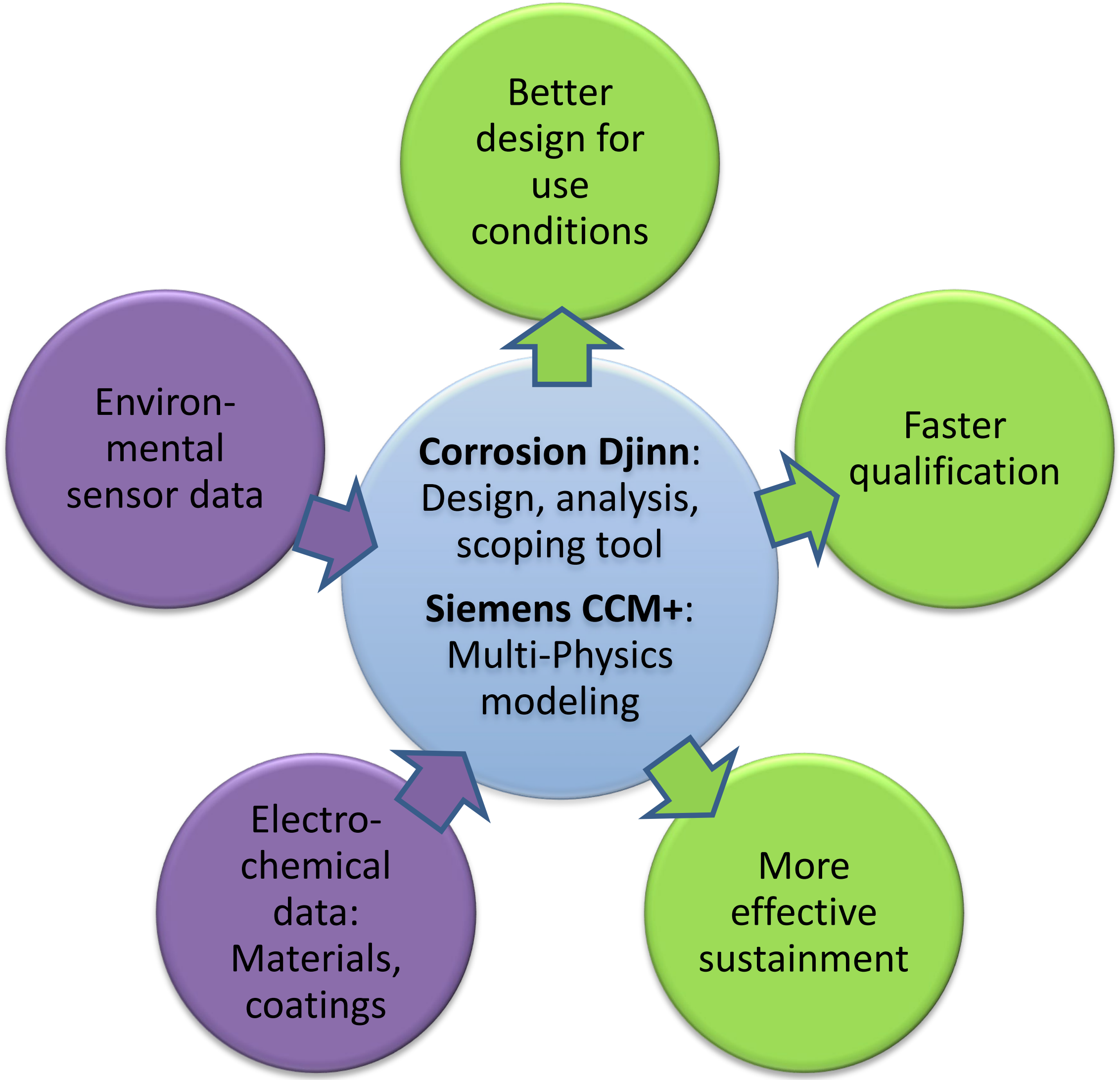
Corrosion Modeling to Relate Corrosion Damage to the Environment

Dr. Alan Rose, Corrdesa LLC

Agenda

- Overview of corrosion analysis
- Adapting to upcoming changes to MIL-STD-889
- Quick analysis tools
- CAE, multi-physics tools for fluids + electrochemistry
- Reducing corrosion risk in
  - Design
  - Qualification
  - Sustainment

Corrosion Modeling Inputs and Outputs



Better design for use conditions

Environ-mental sensor data

Corrosion Djinn: Design, analysis, scoping tool

Siemens CCM+: Multi-Physics modeling

Faster qualification

Electro-chemical data: Materials, coatings

More effective sustainment

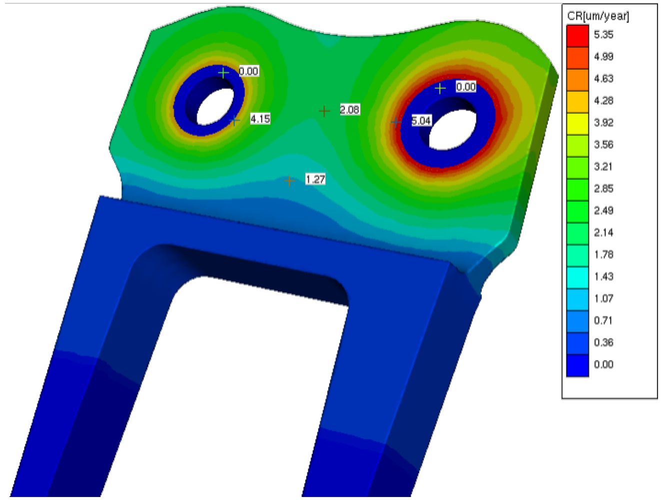
- Modeling does not replace testing
  - You can only model what you know in ways you know how to model
- But modeling is much faster and cheaper than manufacturing, testing and flying for 30 years
  - It is a good way to reduce risk in design and sustainment

Requirements for A & D Modeling & Simulation

For modeling and simulation to have any relevance in aerospace and defense it cannot simply be pretty

For design, quick evaluation and scoping it must be

- Accurate, taking into account the most important variables
- Verified, validated, and ultimately accredited
- Based on qualified data for the relevant materials, treatments, finishes



Requirements for A & D Modeling & Simulation

For detailed evaluation and simulation it must also

- Take into account the geometry of the assembly
- Take into account the time-dependent environment seen by the system, including electrolyte, electrolyte thickness, etc.
- Take into account material degradation (i.e. t>0)
- Take into account different corrosion mechanisms
  - Self-corrosion, galvanic, crevice, pitting, etc.

5

Is corrosion modeling ready for prime time?

The ONR Sea-Based Aviation (SBA) program has been developing computational technology and verifying and validating the methodology for *Durable Aircraft* (see Bill Nickerson briefing, SERDP-ESTCP Symposium 2018)

- Methods using finite element, finite volume, Boundary Element Methods,
- Computational methods using the mixed potential (curve crossing) approach
- Incorporation of CFD for electrolyte properties, thickness
- Verification and Validation of these approaches per MIL-STD-3022

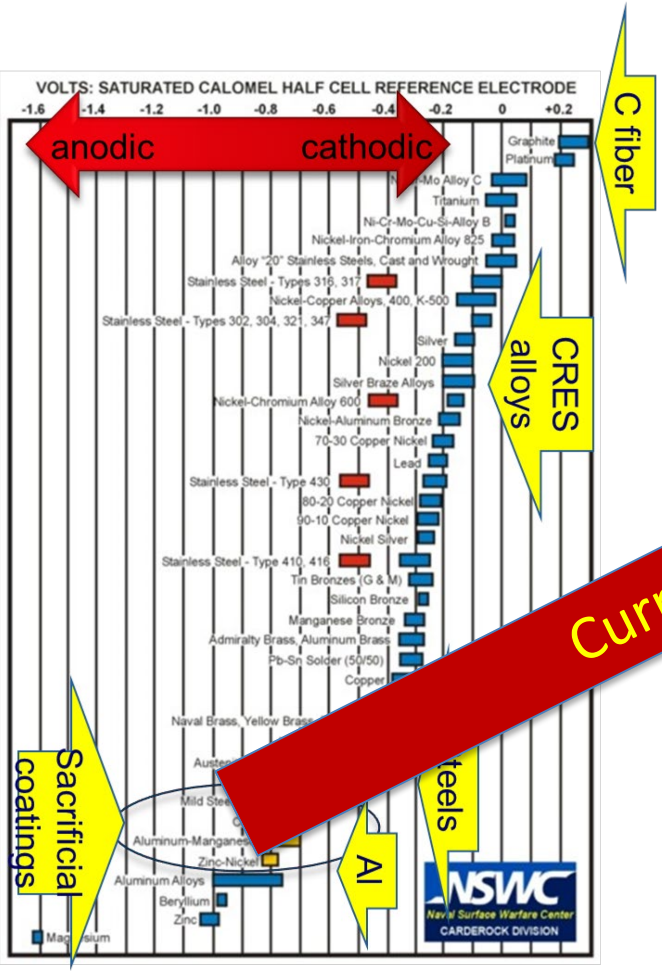
Is corrosion modeling ready for prime time?

