Facilities Environmental Severity Classification Study

Final Report

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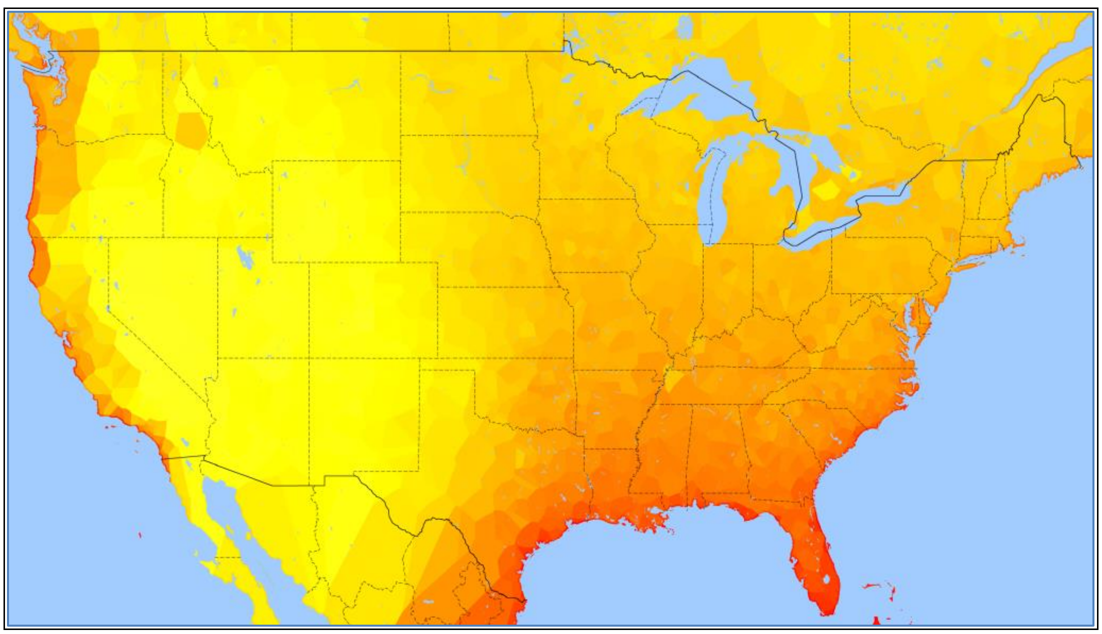

Abstract: This study provides an in-depth review and analysis of existing environmental severity classification and corrosion monitoring efforts and makes recommendations for potentially employing environmental severity classification methodology. By utilizing weather and corrosion data and mapping technology, a baseline environmental severity can be obtained to help decision makers better understand their operating environment and manage the risks associated with corrosion.

Executive Summary

The Department of Defense (DoD) designs, operates, and manages a vast array of assets, including facilities (buildings, structures, and linear structures), in a variety of environments with varying levels of corrosivity, making corrosion control and sustainment an on-going engineering challenge. The annual cost of corrosion for DoD facilities is estimated at almost $3 billion[1]. To address corrosion, planning, design, construction, and sustainment personnel must make decisions based on their respective operational requirements and resource availability. In accordance with DoDI 5000.67[2], the DoD has a requirement to implement Corrosion Protection and Control (CPC) throughout the life cycle of all facilities. Employing environmental severity classification methodology could aid in managing the risks associated with corrosion. Characterization of environmental severity is a technical characteristic that provides a basis for making more informed decisions, such as tradeoff decisions and selection of materials and systems that have appropriate levels of durability in the local atmospheric environment.

Corrosion, although traditionally thought of as simply *rust*, is defined as "the deterioration of a material or its properties due to a reaction of that material with its chemical environment."[3] In this sense, corrosion includes much more than just electrochemical oxidation of metals, such as rotting of wood, degradation of concrete, and degradation of composite materials due to reaction with the environment. The cause, method, and rate by which this reaction occurs are directly affected by the severity of the local environment. Several methods for characterizing and quantifying the corrosive effects of atmospheric environments and service conditions have been developed over the years. The Facilities Environmental Severity Classification (ESC) study was conducted in an effort to identify and evaluate a number these methods. This study provides an in-depth review and analysis of environmental severity and corrosion monitoring efforts and includes recommendations for employing environmental severity classification for the purpose of evaluating atmospheric environments. This report presents the results of a two-part evaluation:

1. an in-depth analysis of existing environmental severity classification methods and corrosion monitoring efforts, and;
2. identification, analysis, and development of high-level tools that employ weather and corrosion data and mapping technology that may assist facilities professionals in making more informed decisions based on their respective atmospheric environment.

This report also presents recommended next steps and recommendations for future work related to this effort.

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[1] *The Annual Cost of Corrosion for the Department of Defense Facilities and Infrastructure: 2009–2011 Update (Revision 1)*, LMI Report DAC21T4, February 2014

[2] DoD Instruction 5000.67, *Prevention and Mitigation of Corrosion on DoD Military Equipment and Infrastructur*e, February 1, 2016

[3] 10 U.S. Code § 2228

Environmental severity is rarely uniform and can vary widely across different locations and regions. There are many factors that contribute to the severity of a given environment, including climatological, geographical, biological, and human. These factors can vary within a given location and can change year-to-year based upon usage, natural weather patterns, and economic development. The specific environmental factors considered by the environmental severity classification methods evaluated by this study, either directly or indirectly, can include temperature, humidity/atmospheric moisture, precipitation, salinity, topography, UV, winds, chloride deposition, sulfur dioxide deposition and other pollutants. Recognizing the effects these factors have on the corrosion susceptibility of facilities and prioritizing the mitigation of these effects can significantly impact not only life cycle cost but readiness and safety as well. Characterization of environmental severity for DoD locations and operational environments can aid in minimizing these risks.

In 2013, the Corrosion Policy and Oversight Office conducted the *Facilities and Infrastructure Corrosion Evaluation Study* (FICES)[4] in response to House Report 112-78, accompanying H.R. 1540, National Defense Authorization Act for fiscal year 2012. The purpose of this study was to conduct an evaluation of key cost drivers and strategies to mitigate their impact, an assessment of a planned facilities construction program, and the examination and documentation of maintenance and facility engineering processes. Among its findings, the FICES noted that "installations located in severe environments are subject to greater corrosion costs," and that "appropriate CPC planning and decisions made during the planning phase directly enhance a facility's life cycle." One of the key areas of improvement identified in the study was the implementation of CPC requirements during acquisition, design, and construction. Enforcement of CPC in these areas is currently limited by certain factors, including acquisition contract type, and treatment of environmental severity and service life in DoD criteria.

A key outcome of the ESC study was the development of the ISO Corrosivity Category Estimation Tool (ICCET), which comprises the core methodology of ESC Factors. The ICCET is an automated, web-based tool that estimates the ISO Corrosivity Category for a desired location. To use the ICCET, the user inputs their desired location, its salinity factor[5], and the desired time range. The tool then calculates the ISO category using hourly weather data acquired from the National Oceanic and Atmospheric Administration (NOAA) database and relational equations based on known corrosion data[6]. The ICCET can be accessed via www.corrdefense.org.

Based on this report and publication of the ICCET, DoD criteria professionals and designers could implement ISO Corrosivity standards and use this tool to help begin the facilities design process. The environmental severity classification tools proposed by this study simply provide a baseline environmental severity. The preferred methods for determining ISO Categories are Corrosivity

[4] *Facilities and Infrastructure Corrosion Evaluation Study (FICES)*, response to House Report 112-78, accompanying H.R. 1540, National Defense Authorization Act for fiscal year 2012, July 2013

[5] Salinity is an indication of the relative distance of the center of mass of a location to seawater. For the ICCET, a ternary value is used: < 1 mi., => 1 mi. but <= 6 mi., and < 6 mi.

[6] Corrosion data was acquired via corrosion monitoring activities conducted by Battelle using corrosion mass loss data from metal coupons placed at various DoD installations around the world.

Determination (ISO 9223, section 7[7]) and the ICCET. ISO Corrosivity Determination is based on one-year corrosion mass loss or penetration of standard specimen. For the majority of DoD sites that do not have the direct corrosion data necessary for Corrosivity Determination, the ICCET can be used to calculate ISO Corrosivity Categories based on detailed environmental data.

Employing environmental classification methodology may aid in managing the risks associated with corrosion resulting from the atmospheric environment. It is important to note that, while environmental severity classification is a useful tool for these purposes, it is not indicative of absolute corrosion potential or total environmental severity.

No method can accurately cover all situations that occur in natural environments and service conditions.

[7] ISO 9223:2012, *Corrosion of metals and alloys - Corrosivity of atmospheres - Classification, determination and estimation*, International Organization for Standardization, February 1, 2012

Table of Contents

Tables

Figures

1. Introduction

The annual cost of corrosion for DoD facilities is estimated at $3 billion [1]. Corrosion, although traditionally thought of as simply *rust*, is defined as "the deterioration of a material or its properties due to a reaction of that material with its chemical environment," [2]. In this sense, corrosion includes much more than just electrochemical oxidation of metals, such as rotting of wood, degradation of concrete, and degradation of composite materials due to reaction with the environment. The cause, method, and rate by which this reaction occurs are directly affected by the severity of the local environment.

In 2013, the Corrosion Policy and Oversight Office conducted the *Facilities and Infrastructure Corrosion Evaluation Study* (FICES) in response to House Report 112-78, accompanying H.R. 1540, National Defense Authorization Act for fiscal year 2012 [3]. The purpose of this study was to conduct an evaluation of key cost drivers and strategies to mitigate their impact, an assessment of a planned facilities construction program, and the examination and documentation of maintenance and facility engineering processes. Among its findings, the FICES noted that "installations located in severe environments are subject to greater corrosion costs," and that "appropriate CPC planning and decisions made during the planning phase directly enhance a facility's life cycle." One of the key areas of improvement identified in the study was the implementation of CPC requirements during acquisition, design, and construction. Enforcement of CPC in these areas is currently limited by certain factors, including:

- For certain design/construction contract types, a significant amount of flexibility is given to the design/construction team to specify and select materials, coatings and other CPC features. In order to maximize profit, the lowest acceptable technical solution is often chosen which may result in higher life-cycle costs related to corrosion.
- Although CPC is covered in many areas throughout Unified Facilities Criteria (UFC), it is not comprehensively addressed as a key design requirement. Other policy-driven requirements like safety, energy efficiency, sustainability, and accessibility have their own criteria or are addressed in detail in the "General Building" and "Core" UFC's.
- For the most part, Unified Facilities Criteria do not directly address durability or service life of facility systems or components, save for some specific areas.
- Environmental severity is not specifically addressed with respect to CPC except for certain systems applications located near the coastline (i.e. selection of coating systems for fencing), large bodies of salt water, or in tropical environments.

The effects of corrosion and the rate at which they occur are consequences of the corrosion system, which is comprised of a material or physical system, the environment, and operational conditions. Corrosion can occur in many different forms including uniform/general, galvanic, crevice, pitting, dealloying, intergranular, fatigue, erosion/flow-assisted, fretting, stray current, and stress corrosion cracking. The Department of Defense (DoD) designs, operates and manages a vast array of facilities in a variety of environments with varying levels of corrosivity, which makes protecting against and mitigating the effects of these corrosion mechanisms an on-going and ever-present challenge. In accordance with DoDI 5000.67, the DoD has a requirement to implement Corrosion Protection and Control throughout the life cycle of all facilities [4]. As such, characterization of environmental severity could assist in the planning, design, and engineering of DoD Facilities when applied in the appropriate manner.

Many environmental severity characterization methods and corrosion monitoring and evaluation efforts have been undertaken over the years. This Environmental Severity Classification study was conducted to analyze the major efforts that apply to DoD facilities. The specific objectives were to provide:

1. an in-depth analysis of existing environmental severity classification methods and corrosion monitoring efforts, and;
2. identification, analysis, and development of high-level tools that employ weather and corrosion data and mapping technology that may assist facilities professionals in making more informed decisions based on their respective atmospheric environment.

2. Analysis

2.1 Evaluation of Existing Corrosion Related Standards and Data

In accordance with the Defense Standardization Program, it is DoD policy to use non-government standards (NGO) to the greatest extent practicable [5]. After analyzing available environmental severity classification (ESC) methods, it was determined that the ISO 9223:2012 [6] corrosivity of atmospheres classification model based on metal corrosion data was potentially most suitable for these purposes. The proposed strategy was to use ESC factors to aid in the identification of ISO Corrosivity Categories for DoD locations. ESC methodology and ISO Corrosivity Classification could be integrated through inclusion in UFC 1-200-01 [7] and other appropriate Unified Facilities Criteria. Several environmental severity classification methods and corrosion and environmental monitoring and evaluation efforts were analyzed as part of this study. Table 1 below is a list of the major resources that were reviewed:

Table 1 - Data Resources

Resource	Description
DoD and Industry Corrosion Data	
A Decade of Corrosion Monitoring in the World's Military Operating Environments, Battelle Columbus	Presents data summaries, observations, and findings of studies conducted in U.S. military operational environments related to corrosion.
Corrosion Prediction Model database	Environmental corrosion model developed using corrosion data and publicly available environmental data.
ISOCORRAG International Atmospheric Exposure Program	Developed to obtain atmospheric corrosion in a uniform manner and with well-characterized samples. The data collected by this program was used to update the ISO Corrosivity Classification

	method to the latest version.
Weather Data and Climate Modeling	
National Oceanic and Atmospheric Administration (NOAA)	Preserves, monitors, assesses and provides public access to climate and historical weather data and information. For this effort, data obtained from NOAA centered on environmental factors, such as temperature, precipitation, and dew point.
Environmental Protection Agency (EPA) Clean Air Status and Trends Network (CASTNET)	National monitoring network established to assess trends in pollutant concentrations, atmospheric deposition, and ecological effects due to changes in air pollutant emissions.
Community Modeling and Analysis System (CMAS) Community Multi-scale Air Quality (CMAQ)	Open-source development project of the U.S. EPA Atmospheric Science Modeling Division. Consists of a suite of programs for conducting air quality model simulations.
National Atmospheric Deposition Program (NADP)	US federal-state-NGO cooperative effort operating a national precipitation monitoring network to observe geographic and temporal trends in acidity, mercury, and other attributes. For this effort, data obtained from NADP centered on atmospheric contaminants.
ISO Standards	
ISO 9223 – 9227, 8407, 11303, and 12944	Provides methods for classifying environmental corrosivity and selection of protection methods.
Wood Decay Hazard Index	Provides a method for estimating decay hazard to wood exposed to the atmospheric environment (above ground).
Environmental Severity Index/FICES Study/Cost-Based	Environmental severity classification method derived from 10 years of corrosion data.
Dave Rose Cumulative Damage Model	Constructed to predict corrosion rates using the concept of cumulative damage.
Technical Order (T.O.) 1-1-691/Wash Intervals	Set of technical orders that provide information regarding aircraft cleaning and corrosion control functions.
Geographic Corrosivity Index	Models the atmospheric corrosivity at Royal Australian Air Force Installations (RAAF) bases within Australia.
Engineering Model for Timber Decay in Contact with Ground (Australia)	Developed based on monitored stakes placed in soil for more than 30 years and uses a climate index based on rainfall and temperature parameters. This model applies to all locations in Australia.
Maintenance Cost Data	Corrosion cost data provided as a percentage of overall maintenance cost.
Technical Corrosion Collaboration (TCC) Projects	
FY10 3, *Corrosion Damage Evolution for Steel Structures*	Presents results of a study on the static performance of a structural frame system of an industrial chemical process plant based on its as-built condition with various degrees of uniform corrosion.
FY11, *Correlation of Field and Laboratory Studies on the Corrosion of Various Alloys in a Multitude of Hawaii Micro-Climates for FY2011*	Presents the results of a study of corrosion for the relatively new joining technique of friction stir processing (FSP).
***Handbook of Material Weathering*, 4th Edition, 2008**	A comprehensive resource on topics related to material weathering. Focuses on quantification of degradative forces, their relationship to actual weather conditions and their degradative effects.

International Molybdenum Association (IMOA) Site and Design Evaluation System The	Provides a design risk assessment template for stainless steel selection that weighs and scores five major life cycle factors: Environmental/Pollution, Coastal and Deicing Salt Exposure, Local Weather Pattern, Design Considerations (surface finishes, Horizontal/Vertical surfaces, etc.), and Maintenance Schedule.

2.2 ESC Factors and ISO Corrosivity Classification

The ISO Corrosivity Classification method was developed using data obtained from the ISOCORRAG program [8], in which one-year corrosion rate samples were exposed at 53 sites in 13 different countries. In addition, the DoD also has employed corrosion monitoring efforts over the years and has obtained similar one-year corrosion rate data at DoD locations around the world [9]. From these efforts, a hybrid tool using existing modeling and mapping solutions was developed.

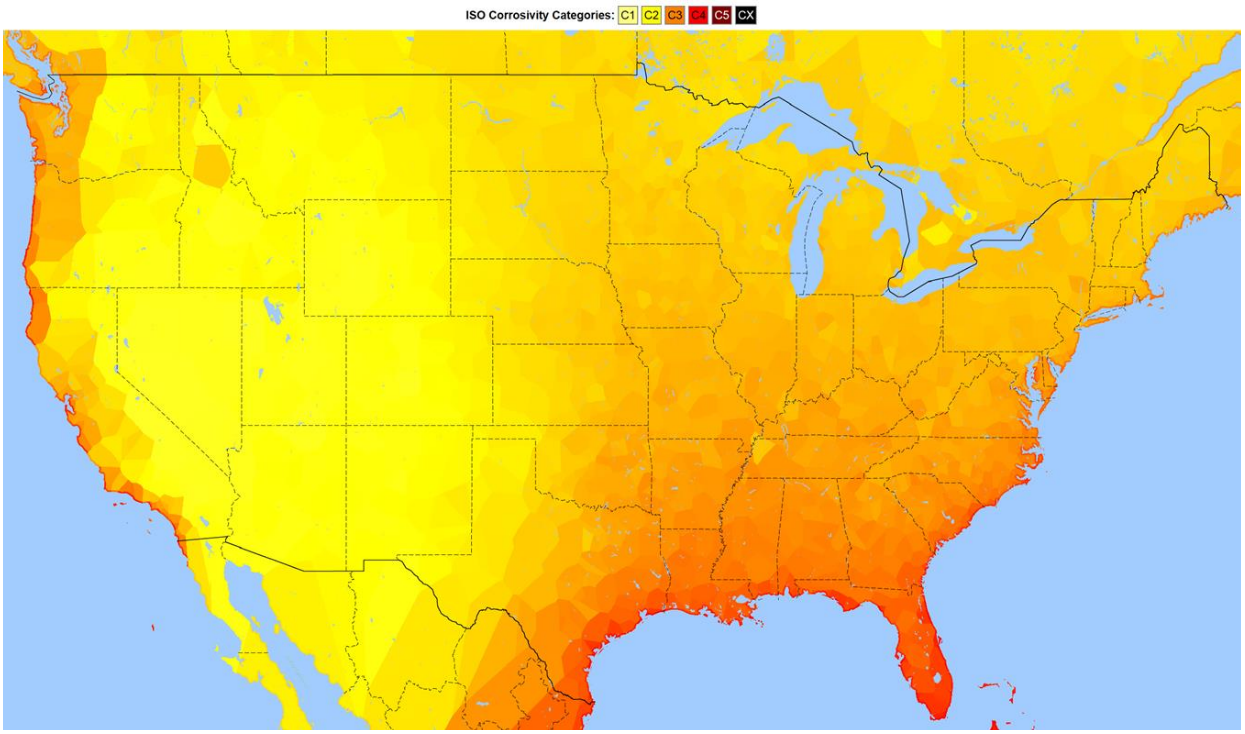
Regression analyses were performed comparing the corrosion data to environmental data and other modeling efforts, such as the Decay Hazard Index for wood. From these regression analyses, three models for estimating corrosion mass loss and ISO corrosivity categories were developed based on hourly temperature and relative humidity data provided by NOAA. Each model is based on a separate salinity value, a measure of relative distance to saltwater:

- Model 1: less than or equal to 1 mile
- Model 2: greater than one mile but less than or equal to 6 miles
- Model 3: greater than 6 miles

These models were built into an automated, web-based tool called the ISO Corrosivity Category Estimation Tool (ICCET). This tool combines these models with NOAA environmental data and the Google Maps API to provide a quick, easy-to-use method for estimating ISO Corrosivity Categories for given locations. This method is referred to as "ESC Factors," and simply provides an easy, alternate method for estimating ISO Corrosivity Categories. From this tool, corrosivity "heat" and "contour" maps were created to depict environmental severity across the U.S.

Figure 1 below shows corrosivity heat map of the U.S. ISO that correspond directly to ISO Corrosivity Categories. This map was calculated using five years of NOAA environmental data (2010 – 2014).

