MICROCLIMATE CORROSION EFFECTS IN COASTAL ENVIRONMENTS

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ABSTRACT

The Albany Research Center is conducting atmospheric corrosion research in coastal environments to improve the performance of materials in the Nation's infrastructure. The corrosion of bare metals, and of painted, thermal-sprayed, and galvanized steels are presented for one-year exposures at sites located on bridges and utility poles along the Oregon coast. The effects of microclimates (for example distance from the ocean, high wind zones, and salt-fog prone regions) are examined in conjunction with sample orientation and sheltered/unsheltered comparisons. An atmospheric corrosion model examines the growth and dissolution of corrosion product layers to arrive at a steady-state thickness and corrosion rate.

Keywords: atmospheric corrosion, microclimate, chloride, corrosion model, copper, steel, zinc, paints, thermal-spray, dry deposition, wet deposition, corrosion film.

INTRODUCTION

The effects of microclimates on atmospheric corrosion are examined for coastal conditions along the Oregon coast. Microclimates are created by local meteorology, air quality, terrain, sheltering, and orientation. Wind driven salt spray and sand may also be factors close to the ocean. Microclimates are the product of local environment chemistry, time-of-wetness, and aerodynamic factors that control deposition of reactants to a metal surface, and of hydrodynamic factors that affect reaction kinetics in the precipitation layer washing the metal surface.

An atmospheric corrosion model is presented with parameters that are directly influenced by microclimate conditions. The model balances the growth of a corrosion product (controlled by transport kinetics through the corrosion product) with the dissolution of the corrosion product (controlled by wet and dry deposition rates of environmental species to the surface). Initial results of atmospheric exposures along the Oregon coast are presented from one-year exposures of a variety of structural metals and paint systems. The test sites are 31 utility poles and 7 bridges along the Oregon coast.

ATMOSPHERIC CORROSION MODEL

Atmospheric corrosion models have been used to characterize the corrosivity of environments in an effort to anticipate severe corrosion conditions.[1-2] Other models based on the chemistry and physics of the corrosion process, *i.e.*, physicochemical models, have been used to quantify the effects of environmental factors such as pollutants and "acid rain".[3-4] Traditionally, empirical atmospheric corrosion rate expressions, such as the bilogarithmic model,

$$\log C = b + a \log t \qquad (1)$$

where C is the total corrosion mass loss and t is exposure time, have been useful for organizing and interpolating experimental corrosion data and for predicting service lives of metals from short-term data.[5-7] However, the bilogarithmic

model parameters "a" and "b" are not based on environmental or corrosion film properties. Nor does the model give the correct slope of the mass loss curve for long term exposures.

In coastal environments, sheltering can increase zinc corrosion rates to more than twice those in the open.[8] Surface orientation greatly affects the delivery and contact of corrosive species with metals.[9] Furthermore, metals used for conduit, fasteners, enclosures, terminals, and switches in service equipment for bridges and utilities are exposed to highly variable microclimates from sheltering, orientation, local meteorology and air chemistry. Physicochemical modelling can provide basic information on the severity of corrosion processes, the importance of specific reactive species, and the role of design and environmental factors on service life of materials used in these applications.

Atmospheric corrosion involves two parallel and competing processes: corrosion film growth and corrosion film dissolution.[3] These processes and the associated wet and dry deposition processes that drive them are illustrated in Fig. 1, where interactions with the environment (weathering) result in mineral changes that stabilize portions of the corrosion film while leaving other portions soluble. The corrosion film grows by oxidation reactions at the metal-film interface, but is thinned when the soluble portions are removed in precipitation that washes the metal surface, *i.e.*, precipitation runoff.

The precipitation runoff loss rate, β, will vary with the mineralogy of the corrosion film and depend on environmental factors such as meteorology, air quality, acid deposition, and particulate deposition.[3-4] However, if we assume the time average runoff loss rate is constant, the total corrosion, C, over the exposure period t is given by the mass balance:

$$C = T + \beta t \tag{2}$$

where T is the mass of metal remaining in the corrosion film and βt is the metal lost in runoff. The corrosion rate is obtained from Eq. (2) by taking the derivative with respect to time:

$$\frac{dC}{dt} = \frac{dT}{dt} + \beta \tag{3}$$

When the corrosion film thickness stabilizes, as in long exposures, $dT/dt = 0$, and the corrosion rate is equivalent to the runoff loss rate, β.