- Best Practices for electrochemical data acquisition
- Methods for deconvoluting and analyzing electrochemical data
- An electrochemical database of curated, validated data designed to be used for computational corrosion and other electrochemical analysis

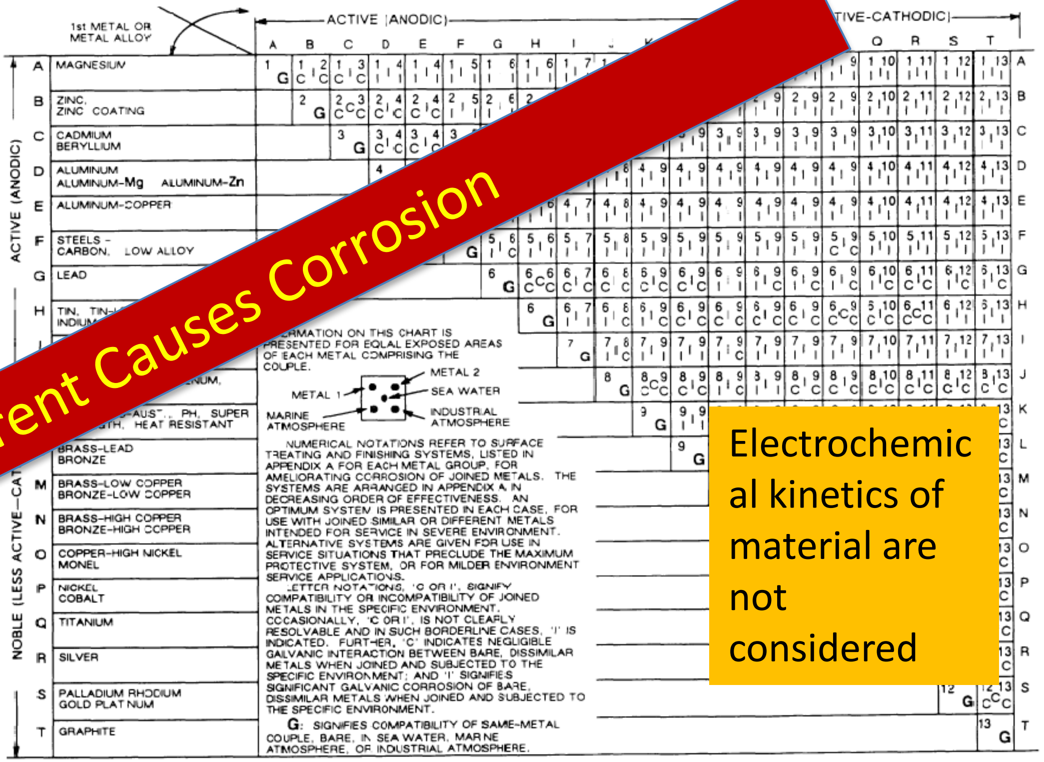
So, yes corrosion modeling is ready for prime time

Standard approach to galvanic corrosion is wrong

MIL-STD-889 now being updated to corrosion current approach (Victor Rodriguez-Santiago)



Designers & sustainment engineers assess galvanic corrosion using tables or specs such as: MIL-STD-889, MIL-DTL-14072, and MIL-STD-1250A



RMATION ON THIS CHART IS PRESENTED FOR EQUAL EXPOSED AREAS OF EACH METAL COMPRISING THE COUPLE.

NUMERICAL NOTATIONS REFER TO SURFACE TREATING AND FINISHING SYSTEMS, LISTED IN APPENDIX A FOR EACH METAL GROUP, FOR AMELIORATING CORROSION OF JOINED METALS. THE SYSTEMS ARE ARRANGED IN APPENDIX A IN DECREASING ORDER OF EFFECTIVENESS. AN OPTIMUM SYSTEM IS PRESENTED IN EACH CASE, FOR USE WITH JOINED SIMILAR OR DIFFERENT METALS INTENDED FOR SERVICE IN SEVERE ENVIRONMENT. ALTERNATIVE SYSTEMS ARE GIVEN FOR USE IN SERVICE SITUATIONS THAT PRECLUDE THE MAXIMUM PROTECTIVE SYSTEM, OR FOR MILDER ENVIRONMENT SERVICE APPLICATIONS.

LETTER NOTATIONS, 'C OR I', SIGNIFY COMPATIBILITY OR INCOMPATIBILITY OF JOINED METALS IN THE SPECIFIC ENVIRONMENT. OCCASIONALLY, 'C OR I', IS NOT CLEARLY RESOLVABLE AND IN SUCH BORDERLINE CASES, 'I' IS INDICATED. FURTHER, 'C' INDICATES NEGLIGIBLE GALVANIC INTERACTION BETWEEN BARE, DISSIMILAR METALS WHEN JOINED AND SUBJECTED TO THE SPECIFIC ENVIRONMENT; AND 'I' SIGNIFIES SIGNIFICANT GALVANIC CORROSION OF BARE, DISSIMILAR METALS WHEN JOINED AND SUBJECTED TO THE SPECIFIC ENVIRONMENT.

G: SIGNIFIES COMPATIBILITY OF SAME-METAL COUPLE, BARE, IN SEA WATER, MARINE ATMOSPHERE, OR INDUSTRIAL ATMOSPHERE.

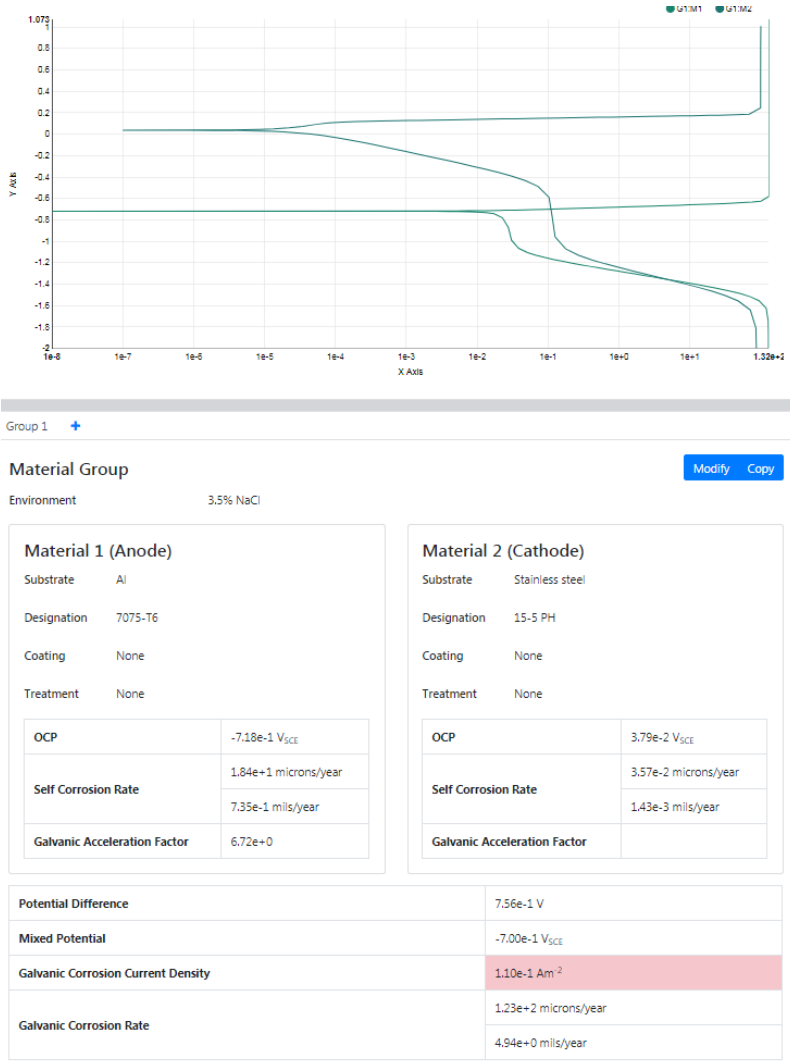
Current Causes Corrosion

Electrochemical kinetics of material are not considered

Most galvanic tables and charts are based on half-century old materials and data

Corrosion Djinn Analysis

- Principle is the well-known Mixed-potential /curve crossing technique
  - Crossing point of curves of V vs ABS(J) shows mixed potential and interfacial galvanic current
  - Conforms with upcoming revision of MIL-STD-889C revision
- Strictly, assumes 2 parallel surfaces of equal area in bulk solution with high conductivity
  - Reports **self** corrosion rate and predicts **galvanic corrosion rate** based on galvanic current
  - In practice it works well with non-parallel surfaces and thin films (with the thin film polarization data)



Material Group

Environment 3.5% NaCl

Material 1 (Anode)

Substrate Al

Designation 7075-T6

Coating None

Treatment None

OCP	-7.18e-1 V_{SCE}
Self Corrosion Rate	1.84e+1 microns/year
	7.35e-1 mils/year
Galvanic Acceleration Factor	6.72e+0

Material 2 (Cathode)

Substrate Stainless steel

Designation 15-5 PH

Coating None

Treatment None

OCP	3.79e-2 V_{SCE}
Self Corrosion Rate	3.57e-2 microns/year
	1.43e-3 mils/year
Galvanic Acceleration Factor	

Potential Difference	7.56e-1 V
Mixed Potential	-7.00e-1 V_{SCE}
Galvanic Corrosion Current Density	1.10e-1 Am^{-2}
Galvanic Corrosion Rate	1.23e+2 microns/year
	4.94e+0 mils/year

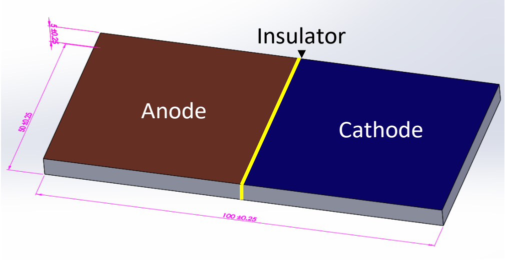
1D Mixed Potential (Curve Crossing) Corrosion Analysis

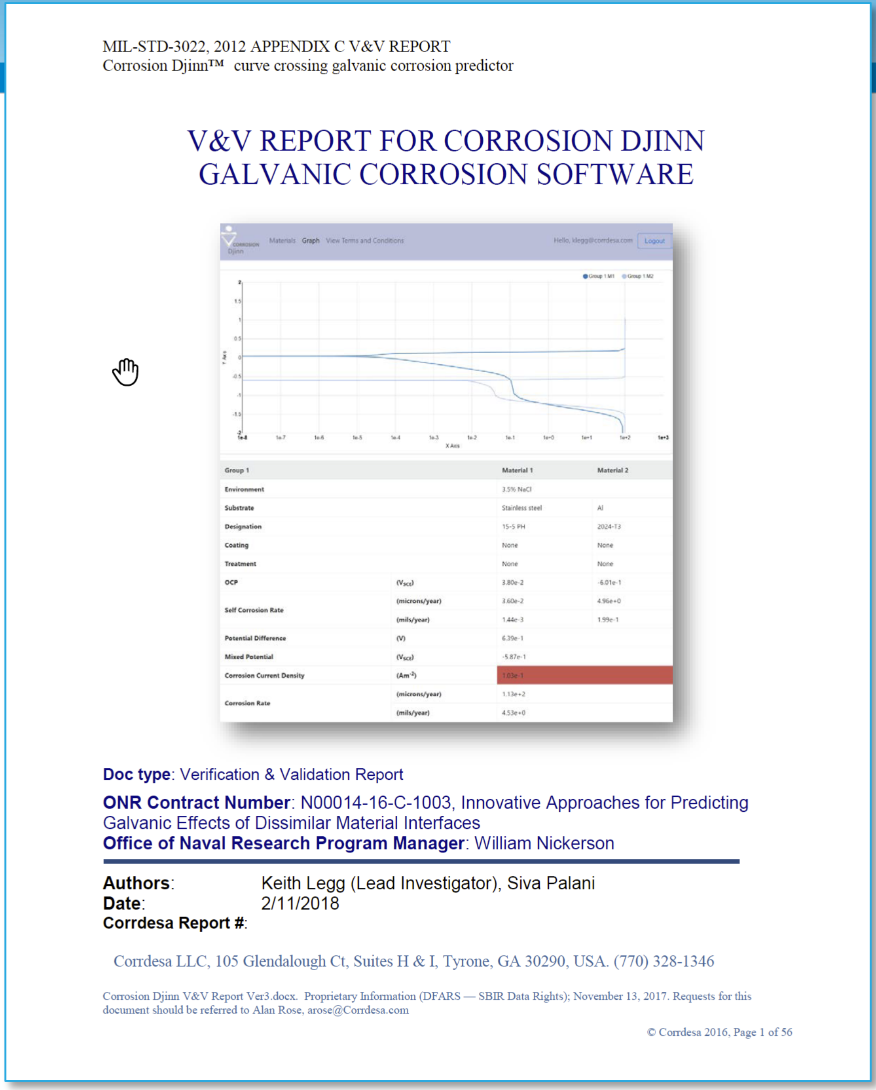
https://corrosiondjinn.com/

Model Verification & Validation

- Corrosion Djinn curve crossing is verified and validated
- Siemens Star CCM+ is already Verified, Validated and Accredited
  - Available on DoD HPC platform