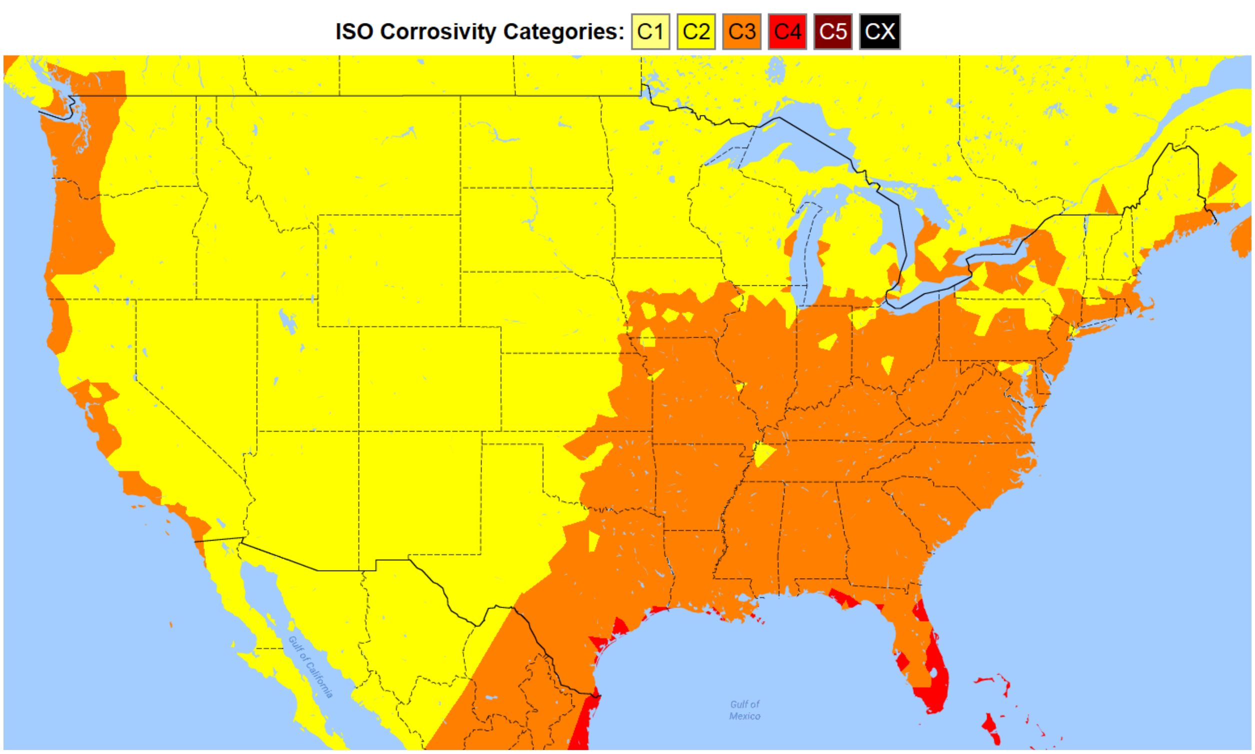
Figure 1 - U.S. ICCET Corrosivity Heat Map



Map Data © 2016 Google, INEGI

Figure 2 below shows corrosivity contour map of the U.S. ISO that correspond directly to ISO Corrosivity Categories. This map was calculated using five years of NOAA environmental data (2010 – 2014).

Figure 2 - U.S. ICCET Corrosivity "Contour" Map

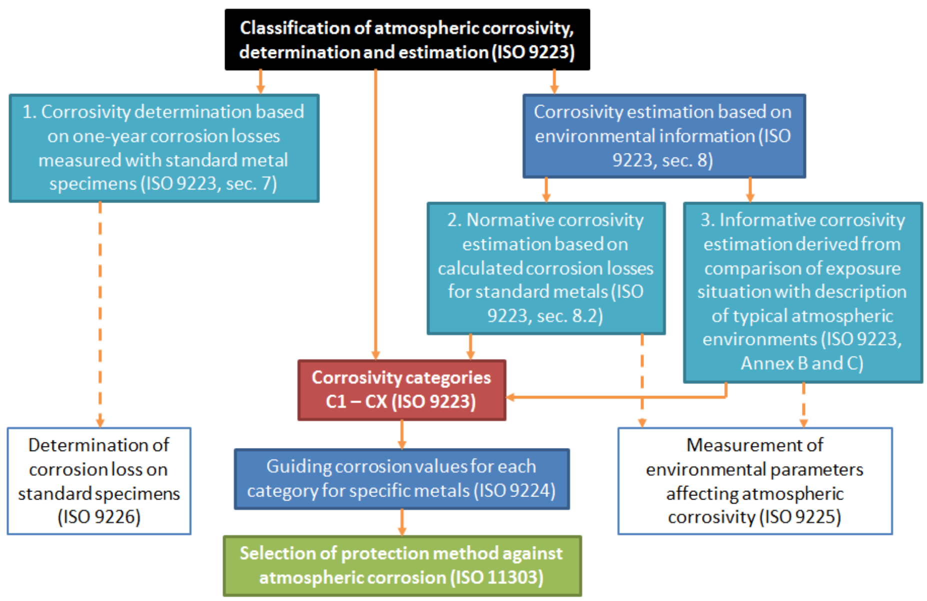


For full versions of these images, visit www.corrdefense.org.

2.3 Classifying Environmental Severity for DoD Locations

The ESC working group completed a review of ISO Corrosivity Classification methods. A flowchart showing the relationship between the ISO Corrosivity methods contained within the ISO standards is provided in figure 3 below:

Figure 3 - ISO Corrosion Classification Flowchart

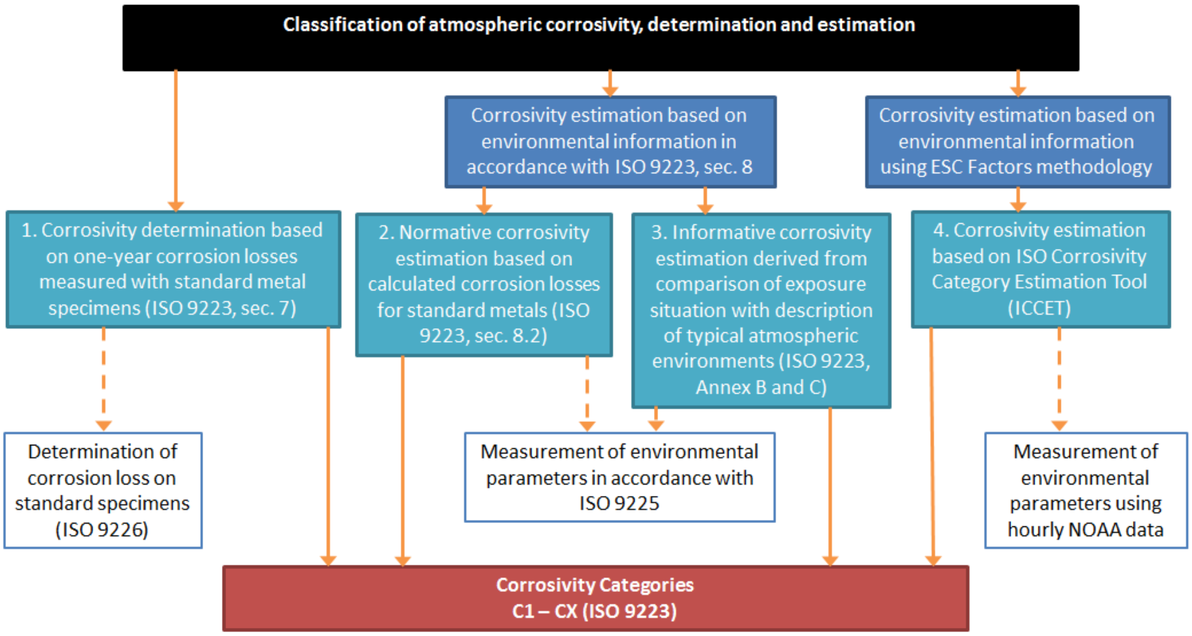


With this, four methods for calculating or estimated ISO Corrosivity Categories were identified using ISO and ESC methodology - three of which are contained within ISO 9223:2012 [6]:

1. Corrosivity Determination (Preferred method):
    a. Based on one-year corrosion mass loss or penetration of standard specimen.
2. Normative Corrosivity Estimation:
    a. Based on calculated corrosion losses for standard metals, dose-response function using environmental factors to estimate one-year corrosion mass loss/penetration.
3. Informative Corrosivity Estimation:
    a. Based on comparison of exposure situations with descriptions of typical atmospheric environments, uses tables in Annex B and C of ISO 9223 [6] to determine ISO corrosivity category.
4. ISO Corrosivity Category Estimation Tool (ICCET)
    a. A new classification tool developed as part of this study. Uses the methodology provided in the ISO Corrosivity Classification standards.

Figure 4 below shows the ISO classification methods with the ICCET included.

Figure 4 - Methods for Determining and Estimating ISO Categories



The preferred methods for identifying ISO Corrosivity Categories are Corrosivity Determination (option 1) and the ICCET (option 4). The Corrosivity Determination method is considered *measured* ISO Corrosivity Category classification as it is directly based on of one-year corrosion mass loss values. ISO Corrosivity Categories based on the Corrosivity Determination method for locations in which one-year mass loss data exists are provided in Appendix C and E. At present, one-year mass loss data suitable for application with the ISO Corrosivity Classification method is only available for around ~152 locations. The ICCET tool is considered *calculated* ISO Corrosivity Category Determination. To access the ICCET tool, visit www.corrdefense.org. Pre-calculated ISO Corrosivity Categories are also provided in Appendix D.

Classification of environmental severity, using ESC factors and ISO Corrosivity classification, may provide designers, planners and decision makers with tools for making more informed decisions based on their atmospheric environments, such as selection of materials and systems that have appropriate levels of durability in that environment. It is important to note that, while environmental severity classification may be useful for these purposes, it is not indicative of absolute corrosion potential or total environmental corrosivity and no method can accurately cover all situations that occur in natural environments and service conditions. In addition, the actual environment that affects a specific material or system correlates directly to the conditions of the micro-environment that it experiences (the “local environment” that occurs on the surface of the material or system).

3. Corrosion Data and Monitoring Efforts

3.1 Battelle Corrosion Monitoring Activities

Over the years, Battelle Columbus has conducted corrosion monitoring activities and gathered corrosion data from a variety of locations all over the world. A detailed report on the some of the results of these efforts is presented in the *A Decade of Corrosion Monitoring in the World's Military Operating Environments – A Summary of Results* [9]. As part of their monitoring efforts, Battelle measured 12-month corrosion mass loss of different types of metal coupons exposed at various sites around the world. The types of metal coupons used were 1010 Steel, Copper, and three different Aluminum alloys (6061, 7075, and 2024). The samples were exposed for three months and then exchanged for new ones. At some locations, silver coupons were exposed as well which were used to measure chloride deposition. Figure 5 below depicts an example test rack used in the study.

Figure 5 - Example of Test Rack from Battelle Study

From *A Decade of Corrosion Monitoring* Report

Based on this mass loss data, a model for predicting mass loss was developed. This model uses three variables:

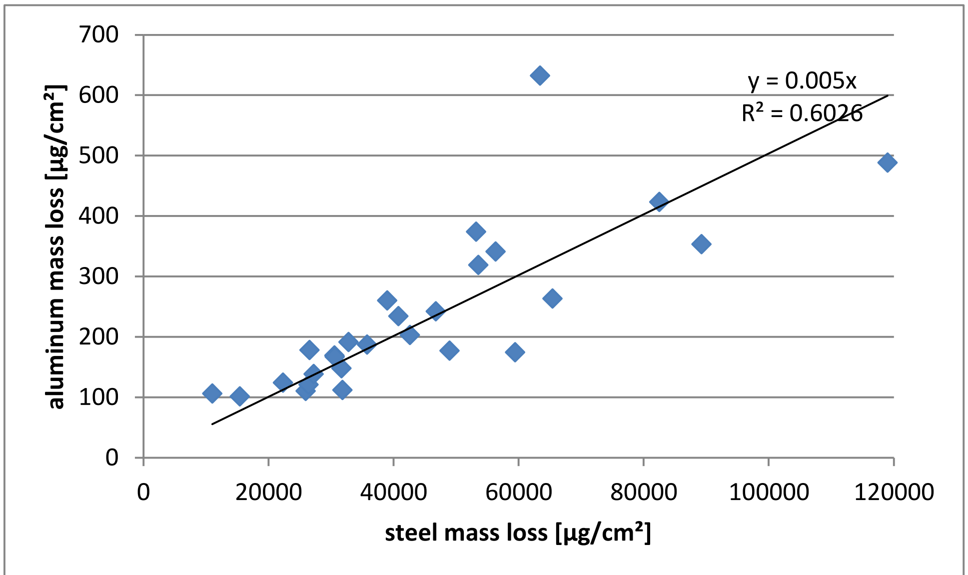
- Humidity values: the percentage of time during the interval in question that the humidity exceeded 70, 80, and 90% RH
- Precipitation: total rainfall in inches for the same period

- Chloride: equivalent film thickness of silver chloride obtained on Battelle silver sensors exposed for the same period

Is the corrosion of steel an indicator for corrosion of other metals?

As depicted in figure 6 below, a comparison of Battelle mass loss data shows that there is a correlation for aluminum and steel, but there is no clear correlation for copper.

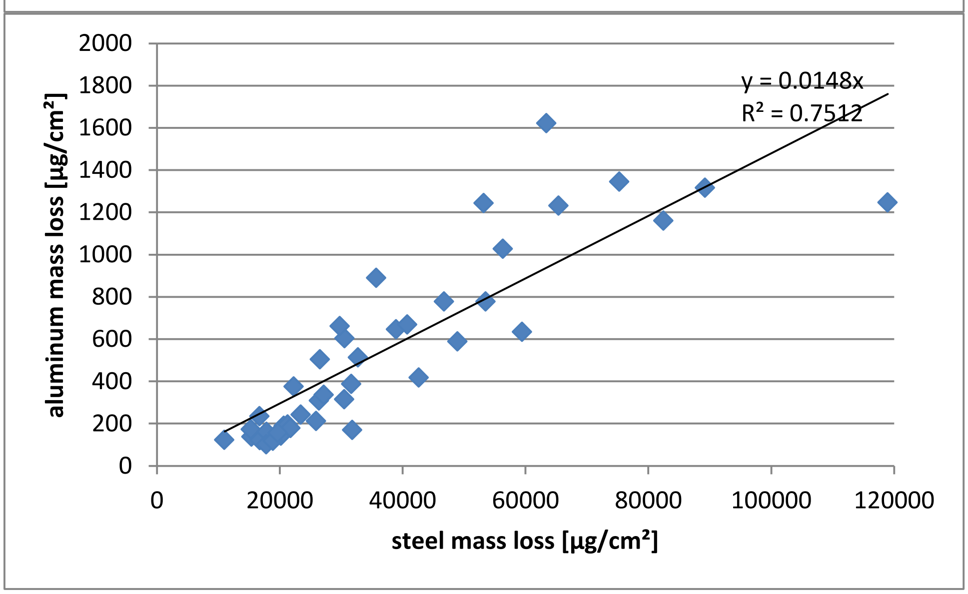
Figure 6 – Steel Data Correlation to Other Metals



Aluminum 6061

trendline with forced intercept at 0/0

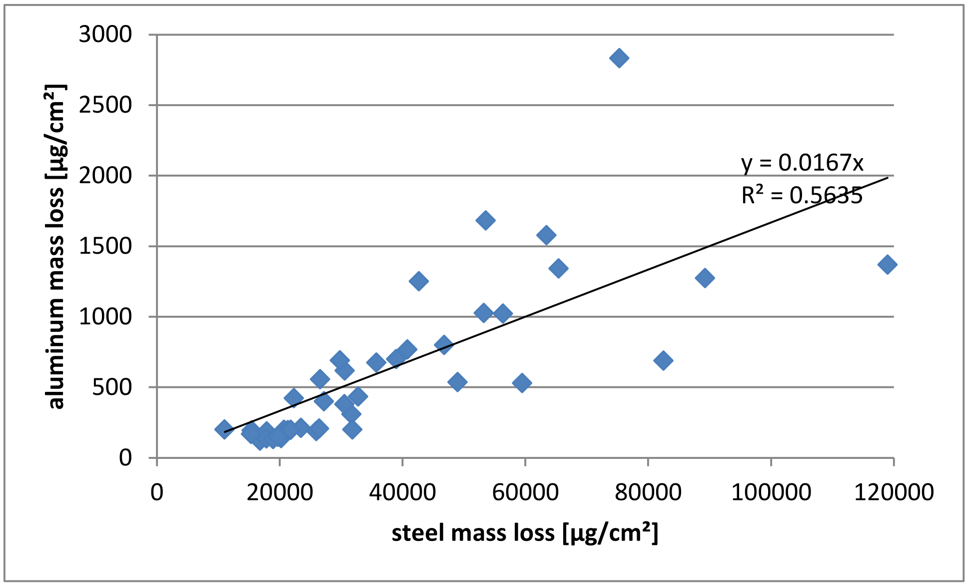
Data Source: Bill Abbott, BaseResponseImport.xls



Aluminum 7075

trendline with forced intercept at 0/0

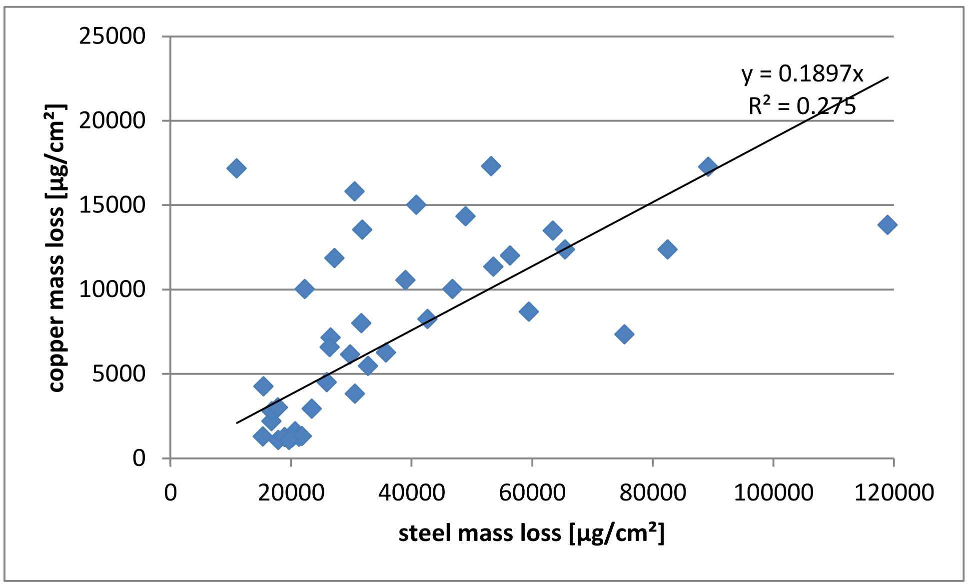
Data Source: Bill Abbott, BaseResponseImport.xls



Aluminum 2024

trendline with forced intercept at 0/0

Data Source: Bill Abbott, BaseResponseImport.xls



Copper

trendline with forced intercept at 0/0

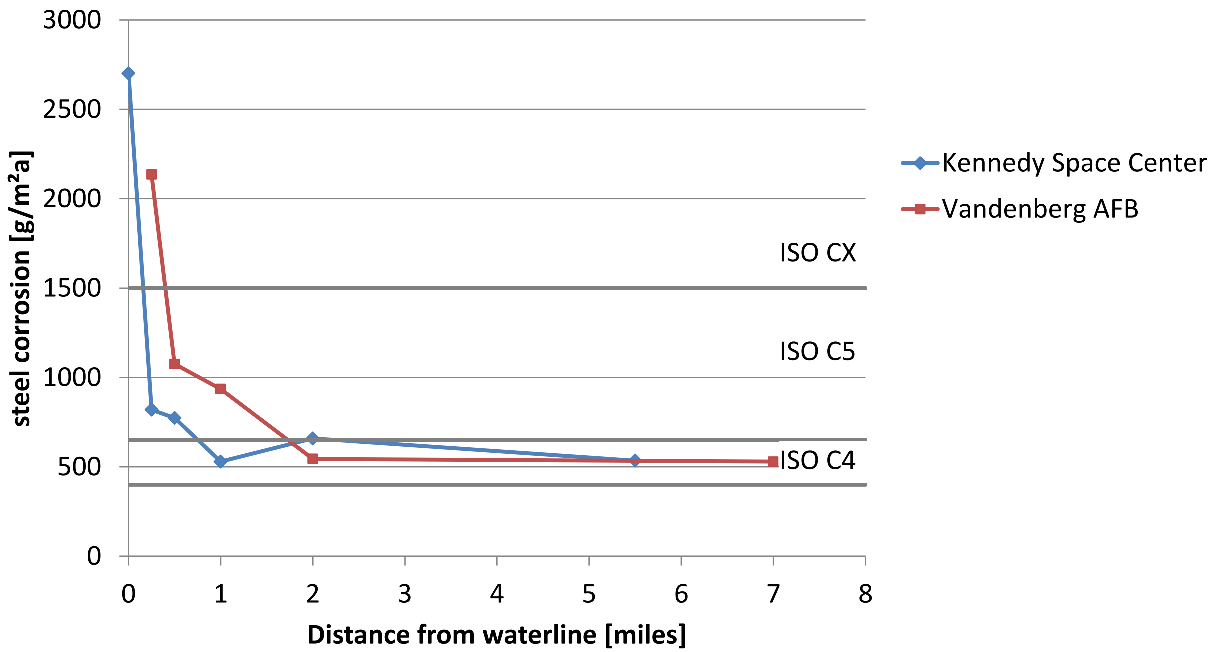
Data Source: Bill Abbott, BaseResponseImport.xls

Influence of Proximity to Salt Water

Generally, the corrosivity of an environment increases the closer it is to salt water and the presence of atmospheric chlorides. The Battelle report [9] provides a chart that shows steel mass loss values taken at different distances to the shore at two sites, Kennedy Space Center and Vandenberg AFB. This chart has been modified below (figure 7) to include ISO Categories.

Figure 7 - Corrosion at Various Distances at KSC and Vandenberg[8]

[8] Original version from Battelle *A Decade of Corrosion Monitoring* report.



