Use of Environment and Corrosivity Monitoring to Characterize Base and Airframe Severity

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ABSTRACT

United States (US) Department of Defense (DoD) aircraft operate in a wide range of climates and environmental conditions that result in variable corrosion severity exposure over the service life of an aircraft. Corrosion degrades aircraft availability and accounts for 24% of total maintenance costs (Herzberg, 2018). Corrosion is managed by set cleaning and inspection schedules that depend on categorizations of corrosive conditions. Improved understanding and assessment of microclimate conditions within an airframe and the dependence on operations, weather events, and climate change may allow for more effective individual aircraft and fleet corrosion management. Testing at multiple geographic locations and in conditions that simulate aircraft structures has been done using environment and corrosion severity monitoring devices. These measurements have been used to quantify environmental severity by location and exposure condition, compare corrosion rates of different materials, and determine relationships between ambient environment and conditions within a simulated aircraft structure. Factors that have been identified as significant are proximity to a source of saltwater, wind, wave height, and sheltering, which limits drying by solar irradiance and allows salt deposition with limited removal by rain and condensation. By making continuous measurements of corrosion rates and environmental factors, the severity for a given site or aircraft can be assessed as function of time to determine the influence of short-term weather events, seasonal variation, and long-term changes in climate. These measurements provide a means to track individual aircraft corrosion severity and tailor corrosion prevention and control.

Keywords: Specialists' Meeting, aluminum, galvanic corrosion, atmospheric corrosion, corrosion severity classification.

1.0 INTRODUCTION

Corrosion is managed by set cleaning and inspection schedules according to general and aircraft specific technical manuals. During scheduled preventative cleaning and inspection, the discovery of corrosion damage may necessitate unscheduled corrective corrosion maintenance. The aircraft usage, environmental conditions, and corrosion severity are expected to influence the amount of corrosion maintenance and repair that will occur on an individual aircraft.

Numerous environmental severity classification methods are utilized across the US DoD (Silver, 2017). Corrosion prevention and control planning and maintenance processes are based on these classifications and are codified in maintenance manuals, technical orders, reports, and standards (TO 1-1-691, NAVAIR 01-1A-509-2). Issues associated with determining service environment severity for aerospace applications and ground equipment are: 1) a lack of commonality in classification systems; 2) antiquated site classifications established anywhere from 20 – 50 years ago; 3) classifications that do not use aerospace materials and do not include galvanic couples; 4) no defined benchmark method for setting or validating classifications; and 5) no accepted method to assess current severity.

Recent studies have demonstrated that environment and corrosivity measurement systems can be used for continuous assessment of corrosion severity (Hoen-Velterop, 2017, Boswell-Koller, 2019, Agnew, 2023). These severity monitoring devices have been used to make environmental measurements at locations relevant to defense aircraft and for on-aircraft monitoring. The environment and corrosivity sensing elements and monitoring devices may be used to assess severity of service environments and track actual asset environment severity for improved preventative maintenance (ISO 22858, SAE AIR6970). In the present investigation, these measurements have been used to quantify environmental severity by location, compare corrosion rates of different materials, and examine relationships between ambient environment and corrosion severity. Given the relationship of environmental conditions to measurements of corrosion severity, a classification approach relevant to aerospace applications is described.

2.0 EXPERIMENTAL

Test locations and materials were selected that are relevant to aerospace applications and marine environment aircraft basing and operations.

2.1 Test Locations

Four exposure sites were included: Battelle Florida Materials Research Facility (FMRF) sites on the Atlantic Ocean (OS) and Halifax River intercoastal (IC) waterway on the east coast of Florida, Boeing El Segundo (ES) site in southern CA on the Pacific Ocean, and the US Naval Air Station Whidbey Island (WH) WA test site on the Salish Sea in the US Pacific Northwest (Table 1 and Figure 1).

Table 1: Test sites for environment and corrosivity characterization.

ID	Test Site	D2C* (m)	Weather station name and number
OS	Battelle FMRF Ocean Site, FL	70	DAYTONA BEACH INTL A, FL US, 74787012834, NDBC 41113
IC	Battelle FMRF Intracoastal Site, FL	800	
ES	El Segundo, CA	50	LOS ANGELES INTL AIRPORT, CA US 72295023174, NDBC 46221
WH	Whidbey Island, WA	35	SMITH ISLAND, WA, US 99418099999, NDBC 46088