Galvanic couple	FEA prediction	Corrosion Djinn prediction	Measured volume loss
CFC-7075 bare	1.25 mm^3	1.25 mm^3	0.84 mm^3
CFC-7075 SAA	1.16 mm^3	1.1 mm^3	1.3 mm^3




MIL-STD-3022, 2012 APPENDIX C V&V REPORT
Corrosion Djinn™ curve crossing galvanic corrosion predictor

V&V REPORT FOR CORROSION DJINN GALVANIC CORROSION SOFTWARE

Group 1		Material 1	Material 2
Environment		3.5% NaCl	
Substrate		Stainless steel	Al
Designation		15-5 PH	2024-T3
Coating		None	None
Treatment		None	None
OCP	**(V_{SCE})**	3.80e-2	-6.01e-1
Self Corrosion Rate	**(microns/year)**	3.60e-2	4.96e+0
	(mils/year)	1.44e-3	1.99e-1
Potential Difference	**(V)**	6.39e-1	
Mixed Potential	**(V_{SCE})**	-5.87e-1	
Corrosion Current Density	**(Am^{-2})**	1.03e-1	
Corrosion Rate	**(microns/year)**	1.13e+2	
	(mils/year)	4.53e+0	

Doc type: Verification & Validation Report
ONR Contract Number: N00014-16-C-1003, Innovative Approaches for Predicting Galvanic Effects of Dissimilar Material Interfaces
Office of Naval Research Program Manager: William Nickerson

Authors: Keith Legg (Lead Investigator), Siva Palani
Date: 2/11/2018
Corrdesa Report #:

Corrdesa LLC, 105 Glendalough Ct, Suites H & I, Tyrone, GA 30290, USA. (770) 328-1346

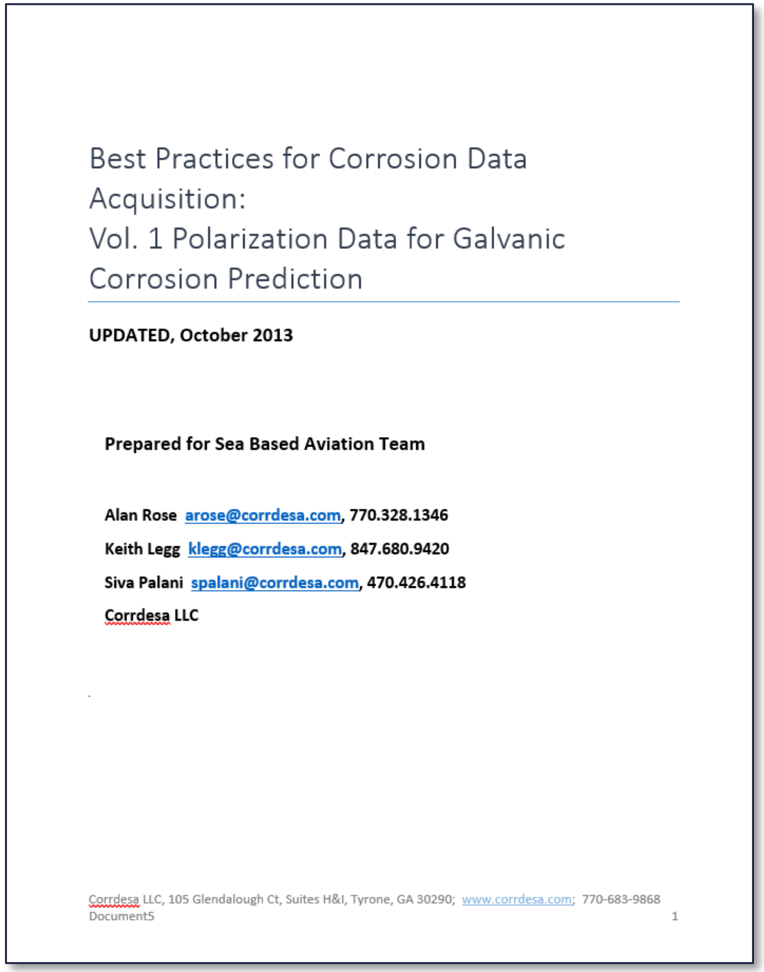
Corrosion Djinn V&V Report Ver3.docx. Proprietary Information (DFARS — SBIR Data Rights); November 13, 2017. Requests for this document should be referred to Alan Rose, arose@Corrdesa.com

© Corrdesa 2016, Page 1 of 56

Best Practices for Polarization Data Acquisition

The Best Practices document for the ONR SBA Team defines the procedures for acquiring high quality polarization data in a consistent manner for incorporation into the Electrochemical Database

The Best Practices document for MIL-STD-889C Technical Revision defines how team members should take data for validation of the acquisition technique



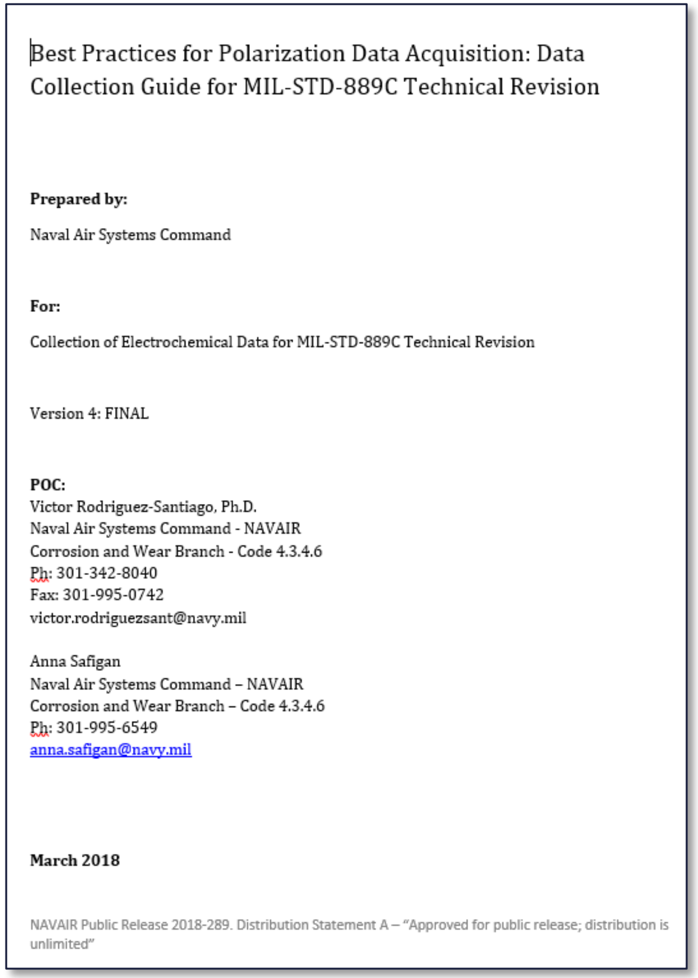
Best Practices for Corrosion Data Acquisition:
Vol. 1 Polarization Data for Galvanic Corrosion Prediction

UPDATED, October 2013

Prepared for Sea Based Aviation Team

Alan Rose arose@corrdesa.com, 770.328.1346
Keith Legg klegg@corrdesa.com, 847.680.9420
Siva Palani spalani@corrdesa.com, 470.426.4118
Corrdesa LLC

Corrdesa LLC, 105 Glendalough Ct, Suites H&I, Tyrone, GA 30290; www.corrdesa.com; 770-683-9868
Document5 1



Best Practices for Polarization Data Acquisition: Data Collection Guide for MIL-STD-889C Technical Revision

Prepared by:

Naval Air Systems Command

For:

Collection of Electrochemical Data for MIL-STD-889C Technical Revision

Version 4: FINAL

POC:
Victor Rodriguez-Santiago, Ph.D.
Naval Air Systems Command - NAVAIR
Corrosion and Wear Branch - Code 4.3.4.6
Ph: 301-342-8040
Fax: 301-995-0742
victor.rodriguezsant@navy.mil

