Paper No.
C2024-20792

ANNUAL CONFERENCE + EXPO
MARCH 3-7, 2024 | NEW ORLEANS, LOUISIANA

ATMOSPHERIC CORROSION: GIS CORROSION MAPPING AND MATERIALS SELECTION FOR ELECTRICAL TRANSMISSION LINES AND SOLAR FARMS

Mehrooz Zamanzadeh, George T. Bayer, Alyson Char, Anil Kumar Chikkam,
Peyman Taheri, and Clinton Char
Matergenics, Inc.
100 Business Center Drive
Pittsburgh, PA 15205

Benjamin S. Jessup
Pepco Holdings/Exelon
701 9th Street NW
Washington, DC 20001

ABSTRACT

The life expectancy of transmission structures depends largely on the material selected and the material's suitability to the environment to which the structures are exposed. The selection of galvanized and weathering steels for above and below grade applications is a matter of corrosion engineering judgement and corrosivity of the service environments, economics, appearance, and aesthetics. The best way to select the right material for T&D applications is to develop a corrosion map for the service territory that addresses both atmospheric and underground corrosion risks. The map would identify areas of high, medium, and low corrosion risks based on quantified corrosion rates. As part of this effort one can perform field inspections to confirm the accuracy of the corrosion risk assessment map for the material selected.

Keywords: galvanized steel, weathering steel, transmission poles and towers, atmospheric corrosion maps, atmospheric corrosion assessment and management

INTRODUCTION

The life expectancy of a transmission structure depends largely on the material selected and the material's suitability to the environment to which the structure is exposed. The purpose of this paper is to assess the suitability of two materials: *weathering steel* and *galvanized steel*. The study examines issues of atmospheric and in-ground exposure and included both a desk study and on-site sampling and analysis.

Corrosion risk assessment of transmission structures begins long before the structure is ever placed in service. Risk assessment should start at: a) the design stage with materials selection, b) continue through the manufacturing process, c) then during storage, shipping and handling, d) in construction, and finally, e) in service life. This study focuses on corrosivity of the environment and assumes when the structure is commissioned for service it is not damaged.

For both weathering steel and galvanized steel, two factors are most important with respect to corrosion in atmospheric exposure: a) time-of-wetness, and b) contact with corrosive ions, especially chlorides and sulfates. With respect to in-ground exposure, two factors dominate: a) soil resistivity and how it varies with moisture

© 2024 Association for Materials Protection and Performance (AMPP). All rights reserved. This work is protected by both domestic and international copyright laws. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means (electronic, mechanical, photocopying, recording, or otherwise) without the prior written permission of AMPP.

Positions and opinions advanced in this work are those of the author(s) and not necessarily those of AMPP. Responsibility for the content of the work lies solely with the author(s).

content of the soil, and b) the presence and type of corrosive ions, e.g., chlorides, sulfates.

Generally, weathering, and galvanized steel should not exhibit accelerated corrosion or significant thickness loss in mild corrosive environments. However, localized conditions dominate and can present an environment that promotes accelerated corrosion, and such risk potential must always be considered for specific locations.

Internal corrosion is of concern for poles when moisture accumulates inside the poles—either galvanized or weathering steel poles. In general grouting prevents drainage of moisture which may result in internal corrosion specially for aging poles.

Monitoring the corrosion condition of weathering steel structures is recommended. The protective outer layer, called goethite, takes years even decades to fully develop. Monitoring the development of this layer involves evaluating the layer's adhesion and thickness, as well as its color. For the case of galvanized steel, monitoring the galvanized layer thickness determines the remaining life and time to coating application. Maintenance coating should be considered when *eta*, *zeta* and *delta* intermetallic galvanized layers are corroded. Structural corrosion starts after five to ten years depending on corrosivity of the environment.

Localized conditions and internal corrosion must be considered where corrosive moisture accumulates. In any local area where above-ground time-of-wetness would run higher, the risk of atmospheric corrosion runs higher. For prolonged time-of-wetness, galvanized steel is the preferred choice and maintenance painting may be required. With respect to in-ground, both weathering and galvanized steel should have cathodic protection and a suitable coating applied to protect against the adverse effects of higher-than-normal soil corrosivity.

In the past materials selection for transmission towers/poles in electric utilities and solar farms was not based on classification of environment and corrosion mapping, thus they were prone to all kinds of misapplications and corrosion attack due to unexpected corrosivity of the service environment. These problems lead to more analysis and factual date gathering prior to materials selection for transmission applications. That is why this study is important. To our knowledge this is the first time that the service areas of structures are classified for corrosivity by GIS corrosion mapping.

ATMOSPHERIC CORROSION MAPING

The construction of atmospheric corrosion maps can be based on corrosive SO_2/NO_x deposition, chloride deposition and time-of-wetness. These results, in addition to a geostatistical approach will provide a map of atmospheric corrosion in region of interest.

Corrosion cannot take place without presence of moisture (electrolyte) and corrosive ions. The time-of-wetness (TOW) is a measure of how much time the material will be in contact with a conducting solution. Wet surfaces are formed by factors such as dew, rainfall, melting snow, or fog and high humidity. These conditions are estimated by looking at the time during which the relative humidity is greater than 80% at temperatures greater than 0°C. Sulfur dioxide pollution is another major cause of atmospheric corrosion and is more prevalent in industrial and urban environments. Chlorides are a known corrosion risk for several reasons. Firstly, they are a major component of most salts, which accelerate corrosion due to their hydrophilic nature. When a salt attracts water and dissociates, it produces a highly conductive electrolyte. Secondly, chlorides are the main catalyst for pitting corrosion, which is an autocatalytic localized attack. Chlorides are known to cause hydrolysis and create acidic chlorides in reducing conditions. In addition, corrosion products that contain chlorides are typically more soluble than those that contain oxides. One can monitor airborne salts carried by the wind from the ocean. Airborne chloride concentrations are not monitored by weather stations and the models that we use to determine them are only accurate up to a few miles from the shore. As such, most estimates using the model in conjunction with ISO 9223:2012[1] will be utilized for atmospheric corrosion maps. With on-site measurements more accurate deposition rates for chlorides, sulfates and TOW can be obtained, per ISO 9223:2012.[1]

For example, estimates show that Los Angeles is typically either C3 or C4 (moderate to high corrosion rates). For carbon steel, this equates to 25 to 80 µm/year corrosion rate. For zinc, this equates to 0.7 to 4.2 µm/year.

