods are naturally acidic. Even though heartwoods are generally more acidic than sapwoods of the same species (Farmer 1962), increasing the amount of heartwood can help as a "green" way to minimize corrosion (Figure 5).

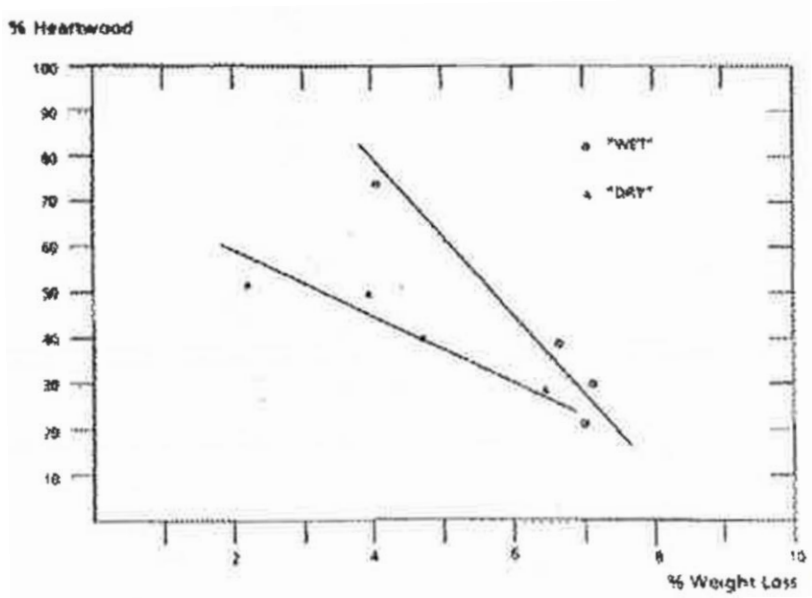


Figure 5: Relationship between heartwood and corrosion rate for mild steel (Simm et al. 1985).

The table below summarizes the pH ranges of some of the more familiar typical woods used in construction.

Table 3: Reference pH values of some common timbers.

Softwoods	**pH**	**Hardwoods**	**pH**
Spruce	4.0 - 5.5	Chestnut	3.6
Pine	3.8	Oak (Europe and US)	3.3 - 3.9
Douglas Fir	3.1 - 4.4		
Western Red Cedar (US)	2.9 - 4.0		

As can be seen above, embedded fasteners are already off to a poor start, given that their environments in wood are already in a state where corrosion is likely. Based on early literature (Farmer 1962), corrosion is more prolific under a pH of 4.3 and significantly decreases over a pH of 5. It is possible that during the kiln drying process, certain timber constituents break down into acetic acid (Smith 1982), helping contribute to the lower pH values. This is why oak can be quite corrosive, because of its increased amount of acetic acid. These acids can increase the solubility of the primary corrosion product and exacerbate the corrosion process.

Other factors that should be considered are the permeability and density of the wood. Less permeable, denser woods provide longer service lives than more permeable, less dense woods. One example of this can be found with beech wood, which is highly permeable and therefore lends itself to higher corrosion rates. The source of the wood should also be considered. Logs floating in salt water, such as nyatoh timber from southeast Asia, have been known to corrode embedded metals (Farmer 1962).

When using nails in western cedar, using stainless steel would be prudent and aluminum, as an amphoteric material, could be a possible alternative. Based on Graham's annotated bibliography, both perform much better than plain, coated or galvanized steel and for redwoods - steel fasteners should be galvanized at a minimum (Graham et al. 1976).

