

Understanding Atmospheric Corrosion Damage on an Aircraft Representative Galvanic Test Article - A Two-Pronged Approach That Combines Modeling With Experimental Measurement

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ABSTRACT

A comprehensive modeling exercise was undertaken to better understand, the spatial distribution of corrosion damage, measured on aircraft representative, galvanic test articles, exposed to two significantly different corrosive environments. One set of test articles was exposed to ambient conditions in a coastal marine environment for approximately two months, while a second set was further exposed to controlled seawater spray dosing for an additional two months. Both environmental loading scenarios are assessed, analyzed, and modeled. The performance of a three-dimensional (3D) finite element model, of the multi-material galvanic test article, is discussed, along with some of the challenges associated with selecting appropriate input parameters to best represent the two different exposure conditions. The measured spatial distribution of corrosion damage is compared to the galvanic simulation model solutions. A complex pattern of corrosion damage is observed, that includes, localized galvanic corrosion at the fastener, crevice corrosion beneath the bushing flange, and galvanic interaction between the fastener and larger diameter bushing. The sensitivity of the models to electrolyte resistance (film thickness, conductivity) and extent; and the metal resistance (polarization curves), representing each environment, are explored.

Key words: atmospheric exposure test, laser profilometry, spatial corrosion damage, thin film galvanic corrosion, crevice corrosion

INTRODUCTION

Aircraft representative galvanic test articles and witness coupons were placed out for atmospheric exposure testing at the U.S. Naval Research Lab (NRL) site in Key West, Florida. One set of test specimens was exposed to only ambient environment for a 62 day period; a second set of test specimens was exposed to both ambient environment (initial 62 days), and a short duration, twice daily, seawater spray protocol over a further 55 day period. Environmental loading was monitored using sensors that measured temperature, relative humidity, rainfall, and time of wetness (TOW), at 30 minute intervals. Following retrieval, the test articles were inspected in the laboratory using laser profilometry to characterize the spatial distribution and depth of corrosion damage. Mass loss measurement using the witness coupons was used to estimate relative corrosion rates for the two periods. Galvanic solutions from a computational model (FEA), representing the test article, are compared to experimental measurements to assess predictive capability. The sensitivity of the solution to key input parameters (e.g. electrolyte properties and metal polarization curves) and different model configuration is investigated; measured damage morphology is used to guide modeling assumptions where appropriate.

GALVANIC TEST ARTICLE DESIGN

Review of an F/A-18 outer wing teardown inspection report was used to select a structural component (aileron attachment hinge) that exhibited both galvanic damage and corrosion related fatigue cracking. A notional version of this component was designed and fabricated (Figure 1); this representative aircraft galvanic test article formed the basis for the exposure testing program. The test articles include stainless steel fasteners (UNS S30400, UNS S17400) and aluminium-bronze (UNS C95400) flanged bushings of different sizes inserted in dog-bone shaped aluminum alloy plates (UNS A97075); the fastener locations are slightly biased toward the larger diameter bushing to assess galvanic interaction. Key considerations in the design include using multiple aerospace metal alloys for components, maintaining a similar combination of bushing and fastener geometry, and ensuring a non-symmetric layout to promote discrete areas of galvanic damage.