This agrees with data from the American Galvanizers Association (21.4 µm/year for carbon steel and 1.09 µm/year for zinc).[2] It should be noted that this assumes that the structure in question is not too close to the ocean.

Along the coastline, a C5 (very high corrosion rate) can be expected due to higher chloride deposition rates. Concentration of sea salt aerosols, which are the main atmospheric pollutants in coastal regions, gives an indication of the probability of the atmospheric corrosion. A combination of the results with a geo-statistical approach and modeling may be used to construct the corrosion map. The specific environmental conditions, which are affecting the source and distribution of airborne salinity should also be considered in construction of corrosion risk maps.

The construction of atmospheric corrosion risk map consists of two phases:

- The relevant data will be collected, categorized, and analyzed with respect to the project objectives. The information will consist of several distinctive sets of data such as chloride deposition rates, sulfate deposition rates, time of wetness and wind data.
- A knowledge-based approach along with adequate and accurate equipment, and advanced techniques, will be used to collect, analyze, and verify the Phase I corrosion mapping at statistically representative selected sites. The investigators should not only consider atmospheric parameters, but also corrosion sources – such as presence of chemical plants emitting corrosive gases, electric generation plants, salt sprays sources, wind loads.

An example of an underground corrosion map is shown in Figure 1.

UNDERGROUND CORROSION MAPPING

In order to develop an underground corrosion map, five sets of data are required, as listed below:

- **Data Set 1:** Coordinates for assets and the service territory.
- **Data Set 2:** Structural data including foundation designs for the structures. This information includes the foundation material, presence of protective coating, presence of concrete backfills, and extent of foundations depth.
- **Data Set 3:** Physiochemical properties of soil describe the corrosivity of liquid phase in soil. The main parameters in this category including electrical conductivity (inverse of resistivity), pH level, and concentration of chemical salts.
- **Data Set 4:** Geological information to estimate the moisture content of soil and the time-of-wetness. The main parameters in this category are soil type, soil drainage class, and surface topology. Soil texture refers to the size distribution of soil particles, regardless of the material components. Based on USDA textural classification triangle, soil categorization is made based on the relative proportions of silt, sand and clay that are main soil components with different grain size.
- **Data Set 5:** Location of foreign assets that can become a source for stray current corrosion. This includes ground beds for cathodically protected pipelines, electric rail systems, and buried electrical equipment. The structures located in vicinity of stray current source can experience extensive material loos over a short period, depending on the value of stray current (DC current).

A map for underground corrosion in the considered territory can be development by combining the relevant information from individual maps. The final corrosion map highlights areas with low risk, moderate risk, and high risk of corrosion based on soil properties (data set 3), geological information (data set 4), and presence of stray current source (data set 5). An example of an underground corrosion map is shown in Figure 1.

The collected data from the atmospheric and underground corrosion mapping may be mapped on individual map layers, and all map layers will be combined to generate a corrosion risk assessment map. Geographical information system (GIS) corrosion map layers (for pH, soil type, chlorides, sulfates, drainage, soil resistivity, etc.) are input and weighted to construct the final corrosion map for both soil and atmospheric corrosion. Figure 2 presents an illustration of the concept. The following summary is provided to introduce a selection of concepts in a simplified form that are further described below in the detailed description.

In various implementations, a plurality of disparate datasets is aggregated into a geodata data structure specifying a plurality of geospatial locations and a set of aspatial parameters at each geospatial location. Each aspatial parameter is combined at each geospatial location to generate an atmospheric corrosivity scale parameter at each of the plurality of geospatial locations. A grid is created with cells representing each of the plurality of geospatial locations and each of the corresponding atmospheric corrosivity scale parameters. The grid is stored for output of at least a portion of the plurality of geospatial locations and the corresponding atmospheric corrosivity scale parameters overlaid on a geographic map.

In other implementations, datasets having aspatial data corresponding to a plurality of geospatial locations from a plurality of data sources are imported. The datasets are stored in a plurality of file attribute tables with the aspatial data linked to the corresponding plurality of geospatial locations within the plurality of file attribute tables. A plurality of data layers is aggregated from the plurality of file attribute tables to determine an atmospheric corrosivity scale parameter at each of the plurality of geospatial locations. A grid with cells representing each of the plurality of geospatial locations and the corresponding atmospheric corrosivity scale parameters is created. The grid is stored for output of at least a portion of the plurality of geospatial locations and the corresponding atmospheric corrosivity scale parameters overlaid on a geographic map.

The final corrosion map identifies areas with low to severe risk of underground corrosion. A proprietary method will be utilized for corrosion risk assessment. The method includes an algorithm to assign a corrosivity index to each location on the map based on soil properties, geological data, and external corrosion factors. The accuracy of this algorithm has been field-tested in several projects.

THE MATERIALS OF CHOICE FOR ELECTRICAL TRANSMISSION STRUCTURES

Weathering Steels

Weathering grade steels have been available for electric power transmission applications for many years. Figure 2 presents a photograph of a weathering steel pole. Their cost-effectiveness has been demonstrated in practice: the upfront premium is offset by the elimination of initial and maintenance paining, and inspection requirements. The selection of weathering steels for transmission applications is a matter of corrosion engineering judgment. Three key factors to evaluate are: environment, economics, and appearance (aesthetics).

Weathering steels are low-alloy steels that contain a few percent of alloying elements: copper, chromium, nickel, vanadium and silicon. The presence of these alloying elements in weathering steel is believed to facilitate the formation of stable, protective oxide layers that develop progressively over many years of exposure. Densely packed protective layers impart the greatest corrosion resistance. In general, the surface oxide layers formed on weathering steel undergo progressive transformations as follows.

- Hematite α-Fe_2O_3: time to formation – days and months.
- Amorphous substances – several years.
- Protective goethite α-FeO (OH) – decades.