* D2C – distance to nearest coastline

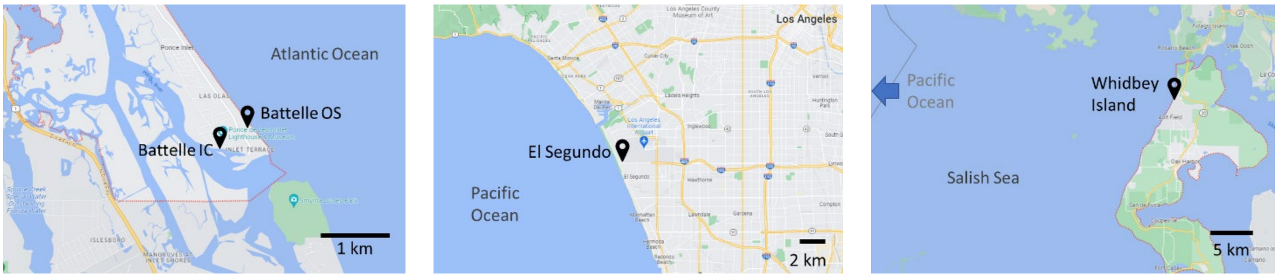

Figure 1: Locations for environment and corrosivity measurements.

2.2 Environment and Corrosivity Measurements

Weather data was obtained using the Integrated Surface Database Lite from the US National Oceanic and Atmospheric Administration (NOAA) (Table 1). NOAA weather station and National Data Buoy Center (NDBC) data used for this study included dew point, temperature, wind direction, wind speed, and wave height. Salt deposition rates were measured at the Battelle OS and Battelle IC sites using ASTM G140 wet candle measurements.

In addition to the NOAA weather station data, environment and corrosivity measurements were made using commercially available corrosion severity monitoring devices that have been developed for aircraft use (Agnew, 2023) (Figure 2). The sensing elements and devices have been described in detail in multiple publications and standards (ISO 22858, SAE AIR 6970, AMPP TM21449). Environmental measurements made by these devices include temperature, relative humidity (RH), and conductance. The conductance measurement is used to quantify the presence of an electrolyte on the surface of a gold interdigitated electrode (IDE) sensor. Conductance is dependent primarily on RH and planar density of salts (salt loading). Conductance is reported in units of siemens and is determined from the ratio of the measured current response to the excitation voltage. The excitation signal for conductance is a 20 mV peak-to-peak sine wave at a frequency of 25 kHz.

Figure 2. Environment and corrosivity monitoring device (left) and test rack at the Battelle IC site with monitoring devices and SAS boxes (right).

The corrosion severity monitoring devices also include galvanic and free corrosion IDE sensors. For this study the free corrosion sensors were fabricated from aluminum alloy AA7075-T6 sheet 0.032 inch thick (0.8 mm). The two electrodes of the sensor each have eight digits of equal area and the total area of one electrode is 1.445 cm^2. The free corrosion current is the root mean square current response of the two electrode sensor to a 20 mV peak-to-peak sine wave excitation at a 0.5 Hz frequency. The corrosion current is reported in units of microamps and total corrosion, the integral of current, is reported in coulombs.

The galvanic corrosion sensors were fabricated from AA7075-T6 sheet that was coupled to either titanium alloy Ti-6Al-4V, stainless steel A286, or carbon fiber reinforced polymer (CFRP). The Ti-6-4, A286, AA7075-T6 galvanic couple electrodes all used the same sheet thickness of 0.032 inch thick (0.8 mm) and had the same electrode areas of 1.445 cm^2 with each electrode having eight digits. For the AA7075/CFRP galvanic couple, the sheet thickness, number of digits in the IDE, and electrode areas were 0.08 inch (2 mm), three digits, and 1.548 cm^2 for AA7075-T6, and 0.063 inch (1.6 mm), four digits, and 1.626 cm^2 for the CFRP, respectively.

2.3 Test Conditions and Locations

At each of the four test sites, measurement devices were exposed without shelter on racks with the test surfaces oriented 30 degrees from horizontal (Figure 2). The test racks were oriented to be facing the coastline or nearest body of water. A sufficient number of environment and corrosivity devices were deployed such that every corrosion measurement could be made in triplicate. Environment and corrosivity monitoring devices were also placed within simulated aircraft structure (SAS) boxes fabricated from aluminum sheet that were 20 inches by 23.5 inches by 8.5 inches (50.8 x 59.7 x 21.6 cm) (Figure 2). The boxes were mounted with the same orientations as the devices tested without shelter. The SAS boxes were left open on the bottom side, and therefore, contaminants could easily ingress from the underside, but the SAS box sheltered the devices from precipitation and direct solar irradiance.