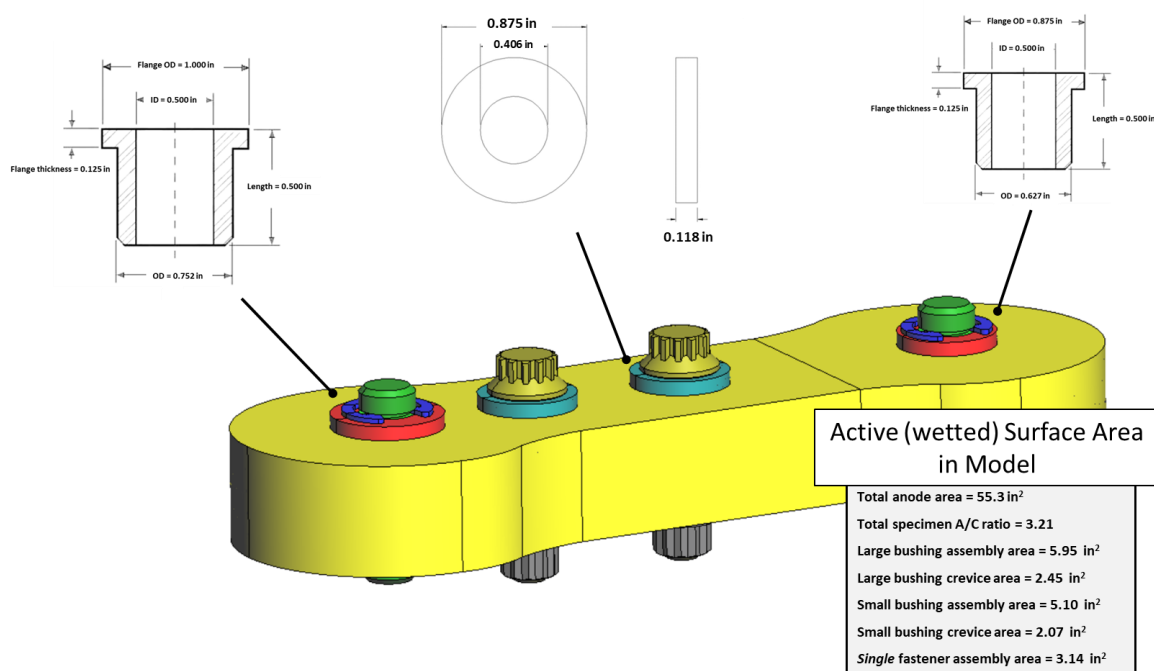


Figure 1: Representative aircraft galvanic test article design (bushing assembly area includes bushing, clevis pin, clip ring - fastener assembly area includes bolt, nut, washer)

ATMOSPHERIC EXPOSURE TEST PROGRAM

A mounting panel that included both galvanic test article pairs and witness coupons (UNS G10200 carbon steel and UNS A97075 aluminum alloy) was initially placed on an exposure rack at the NRL Key West site on May 17, 2019. The first set of test articles and witness coupons (Exposure Period 1) were collected on July 17, 2019; this represented a 62 day period of exposure (Figure 2a). A second pair of test articles and witness coupons (Exposure Period 2) were collected on September 11, 2019; representing an additional 55 day exposure period during which only the test articles were subjected to a controlled, cyclical, seawater spray protocol (twice daily for 45 seconds) (Figure 2b). A third pair of test articles and witness coupons (Exposure Period 3) were collected on November 13, 2019, however data from that exposure period is not discussed in this work.



Figure 2: Atmospheric exposure test panel at NRL Key West site (seawater spray rack shown on right)

The temperature, relative humidity, and rainfall data, available from a weather station located at the NRL Key West site, is processed to characterize the environmental history during the testing program. A plot of the change in relative humidity and temperature during the test period is shown in Figures 3.