The appearance, texture, and maturity of the oxide layer depend on three primary interrelated, natural factors: time, degree of exposure, and atmospheric environments.

The oxide layer incorporates alloying elements such as Cr, Cu and Ni, as shown in our x-ray mappings. The presence of these alloying elements in the oxide layer at the substrate surface assists the transformation of γ-

FeO(OH) to the more protective, densely-packed barrier coating of α-FeO(OH). This layer significantly reduces the permeation of moisture and corrosive ions, enhancing corrosion resistance by isolating the weathering steel substrate from the environment. However, the presence of reducing ions (chlorides) in a continual wet environment can inhibit the formation of this protective layer or destroy an existing one. In this case, non-protective, bulky oxides containing magnetite form. This outcome has been personally observed in communication towers where joints hold moisture. The rust buildup, called “pack-out,” can contribute to cracking and failure of load bearing members.

The single most important finding from previous field investigations is that the presence of excessive chlorides (reducing conditions) does not allow the formation of the compact and protective α-FeO(OH) on weathering steel.

Galvanized Steels

Galvanized steel is one of the most often specified materials for electric transmission assets such as lattice towers and poles, solar farm piles and especially for high-voltage transmission line structures and substation structures. Figure 2 is a photograph of galvanized towers. This material has a long record of proven performance. In a recent field assignment to Texas, galvanized lattice towers dating back to the early 20th century were observed to exhibit an intact galvanized layer even after 100 years of service. Figure 3 graphically illustrates the time to first maintenance of galvanized steel as a function of average zinc thickness and environment.[2] Solar farm piles are similar in corrosion behavior to galvanized poles.

Galvanized steel structures are protected from corrosion attack due to both the barrier effect and the galvanic (sacrificial) action of zinc. The applied zinc coating typically does an excellent job protecting steel when located in moderately corrosive environments in which oxidizing conditions prevail.

The quality of the galvanized product is most dependent on the practices of the galvanizing facility. There are wide variations in quality between galvanizers, and even within each galvanizer. The production of high-quality galvanized steel structures begins with the chemistry of the underlying steel as purchased by the galvanizer, as it determines the desired metallurgical reaction between steel and molten zinc. Next is the quality of the preparation of the steel, and the makeup and consistency of the zinc bath chemistry. Cooling rate is next. Often overlooked are the subsequent shipping, handling and storage, as these introduce conditions that may promote unfavorable surface reactions.

Figure 4 presents a photograph of corrosion of a galvanized base plate. The factors often associated with corrosion failure of a galvanized steel structure are improper thickness, excessive brittleness of the intermetallic alloy layer, general galvanizing failure, substrate surface preparation (especially if previously coated), storage conditions, installation damage, soil service conditions, or unsuitable coating selection for the soil or expected in-service atmospheric exposure conditions. Galvanized surface colors (different shades of gray) may be specified based on project site requirements and aesthetics. Chemical and electrochemical treatments may also be utilized to achieve specified project or asset coloring as may be required to achieve stakeholder acceptance. The following summarizes important parameters:

1. Barrier Protection
    - Isolates metal from the environment.
    - Must adhere to the base metal.
    - Must be resistant to abrasion.
2. Cathodic Protection
    - Change electrochemistry of corrosion cell.
    - Based on the electrochemical series.
    - Insure. that base metal is the cathodic element.
3. Hot-Dipped Galvanizing Provides Both Kinds of Protection
    - Strongly resistant to most oxidizing environments.
    - Rate of corrosion is significantly less than steel called “Patina.”
    - Life of the zinc coating depends on zinc thickness and corrosivity of the environment.
4. Stability of Galvanized Steel

- Oxygen, water, corrosive ions (chloride).
- Thickness.
- Corrosion rate.

Recognizing that structures are exposed to moisture and corrosive ions, it is critical for asset owners to effectively anticipate, mitigate and manage the effects of corrosion in aging structures. This knowledge leads to a realization that corrosion can and will occur above ground and out of sight below ground and under certain conditions even in the absence of oxygen.

General Materials Selection Issues

There are documented cases where application of weathering and galvanized steel in improper locations or under improper conditions has resulted in less than desirable performance of the material. In most cases, this poor performance was the result of a lack of understanding of the limitations of weathering grade steels, or from poor detailing which caused excessive corrosion exposure.

Problems that have been identified in the past are as follows.

- High elevation corrosion of T&D structures in marine environments
- Excessive corrosion of foundation of lattice towers and poles.
- Corrosion at the interface of bare material and the below grade protection coating on embedded designs.
- Corrosion on the top surface of horizontal tubular members.
- Internal corrosion of poles.
- Corrosion at attachment details.
- “Packout” failure of connections in lattice towers and poles.
- Corrosion during prolonged storage.
- Mixing steel and weathering structures.
- Aromatic polyurethane coatings with no ultra-violet protection.
- Stray current corrosion.
- Galvanic corrosion due to copper grounding, in particular, near substations with high conductive soils.

Atmospheric Corrosion Assessment

In classifying the corrosivity of the project site per the ISO 9223:2012~~[1]~~ standard, the following parameters are considered: temperature, time-of-wetness, airborne chlorides and sulfur dioxide in addition to wind direction. In general, the atmospheric corrosion of weathering steel structures is affected primarily by bulk weather conditions (prevailing winds, corrosive ions, condensation & precipitation). The tower sites are an environment with very low frequency of condensation, rain, and low deposition of chlorides and low concentration of SO_2. Figure 6 presents an example map of general atmospheric environmental zones in southern California near San Diego generated by the authors’ company.

The following sections discuss these factors and how it relates to the site characteristics. Temperature by itself influences corrosion rate but can have several effects: increasing temperature accelerates the rate of the corrosion reactions if moisture is present, but, on the other hand, leads to more rapid evaporation, thus shortening the time-of-wetness and decreasing the corrosion rate.

Time-of-Wetness (Temperature-Humidity Complex)

Time of wetness is the length of time during which the metal surface is covered by a film of water, which renders atmospheric corrosion possible. ISO 9223:2012[1] defines this period as the number of hours per year that the relative humidity is above 80% for temperatures above 0°C. According to this standard, the time-of-wetness at the San Diego Lindbergh Field is less than 250 hours per year.