As in the development of rate laws for oxidation kinetics, one can assume the corrosion rate is inversely proportional to film thickness, or the equivalent variable T. In the most general case, the corrosion rate becomes:

$$\frac{dC}{dt} = \frac{\alpha}{T^n} \tag{4}$$

where α is a diffusivity parameter. The exponent n is the order of the corrosion reaction: n = 0 for linear kinetics; n = 1 for parabolic kinetics; and n = 2 for cubic kinetics. Substituting Eq. (4) into Eq. (3) and rearranging yields the differential equation describing corrosion film growth.

$$\frac{T^n dT}{\alpha - \beta T^n} = dt \tag{5}$$

This equation can be solved in closed form for integer values of n. Substituting Eq. (2) for T yields solutions to Eq. (5) in terms of the total corrosion, C. These solutions are the atmospheric corrosion equivalents of the linear, parabolic and cubic rate laws for oxidation kinetics and are the basis for the physicochemical model. They are:

linear (n = 0):

$$C = \alpha t \tag{6}$$

parabolic (n = 1):

$$C = \frac{\alpha}{\beta}\left[1 - \exp\left(-\frac{\beta C}{\alpha}\right)\right] + \beta t \tag{7}$$

and cubic (n = 2):

$$C = \sqrt{\frac{\alpha}{\beta}} \tanh\left(C\sqrt{\frac{\beta}{\alpha}}\right) + \beta t \tag{8}$$

Linear kinetics do not adequately describe most atmospheric corrosion kinetics, which are generally nonlinear over some time frame. The parabolic model, Eq. (7), has been used to describe the effects of pollutants on the long term atmospheric corrosion of zinc, galvanized steel[3-4] and copper.[4] Edney[9] has used it to analyze size and orientation effects of acid deposition on galvanized steel corrosion. Spence *et al.*[10] used it to describe wet and dry deposition effects on galvanized steel and weathering steel.

The parabolic model gives a limiting slope of ½ on a logarithmic plot of mass loss versus time for short exposure times where film growth dominates; the cubic model gives a limiting slope of ⅓. Both models give a limiting slope of 1 in long exposures where runoff losses dominate. The diffusivity term α is expected to depend largely on properties of the corrosion film. The runoff loss rate, β, is the same in both models. β modifies the oxidation rate laws to admit a broader range of oxidation processes.

The parabolic and cubic models both predict the nonlinear corrosion behavior observed for many metals and historically represented well by the bilogarithmic model. The bilogarithmic, parabolic and cubic models were fit to mass loss data for 16-year exposures of weathering steels and carbon steels in a wide range of environments,[11] 16-year marine exposures of zinc,[12] and 20-year marine exposures of copper alloys.[13] The parabolic and cubic models both fit the data substantially better than the bilogarithmic model as measured by the standard error of the estimate, s (which is the square root of the variance, s^2). The cubic model fit the data better than or equivalent to the parabolic model. Results for four representative alloys and exposures are given in Table 1. The long term film thickness (expressed as μm of metal), T_s, is computed from model parameters. For the parabolic model, $T_s = \alpha/\beta$; for the cubic model $T_s = (\alpha/\beta)^{\frac{1}{2}}$.

