Corrosion Resistant Design

Using CCM+ to model electrochemical processes and guide material choice in aerospace and automotive systems

Alan Rose, Corrdesa LLC. GA, USA

Corrdesa

- Established 2011 – corrosion simulation
- Georgia, USA, 30 mins from Atlanta airport
- Staff 7, 8 - & growing…
- 1/3 – 1/2 building devoted to lab/testing
- CAE design optimization – CFD, cluster
- We invest heavily in development & transition of electrochemical technologies and software
- Federal & commercial consultancy as coatings, materials, corrosion & REACH experts

Corrdesa – Tyrone GA

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CORROSION Djinn

Agenda

- Corrosion assessment needs in aerospace and defense (A&D)
  - Where are we going and why?
- Changes in how A&D industry approaches corrosion assessment & risk
- In view of these changes
  - Practical corrosion system design approach
  - **Database**
  - Corrosion Djinn for system-wide analysis
  - Star CCM+ for detailed analysis
- Wrap-up summary

Corrosion Analysis – where we are going

- ✓ One electrochemical database – two tools
- ✓ Use Corrosion Djinn tool for aircraft-wide interface analysis, simple geometries and scoping during/after design
  - Takes seconds/ interface
- ✓ Use 3D CAE for the difficult and critical areas
  - Takes hours or days/ interface

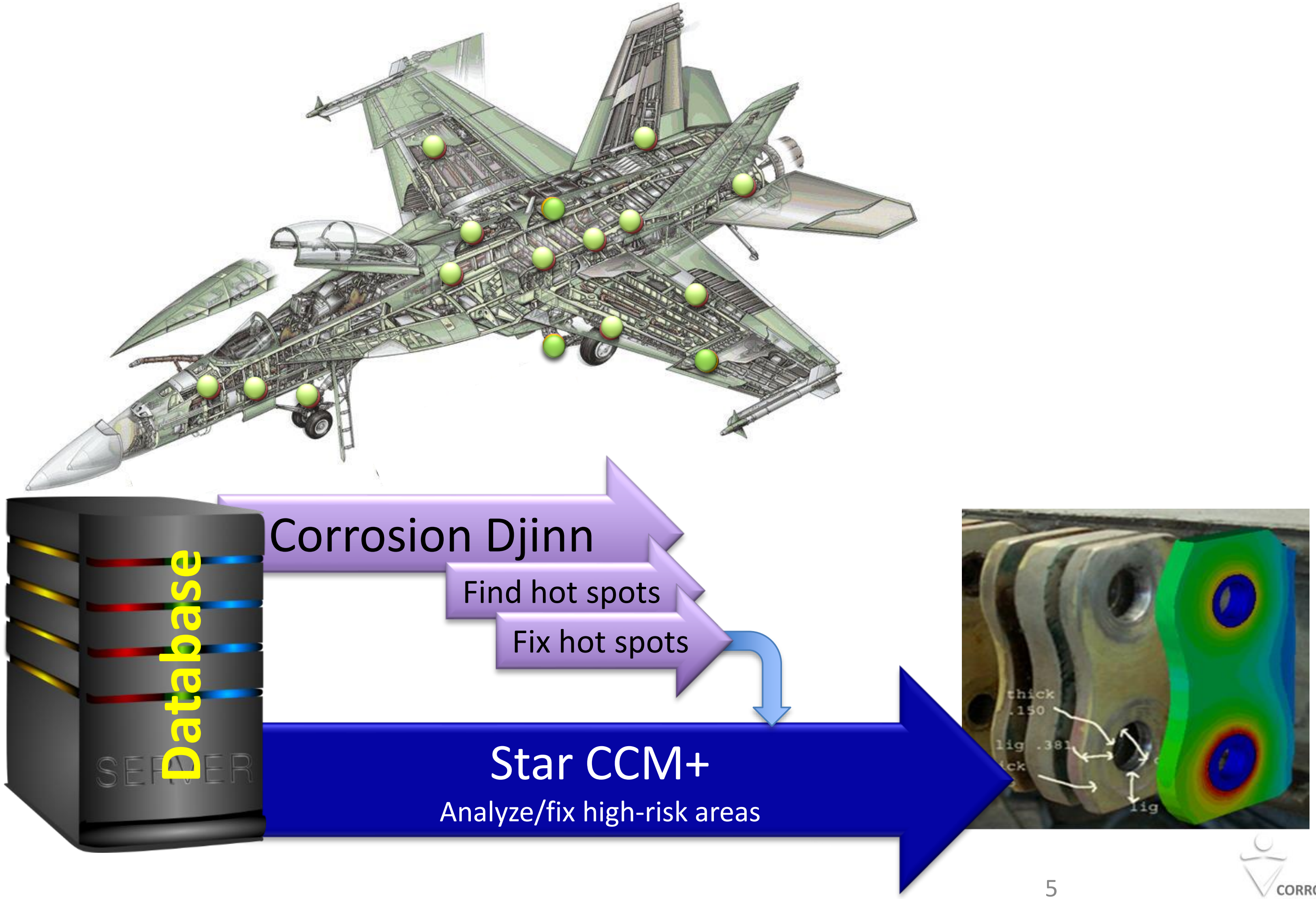
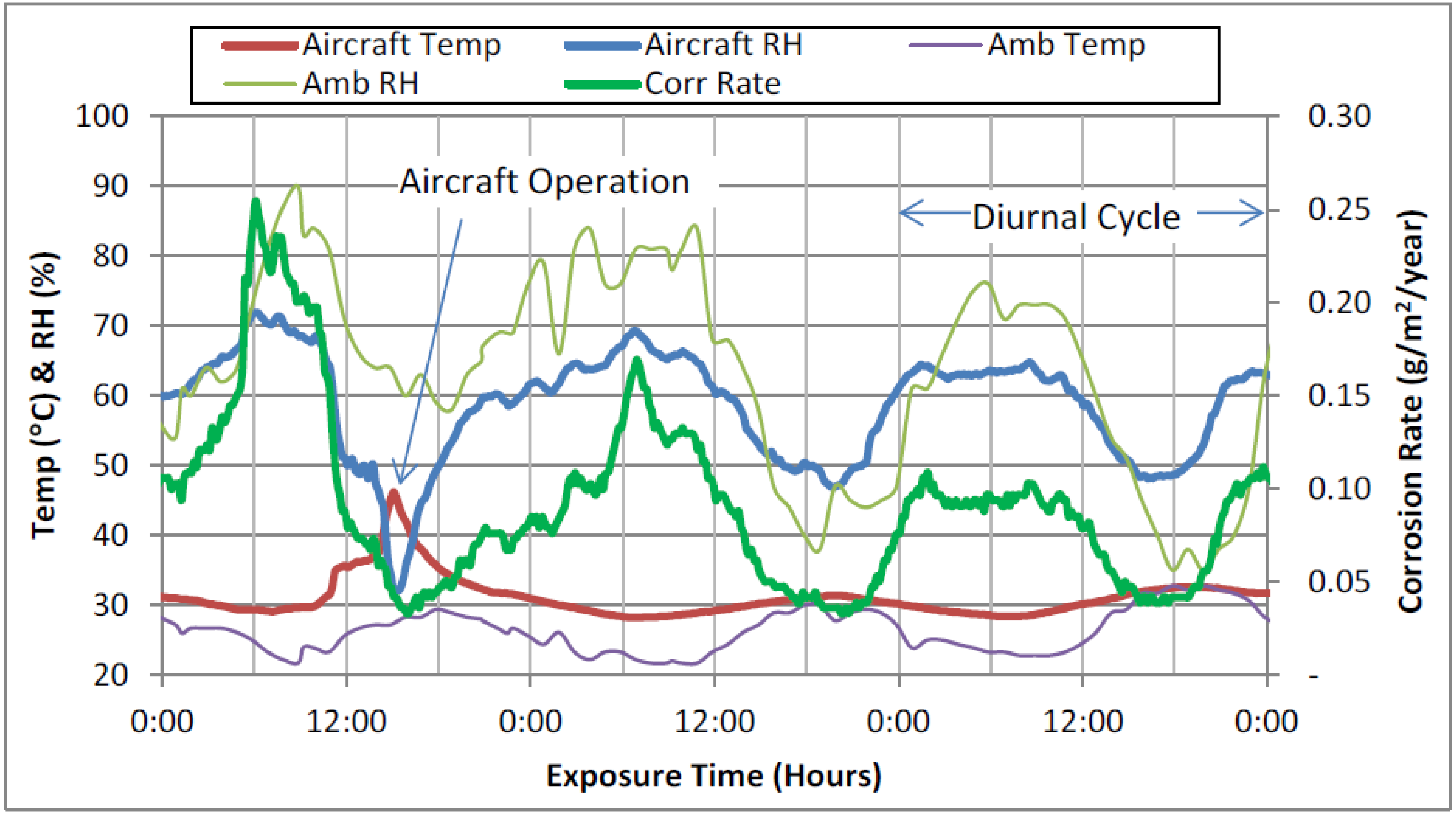


Photo MC3 Matthew Riggs

Environment - Diurnal weather effects

https://lunainc.com/wp-content/uploads/2017/03/Luna-Sensor-Suite-for-Aircraft-Corrosion-Monitoring-LS2A_4Page.pdf



Why is corrosion a big concern?

USS Kitty Hawk in Sea of Japan during a storm

https://youtu.be/Z0Jzb8dfcC4

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F-18 wing and airframe corrosion

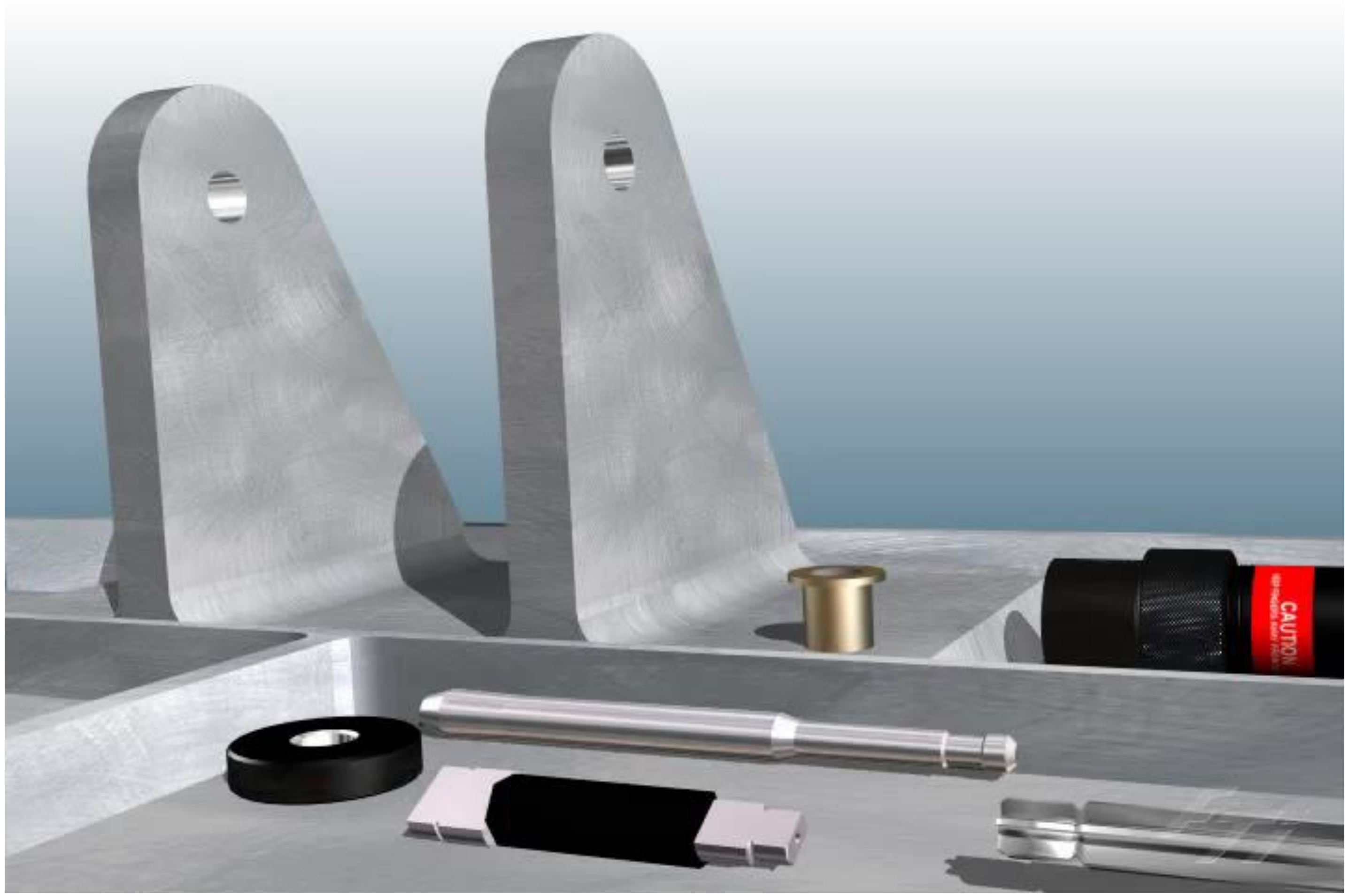
Take the skin of an F-18 and this is what you see

NAVAIR Public Release SPR-2012-982

Repair: Remove corrosion and bush hole with PH stainless; now corrodes even faster around bushing, just as we predict computationally

All of these damaged holes require bushing repair

- Some interfaces are quite simple but numerous
  - e.g. bushings and fasteners throughout the aircraft
  - Bushing installation with Forcemate