An essential factor in corrosion of transmission towers and poles is the presence of water on the surface of the structure. This water need only be present in microscopic amount yet is necessary as the electrolyte in the electrochemical corrosion process. Time-of–wetness is a measure of how much the local environment promotes this presence, expressed either as hours per year of as a percentage of time. Estimating time-of-wetness can be done by gathering hourly weather data from airports atmospheric research centers and universities.

For example, for weathering steel there is a criterion that if relative humidity exceeds 80% for less than 5300 hours per year, then time-of-wetness is likely not a contributor to accelerated corrosion. Time-of wetness is generally not a concern in San Diego. Specific sites may have conditions that differ from this general conclusion.

Figure 6 presents a relative humidity map of the mainland United States.

Corrosive Ions

Deposition of chlorides. In coastal areas is strongly dependent on the variables influencing the transport of salt, such as wind direction, wind velocity, local topography, distance of the site from the sea, etc. In the presence of moisture, water-absorbing salts accelerate the corrosion of weathering steel and prevents the formation of protective layer.

Airborne salinity is a powerful stimulant for atmospheric corrosion and the deposition rate of salt in non-sheltered situations is directly proportional to the concentration of salt in the atmosphere. Airborne salt has a major influence on corrosion rates. Consequently, it is most important in cases of materials used near bodies of saltwater to consider the effect airborne salinity has on those materials. Airborne salinity is strongly dependent on the variables influencing the transport inland of sea-salt, such as wind direction, wind velocity, local topography, and especially the distance of the exposure site from the sea.

It is generally considered that he highest chloride depositions are usually within 200 to 300 meters of the saltwater body's shoreline and decreasing exponentially, depending upon prevailing winds and topography. Figure 7 presents a chloride deposition map of the United States generated by the authors' company.

Sulfate Deposition. Deposition of sulfates on the surface of weathering steel towers generally depends on atmospheric concentrations of and the local climate. Once the corrosive sulfates are on the surface, interactions will vary depending on the amount of exposure, the reactivity and the amount of moisture present. The transformation reactions may take place both in gas phase and in aerosol phase. For most of the materials, SO_2 is the main corrosive agent in the air. Research has discovered that when NO_2 is presented with SO_2, increased corrosion rates occur. The NO_2 oxidizes the SO_2 to sulfate thereby promoting further SO_2 absorption. As a result, SO_2 is considered as a major contributor to deterioration. Moisture conditions are strongly correlated with relative humidity and temperature in absorption process deep in to the exposed components. Sulfates are primarily an anthropogenic corrodent, produced by the burning of coal and high sulfur fuels. Prevailing wind currents have flooded the rust belt of America with sulfates for decades from coal plants from Oklahoma City to Boston. Even though these levels of sulfates have come down from astronomical levels, the eastern United States still has an ethereal elevated sulfate level. California, however, has no anthropogenic sources of sulfates. The state has the strictest guidelines on sulfur in fuels for power plants and vehicular transportation. Figure 8 presents a map of sulfate ion wet deposition of the United States in 2013.[3]

Environmental Factors

Atmospheric Exposure. The metal structure is essentially immersed in an uncontained volume of air and all that comes with it. The "composition" of that ever-moving air can vary dramatically by time of day, time of year, and by location.

Industrial environments are generally the most aggressive in terms of corrosion. Air emissions may contain some sulfides and phosphates. Automobile, truck and industrial plant exhaust are examples of these emissions. Most city or urban areas are classified as moderately industrial. Galvanized steel exhibits accelerated corrosion in heavy industrial environments.

<u>Wind.</u> Wind plays a pivotal role in the delivery of the above substances to the structure's surface. Consequently, wind properties are important, such as direction, speed, and frequency. There are regional, general wind properties, and there are localized wind properties, which are more difficult to determine, though some utilities have measurement capabilities to overcome this complication.

RECOMMENDED ABOVE GRADE ASSESSMENT PROTOCOL

Recommended standards for above-grade corrosion assessment focuses on: (1) Assessment of the service environment based on ISO standard to rate corrosivity; (2) Visual inspection of higher elevation segments of the structure to identify gross forms of corrosion and galvanizing / coating loss; and (3) Focused assessment of the ground-level section of the structure to quantify galvanizing / coating loss.

These factors are taken into consideration along with structure age, size, and importance and each structure is assigned an Above Grade Corrosion Risk Factor (AGCRF). This rating should be used to recommend appropriate remediation and mitigation procedures.

Evaluation of Environment Based on ISO 9223:2012, "Corrosion of Metals and Alloys – Corrosivity of Atmospheres – Classification."[1]

Classification of an atmospheric service environment consists of three primary factors: (1) chloride contamination from ocean; (2) sulfur or other chemical contamination from industrial or agricultural activity; and (3) Time of wetness as defined by yearly weather patterns.

<u>Evaluation of Corrosion Condition.</u> The corrosion condition of the above-grade portion of a weathering steel and galvanized steel structure is performed visually and by non-destructive measurements. The structure is first evaluated for condition of at higher elevation. The fasteners are the most susceptible to corrosion due to the thinner galvanizing and complex geometries which may harbor corrosion cells. High elevation inspection is performed visually using binoculars.

Components at ground level are then assessed visually and by surface testing. Galvanizing thickness and patina thickness measurements are taken at several locations on each zone. Surface electrochemical measurements are taken at the same locations. Table 1 presents a rating scale for patina development on weathering steel.

By assessing the thickness measurement along with the electrochemical measurement and visual appearance, the type of oxide on weathering steel actual remaining amount of galvanizing can be estimated.