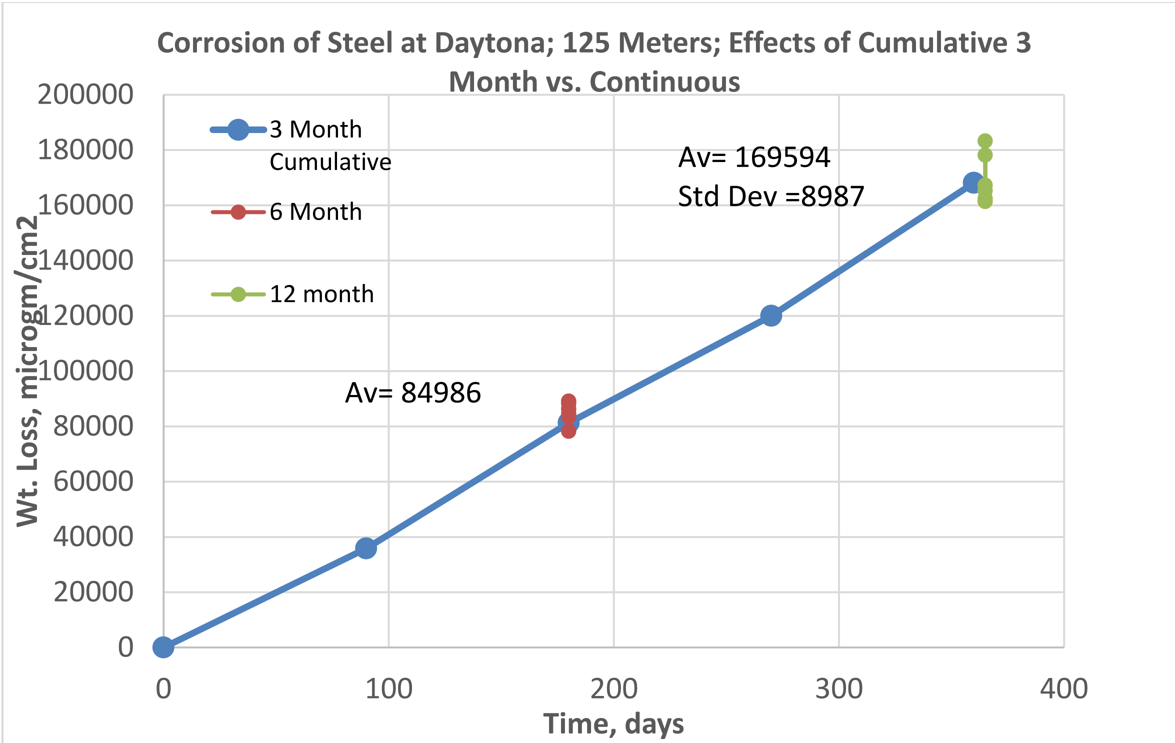
This chart shows that as you get farther from the shoreline, corrosion drops. The most significant drop occurs within the first mile from shore, and by about 2 miles there is little change the farther you go.

Use in ISO Corrosivity Classification Method - Preferred use vs Accepted Use

For ISO category determination, it is preferred that the samples used to determine ISO Categories are in accordance with ISO 9226 - Determination Of Corrosion Rate Of Standard Specimens For The Evaluation Of Corrosivity [10]. The preferred samples size for specimens 4 x 6 inches (.04 inches thick). The samples used in the Battelle study were 0.5 x 3 inches (0.03 inches thick). In addition to this, instead of using a continuous one-year sample monitoring method, the Battelle Study measure samples at three-month intervals. This was accomplished by removing the samples every three months, conducting sample measurements, and exchanging them with new samples. After each three-month measurement was conducted, the data would be recorded and added to the last three-month period's measurement. At the end of 12 months, the data would be added together to create a one-year cumulative value.

Although this is not the preferred method for collecting sample data, it is considered accepted use and can be used as one-year values from which ISO Categories can be calculated (see figure 8 below).

Figure 8 - Corrosion of Steel and Daytona, Effects of Cumulative Three Month vs. Continuous[9]



3.2 ISOCORRAG International Atmospheric Exposure Program

The ISOCORRAG Program was developed to obtain atmospheric corrosion data carried out in a uniform manner and with well-characterized, one-year corrosion rate samples exposed at 53 sites in 13 different countries. The goal was to eliminate testing variations that made many of the earlier studies unreliable. Two types of samples were exposed: flat panels and wire helix specimens. The metals used for the samples were steel, copper, aluminum, and zinc. Samples were exposed at 1, 2, 4, and 8-year intervals. This program also accumulated environmental and atmospheric data from the test sites, including temperature, relative humidity, sulfur dioxide, and sodium chloride deposition rates. This data was then used to determine the accuracy of the ISO 9223:2012 [6] and ISO 9224:2012 [11] standards and to provide the basis for updating them.

The corrosion rate measurements provided by this program are expressed in micrometers per year (µm/year), which is a measurement of "corrosion penetration." To compare this data to the Battelle mass loss data it was necessary to convert it to micrograms per square centimeter per year (µm/cm^2/year) which is a measurement of mass loss. More information regarding the ISOCORRAG Program can be found in the ISOCORRAG: Summary of Results report [8].

Issues

The data used for the ISOCORRAG study is somewhat older that the Battelle Study samples, as the ISOCORRAG samples were exposed between 1986 and 1994. Specific location and distance to salt

[9] Provided by Bill Abbott.

water are not provided in the data. Because of this, this data was not included in the database used to develop the relational equations on which the ICCET tool is built. Additionally, due to the lack of specific thickness measurements, the wire helix sample data was not used for any purpose as part of this effort.

4. Environmental and Climate Data

4.1 Weather

The National Oceanic and Atmospheric Administration (NOAA) provides current and historical weather data via the National Centers for Environmental Information (NCEI) database. Data is presented in many formats, including yearly, monthly, daily, hourly, and historical normals. For the purpose of this study, all environmental data was obtained using the NCEI database.

4.2 Pollution and Atmospheric Contaminants

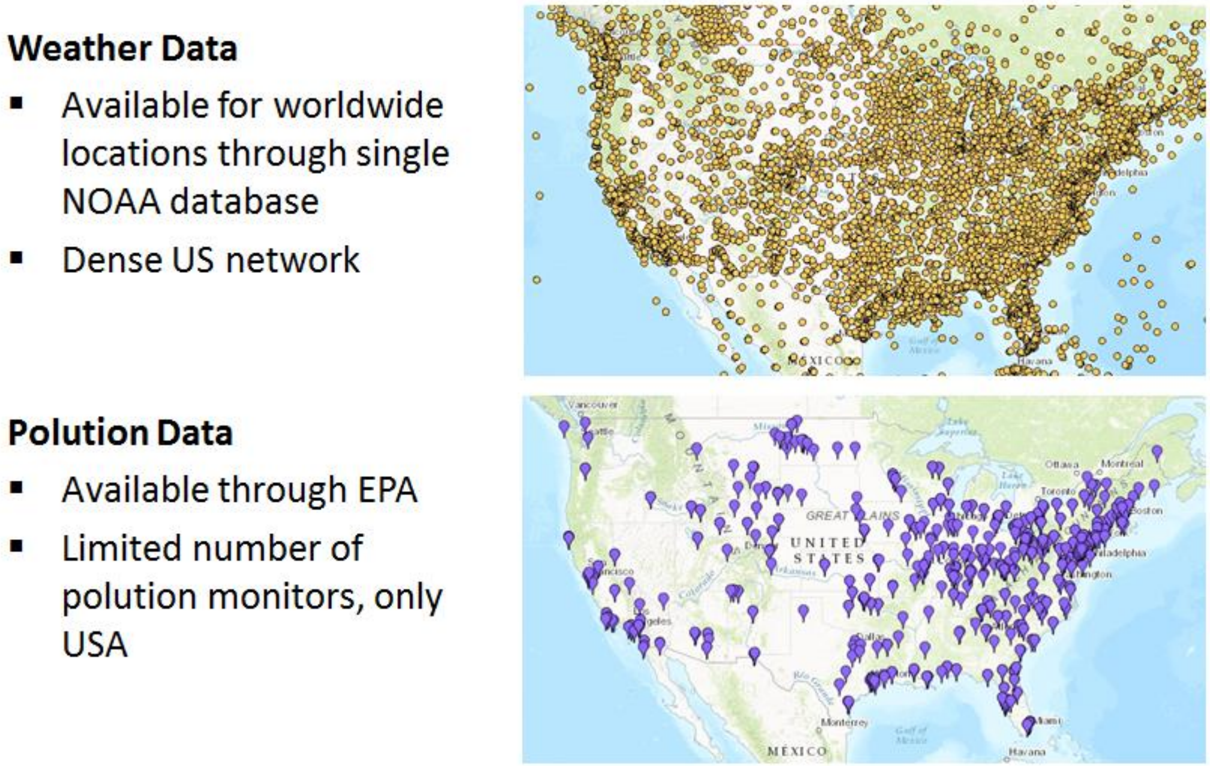
Several pollution and atmospheric contaminants databases were evaluated for use in ESC. For this effort, data obtained from NOAA centered on environmental factors, such as temperature, precipitation, and relative humidity. Pollution and atmospheric contaminants, including sulfur dioxide (SO_2), chloride (Cl), and Ozone (O_3) have been shown to affect the rate of corrosion. Several atmospheric contaminate databases and modeling efforts were evaluated:

- Environmental Protection Agency (EPA) Clean Air Status and Trends Network (CASTNET): Preserves, monitors, assesses and provides public access to climate and historical weather data and information.
- Community Modeling and Analysis System (CMAS) Community Multi-scale Air Quality (CMAQ): Open-source development project of the U.S. EPA Atmospheric Science Modeling Division. Consists of a suite of programs for conducting air quality model simulations.
- National Atmospheric Deposition Program (NADP): U.S. federal-state-NGO cooperative effort operating a national precipitation monitoring network to observe geographic and temporal trends in acidity, mercury, and other attributes.

Issues

Pollution and atmospheric contaminate data availability is significantly limited compared to environmental data as evidenced in the figure 9 below. As such, using this data to evaluate corrosivity is only possible at locations where the necessary data is actively monitored, or for which significant historical data exists. In addition, the methods by which this data is captured must be compatible with the evaluation mechanism (wet vs. dry chloride monitoring).

Figure 9 - Comparing Weather and Pollution Data Availability[10]



5. Summary of Environmental Severity Characterization Methods

This section presents the analysis conducted on the main environmental severity characterization methods that apply to DoD sites.

5.1 ISO 9223:2012 Corrosivity Classification Method

Corrosivity Determination (based on standard specimens)

The ISO Corrosivity Classification method is contained in ISO 9223:2012 [6]. This method consists of corrosivity categories defined by first-year corrosion effects on standard specimens as specified in ISO 9226 [10]. ISO Corrosivity Categories can be assessed in terms of the most significant atmospheric factors that influence the corrosion of metals and alloys. In this sense, ISO Corrosivity Categories characterize the corrosivity of the atmospheric environment and can provide a basis for the selection of materials and systems that are subject to the demands of the specific application and its required service life.

The ISO Corrosivity Classification table defines six corrosivity categories (C1, C2, C3, C4, C5, CX) based on one-year corrosion mass loss or penetration of steel, zinc, copper, and aluminum coupons. Corrosivity Category determination based on corrosion rate measurement of standard specimens

[10] Top picture: gis.ncdc.noaa.gov/maps/ncei/cdo/hourly, bottom picture: epa.maps.arcgis.com.

table can be found in ISO 9223, Table 2 [6]. Examples of typical environments and their relation to corrosivity categories can be found in ISO 9223, Annex C [6].

The ISO Corrosivity Category method is recommendedfor a variety of reasons, including current DoD policy mandating use of Non-Government Standards (NGOs), correlation to other environmental severity methods, applicability of existing metal corrosion data, and applicability and correlation of available and easily accessible environmental data. Unified Facilities Criteria are generally based on nationally and internationally recognized technical, professional, and industry standards. DoD standards are mandated to use NGOs to the extent possible by the Defense Standardization Program, pursuant to DoDI 4120.24 *Defense Standardization Program (DSP)* [5].

5.2 Other ISO Series Corrosivity Methods and Uses

Normative Corrosivity Estimation

ISO Normative corrosivity estimation is based on calculated corrosion losses for standard metals (ISO 9223, sec. 8.2) [6]. This method was developed using dose-response functions for four standard metals that describe the corrosion attack after the first year of exposure to open air as a function of sulfur dioxide (SO_2) dry deposition, chloride (Cl) dry deposition, temperature, and relative humidity. Methods for measuring SO_2 and Cl are listed in ISO 9225:2012 [12]. These functions can be found in ISO 9223, section 8.2 [6].

It is important to note that this method uses SO_2 and Cl deposition gathering methods that are not commonly used at most pollution and atmospheric contaminate monitoring sites. Gathering the data necessary to calculate ISO Corrosivity Categories would most likely have to be done on a case-by-case basis. Because of this, use of this method to determine ISO Corrosivity Categories is not recommended simply because easier methods exist.

Informative Corrosivity Estimation

The corrosivity of an atmospheric environment increases with the effect of temperature, relative humidity, and the levels of other corrosive factors such as pollution and atmospheric contaminants. Typical atmospheric types of pollution and levels and associated ISO Corrosivity Categories are provided in ISO 9223, Annex B [6].

Exposure conditions influence the impact of the environment. For informative corrosivity estimation, a qualitative description of typical environments and their associated ISO Corrosivity Categories is provided in ISO 9223, Annex C [6]. This method can be used to determine ISO Corrosivity Categories if all other recommended methods are not suitable.

Guiding Corrosion Values

Specific calculation models, guiding corrosion values and additional information regarding long-term corrosion behavior are provided in ISO 9224:2012 - *Guiding values for the corrosivity categories* [11]. One year corrosion values generally cannot be extrapolated to predict specific mass loss over longer periods, although they can be used to estimate it. The rate of corrosion for metals and alloys exposed to the atmospheric environment is not always consistent with the time of exposure. Over time, the surface profile of a material or system and accumulation of corrosion product changes.

The relationship between corrosion and time is generally observed to be linear only when the total damage is plotted against exposure time on logarithmic coordinates, at least for the first 20 years. ISO 9224:2012 [11] provides functions for standard structural metals, based on the ISOCORRAG Program, to estimate corrosion over longer periods of time, using either 1-year corrosion data or more (not more than 20 years in most cases). After 20 years, this relationship at some point becomes linear. A separate function for periods greater than 20 year is provided in ISO 9224, sec. 7 [11]. The output of this method is called *guiding corrosion values*, which describes “total attack” and is expressed as either mass loss per unit area or penetration depth.

ISO 9224:2012 [11] states that “Guiding corrosion values for standard structural materials can be used for engineering calculations.” Guiding corrosion values can also be used for the selection of protection systems using ISO 11303:2002 - *Guidelines for selection of protection methods against atmospheric corrosion* [13].

It is important to note that guiding corrosion values is a broad estimation of corrosion over periods of time for specific materials. While it can be a useful tool for selection of protection methods, it is NOT indicative of absolute corrosion potential or environmental severity, nor can it accurately cover all situations in natural environments and service conditions.

5.3 ISO Corrosivity Category Estimation Tool (ICCET)

One of the main goals of the ESC study was to identify and develop high-level tools for facilities designers, planners, and decision makers that may assist with making more informed decisions based on their respective atmospheric environment. To accomplish this, an automated, web-based tool was developed for the purpose of providing an easy and effective way to estimate locational ISO Corrosivity Categories based on real-time and easily accessible environmental data. This tool also fills a gap where specific corrosion mass loss data is not available for a desired location, an issue that affects many DoD sites. This tool, developed by Wolfgang Gaebel (OUSD(AT&L) Corrosion Policy and Oversight Office), estimates ISO Corrosivity Categories using NOAA data (NOAA ISD-Lite database) and models based on one-year corrosion mass loss data and salinity. To access this tool, visit www.corrdefense.org.

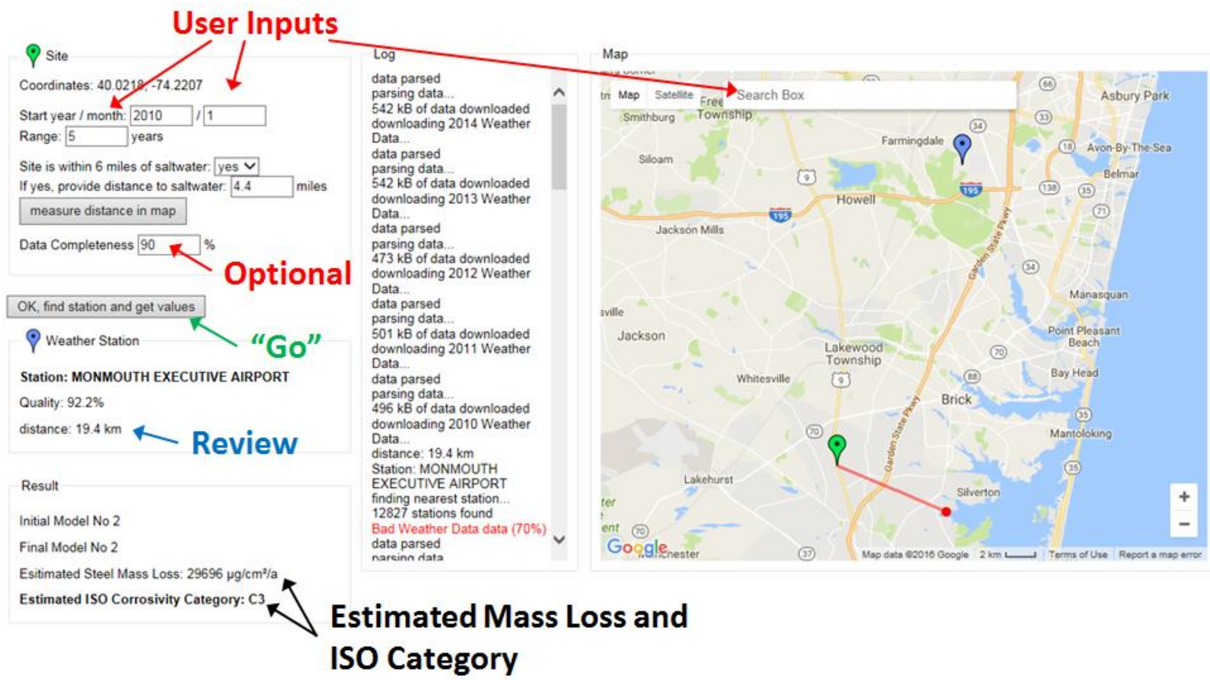
Using the ICCET

The ICCET is designed to be straightforward and easy to use. The user simply inputs:

- Location (via google map interface)
- Starting year/month and range (in years, at least five years is suggested)
- Salinity (> six miles, between six miles and one mile, and less than one mile)
- Data completeness (optional, default is 90%)

The tool allows the user to select their desired location using a Google maps interface and then input their desired date range and salinity. Although not required, it is suggested that at least five-year intervals are used for optimal results. If the user's salinity is not known, or not easy to discern using the map, the tool provides and easy “drag and drop” feature for determining the distance from the nearest body of salt water. The user can also select the level of data completeness they want, though it is suggested that the default 90% is optimal. Occasionally, there are gaps in the NOAA data where either it was not captured or reported for a given time. To account for this, the tool will interpolate missing data points as long as long as the percentage of missing data does not exceed the user-defined "data completeness" threshold. Figure 10 below shows the ICCET interface.

Figure 10 - ICCET Interface

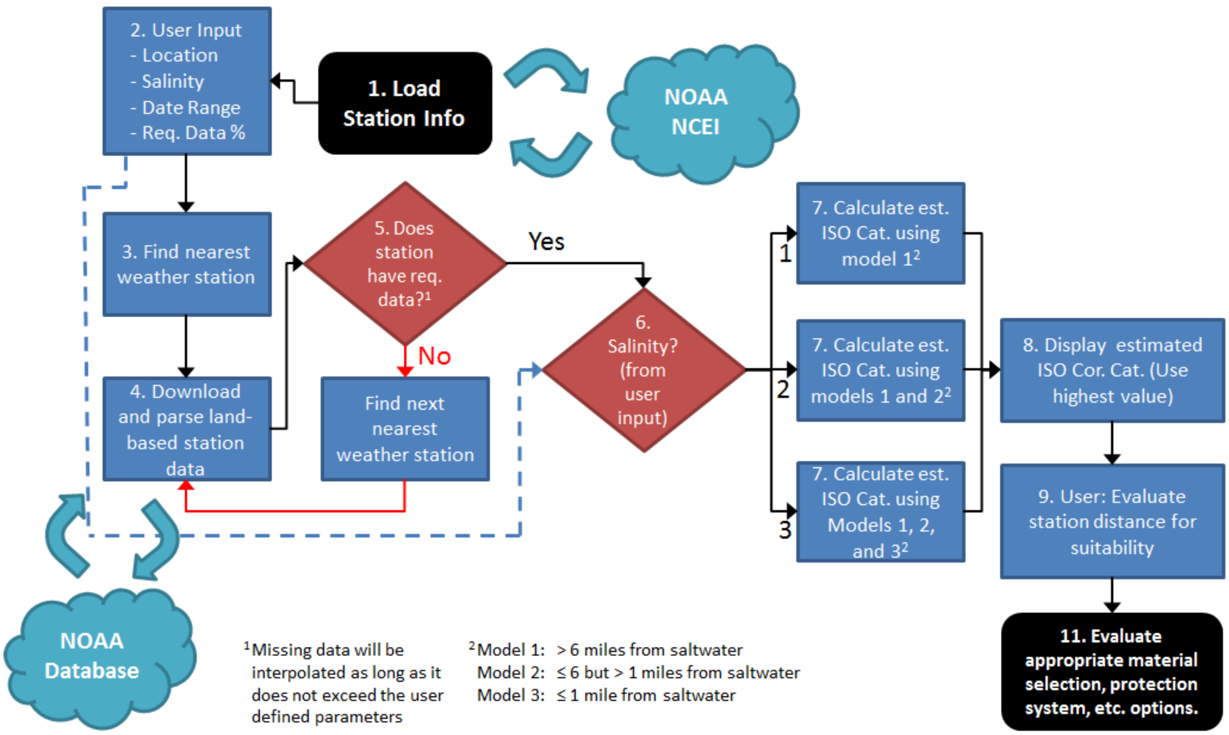


www.corrdefense.org

After all desired parameters have been entered, the user clicks the "OK, find station and get values" button. Using the NOAA database and Google Maps API, the ICCET automatically finds the nearest weather station and evaluates the weather data for completeness within the given data completeness range. If the data is not sufficient, the tool will find the next nearest weather station. It will continue this process until a station with necessary data is found. The distance between the station and the user's location is displayed and should be evaluated for suitability. There is no exact distance that is necessary for each location. The distance of the nearest station from the user's desired location needs to be evaluated on a case-by-case basis, although it has been found that most locations that have been tested have a suitable station nearby. Factors like salinity, geography, and elevation can affect the distance necessary for suitability. If no weather station is suitable, other methods of determining the ISO Corrosivity Category should be pursued (see Appendix C – G, and sections 5.1 and 5.2).