3.0 RESULTS AND ANALYSIS

The environment and corrosivity monitoring devices provide both environmental data and corrosion rate measurements to assess severity of exposure conditions and different geographic locations. The environment and corrosivity measurement devices were exposed for approximately one year, except for the SAS box devices that were started at a later date (Table 2). NOAA weather station data were pulled for each test site for the coincident time periods.

3.1 Environment Spectra

The environmental data from the different sites and exposure conditions were determined from NOAA weather station, NDBC, and severity monitoring devices (Table 3). The air temperature and RH data are annual averages. The time of wetness (ISO ToW) expressed as a percentage was determined using the ISO 9223 definition (time where RH greater than 80% RH and temperature above 0 ˚C). Similarly, percentage time wet (TW), semi-wet (TSW), and dry (TD) were determined where RH below 50% and RH above 70% define the ranges for dry and wet conditions when temperatures are greater than -20 ˚C, respectively. The definitions for wet, semi-wet, and dry time have been adjusted relative to the work of Boswell-Koller (2019). The severity monitoring devices were used to obtain average daily total conductance (Cond). Using NOAA weather station and NDBC data, the effective average total daily wind (WE) and average annual wave height (WVHT) were calculated. Effective wind is defined as the magnitude of the component of onshore wind for wind speeds greater than 4 m/s (Figure 3). The effective wind is expressed as daily average for the given test period. Salt deposition (S_d) is determined by wet candle and related measurements include conductance, effective wind, and wave height. Salt deposition measurements were collected every month for the Battelle OS site and every two months for the Battelle IC site. The cumulative salt loading is used to obtain an average daily deposition rate. The typical average rainfall for each location has also been noted in Table 3.

Table 2: Exposure dates and total times by test site and condition.

Site, State	Start Date	End Date	Time (days)
OS, FL	12/21/2021	12/13/2022	357
IC, FL	12/21/2021	12/13/2022	357
IC SAS, FL	8/29/2022	12/13/2022	106
ES, CA	1/11/2022	1/18/2023	372
WH, WA	4/29/2022	4/26/2023	362

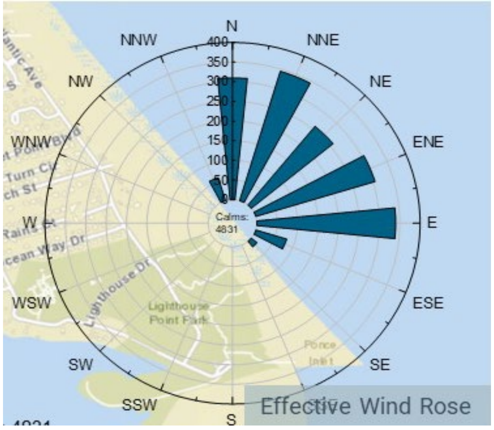

Figure 3: Wind rose for effective wind at Battelle FMRF ocean site (OS).

Table 3: Environment spectra data.

	Severity Monitoring Device					NOAA		
Site	**OS**	**IC**	**IC SAS**	**ES**	**WH**	**OS**	**ES**	**WH**
Air Temp (°C)	26.0	27.0	24.7	23.8	12.5	22.4	17.7	9.4
RH (%)	75.2	73.7	77.6	65.5	79.7	74.8	66.7	89.9
ToW ISO (%)	54.4	55.2	53.5	49.6	58.3	45.7	29.4	84.9
TW AC (%)	62.7	62.7	68.6	55.0	70.5	62.2	52.3	93.9
TSW AC (%)	12.0	10.7	22.3	8.3	11.2	30.3	30.3	5.6
TD AC (%)	23.7	26.7	9.1	36.8	18.3	7.5	17.3	0.5
Cond (C/V/d)	66.38	15.28	356.29	124.28	52.43	-	-	-
WE (km/d)	-	-	-	-	-	86.61	164.04	146.34
WVHT (m)	-	-	-	-	-	0.71	1.00	0.40
S_d (mg/(m^2·d))*	95.1	42.1	-	-	-	-	-	-
Rain (mm/yr)**						1050	345	515

* Wet candle

** Climate-Data.org

3.2 Corrosivity

The annualized corrosion for the four material combinations at each test site were determined using data from the severity monitoring devices. Given that the corrosion sensors are degrading during the exposure period and the rate of corrosion is dependent on the material couple, sensor life varied from 30 days to a full year for AA7075-T6/CFRP galvanic couple at the highest and lowest severity sites. In order to compare across materials and test sites the corrosion rates are annualized (Figure 4 and Table 4).