Based on fitting selected mass loss data, typical values of the cubic model parameters are given in Table 2. Direct comparison of such results with experimentally derived parameter values has not been done. However, values of the runoff loss rate, β, for zinc and the copper alloys are the right order in magnitude when compared to other values of β reported for zinc and copper based on runoff measurements.[3-4] Values of β for weathering steels are similar in magnitude to those reported by Spence *et al.*[10]

The equation for the cubic model, Eq. (8), can be recast in dimensionless form using the following transformations:

$$C^* = C\sqrt{\frac{\beta}{\alpha}} \tag{9}$$

and

$$t^* = t\sqrt{\frac{\beta^3}{\alpha}} \tag{10}$$

The dimensionless form of the cubic model, Eq. (8), is:

$$C^* = \tanh C^* + t^* \tag{11}$$

Equation (11) corresponds to a universal curve for the cubic model and is represented by the solid line in Fig. 2. Atmospheric corrosion data expressed in this way should fall on the curve. Mass loss data for the four alloys from Table 1 have been plotted in Fig. 2. They represent materials with widely different corrosion performance and yet they agree well with the universal curve. These results suggest a general way to organize and interpret atmospheric corrosion data based on physically meaningful principles. This approach is being explored in the current research and will be the basis for interpreting the experimental atmospheric corrosion results.

From the universal curve, an equivalence can be established between the parameters of the empirical bilogarithmic and the cubic model. In this case:

$$a = \frac{1}{\tanh^2 C^*} - \frac{1}{C^* \tanh C^*} \qquad (12)$$

and

$$b = (3\alpha)^{\frac{1}{3}} \qquad (13)$$

From this analysis, it is clear that the parameter "a" is a function of the amount of corrosion, while "b" is not.

<div align="center">EXPERIMENTAL DESIGN</div>

Sample Preparation and Placement

Mass loss samples were placed on each of the seven bridges shown on the map in Fig. 3 to determine microclimate effects associated with bridges, *i.e.*, environment chemistry, sheltering and orientation. The 3 x 6 inch (7.5 x 15.2 cm) samples included copper, mild steel, zinc, thermal-sprayed zinc, aluminum alloys (5051 and 6061), a three coat bridge paint system on 1010 mild steel,[1] and sealed thermal-sprayed aluminum on 1010 mild steel.[2] The painted and thermal-sprayed samples were scribed from corner to corner with an "X". Samples were boldly exposed on the west-facing side of the bridges, and exposed in a sheltered environment immediately under the bridge deck. Samples were oriented at 0, 30 and 90 degrees with the horizon to examine precipitation residence time and deposition effects. A 7.5 ft (2.3 m) long boldly exposed rack on the Spencer Creek bridge is shown in Fig. 4. At each sample position on the rack are a pair of one-sided samples-- one facing upward and one facing downward, both with their backs taped to permit corrosion on only one face.

To generalize the corrosion measurements for the coastal zone extending inland roughly three miles (4.8 km), boldly exposed mass loss samples were exposed in eight other areas along the coast (Fig. 3). Sample racks were mounted on utility poles at sites in each area at nominal distances of 250 ft (75 m), and 0.25, 1, and 3 miles (0.4, 1.6, and 4.8 km) from the ocean to assess the effects of changing chloride levels and climatic factors. Three reference sites were established east of the coastal mountain range in Portland, Albany, and Grants Pass. All of the utility pole sites used one-sided, back-to-back samples, exposed at 30 degrees with the horizon, approximately 15 ft (4.6 m) from the ground, and facing west into the prevailing winds. The samples included zinc, mild steel, galvanized steel, copper, aluminum alloys 5051, 6061, and 3105, type 304L stainless steel, and an experimental low-Cr stainless steel. Additional experimental design details have been described elsewhere[14-15] for both the bridge and utility pole sites.

Climatography

Because extensive environmental monitoring was beyond the scope of this work, the bridge sites were characterized in terms of their physical setting and three empirical corrosivity factors for wind, airborne sand, and salt spray (Table 3). All of

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[1] Oregon Department of Transportation (ODOT) bridge paint system applied by spraying. Primer is 3 mils (0.0762 mm) of zinc dust filled polyurethane. Intermediate coat is 3 mils (0.0762 mm) of moisture cured polyurethane, Topcoat is 3 mils (0.0762 mm) of moisture cured polyurethane with pigment. ODOT Painting Specification for Bridges--Section 00594, Coatings Material--Section 02210, Subsection C for steel in marine environment.
[2] 8-10 mils (0.2-0.25 mm) of thermal-sprayed aluminum sealed with 1 mil (0.025 mm) of low-viscosity epoxy preprime followed by a 2 mil (0.051 mm) urethane topcoat.

