VALIDATION of "Time 0" GALVANIC CORROSION MODEL & DEVELOPMENT OF CORROSION SERVICE LIFE MODEL for AIRCRAFT STRUCTURES

ASETSDefense Workshop

Joint Session with ONR Sea Based Aviation

August 22, 2018

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Computational Mechanics International Inc.

Helping Engineers Control Corrosion & Cracks

BEASY SOFTWARE & SERVICES

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Contract Details

USAFA Cooperative Agreement

Agreement No. : FA7000-16-2-0017

Contractor Name: Computational Mechanics International Inc.

Period of Performance – Sept. 30, 2016 to Sept. 29, 2019

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Discussion Topics

- Project Goal & Objective (Year 2)
- Key Activities & Accomplishments
- Corrosion SLM Software Framework
  - Electrochemical Database (PDS curve management and improved analytics)
  - Corrosion Susceptible Part Library (riveted panel model with coating damage scenarios)
  - Corrosion Pitting Model
- Developing an Environmental Exposure Spectrum *(data sources and methods)*
  - Historical Records
  - Sensor Measurement Data
- Demonstration Model
  - Selection Criteria
  - Sequential Environmental Loading & Cumulative Corrosion Damage Prediction
  - SLM Modeling Results (current status)
- Challenges Encountered
- Future Work

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Overall Goals

1. **Use a validated computational approach to develop an integrated suite of galvanic corrosion modeling tools to support galvanic risk assessment.**

2. **Extend this methodology to include the dynamic changes in environmental exposure for a typical aircraft usage spectra - Service Life Model (SLM).**

The validation and development of computational corrosion modeling tools has the potential to dramatically improve the durability of an aircraft through better material selection, improved corrosion resistant design, and better predictive maintenance schemes.

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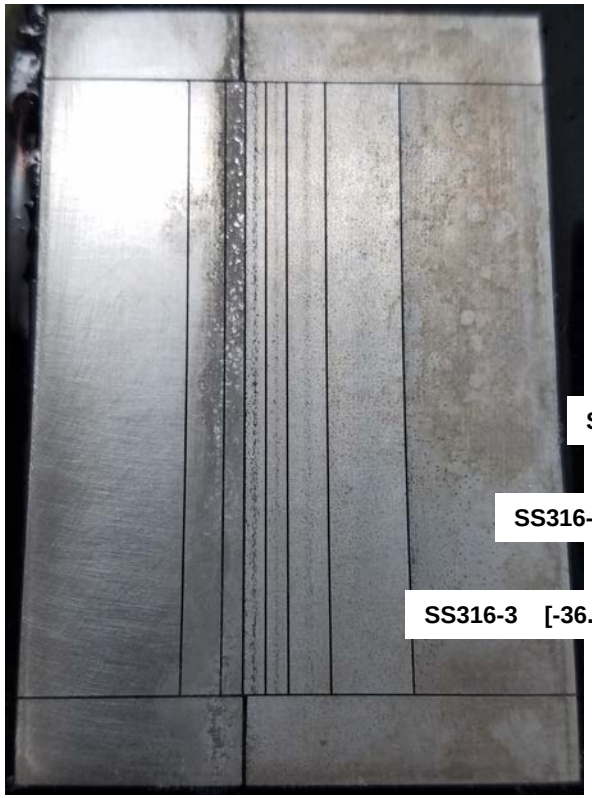
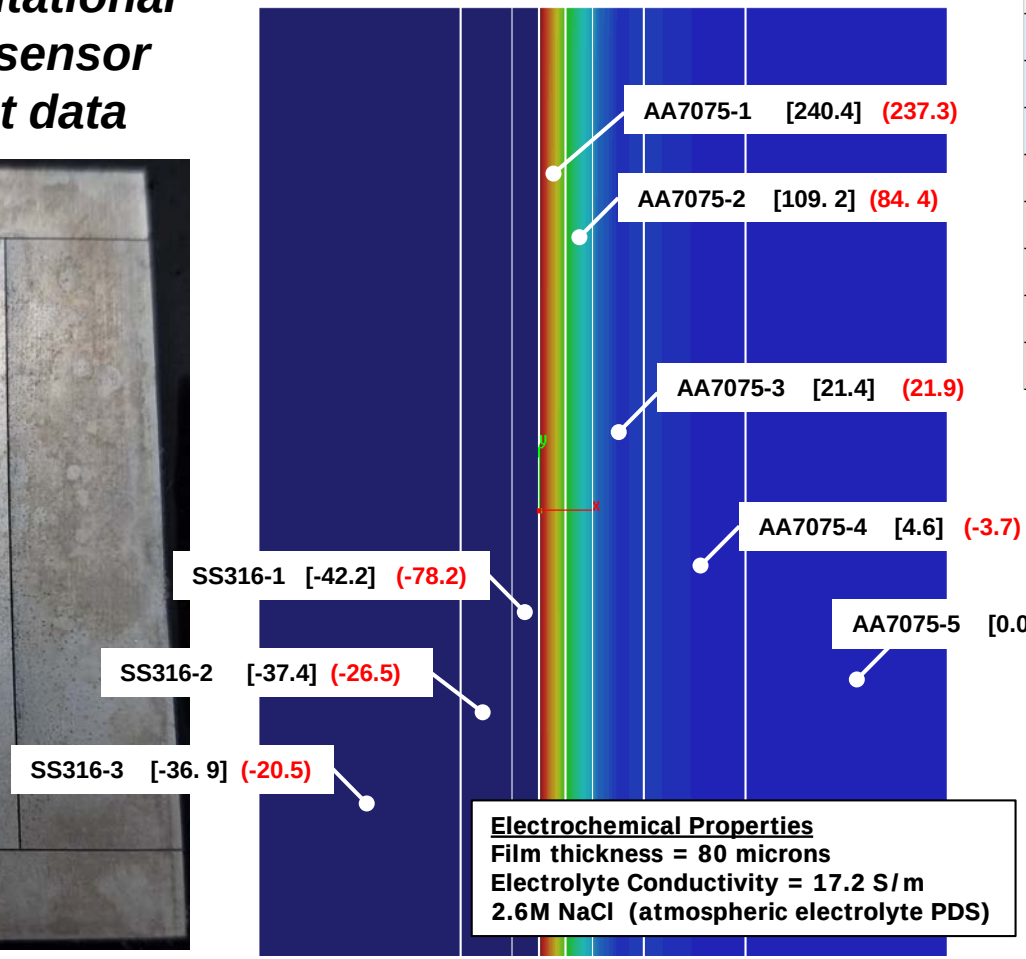
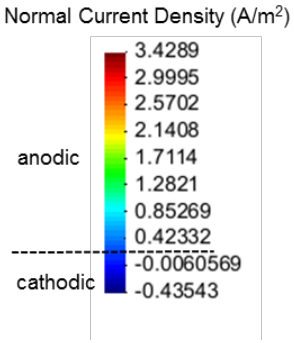
Project Goal & Objective - Year 1 (*Review*)

Validate computational results using sensor measurement data





BEASY	LUNA	% Difference
-36.9	-20.5	57.1%
-37.4	-26.5	34.1%
-42.2	-78.2	59.8%
240.4	237.3	1.3%
109.2	84.4	25.6%
21.4	21.9	2.3%
4.6	-3.67	1778.5%
0.0	-	N/A



[net current, μA] BEASY model using thin film PDS data

(net current, μA) Luna electrode measurement (at equilibrium conditions)

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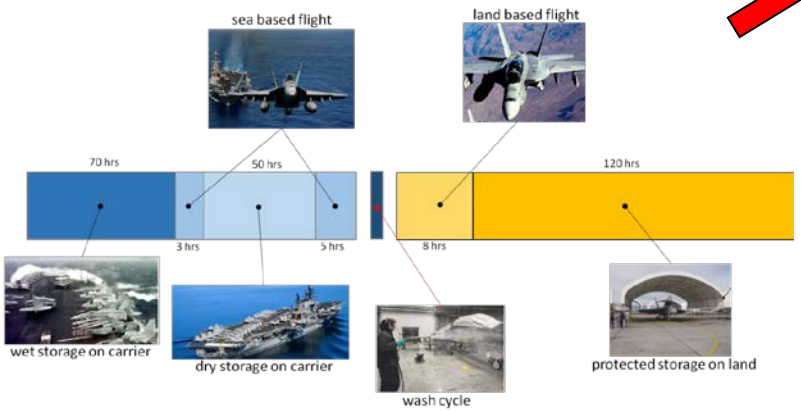
Project Goal & Objective - Year 2

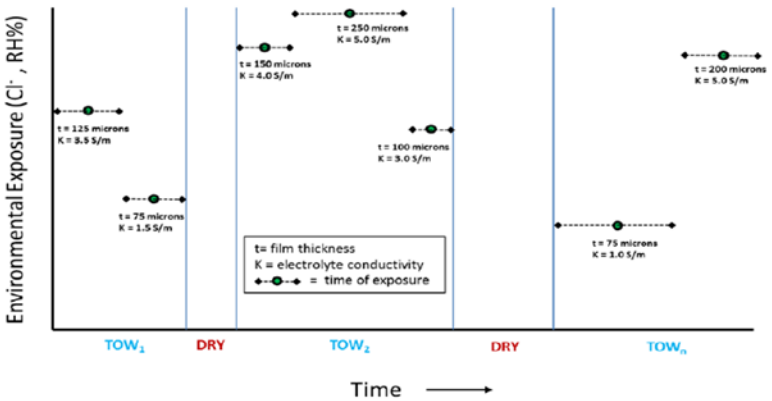
Develop a Corrosion Service Life Model to predict the cumulative galvanic damage (*Faraday metal loss calculation*) and other corrosion related attack (*crevice and pitting).*

Operational Environment History

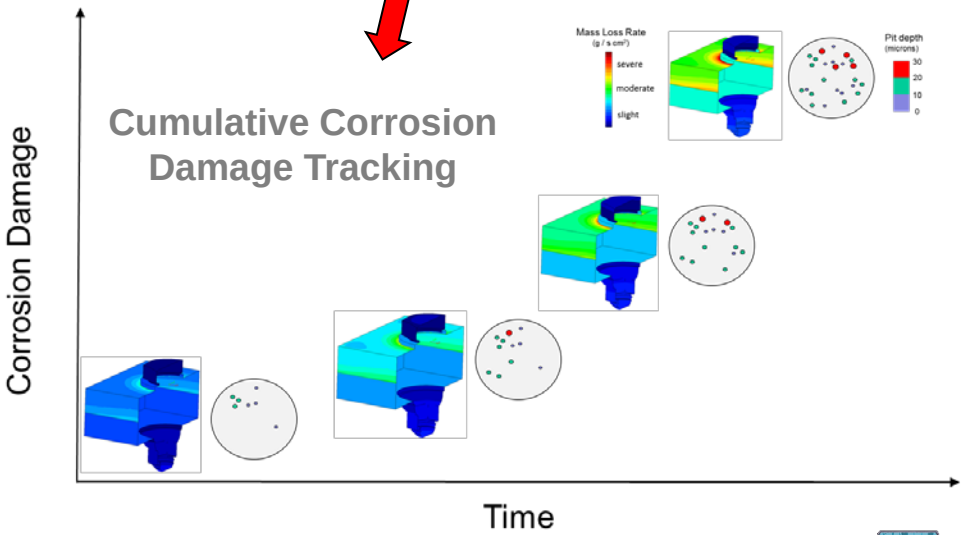


Relate prediction to defined aircraft usage periods that reflect actual in-service environmental exposure.

Model Input Requirement



Cumulative Corrosion Damage Tracking



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Key Activities & Accomplishments

- A number of critical software modules have been completed. The modules represent the computational modeling framework needed to perform accumulated corrosion damage studies.
- Investigated and sourced environmental data that can be used to build environmental exposure spectra.
  - Reviewed available data sources based on historical records that could be used to inform computational corrosion models.
  - Investigated and demonstrated the use of corrosion sensor data to inform computational models - currently working to further connect this measurement data with our computational modeling approach
- Evaluated and selected a corrosion pitting model for integration within the SLM framework
- Review the F/A 18 Outer Wing Teardown Inspection Report and selected a representative aircraft component to use for SLM method demonstration
- Continue to identify gaps in the computational model input data and explore appropriate validation metrics for the corrosion SLM approach.