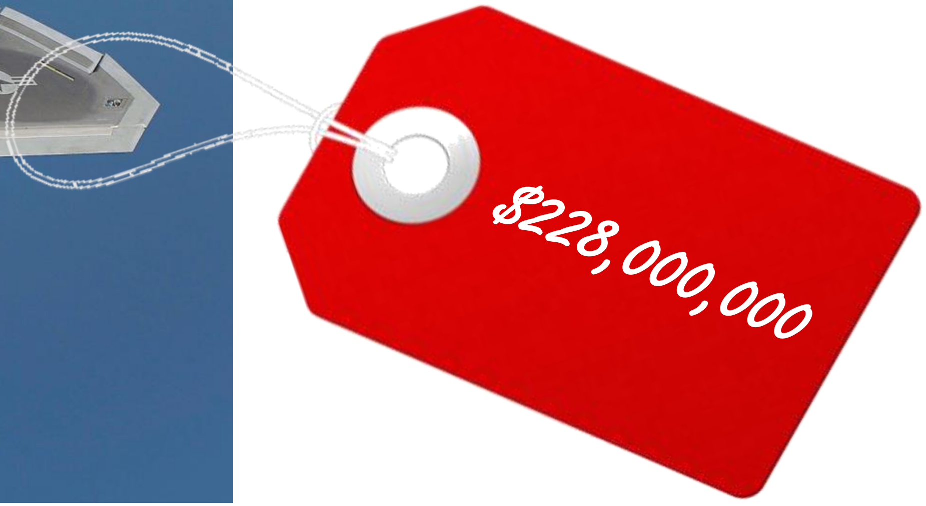


https://youtu.be/TbmwKfIbMHo

Corrosion Problems Persist in New Platforms

DoD Assesses Corrosion Potential on F-35 and F-22

"The root cause of this problem lay within the galvanic couple between the conductive gap filler and aluminum skin panels." Daniel J Dunmire, Director, DoD Corrosion Policy and Oversight Office, reported in CorrdeDefense, Spring 2011, Vol7, Number 1



https://www.f35.com/media/photos

It isn't just military aircraft

- FedEx: Landing gear collapsed during landing
- Wing dragged along ground and fuel ignited
- Cause was stress corrosion cracking in landing gear

https://www.youtube.com/watch?v=qlW_oqqapEc

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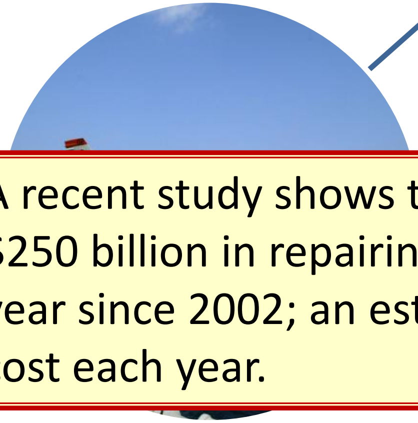
The Corrosion Problem

80% of structural failures stem from corrosion pits – primarily galvanic corrosion

<u>Annually</u>



Cost
- $20.9bn

A recent study shows that the US economy has spent over $250 billion in repairing corrosion damage as a direct cost each year since 2002; an estimated $1 trillion of direct and indirect cost each year.

Readiness
- 25 days unavailable

To make matters worse we are now
- ➢ Lightweighting with incompatible materials (CFCs, Al, Mg)
- ➢ And we can no longer use the old but effective standbys (Cd, Chromates, etc.)
- ➢ **So, we can no longer use the same outdated rule-of-thumb design methods**

Corrosion Resistant Design Philosophy

- Coatings/materials ALWAYS degrade and become damaged
- It is vital to look at ‘what-if’ scenarios, assume failure of some part of the coating stack-up and see what ensues
- We can no longer use wonderful cadmium and chromates, so we have to implement new coating options… quickly
- New acquisitions demand a Corrosion Prevention Control Plan – with substantiating analysis

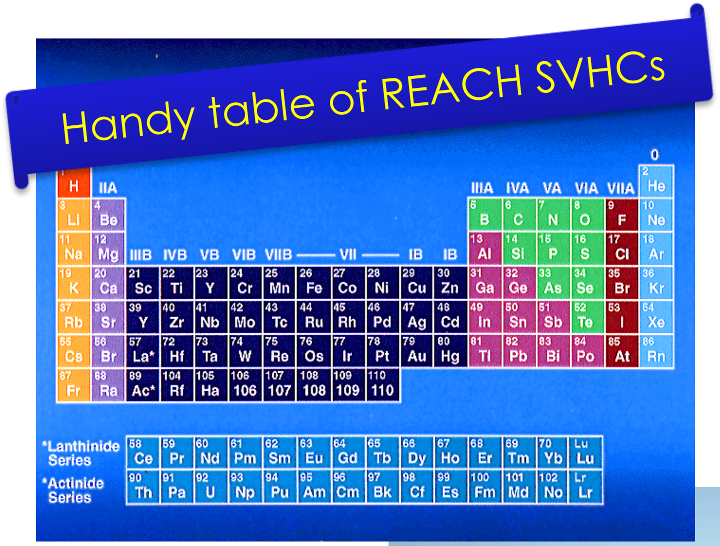
Computational modeling helps to address all of these issues

DoD is increasing emphasis on corrosion

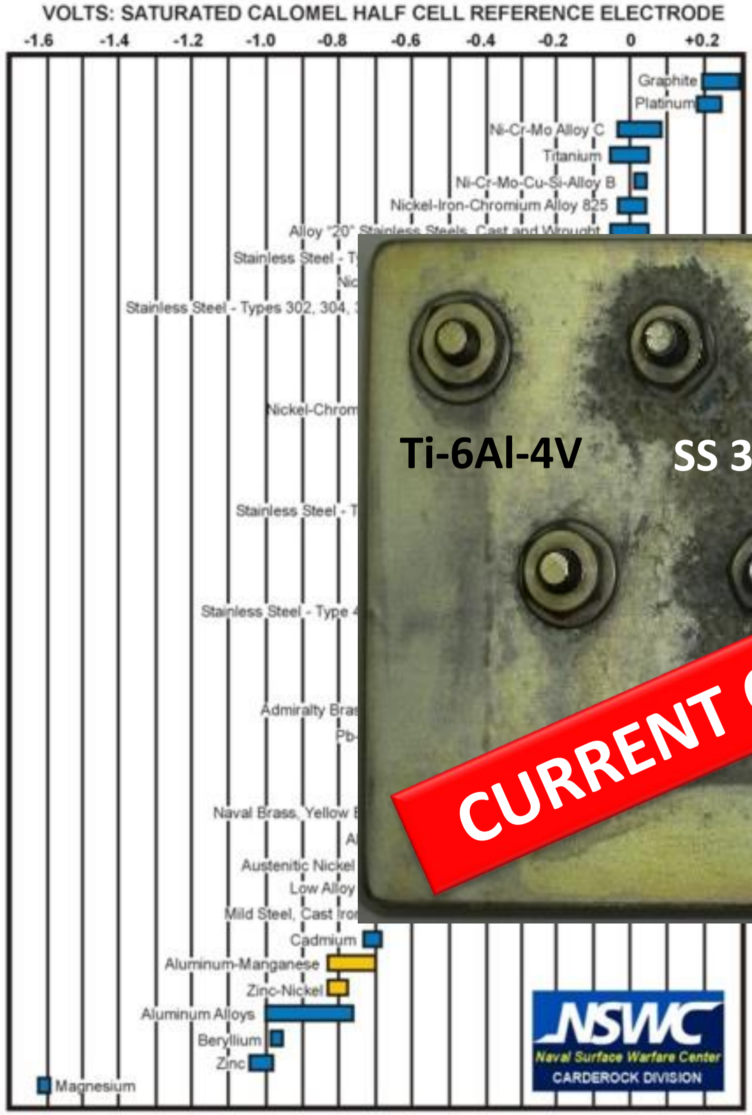
- Corrosion executives
  - Congressionally mandated DoD Corrosion Office
  - Each service has a Corrosion Executive
  - Cost of corrosion analyzed annually
- Corrosion Prevention Advisory Boards for all new systems
- New corrosion test methods under development for better corrosion prediction
- Office of Naval Research Sea-Based-Aviation program developing computational methods for corrosion analysis and prediction to develop "Durable Aircraft"

Materials changes

- European REACH and RoHS environmental regulations
  - Can no longer use cadmium and chromates for corrosion control
  - Affects the entire worldwide industry
- Use of new materials
  - Carbon fiber composite skins on aluminum and titanium airframes

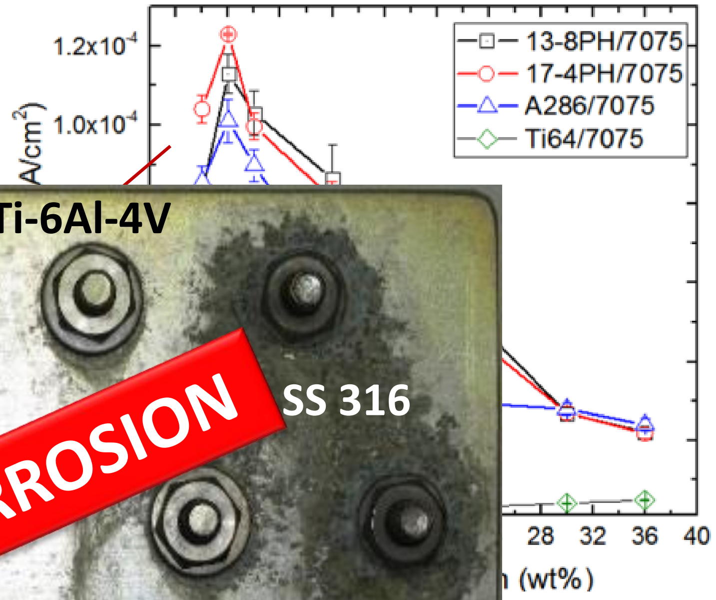


DoD approach to galvanic corrosion is changing

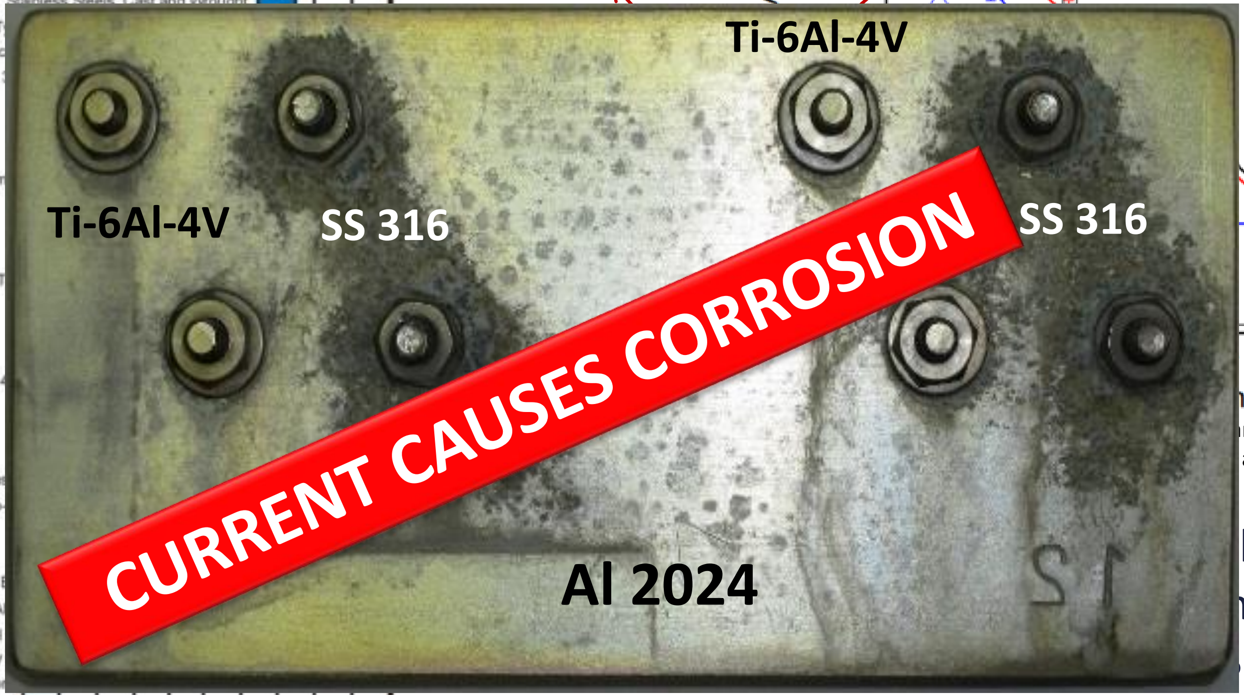


Titanium

Al Alloys



n. A (2018) Galvanic
and Standardization



ls (SS) are a
n titanium
ut, SS result
almost an order of magnitude higher
galvanic current.

Update to MIL-STD-889

Galvanic Compatibility Assessment: New Methodology and Standardization

21 AUG 2018

Presented to: ASETSDefense Workshop 2018

Presented by: Victor Rodriguez-Santiago, Anna Safigan

NAVAIR

NAVAIR Public Release 2018-631. Distribution Statement A – "Approved for public release; distribution is unlimited"

MIL-STD-889: Dissimilar Metals

- **Purpose:** This standard defines and classifies dissimilar metals and establishes requirements for protecting coupled dissimilar metals against corrosion with attention directed to the anodic member of the couple.
- **Modernized Revision:** Current version was modernized in 2016 to replace obsolete references to other standards (MIL-STD-889C).
- **Last Technical Revision:** The last technical revision was done in 1967, based on an AMCOM report (TR-67-11). Was not done in sea water.
- **Proposed Approach:** The proposed approach is to move to galvanic current, rather than potential, in order to determine galvanic compatibility.

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NAVAIR Public Release 2018-631. Distribution Statement A – "Approved for public release; distribution is unlimited" 2

Aim to issue next version end of 2019

What does an updated MIL-STD-889 mean for A&D?

MIL-STD-889 is the standard required of all military aircraft acquisition programs and the old galvanic table approach is used throughout the industry. This will change all aircraft design and we need to be ready to offer design solutions

MIL-STD-889C (August 2016):

"………. the [corrosion] reaction is not controlled solely by difference of potential. The reaction is controlled by polarization of the anode, the cathode or both, and by the resultant galvanic current flow."