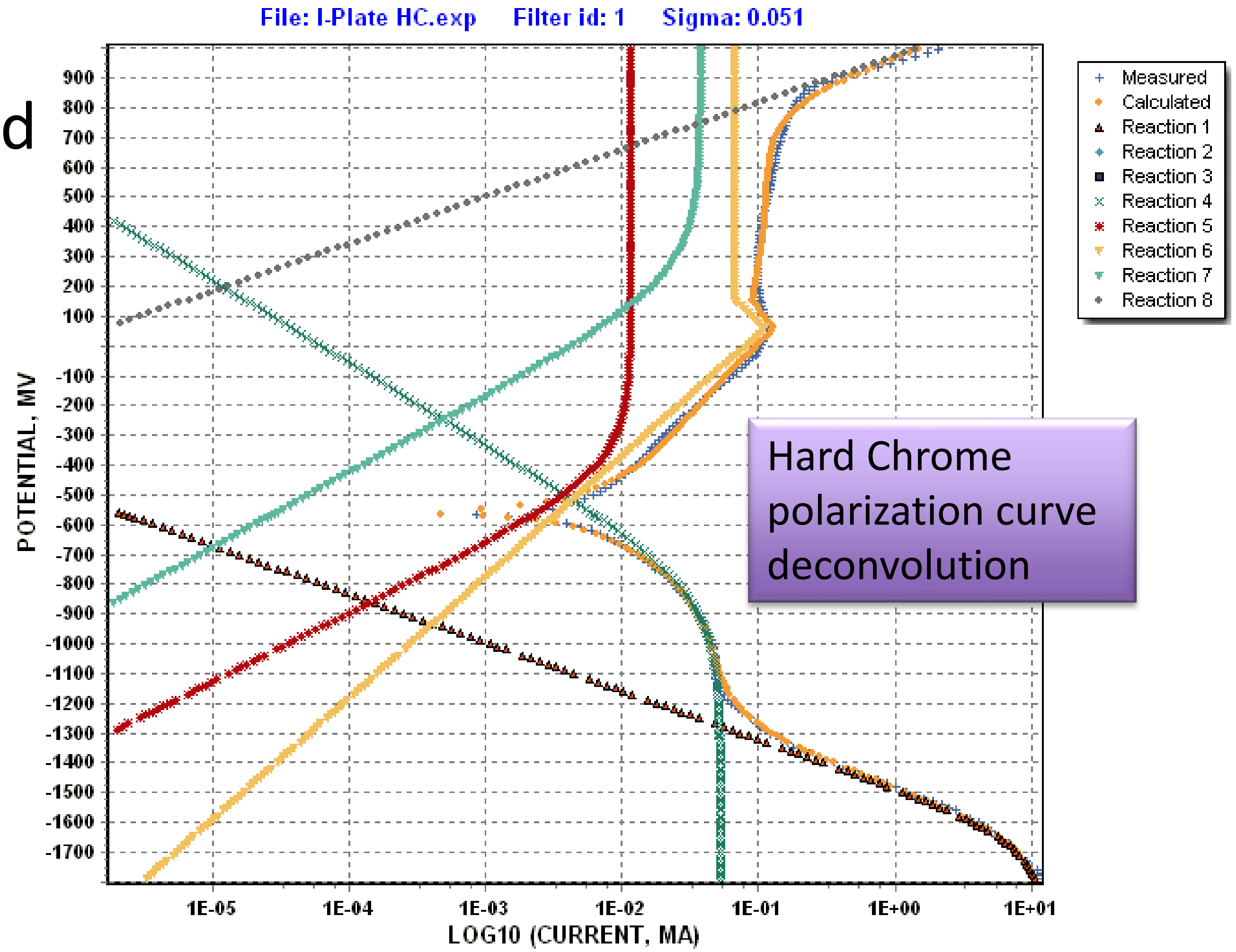
Anna Safigan
Naval Air Systems Command – NAVAIR
Corrosion and Wear Branch – Code 4.3.4.6
Ph: 301-995-6549
anna.safigan@navy.mil

March 2018

NAVAIR Public Release 2018-289. Distribution Statement A – "Approved for public release; distribution is unlimited"

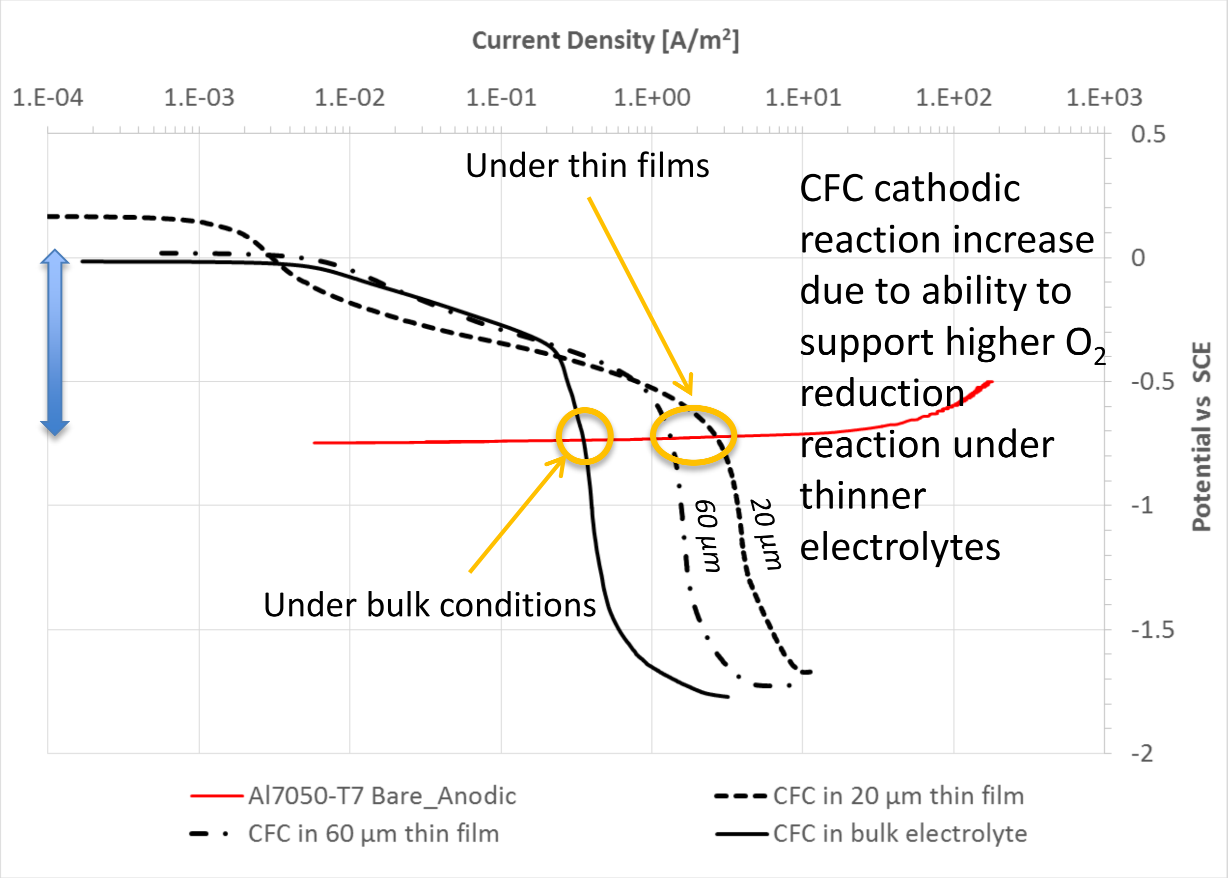
Polarization Curve Deconvolution

- Polarization curves can be deconvoluted into the anodic and cathodic electrochemical reactions that create them using a fitting technique
- Deconvolution makes it possible to create a well-defined curve and accurately determine self-corrosion rate and OCP



Hard Chrome polarization curve deconvolution

Impact of electrolyte thickness on corrosion



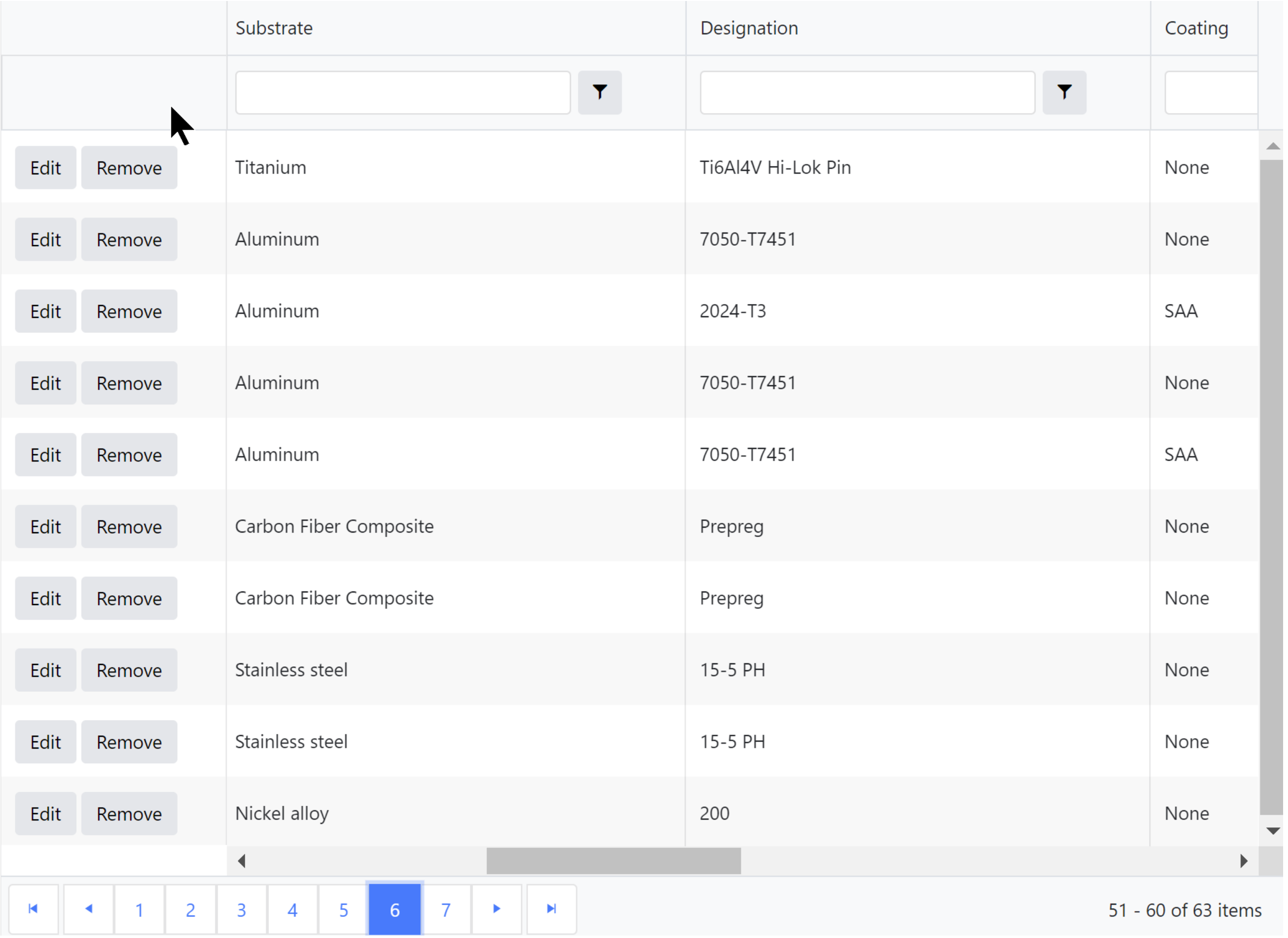
CFC cathodic reaction increase due to ability to support higher O_2 reduction reaction under thinner electrolytes