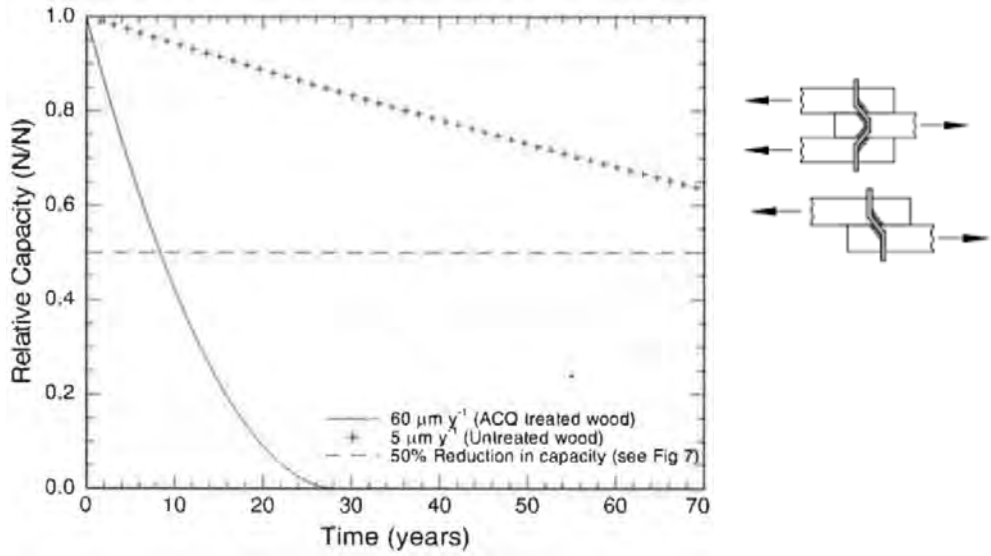
EFFECTS OF WOOD PRESERVATIVES ON METAL FASTENERS

The earlier wood preservatives consisted of zinc chloride, which somewhat increased corrosion, assuming sufficiently high moisture content[1], and Creosote, an oil based preservative, that showed less corrosion compared to non-treated woods, due to its protective film surrounding the metal (Farmer et al. 1962, Wallin 1971, Graham et al. 1976). These wood preservation treatments are not used in residential applications today due to the creation of more effective and economical treatments.

The next and most impactful evolution in wood preservation was the use of CCA. The copper acts as a fungicide, while arsenic serves as an insecticide and protects against fungi tolerant to copper, and chromium improves fixation and leach resistance of the treatment (Dennis et al. 1994). Almost all studies show that CCA treated wood will corrode metals faster than untreated wood – approximately 2 times more corrosive than untreated wood (Cook 2004). Most of the preservative is fixed (bonds to the wood) but not all. Some of the preservative remains in ionic form and these soluble copper ions deposit themselves onto the fastener creating a galvanic couple. This is why, as mentioned earlier, only metal fasteners cathodic to copper (higher in nobility or electropotential) should be used unless protected with a robust coating. Aside from helping the preservative bond to the wood, the chromium, in the form of chromates, have been found to act as corrosion inhibitors (Baker 1980). For instance, Type A – CCA (65.5% chromates) is less corrosive than Type C – CCA (47.5% chromates) (Barnes et al. 1984). It should also be noted that older formulations of CCA were salt based, whereas for the last 30 years, the formulations have all been oxide-based. The former were more corrosive (Barnes et al. 1984) – up to 5 times more corrosive (Cross 1991). In 1993, Davis and Allen found that CCA salts increase the corrosion rates for mild steel, zinc plated steel and aluminum alloy fasteners (Davis et al. 1993). Lastly, the arsenates may play a role as a corrosion inhibitor (Zelinka et al. 2010), although a much lesser corrosion-inhibiting role than the chromates.

As mentioned in the previous history of wood preservation, one of the later wood preservatives that gained significant market access was ACQ. Virtually all studies conclude that ACQ treated wood is more corrosive than CCA treated wood. Zelinka and Rammer (2009) showed that ACQ is more corrosive than CCA for carbon steel nails, HDG nails, aluminum alloy nails, electroplated galvanized steel screws and stainless steels - more than 6 to 10 times more corrosive than CCA for HDG fasteners (exposed to 100% RH) and more than 5 to 7 times more corrosive than CCA for aluminum (Zelinka and Rammer 2009). ACQ formulations contain more soluble copper and chlorides, which can attack the metal and increase conductivity. A formulation where the chloride is replaced with a carbonate is less corrosive.

Based on the graph below, 8d galvanized decking nails embedded in wood treated with ACQ will exhibit a 50% loss of structural capacity at about 10 years. However, it should be noted that the tests were short term and the initial rapid corrosion rate from ACQ treated wood due to free copper and ethanolamine drops rapidly once these have been leached out.



Figures 6 and 7: Reduction in capacity of an 8d galvanized decking nail for two different corrosion rates exhibiting a Mode IV failure (left) and Mode IV failure illustrated (right): wood bearing failure with two plastic hinges (Zelinka and Rammer 2011b and Baker 1992).