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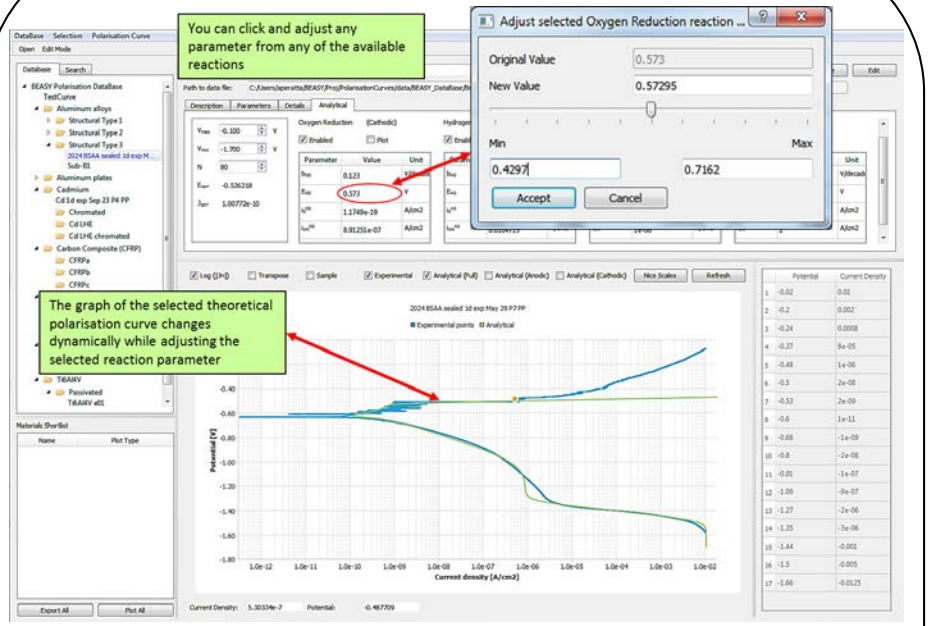
SLM Software Framework

Electrochemical Database Management Tool

1. Improved Electrochemical Database and PDS curve management
2. Incorporates methodology and data from the Boeing Galvanic Corrosion Prediction Tool (GCPT)
3. Now possible to create analytical representations of polarization curves and perform curve crossing

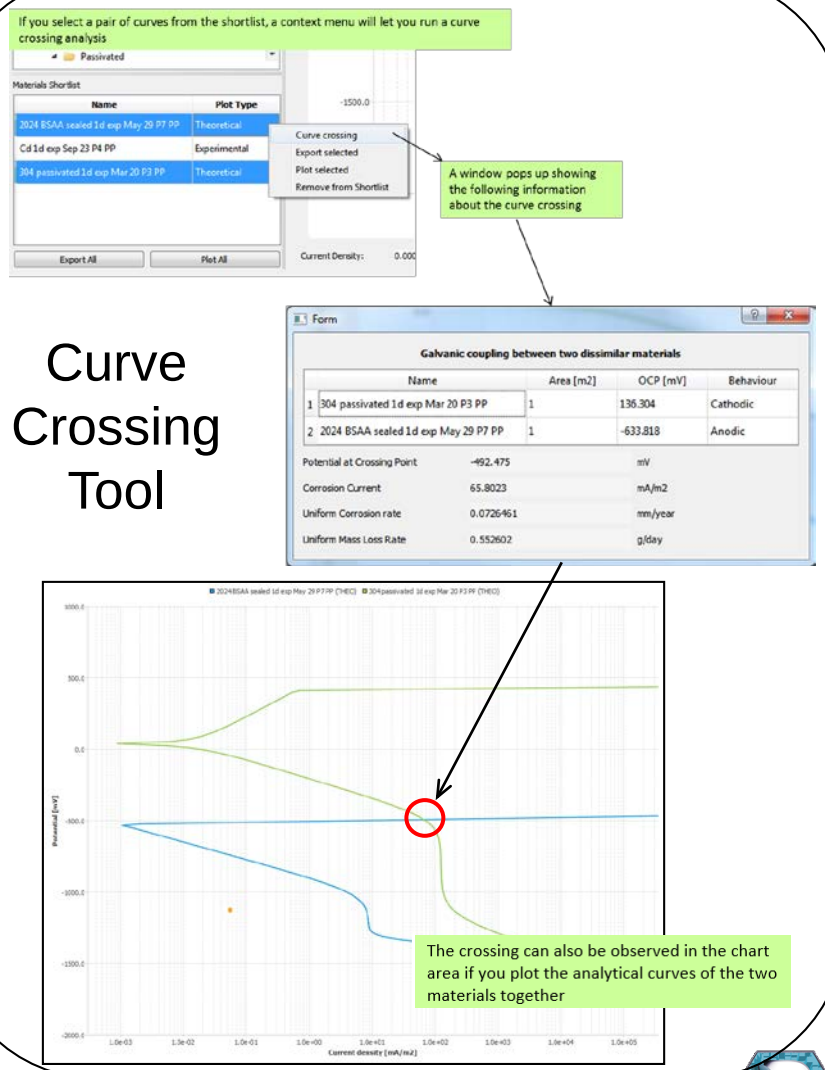
SLM Software Framework

Electrochemical Database Management Tool



Analytical polarization curves

reactions modeled using Butler-Volmer type model



Curve Crossing Tool

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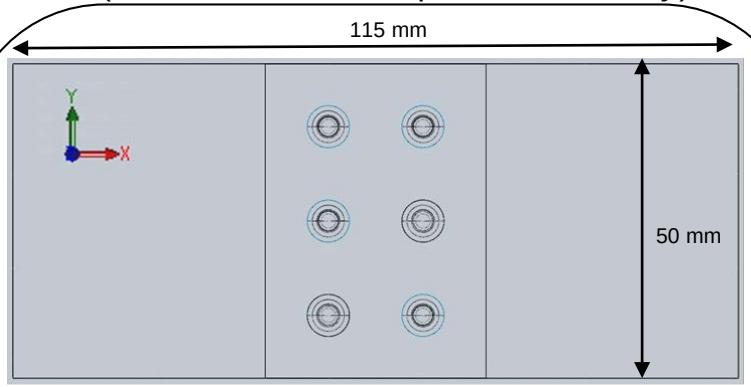
SLM Software Framework

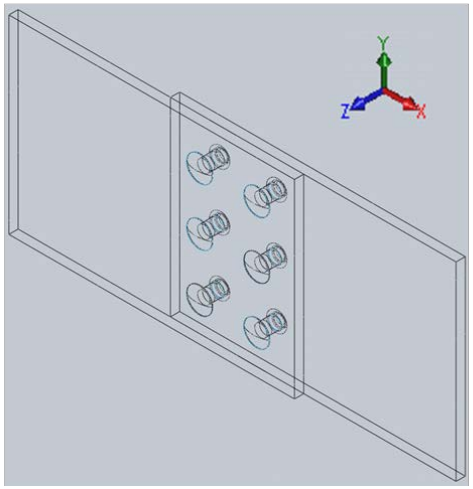
Corrosion Susceptible Part Library

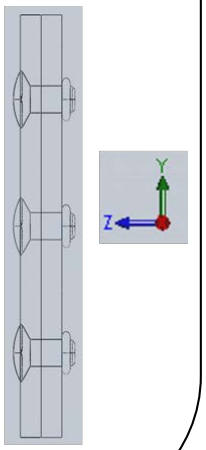
Component Geometry

(*from Corrosion Susceptible Part Library*)



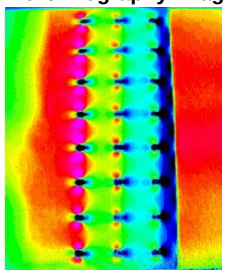
Plates: Al-2024-T3 (2.43 mm thick)
Rivets: cadmium plated steel



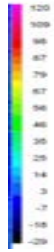


Justification for Selected Damage Scenario

IR thermography image

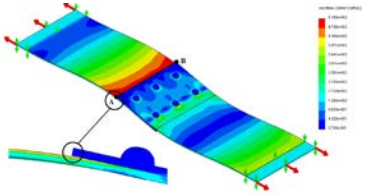


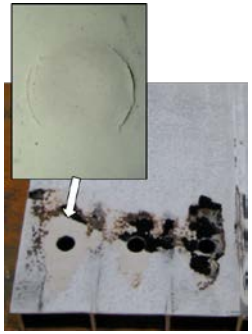
Stress (MPa)



high stresses associated with the rivets in the first row

Ref. 1: Engineering Fracture Mechanics 87 (2012) 1–15 "*A study of the effect of CPCs on fatigue crack propagation in a representative fuselage lap joint specimen*".





Ref. 2: 27th International Congress of the Aeronautical Sciences, 2010, *Critical Strain Performance of Coating Systems at Aircraft Joints*

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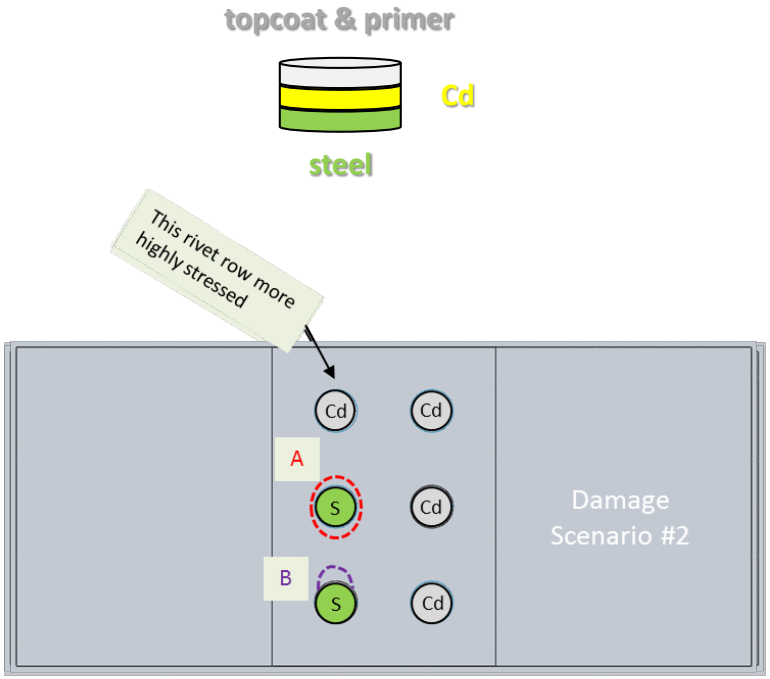
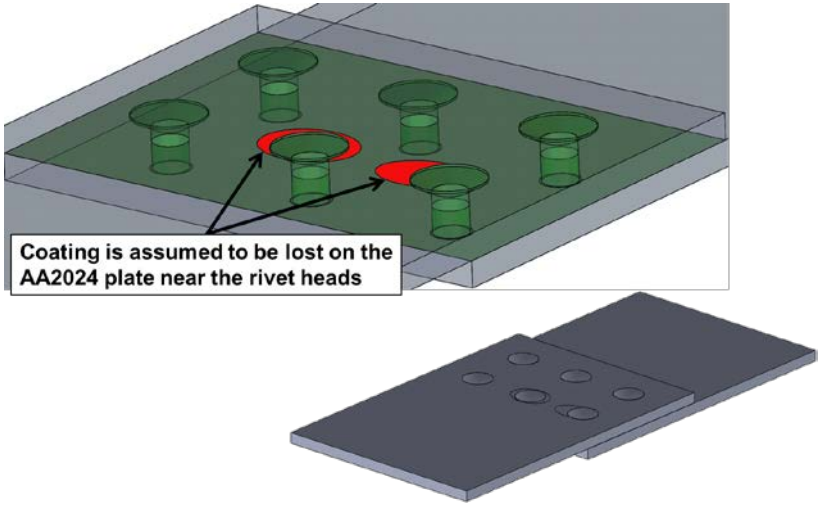
SLM Software Framework

Progressive Damage Scenarios

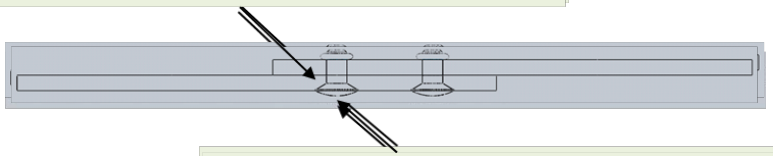
Local Coating Condition on Rivet (A,B only)



*All fasteners with good quality primer/topcoat



A - Simulate damage in panel coating by modeling bare AA2024 in an elliptically area around rivet. Cd plating on fastener fully exhausted exposing steel rivet head.



B - Simulate damage in panel coating by modeling bare AA2024 in an semi-elliptically area around rivet. Cd plating on fastener fully exhausted exposing steel rivet head.

Film thickness = 200 microns
Electrolyte conductivity = 5 S/m
Coating resistance (R_{coat} = 1 x10^8 ohm/cm^2, B_f = 0.0001)

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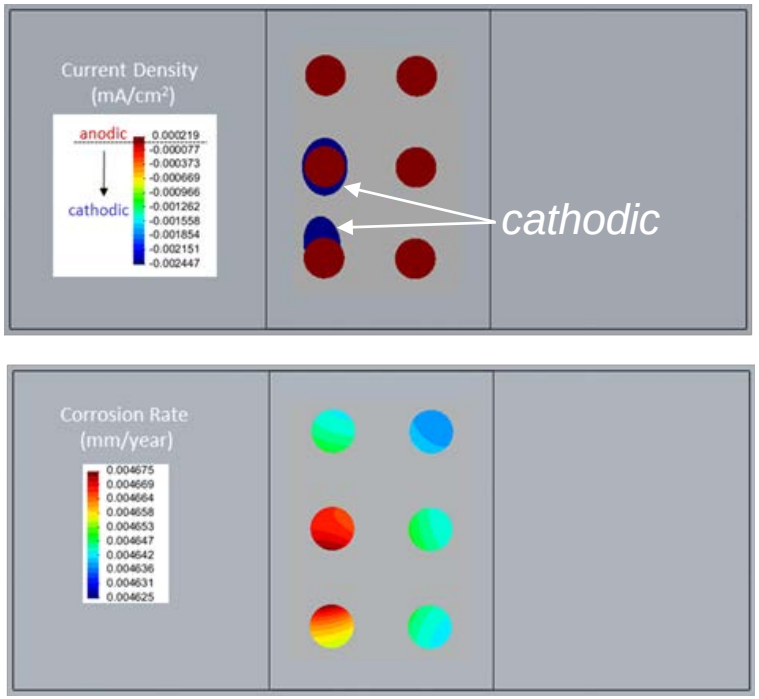
Damage Case Scenario 1a,1b