the corrosivity factors were ranked on a scale from 0 to 3, with 3 indicating the most intense level. The wind factor represents the wind speed amplification expected at the site. A factor of 1 indicates wind is unaltered as it comes in off the ocean. The factor of 3 at Brush Creek is a consequence of extreme terrain adjacent to the bridge which funnels wind up the narrow ravine spanned by the bridge. The sand factor indicates the likelihood of airborne sand impacting the samples. The salt spray factor ranks the amount of chloride delivered by salt spray or as an aerosol to the bridge. A value of 1 characterizes sheltered bays.

Utility pole sites extend from the northern to the southern coast of Oregon (Fig. 3). Average monthly temperatures and precipitation are shown in Fig. 5 for the Oregon coastal area.[16] In general, the coastal climate is mild but wet with an average mean winter temperature of 6.9°C and summer temperature of 16.6°C. Average annual rainfall is 194 cm (76 in) with most occurring from November to May. The average rain pH is 5.4. The sites are in the westerly wind belt[17] with wind gusts to 130 to 240 km/h (80 and 150 mph) for northern and southern Oregon, respectively. High winds occur mainly in the winter. Dense fogs are common. Salt fogs in the summer can carry chloride particulates several miles inland.

The utility pole sites in Brookings (located on the southernmost part of the Oregon coast, Fig. 3) experience warmer conditions than the rest of the coast. Many Brookings residents call their part of the coast "Oregon's Banana Belt." This is due to frequent thermal troughs that bring warm air north from California's hot Central Valley. These troughs influence winter conditions the most, raising the temperature by an average of 2.0°C.[16]

Sixty five kilometers inland from the coast, at the Alsea Guard Ranger Station on the east side of the coastal mountain range, the average annual precipitation chemistry is, in mg/L: Cl - 1.46; SO_4 - 0.34; NH_4 - 0.02; Ca - 0.05; Mg - 0.099; K - 0.034; Na - 0.804; and H - 0.00467.[18] The two northern inland reference sites have an average summer temperature of 18°C (1.4°C warmer than the coast) and an average annual precipitation of 106 cm (88 cm dryer than the coast).[16] The southern inland reference site (Grants Pass) has an average summer temperature of 21°C (4.4°C warmer than the coast) and an average annual precipitation of 79 cm (115 cm dryer than the coast).[16]

Analysis Techniques

After one year of exposure, half of the mild steel, copper, zinc, and galvanized steel samples were removed from each rack and replaced. The remaining materials were observed in place for signs of rust, discoloration, pitting, corrosion deposits and, in the case of the coated samples, delamination and bubbling.

The corrosion products of the copper samples were analyzed while attached to the base metal. X-ray diffraction was used to determine the minerals present in the corrosion product. Intensities of characteristic diffraction lines provided a measure of the relative abundance of each compound. Non-destructive chemical analysis was also performed using energy-dispersive x-ray analysis (EDS).

X-ray diffraction and EDS analysis on other samples are currently in progress, as well as chemical stripping of all metal samples. After the stripping, mass losses will be determined and corrosion rates calculated. Chemical analyzes of the stripping solutions will provide additional data on the composition makeup of the corrosion product. Since the best methods of chemical stripping involve chloride solutions, it was important to use non-destructive techniques prior to stripping to quantify the Cl⁻ levels.

RESULTS AND DISCUSSION

Observations

The one-year observations of coating systems show considerable differences in the amount of coating delamination or undercutting. Only one of the 70 sealed thermal-sprayed aluminum samples showed any evidence of delamination. In contrast, 43 of the 70 three coat bridge paint system samples exhibited some delamination. The extent of delamination was greatest at the four bridges closest to the ocean. Considering all of the painted samples at the 7 bridge sites, the extent of delamination was much greater for the boldly exposed samples (average of 4.0 mm undercutting) than it was for the sheltered samples (1.3 mm undercutting). Differences in the extent of delamination were not significant for other variables, *i.e.*, orientation or angle of inclination.