Once a suitable station is identified, the tool calculates the estimated ISO Corrosivity Category using the user-defined salinity and displays it in the results box. Figure 11 below shows the algorithm used by the ICCET.

Figure 11 - ICCET Process/Algorithm

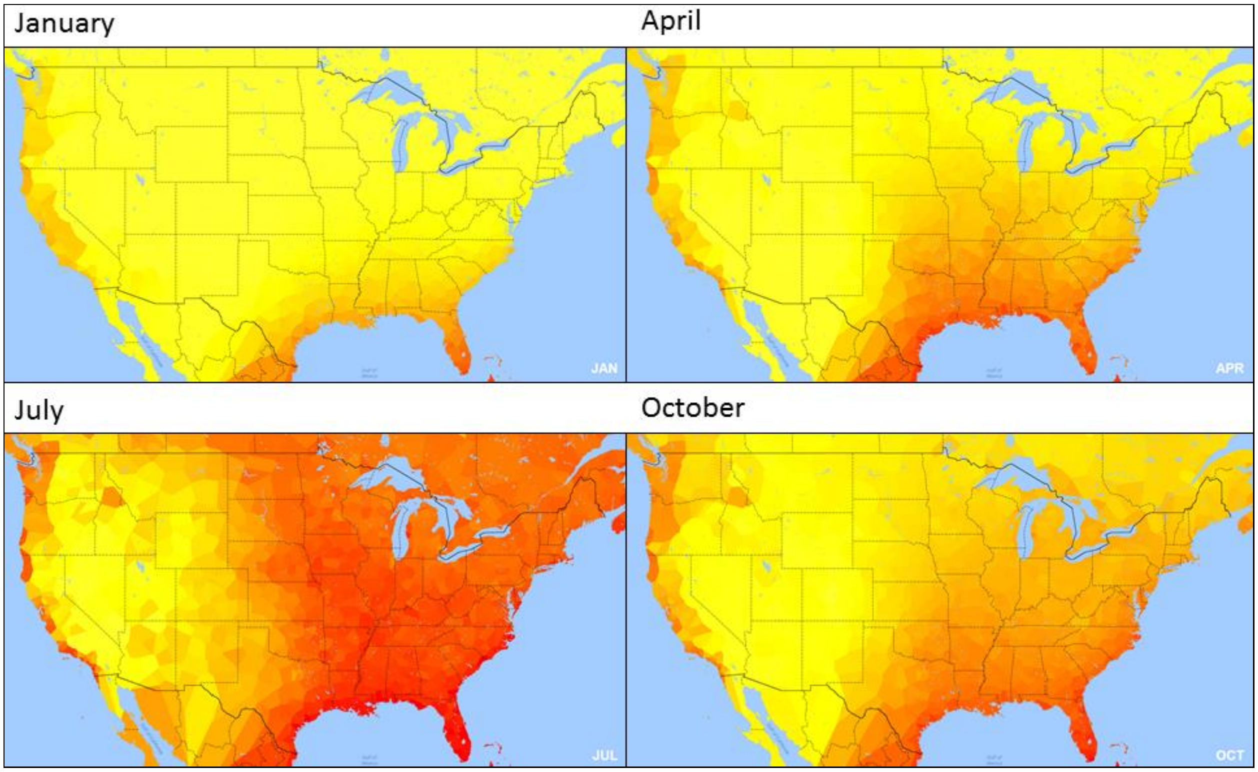


ICCET Modeling and Algorithm Development

The ICCET method is similar to the Cumulative Corrosion Damage Model (CCDM) [14] in that it uses hourly environmental data instead of monthly or yearly averages, but unlike the CCDM it does not use sulfur dioxide and ozone data. As noted in section 4.2, this is due to the low availability of pollution and atmospheric contaminate data necessary for incorporating these parameters (see figure 9).

The environmental factors that affect the rate of corrosion change constantly throughout the year. Because of this, it is necessary to use the most detailed and up-to-date environmental data available. All environmental data used by the ICCET it pulled directly from the NOAA database. In his Ph.D. dissertation [14], Dr. Rose notes that the "principal advantage of using hourly predictions is that the effects of diurnal and seasonal temperature cycles and related changes to relative humidity are explicitly considered." Figure 12 below shows seasonal variation in corrosivity. Visit www.corrdefense.org for animated heat maps of ISO Corrosivity Category variation over 12 month periods.

Figure 12 - Environmental Severity Seasonal Variation (10 Year Monthly Avg. 2007-2016)



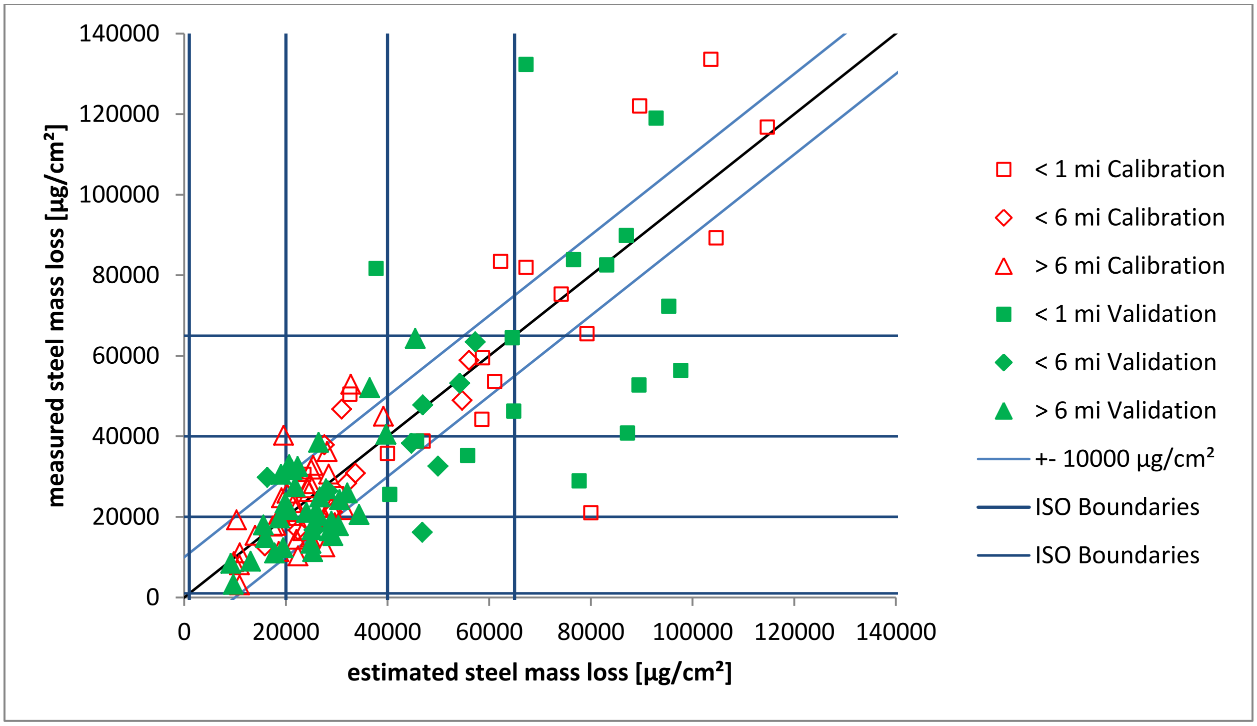
Map Data © 2016 Google, INEGI

Regression analyses were performed using the Battelle corrosion and NOAA environmental data, from which three models were developed to calculate ISO Corrosivity Categories based on salinity levels:

- Salinity 1 - greater than six miles from salt water
- Salinity 2 - between one and six miles from salt water
- Salinity 3 - less than one mile from salt water

For salinity 2, the tool will calculate the ISO Corrosivity Category using model 1 and 2 and display the highest value. For salinity 3, the tool will calculate the ISO Corrosivity Category using model 1, 2 and 3, and display the highest value. Figure 13 below shows the regression analysis used to develop the three ICCET models based on salinity.

Figure 13 - ICCET Model Regression Analysis



The data used to develop these models was not sampled or cherry-picked. All high-confidence data was used, and no outliers were thrown out. The formula used for each of the three models described above is expressed as:

Parameter Overview			
Distance	> 6 mi.	<= 6 mi. but >= 1 mi.	< 1 mi.
a	0.7	0	0
b [µg/cm²]	0.6575	6.7471	25.688
c [µg/cm²]	6786.1	7904.5	-105366
T_{TH} [°C]	3	9	2
RH_{TH}	0.63	0.65	0.62

$$MassLoss = \left[\sum_{t=1}^{8760} \tau (T - T_{TH})^a\right] b + c$$

Where:

$\tau = 1$ if $T \geq T_{TH}$ and $RH \geq RH_{TH}$

$\tau = 0$ if $T < T_{TH}$ or $RH < RH_{TH}$

A, b, c are simply modifiers used for each modelT_{TH} is the temperature threshold

RH_{TH} = relative humidity threshold

τ = exposure time in hours

When broken down into each salinity model, the formula can also be expressed as:

<u>Model 1</u> (Greater than six miles)

$$MassLoss = \left[\sum_{t=1}^{8760} \tau (T - T_{TH})^{0.7}\right] 0.6575 + 6786.1$$

Where:

$\tau = 1 \text{ if } T \geq 3 \text{ and } RH \geq 0.63$

$\tau = 0 \text{ if } T < 3 \text{ or } RH < 0.63$

<u>Model 2</u> (Between six miles and one mile)

$$MassLoss = \left[\sum_{t=1}^{8760} \tau\right] 6.7471 + 7904.5$$

Where:

$\tau = 1 \text{ if } T \geq 9 \text{ and } RH \geq 0.65$

$\tau = 0 \text{ if } T < 9 \text{ or } RH < 0.65$

<u>Model 3</u> (Less than one mile)

$$MassLoss = \left[\sum_{t=1}^{8760} \tau\right] 25.688 - 105366$$

Where:

$\tau = 1 \text{ if } T \geq 2 \text{ and } RH \geq 0.62$

$\tau = 0 \text{ if } T < 2 \text{ or } RH < 0.62$

How to Calculate Relative Humidity and Absolute Humidity from Available NOAA Data

Relative humidity data is not generally provided by the NCEI database. However, the Integrated Surface Data (ISD) provides hourly temperature and dew point data. Relative and absolute humidity can be calculated from these values using the following method:

p_a: actual vapor pressure
$p_s(\vartheta)$: saturation vapor pressure
ϑ: temperature in ℃
T: temperature in K
τ: dew point in ℃
$K_1 = 611.2\ Pa$
$K_2 = 17.62$
$K_3 = 243.12$ ℃

Definition of relative humidity: $\varphi = \dfrac{p_a}{p_s(\vartheta)}$

Magnus-Formula (-45 ℃ $\leq \vartheta \leq$ 60 ℃):

$$p_s(\vartheta) = K_1 e^{\left(\frac{K_2\vartheta}{K_3+\vartheta}\right)}$$

at dew point τ: $p_a = p_s(\tau)$

$$\varphi(\tau,\vartheta) = \frac{p_a}{p_s(\vartheta)} = \frac{p_s(\tau)}{p_s(\vartheta)} = \frac{K_1 e^{\left(\frac{K_2\tau}{K_3+\tau}\right)}}{K_1 e^{\left(\frac{K_2\vartheta}{K_3+\vartheta}\right)}} = e^{\left(\frac{K_2\tau}{K_3+\tau}-\frac{K_2\vartheta}{K_3+\vartheta}\right)}$$

The absolute humidity/water content of air in kg/m³ can be calculated as follows:

$$\rho_w(\tau,T) = \frac{p_a}{R_w T} = \frac{K_1 e^{\left(\frac{K_2\tau}{K_3+\tau}\right)}}{R_w T} = \frac{K_1}{R_w T} e^{\left(\frac{K_2\tau}{K_3+\tau}\right)}$$

Limitations of the ICCET

Inherent in all environmental severity methods are limitations to what can be discerned from the information each method provides, such as data gaps and variability in climates. No environmental severity classification method can cover all situations that occur in natural environments and service conditions. It is important to understand that the ICCET method is specific to atmospheric corrosivity and at this time does not consider other types of exposure environments, such as subterranean (i.e. soil corrosivity and submerged environments. The ICCET is based on atmospheric corrosivity of steel coupon samples. While this data is sufficient to determine general differences in atmospheric corrosivity between locations and environments for design and decision-making purposes, it is important to consider that other materials can degrade differently in similar environments, such as electrical components, roofing, etc. In environments with high corrosion gradients and “microclimates,” corrosivity can also vary within a given region. This applies in particular to locations near the coastline, large bodies of salt water or industrial zones with high pollution. In addition, some DoD locations in these environments are large enough that more than one ISO Corrosivity Category can be present. Table 2 below demonstrates this at Vandenburg AFB.

Table 2 - ISO Corrosivity Categories for Varying distances at Vandenberg AFB (2006)

Base Name	Location	Year	Distance to coastline (in miles)	ISO Corr. Cat.
Vandenberg AFB	Santa Barbara, CA, US	2006	0.25	**C5**
Vandenberg AFB	Santa Barbara, CA, US	2006	0.5	**C5**
Vandenberg AFB	Santa Barbara, CA, US	2006	1	**C5**
Vandenberg AFB	Santa Barbara, CA, US	2006	2	**C4**
Vandenberg AFB	Santa Barbara, CA, US	2006	5	**C4**
Vandenberg AFB	Santa Barbara, CA, US	2006	7	**C4**

More detail on other issues and gaps faced by the ICCET and environmental severity classification methods can be found in Section 6.

5.4 Decay Hazard Index for Wood

The Decay Hazard Index was developed as a method to estimate decay hazard for a given geographic location (within the conterminous United States) for wood exposed to the atmospheric environment [15]. This method was devised to be easily calculated from climatic data available from the U.S. National Weather service (now NOAA). The function is expressed as:

$$Index = \sum_{Jan}^{Dec} (T_F - 35)(D - 3)\frac{1}{30}$$

Where:

T_F = mean monthly avg. temp (Fahrenheit);

D I = mean number day per month with .01 in. or more of precipitation

And $(T_F - 35) \equiv 0$ if $T_F < 35$

Alternately expressed as:

$$Index = \sum_{Jan}^{Dec} \left(T_C - \frac{5}{3}\right)(D - 3)\frac{3}{50}$$

Where:

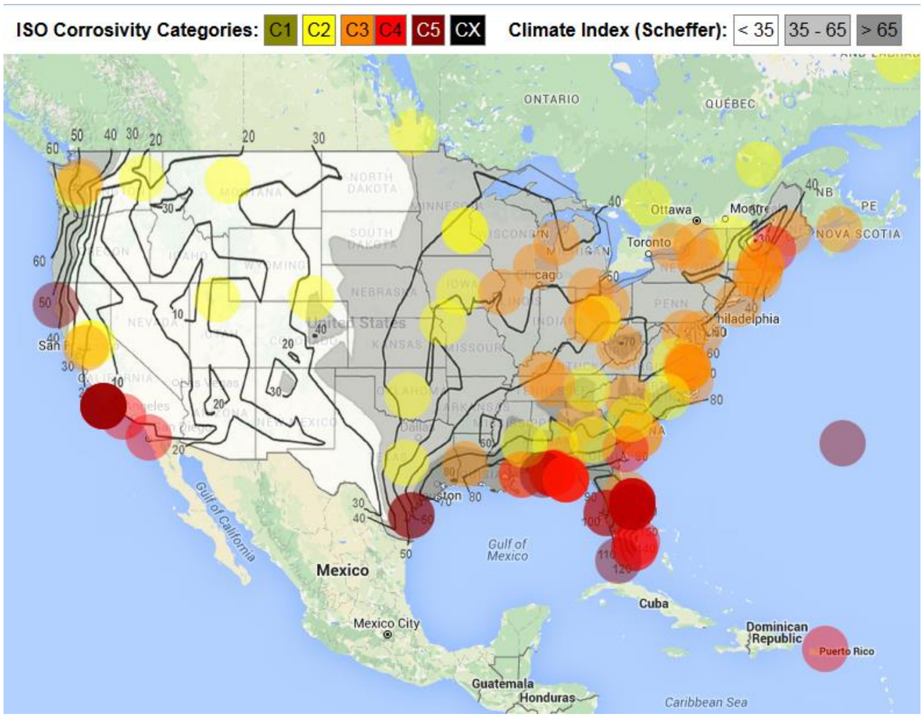
T_c = mean monthly avg. temp (Celsius);

D = mean number day per month with .25 mm or more of precipitation

And $(T_c - \frac{5}{3}) \equiv 0$ if $T_c < \frac{5}{3}$

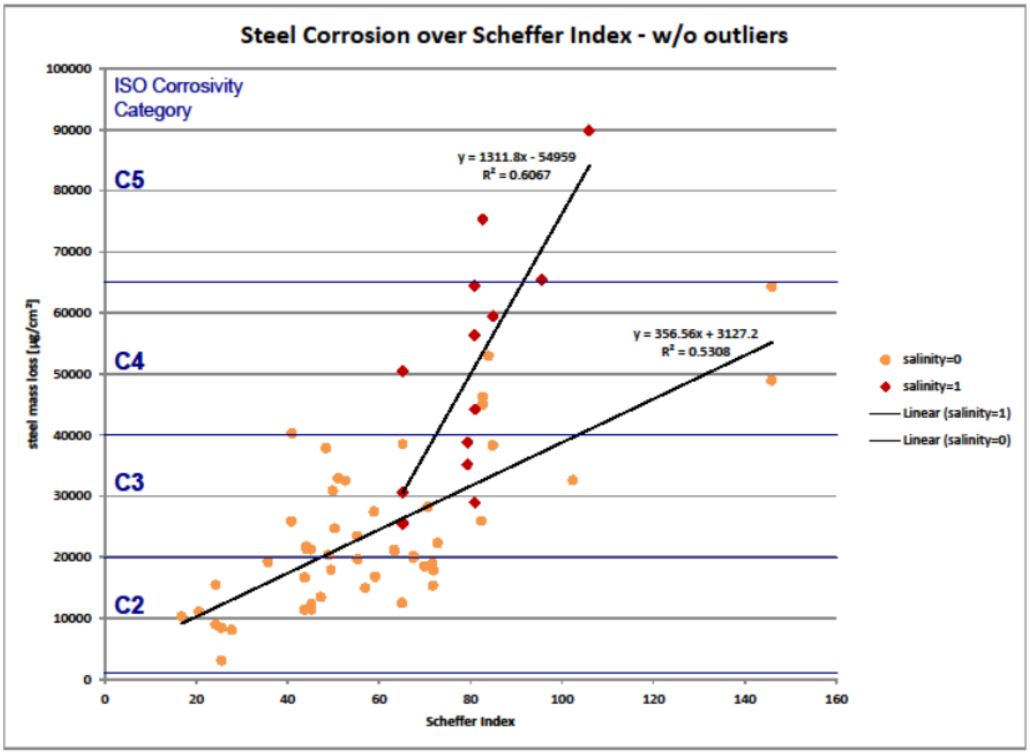
A formula for estimating corrosion mass loss and ISO corrosivity categories using NOAA weather data was developed using regression analyses comparing the corrosion data to the decay hazard values. Figure 14 and 15 below depict the relationship between the Decay Hazard Index and ISO Corrosivity Categories (based on steel mass loss data).

Figure 14 - Decay Hazard Index with ISO Corrosivity Categories



Map Data © 2016 Google, INEGI

Figure 15 - Regression Analysis of Steel Corrosion Data and Decay Hazard Index

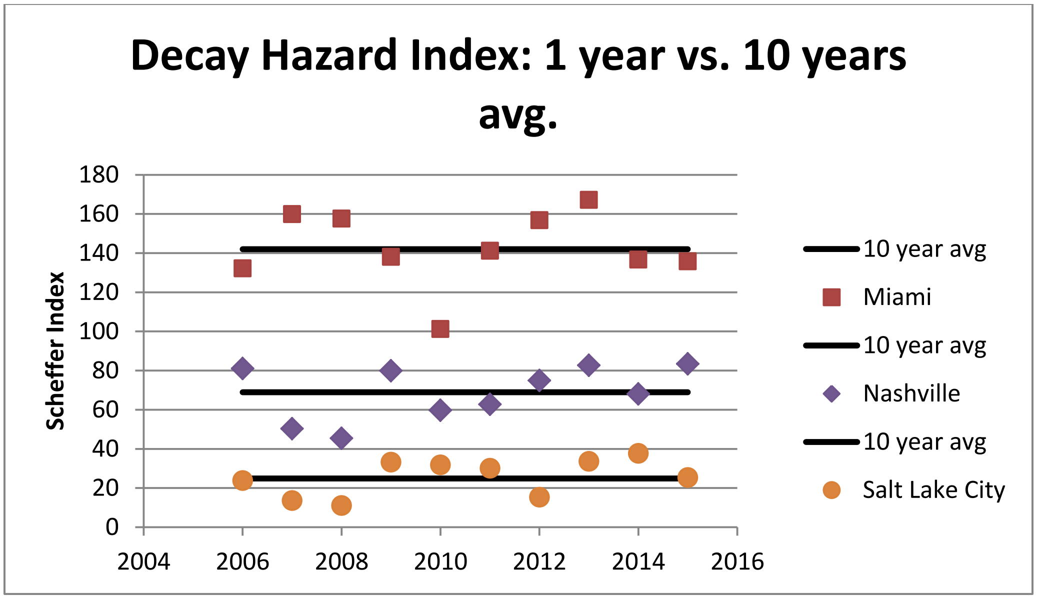


This formula was originally used in the ICCET tool to perform the estimated ISO Corrosivity Category calculations. Although this method showed moderate correlation, the formula was modified to use hourly relative humidity instead of average day per month with .01 inches of precipitation and hourly temperature. The reason for was that hourly environmental data provides a more accurate data set and relative humidity provides a more accurate representation of potential atmospheric moisture – a signification factor in corrosivity as it applies to metals and other materials. When compared to the Battelle corrosion mass loss data, the Decay Hazard Index shows a correlation.

Issues

The Decay Hazard Index is specific to wood decay. Locations with higher average Decay Hazard Indexes tend to show more variability over time than locations with lower indexes. Figure 16 below shows the Decay Hazard Index variability over 10 years for three locations with varying levels of wood corrosivity.