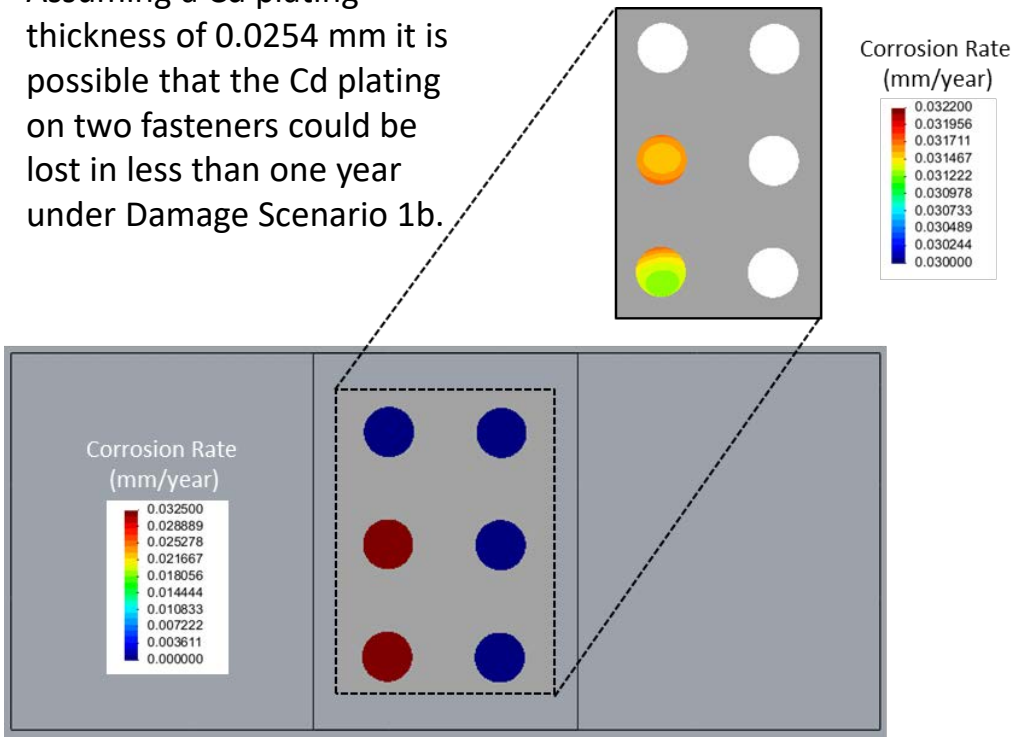


Damage Scenario 1a

MAX Corrosion Rate = 0.004675 mm/yr

Corrosion rate on fasteners increases with localized loss of topcoat & primer – discrete damage areas on AA2024 panel remain protected (*Cd more noble compared to AA2024*)

Assuming a Cd plating thickness of 0.0254 mm it is possible that the Cd plating on two fasteners could be lost in less than one year under Damage Scenario 1b.



Damage Scenario 1b

MAX Corrosion Rate = 0.0325 mm/yr

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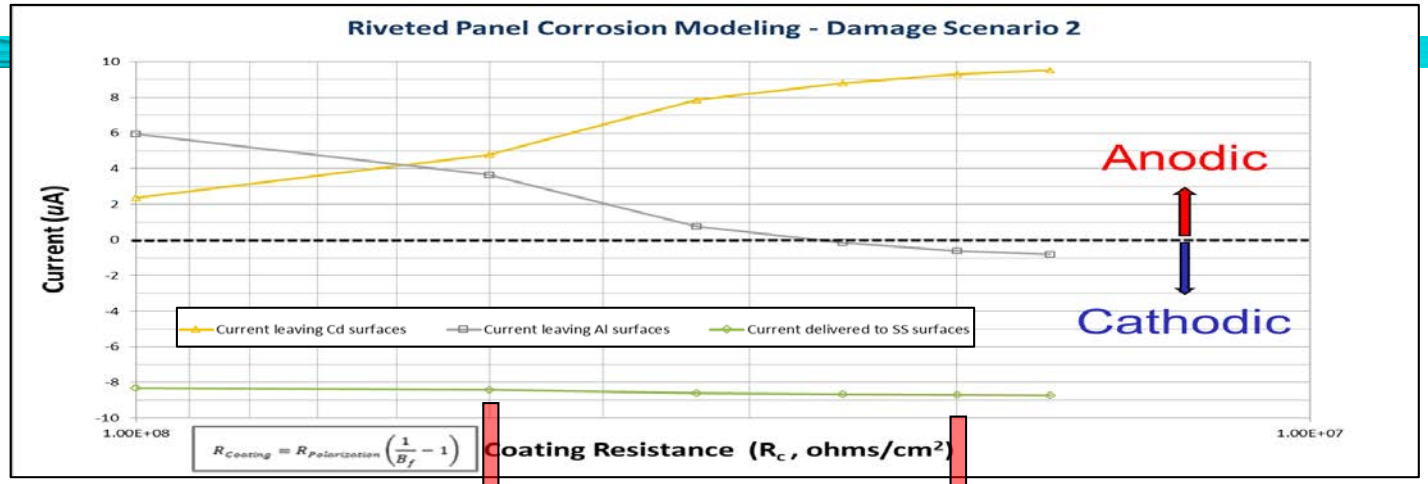
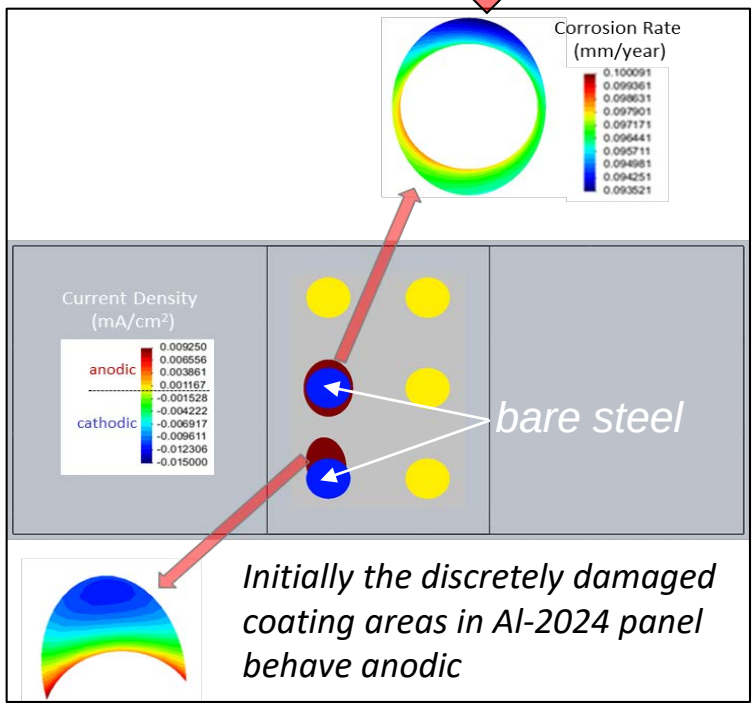
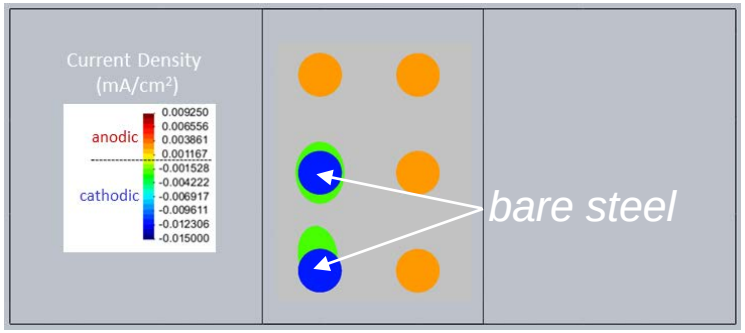
Damage Case Scenario 2





Initially the discretely damaged coating areas in Al-2024 panel behave anodic



As the coating continues to age the Cd from the other fasteners (orange shading) behaves increasingly anodic and starts to protect the discrete damage areas in the Al-2024 panel

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SLM Software Framework

Corrosion Pitting Simulator

The Need: Develop a method to quantify the *severity* of the pitting using a computational tool.

Our Current Approach: Adopt forecasting methodology based on statistical analysis of a series of experimental data sets (Ref. 3). Probabilistic galvanic models that are functions of Cl^- concentration, current density, and time.

$$\alpha(t,i) = \frac{[a_1 + KCl * Log(Cl) + K_i * Log(i)]}{\left[1 + \frac{a_2}{t}\right]}$$

Maximum Pit Depth (microns)

$$N(t,i) = \frac{N_{max}}{1 + e * \exp(-1 * (a + b * t + c * i^d))}$$

Pit Density (log10 of the number of pits/in^2)

Limitations: Assumes constant environmental condition (uniform current density over specimen), short term experimental tests for specific alloys, pit clustering characteristics not predictable.

Future Need: *Extension to dynamic environments (i.e. SLM operating scenarios) needs further investigation.*

Ref. 3: Mark Jaworowski. Electrochemical Measurement and Modeling of Localized Corrosion. Final report. Grant/Contract Number: N00014-15-C-009. United Technologies Research Center

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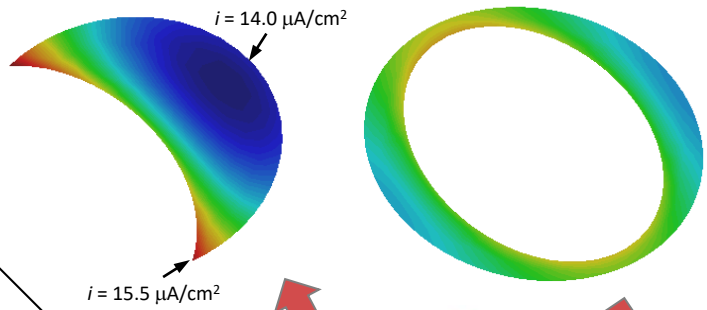
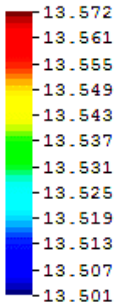
Predicted Pit Depth for Damage Scenario #2

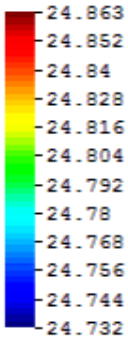
Predicted pit depth shown on the bare metal (area of discrete coating damage) next to the steel fastener

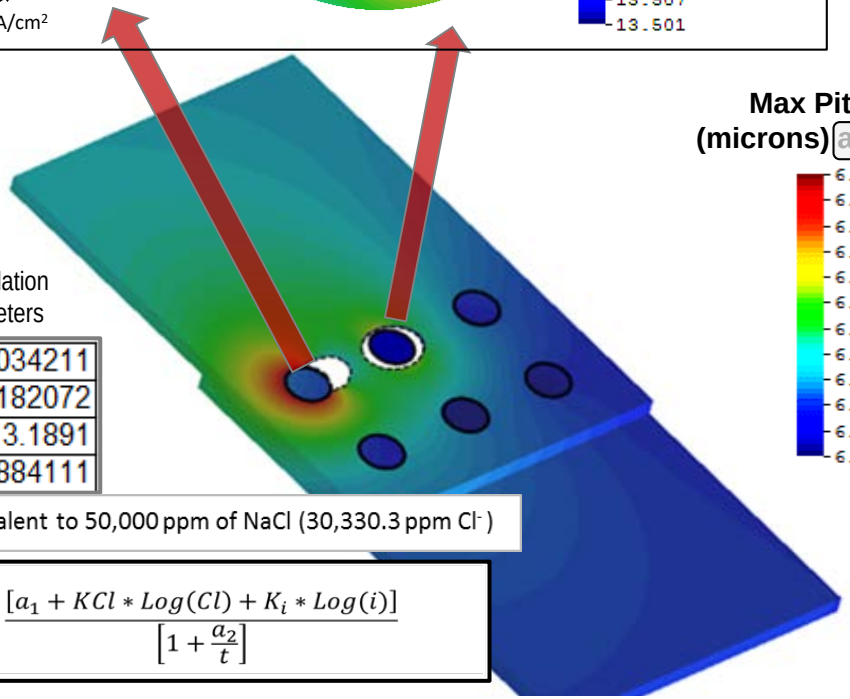


Max Pit Depth (microns) after 24 hrs

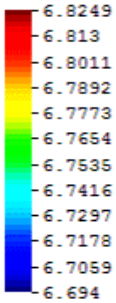


Max Pit Depth (microns) after 31 days

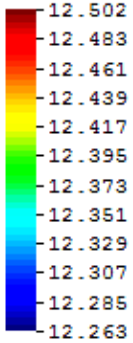




Max Pit Depth (microns) after 24 hrs



Max Pit Depth (microns) after 31 days



AA2024 Population Model Parameters

a1	3.034211
KCl	4.182072
Ki	3.1891
a2	0.884111

5% NaCl is equivalent to 50,000 ppm of NaCl (30,330.3 ppm Cl^-)

$$\alpha(t,i) = \frac{[a_1 + KCl * Log(Cl) + K_i * Log(i)]}{\left[1 + \frac{a_2}{t}\right]}$$

Ref. 3: Mark Jaworowski. Electrochemical Measurement and Modeling of Localized Corrosion. Final report. Grant/Contract Number: N00014-15-C-009. United Technologies Research Center

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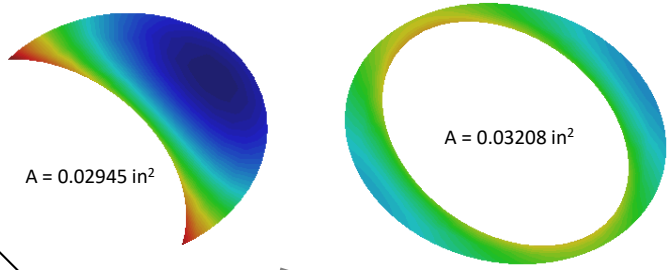
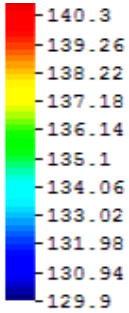
Predicted Pit Density for Damage Scenario #2