Because Mode IV failures are inversely related to the square of the diameter, the lateral capacity will decrease quite rapidly with time as the corrosion rate increases (Zelinka 2013b). This is why steel fasteners, even when hot dipped galvanized, should be used very cautiously with ACQ treated wood, especially if applications consist of primary structural applications or if there is a chance of increased humidity levels/moisture in the wood. In humid and temperate climates, it may be prudent to simply specify stainless steel fasteners on wood, unless you are certain of the wood preservation treatment (e.g. borate). However, there should not be great concern for thicker diameter fasteners such as through bolts. Though not immune to corrosion, the reduction in cross sectional area of thick bolts is minimal and not expected to cause a significant reduction in strength (Bailey et al. 1984). This is important in roof trusses and other primary structural joints, where thick bolts are used, as just the sight of corrosion product on bolt heads can cause panic.

With respect to CA treated timbers, they are considerably more corrosive than CCA (with the same copper concentration) based on weight loss studies - Zelinka and Rammer showed this to be by a factor of 3 to 11 times (Zelinka et al. 2013a). CA and ACQ typically have more copper than CCA, which is likely why they are more corrosive. A technical bulletin published by Simpson Strong Tie in 2008 stated that both CA and ACQ are roughly twice as corrosive as CCA (Zelinka et al. 2009). It should also be noted that a variation of CA, known as MCA (Micronized Copper Azole) exists and has recently been commercialized in Canada. This formulation contains the same amount of copper but uses particulate copper carbonate, which has extremely low solubility and is therefore like its counterpart, micronized copper quaternary, but less corrosive (Zelinka et al. 2010).

To help compare the corrosive effect of these wood treatments, a graphical summary of 1 year corrosion rates for plain and HDG fasteners is shown below.

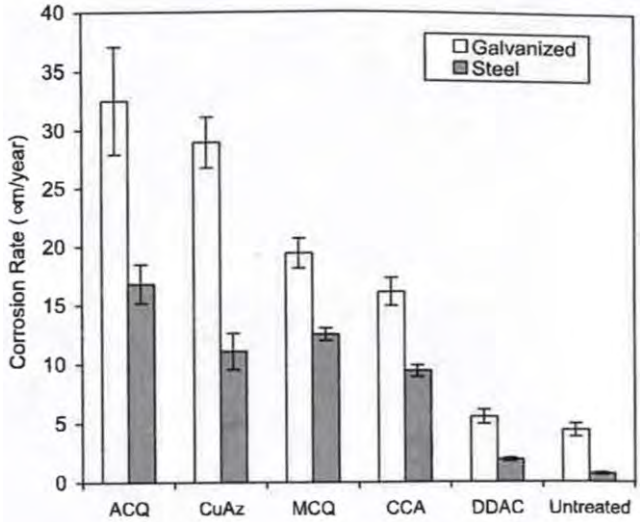


Figure 8: Corrosion rate measured in the 1-year, 27oC, 100% RH exposure test for HDG (white) and steel (gray) fasteners for different wood preservative treatments (Zelinka et al. 2010).

The graph shows the relative corrosive effects of various wood treatments on bare and galvanized steel. For explanatory purposes, the increased corrosion rates in galvanized fasteners accounts for the fact that zinc is a strongly oxidizing metal - the very reason it is used as a sacrificial protective constituent.

The more corrosive nature of ACA and ACQ can be explained by their higher amounts of mobile copper ions, are soluble and deposit themselves on the fastener surface causing galvanic coupling. These ions also contribute to a lower resistance in the electrolyte. See the table below for typical formulations of ACQ, CCA and ACA.

Table 4: Retention and composition of the wood preservatives used in the study (Zelinka et al. 2009).

	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	—

Also note that ACA contains no chromates, which recall act as corrosion inhibitors, and is therefore more corrosive than CCA (Baker 1980). This was later confirmed by Barnes et al. in 1984. ACA is no longer used in North America.

Understanding the balance of how these preservatives are harmful and helpful is required for many facets in design. For instance, at foundation slabs, one can use a double sill plate, where the bottom is treated or consists of a more naturally durable species. Another consideration would be to use a half inch of inert material between untreated wood and concrete. Sometimes, designers employ the use of spacer materials between fasteners and treated wood by using EPDM or plastic washers. These solutions are not perfect, as there is still metal to wood contact and EPDM washers can retain moisture, but these solutions can provide visible means of achieving required engineering results.