The 3105, 5052, and 6061 aluminum samples from the bridge and utility pole sites were visually examined after one year for corrosion and pitting. There was no sign of pitting, but localized corrosion was evident. Localized corrosion

generally resulted in a discontinuous or continuous network of gray etched areas, sometimes containing accumulations of white corrosion product. This network appeared to result from precipitation drying patterns. In a few cases, the white corrosion product was wiped off and no pitting was observed. Based on these observations, the groundward facing samples were slightly less corroded than the skyward facing samples. Increasing the distance from the ocean decreased the corrosion attack--no corrosion was observed at the three inland sites. Overall, the corrosion of the 5052 Al was less than that of the 6061 Al, which was less than that of the 3105 Al.

X-Ray Diffraction Analyses.

Cuprite (Cu_2O) was present in the copper corrosion films at all sites, in all orientations, both sheltered and unsheltered. At nearly all coastal sites atacamite (copper hydroxychloride) was also present. Atacamite was not present at the inland reference sites. Atacamite was present in reduced amounts on the groundward side of sheltered samples from the Spencer Creek bridge, replaced by chalconatronite (sodium copper carbonate hydrate). These three minerals, along with copper from the substrate, accounted for all of the significant diffraction lines for samples from all sites. In several cases silica dusts were also observed at low levels in the corrosion films.

Attenuation of the copper 2.08 Å x-ray diffraction line was used as an indication of relative corrosion film thickness. The more copper detected, the less the thickness of the film. Corrosion films were thinnest at the reference sites and thickest at the sites closest to the ocean. Sheltered corrosion films were thicker than boldly exposed films, presumably because of corrosion product losses from the washing effects of precipitation on boldly exposed samples.

The amount of atacamite in the films increased at sites closest to the ocean for skyward facing samples. Groundward facing samples gave results dependent on the exposure site, with an increase in atacamite near the coast for Cape Blanco and essentially no change for Astoria and Brookings. On the other hand, cuprite increased near the coast for skyward samples from Astoria and Brookings but decreased for Cape Blanco where washing effects would be large.

Corrosion film thicknesses were thicker at the Spencer Creek Bridge than the Rogue River Bridge for both skyward and groundward facing samples regardless of orientation. Orientation (0, 30, and 90 degrees) had relatively little effect on the amount of atacamite and cuprite in the corrosion films. The exception was skyward facing samples at Spencer Creek, where there was more atacamite in the corrosion film on vertical samples than horizontal samples.

The results reflect strong effects of microclimate. The absolute and relative amounts of mineral species on the sample surfaces vary from site to site, for different orientations, and with sheltering. In some cases the differences are substantial and will result in significantly different corrosion performance.

Atmospheric Corrosion Model

Mass loss measurements yield values of C rather than β. They are the traditional measure of a metals response to atmospheric weathering. Mass loss measurements are not usually resolved into component contributions from environmental factors. However, they can be used to evaluate the influence of β in experimentally complex conditions such as those which arise from sheltering and orientation. Physicochemical models, such as given by Eqs. (7-8), provide the basis for resolving mass loss measurements into component contributions from film growth and runoff.

Precipitation runoff measurements provide a direct and unambiguous measure of β.[4,19] Such measurements involve determining precipitation chemistry and the chemistry of the soluble corrosion products washed from the metal surface. They can be rationalized in terms of the reactive environmental species that cause corrosion products to dissolve. When combined with air quality data, mass transfer coefficients such as the deposition velocity, v_d, which quantify the delivery of reactants to surfaces, can be computed from the runoff measurements.