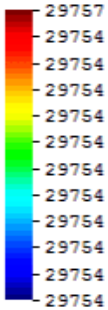
Predicted pit density shown on the bare metal (area of discrete coating damage) next to the steel fastener

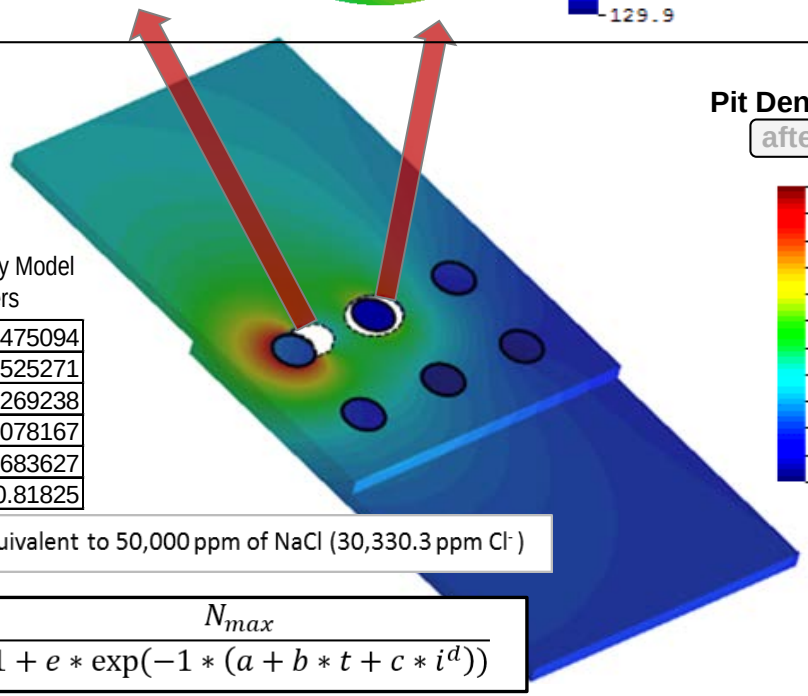


Pit Density (N / in²)
after 24 hrs

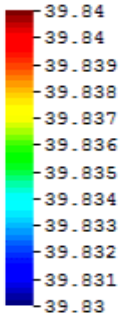


Pit Density (N / in²)
after 31 days

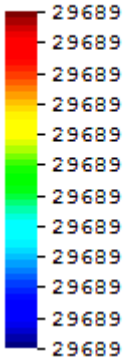




Pit Density (N / in²)
after 24 hrs



Pit Density (N / in²)
after 31 days



AA2024 Density Model Parameters

Nmax	4.475094
a	1.525271
b	0.269238
c	0.078167
d	0.683627
e	10.81825

5% NaCl is equivalent to 50,000 ppm of NaCl (30,330.3 ppm Cl^-)

$$N(t,i) = \frac{N_{max}}{1 + e * \exp(-1 * (a + b * t + c * i^d))}$$

Ref. 3: Mark Jaworowski. Electrochemical Measurement and Modeling of Localized Corrosion. Final report. Grant/Contract Number: N00014-15-C-009. United Technologies Research Center

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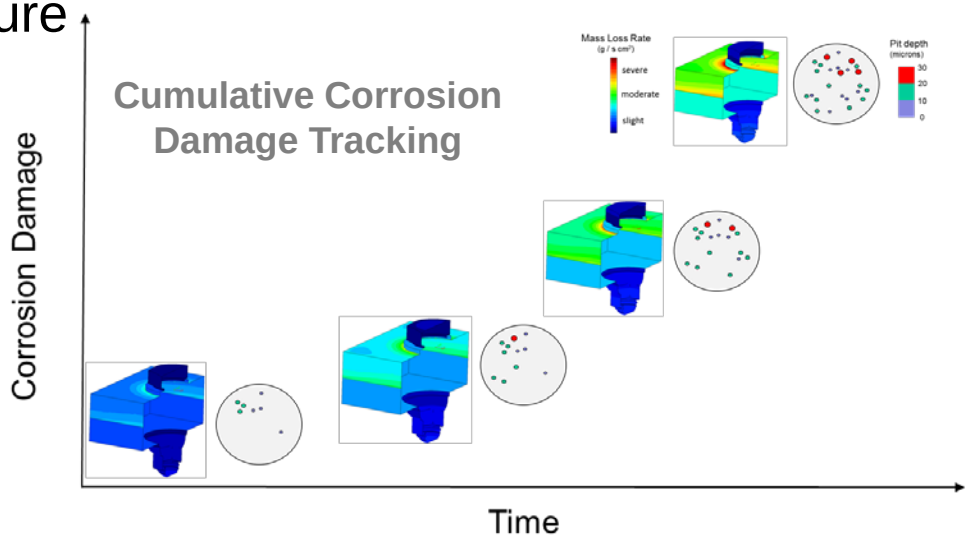
Service Life Model

Prediction Of Accumulated Corrosion Damage

- Knowing the environmental exposure of an aircraft over the course of its lifetime is critical to making meaningful predictions of accumulated corrosion damage
- Data may be available from either historical records or dynamic environmental monitoring using sensor technology



- Computational models require information on electrolyte conductivity, film thickness, and polarization properties to make predictions of galvanic stress and metal loss.
- Estimates of TOW are required to extend this technology to making predictions of accumulated corrosion damage
- If data can be successfully manipulated to characterize typical aircraft exposure environments it may be possible to create a library of standard operational environment's.

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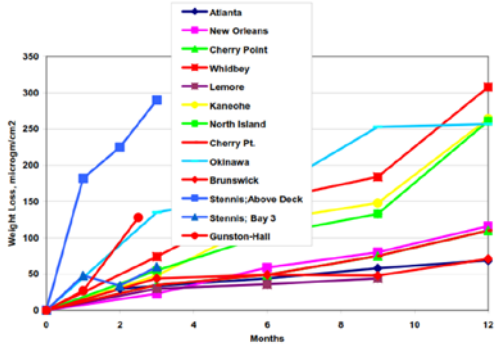
Historical Records – Data Sources

Source 1: Abbot 2008 Report



Ref. 4: W. H. Abbott, "A Decade of Corrosion Monitoring in the World's Military Operating Environments: A Summary of Results," Battelle Memorial Institute, Columbus, OH, 2008

Abbot - Comprehensive monitoring program where mass loss measurements are made on standard coupons in different field environments

1. TOW not measured
2. Provides an *AVG current density* using mass loss measurement with Faraday's Law

Key challenges - *configuring this type of data for input in a computational corrosion model. TOW estimates would be very approximate. Remote measurement sites (i.e. not on aircraft)*

Source 2: NADP/NOAA

National Atmospheric Deposition Program

Monthly Data Summary For Each Site

El Verde, Puerto Rico
Mar 2017

site ID	month	yr	Mg (mg/L)	Na (mg/L)	Cl (mg/L)	SO_4 (mg/L)	pH	conduc (mS/cm)	ppt (cm)
PR20	1	2017	0.335	2.662	5.398	0.932	5.268	22.772	12.802
PR20	2	2017	0.19	1.588	2.906	0.719	5.116	15.646	10.008
PR20	3	2017	0.509	4.09	7.68	1.319	5.181	33.634	42.266
PR20	4	2017	0.134	1.078	2.003	0.533	5.133	11.873	75.057
PR20	5	2017	0.093	0.692	1.369	0.501	5.231	8.419	10.465
PR20	6	2017	0.135	1.035	1.945	0.537	5.386	10.78	36.906
PR20	7	2017	0.128	0.988	1.818	0.486	5.379	10.179	41.707
PR20	8	2017	0.088	0.666	1.249	0.358	5.375	7.622	46.753
PR20	9	2017	0.079	0.522	0.967	0.622	5.2	8.3	3.128
PR20	10	2017	-9	-9	-9	-9	-9	-9	1.879

NAS Patuxent River
Apr 2017 May 2017 June 2017

siteID	month	yr	Mg (mg/L)	Na (mg/L)	Cl (mg/L)	SO_4 (mg/L)	pH	conduc (mS/cm)	ppt (cm)
MD15	1	2017	0.158	1.325	2.405	0.699	5.096	15.522	5.613
MD15	2	2017	0.097	0.736	1.34	0.671	4.906	14.366	1.945
MD15	3	2017	0.148	1.146	2.134	0.503	5.583	12.148	8.331
MD15	4	2017	0.314	0.804	1.464	0.58	5.24	20.3	8.306
MD15	5	2017	0.086	0.681	1.271	0.453	5.294	9.086	13.03
MD15	6	2017	0.053	0.404	0.741	0.361	5.138	7.692	3.302
MD15	7	2017	0.071	0.539	1.013	0.527	4.97	10.571	19.507
MD15	8	2017	0.085	0.659	1.225	0.402	5.026	10.557	7.364
MD15	9	2017	0.094	0.777	1.413	0.357	5.286	9.21	10.909
MD15	10	2017	0.08	0.671	1.289	0.283	5.224	7.872	15.418

NAS Jacksonville
July 2017

siteID	month	yr	Mg (mg/L)	Na (mg/L)	Cl (mg/L)	SO_4 (mg/L)	pH	conduc (mS/cm)	ppt (cm)
FL03	1	2017	0.422	3.302	5.64	4.768	4.32	53.8	4.597
FL03	2	2017	0.061	0.46	0.846	0.553	4.912	9.25	3.937
FL03	3	2017	0.111	0.613	1.234	1.269	5.02	13.8	1.93
FL03	4	2017	0.029	0.196	0.362	0.78	5.08	7.7	8.382
FL03	7	2017	0.012	0.139	0.237	0.959	4.958	6.672	42.418
FL03	8	2017	0.028	0.171	0.295	0.311	4.907	7.539	10.033
FL03	9	2017	0.042	0.309	0.578	0.419	5.065	6.831	5.817
FL03	10	2017	-9	-9	-9	-9	-9	-9	2.54

NAS Fallon
August 2017

siteID	month	yr	Mg (mg/L)	Na (mg/L)	Cl (mg/L)	SO4 (mg/L)	pH	conduc mS/cm)	ppt (cm)
NV03	1	2017	-9	-9	-9	-9	-9	-9	0
NV03	2	2017	0.003	0.008	0.017	0.049	5.485	2.017	3.556
NV03	3	2017	0.005	0.007	0.018	0.099	5.61	3	0.726
NV03	4	2017	0.007	0.015	0.033	0.153	5.736	2.605	2.845
NV03	5	2017	0.047	0.226	0.237	0.441	6.51	8.2	2.388
NV03	6	2017	-9	-9	-9	-9	-9	-9	0
NV03	7	2017	0.042	0.097	0.126	0.498	6.296	9.187	2.54
NV03	8	2017	0.036	0.073	0.203	0.676	6.086	12.638	0.660
NV03	9	2017	0.044	0.153	0.248	0.34	-9	-9	0.381
NV03	10	2017	0.014	0.027	0.048	0.095	6.16	5	0.102

NOAA NATIONAL CENTERS FOR ENVIRONMENTAL INFORMATION

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
National Environmental Satellite, Data, and Information Service

Local Climatological Data
Hourly Observations
July 2017
Generated on 04/10/2018

National Centers for Environmental Information
151 Patton Avenue
Asheville, North Carolina 28801

Current Location: Elev: 31 ft. Lat: 29.1828° N Lon: -81.0483° W
Station: DAYTONA BEACH INTERNATIONAL AIRPORT, FL US 12834