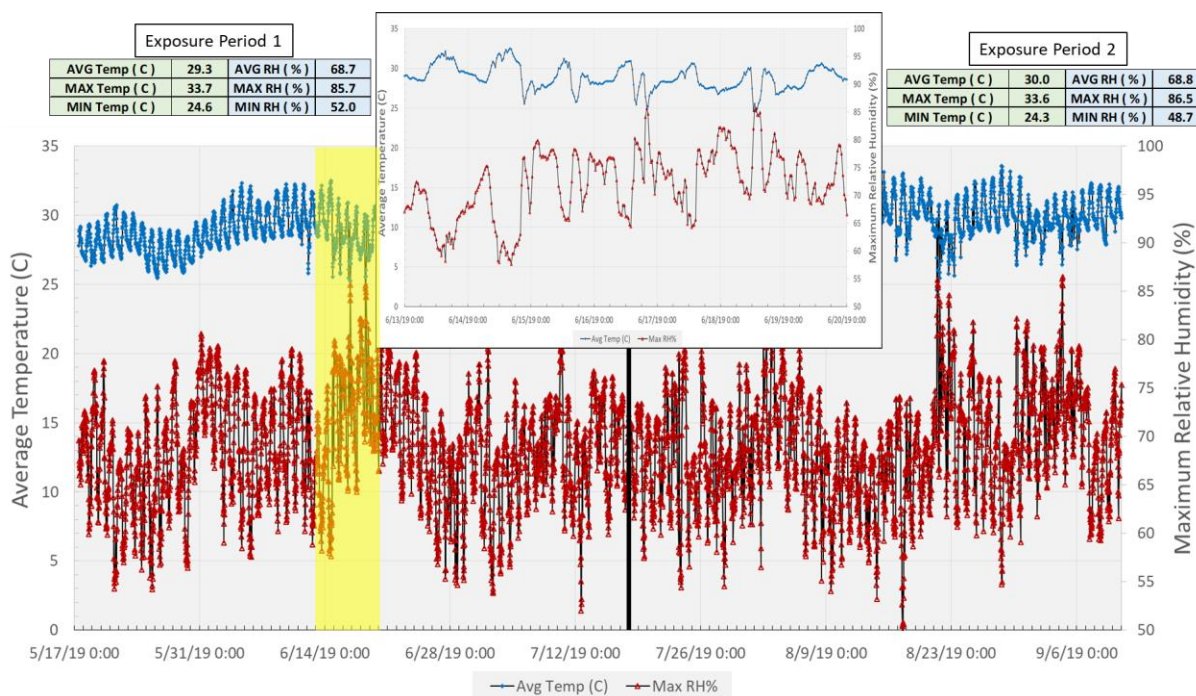


Figure 3: Relative humidity and temperature over the two exposure periods (yellow shaded region identifies data in detailed inset view)

The time of wetness (TOW) was measured using a Campbell Scientific^{†1} Model 237-L leaf wetness sensor and this data is shown in Figure 4. This data was processed, according to manufacturer guidelines, to determine the percentage of time that the sensor was recording WET, SLIGHTLY WET, or DRY conditions. This data is useful in evaluating the comparative differences in wetness between the two exposure periods. With some caution this data can also be used as a surrogate for wetness on the galvanic test articles, however additional, more robust measurement sensing, is needed to better approximate the extent and thickness of electrolyte films. The leaf wetness sensor was not directly exposed to seawater spray dosing during Exposure Period 2, as such, the sensor measurements during

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that period, cannot be directly used to indicate the occurrence of surface moisture at the test panel location.

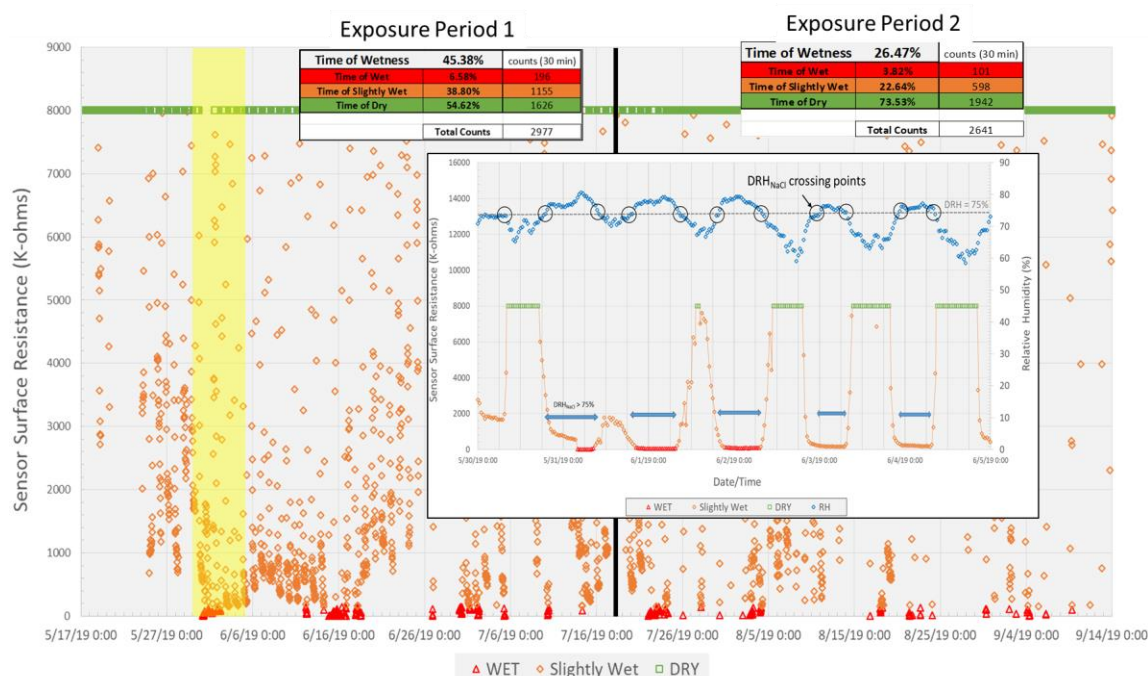


Figure 4: Leaf wetness sensor measurement data for Exposure Periods 1 & 2 (yellow shaded region identifies data in detailed inset view)

ATMOSPHERIC GALVANIC CORROSION MODELING

Atmospheric corrosion is a complicated phenomenon affected by multiple external variables including relative humidity, temperature, salt deposition density, solution chemistry, and electrolyte layer thickness. Galvanic coupling in complicated geometry makes conventional experimental characterization on galvanic-couple-induced atmospheric corrosion difficult. Liu and Kelly [1] suggest that using computational modeling, combined with experimental characterization, can increase understanding of the dependence of corrosion susceptibility on external variables. Our work is focused on using a two-pronged approach where both computational and experimental methods are used to quantify the important characteristics that control corrosion rate and resultant corrosion morphology.