OTHER FACTORS INFLUENCING CORROSION

Fixation Time. The time between treatment and embedding fasteners is important. Seasoning the wood before embedding fasteners will ensure less corrosion (Baechler 1949). This is obvious as sufficient time is required for copper to bond to the wood before they get a chance to deposit on the fastener surface. This was later confirmed by Simm and Button in 1985 who indicated that treated wood ideally be allowed to dry for 1 to 2 weeks to let the preservative salts "fix" into a more insoluble state (Simm et al. 1985).

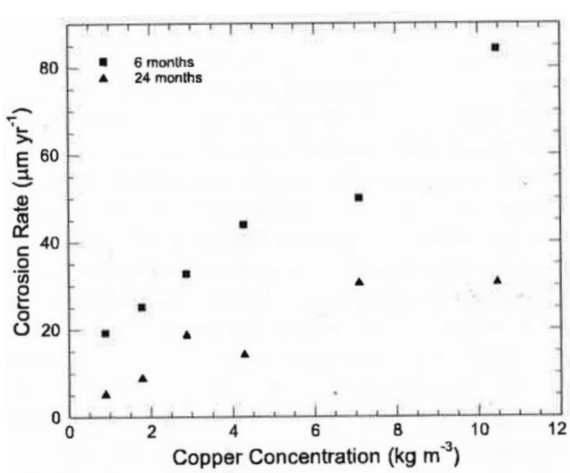
Fire Retardant Chemicals. Due to the brackish nature of fire retardants, they can increase the conductivity and therefore increase ionic flow. Boric acid, borax, ammonium sulfate, aluminium sulfate, and other phosphates are corrosive to metals in humid or moist environments (Baker 1980).

Temperature. Corrosion of metal is generally increased with temperature. Based on past studies, fastener weight loss at 21ºC was much less than at 52ºC (Bengelsdorf 1983), which was later confirmed by Barnes et al. (1984). The corrosion rate of mild steel in CCA treated redwood increased fiftyfold when the temperature increased from 10ºC to 25ºC.

Residual Stresses. Internal stresses have always been known to increase the propensity of stress corrosion cracking. In tests where metal coupons were sandwiched between treated wood wafers and placed in beakers containing water at 38ºC, the most significant corrosion was observed at identification stamps, implying exacerbation of corrosion due to metal stresses (Barnes et al. 1984). Therefore, the galvanizing process with steel fasteners adds another advantage of tempering the steel and relieving it of unwanted residual stresses.

Grain Angle. The grain angle affects water flow and therefore affects ion transfer. Corrosion has been found to be greater in the transverse direction (Jack et al. 1987). This is because diffusion of moisture is greater down the open tracheids than across them. In 1991, Cross indicated that corrosion of mild steel in CCA treated redwood at 26% MC was 50% greater along the grain than across the grain, due to the increased ionic conductivity along the grain (Cross 1991).

Chemical Composition of Treatment. As mentioned earlier, corrosion will increase with the amount of copper content and decrease with the amount of chromium content.



	Cu metal concentration (kg m^{-3})	Corrosion Rate (µm yr^{-1})
Untreated	-	5
Cu+Cr "light"	2.0	5
Cu+Cr "heavy"	4.4	9
Cu+As "light"	2.0	20
Cu+As "heavy"	5.6	20

Figures 9 and 10: Corrosion rate of carbon steel nails as a function of copper concentration at 6 and 24 months of exposure at 27°C, 75% RH (left, Zelinka et al. 2011b). Corrosion rates for stakes treated with copper arsenate and copper chromate (right, Zelinka et al. 2011b).

The graph illustrates the linear effect of copper and the table shows the effect of chromium. When comparing the lightly retained Cu+Cr preservative with the untreated wood, there is no difference in corrosion rate, but when the Cu+Cr preservative is compared to its arsenic counterpart (without chromium), the corrosion rate is quadrupled.

Metallurgical Characteristics. The inherent properties and conditions of the metals will undoubtedly contribute to the propensity of corrosion. A uniform surface is less likely to corrode because of its homogeneity in chemical potential. However, fastener surfaces have an abundant amount of irregularities and non-uniformities such as its chemical composition, roughness, grain boundaries, areas of stress and strain, surface inclusions. The slightest difference in electrochemical potential will lead to the formation of anodes and cathodes (Graham et al. 1976).

Also as a final note, the presence of oxygen, salts, low pH, stray current and depolarizers will all accelerate corrosion.