Corrdesa is involved in this update as we are part of the SBA Team, concentrating on galvanic corrosion modeling

MIL-STD-889C (~late 2019):

Will include some kind of galvanic current table between a presumably limited number of materials

MIL-STD-889D (~2020-21?):

NAVAIR intends that this version will refer people to methods of calculating corrosion currents between materials, including the mixed potential method (used in Corrosion Djinn)

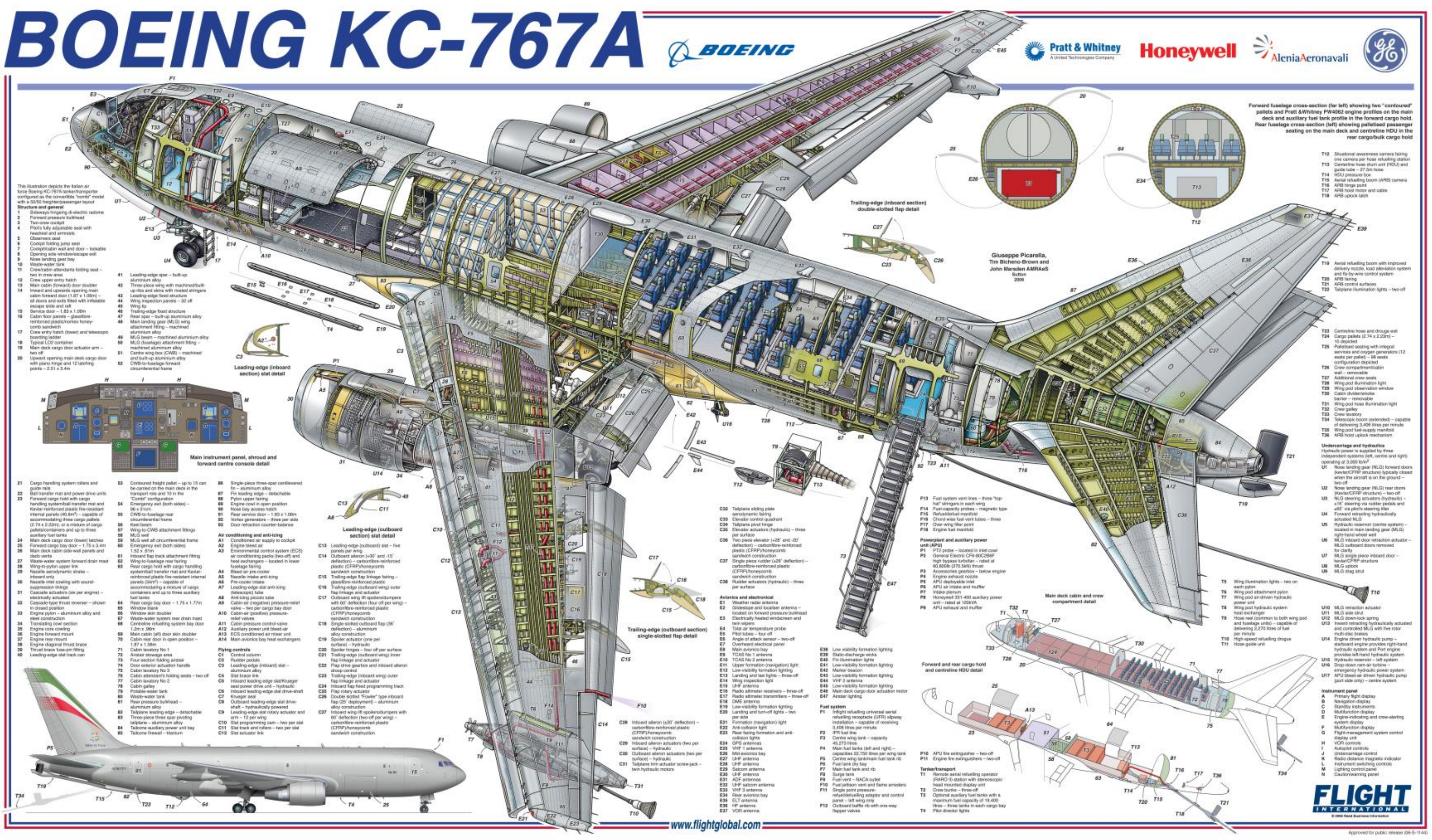
Siemens Teamcenter - PLM

- The use of Product Life Management software is growing
  - Navy and Air Force organizations are beginning to implement Teamcenter
- **If aircraft designers and maintainers are to successfully introduce and use new materials, new coatings, and new methods of making material choices, they must have access to the necessary data and corrosion analysis methods in their design and PLM software**

Leveraging change

- The aim of the SBA program is to implement corrosion modeling and prediction firmly as an essential part of design, like stress analysis, thermal analysis, etc.
- Corrdesa has assembled the elements necessary for accurate analysis:
  - **Database** – an accepted electrochemical database equivalent to MMPDS
    - Including a standardized methodology for data acquisition and reduction
  - A quick and easy way of analyzing corrosion threats throughout the aircraft
    - Suitable for use by the designer
  - An accurate and consistent methodology for detailed analysis that includes electrochemical modeling of corrosion with CFD modeling of the electrolyte
    - Used for complex components and exposure scenarios

How can we tackle this problem?



Corrdesa is beginning a USAF program to apply corrosion analysis to new tankers

- ~70,000 interfaces in airframe
- How many in all the systems?
- How many are problematic?
- How do you even find them all?
- PLM can identify the locations and materials of all the interfaces, bushings, fasteners etc.
- It would take far too long to analyze all those interfaces with CAE
  - But you don't have to
  - The same interface repeats thousands of times
- 80-90% are common/simple items handled by Corrosion Djinn
- The complex ones need Star CCM+

Computational corrosion analysis – database

We use computer simulations throughout the design process:

- Stress analysis
- Thermal analysis
- Fluid flow analysis (CFD)
- Combustion analysis

Why do we not use corrosion simulation?

1. Modeling and simulation is not yet firmly established
2. **Most importantly, there is no recognized electrochemical database of electrochemical data**

“Corrosion MMPDS”

- Corrdesa has assembled an accurate, consistent, curated database of polarization curves and other electrochemical data using accepted Best Practices developed with the SBA Team
  - Will include all NAVAIR aerospace data
  - Data for materials used by other industries


Metallic Materials Properties Development and Standardization (MMPDS)

CORROSION

MMPDS-12

COMPLETE

July 2017

Scientific Source:
Metallic Materials design data acceptable to Government procuring or certification agencies.

A joint effort of government, industrial, educational, and international aerospace organizations.

MMPDS-12

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Best Practices for Polarization data Acquisition

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

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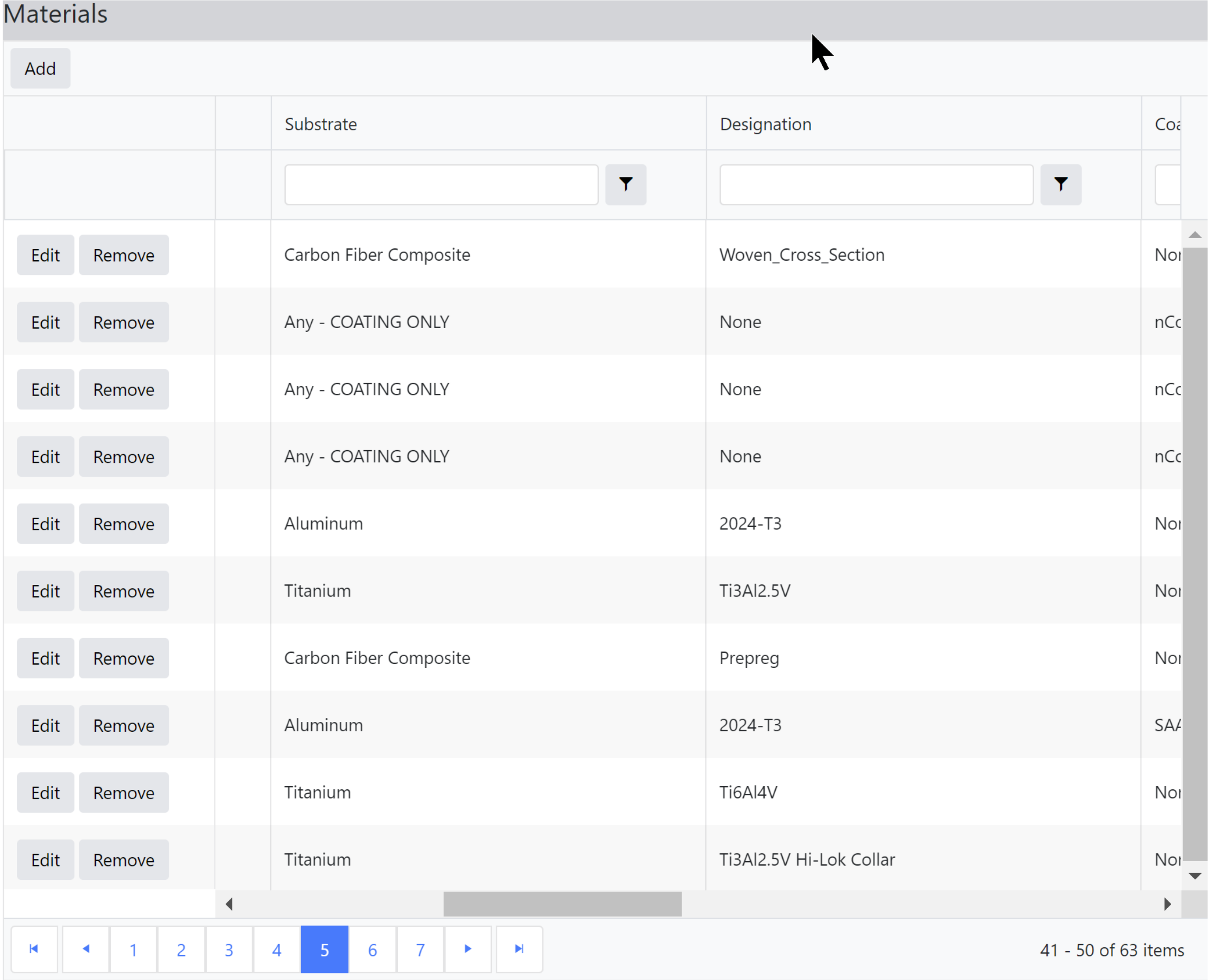
anna.safigan@navy.mil

March 2018

- For this to work the underlying data MUST be acquired in a consistent way
- Corrdesa has worked with ONR and NAVAIR to develop the Best Practices for polarization data acquisition
- Modified to create the Best Practices used for an international Round Robin to validate the methodology
- Database built only on data meeting Best Practices requirements

Constantly growing database

Currently ~70 materials, coatings, finishes. More being added all the time



Materials

Add

	Substrate	Designation	Coa
Edit Remove	Carbon Fiber Composite	Woven_Cross_Section	Nor
Edit Remove	Any - COATING ONLY	None	nCo
Edit Remove	Any - COATING ONLY	None	nCo
Edit Remove	Any - COATING ONLY	None	nCo
Edit Remove	Aluminum	2024-T3	Nor
Edit Remove	Titanium	Ti3Al2.5V	Nor
Edit Remove	Carbon Fiber Composite	Prepreg	Nor
Edit Remove	Aluminum	2024-T3	SAA
Edit Remove	Titanium	Ti6Al4V	Nor
Edit Remove	Titanium	Ti3Al2.5V Hi-Lok Collar	Nor

1 2 3 4 5 6 7

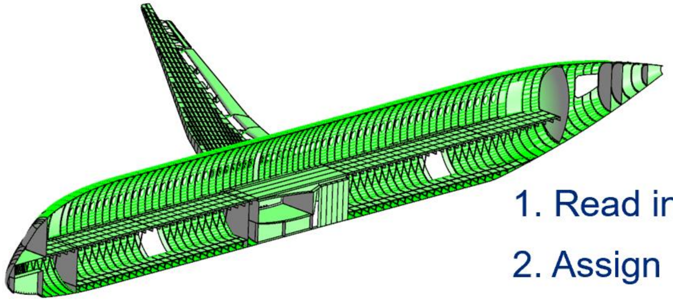
41 - 50 of 63 items

Approach being developed by Boeing

Galvanic Corrosion Risk – *Greater than the sum of the parts*

Kristen Williams, Boeing
ASETSDefense Workshop
2018

Example: Notional geometric model of commercial aircraft. Random assignment of materials.



1. Read in aircraft geometry
2. Assign materials to geometry
3. Build material contact list
4. Build corrosion lookup table
5. Calculate corrosion rates on material contacts
6. Aggregate surface risks
7. Create visualization plots

```
*****************************************************************************
RACE B787-900 EXAMPLE CORROSION DEMONSTRATION CODE: CONCEPT #1
    Joel Thompson
    Applied Mathematician
    richard.j.thompson3@boeing.com
    256-464-7681
*****************************************************************************
Reading RACE B787-900 aircraft geometry...
    ...found 3076 aircraft parts
Randomizing material assignments to the 787 aircraft manifest...
Building 787 connectivity mapping...
    ...building bounding box information around aircraft parts...
    ...built 3076 bounding boxes
Building 787 material contact list...
    ...built 73380 material contacts.
Building corrosion property lookup table...
    ...built 2209 table elements
Calculating corrosion properties...
    ...pinging 73380 requests to the corrosion tool...
    (took 319.00ms to calculate corrosion properties...)
Calculating aggregate corrosion risks on aircraft parts...
    (took 2.50m to aggregate corrosion risks...)
Rendering aggregate risk color plot...
total program execution time: 6.15m
```

3076 parts

73380 material contacts!