Corrosion Model

A BEASY^{†2} corrosion model was developed based on the test article design shown in Figure 1 and used to predict the distribution and magnitude of galvanic potential and current density. Surface groups, representing the various anodic and cathodic materials in the test article, are created. Crevice conditions are only modeled at bushing-plate mating surfaces. The model geometry is discretized with elements using an appropriate meshing scheme. Boundary conditions based on the electrochemical kinetics (polarization curves) are applied to represent the various component materials. Polarization curves (Figure 5) used in this work are obtained from the technical literature [2, 3, 4]. These curves are primarily based on an artificial seawater electrolyte but in some instances polarization curves were only readily available for a very similar, but slightly different, 0.6 M NaCl electrolyte solution. Some of these curves have been modified using analytical transforms, based on the Levitch equation, to create thin film

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representations. The characteristics of the electrolyte film (conductivity, thickness, extent) are also assigned. The solution for the electrochemical distributions is found using an FEA approach based on the Laplace Equation.

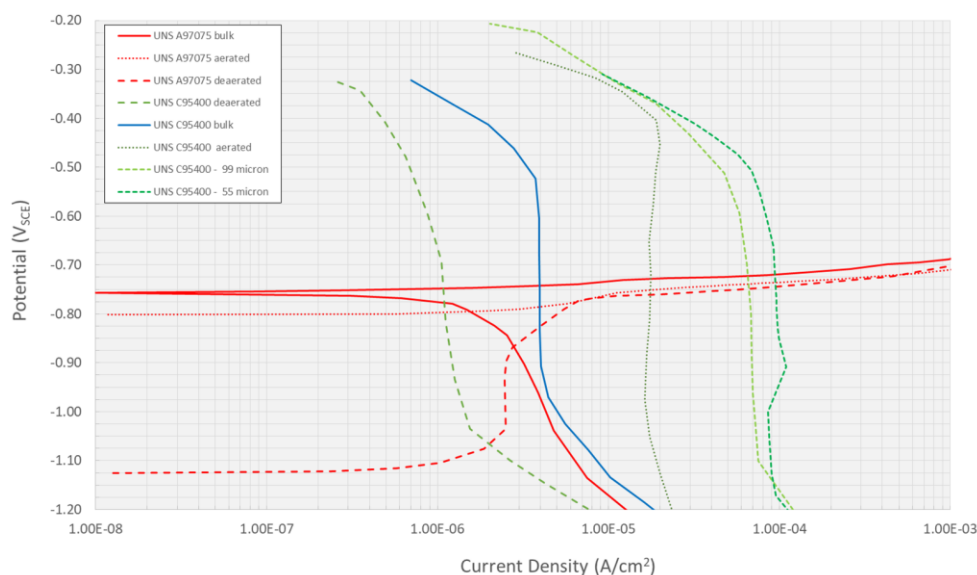


Figure 5: Polarization curves [2, 3, 4] used in models (stainless steel and full cathodic curves not shown)

Crevice Specific Modeling Consideration at Bushings

An important aspect of this modeling work was to properly represent the boundary conditions in the crevice area. Special finite elements have been developed to handle unique cases where surfaces are nearly coplanar as in the case of extremely thin gaps (e.g. crevice). Corrosion inside a crevice is a very transient, time-dependent event, with complex changes in solution chemistry as the crevice environment evolves. It is thought that the crevice environment initially develops when oxygen is depleted in the crevice causing the crevice to act anodic relative to the boldly exposed surface. Chloride ions then enter the crevice to maintain electro-neutrality; this process is followed by increasing acidification inside the crevice, often at some critical distance from the mouth, due to metallic ion hydrolysis [5].