Date	Time (LST)	Sky Cond. Type	Sky Conditions	Visibility	Weather Type (see documentation) AU | AW | MW	Dry Bulb Temp (F)	Dry Bulb Temp (C)	Wet Bulb Temp (F)	Wet Bulb Temp (C)	Dew Point Temp (F)	Dew Point Temp (C)	Rel Hum %	Wind Speed (MPH)	Wind Dir (Deg)	Wind Gusts (MPH)	Station Press (inHg)	Press. Tend	Net 3-Hr Change (inHg)	Sea Level Press. (inHg)	Report Type	Precip Total (in)	Altimeter Setting (inHg)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
04	0053	7	FEW:02 200	10.00		76	24.4	75	23.7	74	23.3	94	0	000		30.06	8	+0.02	30.10	FM-15	0.00	30.10
04	0153	7	FEW:02 200	10.00		75	23.9	74	23.5	74	23.3	96	3	170		30.05			30.08	FM-15	0.00	30.09
04	0253	7	CLR:00	10.00		75	23.9	74	23.1	73	22.8	94	0	000		30.04			30.07	FM-15	0.00	30.08
04	0353	7	CLR:00	10.00		76	24.4	74	23.3	73	22.8	91	6	170		30.04	5	+0.02	30.07	FM-15	0.00	30.08
04	0453	7	FEW:02 200	10.00		75	23.9	74	23.1	73	22.8	94	0	000		30.05			30.08	FM-15	0.00	30.09
04	0553	7	FEW:02 200	10.00		75	23.9	74	23.1	73	22.8	94	3	180		30.06			30.09	FM-15	0.00	30.10
04	0653	7	FEW:02 200	10.00		78	25.6	76	24.4	75	23.9	90	0	000		30.06	1	-0.03	30.10	FM-15	0.00	30.10
04	0753	7	FEW:02 200	10.00		82	27.8	79	25.4	76	24.4	82	6	240		30.09			30.12	FM-15	0.00	30.13
04	0853	7	FEW:02 200	10.00		85	29.4	79	25.6	75	23.9	72	8	260		30.09			30.12	FM-15	0.00	30.13
04	0953	7	FEW:02 30 FEW:02 200	10.00		87	30.6	78	25.5	74	23.3	65	3	250		30.09	1	-0.03	30.13	FM-15	0.00	30.13
04	1053	7	FEW:02 35 FEW:02 200	10.00		90	32.2	79	25.9	74	23.3	59	5	320		30.09			30.13	FM-15	0.00	30.13
04	1153	7	SCT:04 40 SCT:04 200	10.00		91	32.8	79	26.0	74	23.3	57	3	VRB		30.08			30.11	FM-15	0.00	30.12
04	1253	7	SCT:04 35 SCT:04 200			91	32.8	81	27.1	77	25.0	64	10	060		30.07	8	+0.02	30.11	FM-15	0.00	30.11
04	1353	7	SCT:04 30	10.00		90	32.2	81	27.0	77	25.0	66	10	060		30.07			30.10	FM-15	0.00	30.11
04	1453	7	FEW:02 35 FEW:02 250	10.00		89	31.7	81	27.2	78	25.6	70	11	090		30.06			30.09	FM-15	0.00	30.10
04	1553	7	FEW:02 35 FEW:02 250	10.00		89	31.7	80	26.8	77	25.0	68	8	080		30.05	8	+0.02	30.09	FM-15	0.00	30.09
04	1653	7	FEW:02 35 FEW:02 250	10.00		89	31.7	79	26.1	75	23.9	63	6	090		30.04			30.08	FM-15	0.00	30.08
04	1753	7	FEW:02 35 FEW:02 130 BKN:07 250	10.00		89	31.7	78	25.8	74	23.3	61	7	140		30.05			30.09	FM-15	0.00	30.09
04	1853	7	CLR:00	10.00		86	30.0	78	25.7	75	23.9	70	5	160		30.04	8	+0.01	30.07	FM-15	0.00	30.08
04	1953	7	FEW:02 35 SCT:04 250	10.00		84	28.9	77	25.0	74	23.3	72	0	000		30.04			30.08	FM-15	0.00	30.08
04	2051	7	FEW:02 1 FEW:02 35 SCT:04 250	10.00		81	27.0	77	24.9	75	24.0	84	0	000		30.06				FM-16		30.10
04	2053	7	FEW:02 1 FEW:02 35 SCT:04 250	10.00		81	27.2	77	25.3	76	24.4	85	0	000		30.07			30.10	FM-15	0.00	30.11
04	2153	7	SCT:04 250	10.00		78	25.6	76	24.4	75	23.9	90	5	240		30.09	3	-0.05	30.13	FM-15	0.00	30.13
04	2253	7	SCT:04 250	10.00		76	24.7	75	24.2	74	23.3	85	3	180		30.09			30.12	FM-15	0.00	30.13
04	2353	7	SCT:04 250	10.00		76	24.4	75	23.7	73	22.8	85	0	000		30.10			30.13	FM-15	0.00	30.14

NADP - Spatial and temporal trends in atmospheric deposition (precipitation chemistry)

NOAA – Precipitation amount, temperature, relative humidity

Ref. 5: NADP (http://nadp.slh.wisc.edu)
NOAA (https://www.ncdc.noaa.gov)

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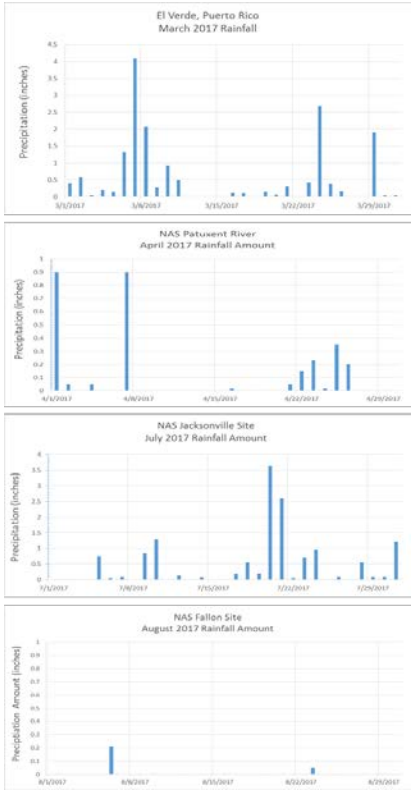
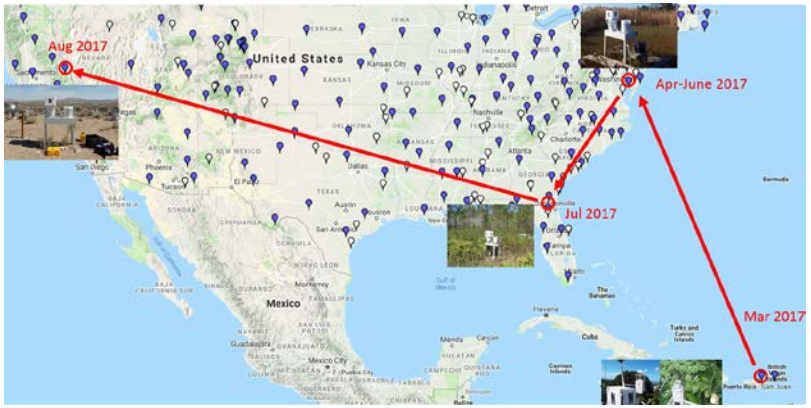
Historical Records - *Implementation ?*

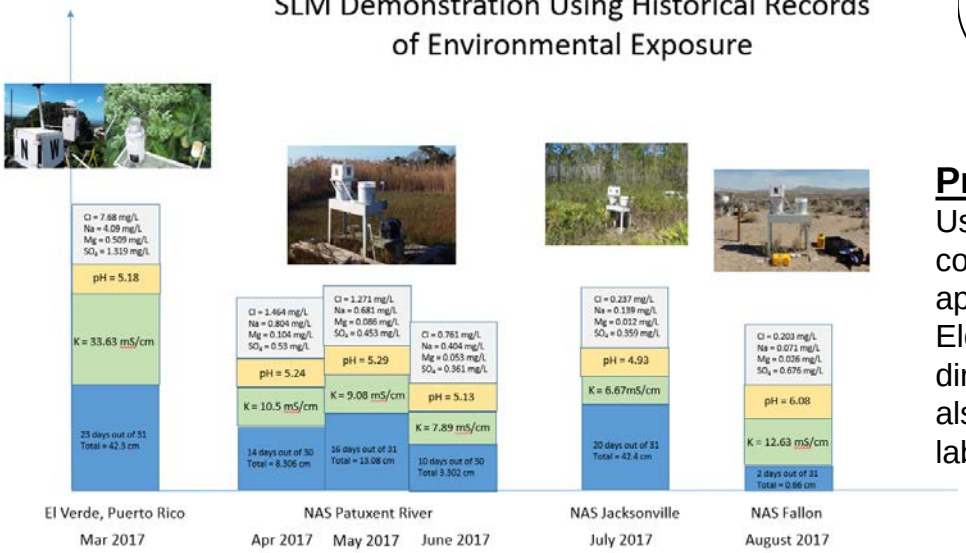
TOW from precipitation records - if it rains, assume WET for 24 hr period. Assume bulk electrolyte conditions (1000 micron film thickness).



Account for changing environments if monitoring station data is available nearby



SLM Demonstration Using Historical Records of Environmental Exposure



General comment on use of historical records

Backward looking approach with limited value in informing computational models, but could be used to make relative comparisons

<u>Precipitation chemistry</u>

Useful in estimating electrolyte concentrations in order to select appropriate polarization curves. Electrolyte conductivity and pH directly measured. Data could also be used to guide laboratory testing.

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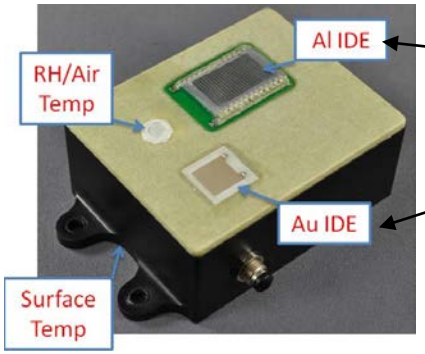
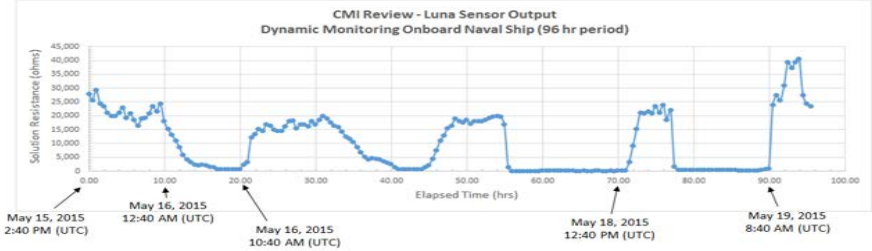
Sensor Measurements - Overview

- Sensor measurements can be used to provide the data for computational models.
- More attractive option, compared to using historical records, because the sensor is located directly on the structure and provides an accurate, time-based, measure of the environmental exposure (e.g. T, RH, Rs, Rp).



polarization resistance (R_p)

solution resistance (R_s)



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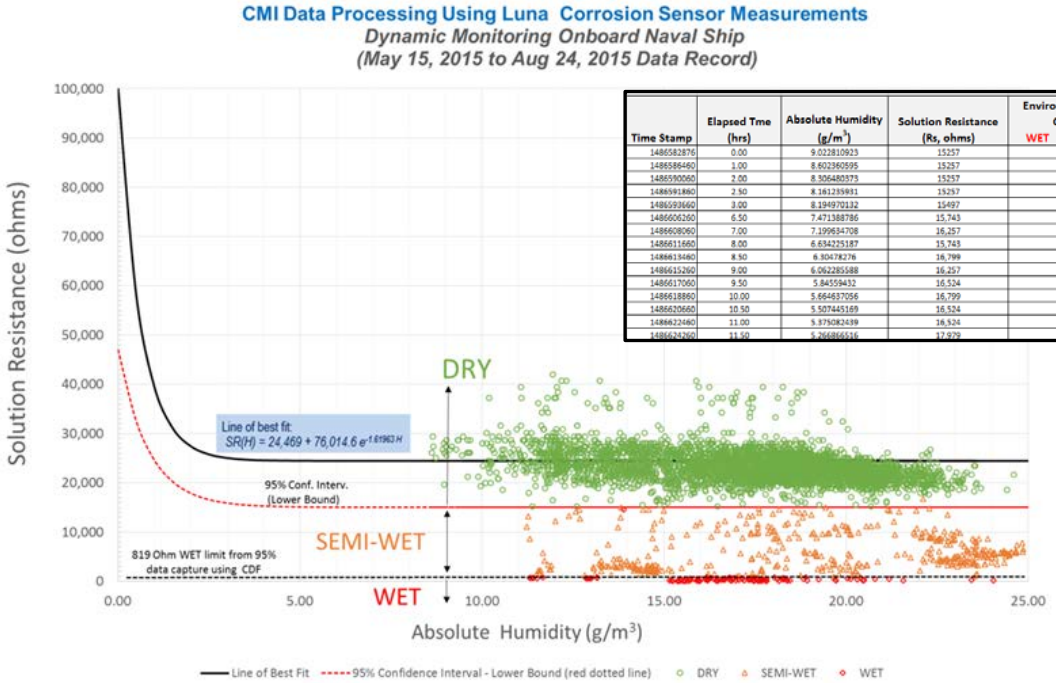
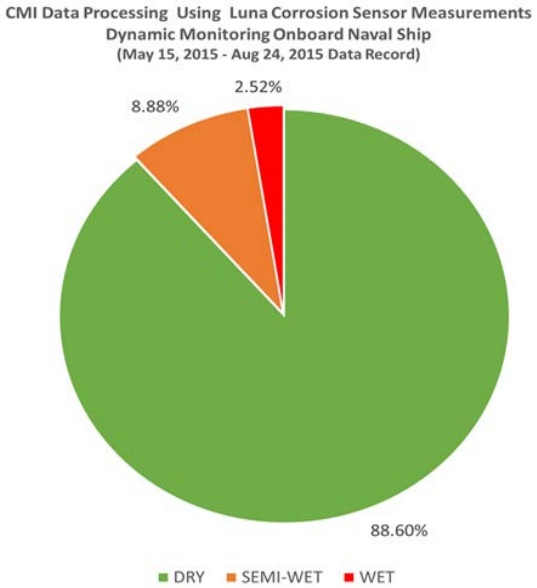
Sensor Measurements – Wet, Semi Wet, Dry Classification Scheme



Time Stamp	Elapsed Tme (hrs)	Absolute Humidity (g/m³)	Solution Resistance (Rs, ohms)	Environmental Exposure Classification WET SEMI-WET DRY
1486582876	0.00	9.022810923	15257	DRY
1486586460	1.00	8.602360595	15257	DRY
1486590060	2.00	8.306480573	15257	DRY
1486591860	2.50	8.161235931	15257	WET
1486593660	3.00	8.194970132	15497	WET
1486606260	6.50	7.471388786	15,743	WET
1486608060	7.00	7.199634708	16,257	DRY
1486611660	8.00	6.634225187	15,743	DRY
1486613460	8.50	6.30478276	16,799	DRY
1486615260	9.00	6.062285588	16,257	DRY
1486617060	9.50	5.84559432	16,524	SEMI-WET
1486618860	10.00	5.664637056	16,799	SEMI-WET
1486620660	10.50	5.507445169	16,524	DRY
1486622460	11.00	5.375082439	16,524	DRY
1486624260	11.50	5.266866516	17,979	DRY