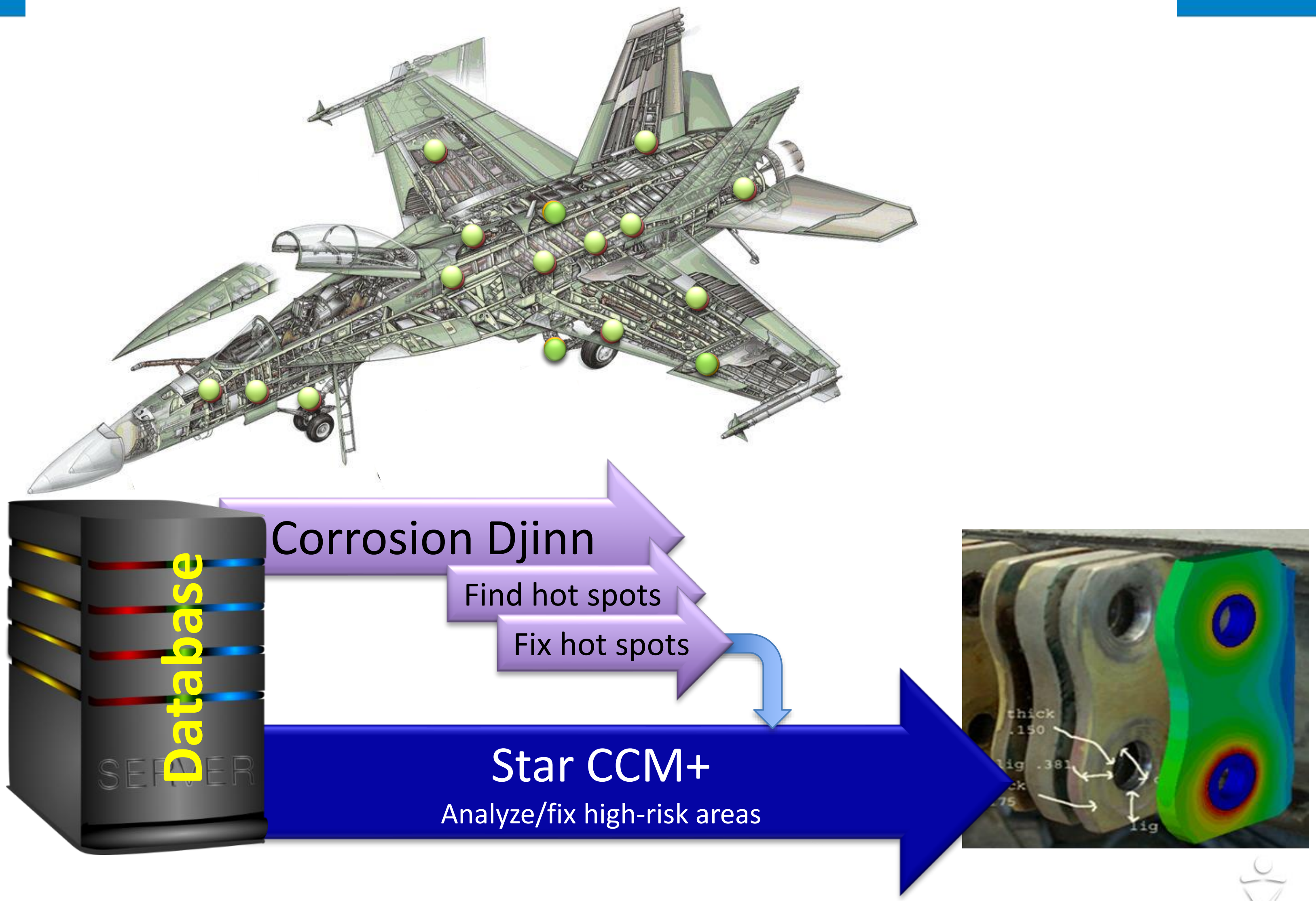
Note: Aircraft model is notional and does not correspond to a formal engineering drawing.

ASETSDefense Workshop, August 21-23, 2018
EAR99 – No License Required

Thompson, R.J., et al. U.S. Patent Application No. 15,213,116 (2016)

Corrdesa corrosion analysis engineering workflow

- ✓ One electrochemical database – two tools
- ✓ Use Corrosion Djinn tool for aircraft-wide interface analysis, simple geometries and scoping during/after design
  - Takes seconds/ interface
- ✓ Reserve 3D CAE for the difficult and critical areas
  - Takes hours or days/ interface



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Polarization curves – curve crossing

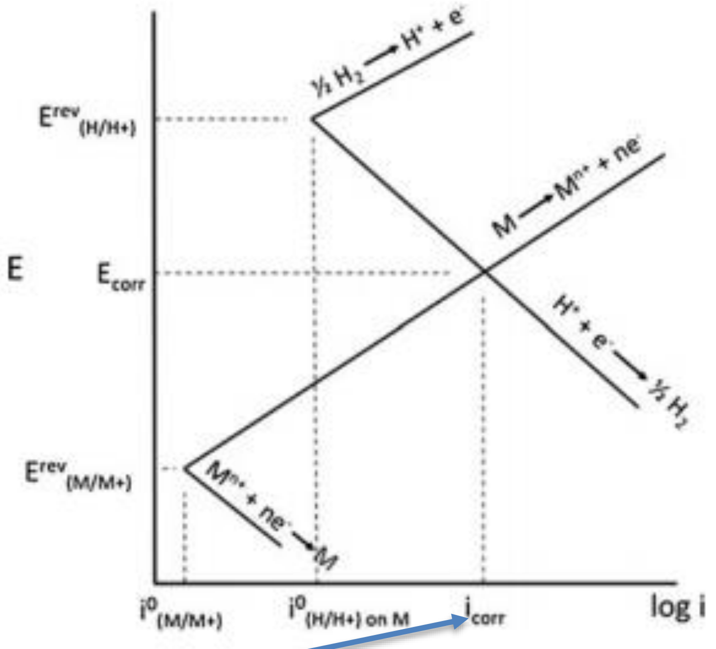
Based on the well-established mixed potential principle

By charge conservation:

to avoid the accumulation of charge on a freely-immersed electrode, the sum of all of the oxidation currents must equal the sum of all of the reduction currents

So at our metal interface, we will reach a mixed potential between the material OCPs and this crossing point will define the corrosion current

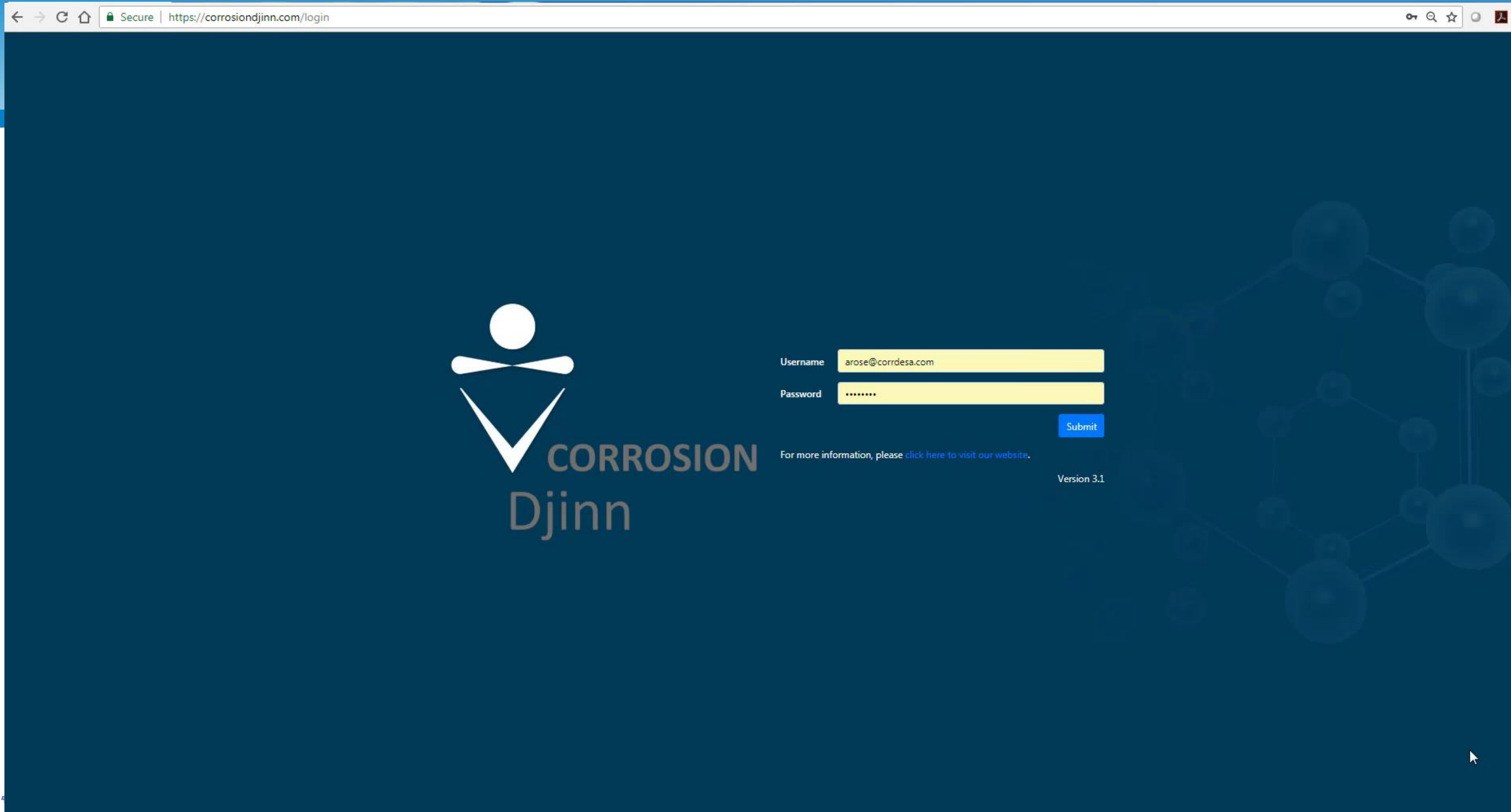
Djinn comprises a database of material polarization curves, each measured against a single reference (SCE) and when the user chooses the materials the respect anodic and cathodic components are intersected to calculate the **corrosion current**



Evans Diagram
(GS Frankel Corrosion Kinetics)

This is how we evaluate large numbers of simple interfaces

Computerized as Corrosion Djinn with our database it takes a few seconds to analyze a galvanic couple, and a few minutes to identify optimal materials or coatings


Secure
https://corrosiondjinn.com/login
CORROSION
Djinn
Username
arose@corrdesa.com
Password
Submit
For more information, please click here to visit our website.
Version 3.1

Summary of galvanic couple

Group 1 +

Material Group

Modify Copy

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

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Identifies anodic and cathodic materials

Group 1 +

Material Group

Material 1 (Anode)

Substrate Al

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

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

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Reports Open Circuit Potentials (OCP)

Group 1 +

Material Group

Modify Copy

Environment 3.5% NaCl

-7.18e-1 V_{SCE}

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 (Cat

Substrate Stai

Designation 15-5

Coating Non

Treatment Non

3.79e-2 V_{SCE}

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

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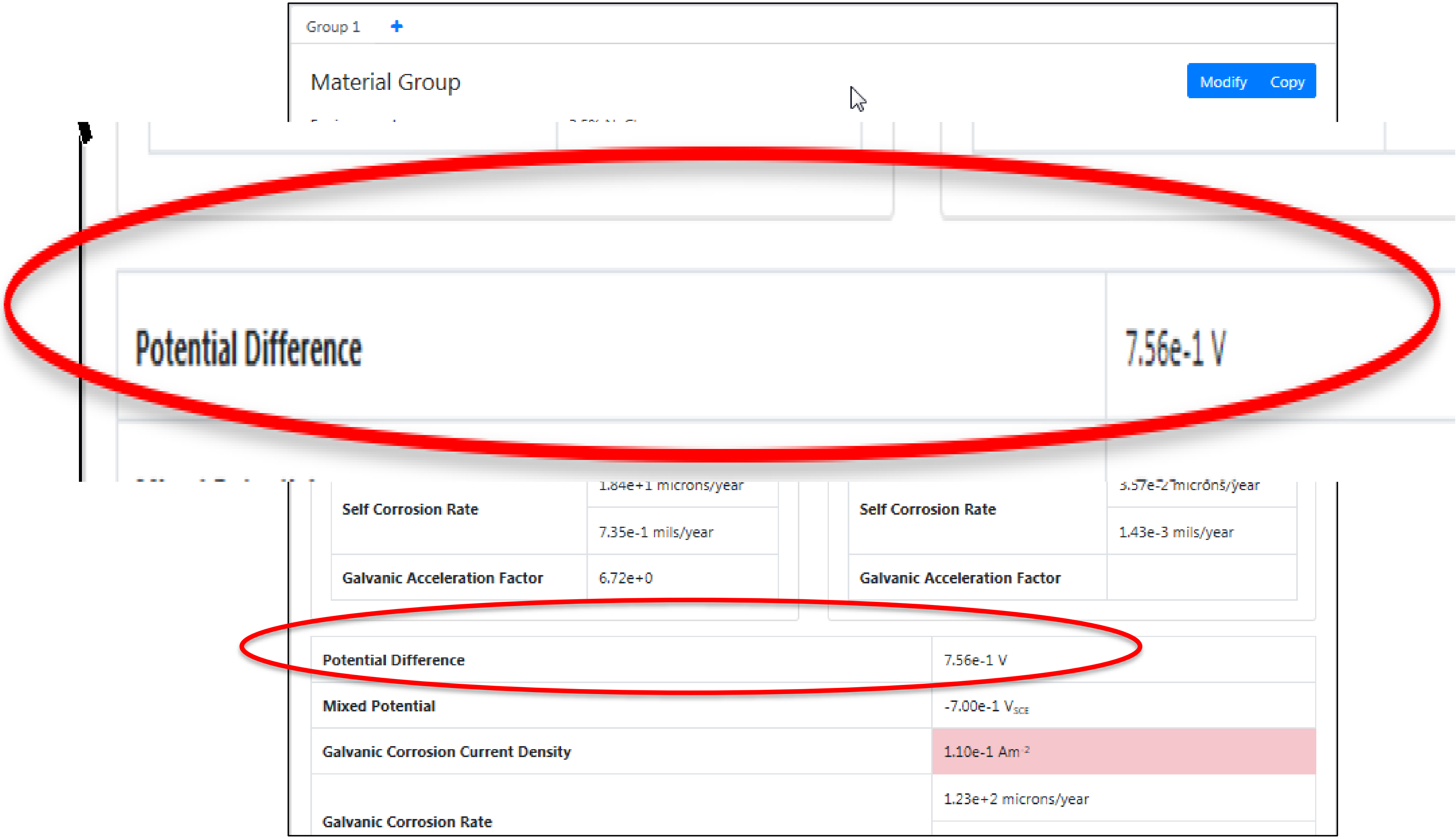
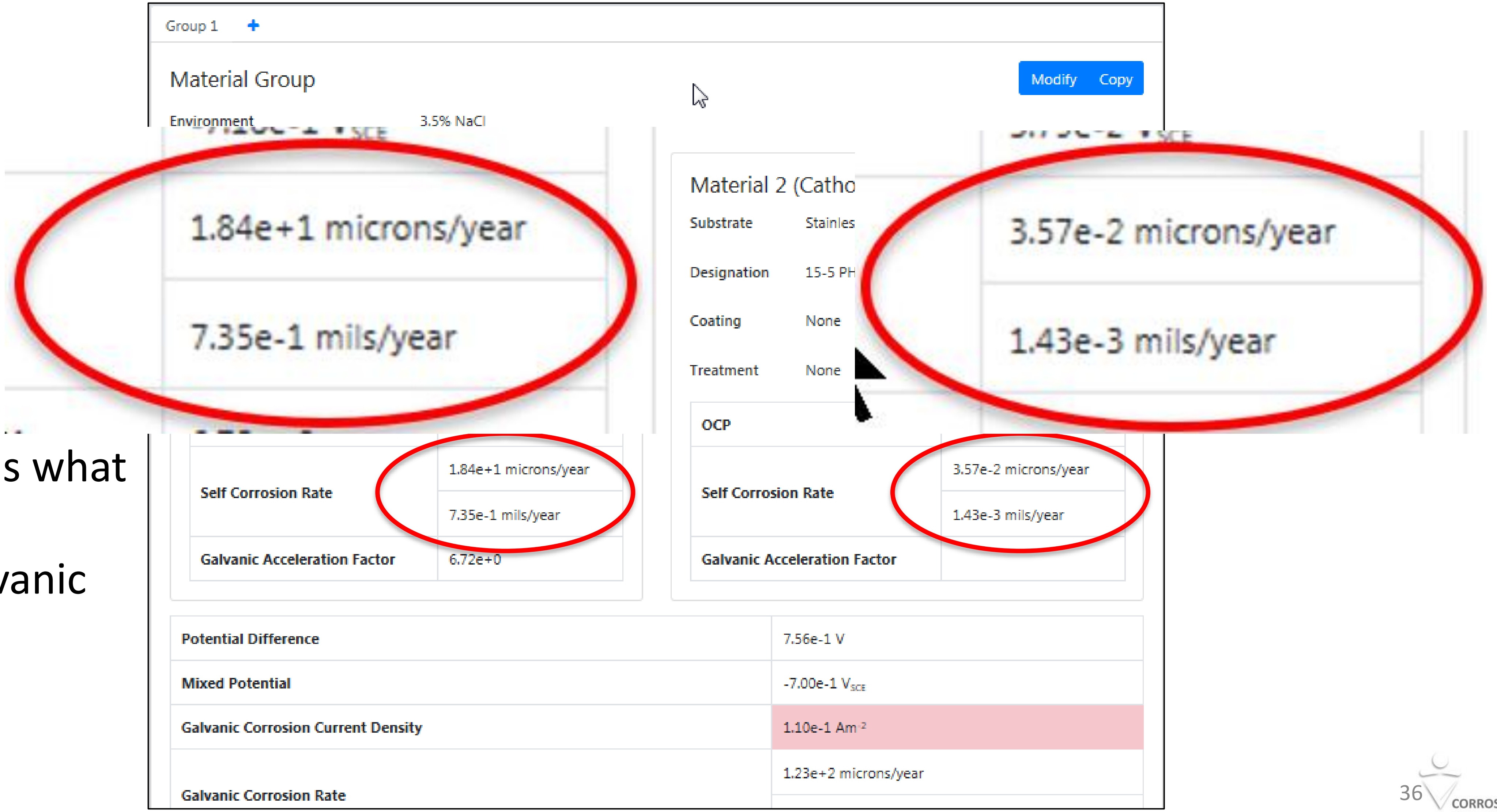
Reports potential difference