Figure 16 - Yearly Variation of Decay Hazard Index



5.5 Environmental Severity Index (ESI)

Using the Battelle corrosion data, the Environmental Severity Index (ESI) was developed by LMI to classify each military installation worldwide based on its location and corresponding environmental severity relative to corrosion. ESI is broken out into 20 zones based on the observed mass loss of the Battelle samples. For DoD locations that do not have mass loss data, ESI zones were calculated using the relationship between Time of Wetness (ToW, τ) and salinity (S).

This formula is expressed as:

$$ESI = 2.25 \cdot \tau + 7.14 \cdot S$$

ToW: number of hours with temperature higher than 32°F (0°C) and humidity higher than 80%

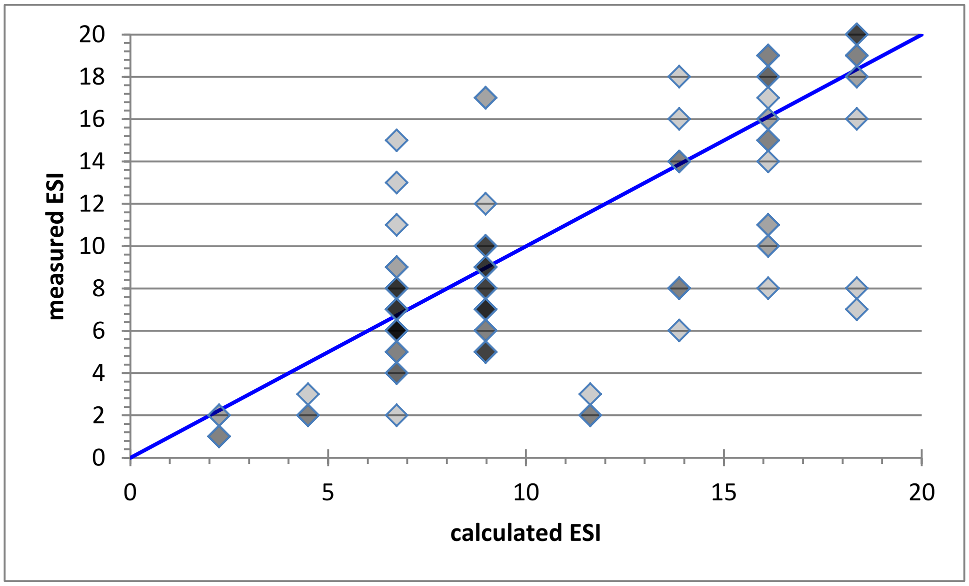
RH: Five intervals according to ISO 9223, Appendix B [6]

Salinity (S): binary, installation is within 1 mile of seawater (1 = yes, 0 = no)

ToW intervals according to ISO 9223, Appendix B [6]

Figure 17 below shows a comparison of measured and calculated ESI.

Figure 17 - Calculated vs Measured ESI



However, a closer look revealed some inconsistency:

In the Battelle report [9], mass loss values were given for three month intervals as total cumulative values: 1st interval - mass loss of the first coupon, 2nd interval - sum of the mass losses of the first and the second coupon, 3rd interval - the sum of the first three coupons and so on. This led to an error in the way the data was calculated for determining ESI. Instead of using the last value in the series, which would be the total mass loss for the year, all four of the intervals were added together, creating exaggerated mass loss values.

In about half of the sites, a series consisted of 4 measurements. The average that was calculated is about 7.5 times the monthly average. Since the values were cumulative 3, 6, 9 and 12-month values, there is an emphasis on the first measurement. The first measurement is represented four times in the average where the last measurement is only represented one time. Table 3 below shows the original version of the ESI table.

Table 3 - ESI Table, Original Version

12-month steel mass loss		
	r_{corr} [µg/cm²]	
ESI Zone	**≥**	**<**
1	0	2000
2	2000	4000
3	4000	6000
4	6000	8000
5	8000	10000
6	10000	12000
7	12000	14000
8	14000	16000
9	16000	18000
10	18000	20000

11	20000	22000
12	22000	24000
13	24000	26000
14	26000	28000
15	28000	32000
16	32000	36000
17	36000	40000
18	40000	50000
19	50000	75000
20	75000	∞

In the other cases, the data consists of incomplete series (i.e. only partial 12-month period covered) or longer series for (i.e. 15-month series).

The ESI definition-table was adjusted and the ESI was recalculated for those sites with consistent data. The found relationship between ESI and TOW/S was reviewed and the coefficients were recalculated. Table 4 below shows the updated ESI table (ESI 2.0).

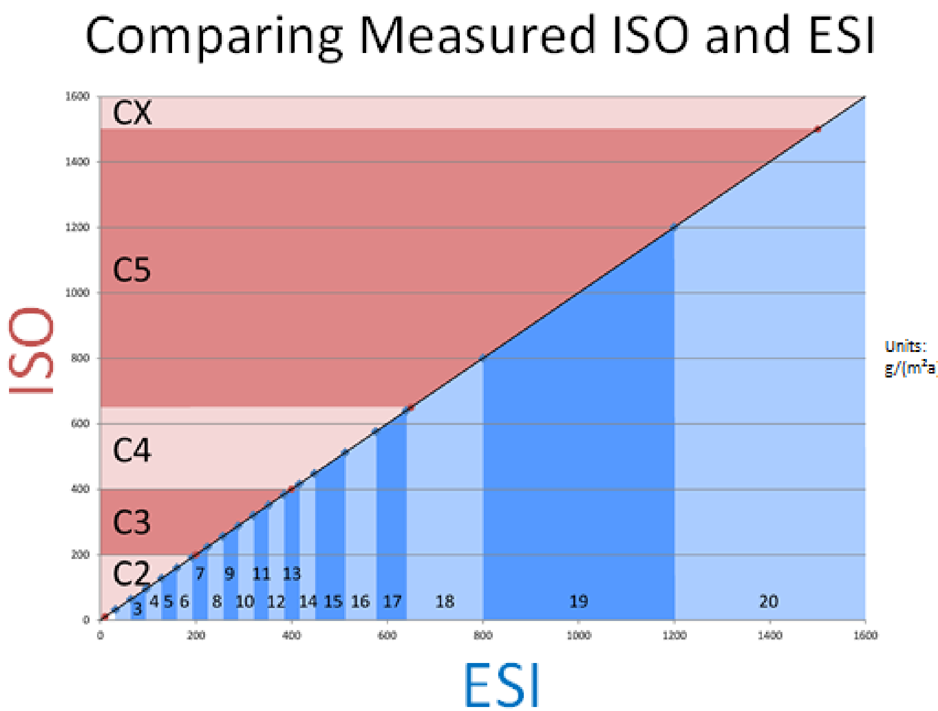
Table 4 - Adjusted ESI Table, "ESI 2.0"

12-month steel mass loss		
	r_{corr} [µg/cm²]	
ESI Zone	**≥**	**<**
1	0	3200
2	3200	6400
3	6400	9600
4	9600	12800
5	12800	16000
6	16000	19200
7	19200	22400
8	22400	25600
9	25600	28800
10	28800	32000
11	32000	35200
12	35200	38400
13	38400	41600
14	41600	44800
15	44800	51200
16	51200	57600
17	57600	64000
18	64000	80000
19	80000	120000
20	120000	∞

Measured ISO Corrosivity Categories vs Measured ESI (2.0)

Figure 18 below shows a comparison of measured ISO and measured ESI (2.0).

Figure 18 - Comparison of Measured ISO and ESI



Essentially, these two methods are simply different ways of displaying the same information, the main difference being that ISO has only six categories while ESI has 20. Both categories are determined using one-year mass loss values.

Calculated ISO Corrosivity Categories vs. Calculated ESI

For the calculated versions of these methods, the difference lies in the types and frequency of data that is considered. Calculated ESI considers the (TOW) and salinity. TOW is the number of hours a location experiences greater than 32-degree temperatures and greater than 80 percent relative humidity. The salinity value is a binary measurement that considers whether the center of mass of the location is within one mile of seawater – simply a yes or no value.

Calculated ISO using the ICCET method considers hourly temperature, hourly relative humidity, and a ternary salinity measurement. This method also allows users to use data from any time range they prefer and the environmental databases that this tool uses are updated in real time. See section 5.3 for more information on the ICCET method.

5.6 Cost-based Environmental Severity Method

The Cost-Based Environmental Severity model was developed by Steve Geusic (Policy Engineer, in support of OUSD (AT&L), Corrosion Policy and Oversight Office) and is based on the cost of corrosion (as measured by CPO Cost of Corrosion studies) as it relates to ESI levels. This method approaches environmental severity from a cost-driven basis to re-categorize ESI categories for DoD locations into low, moderate, high and severe levels (table 5).

Table 5 - Cost-Based Environmental Severity Levels

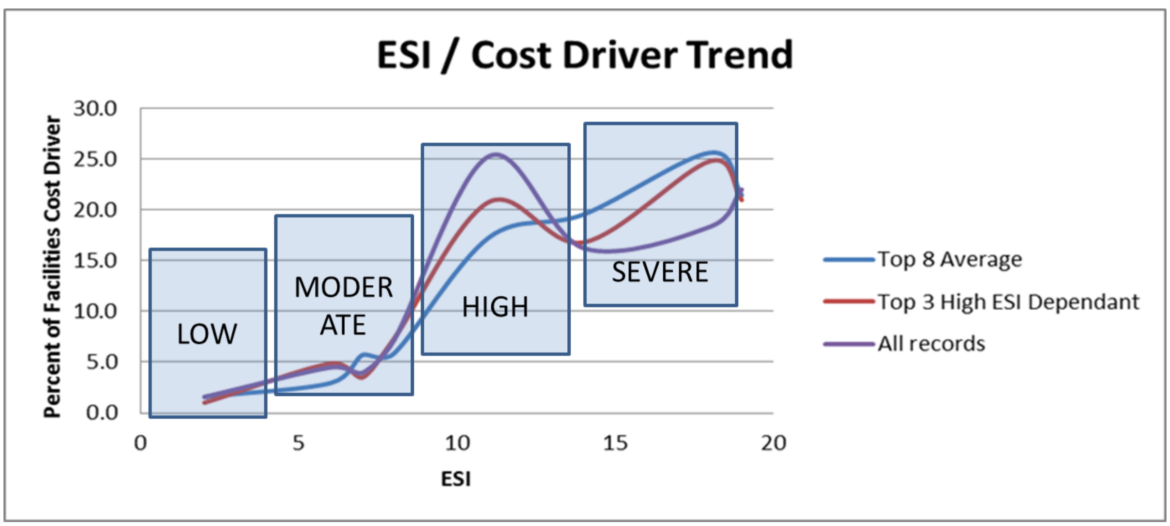
ESC	ESI (1.0)
Low	1 - 3
Moderate	4 - 8
High	9 - 13
Severe	14 - 19

In many cases, ESI categories do not consistently correlate with the sustainment cost data. This can be attributed to an imbalance of records for each ESI level, as well as the variability associated with how the maintenance data was recorded at each installation. There is, however, a general trend in which sustainment costs increases with ESI level. A simple trend analysis was conducted based on the cost drivers identified in FICES [3]. The percentage of corrosion cost of the driver is plotted for the ESI zones. A plot was conducted for:

1. All records – 35 cost drivers
2. Top 10 cost drivers – reduced to Top 8 as two of the drivers are not influenced by ESI (Interior elements - Water Heater and Plumbing)
3. The top 3 cost drivers which have high influence by ESI (Facilities/Structure, Electrical, and Fence)

Figure 19 shows a comparison of percentage of facilities cost drivers and ESI (1.0).

Figure 19 - ESI/Cost Driver Trend[11]



This analysis shows that here is a general trend that sustainment costs increase with ESI. There is a spike in costs around ESI 9. Also, ESI values 11 – 14 are almost as severe as ESI levels 18/19. There are two possible reasons for this:

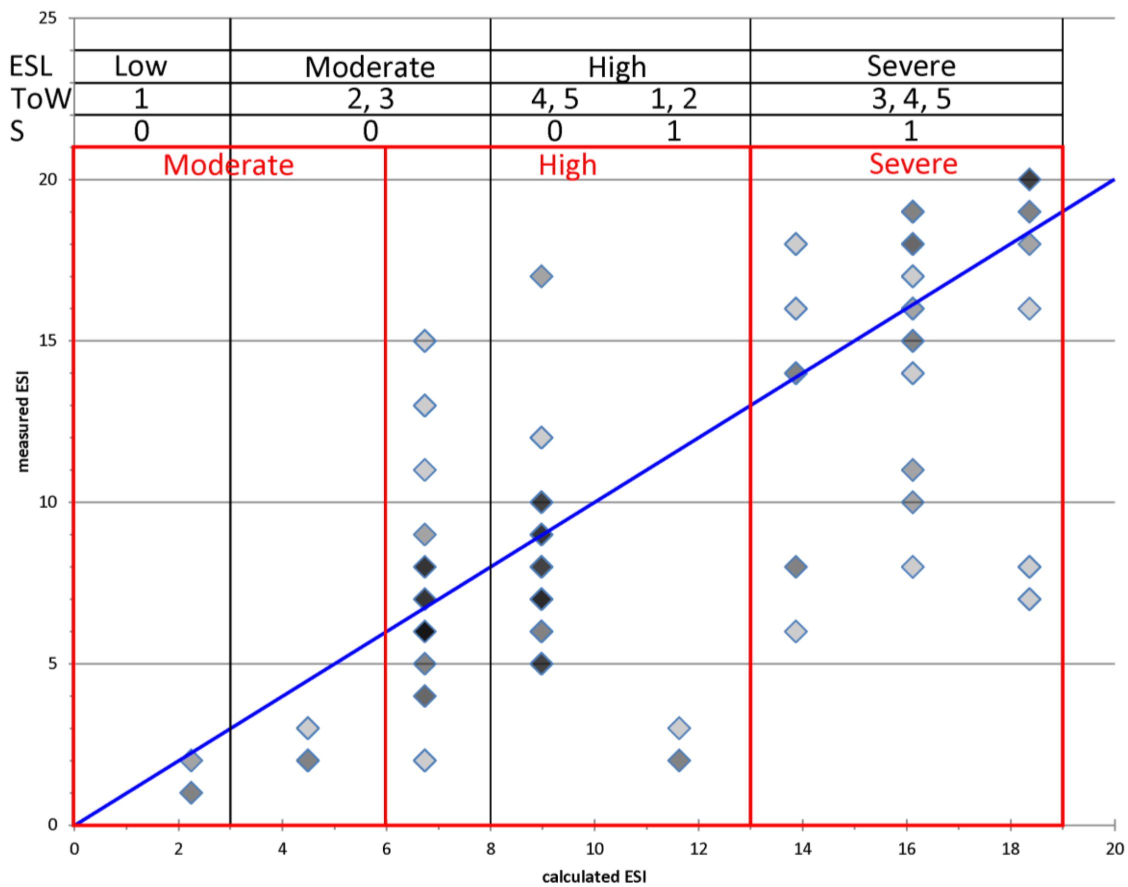
- Skewed data based on an imbalance in the number of installations at each ESI.

[11] Provided by Steve Geusic.

- A more likely explanation is that levels 18/19 are tropical environments and have stricter local and UFC criteria. ESI locations 11-14 share the same minimum CPC criteria as ESI 1-10 even though the coupon degradation is more severe.

An analysis was conducted to compare this method to the Battelle corrosion data. This analysis showed a slight modification could be made to better fit the mass loss data as it relates to measured and calculated ESI (figure 20).

Figure 20 - Modified Cost-based Method



Issues

Corrosion cost data is generally limited by gaps in the process by which it is recorded and the factors that cause maintenance actions to be executed. How and when maintenance actions are executed is based upon resource constraints which often results in maintenance actions being deferred. Corrosion cost data is also based off of small snapshot of data. The data used in the FICES does not provide the information required to determine root cause, including facility age, local environment, or specific maintenance actions that were performed. Because of this, sometimes it is difficult to determine whether a maintenance action constitutes CPC.

5.7 Cumulative Corrosion Damage Model (CCDM)

The Cumulative Corrosion Damage Model (CCDM) was developed as a proof-of-concept by Dr. Dave Rose to predict corrosion rates using the concept of cumulative damage, using hourly weather data (temperature, relative humidity, sulfur dioxide, chloride, and ozone). This model is based upon the Eyring equation, a function used in chemical kinetics to describe the variance of the rate of a chemical reaction with temperature. The CCDM makes hourly weight loss predictions which can be added together to make longer-term "cumulative" predictions. Hourly weather data is used because "the main advantage of using hourly predictions vs using yearly or monthly averages is that the effects of diurnal and seasonal temperature cycles and related changes to relative humidity are explicitly considered," [14].

Issues

Like all environmental severity classification models, issues exist with this approach. It is important to note that this method is still currently proof-of-concept and the development of a mature model is still ongoing.

<u>Environmental Data</u>

This model depends heavily on the availability of local atmospheric contaminant data. The density of pollution monitoring sites is too low to use this model in a broader application (see figure 9), although other methods for obtaining or modeling atmospheric parameters may be able to be used in the future. In addition, this model shows good results for a few selected sites in humid locations with lower rates of chloride deposition.

<u>CCDM Formulas</u>:

Upon a closer look, the formulas in the CCDM are overly complex and can be simplified. With the given coefficients on page 148 of the Dr. Rose's dissertation [14] the temperature-shape-function (for Chloride) can be expressed as:

$$f(T) = e^{\frac{\Delta H}{kT}} (T-k)^{2.5}\, T^{\alpha_{Cl}} = e^{\frac{19496}{T}} (T-273.15)^{2.5} T^{4.776592}$$

More specifics on how this function was calculated can be found in Appendix B.

6. Issues and Gaps

The atmospheric environment itself is a variable that constantly changes with time and condition. Classification of environmental severity provides designers, planners and decision makers with tools for making more informed decisions based on their respective atmospheric environment, but cannot provide a one-stop shop for assessing absolute corrosion potential or corrosive attack. Below are issues and gaps faced by environmental severity characterization methods:

- No method can cover all situations that occur in natural environments and service conditions. None of the available methods establish severity indices for all of the materials and components used in DoD weapon systems and facilities (e.g. metals and alloys degrade differently than electrical components when exposed to the same environmental stressors).

- The rate of corrosion for metals and alloys exposed in the atmospheric environment is not always consistent with the time of exposure. Over time, the surface profile of a material and the accumulation of corrosion product changes.
- Application in locations with high corrosivity gradients: Environmental severity can vary within locations with high corrosivity gradients and micro-climates. This is particularly true for sites located near large bodies of salt water (i.e. high salinity zone). In some situations, a DoD installation may be large enough to fit into more than one ISO Category. The environment that affects a specific material or system correlates directly to the conditions of the micro-environment that it *actually* experiences (the "local environment" that occurs on the surface of the material or system).
- Lifetime prediction of corrosion damage from atmospheric corrosivity is possible, but it is limited by the fact that the environment itself is a variable that constantly changes with time and condition. While the principles of thermodynamics and corrosion kinetics (e.g. Pourbaix Diagrams) can be employed to evaluate the theoretical activity of a given metal or alloy in a corrosion situation, the total chemical make-up of the environment in which the reaction is occurring must be known [16]. At present, this is not possible on a large scale outside of laboratory testing or sites with active environmental or corrosion monitoring solutions. Estimation of lifetime corrosion damage can be accomplished (see section 5.2, Guiding Corrosion Values) but one must consider that these methods provide only a broad estimation of corrosion over periods of time for specific materials.
- Availability and fidelity of corrosion, weather, and cost data: One of the biggest issues related to environmental severity classification efforts is availability and fidelity of data. Currently, one-year mass loss data suitable for use in ISO only around ~152 locations. In addition, pollution and atmospheric contaminate monitoring solutions only exist for a relatively small number of locations.
- Variance in weather/climate year-to-year: Environmental factors, such as average temperature, relative humidity, precipitation, wind, can vary month-to-month and year-to-year. Visit www.corrdefense.org to see animated maps showing how corrosivity in the U.S. varies over time the ICCET model.
- Variance in weather data gathering methods and equipment: Although there are standard methods for gathering environmental data, not all weather monitoring station uses the exactly same methods, tools, and sensors for gathering weather data.
- Weather station equipment accuracy and calibration: In addition to the above, the equipment, tools, and sensors used by weather monitoring stations must be regularly maintained and calibrated to ensure accuracy. Currently, there is no clear way to thoroughly evaluate this for every station. The NOAA data is considered trustworthy and suitable for use in environmental severity characterization.

- Standard error rates of modeling efforts: All modeling efforts have standard error rates. No environmental severity classification model can account for all potential variables. These rates must be evaluated and considered when using these methods to influence decisions.

7. Conclusion

Based on this report and publication of the ICCET, DoD criteria professionals and designers could implement ISO 9223:2012 [6] and associated corrosion standards and may use this tool to help begin the facilities design process. Classification of environmental severity, using ESC factors and ISO Corrosivity classification, may provide designers, planners and decision makers with tools for making more informed decisions based on their atmospheric environments, such as selection of materials and systems that have appropriate levels of durability in that environment. ESC methodology and ISO Corrosivity Classification could be integrated through inclusion in UFC 1-200-01 [7] and other appropriate Unified Facilities Criteria.

The preferred methods for determining ISO Categories are:

1. Corrosivity Determination based on one-year corrosion mass loss or penetration of standard specimen. Specifics regarding this method can be found in ISO 9223, section 7.
2. Calculated ISO Categories using the ICCET, which is based on detailed environmental information. Specifics regarding his method can be found in section 5.3 of this report.

ISO Categories measured using the Corrosivity Determination method are provided in Appendix C and E. For the majority of DoD sites that do not have the direct corrosion data necessary for Corrosivity Determination, the ICCET provides a quick and easy baseline severity based on best available data without having to do on site long term corrosion testing. This tool helps bypass the need to collect the necessary environmental data and performing the calculations separately. Appendix D provides pre-calculated ISO Corrosivity Categories using the ICCET for 482 DoD installations. The ICCET can be found at www.corrdefense.org.