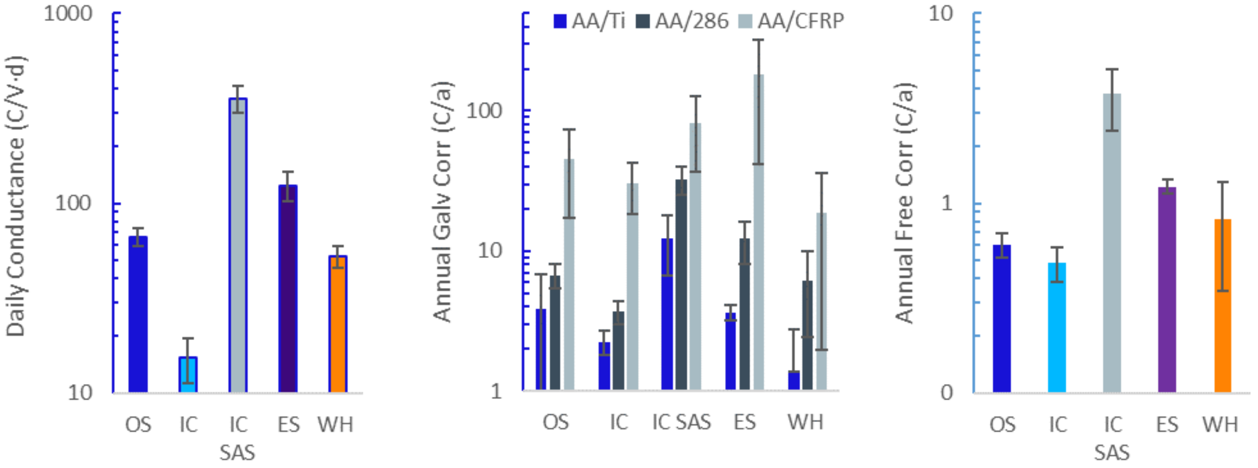

Figure 4: Severity monitoring device results for daily conductance, galvanic corrosion, and free corrosion (left to right). Error bars are 95% confidence intervals.

Table 4: Annual total corrosion and coefficient of variation (CV).

Alloy	AA7075/Ti6-4		AA7075/286		AA7075/CFRP		AA7075 Free Corr	
Site	(C/a)	CV (%)	C/a	CV (%)	C/a	CV (%)	C/a	CV (%)
OS	3.87	30	6.75	8	45.21	25	0.60	6
IC	2.24	8	3.70	8	30.42	16	0.48	8
IC SAS	12.39	19	32.55	9	81.97	22	3.76	14
ES	3.65	5	12.22	14	180.31	31	1.22	3
WH	1.39	41	6.18	25	18.88	36	0.82	23

4.0 DISCUSSION

The results demonstrate the use of environment and corrosion data from weather stations and local severity monitoring devices to track and quantify conditions at different geographic locations and exposure configurations using a variety of material combinations.

4.1 Environment Spectra

The three different sites represent a variety of climates with Florida OS and IC - subtropical, El Segundo - warm-summer Mediterranean, and Whidbey Island - temperate oceanic. Whidbey Island has the combination of coldest average conditions and with highest average RH (Table 3). These conditions produce very high time of wetness and corresponding reduced dry time at Whidbey Island compared to the other locations. With regards only to humidity and time of wetness Whidbey is the most severity site.

The boldly exposed severity monitoring devices consistently have higher average annual temperature compared to the NOAA weather station data (Table 3). Other than Whidbey Island, the NOAA and monitoring device annual average RH are relatively similar for Battelle OS, Battelle IC, and El Segundo. The reason for the higher average monitoring device temperature is solar radiation heating during the day

(Figure 5). With respect to temperature change, black body radiation produces lower device temperature overnight, but this undercooling temperature change at night is much less than that produced by solar radiation during the day. These radiation effects on temperature have a significant effect on monitoring device RH where low RH conditions are produced during the day and high RH occurs at night. For extremely wet environments, like Whidbey Island, these higher overnight RH conditions are not as significant as what occurs in the more arid climate of El Segundo CA.