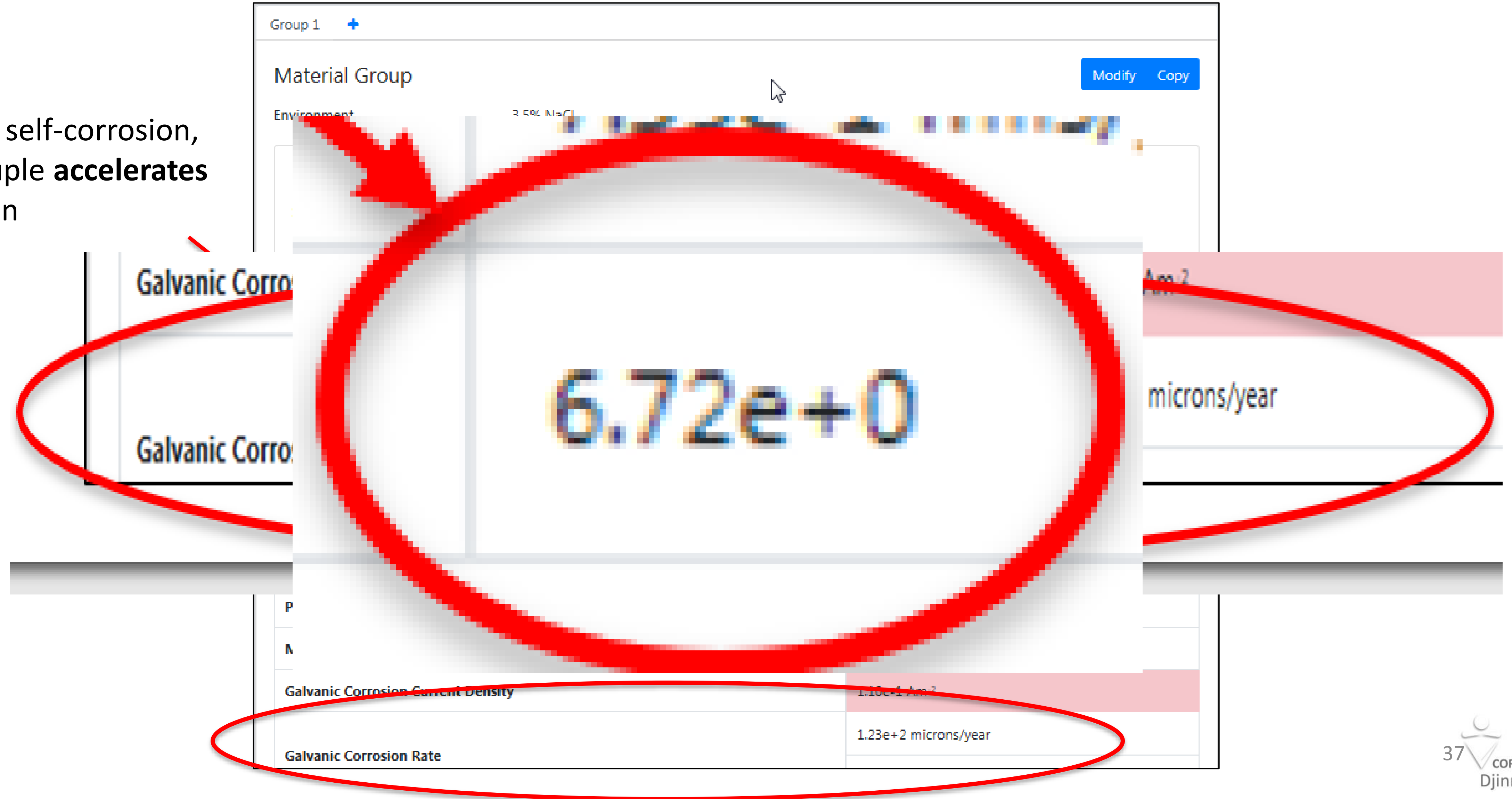
Reports self corrosion rates



Self-corrosion is what happens in the absence of galvanic interactions

Reports galvanic corrosion **rate**

Despite low self-corrosion, galvanic couple **accelerates** the corrosion



When complexity demands 3D CAE

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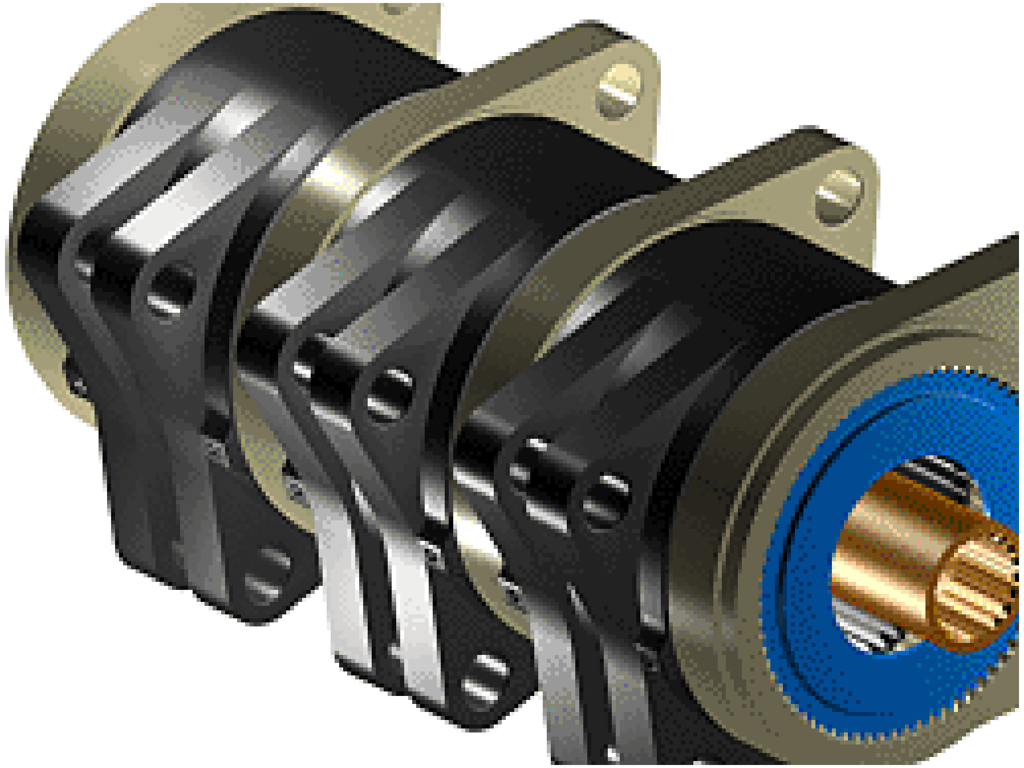
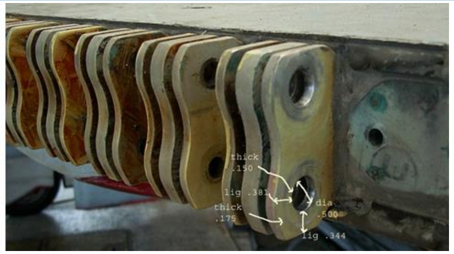
When complexity demands 3D CAE

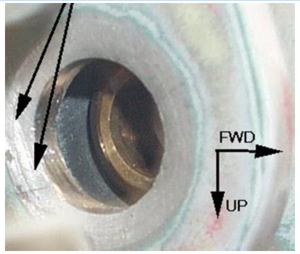
- On average, over 2,400,000 fasteners are used to assemble a single Boeing 787 aircraft.
- 1500 fasteners in forward fuselage, 3000 in each wing for F-35
- Rotary Gear Actuators (RGAs) for leading-edge flaps
- Even bushings and fasteners – thousands in every aircraft