Thinner electrolyte layers

- allow O_2 to diffuse to surface more rapidly causing more rapid corrosion
- constrain galvanic current close to the interface
- Result:
    - rapid, deep corrosion at interface
- Thin electrolytes (condensates) increase corrosion often by ~10x

Electrochemical Database

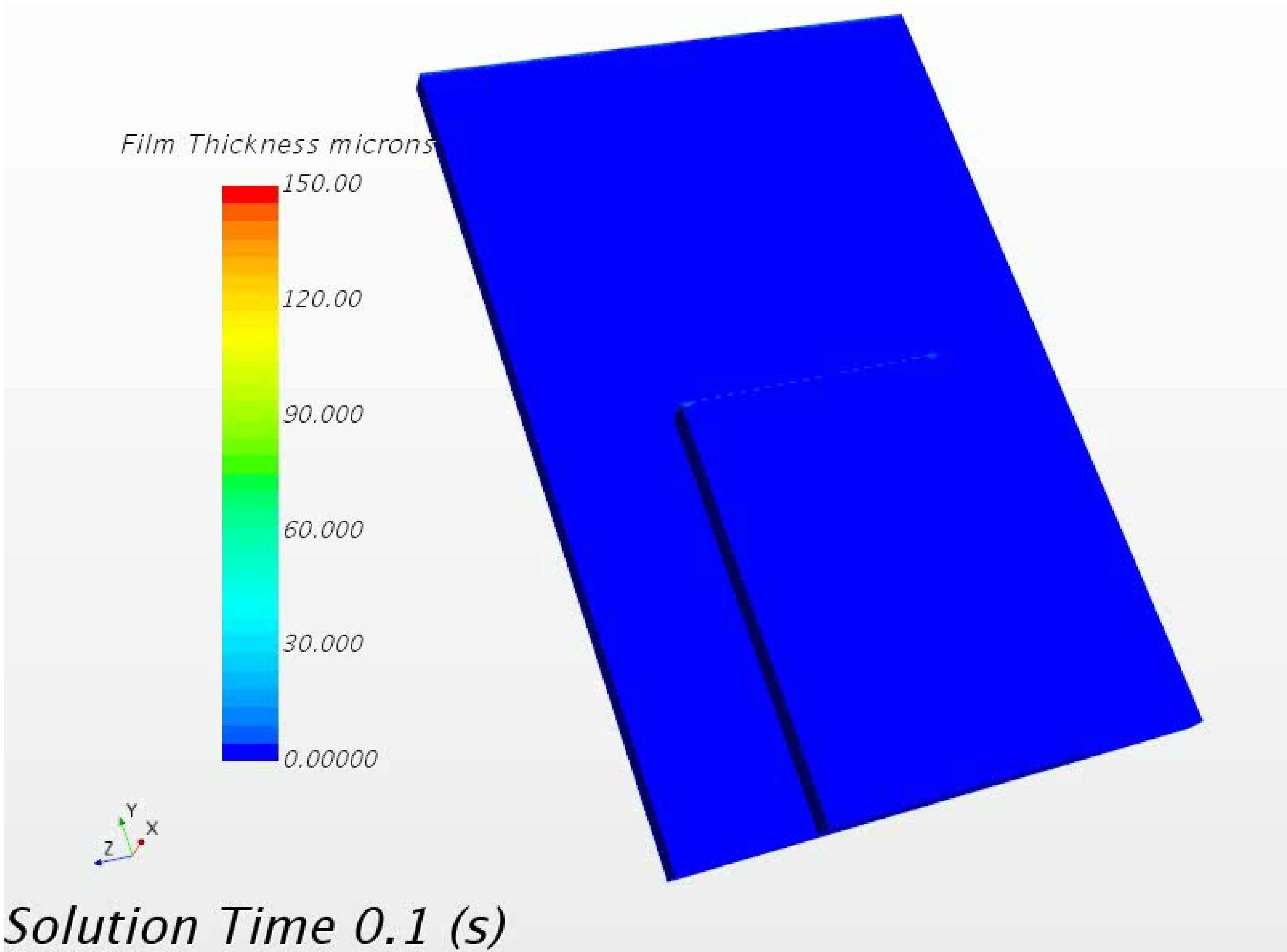
- Database of qualified, consistent polarization data taken using Best Practices
- Constantly being expanded



Substrate	Designation	Coating
Titanium	Ti6Al4V Hi-Lok Pin	None
Aluminum	7050-T7451	None
Aluminum	2024-T3	SAA
Aluminum	7050-T7451	None
Aluminum	7050-T7451	SAA
Carbon Fiber Composite	Prepreg	None
Carbon Fiber Composite	Prepreg	None
Stainless steel	15-5 PH	None
Stainless steel	15-5 PH	None
Nickel alloy	200	None

51 - 60 of 63 items

Modeling the electrolyte



17

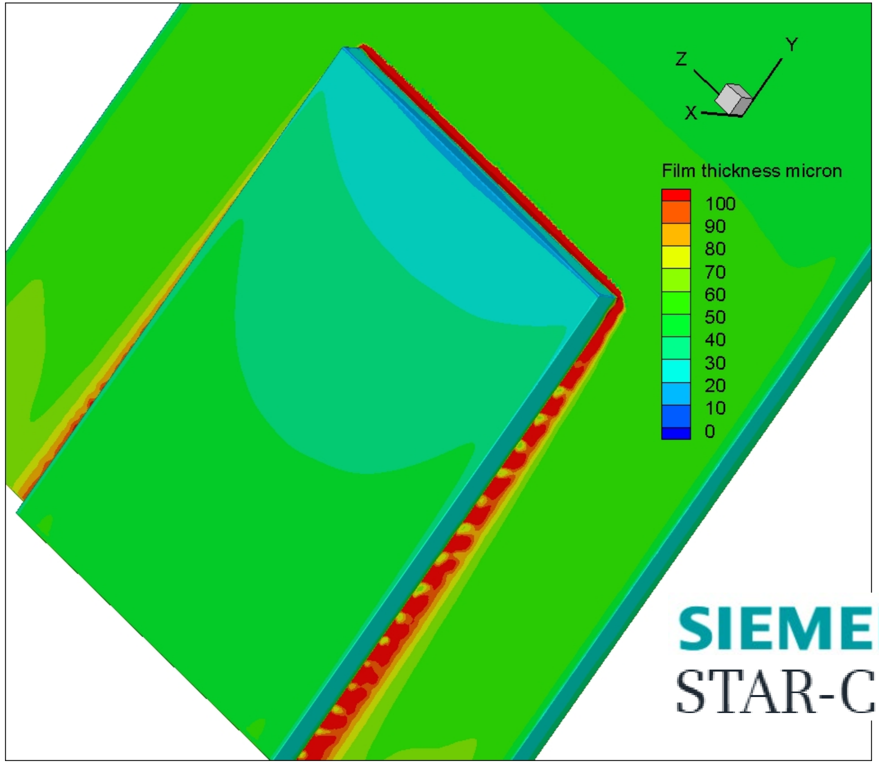
Modeling the electrolyte

Electrolyte thickness is highly variable

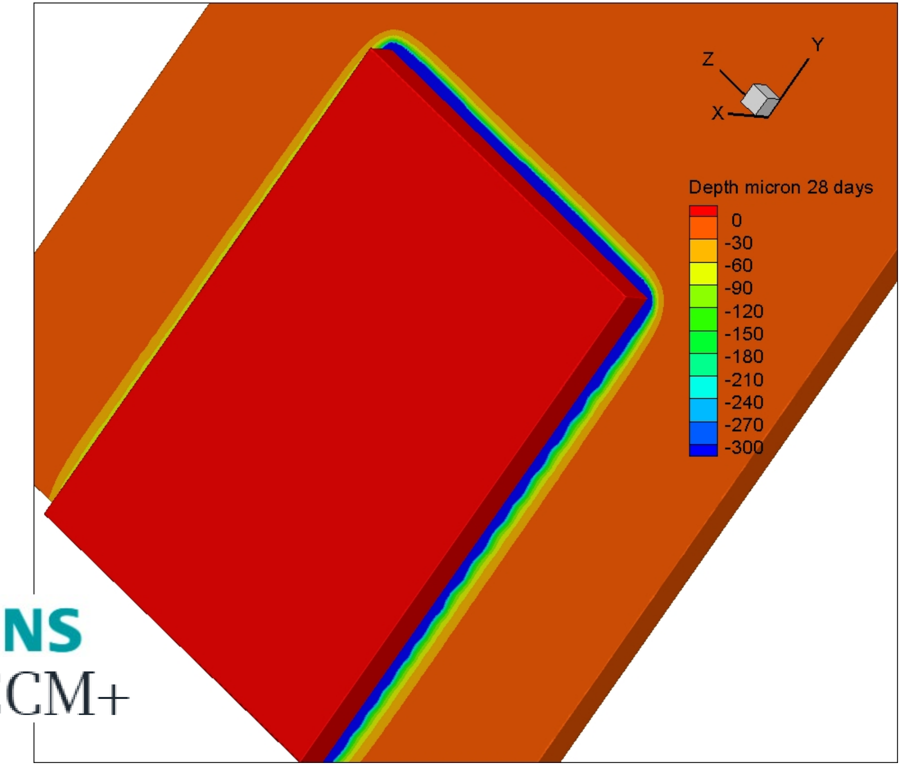
- By location on complex assemblies
- Over time in real atmospheric conditions with diurnal humidity changes, rain
- With mission parameters, such as temperature, elevation, etc.