In order to approximate this crevice environment in the model we have followed guidance [2, 6] on the selection of polarization curves for occluded spaces; in this way we are able to adopt a steady state modeling approach and mimic the electrolyte chemistry inside the crevice. The bushing crevice was generally modeled using boundary conditions and electrolyte properties suggested by others [2] and listed below:

- Aerated, low pH condition near the crevice mouth and a deaerated, high pH condition deeper into the crevice near the crevice tip.
- Piecewise increase in conductivity from mouth to tip (5.8 S/m boldly exposed, 8.5 S/m beneath bushing flange, 10 S/m in the upper bushing shaft region, and 12 S/m in the lower bushing shaft region near the crevice tip).

RESULTS AND DISCUSSION

Figure 6 shows the difference in corrosion severity after each exposure period upon retrieval of the test articles. The test article from Exposure Period 1 (Figure 6A) shows insignificant corrosion although there is some slight discoloration around edge of the bushing, being less so near the edge of the washer. The Exposure Period 2 test article (Figure 6B) shows noticeable corrosion product buildup circumferentially

around the edge of the bushing and washer; being more significant at the larger bushing location. Corrosion product accumulation is visible at the bottom of the bushing flange. This deposit is slightly protected, by the bushing geometry, from any washing effect that may occur on the plate surface during rainfall events. Given the differences in corrosion severity, modeling schemes are developed to address both the ambient coastal marine, and the more aggressive seawater spray dosing environment; with considerations for the differences in salt loading, period of wetness, and corrosion damage morphology.

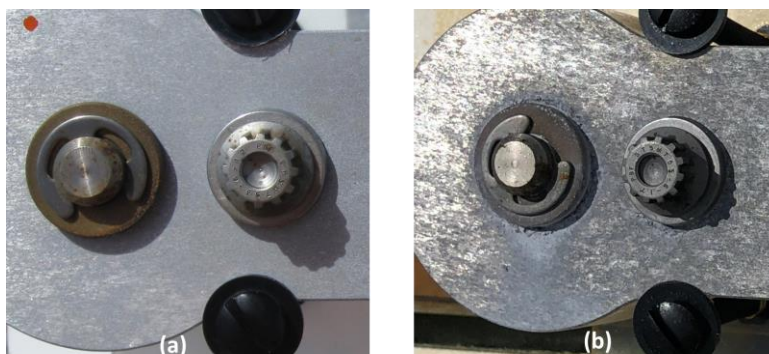


Figure 6: Galvanic specimen appearance upon retrieval (a) Exposure Period 1 (b) Exposure Period 2

Exposure Period 1 - Ambient Marine Coastal Environment

Exposure Period 1 represents a coastal marine environment with low salt loading (e.g. 7 to 20 $\mu\text{g Cl}^- / \text{cm}^2 \text{ day}$) [7, 8]. Discussion of the measured corrosion damage morphology for this period along with results from an associated galvanic simulation are presented. Modifications to the model configuration, and changes in input parameter assumptions, that improved comparison to experimental measurement, are also discussed.

Corrosion Damage Morphology.

A Keyence[†] VK-X250 3D laser scanning confocal microscope is used to measure corrosion penetration depth at the bushing and fastener locations. Measurements of the maximum corrosion penetration depth, on the top surface of the test article, are shown in Figure 7. These locations are marked by an oval arrowhead on the test article image. An associated reference label (e.g. 1A-1) is used to indicate this same location on the profilometry scan. In general, a full scan near the edge of the washers was obtained, however only more local scans of the area beneath the bushing flanges were available.

Key findings from Exposure Period 1 indicate approximately 8-12 μm of damage at the edge of the stainless steel washers and no evidence of damage directly beneath the washer. The damage at the fastener holes is located circumferentially around the edge of the washer, however the depth of penetration is fairly non-uniform with greater penetration depths at locations 2A and 3A. There does not appear to be any significant difference in the damage pattern between the two fastener holes.

The maximum corrosion penetration measured at the bushing locations ranges from 25-28 μm . This damage is located primarily beneath the bushing flange. The flange of the bushing creates an annular crevice where it mates with the plate; the bushing is a loose fit installation and the gap is approximately 50 μm . Corrosion penetration depths are greatest at the edge of the bushing bore (1A-1), and under the inner flange section (5A-2) slightly remote (approx. a 750 - 1250 μm radial distance away) from the edge of the bushing bore. The damage at the bushing locations appears to be more randomly located compared to that measured at the fastener locations, with discrete areas of more localized damage measured beneath the flanges. There is a slight difference between the damage patterns measured at the two bushing locations. At the larger diameter bushing the damage is mostly at the edge of the bore

[†] Tradename

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