Table 1: Weathering Steel Patina Development

Rating	Color	Condition	Texture	Typical Environment
1	-Dark Chocolate brown to Purple brown	-Fully matured protective goethite layer, tightly adherent and dense	-Durable, tightly adherent surface capable of withstanding hammering or vigorous wire brushing -Few oxide particles removed by tape test	-Moderate climate with humidity and frequent exposures to sun and rain, protective oxide develops rapidly in industrial areas. -Rural environments may require more than 3-5 years to achieve maturation
2	-Color range between yellow-orange to reddish brown	-Initial stages of exposure -Juvenile lepidocrocite or mixed protective oxide	-Dusty -Loose oxide particles may appear on tape test -Light sanding may expose shiny metal	-Moderate climate with humidity or arid climate with proximity to coastal waters, streams, and or industrial centers and occasional rain. -Protective oxide develops rapidly
3	-Brown, tan, red	-Non-protective hematite oxide	-Loose, powdery to sandy feel	-Arid sunny climates -Seasonal rains

		-May indicate potential problems depending on age and location of structure	-Small yet excessive particles removed by tape test	
4	-Dark brown to black -Patchy or localized black areas -Glittery if small and dispersed	-Non-protective magnetite oxide -Excessive and./or deep pitting may occur, depending on age	-Small flakes ¼ to ½ inch or larger laminar sheets -Sharp or prickly to touch -Large distinguishable flakes and excess of particles removed by tape test	-Long periods of rain followed by complete dry out cycle -Marine environments -Proximity to roads where de-icing salts are used -Chemical treatment -High pollution areas

Now it is generally agreed that both common carbon steel and weathering steel form corrosion products (rusts) that tend to stratify with exposure time. Both common carbon steels and weathering steels present a rust layer that is in turn composed of two sublayers, a reddish outer layer and a dark grey inner layer. This stratification is independent of the degree of protection afforded by the rust. The composition and morphology of the protective patina formed on weathering steel is very different to the coating formed on carbon steel. The difference between the rust layers formed on carbon steel and on weathering steel is that the α-phase (goethite phase) on the latter forms a densely packed and uniform layer of nanometer-sized particles, which are closely attached to the underlying steel. According to Kamimura et al.[4], the protective rust layer on weathering steel is usually formed spontaneously after a certain number of years of exposure. Until the protective ability of the rust layer emerges, the weathering steel corrosion rate is not especially low. Furthermore, the protective rust layer cannot form in coastal environments where the amount of airborne sea-salt particles is relatively high. The higher the chloride deposition rate in marine atmospheres, the greater the degree of flaking observed, with loosely adherent flaky rust, favoring rust film breakdown (detachment, spalling) and the initiation of fresh attack.

The morphologic characteristics of the protective patina will therefore depend on the type of environment (rural, urban, industrial, or marine), weathering steel composition, years of exposure, relative humidity, temperature, and pollutants (SO_2, Cl^-, etc.) as the main factors governing the formation and transformation of the protective layer.

<u>Galvanized steel.</u> Hot dip galvanizing exhibits a top layer of nearly pure zinc and three distinct zinc-iron intermetallic layers beneath. The surface electrochemical measurement helps determine how much galvanizing loss has actually occurred as it identifies which intermetallic layers are exposed. Both visual analyses and galvanizing thickness measurements on aged, galvanized steel can be misleading without this additional measurement.

IN-GROUND / WATER-SOIL EXPOSURE ASSESSMENT PROTOCOL

In order to fully understand the corrosion risk to the buried portion of transmission and distribution structures or any physical asset, a basis for estimating the probability of corrosion for external surfaces in contact with soil must be established.

However, the probability of corrosion of these items is not only governed by the corrosiveness of the soil and the properties of the galvanized steel, but also by their design, their size and by external electrochemical effects (i.e., stray currents, etc.). Since these parameters cannot always be described with adequate accuracy, the likely corrosion behavior can only be estimated.

In determining the corrosivity of a soil, the different constituent soil characteristics and relevant attributes of the physical environment should be considered. A ranking of the various factors is assigned in order of importance (relevance to corrosion science). The sum of those rating factors is a measure for the overall soil corrosivity.

The key characteristics usually considered include the following.

- Soil Characteristics - Factors and Attributes: Soil type, homogeneity, moisture content, pH, resistivity, chemical properties, buffer capacity, level of oxidation, organic content, presence of excessive sulfates and chlorides could lead to micro-biological induced corrosion (MIC).

- Physical Environmental Characteristics – Factors and Attributes: Time of wetness and ground water, land use – indicates possible chemicals and salts, electrical and impressed current cathodic protection (ICCP from gas lines) interference, stray currents, and galvanic action due to grounding, contamination.

It is important to have an understanding of the key factors that are measured or assessed in order to accurately and adequately interpret the results. For example, soil resistivity which is an approximate measure of the concentration of reactant ions leading to corrosion typically decreases as the moisture and ionic concentration increases. Generally, terrains with lower resistivity and reducing properties experience higher corrosion rates. All tests for the defined corrosion factors are typically performed using standard methods (or modified methods) developed from experience and testing.

For example, one method of measuring soil resistivity is that described in AASHTO T 288, "Determining Minimum Laboratory Soil Resistivity."[5] This method was developed from a California Department of Transportation procedure sanctioned by the Federal Highway Administration (FHWA) for evaluating mechanically stabilized earth (MSE) backfill. The American Society for Testing and Materials (ASTM) has a different procedure. The method described in ASTM G57 – 06(2012), "Standard Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method"[6] will be replaced by a two-part standard: Part A covers the four-electrode method for in situ field measurements, and Part B covers the use of a soil box for laboratory and field-test measurements. Corrosion tests on galvanized steel poles buried at different sites are performed by soil resistivity measurements at different depths, pH measurements, Total Dissolved Solids (TDS) chlorides and sulfate, redox potentials (where applicable), resistance polarization (Rp) measurements and corrosion rate. It was found that the galvanized steel resisted corrosion far better than bare steel at all sites. The zinc corrosion rate for sixty sites in mils per year was found to be as shown in the following Table 2.