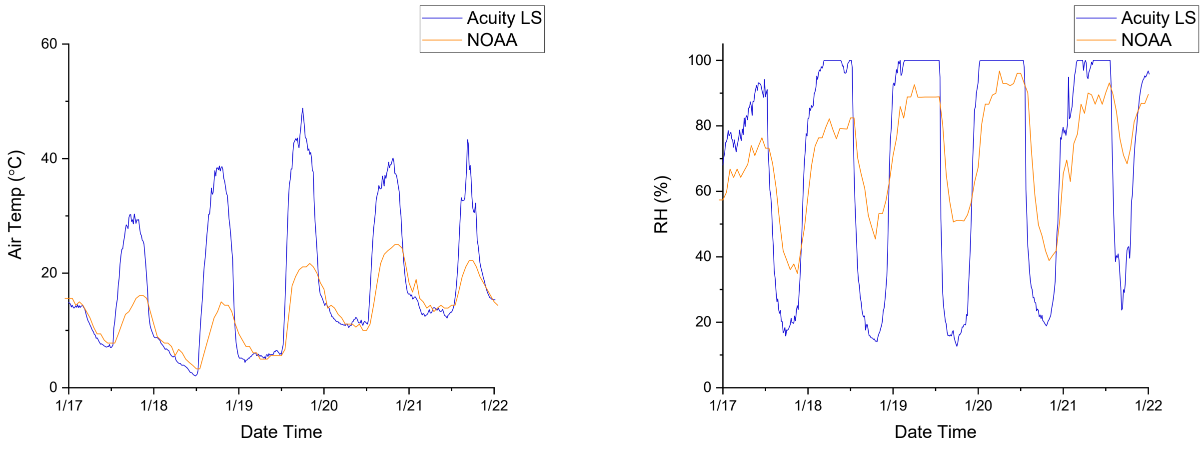

Figure 5: Severity monitoring device and NOAA weather station data for Battelle FL.

The accepted standard measurement for salt deposition rate is wet candle, and these results have a factor of two difference in salt deposition between the Battelle OS site and Battelle IC site that is 800 m inland (Table 3 and Figure 6). The average daily conductance measurement at the Battelle OS and Battelle IC sites differed by a factor of four. The conductance measurement is dependent on both planar density of salt and RH, but for the two sites 800 m apart, the relative humidity is similar. The primary factor for the conductance measurement difference between the two sites is assumed to be salt loading. A possible explanation for the differences in salt loading factors between the two sites using wet candle and conductance is that wet candles have roofs that may attenuate the salt deposition as compared to the boldly exposed monitoring devices.

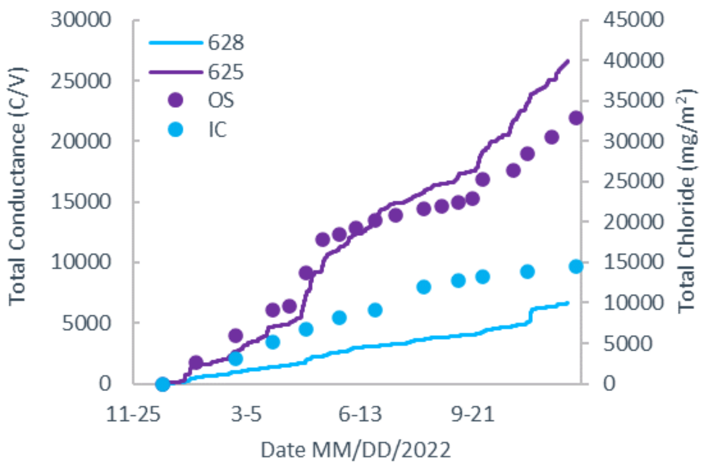

Figure 6: Wet candle (points) and severity monitoring device conductance (lines) for Battelle OS and IC sites.

Besides distance from the coast, it is assumed that salt deposition is dependent on a combination of factors including wave height and effective wind (Figure 7). Qualitatively, wet candle, wave height, and effective wind have similar time dependent trends. Salt removal by condensation and precipitation is also expected to be important for determining the amount of salt on a surface at any given time. Both salt deposition and removal are dependent on orientation of the test surface and for this study orientation was the same for the monitoring devices. Again, there are qualitative agreement between conductance measurements and wet candle, wave height, and effective wind data, but removal of salts from boldly exposed sensor surfaces would be expected to alter these relationships. With respect to conductance, the Battelle IC coastal site is the least severe location, but the SAS box shelter at Battelle IC produces the most severe conductance measurement (Table 3).