- Corrosion sensor is calibrated using a controlled set of exposures (T, RH) in a Thermotron. A “Line of best fit” is created and the lower bound of the 95% C.I. is used to separate the DRY and SEMI-WET data points
- The SEMI-WET data is further divided into a SEMI-WET and WET classification using 95% of the data under the PDF curve (non-dry data)

Reference: Cosima Boswell-Koller, Victor Rodriguez-Santiago, Corrosion Risk Assessment Through Dynamic Environmental Monitoring Onboard a Naval Ship, DoD Allied Nations Corrosion Conference, Aug 2017

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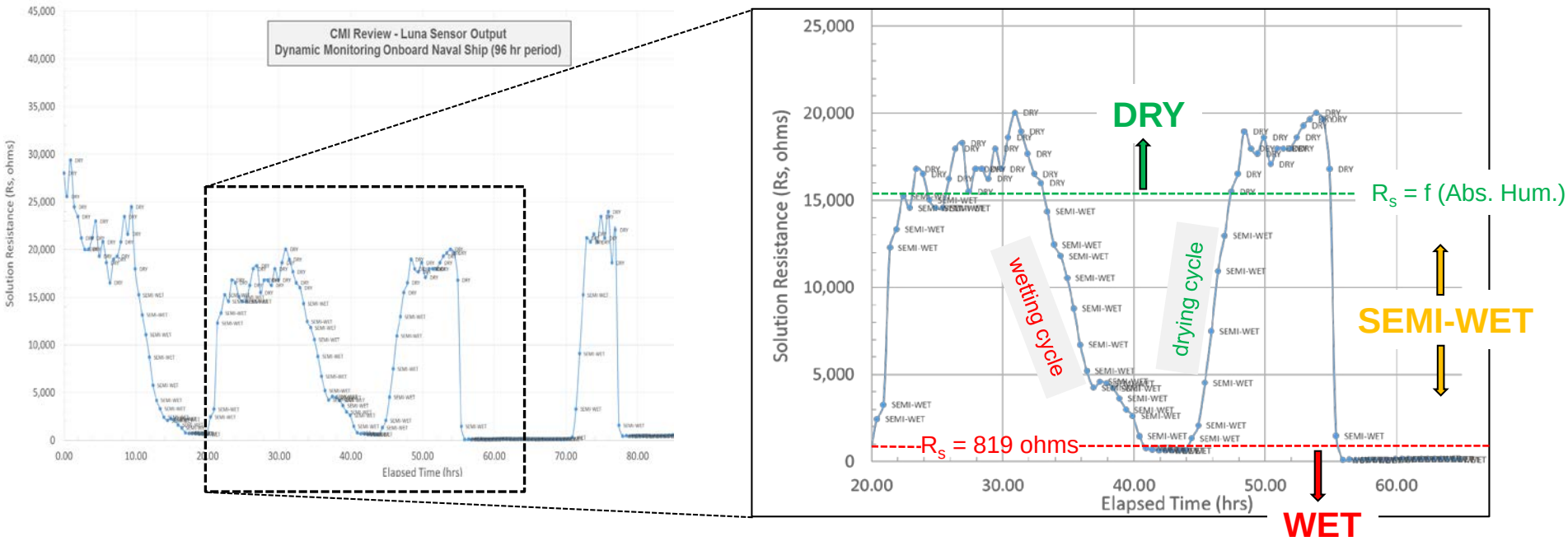
Sensor Measurements – Wet, Semi Wet, Dry Classification Scheme

What does the WET, SEMI-WET, DRY classification really mean ?



For cases where uniform corrosion loss is assumed

$$m_{loss}^{pred} = (TOS^{Nav} \cdot CR_{sw} + TOW^{Nav} \cdot CR_{w}) \cdot A_{wc}$$

sensor lab sensor lab

where:

TOW = time of wet
TOS = time of semi-wet
CR_w = corrosion rate for wet condition
CR_{sw} = corrosion rate for semi-wet condition

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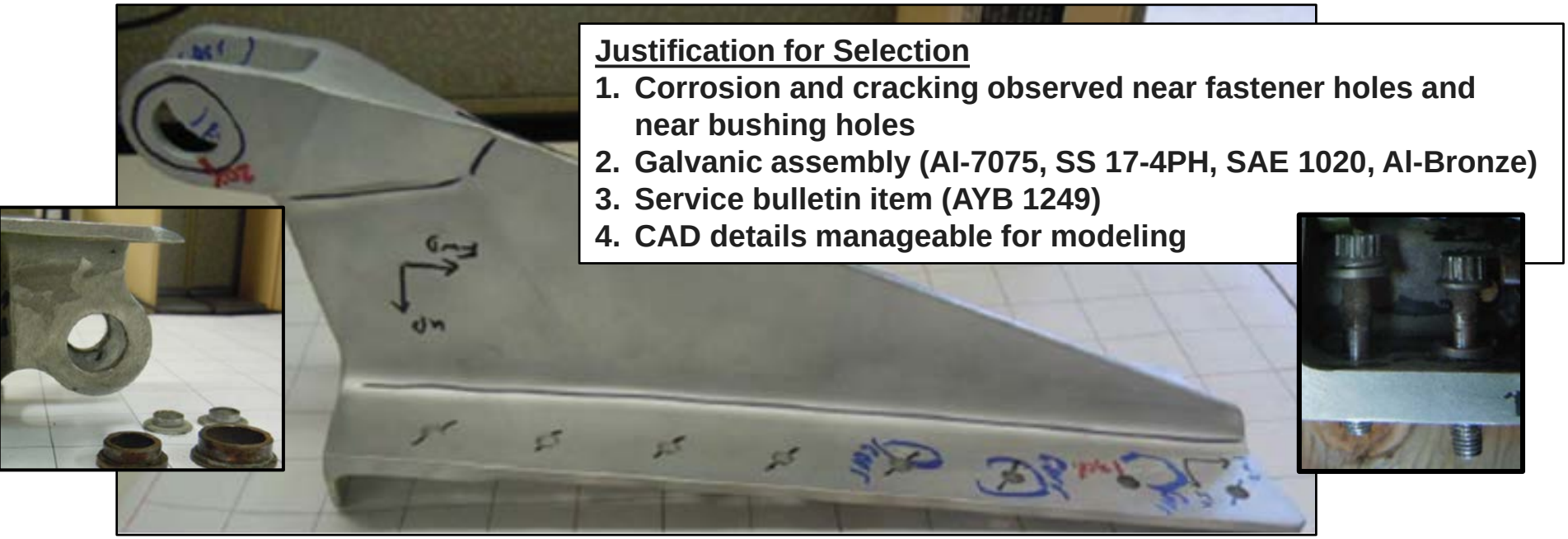
Demonstration Model Selection



Outboard Aileron Hinge Showing Locations of Corrosion Damage and Cracking

- Representative aircraft component selected following review of the F/A-18 Outer Wing Inspection Teardown report (*7319 flight hours*)
- The SLM methodology is demonstrated using a multi-material component, subject to measured environmental conditions aboard a Naval ship, to predict accumulated corrosion damage.

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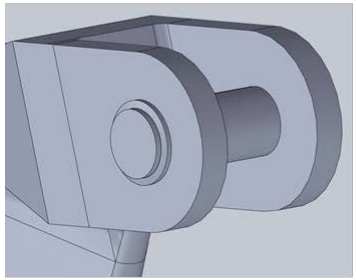
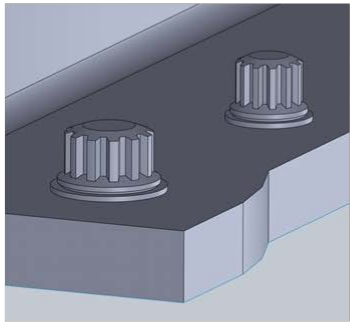
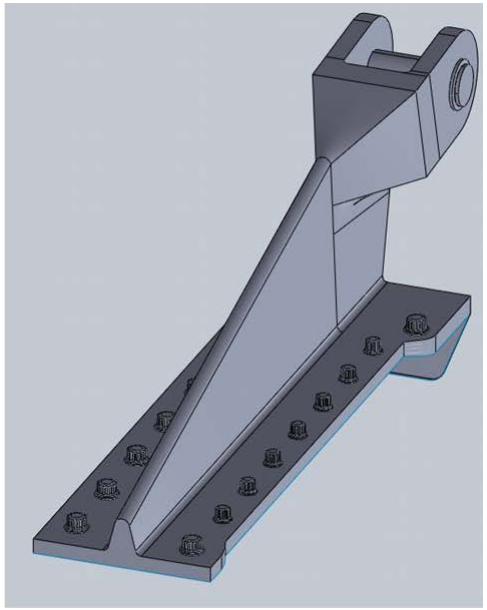
Demonstration Model Selection –

Components/Materials

- Aileron Hinge - Aluminium Al-7075
- Large Fasteners x10 (dia. = 0.4 in) - Stainless Steel 17-4PH
- Small Fasteners x7 (dia. = 0.3 in) - Stainless Steel 17-4PH
- Washers - Stainless Steel 17-4PH
- Pin (dia. = 0.675 in) - Carbon Steel S1020
- Bushings (x2) - Al-Bronze AMS 4640







- The aileron hinge mounts to the rear and aft spars and a connecting rib in the outer wing section.
- CAD geometry of the aileron hinge created using data available in the F/A-18 Outer Wing Inspection Teardown report.
- Fastener and pin-bushing material properties received from NAVAIR. Aileron hinge material identified in the teardown report.

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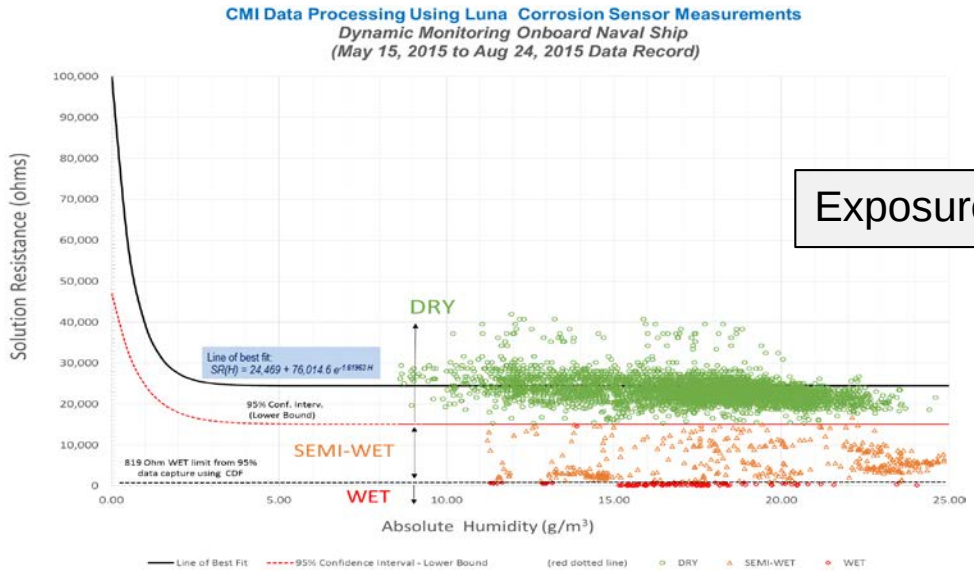
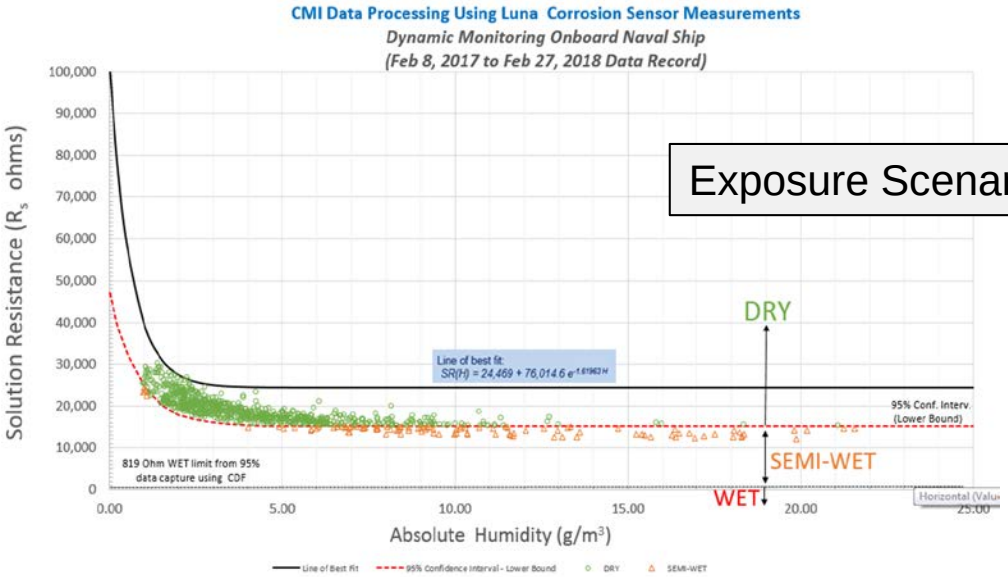
Demonstration Model Selection – Operational Environment Scenarios