Galvanic corrosion prediction workflow

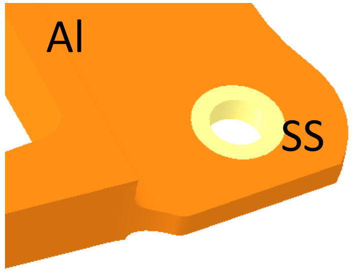
Define the problem



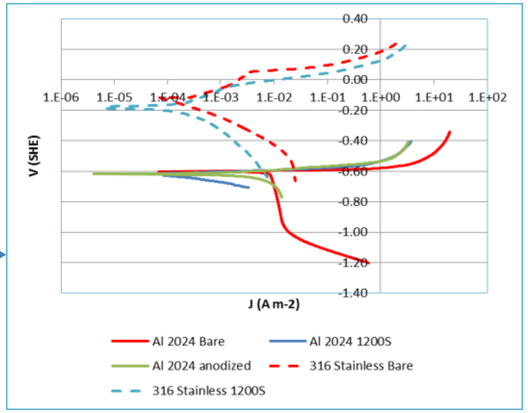


Acquire the assembly geometry

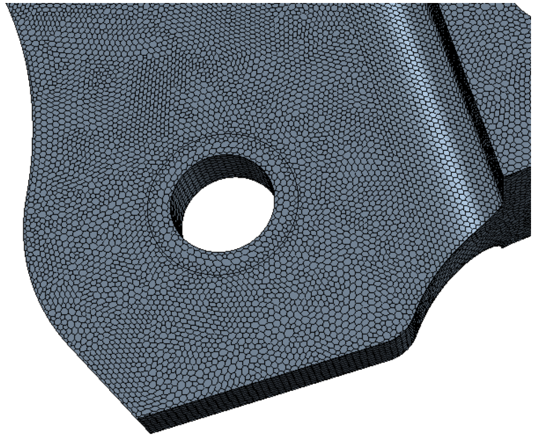
Define the assembly materials/finishes



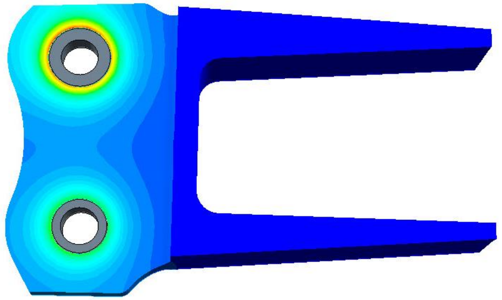
Define environment & electrochemistry



Build the galvanic model



Evaluate design options



Impact of electrolyte thickness

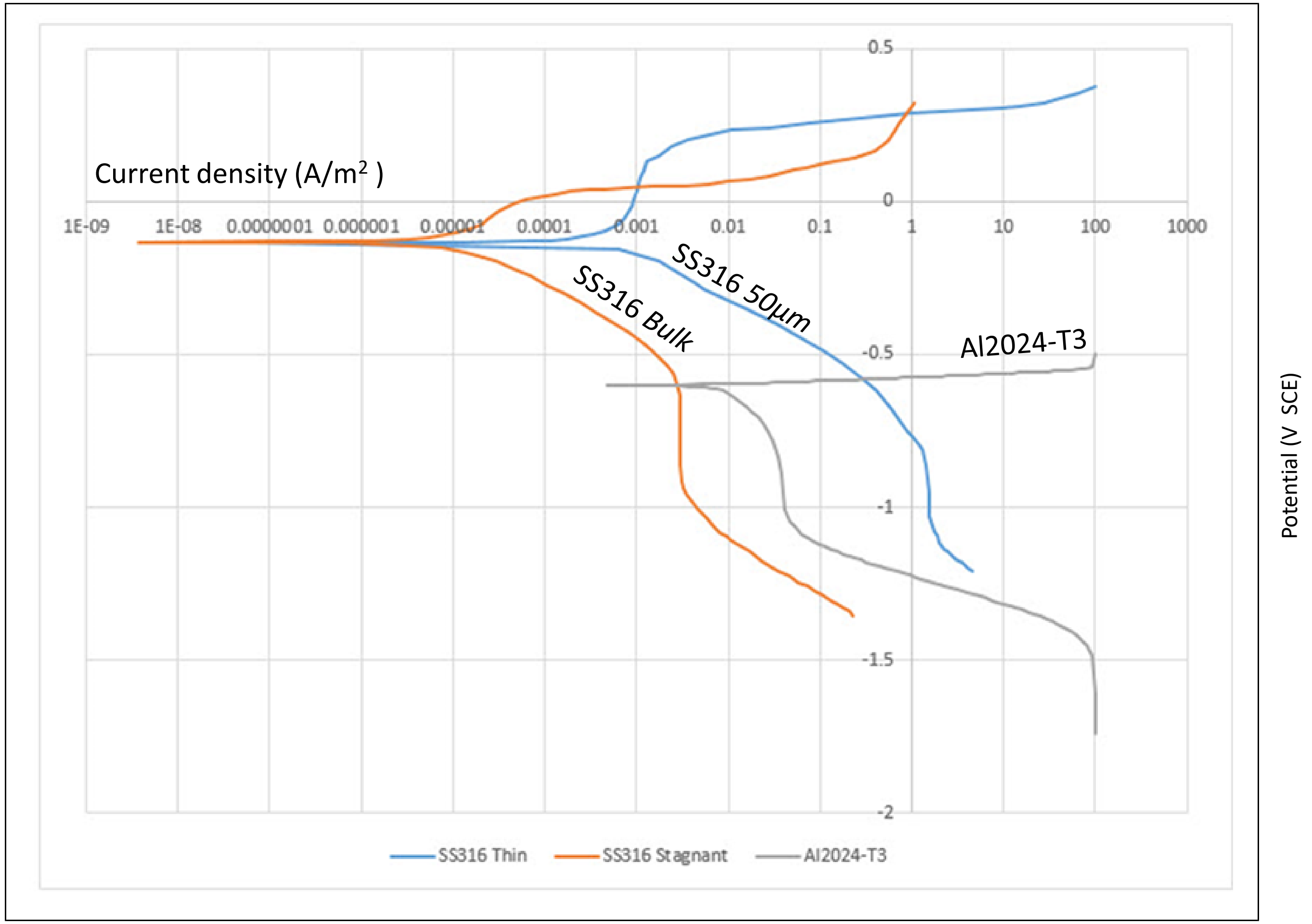


Figure 5: Polarization curves for 2024-T3 Al (gray), versus 316 stainless steel under stagnant (bulk) conditions (orange) and 50 µm thin-film conditions (blue).

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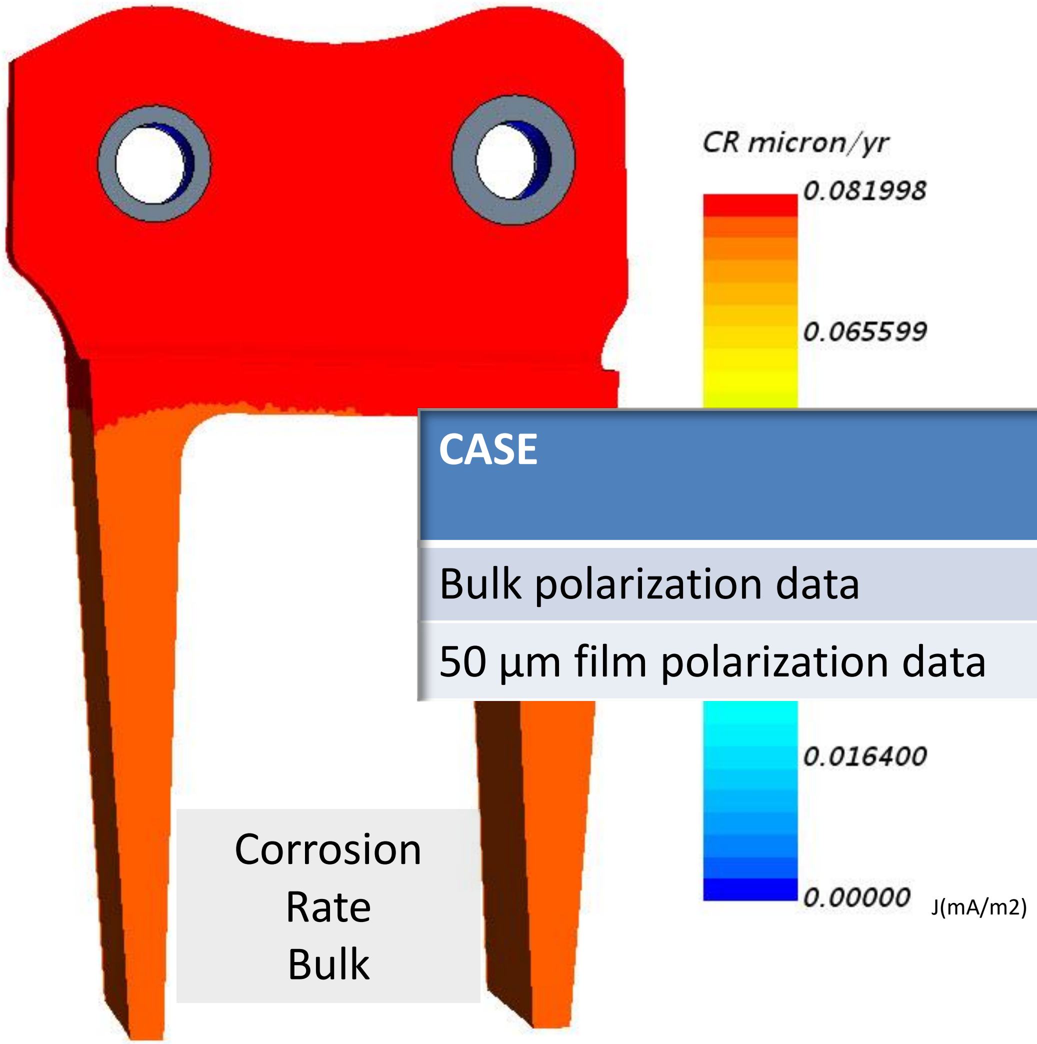
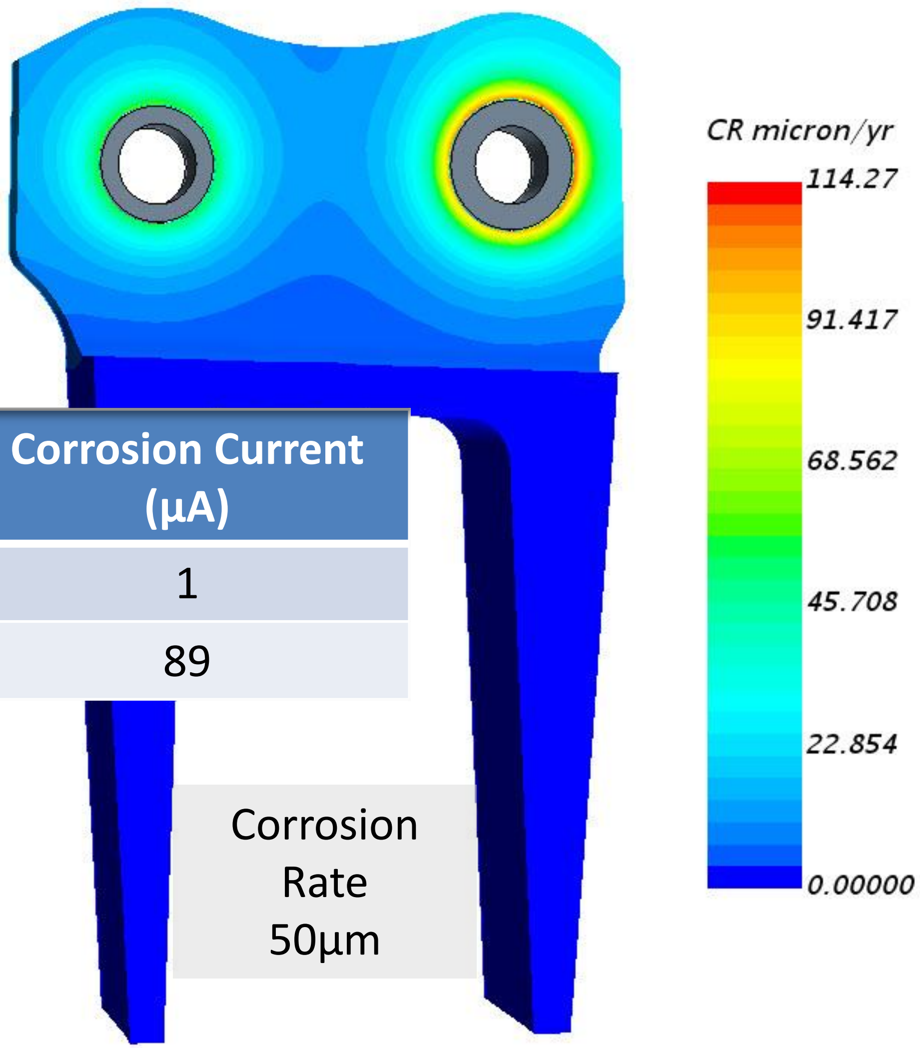
CORROSION Djinn

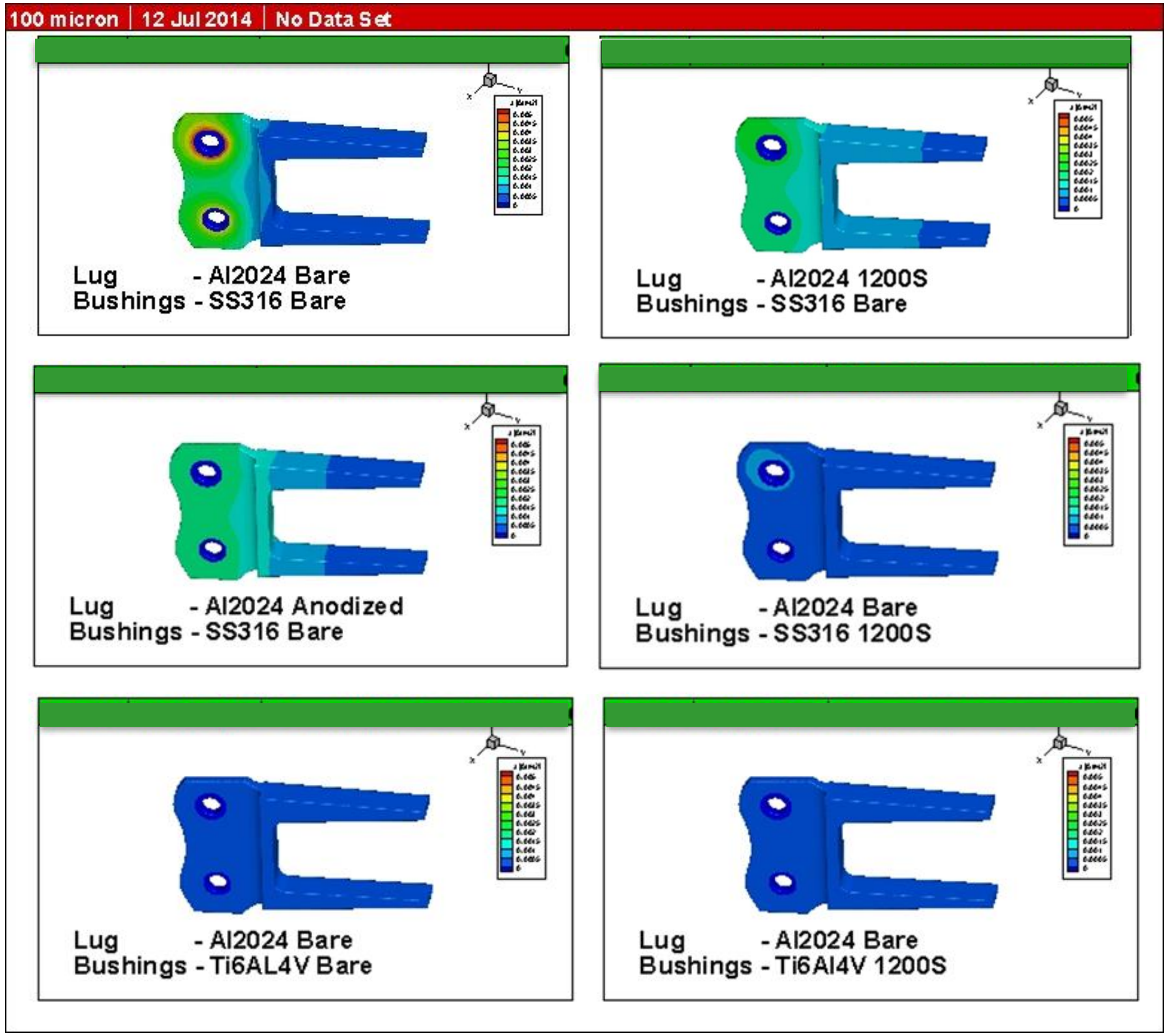
3D CAE model – uncoated lug/bushing



CASE	Corrosion Current (µA)
Bulk polarization data	1
50 µm film polarization data	89



Compare the options



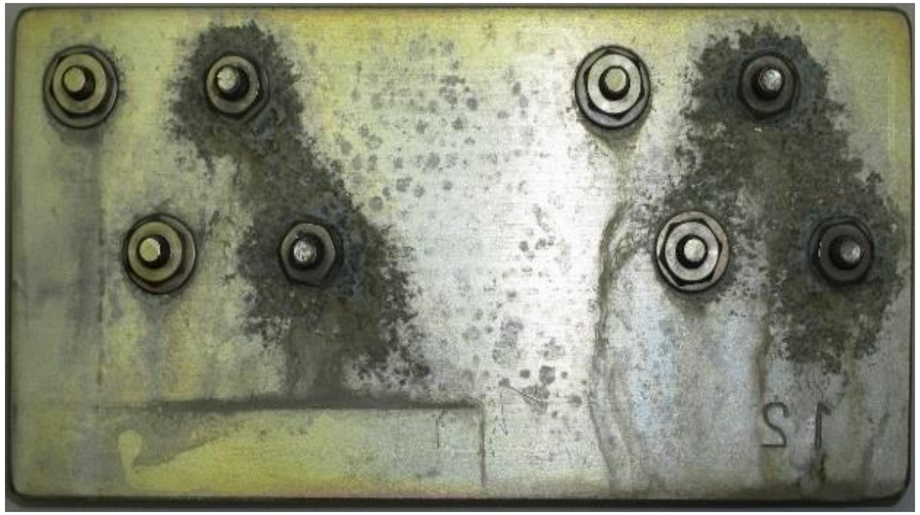
Results shown in order of reduced corrosion current.