Precipitation runoff measurements are based on a detailed mass balance of chemical species delivered to and removed from the corroding surface, Fig. 1. The mass balance yields the flux of reactive species delivered to the metal surface in wet and dry deposition. Reaction stoichiometry is used to resolve the measurements into contributions to the corrosion process from individual environmental species. Earlier studies[3-4] have shown that chemically complex and diverse environments, such as found in the eastern U.S., can be treated in this way to yield values of β for copper, zinc and galvanized steel. In doing so, β was separated into the following contributions from environmental species:

$$\beta \; = \; H^+ \; + \; [SO_2] \; + \; [HNO_3] \; + \; rSV \; - \; CaMg_{H^+} \tag{14}$$

H^+ represents the excess hydrogen ions in "acid rain", $[SO_2]$ and $[HNO_3]$ the dry deposition of the acidic gases sulfur dioxide and nitric acid, respectively, $CaMg_{H^+}$ the dry deposition of basic particulates, and rSV a "clean rain" term representing baseline corrosion in the absence of pollutants. Computation of the individual terms has been treated elsewhere.[3,19-20]

Cumulative contributions of the terms in Eq. (14) are shown in Fig. 6 for zinc corrosion in Washington, D.C., over a 33 month period. The solid curve is the experimentally measured zinc in the runoff. The close agreement between these values and curve 5, representing the summation of terms in Eq. (14), indicates the precipitation runoff process is well described by Eq. (14). In addition, the slope of the measured zinc curve varies little over the 33 month exposure period. This conforms with the assumption of a constant β used earlier to develop the parabolic and cubic models.

At present, precipitation runoff equations analogous to Eq. (14) for metals exposed on the Oregon coast have not been determined. Studies are planned for thermal-sprayed zinc, copper, and weathering steel. The equations are expected to include a "clean rain" term plus other terms representing perhaps soluble chloride complexes of the metal ions. They should also include a factor allowing for the high time of wetness associated with frequent fogs and extended periods of rainfall. In addition, precipitation runoff measurements from bridge surfaces are planned that should yield estimates of the chloride flux delivered to the bridges by wet and dry deposition.

Results from Gullman[21] for metals exposed along the Swedish coast can be used as an example of how microclimates influence the values of α and β. In this case the microclimate is characterized by Cl^- deposition rates. Figure 7 shows how α changes as a function of Cl^- deposition. The cubic model of Eq. (8) was used to fit the 8 year mass loss data from each site. Except for zinc at the high Cl^- deposition site, the value of α for each metal increased for increasing Cl^- deposition. This indicates a strong affect of chloride on the diffusivity of the corrosion film. Figure 8 shows the corresponding values of β for the same 8 year mass loss data. In contrast to α, there is little variation in β (except possibly for carbon steel) indicating that Cl^- deposition does not change the runoff loss rate. This suggests that Cl^- deposition results in a breakdown of the protective film and an increase in the reaction rate at the metal-film interface, as opposed to taking part directly in reactions that increase the solubility of the corrosion film in precipitation runoff.

SUMMARY AND CONCLUSIONS

Samples of metals and bridge paint systems have been exposed on and under seven bridges and on 31 utility poles in coastal Oregon to determine the effects of microclimate on corrosion performance. Samples were placed so as to examine the effects of distance from the ocean, sheltering, sample inclination, sample orientation, and local climatography. Initial results after one-year of exposure show strong effects from differences in microclimate.

With respect to coating delamination, sealed thermal-sprayed aluminum samples were superior to three coat bridge paint system samples. Delamination of the paint samples was greatest at the four bridges closest to the ocean. The extent of delamination was much greater for the boldly exposed samples than it was for the sheltered samples under the bridge. The extent of delamination was similar for all sample orientations (0, 30, and 90°).

The corrosion of 3105, 5052, and 6061 aluminum was greatest close to the ocean. The groundward facing samples were slightly less corroded than the skyward facing samples. Overall, the corrosion of the 5052 Al was less than that of the 6061 Al, which was less than that of the 3105 Al.

X-ray diffraction indicated corrosion film composition and chemistry on copper samples was strongly affected by microclimate. Three minerals were identified in the corrosion product on copper: cuprite, atacamite, and chalconatronite. The absolute and relative amounts of these minerals varied from site to site, for different orientations, and with sheltering. In some cases the differences were great and would result in significantly different corrosion performance.