It is important to note that, while environmental severity classification may be a useful tool for the characterization of local environments, it is not indicative of absolute corrosion potential or total environmental corrosivity. No classification method can accurately cover all situations that occur in natural environments and service conditions. In addition, the actual environment that affects a specific material or system correlates directly to the conditions of the micro-environment that it experiences (the “local environment” that occurs on the surface of the material or system), which can vary even over small distances.

8. Next Steps and Recommendations for Future Work

8.1 Implementation

Since facilities are fixed and exposed to constant environments, DoD criteria professionals and designers could implement ISO 9223:2012 [6], associated corrosion standards, and ESC methodology in Unified Facilities Criteria. This could potentially be used to help begin the facilities design process and would require codifying the ISO Corrosion standards in appropriate criteria. Classification of environmental severity, using ESC factors and ISO Corrosivity classification, may provide designers, planners and decision makers with tools for making more informed decisions based on their atmospheric environments, such as selection of materials and systems that have appropriate levels of durability in that environment.

8.2 Environmental Severity Classification for Other Types of Materials

The ESC effort focused on atmospheric corrosion of metal and wood. There are many other materials, components, and systems used in the design and construction of DoD facilities and weapon systems. An initial analysis of other environmental severity classification methods was conducted, but a more in-depth analysis would be beneficial. This preliminary analysis revealed that, outside of metals and wood, there aren't many environmental severity efforts for other types of materials and systems on the scale of the ICCET, CCDM, etc. The materials that should be considered as part of this in-depth analysis are:

- Concrete
- Pavement
- Other types of masonry
- Paints and Coatings
- Composites
- Polymers/Plastics
- Ceramics

8.3 Non-Atmospheric Environmental Severity Methods

This study focused mainly on atmospheric environmental severity as it related to metals and timber. Other types of environmental severity, such as soil corrosivity, should be explored for applicability and in DoD facilities planning, design, and construction. An engineering model for timber decay in contact with the ground for Australia, developed by R.H. Leicester et al., is of particular interest [17]. The model uses a climate index based on rainfall and temperature parameters and applies to all locations in Australia, including hot tropical regions and desert areas. With slight modifications and adjustments for specific environments, this model can be applied "to any structure, fabricated from any species and located anywhere in the world." In fact, this model was later adjusted for use in Sao, Paulo Brazil [18].

In the civil world, corrosion of underground piping and other subterranean systems is a major concern. Modification of this model to apply to materials other than timber would be of great benefit to DoD design and construction processes and should be explored.

8.4 Materials Exposure Factors Matrix

To further assist designers and risk managers in assessing potential corrosivity of different environments, it would be beneficial to develop a Materials Exposure Factors Matrix. This matrix would contain a list of different materials used in DoD applications and the potential corrosivity that certain environmental factors have on those materials. An example of what this could look like is provided below (table 6):

Table 6 - Example of Environmental Factors Matrix

Example Environmental Factors Matrix						
	Humidity	**Temp.**	**Precip.**	**uV**	**Biological**	**Chloride**
Metal	+++	+++	+++	++	++	+++
Wood	++	+++	+++	+++	+++	+
Concrete	++	+++	+++	++	++	+++
Other Masonry	++	+++	+++	++	++	+++
Composites (non-metal)	+	++	++	+++	+	++
Coatings	++	++	+++	+++	++	++

8.5 Broad Design Risk Assessment

In the design of DoD Weapon Systems and Facilities, aesthetic and performance requirements must be balanced against budget considerations to achieve cost effective material/system specification and design. As such, it may be beneficial to develop a broad design risk assessment for material and system selection that encompasses not only environmental severity, but other life-cycle factors such as maintenance, management, contracting, training, and safety.

An example of this is the Site and Design Evaluation System [19] developed by The International Molybdenum Association (IMOA) for the selection of stainless steel. This guide provides a template that weighs and scores five major life cycle factors: Environmental/Pollution, Coastal and Deicing Salt Exposure, Local Weather Pattern, Design Considerations (surface finishes, Horizontal/Vertical surfaces, etc.), and Maintenance Schedule. The total score is then used to determine the appropriate stainless steel type for the application. The guide also provides methods for reducing the score in order to use more cost-effective type if desired.

8.6 Other Environmental Factors for ESC Methodology

Data exists for other environmental factors that have been shown to contribute to environmental severity, including prevailing winds, pollution/atmospheric contaminates, and precipitation. It would be prudent to explore these factors in a separate, modified version of the ICCET and ESC factors that can be used on a case-by-case basis when local data for these factors exists via an easily accessible method (NOAA database, EPA database, etc.).

- Prevailing Winds: An environmental corrosivity tool for bases and airports within Australia called the Geographic Corrosivity Index (GCI) uses a wind aggregate as part of its methodology. The tool considers the strength of the wind blowing from directions likely to carry the most sea generated salt aerosol to the site (i.e. off-sea winds) and calculates an aggregate that is included in the GCI algorithm. Average wind speeds for each of the major and minor ordinal wind directions – N, E, S, W, NE, SE, SW, and NW - are used. More information on the development and use of the wind aggregate and research on the deposition of marine salts can be found in references [20] and [21].
- Pollution and Atmospheric Contaminants: Pollution and atmospheric contaminates, such as sulfur dioxide and ozone, have been shown to affect the occurrence and rate of corrosion. Data for these elements exist in easily accessible databases, although the number of monitoring stations is limited (see figure 9). This means that broad use of these factors in the ICCET is not possible at this time. It may be beneficial to develop separate, modified version of the ICCET to incorporate these elements and use them to determine ISO categories when appropriate.
- Precipitation: Precipitation and humidity act as the electrolyte necessary to complete the corrosion cell in the atmospheric environment. Precipitation, especially rain, contributes to the accumulation of surface wetness which greatly affects the rate of corrosion. Some materials are also affected by hydrolysis, the chemical breakdown of a compound due to reaction with water. Polymers "such as polycarbonate, polyester, polyamide and many others hydrolyze in the presence of water," [22] leading to premature degradation. Although relative humidity tends to be the main source of atmospheric moisture, precipitation can affect the rate of corrosion and as such it is worth exploring how to include a measure of precipitation in the ICCET. Precipitation data is generally widely available for most locations for which there are nearby NOAA weather stations. Precipitation can also contribute to the deposition of pollution and atmospheric contaminates, taking contaminants concentrated in one area and depositing them in another (i.e. acid rain). Currently, precipitation data is used as a component of the Wood Decay Hazard Corrosion Index for classifying environmental severity for timber (see the section 5.4).UV Degradation: UV radiation can contribute to environmental severity for certain materials, such as degradation of non-UV-stable polymers. In the U.S., UV radiation data is obtained from satellites operated by NOAA and provided in the NOAA database.

8.7 Advanced Data Gathering and Environmental Modeling

Advanced technological initiatives such as *big data* and the *Internet of Things* (IoT) have led to the development of advanced data gathering and environmental modeling efforts. Exploring how some of these efforts can benefit the ESC methodology may be beneficial to the overall goal of CPC:

- NOAA/AWS Big Data Project and NEXRAD: NOAA and Amazon Web Services (AWS) recently entered into a research agreement to explore the development of sustainable models for increasing the output of open NOAA data using cloud computing technologies. This effort will also incorporate NOAA's Next Generation Weather Radar (NEXRAD), which detects and disseminates environmental data in five-minute intervals. This effort is still in its infancy and at present does not provide any further capabilities for the ESC methodology, but when larger, more detailed and up-to-the-minute data sets are available, this effort could provide increased capabilities for the ICCET. More information can be found at https://www.ncdc.noaa.gov/data-access/radar-data/noaa-big-data-project.
- EPA Air Quality Modeling: One of the biggest issues with respect to pollution and atmospheric contaminant data is availability due to the low number of monitoring stations. The EPA's Support Center for Regulatory Atmospheric Modeling (SCRAM) currently provides models for simulating air pollutants dispersed in the atmospheric environment.
- Other advanced weather prediction and atmospheric modeling efforts, such as the Leidos Operation Multiscale Environment Model with Grid Adaptively (OMEGA) may provide benefits as well. OMEGA can simulate atmospheric phenomena from global to local scale and can generate microclimatologies for small regions and account local complex terrain.
- Modular Integrated Sensor Networks and the *Array of Things*: With the diminishing size and cost of sensor technologies and modular systems, complex sensor networks for collecting extremely detailed and real-time data have become more viable. In some cases, urban areas have begun exploring the development and implementation of these types of systems, such as the *Array of Things* (AoT) network currently being deployed in the city of Chicago. The AoT is a network of interactive sensors housed in modular boxes that collect real-time data on the city's environment, infrastructure, and activity. This data includes air temperature, humidity, barometric pressure, sound, vibration, nitrogen dioxide, ozone, carbon monoxide, hydrogen sulfide, sulfur dioxide, light intensity, imagery, and others. All of this data is "open source" and freely available to the public. Currently, only a few of these systems exist around the U.S. but as the technology becomes more viable more cities and populated areas will begin to deploy similar systems, facilitated by the development of "smart cities." The data provided by these systems has great use for environmental severity classification and integration with ESC methodology and the ICCET should be explored in the future.

8.8 Corrosion Contour/Heat Maps and Animated Corrosion Maps in Marketing Materials

Using the ICCET, Mr. Gaebel has developed several maps depicting environmental severity over the world and how it changes over time. People are generally visual in nature and when they hear the terms corrosion or environmental severity they picture rust, not the ever-present degradative effects of the environment on the equipment and structures we see and use in our everyday lives. These maps can be found in Appendices E and F and at www.corrdefense.org. It would be beneficial to explore the use of these in CPO marketing and educational materials.

Glossary

Definitions

corrosion. The deterioration of a material or its properties due to a reaction of that material with its chemical environment (Ref. Section 2228 of Title 10, U.S.C). Traditionally thought of only as deterioration of metal (i.e., the rusting of steel), but now expanded to include degradation of non-metallic materials as well. Some non-traditional examples include the rotting of wood, the degradation of concrete (carbonation, alkali-silica reaction phenomena), and the degradation of composite materials due to reaction with the environment.

corrosion protection and control (CPC). The engineering, design and analysis, testing, quality assurance, nondestructive inspection, manufacturing/construction, operational, and sustainment activities undertaken to prevent, control, and mitigate corrosion.

criteria (facilities). The overarching term used to describe the technical documents that the Military Departments, Defense Agencies, and DoD Field Activities are required to use, regardless of funding source, for planning, design, construction, sustainment, restoration, and modernization of facilities in accordance with DoD Directive 4270.5 (Military Construction) and the USD(AT&L) Memorandum of May 29, 2002. The Construction Criteria Base is an extensive electronic library of construction guide specifications, manuals, standards, and many other essential criteria documents (Ref. MIL-STD-3007F and WBDG).

environmental severity. Describes the corrosivity of the local environment of a given location or region.

facility. A "facility" is a real property entity consisting of one or more of the following: a building, a structure, a utility system, pavement, and underlying land. The term ''facility'' means a building, structure, or other improvement to real property.

guidance. Written guidelines that provide broad advice in following a procedure or process, instead of providing a set of precise requirements or standards that implements policy

installation. A base, camp, post, station, yard, center, or other activity, including leased facilities, under the jurisdiction, custody, or control of the Secretary of Defense or the secretary of a military department or, in the case of an activity in a foreign country, under the operational control of the Secretary of Defense or the secretary of a military department, without regard to the duration of operational control. An installation may include one or more sites.

return on investment (ROI). A performance metric used to evaluate the efficiency of an investment or to compare the efficiency of a number of different investments.

sustainment. The maintenance and repair activities necessary to keep a typical inventory of facilities in good working order over their expected service life. Sustainment includes regularly scheduled adjustments and inspections, preventive maintenance tasks, and emergency response and service calls for minor repairs. It also includes major repairs or replacement of facility components (usually accomplished by contract) that are expected to occur periodically throughout the facility service life. This includes regular roof replacement, refinishing wall surfaces, repairing and replacing electrical, heating, and cooling systems, replacing tile and carpeting, and similar types of work.

unified facilities criteria (UFC). UFC documents provide planning, design, construction, sustainment, restoration, and modernization criteria for facilities. These criteria apply to the Military Departments, the Defense Agencies, and the DoD Field Activities, in accordance with DoDD 4270.5 (Military Construction) and MIL-STD-3007F.

unified facilities guide specification (UFGS). UFGS are UFC documents that translate design criteria into construction specification requirements to be incorporated into construction contracts. The DoD UFC program represents the facilities and infrastructure component of the Defense Standardization Program as established by DoD Instruction 4120.24. Prescribes specifications, policy, and requirements for both civil works and MILCON.

policy. States the principles or goals of a DoD mission and defines performance standards and other means by which the DoD components can evaluate their success in implementing the policy. Policy statements are written concisely enough and in sufficient detail to ensure the policies are clearly articulated and to avoid the necessity of the DoD components having to prepare implementing or supplementing documents. This term is not normally used to denote what is actually done, but what is prescribed.

thermodynamics. The branch of physical science that deals with the relationship between heat and other forms of energy (such as mechanical, electrical, or chemical energy), and, by extension, of the relationships between all forms of energy.

Whole Building Design Guide (WBDG). Managed by the National Institute of Building Sciences. The content of the WBDG is a collaborative effort among federal agencies, private sector companies, nonprofit organizations and educational institutions. The WBDG was created to assist the design community with integrating government criteria, non-government standards, vendor data, and expert knowledge into a “whole building” perspective.

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Appendix A – The Corrosion Toolbox

The Corrosion Toolbox

In addition to the ICCET, several other tools related to this effort were developed. The Corrosion Toolbox contains the ICCET and other tools useful for evaluating corrosion severity and environmental data. The Corrosion Toolbox can be accessed via www.corrdefense.org. Figure 21 below shows the corrosion toolbox interface.

Figure 21 - Corrosion Toolbox Interface

Corrosion Toolbox

ISO Corrosivity Category

Uses NOAA data (ISD-Lite) to estimate the ISO Corrosivity Category.
ISO Corrosivity Category Estimation Tool (ICCET)

Wood Decay Hazard Index (Scheffer-Index)

Uses NOAA data (GHCN) to calculate Scheffer Index.
Calculate Wood Decay Hazard Index (Scheffer Index)

Corrosion Map

Display of wood decay hazard index (Scheffer-Index) and ISO Corrosivity Categories (ISO 9223) based on steel coupon outdoor exposure.
Corrosion Map

Air Pollution and Weather Data

This script pulls polution data from EPA databases and NOAA Weather Data from the ISD-Lite Database. Outputs hourly data, missing data is linearly interpolated.
Download Air Pollution and Weather Data

ISO Corrosivity Category and Wood Decay Hazard Index

The first tool is the ICCET (see section 5.3). The second is the Wood Decay Hazard Index (see section 5.4).

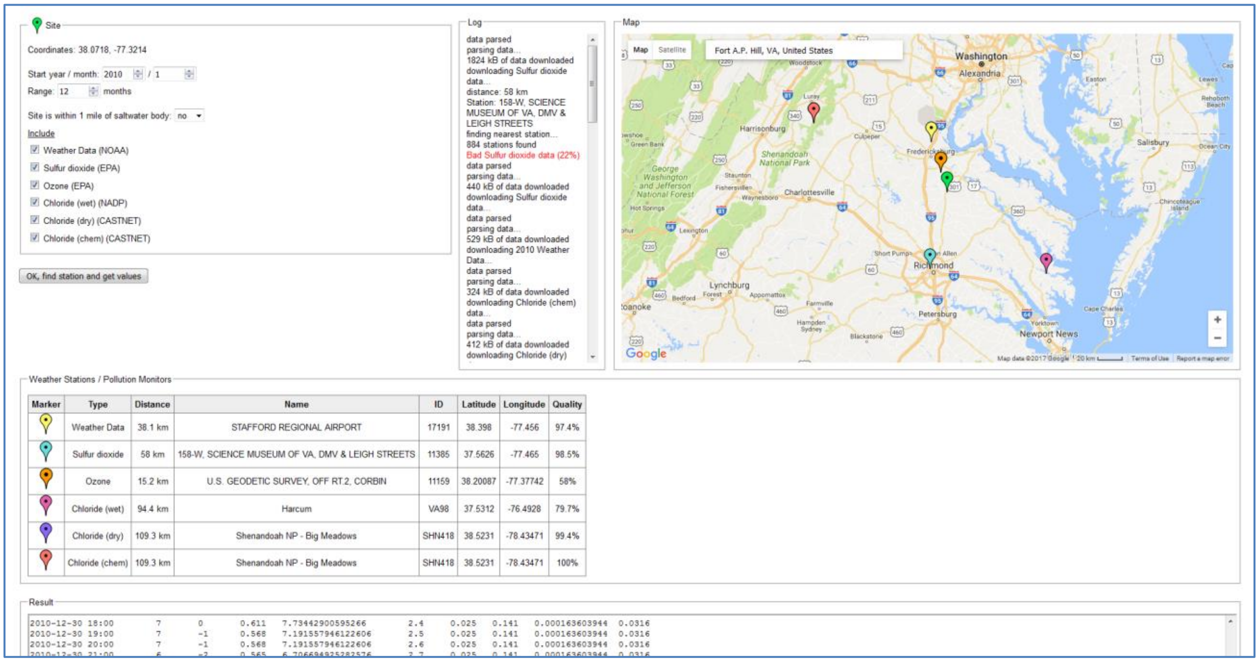
Corrosion Map

The third tool, the Corrosion Map, is an interactive map that displays both the Wood Decay Hazard Index and ISO Corrosivity Categories based on steel coupon outdoor exposure. The user can overlay these maps with data used in the ESC effort including ISO Categories and Validation sites.

Air Pollution and Weather Data

The fourth tool provides hourly air pollution and weather data from both the EPA and NOAA databases. This script pulls pollution data from EPA and NADP databases and NOAA Weather Data from the ISD-Lite Database. Missing data is linearly interpolated. Figure 22 below shows the air pollution and weather data tool interface.

Figure 22 - Air Pollution and Weather Data Tool



www.corrdefense.org

SO_2 and O_3 are generally provided in parts per billion (ppb) by these databases. To compare this data to other monitoring efforts, such as the ISOCORRAG program data, it may be necessary to convert these values to mass per volume, such as µg/m3 (micrograms per cubic meter). Below are the conversion factors for SO_2 and O_3:

- SO_2: 1 ppb = 2.63 µg/m^3
- 0_3: 1 ppb = 2.00 µg/m^3

<u>ICCET Batch Tool</u>

Mr. Gaebel also developed a batch tool for calculating and acquiring ISO Categories and estimated mass loss data for multiple sites at a time. This tool runs a script that allows the user to upload a table with latitude/longitude of the desired locations and outputs the necessary data. The script outputs the estimated steel mass loss (not the ISO category) for the three ICCET models. To determine ISO categories, this data can be input into an Excel spreadsheet with the below formula:

=1+IF(a>=1000,1,0)+IF(a>=20000,1,0)+IF(a>=40000,1,0)+IF(a>=65000,1,0)+IF(a>=150000,1,0)

Where: a = the cell in which the estimated mass loss is contained

A supplemental Excel table containing estimated ISO Corrosivity Categories for 482 DoD locations is provided in Appendix C.

Appendix B – CCDM Derivation of Functions

Based on the temperature boundaries provided in the Dr. Rose's Corrosion Cumulative Damange Model disseration, two constants are defined:

$$k = 273.15K$$

$$d = 47K$$

k can be interpreted as the temperature treshold and d as the temperature range or $k + d$ as the maximum temperature for the model.