CORROSION OF METAL FASTENERS OTHER THAN STEEL

Up to this point, we discussion around corrosion has largely focussed on steel (iron based alloy). The corrosion of all types of metal fasteners embedded in wood generally follows the order given in the galvanic series chart (with the exception of copper, brasses and bronzes when considering chloride attack). For instance, copper and brass show corrosion rates of about 20% or lower compared to ordinary steel (Wallin 1971). Brass screws show little attack - except at 90% RH, where they can become quite brittle due to dezincification (Baechler 1949) and stress corrosion cracking (Wallin 1971). This was later confirmed by Graham et al. in 1976.

Interaction between aluminum and treated wood can have mixed results. In some situations, aluminum can be found contacting treated wood quite safely, especially when anodized. The corrosion rate of aluminum was lower than both HDG and electroplated steel in ACQ, ACA and CCA (Zelinka et al. 2009). Furthermore, two separate experiments by two different researchers, using four different preservatives found corrosion rates to be lower for aluminum compared to galvanized steel (Zelinka et al. 2009). Even though aluminum is anodic steel, steel is usually galvanized or plated with zinc, which is more anodic than aluminum. However, pitting can occur when aluminum flashing is exposed to concentrated wood leachate in above grade conditions. Therefore, some aluminum suppliers recommend a sheet barrier between the metal and wood to be on the safe side.

It should also be noted that copper containing aluminum alloys corroded more than pure aluminum (Farmer 1962) (Graham et al. 1976), which tends to be more sensitive to copper compounds (Farmer et al. 1962). The figure below shows a graphic illustration of how various groups of metals stand up to accelerated exposure.

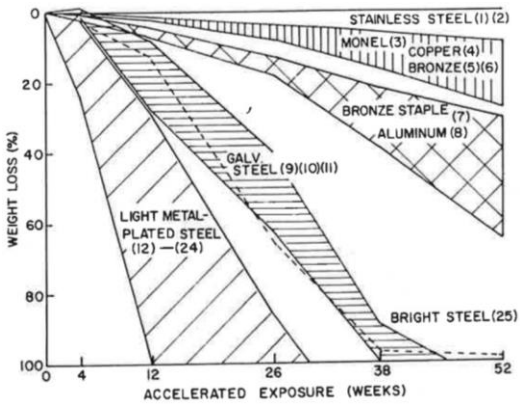


Figure 11: Weight loss of fasteners in ACA treated ground wood during accelerated exposure (Bengelsdorf, 1983).

Polyvinyl Chloride (PVC) and Fibre Reinforced Polymer (FRP) fasteners are also currently being utilized. FRP fasteners consist of fibreglass dust, encapsulated in high strength polymers. They can be cheaper than stainless steel and have no risk of corrosion, but will however experience other forms of environmental degradation such as crazing, embrittlement, or even softening. Zelinka and Rammer showed that FRP fasteners exposed to accelerated weathering (ASTM G154) experienced consistent shrinkage (albeit small) and lost approximately 1% of overall mass, indicating some UV attack. Furthermore, the fasteners, which were exposed to 100% RH, increased their total mass, which was likely due to minor water ingress and retention. The most remarkable changes were caused by moisture, but the data showed that FRP fasteners can be used in wet and humid environments.

EFFECTS OF COATINGS ON STEEL FASTENERS

The most common type of metal fastener is steel and its most common type of coating is zinc based. Aside from its sacrificial action, the zinc layer will also shield the steel from the soluble copper ions depositing on the steel surface. However, it should be stated that this zinc layer has to be of sufficient thickness and composition to have any practical advantage. For instance, electroplated zinc is usually too thin to offer sufficient protection from corrosion and wear in most wet conditions. HDG coatings are thicker (10 to 20 times), more durable (Fe is alloyed into coating via diffusion) and adhere better (given the interfacial alloy exchange). Many nail guns are compatible with HDG fasteners and therefore cannot be used as an excuse for contractors and designers.

Earlier PVC coated nails showed an almost embarrassing amount of corrosion at nail heads because the coatings were destroyed as they were driven (Wallin 1971). This was later confirmed by Bailey and Schofield in 1984. Some polymer coatings in wood screws can be completely stripped while being driven into wood. Polymer coating technology has gotten better but caution should always be used when relying on these layers to eliminate corrosion. Polymer-coated electroplated galvanized fasteners have shown better performance.