Exposure Scenario 1

Total Time = 2421.29 hrs



Exposure Scenario 2

Total Time = 455.68 hrs

SLM Software Framework

Environmental Exposure Scenario Builder

```
SCENARIO: wet storage on carrier

• ENVIRONMENT: Wet
  • Conductivity 13.4     # Typical conductivity [S/m]
  • Thickness    0.05     # Typical electrolyte film thickness [m]
  • Percentage   30%      # Percent of time defined environment active
  • Model "C:|data|Wing|caseA|BN01A.dat"   # Path to the corresponding modeling files

• ENVIRONMENT: Semi Wet
  • Conductivity 66.1     # Typical conductivity [S/m]
  • Thickness    0.001    # Typical electrolyte film thickness [m]
  • Percentage   50%      # Percent of time defined environment active
  • Model "C:|data|Wing|caseB|BN01B.dat"   # Path to the corresponding modeling files
```

Load list of predefined operational scenarios by pushing this button

Assign a duration to each operational scenario

LOAD Operational Scenario

- wet storage on carrier
- sea based flight
- dry storage on carrier

Exposure History

	Operational Scenario	Duration	
1	wet storage on carrier	6	day
2	sea based flight	3	hour
3	dry storage on carrier	18	day

year
day
day
min
s

Number of cycles: 50 Total Time: 200 day

drag & drop operational scenarios to create the exposure history

Define the number of times the exposure history is to be repeated

Total Exposure Time = sum of operational scenario durations * number of cycles through defined exposure history

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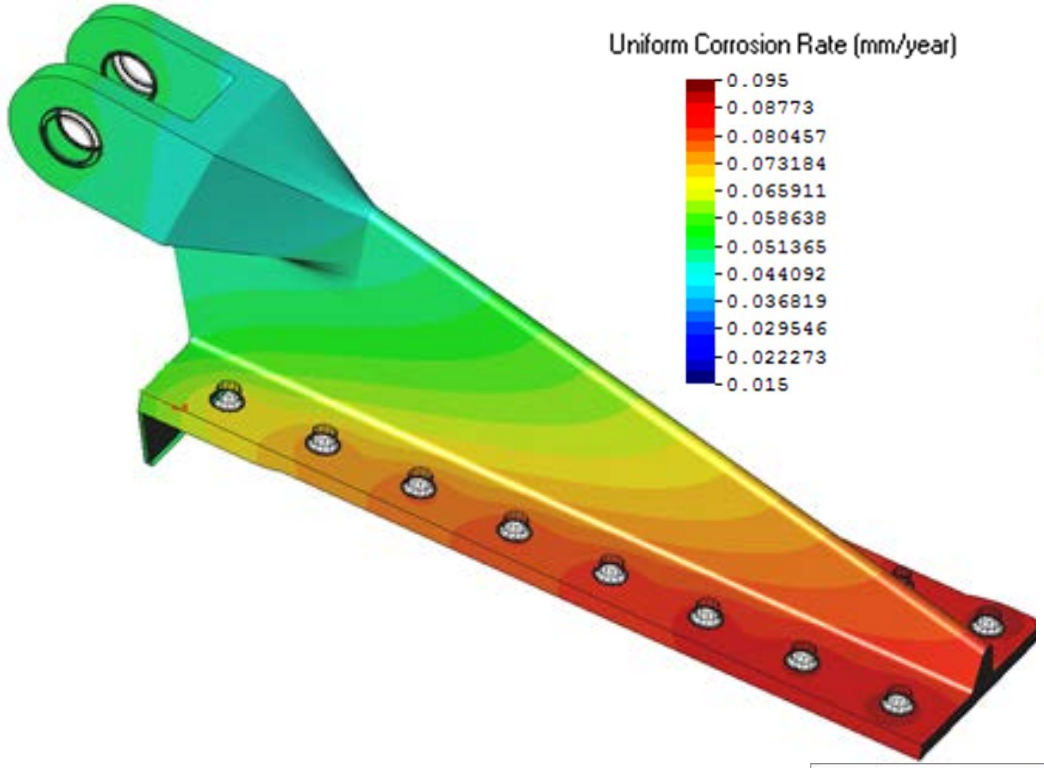
Service Life Model

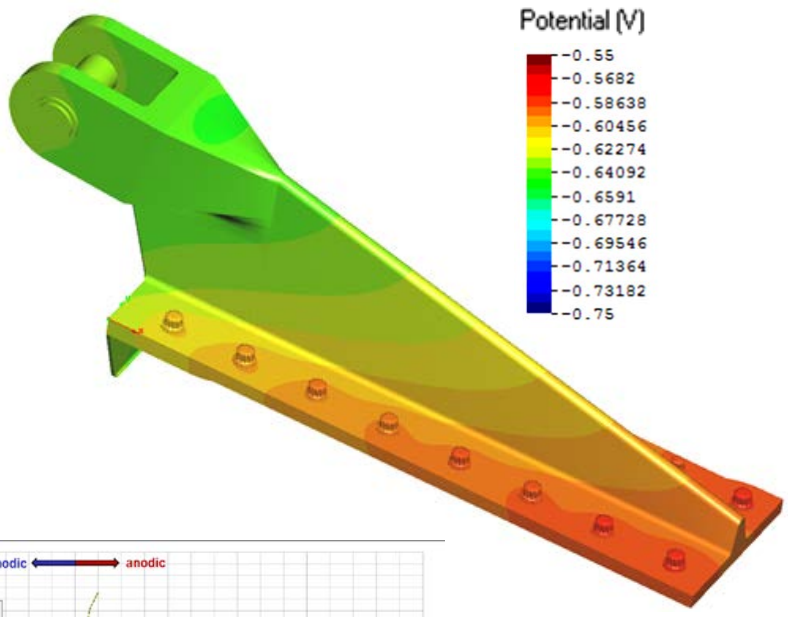
WET Classification (3.5% NaCl) Prediction



Electrolyte Properties

K = 13.41 S/m

t = 500 microns



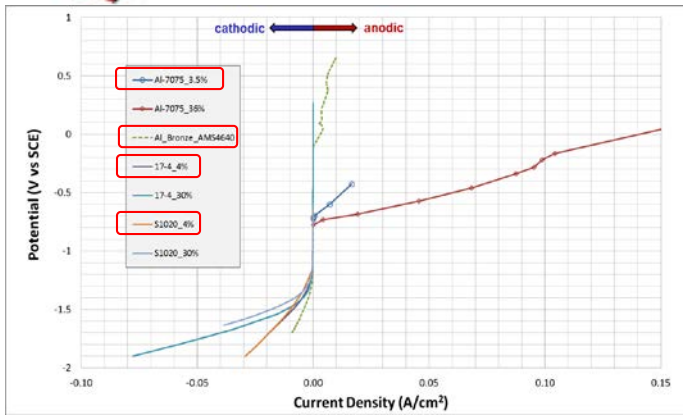
Metal Surface Condition

Aileron hinge - coated (coating resistance = 2×10^4 ohm/cm^2 , $B_f = 0.001$)

All fasteners - bare metal

Bushings - bare metal

Pin - bare metal



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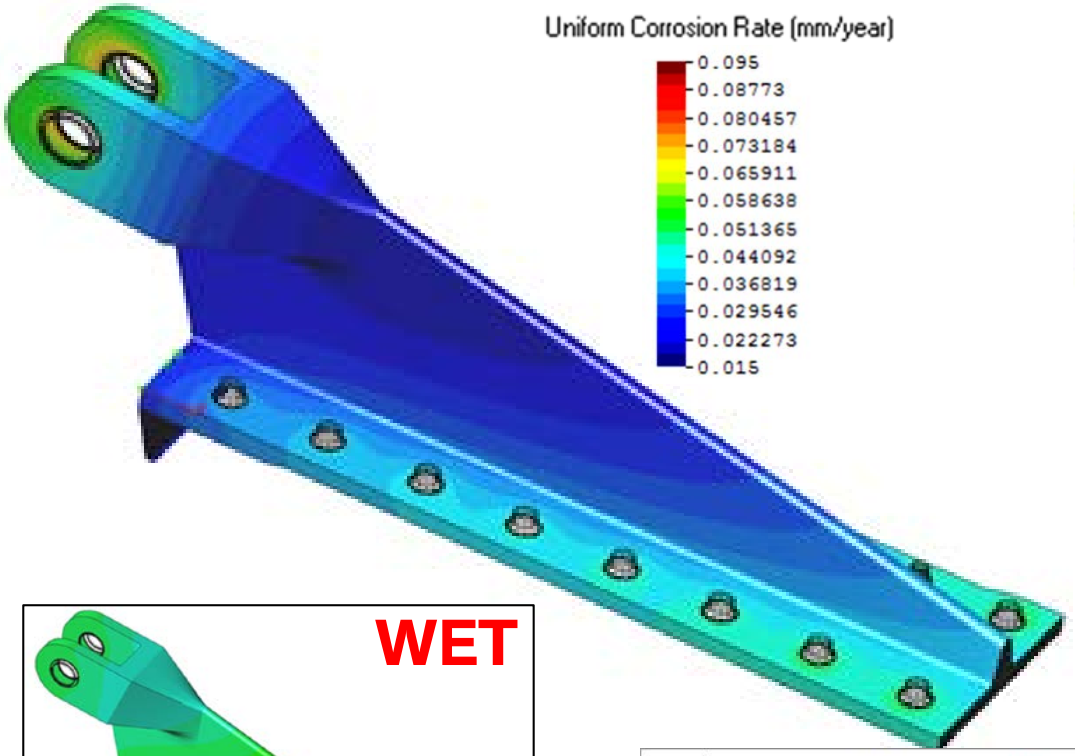
Service Life Model

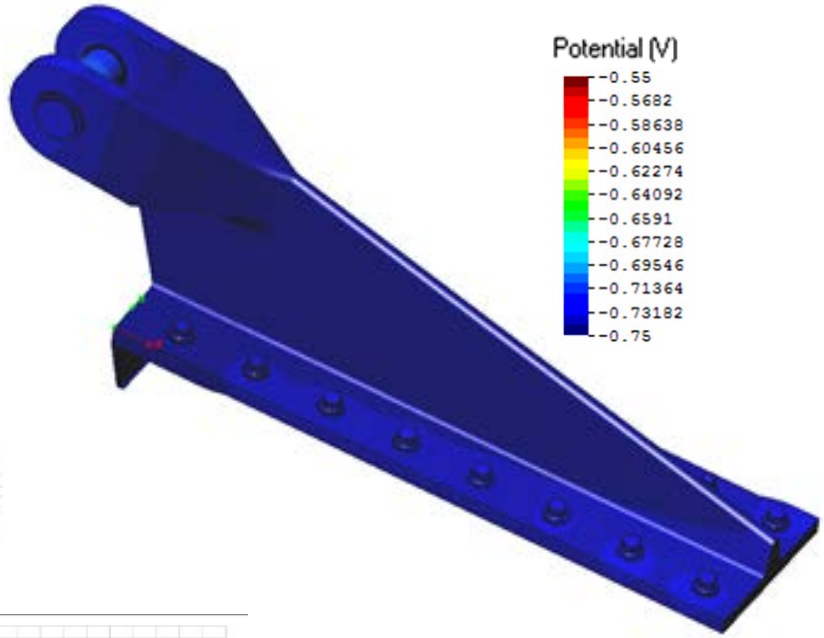
SEMI-WET Classification (36% NaCl) Prediction

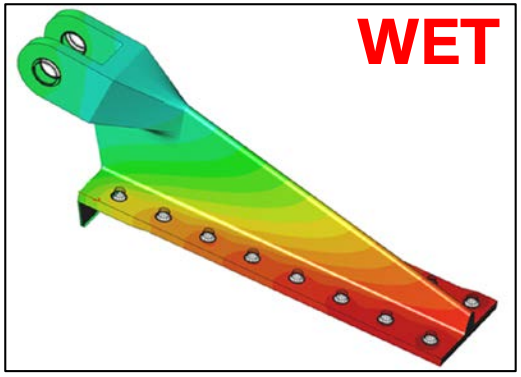


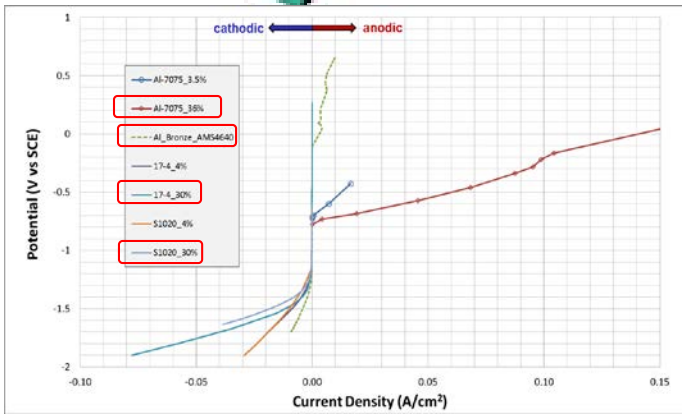
Electrolyte Properties

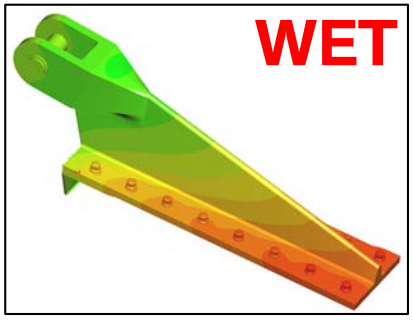
K = 66.14 S/m

t = 50 microns









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SLM Software Framework

Corrosion Damage Accumulator

CM_CaseManager - F:/users/jmwb/Castle_Aileron_example/B/OperationHistoryType1.cm_scn