These all cause large variations in electrolyte thickness, concentration, hence local corrosion rate

Film thickness-
CFD Liquid Film Model



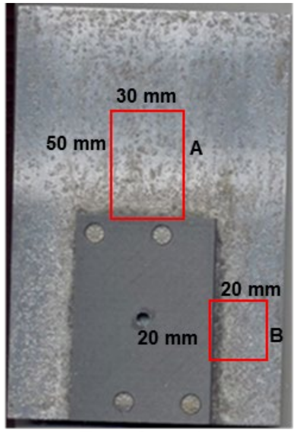
Corrosion depth@28days (µm)-
Laplacian Potential Model



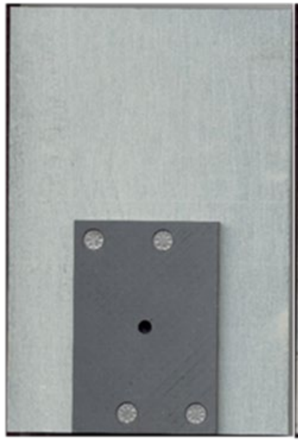
SIEMENS
STAR-CCM+

Modeling the electrolyte (Variable thinfilm)

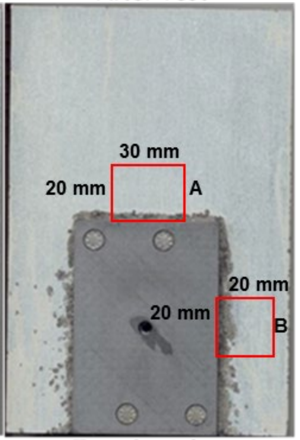
Test Case 1-
Before



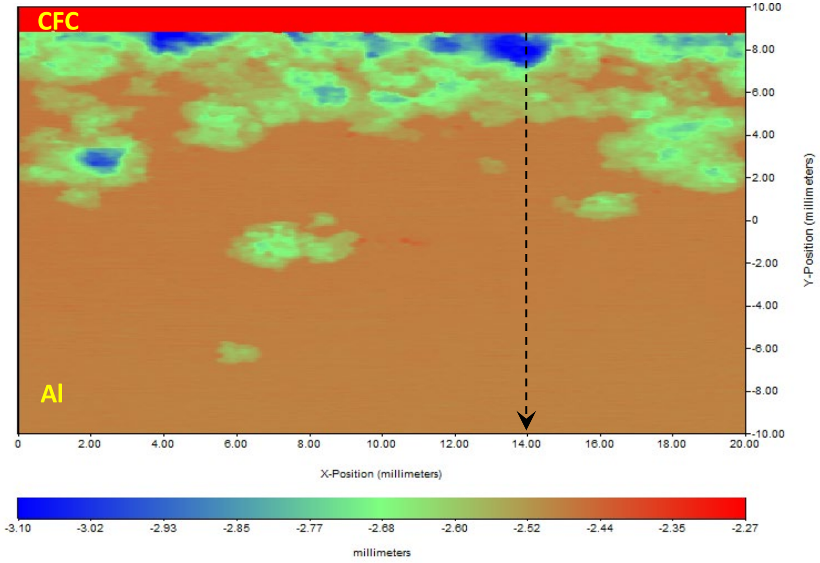
Test Case 1-
After Test

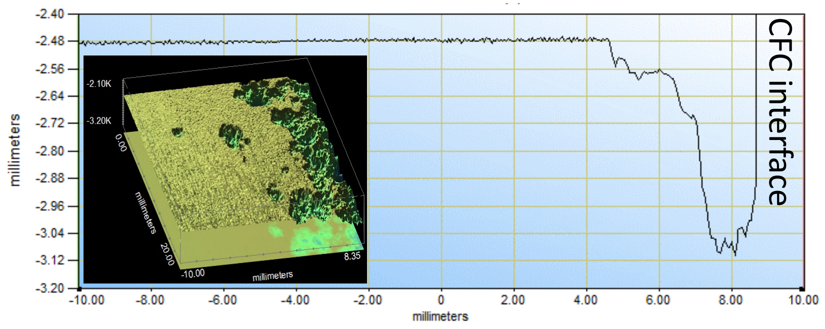


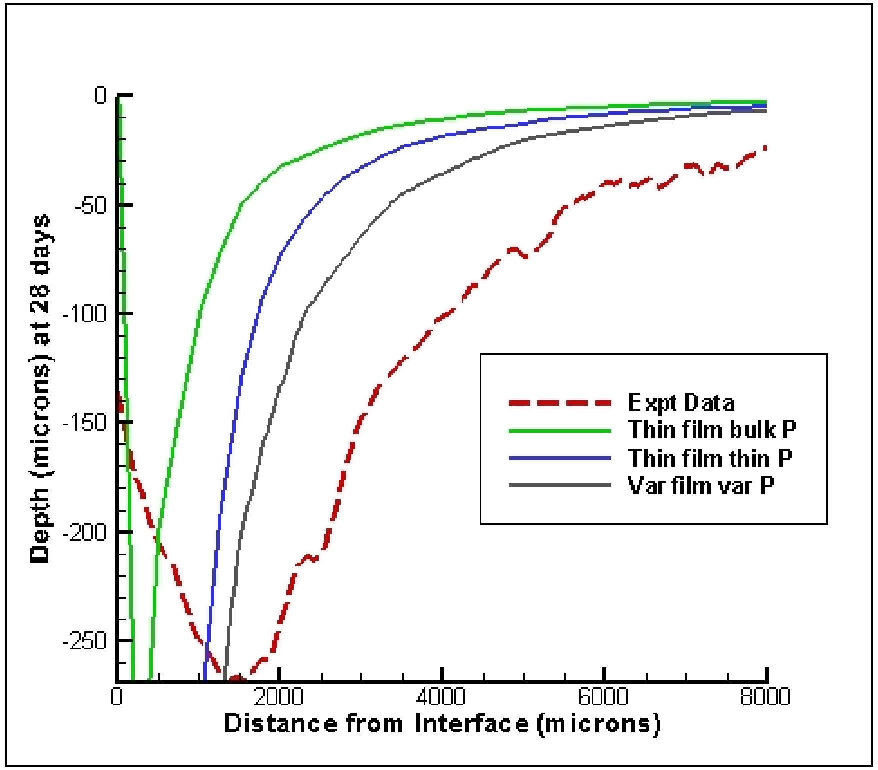
Test Case 2-
Before



Test Case 2-
After Test



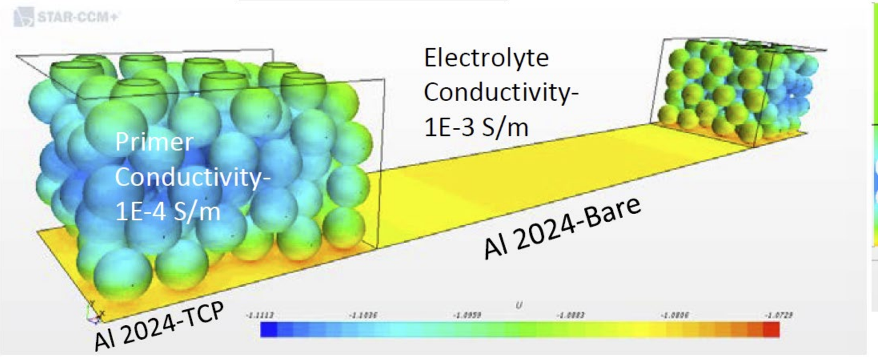




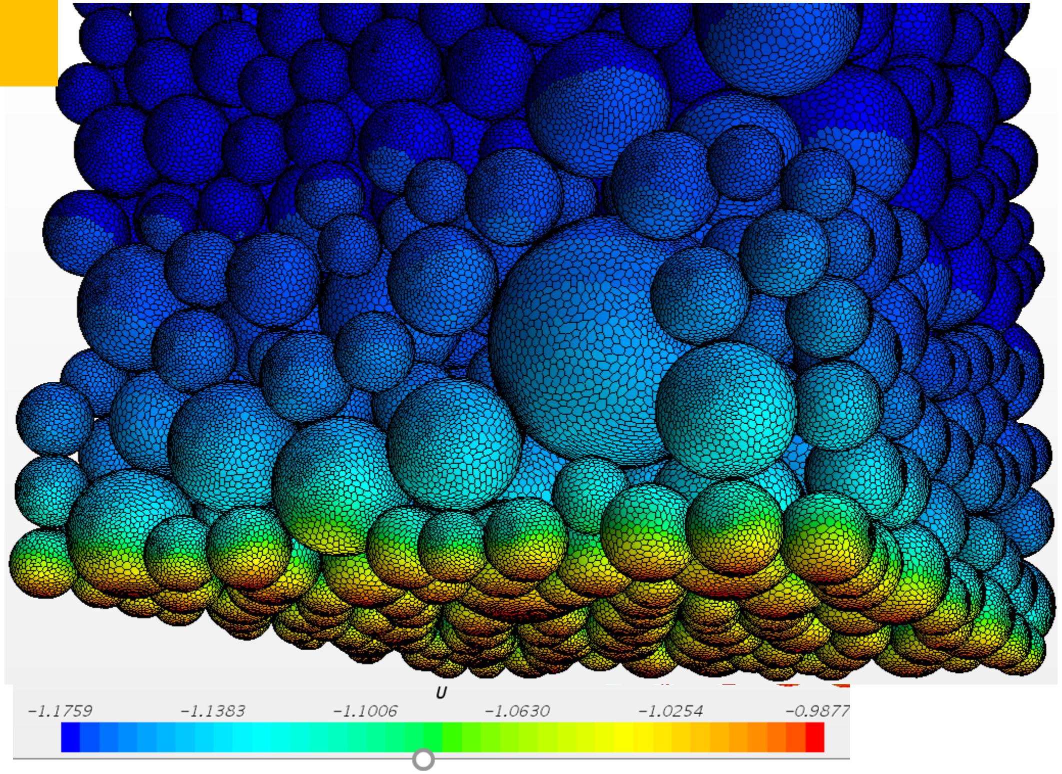
Corrosion Analysis can be macro or micro

We are using CAE to design metal-rich primers and polymers

- Predict how the pigments will corrode
- Predict how the primer will protect airframes



Potential in scribe through Al-rich primer with TCP-treated pigment particles. Primer keeps Al surface below pitting potential



Polydispersed primer model showing mesh and potential fields on particles

HOW DOES MODELING HELP DESIGN, QUALIFICATION AND SUSTAINMENT?