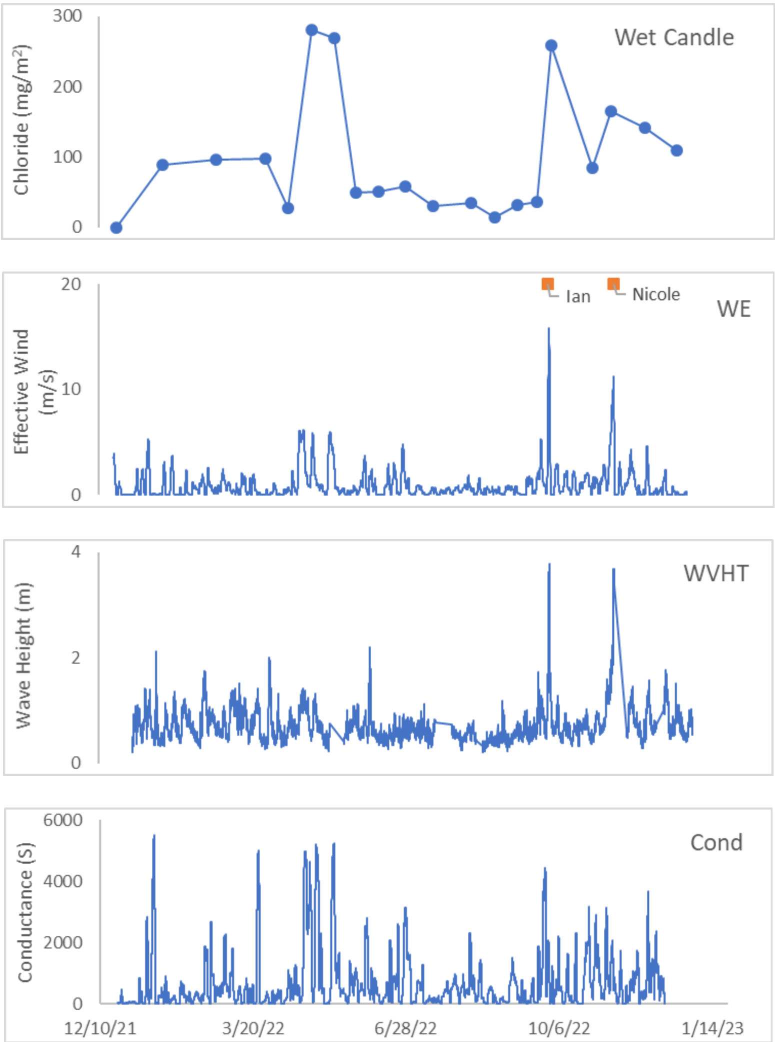

Figure 7: Measurements related to chloride deposition – wet candle, effective wind, wave height, and conductance (top to bottom). Dates for hurricanes Ian and Nicole are noted.

5.0 CORROSIVITY

The severity monitoring device measurements are used to compare different sites, exposure conditions, and materials. With respect to the annualized total corrosion for the galvanic couples tested, the rank ordering was Ti-6Al-4V, A286, and CFRP from least to most aggressive galvanic couples, and this result was independent of exposure site (Figure 4 and Table 4). The exposure site severity had similar rank order dependence using conductance, galvanic corrosion, and free corrosion with the Battelle SAS IC and El Segundo being the most severe and Battelle IC being the least severe. For the boldly exposed conditions, El Segundo had the most corrosive conditions and Battelle IC the least; while the overall most severe condition was recorded with the devices in the SAS box at the Battelle IC location.

5.1 Environment Spectra and Corrosivity

The most corrosive condition occurred in the SAS box at the Battelle IC location even though this location was the least aggressive location for the boldly exposed monitoring devices. The SAS box shelter produced higher wet time (TW), lower dry time (TD), and minimized salt removal by rain and condensation allowing for salt build-up as measured by conductance (Table 3). Similarly, the El Segundo location, with the highest effective wind and wave height and least annual rain fall, was the most severe location even though it had the lowest wetness and highest dry time. These results indicate the importance of rinsing events due to condensation and rain that reduce corrosion severity. The wet candle and daily conductance data indicate lower salt deposition at the Battelle IC site relative to the Battelle ocean site. Being 800 m inland produced a significant, measurable difference in corrosivity. These results indicate that salt deposition and salt removal rate are significant factors in determining corrosion severity.

5.2 Relevance to Aircraft Corrosion

The SAS box was used to produce a condition similar to an aircraft structural element that permits environmental ingress but is sheltered from rinsing. Sheltered areas of a structure that do not get direct solar radiation heating may have higher times of wetness and less drying as compared to boldly exposed surfaces (Table 3). Furthermore, sheltered areas may be prone to accumulating salt contaminants that increase corrosion. The results indicate that sheltered areas of an airframe may have much higher severity as compared to boldly exposed surfaces due to salt contaminant accumulation. The most severe corrosion occurred in conditions and locations with the lowest levels of rinsing by rain (El Segundo and Battelle IC SAS). This indicates that washing and rinsing to remove contaminants from an aircraft structure would be effective for reducing corrosion severity, with particular attention required for occluded and sheltered spaces of the airframe. Measurement of environmental conditions and conductance may be useful for assessing salt deposition and determining appropriate wash intervals.