Table 2: Zinc Corrosion Rates for Corresponding Soil Types (Mils Per Year)

Soil type	Zinc Corrosion Rate (mils per year)
Oxidizing clay	0.05 - 0.20
Reducing acidic soil	0.1 - 2.0
Salty Marsh	0.5 - 2.5
Moist natural clay	0.1 - 0.50

It should be noted that there is a decrease in corrosion rate for oxidizing soils due to formation of protective layers on galvanized steel. However, in reducing soil such a layer is absent and therefore the corrosion rate may increase as a function of time. In this case the structure should be adequately protected when located in reducing soils. For galvanized steel poles especially, the protection should be applied both outside and inside of the pole if water table is high or is expected to be a concern. Agricultural soils are typically more corrosive due to the high concentration of chlorides and sulphates in fertilizers, And, likewise, structures exposed to excess amounts of road or sea water salts (NaCl) experience higher corrosion rates due to more exposure to chlorides. In some cases, the actions of other stakeholders could unknowingly worsen the corrosion risk for structures. For example, new road de-icing formulations such as magnesium chloride ($MgCl_2$) used as alternatives to the traditional salt-sand de-icing mixtures have been shown to have increased negative impacts on structural steel by increasing the corrosion risk.

Inspection Techniques and Confidence Level

The methods for determining corrosion risk of galvanized steel below grade include knowledge-based assessments bringing together materials science, electrochemical and corrosion science as well as an understanding of how a structure is designed, built, and assembled. The key techniques involved are geared towards quantitatively determining the soil and physical characteristics of the service environment in order to carry out a qualitative multi-factor risk-based assessment of corrosion risk. The authors have successfully initiated and carried out work of a similar nature and are available to discuss in further detail. There is ongoing research into the effectiveness of these methods across a wider jurisdiction and this will be combined with work on mitigation techniques and technology for subsequent works. Based on the work done so far, the authors recommend the following activities.

- Physical assessment of the soil service environment to rate corrosivity.
- Electrochemical testing of soil condition and steel interaction (e.g., potential values and soil resistivities to predict corrosion profile at lower depths).
- Focused visual, physical and electrochemical assessment and testing of buried components at a shallow depth.

In risk assessment, these test results should be taken into consideration along with structure age, size, design, function and importance. Each structure is then assigned a below-grade corrosion risk rating or condition assessment value. This rating is used to recommend appropriate remediation and mitigation procedures. Special attention should be given to structure designs that result in accumulation of moisture and corrosive salts regardless of whether the foundation is buried in soil or encased in concrete.

Depending on the method of evaluation, a level of confidence has been assigned to indicate the ability of that procedure to produce reliable corrosion risk data on its own without combining it with another form of assessment.

Below-Ground or Soil Characteristics

The following soil characteristics are important for below-ground corrosion risk assessment.

pH of Natural Soils. Measurements of soil pH should be uniformly acquired, either all at the time of taking the soil sample or all later in the laboratory but should not be mixed. The corrosion literature suggests that in the pH range of 4-10, the corrosion rate for bare steel of any kind is independent of pH and depends only on how rapidly oxygen diffuses on the metal surface.

Salt concentrations in pore liquids (particularly chlorides and sulfates) Chlorides, sulfates and other dissolved salts decrease resistivity, promoting the flow of corrosion currents and impeding the formation of protective layers. All these are summed up in the soil resistivity.

Quantity of pore liquids. The common parameters related to soil moisture are depth to water table, distribution of rainfall and frequency of flooding. The quantity of pore liquids determines the air content, a major determinant of corrosivity.

Organic content. Both plants in contact with the steel and organic acids from decaying plant material can have serious deleterious effects on buried steel structures.

Soil chemistry, Particularly agricultural and industrial chemicals and alkalis. These can have important effects on the chemical environment. Concentrations will vary with depth and evaporation rates, in turn dependent on temperature, humidity and solar input.

Soil origin. In many instances structures may be surrounded by imported back fill, not the original soil. Properly chosen back fill may go a long way to eliminating below-ground corrosion problems with buried steel structures.

CONCLUSIONS

The most important findings of this study are as follows.

- The selection of galvanized and weathering steels for transmission and distribution for atmospheric or direct burial use, is a matter of corrosion engineering judgement and corrosivity of the environment. Some of the factors are corrosion performance, economics, appearance and aesthetics.

- Weathering steel should not be used in chloride containing reducing soils with high time of wetness. Galvanized steel should not be used in high or low pH environments or in areas susceptible to wildfires.

- Protective barrier coatings are essential to avoid direct contact between soil and exposed metal. A fail-safe system for direct burial applications is to have both a protective barrier coating and cathodic protection (CP) to prevent accelerated corrosion when and if moisture/corrosive ions are present.

- Cathodic protection should be applied to aging structures in corrosive soil service environments, to new structures located in corrosive soils, and to those located near pipelines due to potential stray current /galvanic corrosion. This is not the case for poles and tower legs known to be properly encased in concrete.

REFERENCES

1. ISO 9223:2012. *Corrosion of metals and alloys–Corrosivity of atmospheres–Classification, determination and estimation.* International Standards Organization: Geneva, Switzerland, 2012.

2. American Galvanizers Association. *Performance of Hot-Dip Galvanized Steel Products.* American Galvanizers Association: Centennial, Colorado, 2010.

3. National Atmospheric Trends Program/National Trends Network. *Sulfate ion wet deposition, 2013.* http://nadp.isws.illinois.edu, 2019.

4. T. Kamimura, S. Hara, H. Miyuki, M. Yamashita, and H. Uchida. Composition and protective ability of rust layer formed on weathering steel exposed to various environments. *Corrosion Science 48(9),* 2006, pp. 2799-2812.

5. AASHTO T288. *Standard Method of Test for Determining Minimum Laboratory Soil Resistivity.* American Association of State Highway and Transportation Officials: Washington, DC, 2012.