EFFECTS OF METAL ON WOOD

Much discussion and a study on past literature has focussed on damage borne by the fasteners, yet there are deleterious effects on the wood as well. This is often referred to as "nail sickness". This is the decomposition of cellulose originating from soluble metal ions and molecular oxygen. Essentially, the polysaccharides are oxidized and cellulose is depolymerised. The following is a possible scenario: ferrous hydroxide, $Fe(OH)_2$, is first formed; then it is absorbed by cellulose in solution, exposed to air and oxidized to form ferric hydroxide, $Fe(OH)_3$, which is responsible for the addition of oxygen to the cellulosic molecule forming oxycellulose, which is brittle and mechanically weak (Wallin 1971). The corrosion product is in effect digesting the cellulose and making it weaker. It could occur directly adjacent to the metal or deep within the wood. This reduces the tensile strength of the wood but not the compressive strength (Farmer 1962), indicating that the lignin is not as affected as other polysaccharides upon which the tensile strength of wood depends on.

Tropical hardwoods are generally more durable woods. Sapwood is more susceptible to this breakdown than heartwood (Bailey et al. 1984) (even though the latter is more acidic), which was later confirmed by Simm and Button (Simm et al. 1985), partly due to the majority of the preservative being taken up by sapwood. Based on past literature, the lowest corrosion rates were found in wood with the highest proportion of heartwood (Simm et al. 1985). Tracheids in heartwood contain deposits, which block the cell capillaries, reducing the permeability to oxygen, water and the preservative, therefore lowering its permeability and ability for ionic transfer.

It should be noted that the deleterious effects of metals on wood are not typically the case for HDG fasteners, copper, brass or aluminum fasteners. On the contrary, HDG fasteners may corrode in a way that actually wedges the fastener more robustly into the wood, creating a tighter embedment (Wallin 1971). The leached zinc product can also serve as a biocide towards unwanted organic growth.

CONCLUSION

The history of wood preservation has continued to grow at a relatively steady pace for the past two centuries. More recently, its evolution has focussed on minimizing environmental impact and damage to other components, while maintaining its preservation characteristics. As can be seen, moving in any one direction may have unintended consequences on another. It is important when designing or building with treated wood to thoroughly review all material, environmental and installation factors.

Based on the literature review of publications related to the corrosion of metals embedded in treated wood, the author has created a matrix of wood preservation treatments and types of metal fasteners and opined on the suitability of their use together. The design matrix is not intended to replace a thorough analysis of individual situations but meant to provide general guidance given typical environmental conditions in the Pacific Northwest.

Generally more corrosion resistent fastener material →

(with exception of brass, copper and silicon bronze when exposed to chlorides)

Treatment	Bare Steel	Coated/Plated Steel (Zn or Ni)	HDG Steel	Al	Brass	Copper	Silicon Bronze	304 SS	Monel (Cu-Ni alloy)	316 SS
Untreated	2	3	4	4	4	4	4	4	4	4
Penta	3	4	4	4	4	4	4	4	4	4
Creosote	3	4	4	4	4	4	4	4	4	4
ZnCl	1	2	4	4	4	4	4	4	4	4
CCA (Type C)	2	3	4	2	4	4	4	4	4	4
ACA	1	1	2	2	4	4	4	4	4	4
ACZA	1	2	3	3	4	4	4	4	4	4
ACQ	1	1	2	1	3	3	3	4	4	4
MCQ	1	2	3	3	4	4	4	4	4	4
CA	1	1	2	2	3	3	3	4	4	4
Borate	2	3	4	4	4	4	4	4	4	4

In the shaded areas, the author has interpolated and extrapolated based on a lack of past literature/testing.

Notes: The summary assumes Pacific Northwest conditions and generally for metal fasteners that are not completely exposed (e.g. fasteners securing strapping or wall cladding). ZnCl has not been used in North America for over 50 years, ACA for over 20 years and MCQ hardly ever. Performance with Al is mixed - this depends on its coating, location and intimacy with treated wood. Borate is easily leached and its use is therefore limited in completely exposed conditions.

Rating	Description
4	Permitted in almost all situations
3	Permitted in most situations
2	Permitted in some situations
1	Permitted in very few situations

Corrosivity: ACQ > CA > MCQ > CCA > DDAC > untreated

Please keep in mind the following factors:

- Atmospheric humidity
- Temperature of substrate
- Frequency, quantity and type of stresses (dyanamic, static and residual)
- Type of wood
- Macro location (proximity to seawater, altitude)
- Micro location (behind cladding, buried in soil, at pool)
- Type of fastener (nail, staple, screw, bolt)

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