5.2.1 Dynamic Severity Assessment

The environment and corrosion severity are dynamic processes as evidenced by the variable wet candle, effective wind, wave height, and conductance measurements over the exposure period (Figure 7). These dynamic processes are measurable with local climatic data and severity monitoring devices. Corrosive conditions are variable over a range of time scales associated with weather events, diurnal cycles, and seasonal changes (Figure 7 and Figure 8). These results demonstrate that onshore wind and larger wave heights are associated with increased salt deposition. On-shore winds are generally greatest midday; while RH, conductance, and corrosion rates are highest overnight and early in the morning. For a shore-based aircraft located outside, salt deposition would be expected during the day with corrosion occurring overnight (Figure 8). For sea-based aviation, wind speed, independent of direction, and wave height may be determining factors for salt deposition. During the test period, two weather events (hurricanes Ian 28 Sep 22 and Nicole 10 Nov 22) with high winds and wave heights produced transient high salt deposition (Figure 7).

5.2.2 Classification of Severity

Currently, for US Navy and US Air Force aircraft wash and rinse requirements are given by aircraft specific and more general aviation manuals and technical orders (TO 1-1-691, NAVAIR 01-1A-509-2). These practices are associated with specific base severity classification (mild, moderate, and severe), sea-basing, and proximity to a coastline. These are static instructions, except with respect to operations over saltwater, and do not account for long term changes in climate or shorter-term seasonal trends and transient weather events. The ISO 9223 standard provides methods for classification of corrosion severity using mass loss and environmental measurements, and these methods have been adopted for facilities use (Silver, 2017). The ISO 9223 method does not provide for assessments using aerospace relevant materials or galvanic couples.

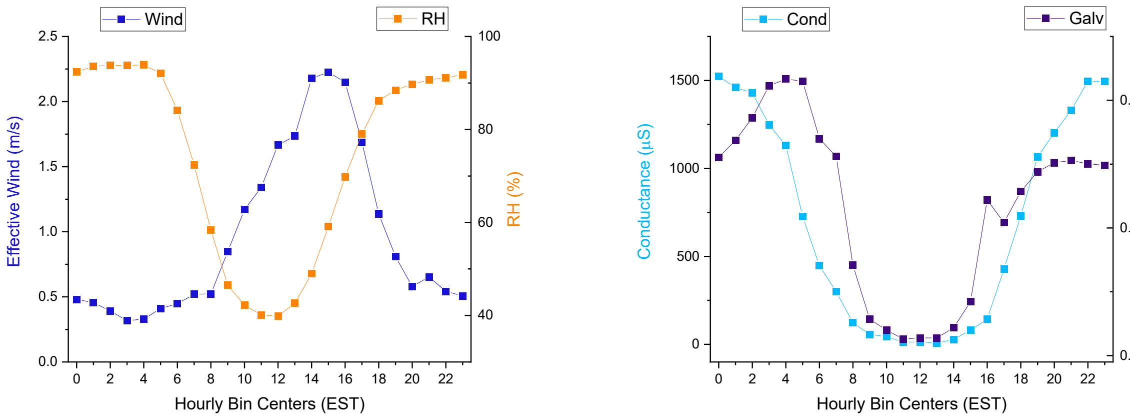

Figure 8: Hourly average diurnal effective wind, relative humidity, conductance, and galvanic corrosion (AA7075/A286) at Battelle OS site. Hourly bins are Eastern Standard Time.

Given the consistency in relative site severity ranking obtained in this study using a variety of aerospace materials and conductance measurements, the severity monitoring may be appropriate for site surveys and asset tracking. The DoD ICCET from Silver (2017) and ISO 9223 methods have six severity categories based on corrosion of standard zinc, steel, copper, and aluminum mass loss coupons. Using the relative ranges for aluminum ISO 9223 severity categories and the assumption that the Battelle OS site is at the lower 20% of the C5 category, proportional spans for classifications based on galvanic corrosion, free corrosion, and conductance used in this study have been proposed by Agnew (2023) (Table 5). The severity categories are reasonably consistent for each measurement, ranging from C3 to CX (Table 5). These classifications provide a means to obtain a uniform severity assessment for locations relevant to US DoD aircraft using monitoring devices.

Table 5: Estimated relationships between annual corrosion, daily conductance, and ISO categories. Highlighted cells indicate alloy preference for classification assessments (Agnew, 2023).