Reducing corrosion risk in design

- Djinn is designed for rapid analysis of galvanic interfaces by the non-expert
  - Quick analysis of interfaces including coatings and treatments
  - Ability to choose alternatives
  - The method can be used to formulate better design rules
  - A version is intended for integration into CAD software as a tool for use during design
- CAE is a multi-physics approach that can be used in parallel with stress analysis, heat analysis, etc. to validate design
  - Part of the suite of tools engineers use for analysis during design

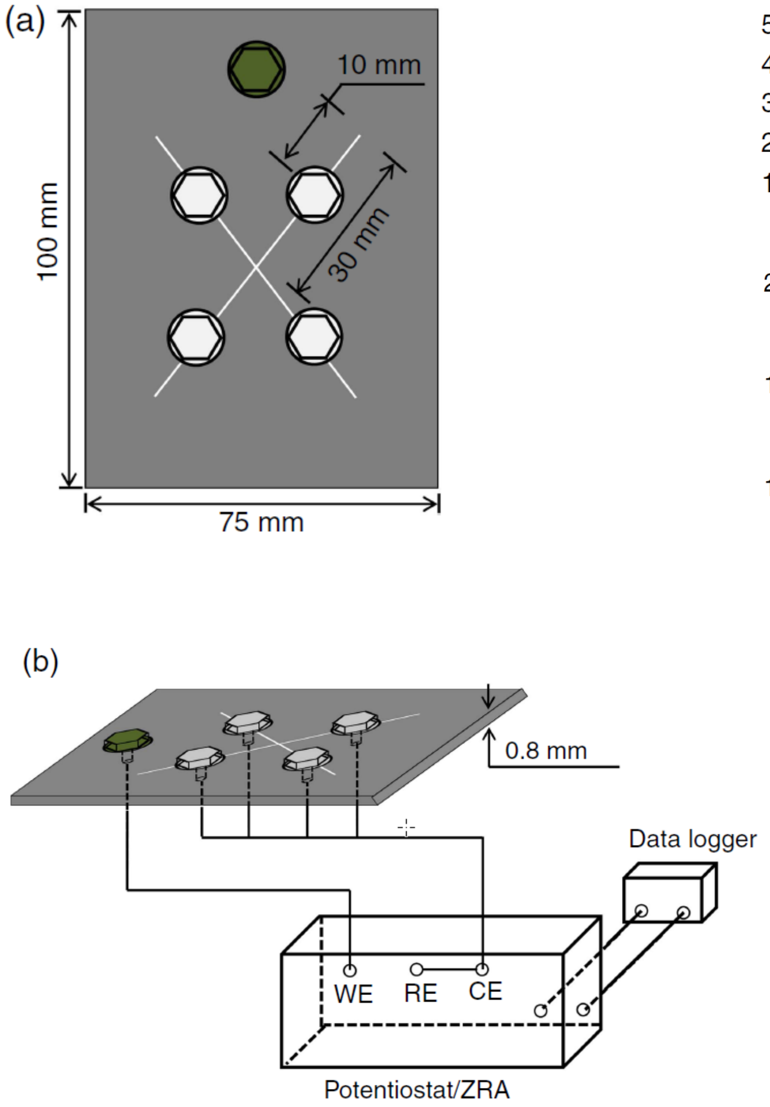
22

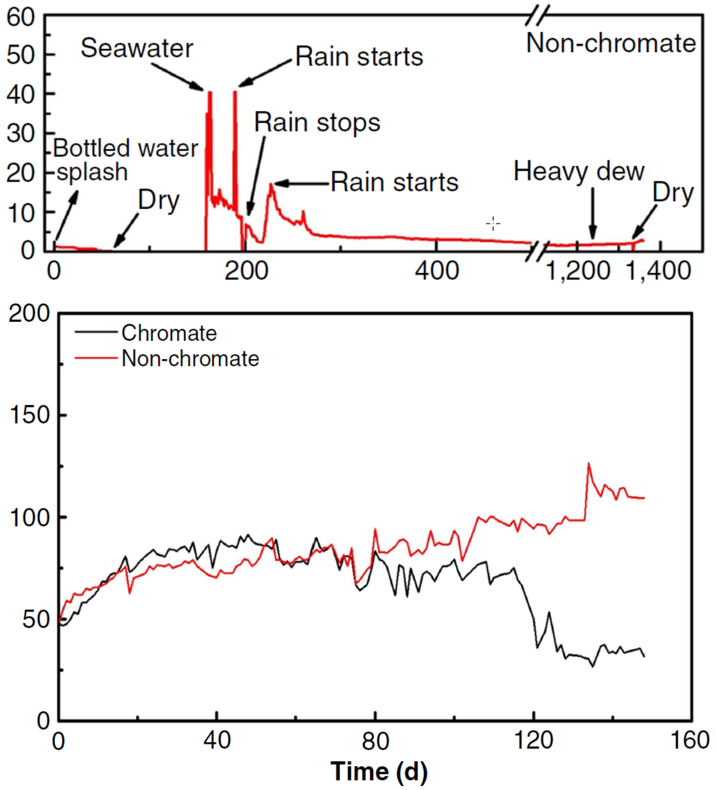
Reducing time and cost of qualification

The major parts of the time and cost of qualification are

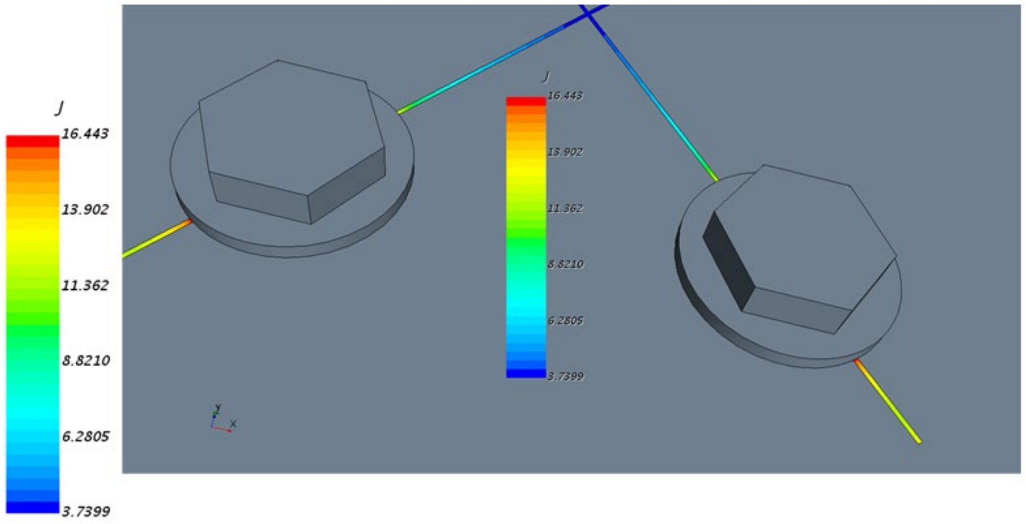
- Qualifying new materials – especially when we must replace chromates, cadmium, etc.
- Qualifying assemblies
  - In this case we can calculate how critical parts of the assembly will behave both in B117 and “the real world”
  - We can make and “test” modifications in models much more cost-effectively than redesigning and retesting
  - Then just need to verify our design modifications by testing rather than retesting
- Modeling does not eliminate testing, but if used correctly it can reduce mistakes and point to optimum materials and designs

ASTM B117 vs Fielded Coupons





Z. Feng, G.A. Frankel, W.H. Abbott, C.A. Matzdorf, "Galvanic Attack of Coated Al Alloy Panels Laboratory and Field Exposure", *Corrosion* 72 (2016); p. 342.

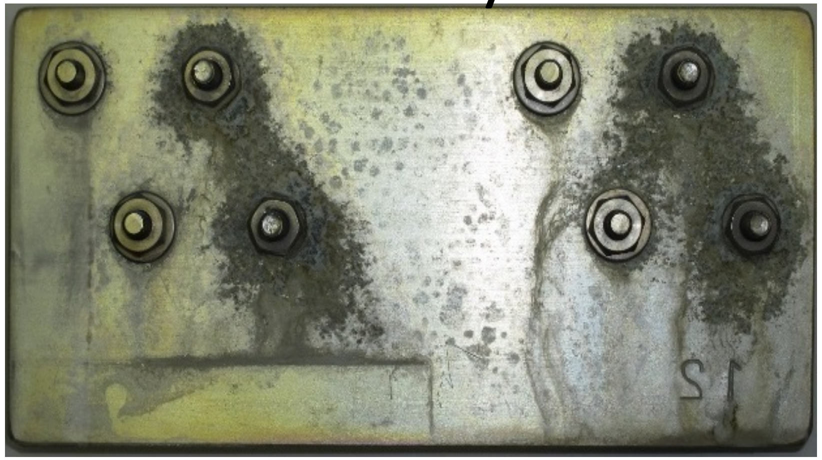


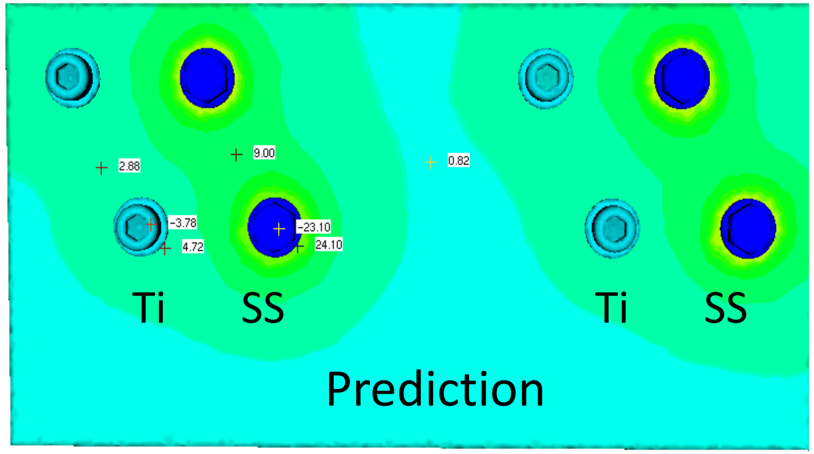
Case	Peak Current Density (A/m2)	Corrosion Current per fastener (µA)
SS316 stagnant data	0.07	0.47
SS316 50 µm pol data, bulk fluid model	8.8	43.7
SS316 50 µm pol data – fluid shell model	16.4	37.5
Experimental-B117 (Feng *et al.*)	-	50