6. ASTM G57 – 06(2012). *Standard Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method*. American Society for Testing and Materials: West Conshohocken, PA, 2012

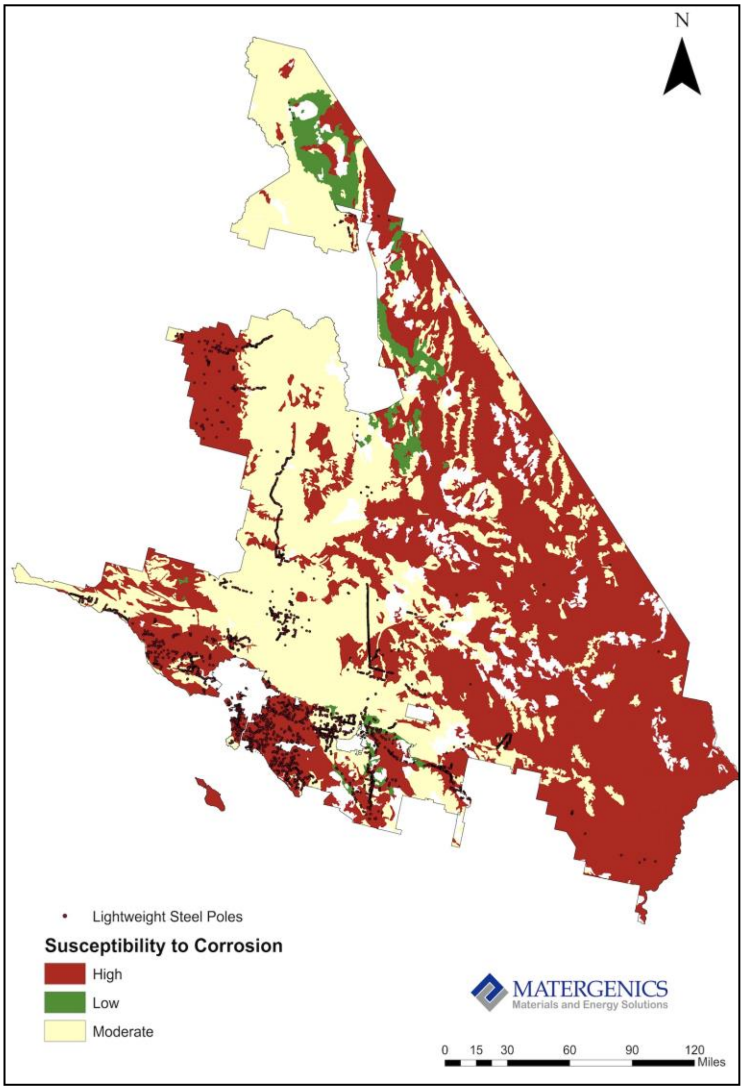


Figure 1: An example of an underground soil corrosion map for weathering steel poles in southern California; generated by the authors' company.

Figure 2: Weathering steel pole (left) and a galvanized steel lattice tower (right).

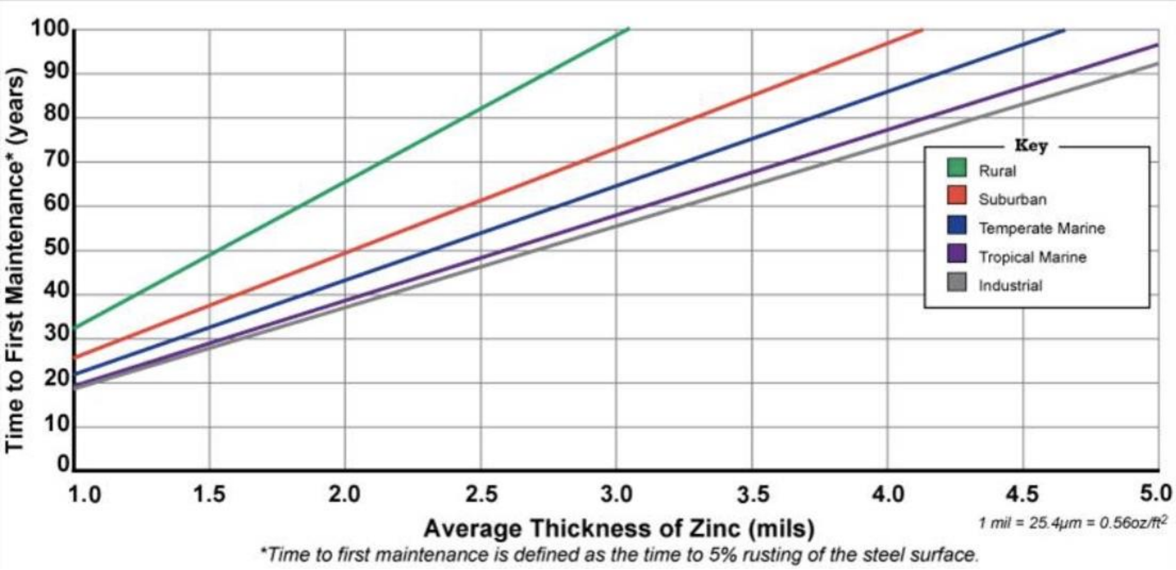
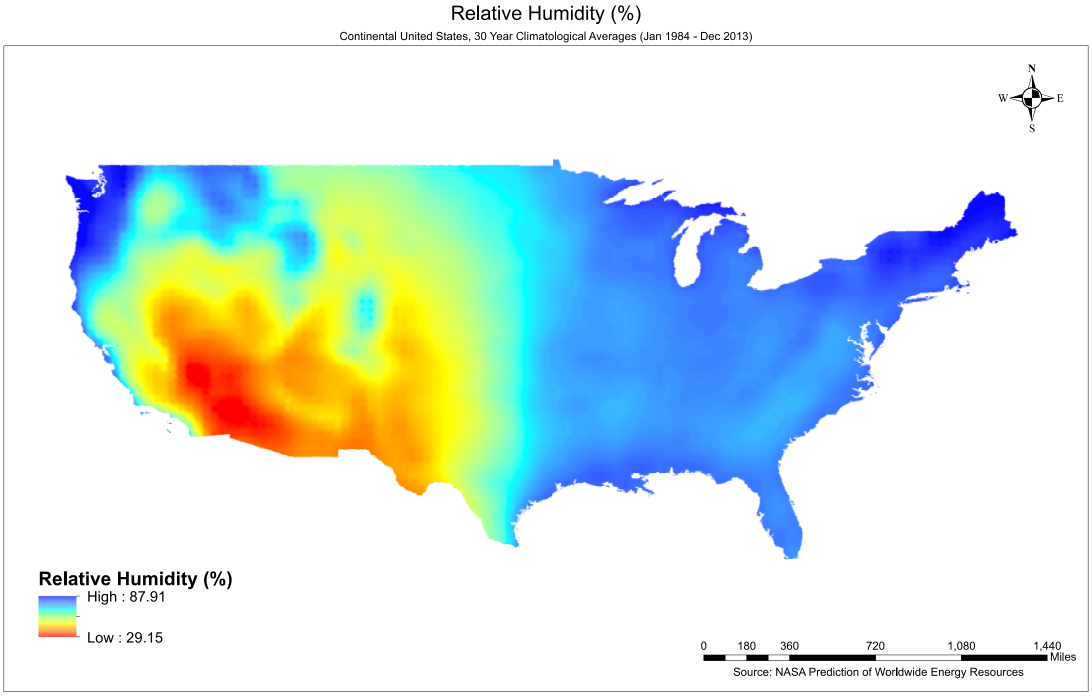