ISO 9223 Category	ISO 9223	Annual Corrosion (r)				Daily Cond (s)
	Aluminum (g/(m²-a))	AA7075/Ti-6-4 (C/a)	AA7075/A286 (C/a)	AA7075/CFRP (C/a)	AA7075 (C/a)	Gold IDE (C/V·d)
C1	negligible	r ≤ 0.02	r ≤ 0.03	r ≤ 0.2	r ≤ 0.03	s ≤ 0.7
C2	r ≤ 0.6	0.02 r ≤ 0.4	0.03 < r ≤ 0.7	0.2 < r ≤ 3.5	0.03 r ≤ 0.06	0.7 < s ≤ 6.6
C3	0.6 < r ≤ 2	0.4 < r ≤ 1.3	0.7 < r ≤ 2.2	3.5 < r ≤ 11.7	0.06 < r ≤ 0.2	6.6 < s ≤ 22.1
C4	2 < r ≤ 5	1.3 < r ≤ 3.2	2.2 < r ≤ 5.6	11.7 < r ≤ 29.2	0.2 < r ≤ 0.5	22.1 < s ≤ 55.3
C5	5 < r ≤ 10	3.2 < r ≤ 6.4	5.6 < r ≤ 11.2	29.2 < r ≤ 58.4	0.5 < r ≤ 1.01	55.3 < s ≤ 110.6
CX	R > 10	6.4 < r	11.2 < r	58.4 < r	1.01 < r	110.6 < s

Table 6: Severity categories using corrosion and conductance measurements. Categories are aligned with ISO 9223 range for aluminum. Corrosion is given in C/a and conductance in C/(V·d).

Site	Severity Categories	C1	C2	C3	C4	C5	CX

Site	AA7075/Ti6-4	AA7075/286	AA7075/CFRP	AA7075	Cond	Mode
OS	3.87	6.75	45.21	0.60	66.38	C5
IC	2.24	3.70	30.42	0.48	15.28	C4
IC SAS	12.39	32.55	81.97	3.76	356.29	CX
ES	3.65	12.22	180.31	1.22	124.28	CX
WH	1.39	6.18	18.88	0.82	52.43	C4

The assessment of severity could be used to update existing base classifications such as mild, moderate, and severe identified in TO 1-1-691. These classifications are used to determine wash intervals ranging from 30, 90, and 180 days, whereas NAVAIR 01-1A-509-2 requires washing every 7 days when aboard ship and every 14 days or less when ashore. Depending on the severity and wash requirements, measurements of severity on the order of days to months would be relevant to tailoring maintenance processes that account for more or less aggressive environmental conditions at specific locations and for individual aircraft.

6.0 CONCLUSION

Service environment severity for aerospace applications can be measured using environment and corrosivity parameters. Severity assessment may include local weather station and buoy data along with spatial mapping and tracking with severity monitoring devices.

These severity measurements can be used to produce classifications that are uniform and consistent with existing categories and could be used to update and maintain current classifications for DoD relevant aerospace locations.

The severity measurement and classification can be made using aerospace relevant materials and galvanic couples.

Climatic variables of wind and wave height were demonstrated to influence salt deposition, conductance, and corrosion rate measurements.

The severity monitoring devices were capable of quantifying differences in environment and corrosivity with small changes in distance and sheltered and unsheltered test conditions.

Sheltered conditions and low levels of rinsing by rainfall or condensate created high salt accumulation and the highest severity conditions measured in the study. This was true for the driest location included in the study.

Sea breezes promote salt deposition during the day while the highest RH and corrosion occur overnight.

Environment and corrosivity measurements could be used to account for more or less aggressive environmental conditions at specific locations and for individual aircraft to optimize wash schedules and preventative corrosion maintenance.

7.0 FURTHER WORK

Modeling – A number of qualitative relationships were observed, and modeling should provide for improved time based corrosion predictions and optimized monitoring to improve aircraft corrosion prevention and control.

Land- and Sea-Based Assessments – Protocols need to be established for conducting site surveys to map, classify, and track severity. Initiatives to standardize the use of these measurements for aerospace and defense applications is continuing through ISO TC 156, AMPP SC 07, and SAE HM-1.

Corrosion Prevention and Control – Technical orders and maintenance manuals need to be updated to allow for adjusted wash and corrosion prevention schedules using weather data, site severity monitoring, and individual aircraft tracking. The benefits need to be documented for improved labor utilization, reduced unscheduled/corrective maintenance, and improved aircraft capability.

8.0 ACKNOWLEDGEMENT

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