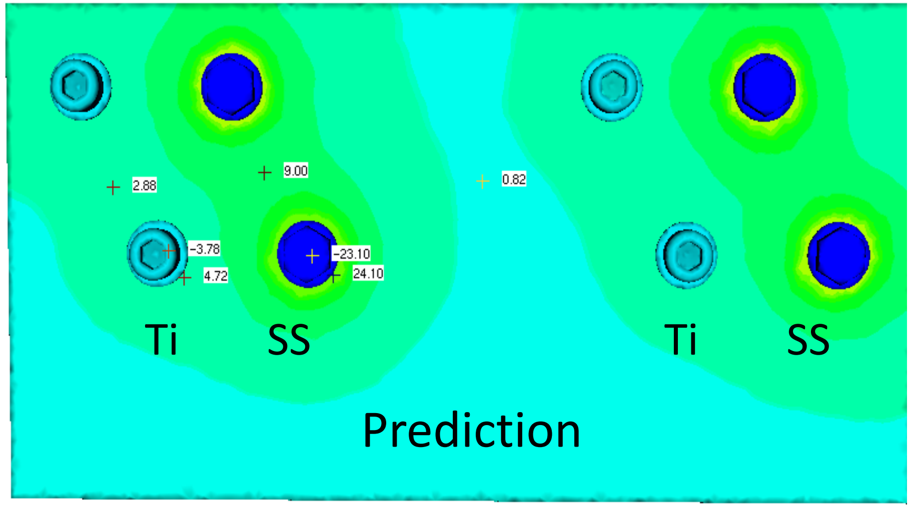
Note: The total corrosion current, and therefore relative order of the coating and treatment options is the same for curve crossing analysis and 3D CAE.

3D CAE also gives the corrosion pattern and therefore the corrosion current density at the interface

VV&A? - NAVAIR Galvanic Coupons

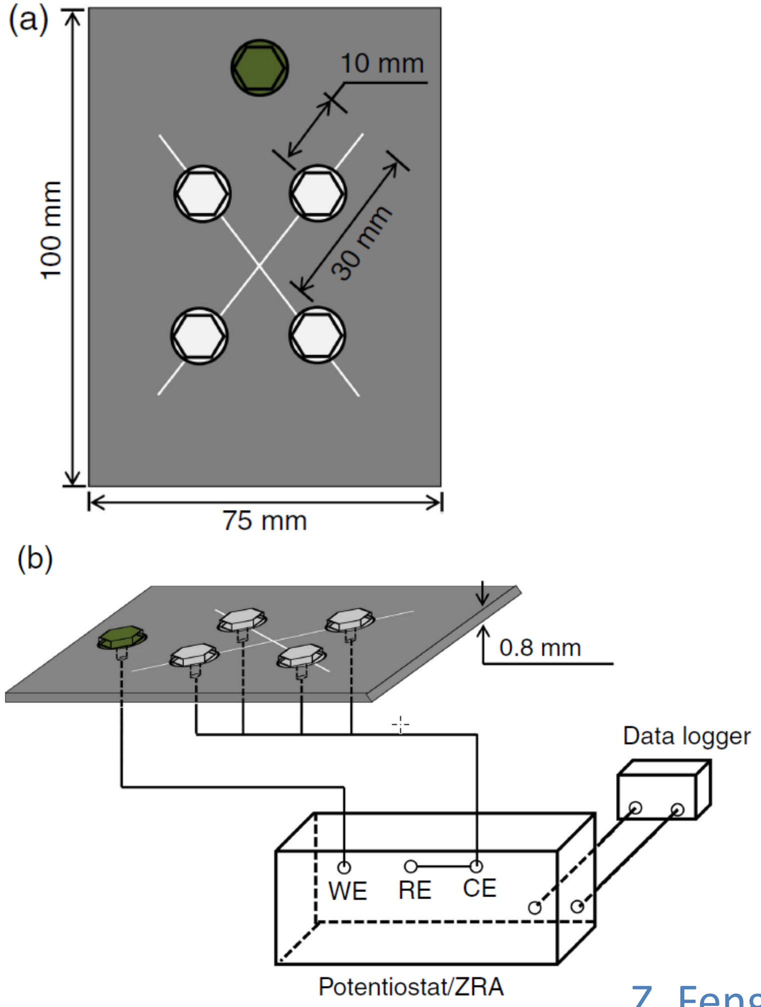
Reality

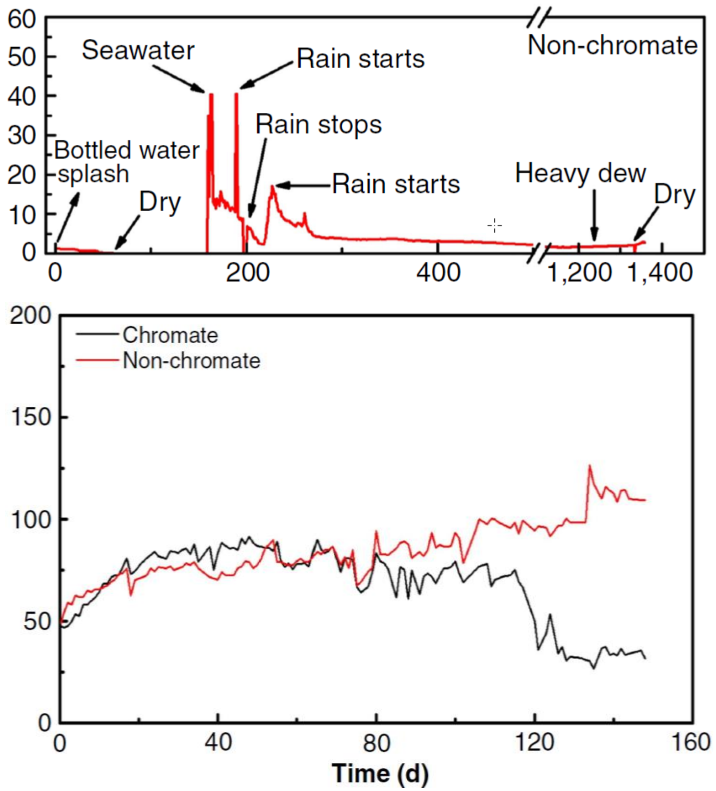


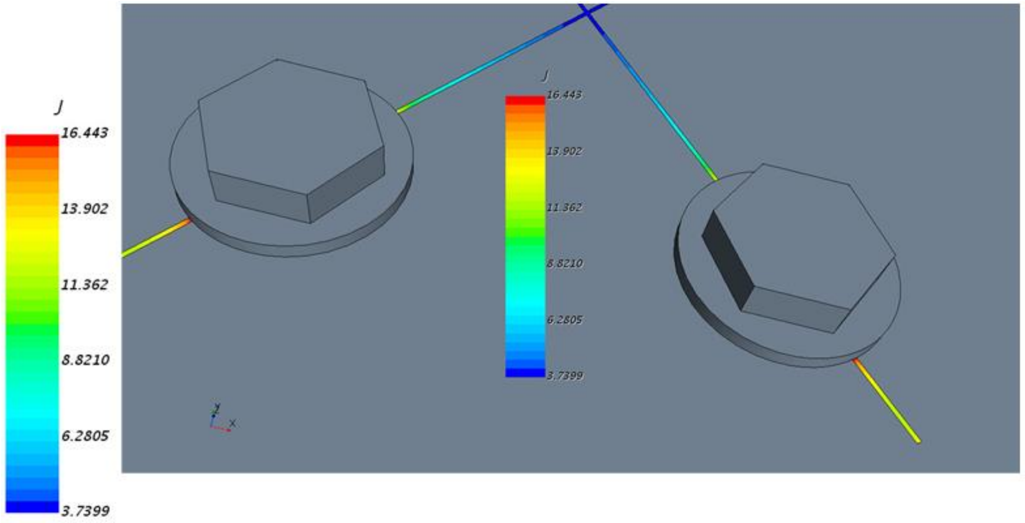


Prediction

ASTM B117 vs Fielded Coupons







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.

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.

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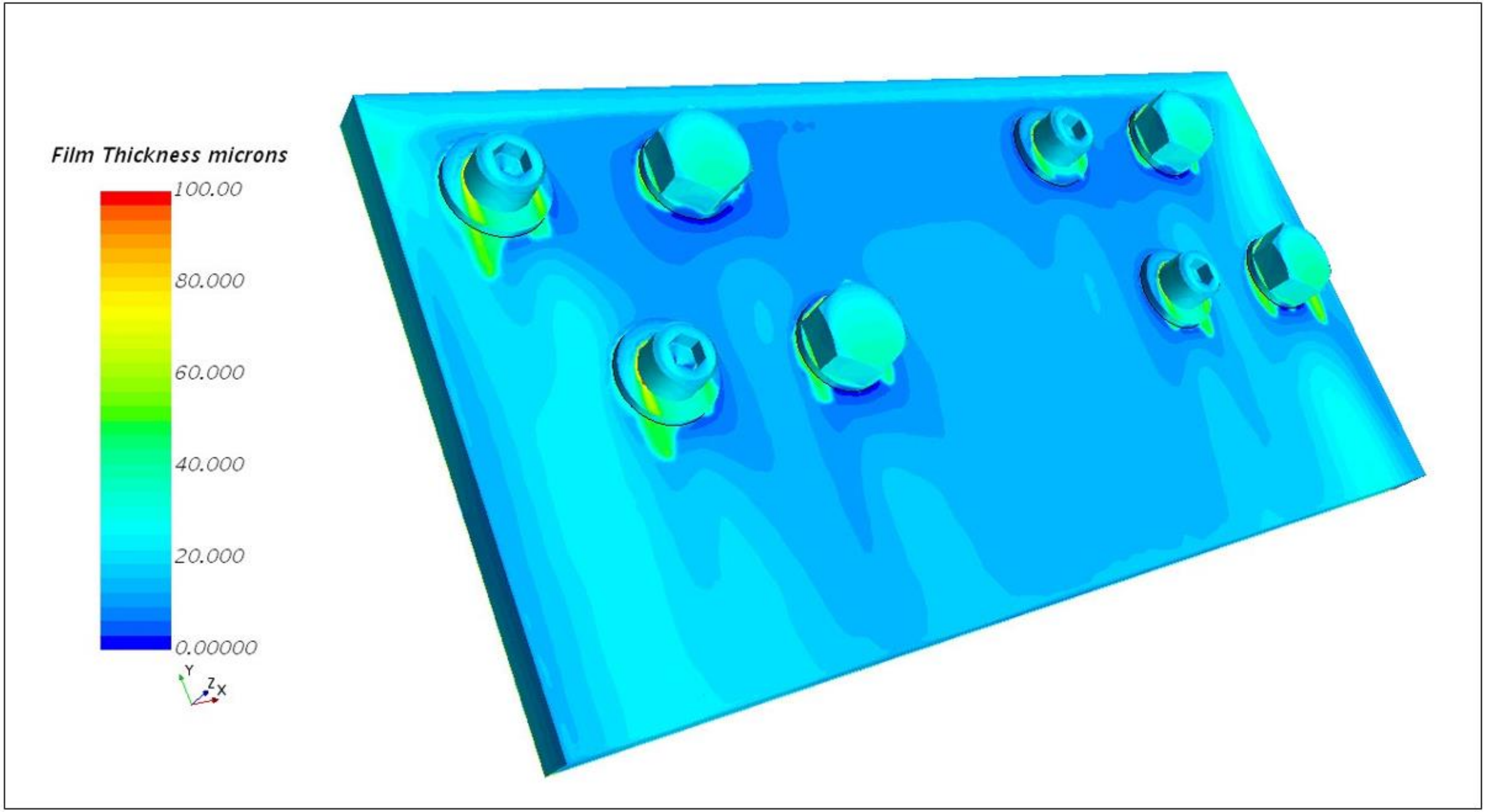
Initial fluid film thickness simulations



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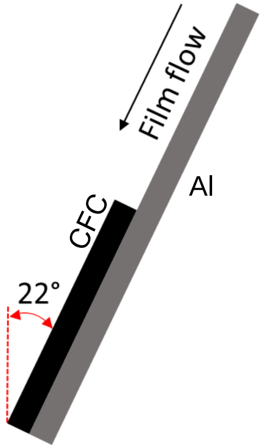
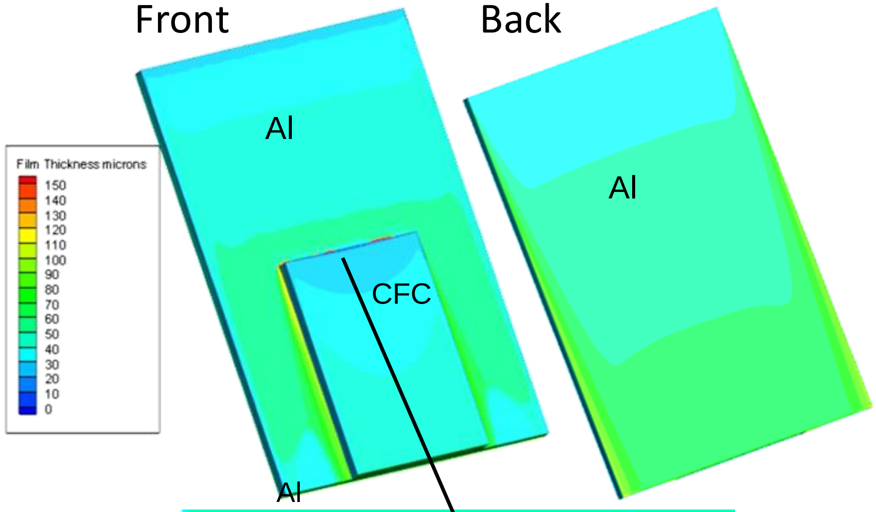
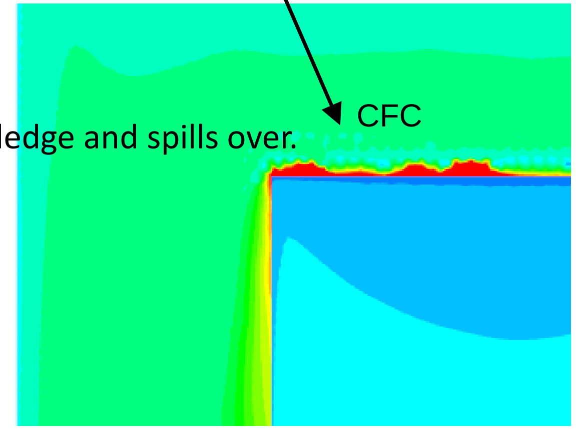
Results (Fluid Film Modeling)

Side View:



Front & Back View:





Electrolyte builds up at ledge and spills over. Thick down sides.