Figure 3: Time to first maintenance of galvanized steel as a function of average zinc thickness and environment.[2]

Figure 4: Photograph of galvanized based plate corroding.

Figure 5: General atmospheric environmental zones in southern California near San Diego; generated by the authors' company.

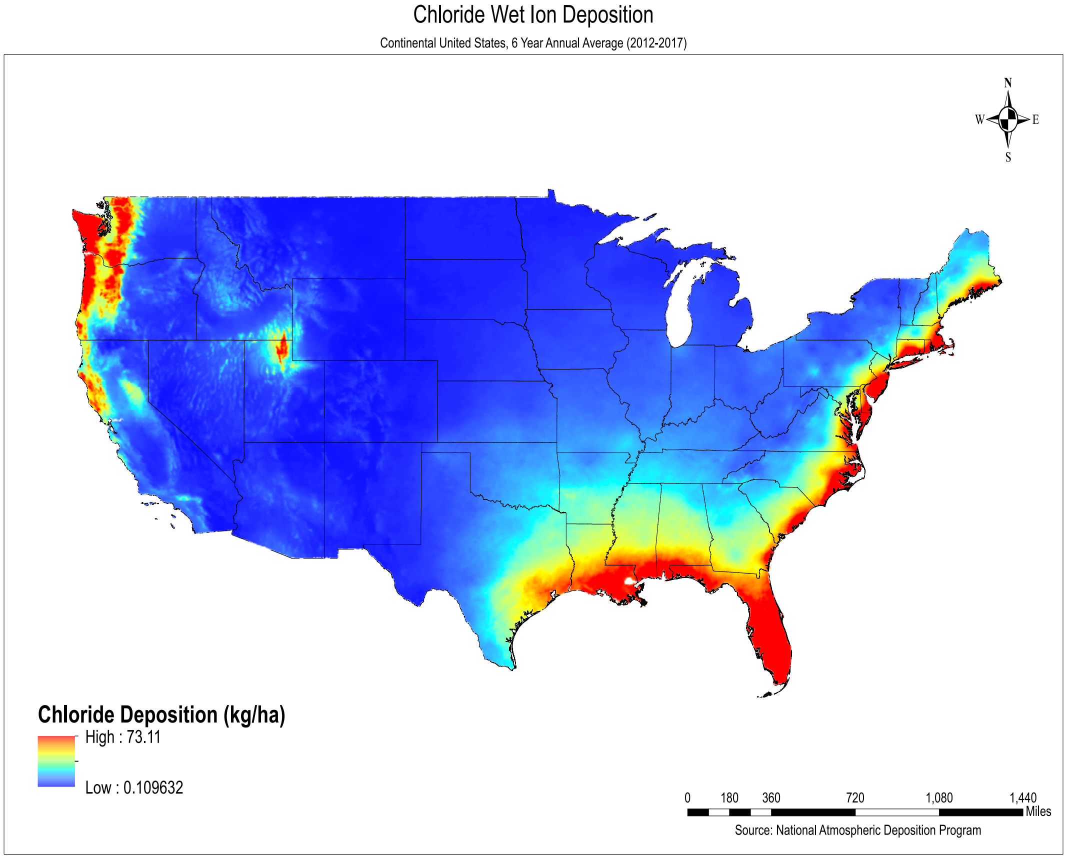


Relative Humidity (%)

Continental United States, 30 Year Climatological Averages (Jan 1984 - Dec 2013)

Source: NASA Prediction of Worldwide Energy Resources

Figure 6: Relative humidity mapping for mainland of United States; generated by the authors' company.

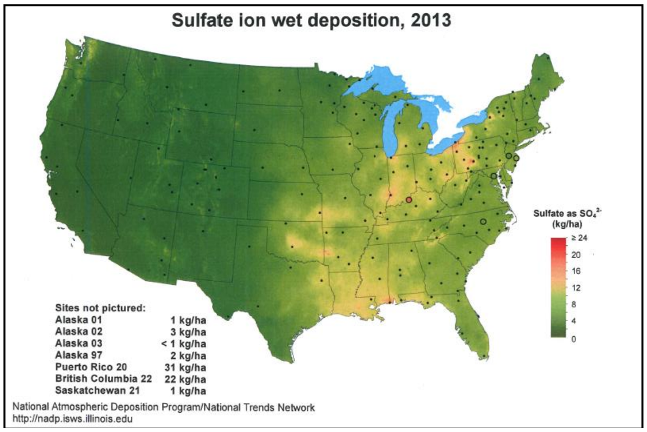


Chloride Wet Ion Deposition

Continental United States, 6 Year Annual Average (2012-2017)

Source: National Atmospheric Deposition Program

Figure 7: Chloride deposition mapping for mainland of United States; generated by the authors' company.



Sulfate ion wet deposition, 2013

Sites not pictured:	
Alaska 01	1 kg/ha
Alaska 02	3 kg/ha
Alaska 03	< 1 kg/ha
Alaska 97	2 kg/ha
Puerto Rico 20	31 kg/ha
British Columbia 22	22 kg/ha
Saskatchewan 21	1 kg/ha

National Atmospheric Deposition Program/National Trends Network
http://nadp.isws.illinois.edu

Figure 8: Sulfate ion wet deposition in the United States; 2013.[3]