The final temperature function (for temperature-contaminant shape-function) is:

$$f(T) = \left(\frac{T-k}{d}\right)^2 f(T)_{max} \tag{4.7}$$

The final temperature-contaminant function is:

$$f(T,C) = \frac{C^2}{C_{max}^2} f(T) = \frac{C^2}{C_{max}^2}\left(\frac{T-k}{d}\right)^2 f(T)_{max} \tag{4.11}$$

The one-hour corrosion rate function is:

$$\begin{aligned} K_i = e^{\frac{\Delta H}{kT}} \{ & A_{Cl} T^{\alpha_{Cl}} f_{Cl}(T,RH) f(T,Cl) + A_{SO_2} T^{\alpha_{SO_2}} f_{SO_2}(T,RH) f(T,SO_2) \\ & + A_{O_3} T^{\alpha_{O_3}} f_{O_3}(T,RH) f(T,O_3) \} \end{aligned} \tag{4.11}$$

$$\begin{aligned} K_i = e^{\frac{\Delta H}{kT}} \left(\frac{T-k}{d}\right)^2 \sqrt{\frac{RH - RH_{TH}}{1 - RH_{TH}}} \sqrt{\frac{T-k}{d}} \\ \cdot \Bigg\{ & A_{Cl}\, T^{\alpha_{Cl}}\, f_{Cl}(T,RH)_{max}\, f(T,Cl)_{max}\, \frac{C_{Cl}^2}{C_{Cl,max}^2} \\ & + A_{SO_2}\, T^{\alpha_{SO_2}}\, f_{SO_2}(T,RH)_{max}\, f(T,SO_2)_{max}\, \frac{C_{SO_2}^2}{C_{SO_2,max}^2} \\ & + A_{O_3}\, T^{\alpha_{O_3}}\, f_{O_3}(T,RH)_{max}\, f(T,O_3)_{max}\, \frac{C_{O_3}^2}{C_{O_3,max}^2} \Bigg\} \end{aligned}$$

$$K_i = e^{\frac{\Delta H}{kT}} \left(\frac{T-k}{d}\right)^{2.5} \sqrt{\frac{RH - RH_{TH}}{1 - RH_{TH}}}$$

$$\cdot \left\{ A_{Cl}\, T^{\alpha_{Cl}}\, f_{Cl}(T, RH)_{max}\, f(T, Cl)_{max}\, \frac{C_{Cl}^2}{C_{Cl,max}^2} \right.$$

$$+ A_{SO_2}\, T^{\alpha_{SO_2}}\, f_{SO_2}(T, RH)_{max}\, f(T, SO_2)_{max}\, \frac{C_{SO_2}^2}{C_{SO_2,max}^2}$$

$$\left. + A_{O_3}\, T^{\alpha_{O_3}}\, f_{O_3}(T, RH)_{max}\, f(T, O_3)_{max}\, \frac{C_{O_3}^2}{C_{O_3,max}^2} \right\}$$

Since A_C, $f_C(T, RH)_{max}$, $f(T, C)_{max}$, $\frac{1}{d^{2.5}}$, and $\frac{1}{C_{max}^2}$ are constants, they can be combined into one constant A'_C:

$$A'_C = \frac{A_C f_C(T, RH)_{max} f(T, C)_{max}}{d^{2.5} C_{max}^2}$$

Simplified final one-hour corrosion rate function:

$$K_i = e^{\frac{\Delta H}{kT}} (T-k)^{2.5} \sqrt{\frac{RH - RH_{TH}}{1 - RH_{TH}}}$$

$$\cdot \left\{ A'_{Cl}\, T^{\alpha_{Cl}}\, C_{Cl}^2 + A'_{SO_2}\, T^{\alpha_{SO_2}}\, C_{SO_2}^2 + A'_{O_3}\, T^{\alpha_{O_3}}\, C_{O_3}^2 \right\}$$

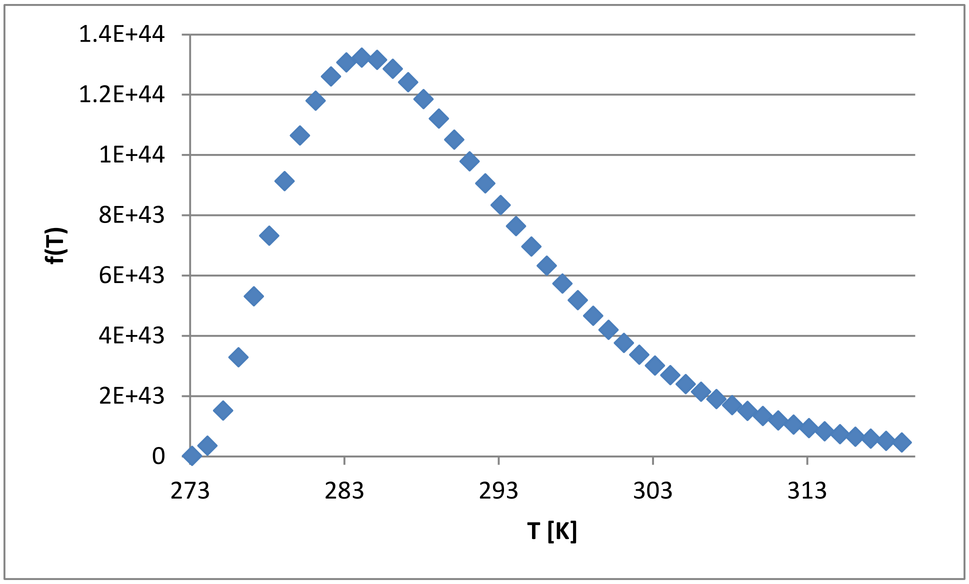
When focusing on one Contaminant, all temperature dependent values can be grouped:

$$K_i = e^{\frac{\Delta H}{kT}} (T-k)^{2.5}\, T^{\alpha_{Cl}} \sqrt{\frac{RH - RH_{TH}}{1 - RH_{TH}}}\, C_{Cl}^2\, A'_{Cl}$$

With the given coefficients on page 148 of the Rose Dissertation the “real” temperature-shape-function (for Chloride) is:

$$f(T) = e^{\frac{\Delta H}{kT}} (T-k)^{2.5}\, T^{\alpha_{Cl}} = e^{\frac{19496}{T}} (T - 273.15)^{2.5} T^{4.776592}$$

A plot of this function is given here:



Derivation of Functions

The provided temperature – relative humidity functions and temperature – contaminant functions of the Cumulative Corrosion Damage Model are displayed in a form that makes them difficult to interpret. Furthermore, since the functions were calculated millions of times when developing the coefficients, a substantial amount of computing power could have been saved.

The A.XXX number below references the sections in the Dr. Rose CCDM dissertation.

<u>Revised Convex Temperature Function (A.3.1.1)</u>

Section A.3.1.2 of the CCDM contains the convex temperature function. The section numbers below correspond to the numbering system used in the CCDM. To simplify:

$$k = 273.15$$

$$d = 47$$

$$a[f(T)_{max}]^2 + b[f(T)_{max}] + c = 320.15 = k + d \quad \text{(A.153)}$$

$$a(0)^2 + b(0) + c = 273.15 = k \quad \text{(A.154)}$$

$$a(-f(T)_{max})^2 + b[-f(T)_{max}] + c = 320.15 = k + d \quad \text{(A.155)}$$

$$a[f(T)_{max}]^2 + b[f(T)_{max}] + k = k + d \quad \text{(A.156)}$$

$$a[f(T)_{max}]^2 + b[f(T)_{max}] = d \quad \text{(A.157)}$$

$$b = \frac{d - a[f(T)_{max}]^2}{f(T)_{max}} \quad \text{(A.158)}$$

$$a(-f(T)_{max})^2 + \frac{d - a[f(T)_{max}]^2}{f(T)_{max}}[-f(T)_{max}] + k = k + d \quad \text{(A.159)}$$

$$a(f(T)_{max})^2 + [d - a[f(T)_{max}]^2][-1] + k = k + d \quad \text{(A.160)}$$

$$a(f(T)_{max})^2 + [-d + a[f(T)_{max}]^2] + k = k + d \quad \text{(A.161)}$$

$$2a(f(T)_{max})^2 - d = d \quad \text{(A.163)}$$

$$2a(f(T)_{max})^2 = 2d \quad \text{(A.165)}$$

$$a = \frac{2d}{2(f(T)_{max})^2} = \frac{d}{(f(T)_{max})^2} \quad \text{(A.166)}$$

$$b = \frac{d - \left[\frac{d}{(f(T)_{max})^2}\right][f(T)_{max}]^2}{f(T)_{max}} \quad \text{(A.167)}$$

$$b = \frac{d - d}{f(T)_{max}} \quad \text{(A.169)}$$

$$b = 0 \quad \text{(A.170)}$$

$$\left[\frac{d}{(f(T)_{max})^2}\right] f(T)^2 + k = T \quad \text{(A.171)}$$

$$\left[\frac{d}{(f(T)_{max})^2}\right] f(T)^2 = T - k \quad \text{(A.172)}$$

The use of the Quadratic Equation is not indicated in this equation.

$$f(T)^2 = \frac{T - k}{\left[\frac{d}{(f(T)_{max})^2}\right]} = \frac{T - k}{d}(f(T)_{max})^2 \quad \text{(A.174)}$$

$$f(T) = \pm\sqrt{\frac{T - k}{d}} f(T)_{max} \quad \text{(A.175)}$$

Revised Convex Temperature-Convex Relative Humidity Shape Function (A.3.1.2)

$$\frac{1 - RH_{TH}}{f(T)^2} f(T,RH)^2 = RH - RH_{TH} \tag{A.193}$$

$$f(T,RH)^2 = \frac{RH - RH_{TH}}{\left[\frac{1 - RH_{TH}}{f(T)^2}\right]} = \frac{RH - RH_{TH}}{1 - RH_{TH}} f(T)^2$$

$$f(T,RH) = \pm\sqrt{\frac{RH - RH_{TH}}{1 - RH_{TH}}} f(T) = \sqrt{\frac{RH - RH_{TH}}{1 - RH_{TH}}}\sqrt{\frac{T - k}{d}} f(T)_{max} \tag{A.194}$$

Revised Concave Temperature Function (A.3.2.1)

$$a(k-d)^2 + b(k-d) + c = f(T)_{max} \tag{A.202}$$

$$a = \frac{f(T)_{max} - c - (k+d)b}{(k+d)^2} \tag{A.203}$$

$$\frac{f(T)_{max} - c - (k+d)b}{(k+d)^2}(k-d)^2 + b(k-d) + c = f(T)_{max}$$

$$[f(T)_{max} - c - (k+d)b](k-d)^2 + b(k-d)(k+d)^2 + (k+d)^2 c = (k+d)^2 f(T)_{max}$$

$$(k-d)^2 f(T)_{max} - (k-d)^2 c - (k-d)^2(k+d)b + b(k-d)(k+d)^2 + (k+d)^2 c = (k+d)^2 f(T)_{max}$$

$$(k+d)^2 c - (k-d)^2 c - (k-d)^2(k+d)b + b(k-d)(k+d)^2 = (k+d)^2 f(T)_{max} - (k-d)^2 f(T)_{max}$$

$$[(k+d)^2 - (k-d)^2]c + [(k-d)(k+d)^2 - (k-d)^2(k+d)]b = [(k+d)^2 - (k-d)^2] f(T)_{max}$$

$$[k^2 + 2kd + d^2 - k^2 + 2kd - d^2]c + [(k^2 - d^2)(k + d - (k-d))]b = [k^2 + 2kd + d^2 - k^2 + 2kd - d^2] f(T)_{max}$$

$$4kdc + (k^2 - d^2)2db = 4kdf(T)_{max}$$

$$(k^2 - d^2)2b = 4kf(T)_{max} - 4kc$$

$$b = \frac{4kf(T)_{max} - 4kc}{2(k^2 - d^2)} = \frac{2k(f(T)_{max} - c)}{(k+d)(k-d)} \tag{A.212}$$

$$ak^2 + bk + c = 0$$

$$= \frac{f(T)_{max} - c - (k+d)\dfrac{2k(f(T)_{max} - c)}{(k+d)(k-d)}}{(k+d)^2} k^2 + \frac{2k(f(T)_{max} - c)}{(k+d)(k-d)} k + c \tag{A.213}$$

$$\frac{f(T)_{max} - c - \dfrac{2k(f(T)_{max} - c)}{(k-d)}}{(k+d)^2} k^2 + \frac{2k(f(T)_{max} - c)}{(k+d)(k-d)} k + c = 0$$

$$\left[(f(T)_{max} - c) - \frac{2k(f(T)_{max} - c)}{(k-d)}\right](k-d)k^2 + [2k(f(T)_{max} - c)](k+d)k + c = 0$$

$$\left[(f(T)_{max} - c)\big((k-d) - 2k\big)\right]k^2 + 2k^2(f(T)_{max} - c)(k+d) + (k+d)^2(k-d)c = 0$$

$$-(f(T)_{max} - c)(k+d)k^2 + 2k^2(f(T)_{max} - c)(k+d) + (k+d)^2(k-d)c = 0$$

$$-(f(T)_{max} - c)k^2 + 2k^2(f(T)_{max} - c) + (k+d)(k-d)c = 0$$

$$-f(T)_{max}k^2 + ck^2 + 2k^2 f(T)_{max} - 2ck^2 + k^2c - d^2c = 0$$

$$f(T)_{max}k^2 - d^2c = 0$$

$$f(T)_{max}k^2 = d^2c$$

$$c = \frac{f(T)_{max}k^2}{d^2} = \frac{k^2}{d^2} f(T)_{max} \tag{A.221}$$

$$b = \frac{2k(f(T)_{max} - c)}{(k+d)(k-d)} = \frac{2k\left(f(T)_{max} - \dfrac{k^2}{d^2} f(T)_{max}\right)}{(k+d)(k-d)}$$

$$b = \frac{\dfrac{2k}{d^2}(d^2 - k^2) f(T)_{max}}{(k+d)(k-d)} = -\frac{2k}{d^2} f(T)_{max} \tag{A.212}$$

$$a = \frac{f(T)_{max} - c - (k+d)b}{(k+d)^2} = \ldots = \frac{1}{d^2} f(T)_{max} \tag{A.203}$$

$$f(T) = \frac{1}{d^2} f(T)_{max} T^2 - \frac{2k}{d^2} f(T)_{max} T + \frac{k^2}{d^2} f(T)_{max}$$

$$f(T) = (T^2 - 2kT + k^2)\frac{1}{d^2}f(T)_{max}$$

$$f(T) = \left(\frac{T-k}{d}\right)^2 f(T)_{max} \tag{A.196}$$

A simplified way to calculate this formula is described below:

Revised Concave Temperature Function (A.3.2.1)

There are different methods of expressing a parabola.

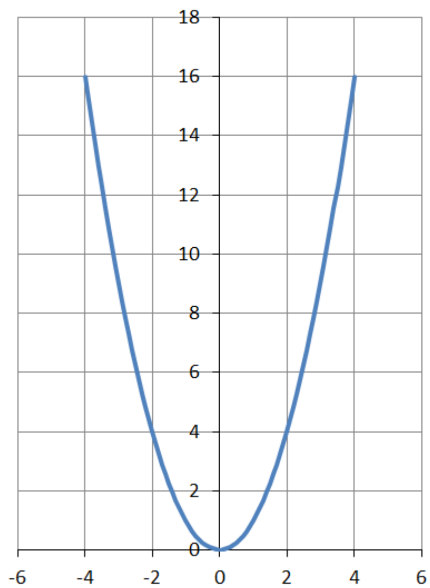
$$f(x) = ax^2 + bx + c \qquad \text{EQ 1}$$

$$f(x) = a'(x-b')^2 + c' \qquad \text{EQ 2}$$

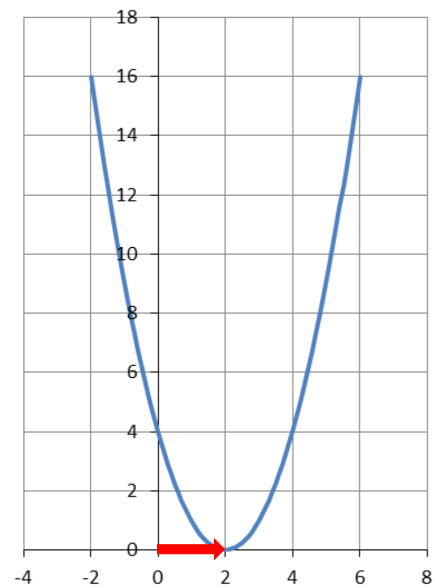
$$f(x) = \left(\frac{x-b"}{a"}\right)^2 + c" \qquad \text{EQ 3}$$

For the given problem, the easiest method is to use equation 3.

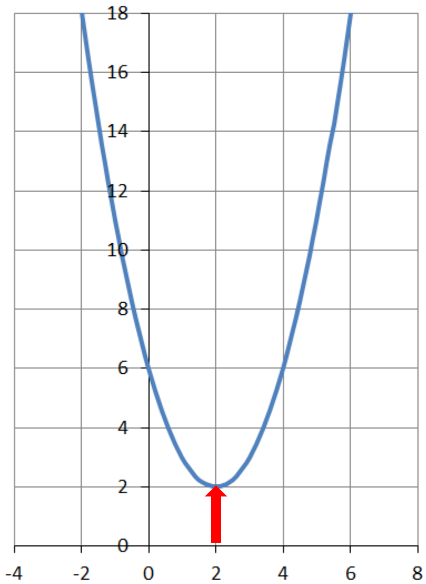
Parameter $b"$ shifts the parabola along the x-axis, parameter $c"$ shifts the parabola along the y-axis and parameter $a"$ shrinks the parabola.



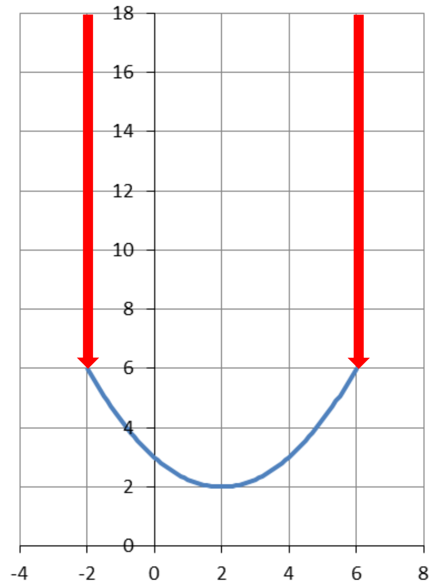
$a"$=1; b" $=0$; $c"$ =0;



$a"$=1; b" $=2$; $c"$ =0;



$a"=1; b" = 2; c" = 2;$



$a"=2; b" = 2; c" = 2;$

In the case of the temperature- contaminant shape function, the boundary conditions are:

$$f'(273.15) = f'(k) = 0 \quad \text{EQ 4}$$

$$f(273.15) = f(k) = 0 \quad \text{EQ 5}$$

$$f(320.15) = f(k+d) = 1 \quad \text{EQ 6}$$

$$f'(k) = 2\left(\frac{k-b"}{a"}\right) = 0 \quad \text{EQ 7}$$

$$f(k) = \left(\frac{k-b"}{a"}\right)^2 + c" = 0 \quad \text{EQ 8}$$

$$f(k+d) = \left(\frac{k+d-b"}{a"}\right)^2 + c" = 1 \quad \text{EQ 9}$$

From EQ 7 $\quad b" = k \quad$ EQ 10

EQ 10 in EQ 8 $\quad c" = 0 \quad$ EQ 11

EQ 10 and EQ 11 in EQ 9 $\quad a" = d \quad$ EQ 12

$$f(T) = \left(\frac{T-k}{d}\right)^2 f(T)_{max} \tag{A.196}$$

Appendix C –Corrosivity Determination: Measured ISO Corrosivity Categories

This table presents ISO Corrosivity Categories based on the Battelle Columbus one-year steel mass loss data collected from 1998 to 2014. ISO Category values range from C1 - C5 + CX.

Base Name	Location	CONUS	Year	Distance to Salt Water (in miles)	ISO Cat.
Al Dhafra AFB	Al Dhafra, N/A, AE	No	2012	10	C3
Al Udeid Air Base	Al Udeid, N/A, QA	No	2004	20	C3
RAAF Base Amberley	Amberley, Queensland, AS	No	2003	47	C3
F16 Base Antofagasta	Antofagasta, Chile	No	2013	2	C4
Naval Support Activity Athens (till 2010)	Athens, GA, US	Yes	1999	2.7	C2
Aviano Air Base	Aviano, Pordenone, IT	No	1999	>10	C3
CFB Bagotville	Bagotville, Quebec, CA	Yes	2005	>10	C2
Bagram Airfield	Bagram, Parwan, AF	No	2005	>10	C2
Bahrain Airport	Bahrain, Bahrain	No	2014	1.1	C2
Baltimore BWI Airport	Baltimore, MD, US	Yes	2006	>10	C3
ANG Bangor	Bangor, ME, US	Yes	2014	>10	C3
NAS Barbers Point; USCG	Oahu, HI, US	No	2003	0.2	C3
Bermuda Biological Station for Research (BBSR), now Bermuda Institute of Ocean Sciences (BIOS)	St Davids Island, N/A, BM	No	2006	0.3	C5
USCG Station Boston	Boston, MA, US	Yes	2006	5	C3
NAS Brunswick	Brunswick, ME, US	Yes	2005	>10	C4
Burlington Int. Airport	Burlington, VT, US	Yes	2014	>10	C2
Richmond Int. Airport	Sandston, VA, US	Yes	2014	>10	C2
Camp Lemonier / Djibouti Int. Airport	Djibouti, Djibouti	No	2013	1.2	C3
USCG Corpus Christi / NAS	Corpus Christi, TX, US	Yes	2003	0.25	C5
Charleston Int. Airport	North Charleston, SC, US	Yes	2013	>10	C3
ANG Yeager Airport	Charleston, WV, US	Yes	2000	>10	C3
Tres Esquinas Airport	Tres Esquinas, N/A, CO	No	2006	>10	C3
El Dorado International Airport	Bogota, CO	Yes	2006	>10	C3
USCG Corpus Christi / NAS	Corpus Christi, TX, US	Yes	2003	0.2	C5
Daytona Beach International Airport	Daytona Beach, FL, US	Yes	1998	3.7	C3
Montgomery Regional Airport	Montgomery, AL, US	Yes	2014	>10	C2
RAAF Base Darwin	Darwin, N/A, AS	No	2002	2.5	C2
Davis-Monthan AFB	Davis-Monthan, AZ, US	Yes	1999	>10	C2
Des Moines Int. Airport	Des Moines, IA, US	Yes	2014	>10	C2

Charlotte Douglas Int. Airport	Charlotte, NC, US; ANG	Yes	2014	>10	C3
Dover AFB	Dover, DE, US	Yes	2001	4.6	C3
Eareckson AF Station	Sheyma Island, AK, US	No	2003	0.4	C4
Eglin AFB	Eglin AFB, FL, US	Yes	2013	1.2	C4
Joint Base Elmendorf-Richardson	Anchorage, AK, US	No	1999	10.6	C2
Joint Base Elmendorf-Richardson	Anchorage, AK, US	No	2013	7.1	C2
Fairchild AFB	Airway Heights, WA, US	Yes	1999	>10	C2
Fort Campbell	Fort Campbell, KY, US	Yes	2006	>10	C3
Fort Drum	Watertown, NY, US	Yes	2006	>10	C3
Joint Base Langley-Eustis	Newport News, VA, US	Yes	2006	6.8	C3
Fort Hood	Killeen, TX, US	Yes	2006	>10	C2
Fort Polk	Leesville, LA, US	Yes	2006	>10	C3
Fort Rucker	Ozark, AL, US	Yes	2006	>10	C3
Francis S. Gabreski Airport, ANG	West Hampton Beach, NY, US	Yes	2001	5.3	C3
NATO Air Base Geilenkirchen	Teveren, Nordrhein-Westfalen, GE	No	2002	>10	C3
Goose Bay Airport	Labrador, Newfoundland, CA	Yes	2005	1.6	C2
CFB Greenwood	Greenwood, Nova Scotia, CA	Yes	2005	7.2	C3
Griffiss Int. Airport	Rome, NY, US	Yes	2014	>10	C3
Great Falls Int. Airport, ANG	Great Falls, MT, US	Yes	2003	>10	C2
Guam National Guard / Guam Reserves	Guam, GU	No	1999	0.9	C5
Hanscomb AFB	Bedford, MA, US	Yes	2014	>10	C3
Joint Base Pearl Harbor-Hickam	Ku'a, HI, US	No	2013	0.5	C3
Hill AFB	Ogden, UT, US	Yes	2000	>10	C2
Homestead Base	Homestead, FL, US	Yes	2013	2	C4
US Coast Guard Station Humboldt Bay	Humboldt Bay, CA, US	Yes	2006	>10	C5
Hunter Army Airfield	Savannah, GA, US	Yes	2006	>10	C4
US Air Force Hurlburt Field	Mary Esther, FL, US	Yes	1999	>10	C4
I70&WJ	Columbus, OH, US	Yes	2005	>10	C3
Incirlik Air Base	Incirlik, TU	No	1999	>10	C3
F16 Base / Diego Aracena International Airport	Iquique, Chile	No	2013	0.8	C4
C130 Base Wyoming	Cheyenne, WY, US	Yes	2000	>10	C2
Kadena Special Facility	Kadena, Okinawa, JP	No	2003	2.5	C4
Kadena AB	Kadena, Okinawa, JP	No	2013	0.8	C5
Keesler AFB	Biloxi, MS, US	Yes	2000	1.2	C3
Keesler AFB	Biloxi, MS, US	Yes	2013	0.8	C4
Keflavik Airport	Southern Peninsula,	No	2014	1.8	C3