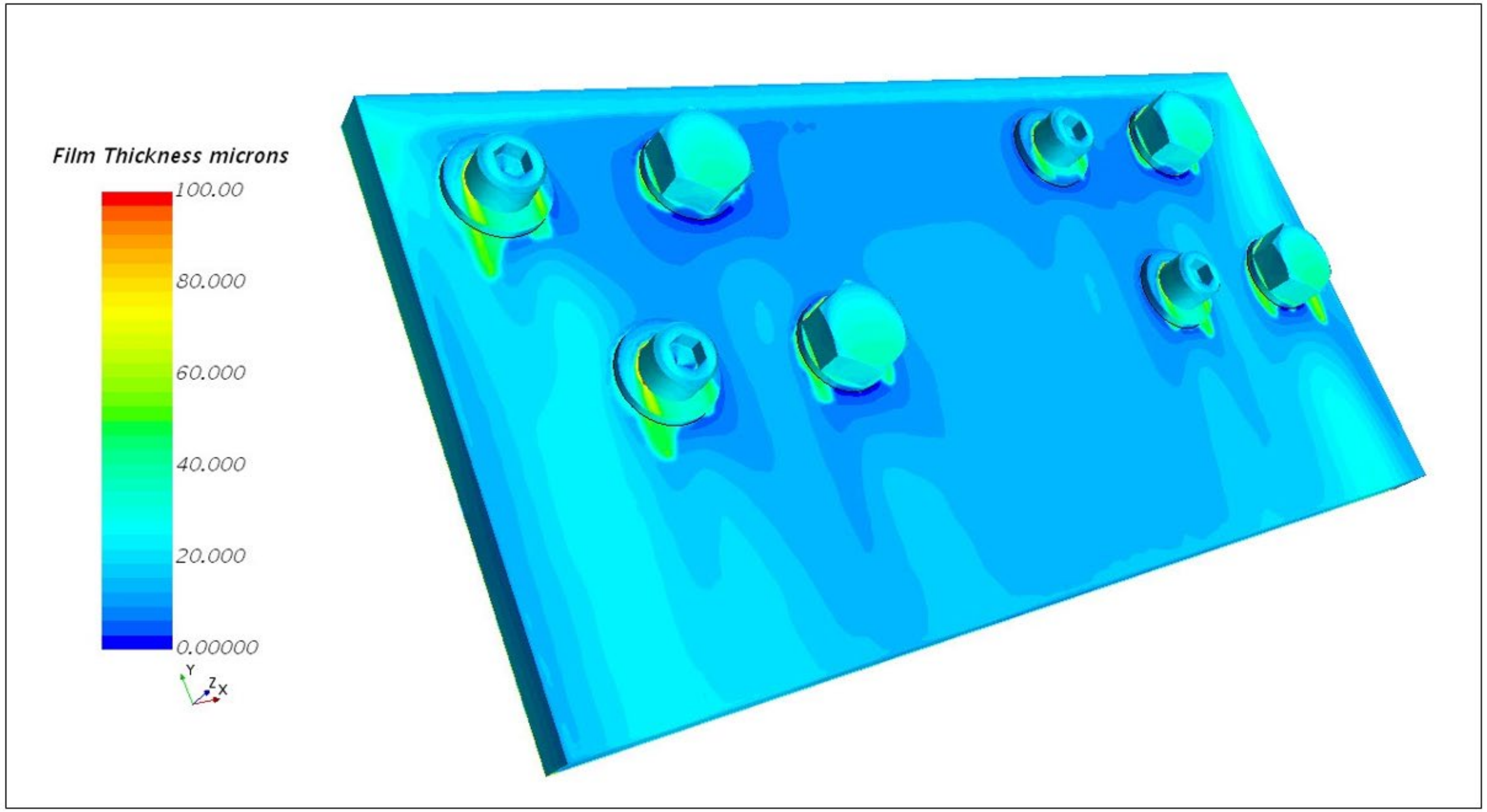
Table 1. Comparison of current density and corrosion current per fastener under thick, stagnant electrolyte and thin-film electrolyte.

Qualitative Comparison

Reality

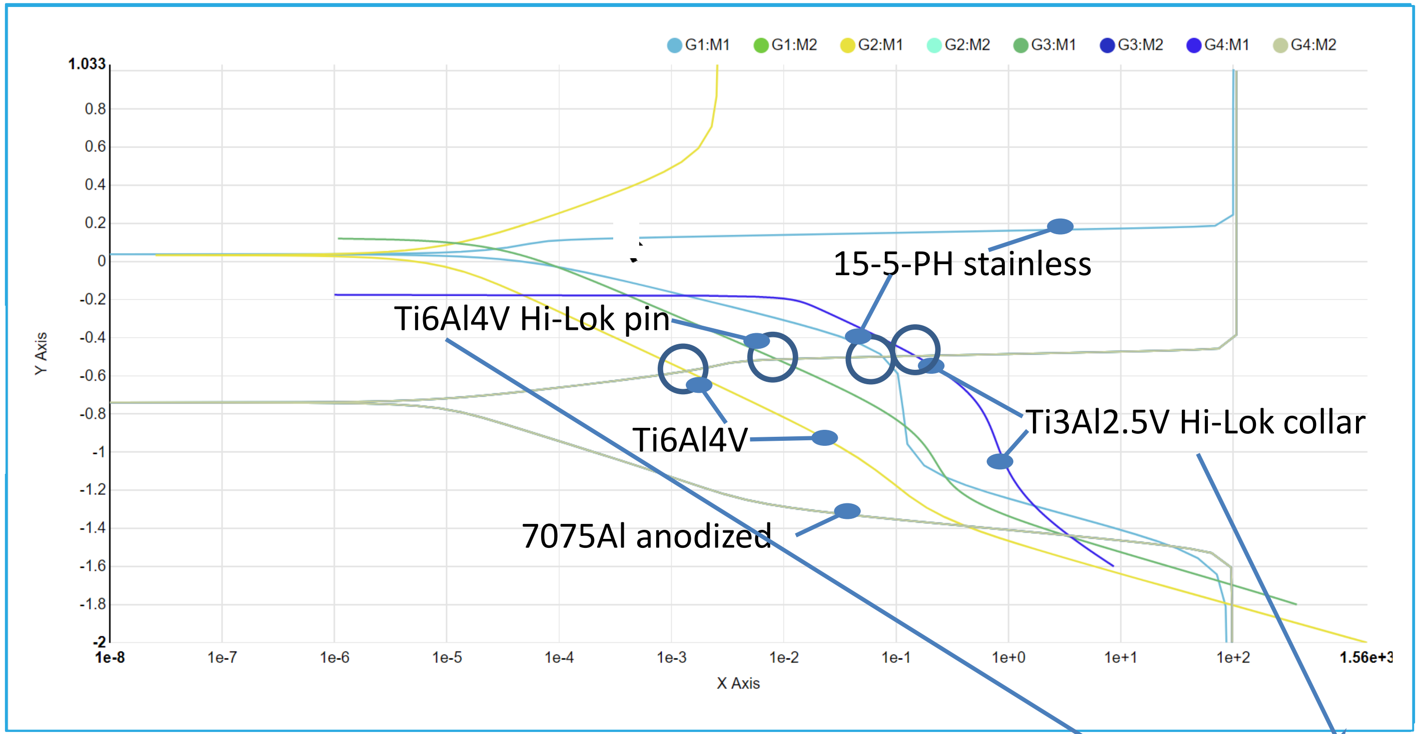




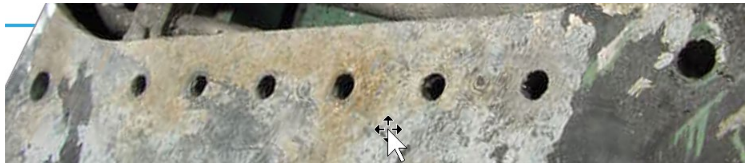


Reducing corrosion risk in sustainment

Cathode	Anode	OCP Al (V SCE)	OCP Cathode (V SCE)	Self-corr rate Al (µm/yr)	Galvanic corr rate Al (µm/yr)	Galv Accel Factor
15-5PH stainless	Al-7075-T6 BSAA	-0.74	-0.38	8.90E-03	85.1	9520
Ti6Al4V	Al-7075-T6 BSAA	-0.74	0.033	8.90E-03	1.55	173



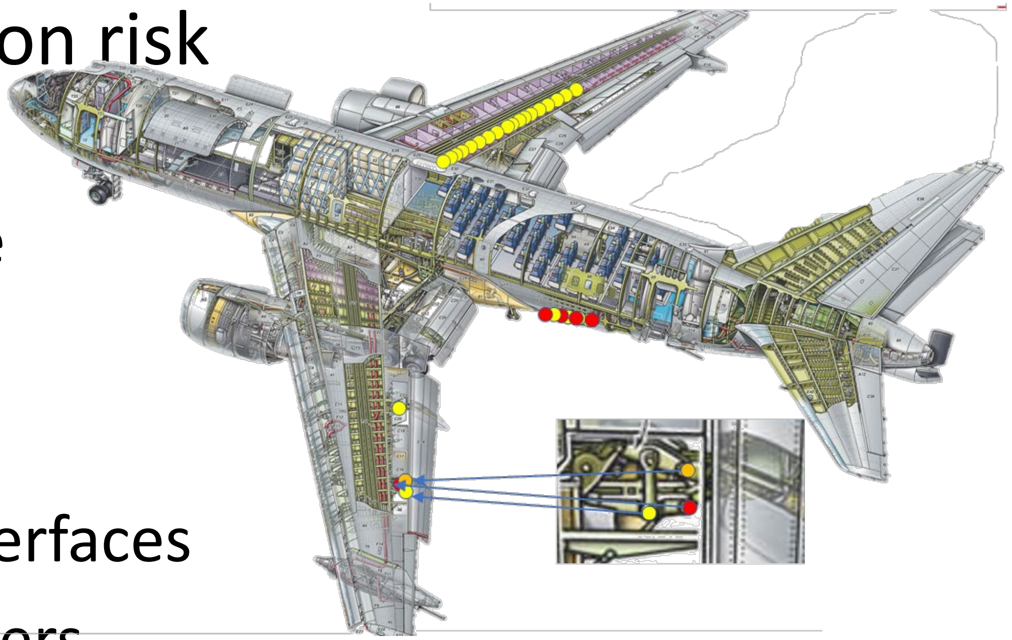
- When airframe corrodes around bolt holes, typically remove damaged Al and bush with stainless bushing
- Analysis shows Ti64 much better
- But Ti64 Hi-Lok worse than plain Ti64 – presumably because it is stressed
- And Ti3Al2.5V Hi-Lok collar worse than 15-5PH bushing



Holes should be bushed with Ti, although harder to machine
But not all Ti is good – depends on alloy and fabrication stress

Rapid corrosion analysis to find corrosion hot spots

- Djinn is fast enough and simple enough to use as a scoping tool to predict high corrosion risk interfaces throughout a platform
  - And provides a way to evaluate alternative materials and coatings
- CAE is required for complex situations
  - Complex assemblies, multiple-material interfaces
  - Lifing with real-life, variable electrolyte layers, coating degradation, etc



27

Capabilities and limitations of corrosion modeling

Capabilities

- Galvanic corrosion and self-corrosion
  - Prediction of corrosion rates and damage evolution
- Fluid dynamics of electrolyte layers
- Cyclic conditions
  - Temperature, humidity, rainfall
  - Test conditions – B117 and cyclic

Limitations

- We cannot calculate *ab initio*
  - Requires accurate polarization and other electrochemical data
  - Requires t>0 data for long-term prediction
- We do not have reliable models for everything, e.g.
  - Crevice corrosion
  - Pitting
- We must have reliable data on the corrosion environment