An atmospheric corrosion model useful for interpreting and extrapolating atmospheric corrosion data was presented based on competing film growth and film dissolution processes. The parameters of the model are related to the physical

properties of the corrosion product and to the deposition of species from the environment. Based on corrosion data from the Swedish coast,[21] chloride was found to alter mass transport through the corrosion product (the α term in the model) and hence, the rate of corrosion at the metal-film interface.

Precipitation runoff measurements were discussed as a means for determining the corrosive species in coastal environments and the delivery mechanism of reactants. Precipitation runoff experiments also provide an independent measure of β in the atmospheric corrosion model. Precipitation runoff experiments are planned in future experiments along the coast.

ACKNOWLEDGMENTS

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TABLE 1
NUMERICAL RESULTS FROM FITTING MODELS TO EXPERIMENTAL DATA

Model	Parameter	Red Brass	Zinc	Weathering Steel	Carbon Steel
bilogarithmic	Slope, a	0.534	0.707	0.587	0.938
	10^b (µm)	0.430	0.465	1.54	1.72
	s (µm)	0.472	1.94	8.53	333
parabolic	α (µm²/y)	2.92	2.93	411	156
	β (µm/y)	0.408	1.30	9.16	47.6
	T_s (µm)	7.16	2.25	44.9	3.29
	s (µm)	0.316	1.68	3.18	286
cubic	α (µm³/y)	6.15	5.45	9600	517
	β (µm/y)	0.581	1.32	10.1	47.6
	T_s (µm)	3.25	2.03	30.8	3.30
	s (µm)	0.233	1.67	2.24	286

TABLE 2
TYPICAL RANGES FOR CUBIC MODEL PARAMETERS

Alloy	α (µm³/y)	β (µm/y)	T_s (µm)
Copper alloys	0.4 - 7.60	0.2 - 2.6	1.0 - 20
Zinc	5.4	1.3	2.0
Carbon steels	520 - 64,000	2.8 - 47	3.3 - 100
Weathering steels	650 - 40,000	1.6 - 16	19 - 88

TABLE 3
BRIDGE CORROSION TEST SITES

Bridge	Distance to Ocean, m	Elevation, m	Year Built	Setting	Environmental Factors		
					Wind	Sand	Salt Spray
Youngs Bay	6,437	12.2	1964	bay, open, flat	1	0	1
Spencer Creek	91	16.2	1947	beach, low hills	1	1	2
Yaquina Bay	457	45.7	1928	inlet, low hills	1	0	1
Cape Creek	91	24.4	1931	ravine, high headland	2	2	2
Umpqua River	792	12.2	1925	river, open, low hills	1	0	1
Brush Creek	244	16.8	1955	beach, mountain headland	3	3	3
Rogue River	1,524	19.8	1930	river, narrow valley	1	0	1

FIGURE 1 - Schematic of chemical, electrochemical and mass transfer processes occurring during atmospheric corrosion.

FIGURE 2 - Universal mass loss curve for cubic model. Experimental atmospheric corrosion data also plotted.

FIGURE 3 - Coastal atmospheric corrosion test site locations at bridges and utility poles in Oregon.

FIGURE 4 - Boldly exposed samples on the Spencer Creek bridge.

FIGURE 5 - Monthly average climatological data for the Oregon coast.[16]

FIGURE 6 - Cumulative runoff loss rate terms for zinc corrosion product dissolution: 1) precipitation, rSV; 2) plus H^+; 3) plus $[SO_2]$; 4) plus $[HO_3]$; 5) minus basic particulate, $[CaMg_{H+}]$. Solid curve is the experimentally measured zinc in runoff.

FIGURE 7 - The α term of the cubic atmospheric corrosion model for various metals as a function of chloride deposition. Calculated from corrosion data for the Swedish coast.[21]

FIGURE 8 - The β term of the cubic atmospheric corrosion model for various metals as a function of chloride deposition. Calculated from corrosion data for the Swedish coast.[21]