	Iceland				
Key Field Meridian	Meridian, MS	Yes	2014	>10	C2
NAS Key West	Key West, FL, US	Yes	2006	0.75	C5
McGhee Tyson ANG Base	Knoxville, TN, US	Yes	2004	>10	C2
USCG Station Kodiak	Kodiak, AK, US	No	2003	0.5	C3
Kennedy Space Center	Cocoa Beach, FL, US	Yes	2006	0	CX
Kennedy Space Center	Cocoa Beach, FL, US	Yes	2006	0.25	C5
Kennedy Space Center	Cocoa Beach, FL, US	Yes	2006	0.5	C5
Kennedy Space Center	Cocoa Beach, FL, US	Yes	2006	1	C4
Kennedy Space Center	Cocoa Beach, FL, US	Yes	2006	2	C5
Kennedy Space Center	Cocoa Beach, FL, US	Yes	2006	5	C4
Joint Base Langley-Eustis	Hampton, VA, US	Yes	1999	0.6	C3
Joint Base Langley-Eustis	Hampton, VA, US	Yes	2003	0.6	C3
Joint Base Langley-Eustis	Hampton, VA, US	Yes	2013	0.3	C3
MacDill AFB	Tampa, FL, US	Yes	2013	0.5	C5
USCG Station	Manistee, MI, US	Yes	2006	>10	C3
Mansfield Lahm Regional Airport	Mansfield, OH, US	Yes	2006	>10	C3
Joint Base Lewis-McChord	Tacoma, WA, US	Yes	2001	1.8	C2
ANG Base Columbia	Columbia, SC, US	Yes	2014	>10	C2
USCG Opa Locka	Miami, FL, US	Yes	2006	9.7	C4
Milwaukee Int. Airport	Milwaukee, WI, US	Yes	2014	>10	C3
Misawa AFB	Misawa, JP	No	2013	2.5	C4
Minneapolis–Saint Paul Int. Airport	Minneapolis, MN, US	Yes	1999	>10	C2
Minneapolis–Saint Paul Int. Airport	Minneapolis, MN, US	Yes	2003	>10	C2
NAS Pensacola	Pensacola, FL, US	Yes	2014	0.6	C5
Nashville Int. Airport	Nashville, TN, US	Yes	2000	>10	C3
F16 Base Leeuwarden	Leeuwarden, Netherlands	No	2013	8	C3
CFB Ontario	North Bay, ONT, CA	Yes	2005	>10	C2
Naha Airport	Okinawa, N/A, JP	No	2004	0.5	C5
Atlantic Aviation OKC	Oklahoma City, OK, US	Yes	2003	>10	C2
F16 Base Orland	Orland, Norway	No	2013	0.8	C3
Osan Military Airport	Special Facility	No	2013	>10	C3
Patrick AFB; C130 Ramp	Cocoa Beach, FL, US	Yes	2000	0.4	C5
Patrick AFB; Wash Area	Cocoa Beach, FL, US	Yes	2004	0.6	C4
Patrick AFB; C130 Ramp	Cocoa Beach, FL, US	Yes	2013	0.4	C5
Pease AFB	Portsmouth, NH, US	Yes	2013	5.5	C3
Norfolk Naval Shipyard	Portsmouth, VA, US	Yes	2006	0.3	C4
NAS Point Mugu	Point Mugu, CA, US	Yes	2013	3	C4
Arturo Merino Benítez Int. Airport	Pudahuel, Región Metropolitana, Chile	No	2013	>10	C2

Ramstein Air Base	Ramstein, Rheinland-Pfalz, GE	No	2001	>10	C2
Rock Island Arsenal	Rock Island, IL, US	Yes	2006	>10	C3
Rosecrans Memorial Airport	Saint Joseph, MISSOURI, US	Yes	1999	>10	C2
Sacramento Army Depot	Sacramento, CA, US	Yes	2003	>10	C2
MC Recruit Depot San Diego	San Diego, CA, US	Yes	2006	0.4	C4
San Juan Airport; F16/C130 Ramp Area	San Juan, PR	No	2013	0.7	C4
Seattle Int. Airport	Seattle, WA, US	Yes	2006	2.2	C3
NAS Sigonella	Sigonella, N/A, IT	No	2005	8.6	C2
NAS Sigonella	Sigonella, N/A, IT	No	2012	6	C3
Thumrait Airport	Thumrait, Oman	No	2005	>10	C4
Toledo Express Airport, ANG	Toledo, OH, US	Yes	1999	>10	C3
Travis AFB	Fairfield, CA, US	Yes	2001	>10	C3
CFB Trenton	Trenton, CA	Yes	2005	>10	C3
Tyndall AFB	Panama City, FL, US	Yes	2000	0.4	C4
Tyndall AFB	Panama City, FL, US	Yes	2003	0.6	C3
Tyndall AFB	Panama City, FL, US	Yes	2006	0.2	C4
Tyndall AFB	Panama City, FL, US	Yes	2013	0.3	C4
Vandenberg AFB	Santa Barbara, CA, US	Yes	2006	0.25	C5
Vandenberg AFB	Santa Barbara, CA, US	Yes	2006	0.5	C5
Vandenberg AFB	Santa Barbara, CA, US	Yes	2006	1	C5
Vandenberg AFB	Santa Barbara, CA, US	Yes	2006	2	C4
Vandenberg AFB	Santa Barbara, CA, US	Yes	2006	5	C4
Vandenberg AFB	Santa Barbara, CA, US	Yes	2006	7	C4
RAF Waddington	Waddington, Lincolshire, UK	No	2013	>10	C3
Wheeler Army Air Field; Reset facility	Schofield Barracks, HI, US	No	2006	9.8	C4
CFB Winnipeg	Winnipeg, Winnipeg, CA	Yes	2005	>10	C2
Robins AFB	Warner Robins, GA	Yes	2000	>10	C2
Yokota Air Base	Yokota, JP	No	2001	>10	C3

Appendix D – ESC Factors: Calculated ISO Corrosivity Categories Using ICCET Model

This linked table below presents calculated ISO Corrosivity Categories for 482 DoD Installations using the ICCET model. These calculations are based on five years of NOAA environmental data from January 1, 2010 to December 31, 2014. ISO Category values range from C1 - C5 + CX. See section 5.3 for information regarding this method.

Appendix D -
Supplemental ICCET I

Appendix E – Measured ISO Corrosivity Categories Based on ISOCORRAG Data

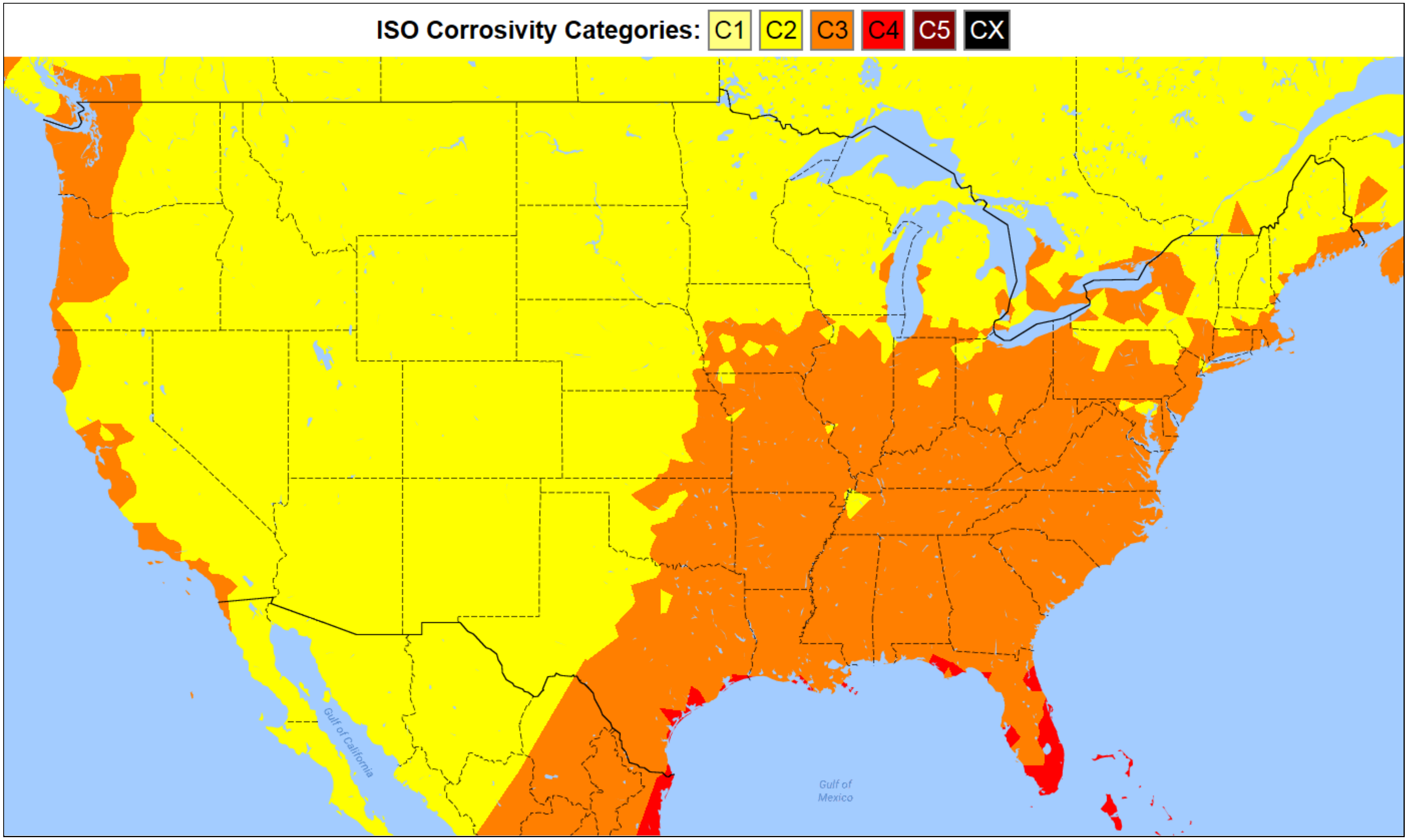
This table presents ISO Corrosivity Categories based the ISOCORRAG Program one-year steel mass loss data collected from 1986 to 1994. ISO Category values range from C1 - C5 + CX.

Name	Country	CONUS	ISO Corr. Cat.
Iugazu	Argentina	No	**C2**
Camet	Argentina	No	**C3**
Buenos Aires	Argentina	No	**C2**
San Juan	Argentina	No	**C2**
Jubay-Antarct.	Argentina	No	**C3**
Boucherville	Canada	No	**C2**
Kašperské Hory	Czech Republic	No	**C3**
Praha-Běchovice	Czech Republic	No	**C3**
Kopisty	Czech Republic	No	**C4**
Bergisch Glad.	Germany	No	**C3**
Helsinki	Finland	No	**C3**
Otaniemi	Finland	No	**C3**
Ahtari	Finland	No	**C2**
Saint Denis	France	No	**C3**
Ponteau Mart.	France	No	**C4**
Picherande	France	No	**C2**
St. Remy	France	No	**C3**
Salins de Gir.	France	No	**C4**
Ostende (B)	France	No	**C5**
Paris	France	No	**C3**
Auby	France	No	**C5**
Biarritz	France	No	**C5**
Choshi	Japan	No	**C3**
Tokyo	Japan	No	**C3**
Okinawa	Japan	No	**C4**
Judgeford	New Zealand	No	**C2**
Oslo	Norway	No	**C3**
Borregaard	Norway	No	**C4**
Birkenes	Norway	No	**C2**
Tannanger	Norway	No	**C4**
Bergen	Norway	No	**C3**
Svanwik	Norway	No	**C2**
Madrid	Spain	No	**C3**

El Pardo	Spain	No	**C2**
Lagoas	Spain	No	**C3**
Baracaldo	Spain	No	**C3**
Stockholm Vanadis	Sweden	No	**C2**
Kattesand	Sweden	No	**C3**
Kvarnvik	Sweden	No	**C4**
Stratford	United Kingdom	No	**C3**
Crowthorne	United Kingdom	No	**C3**
Rye	United Kingdom	No	**C4**
Fleet Hall	United Kingdom	No	**C3**
Kure Beach	United States	Yes	**C3**
Newark	United States	Yes	**C3**
Panama	United States	Yes	**CX**
Res. Tri. Park	United States	Yes	**C2**
Point Reyes	United States	Yes	**C3**
Los Angeles	United States	Yes	**C2**
Murmansk	Russia	No	**C3**
Batumi	Russia	No	**C3**
Vladiostok	Russia	No	**C3**
Oymyakon	Russia	No	**C1**

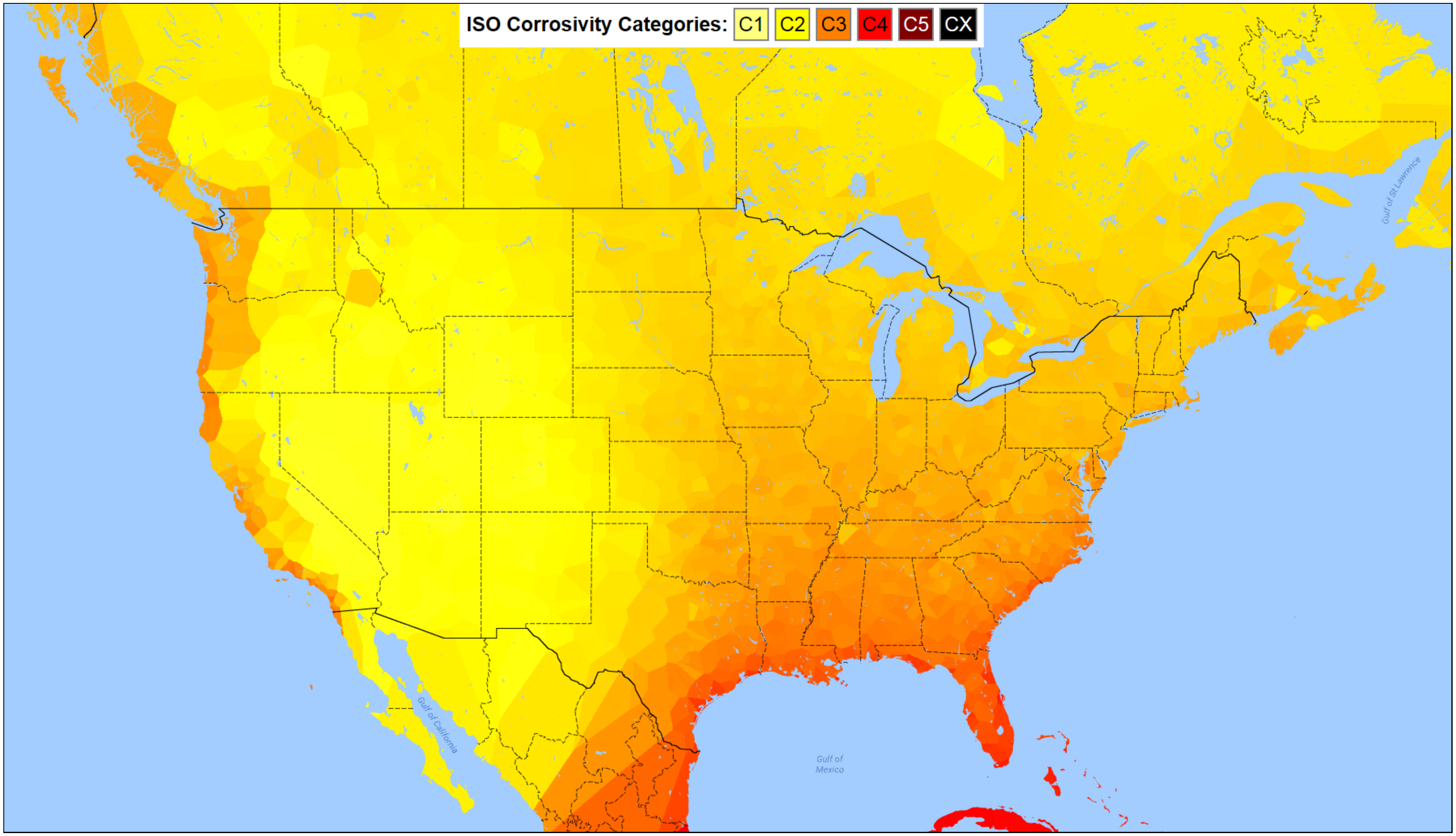
Appendix F – U.S. ISO Corrosion Maps

U.S. ISO Corrosion "Contour" Map – Displays "contours" that correspond directly to ISO Corrosivity Categories. Calculated using the ICCET model and NOAA environmental data from 2010 - 2014.



Map Data © 2016 Google, INEGI

U.S. ISO Corrosion "Heat" Map – Displays "heat zones" that correspond directly to ISO Corrosivity Categories. Calculated using the ICCET model and NOAA environmental data from 2010 - 2014.



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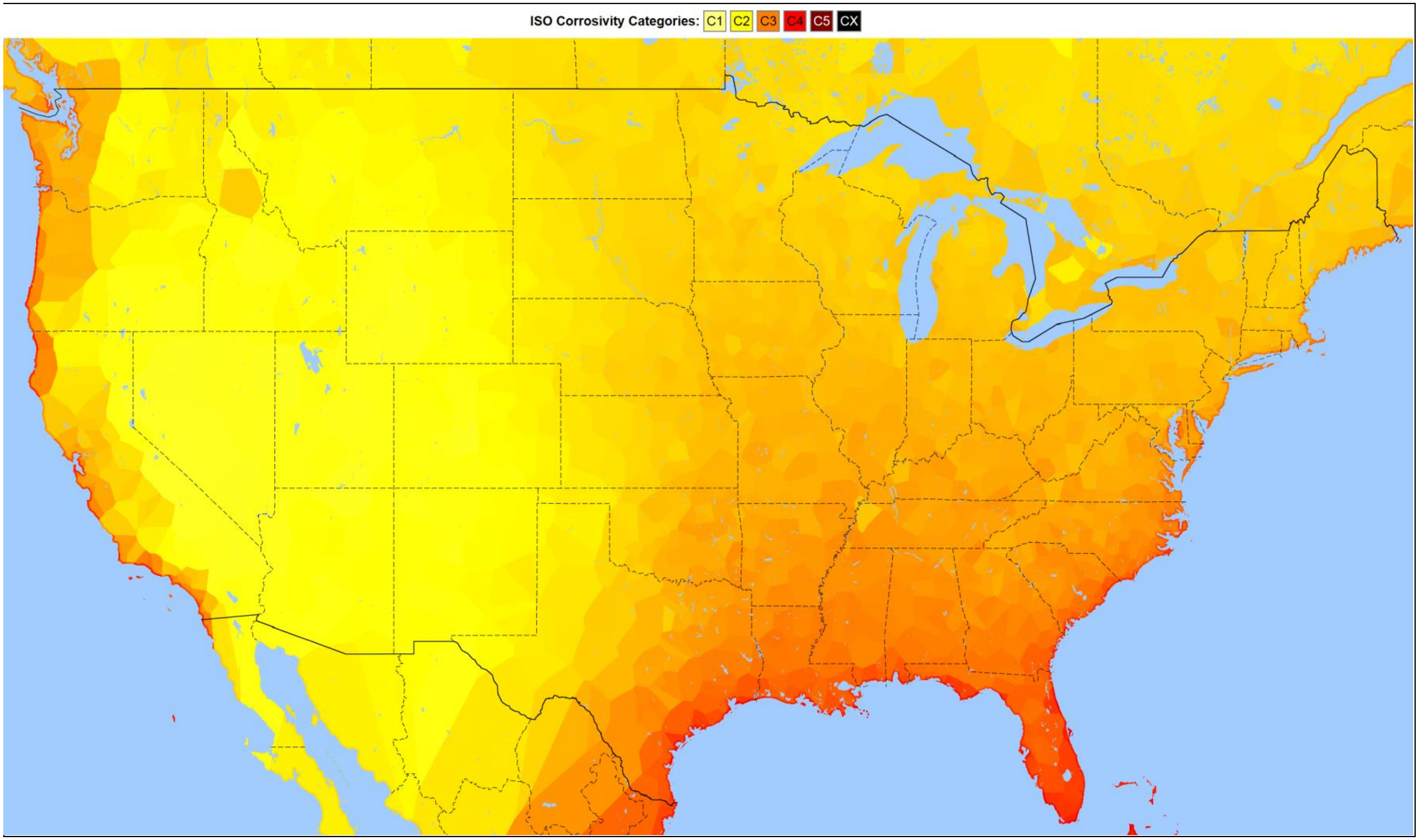
U.S. ISO "Heat" Map with Coastline Adjustment – Displays "heat zones" that correspond directly to ISO Corrosivity Categories and includes an adjustment for the coastline. Calculated using the ICCET model and NOAA environmental data from 2010 - 2014



Map Data © 2016 Google, INEGI

Appendix G – World of Corrosion Map

World of Corrosion ISO "Heat" Map – Displays "heat zones" that correspond directly to ISO Corrosivity Categories. Calculated using the ICCET model and NOAA environmental data from 2010 - 2014. It is important to note that some areas outside of the U.S., such as Africa and South America do not have a dense network of NOAA-accessible weather stations and as such the ISO Corrosivity Category is not as accurate for these areas. This map is provided simply for educational purposes.