File Help

Model Scenarios

- Exposure Scenario 1: Onboard Naval Ship (May 15,2015 to Aug 24,2015 Data Record)
  - SEMI-WET — Duration: 8.8%
  - WET — Duration: 2.52%
- Exposure Scenario 2: Onboard Naval Ship (Feb 8,2017 to Feb 27,2018 Data Record)
  - SEMI-WET — Duration: 11.06%

Operational History

	Operational Scenario	Duration	
1	Exposure Scenario 1: Onboard Naval Ship (May 15,2015 to Aug 24,2015 Data Record)	1.5	year
2	Exposure Scenario 2: Onboard Naval Ship (Feb 8,2017 to Feb 27,2018 Data Record)	0.5	year

Number of cycles: 5

Total Time: 10 year

Exp. Scen. #1 Duration = 1.5 yrs

Exp. Scen. #2 Duration = 0.5 yrs

Results for selected environment (WET) are shown on the left

Accumulated damage from operational history is shown on the right

Total time = 10 yrs

Cycles = 5

Left: Results of selected environment. Right: Damage accumulated by operational history

	Group Name [-]	Polarisation Curve [-]	Surface Area [m2]	Net Current [A]	Mass Loss Rate [g/day]	Most Positive Potential [V]	Most Negative Potential [V]	Max Current Density [A/m2]	Min Current Density [A/m2]	Max Corrosion Penetration Rate [mm/year]	Min Corrosion Penetration Rate [mm/year]	Maximum Accumulated Damage [mm]	Minimum Accumulated Damage [mm]	Accumulated Mass Loss [g]	Net Charge [Ah]	Severity Index [-]
1	AileronHinge_...	Al-7075_1	0.0696237	0.00391243	0.0328563	-0.581694	-0.646223	0.0819665	0.0402856	0.0904914	0.0444755	0.0891125	0.0254869	8.09661	23.1389	0
2	Bushing1_Side1	Al_Bronze_AMS...	0.000254008	-7.04465e-05	0	-0.634311	-0.638115	-0.276917	-0.277932	0	0	0	0	0	-0.512995	0
3	Bushing2_Side1	Al_Bronze_AMS...	0.00025177	-6.98305e-05	0	-0.63[illegible]76	-0.637989	-0.276941	-0.277954	0	0	0	0	0	-0.508549	0
4	Fastener1_Side1	17-4_4	0.000243892	-0.000206016	0	-0.578025	-0.58363	-0.835993	-0.865645	0	0	0	0	0	-1.08968	0
5	Fastener10_Side1	17-4_4	0.000243891	-0.000205974	0	-0.578003	-0.583516	-0.835876	-0.865046	0	0	0	0	0	-1.08964	0
6	Fastener11_Side1	17-4_4	0.000243892	-0.000207813	0	-0.579389	-0.585022	-0.843211	-0.873011	0	0	0	0	0	-1.09286	0
7	Fastener12_Side1	17-4_4	0.000243898	-0.000211969	0	-0.582552	-0.588769	-0.859945	-0.892838	0	0	0	0	0	-1.10062	0
8	Fastener13_Side1	17-4_4	0.000243894	-0.000216981	0	-0.586389	-0.592864	-0.880242	-0.9145	0	0	0	0	0	-1.10989	0
9	Fastener14_Side1	17-4_4	0.000243892	-0.000222343	0	-0.590528	-0.597224	-0.902143	-0.93582	0	0	0	0	0	-1.11971	0
10	Fastener15_Side1	17-4_4	0.000243893	-0.000227939	0	-0.595091	-0.601526	-0.925406	-0.956821	0	0	0	0	0	-1.12999	0
11	Fastener16_Side1	17-4_4	0.000243893	-0.000234771	0	-0.600767	-0.60722	-0.953115	-0.984621	0	0	0	0	0	-1.14285	0
12	Fastener17_Side1	17-4_4	0.000243893	-0.00024491	0	-0.609172	-0.616775	-0.994147	-1.03126	0	0	0	0	0	-1.16289	0
13	Fastener2_Side1	17-4_4	0.000164202	-0.000142563	0	-0.582782	-0.587455	-0.861162	-0.885886	0	0	0	0	0	-0.741524	0
14	Fastener3_Side1	17-4_4	0.000164202	-0.000145797	0	-0.586473	-0.591319	-0.88069	-0.906326	0	0	0	0	0	-0.747779	0

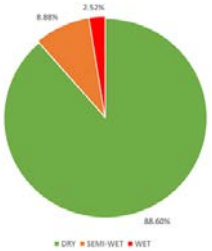
Display file successfully created in "F:/users/jmwb/Castle_Aileron_example/B/case1.post.res"

Service Life Model

Predicted Accumulated Damage After 10 Years

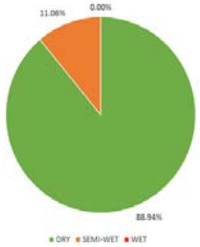
Operational Environment

Exposure Scenario #1 (1.5 yr period)



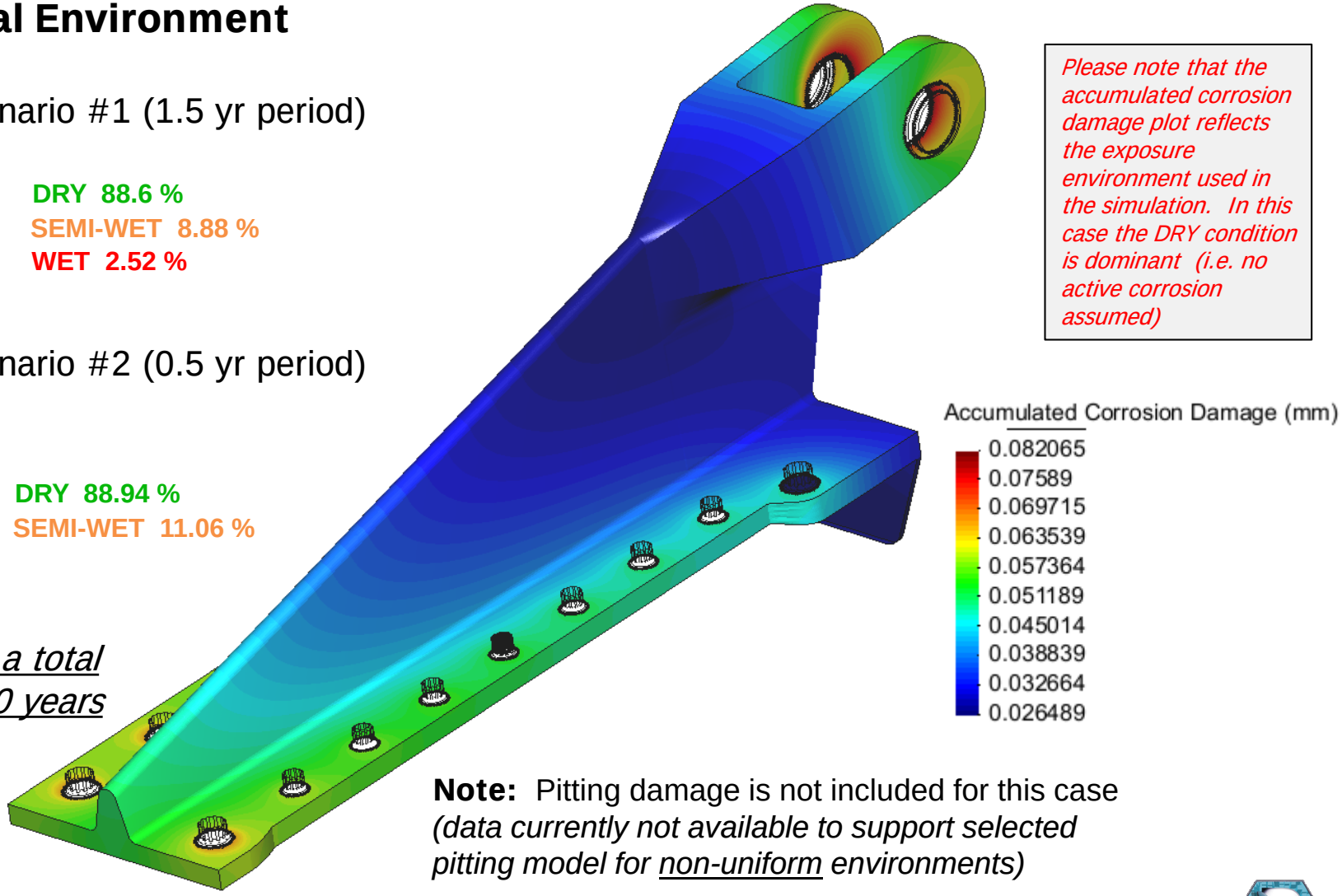
DRY 88.6 %
SEMI-WET 8.88 %
WET 2.52 %

Exposure Scenario #2 (0.5 yr period)



DRY 88.94 %
SEMI-WET 11.06 %

Repeated for a total duration of 10 years



Please note that the accumulated corrosion damage plot reflects the exposure environment used in the simulation. In this case the DRY condition is dominant (i.e. no active corrosion assumed)

Note: Pitting damage is not included for this case *(data currently not available to support selected pitting model for non-uniform environments)*

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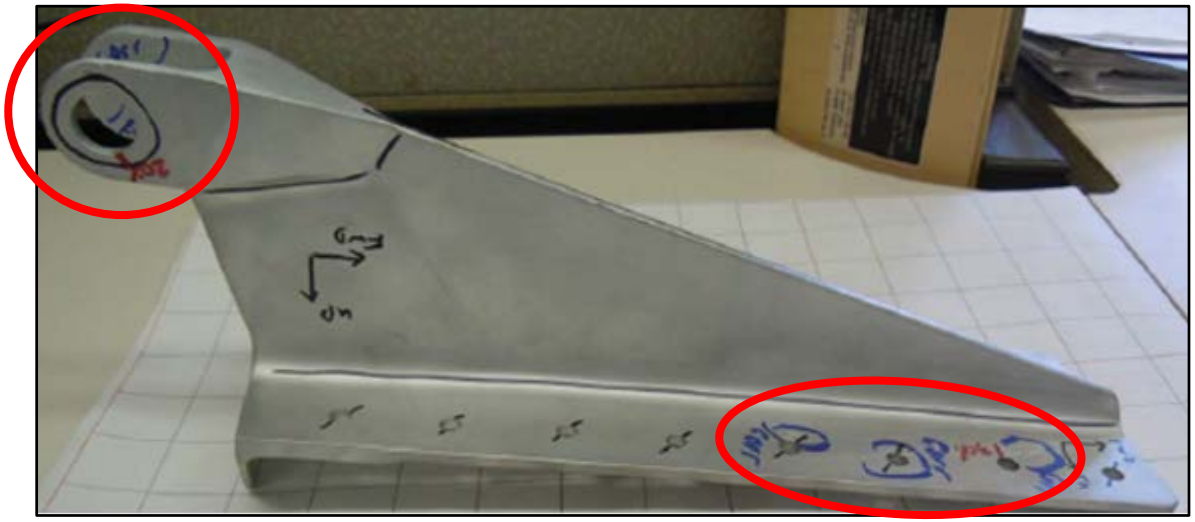
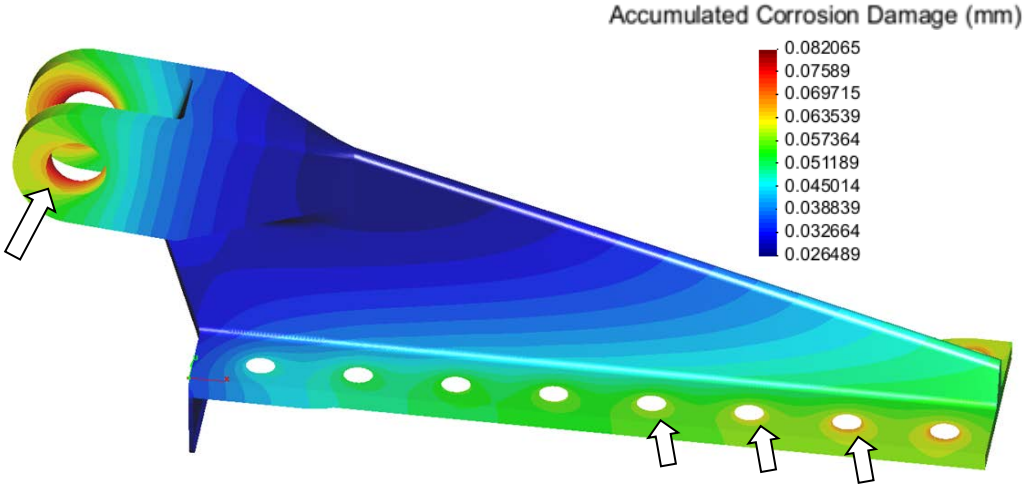
Service Life Model
Qualitative Comparison



Model predicts higher corrosion rates for the Al-7075 aileron hinge near the bushing and more remote fasteners.

Although qualitative, the model reflects the general location of the corrosion damage observed, following teardown inspection, in the actual part.



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Challenges Encountered

- Limited access to long term environmental exposure measurement data (i.e. building relevant exposure spectra)
- Relating film thickness variation to sensor measurement parameters (improve connection for SEMI-WET condition)
- Validating real aircraft galvanic assembly computational models in a service life type environment – What metrics to use? Is data available ?
- Lack of experimental data (or pitting models) to support corrosion pitting predictions for actual service life conditions (i.e. non-uniform and dynamic environments)

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Future Work

- Corrosion pitting and pit-to-crack transition models
- Coating degradation models
- Corrosion SLM design case study

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