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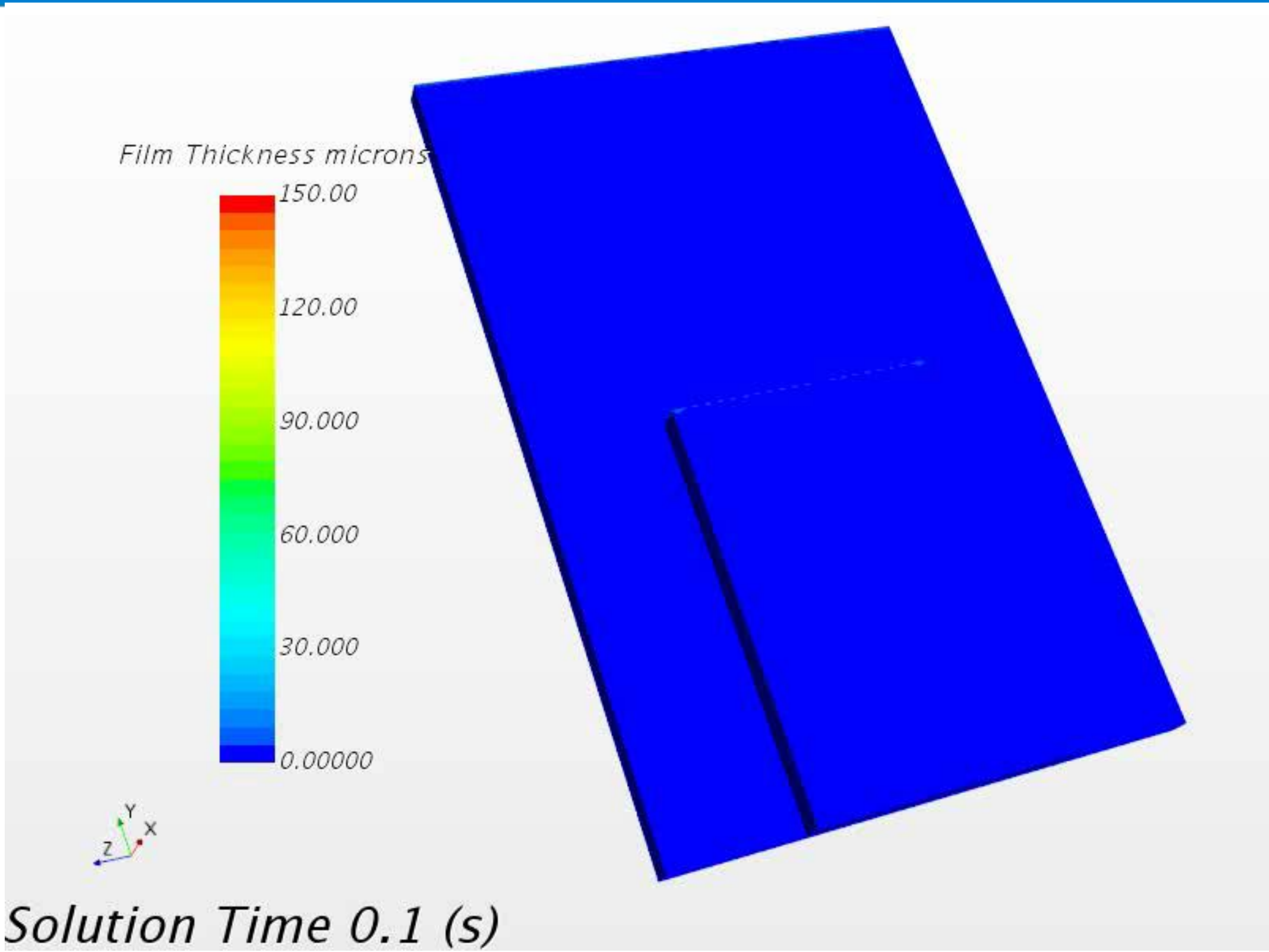
- Fluid flow
- Heat transfer
- Multi-phase, to capture
  - water vapor, ambient air
  - water liquid

Key Assumptions: Filmwise condensation (from gaseous to liquid)

Palani, S., Rose, A., Legg, K., Modelling Galvanic Corrosion Behavior of Carbon Fiber Composite/Al-7050 Joints under Extended Exposures. 2017 Department of Defense - Allied Nations Technical Corrosion.

Results (Fluid Film Modeling)



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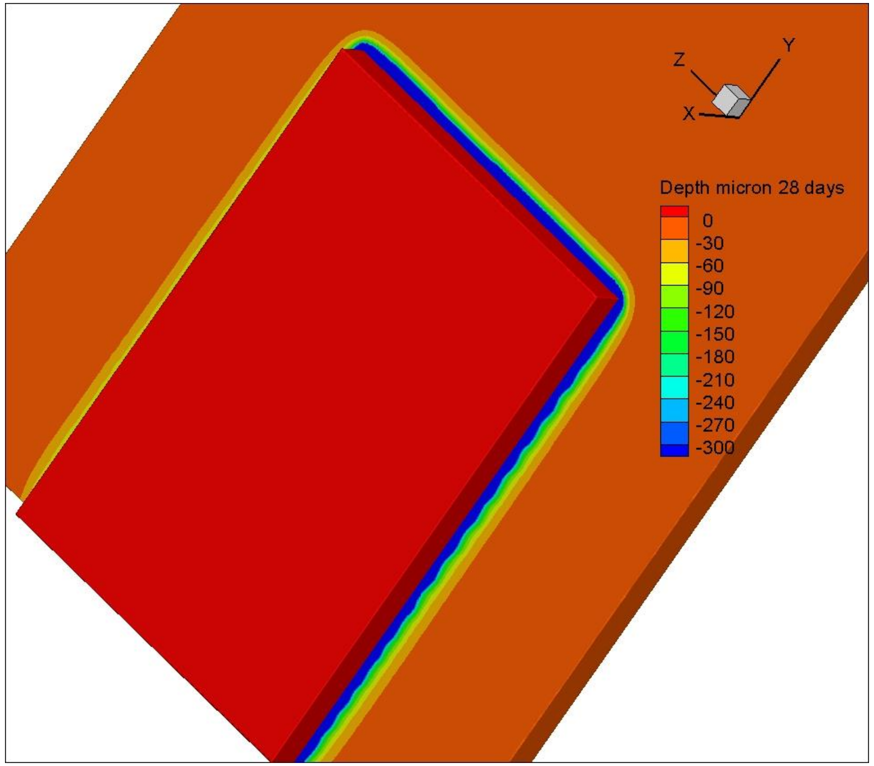
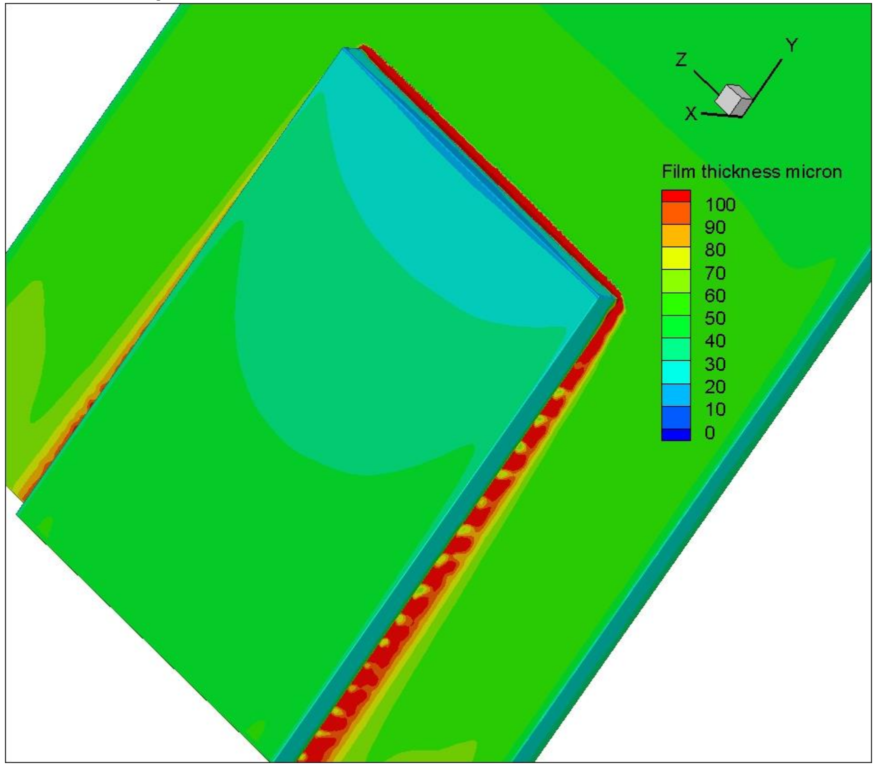
Model Predictions (Variable thinfilm)

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



Film thickness-
CFD Liquid Film Model



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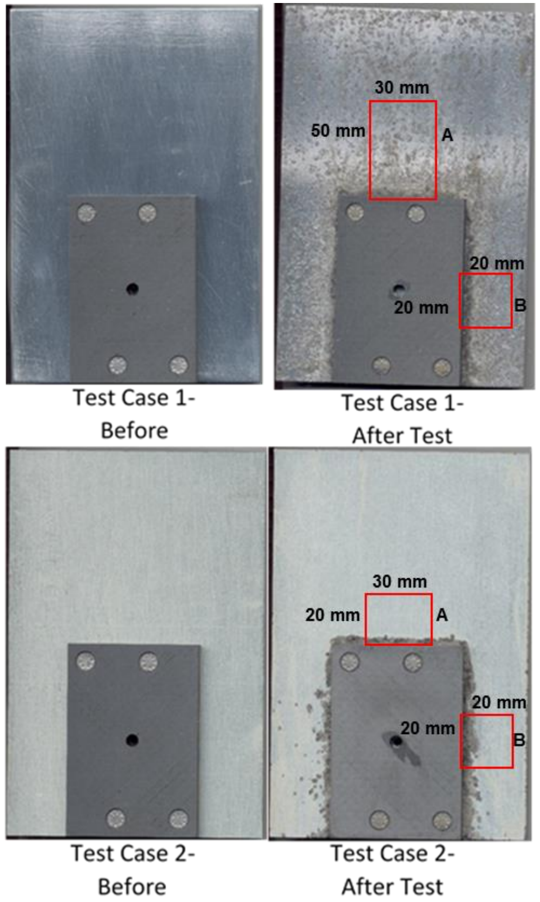
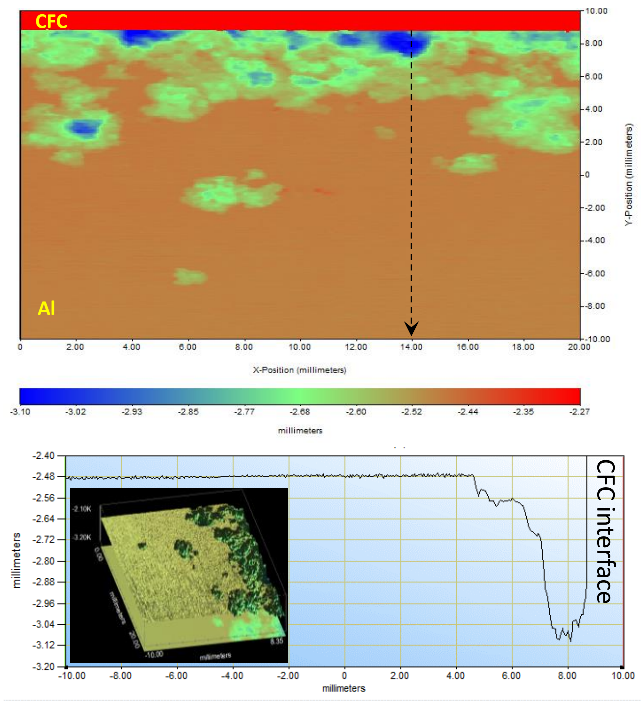
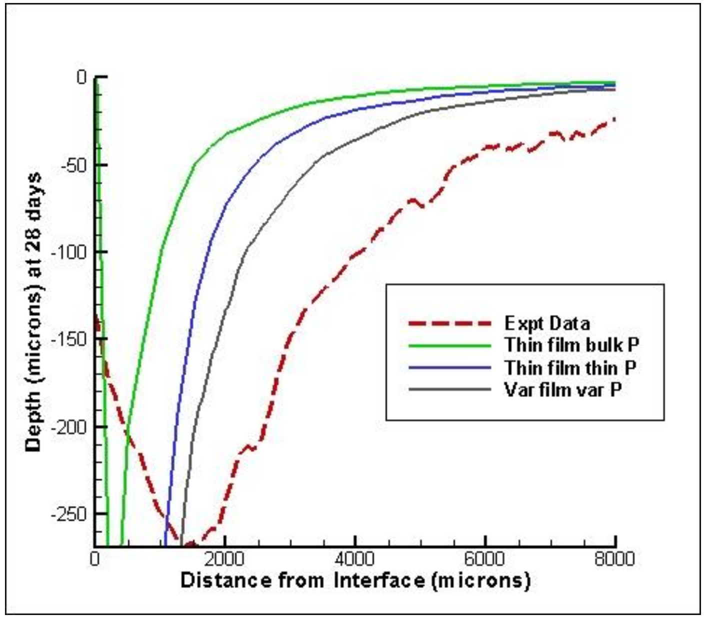
Model Predictions (Variable thinfilm)







Summary

- The A&D community is becoming increasingly concerned with corrosion, particularly galvanic, and is developing computational galvanic prediction and new test methodologies. New regulations are also forcing material changes
- The old galvanic series is being superseded and new systems will require newly-available quantitative computational methods relying on a qualified database
- This is a perfect fit for Siemens software
  - Teamcenter PLM to identify locations and materials
  - Teamcenter or Simcenter to hold the electrochemical database
  - Simcenter to hold the Corrosion Djinn design and evaluation tool
  - Multiphysics CAE – electrochemical and CFD modeling for analysis of complex assemblies and environments
- The combination of Corrosion Djinn and Star CCM+ provides an opportunity to deploy consistent design and galvanic risk assessment across the enterprise

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