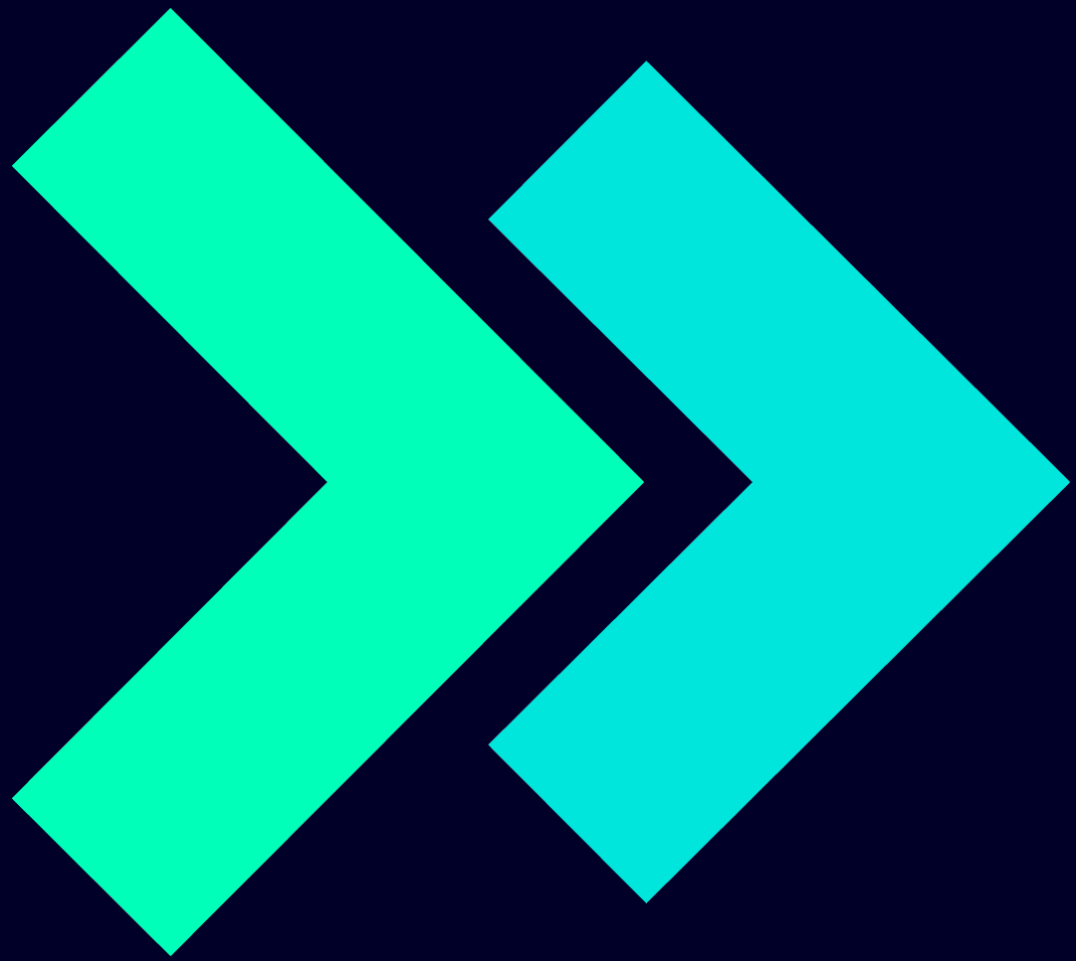
Computational Corrosion Analysis

Alan Rose, John Daniels-Wright, Corrdesa Limited
Ryan Larsson, Emixa



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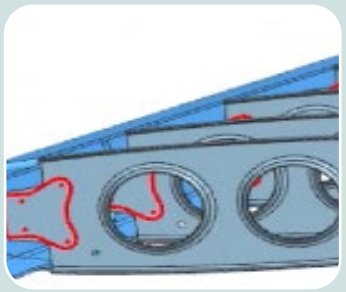
CORRDESA'S WORLD: Modern materials – Define, Develop, Deploy

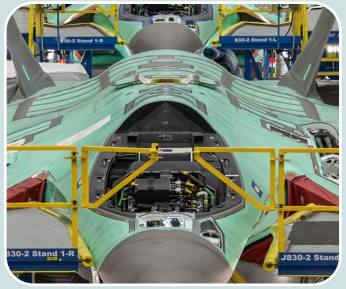


Design

CAD/CAE
CFD

Testing

Qualification
B117
Chamber
Beach



Production

Coating Stack-ups
Optimization

Operations

Environments
Missions

Sustainment

Corrosion Remediation
Anodize-plate
REACH

DIGITAL TRANSFORMATION – COMMERCIAL PLM, SIEMENS

Why should you be bothered?

“All materials degrade and become damaged”

“Everything corrodes”

*Therefore, **ALL** industry sectors have a stake wrt the impact of corrosion*

Corrosion Market trends

Corrosion costs the global economy an estimated $2.5 trillion per year, which is 3.4% of global GDP. Cost is calculated in replacement, repair, maintenance and lost productivity.

- **Financial cost**: Corrosion has significant impact on various industries and economies. Maintenance, repair, reduced operational efficiency.
- **Safety & Environmental Risk:** compromise structural integrity of key infrastructure and lead to safety & environmental damage. Aircraft, bridges, pipelines, buildings, automobiles.
- **Indirect cost:** reduced productivity, lost time due to repairs, overtime paid.
- **Specific Industries:** corrosion impacts wide range of industries: transportation, manufacturing, energy and construction.

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Corrosion Analysis – Impact of corrosion on Aerospace Industry

The total annual direct cost of corrosion to U.S. aircraft industry is estimated at $2.2 billion. Design, manufacturing and maintenance.

- Design $0.2b, maintenance $1.7b, downtime $0.3b
- Safety – FAA, 23% of failures are corrosion related
- 70% sustainment costs are locked in by the initial design
- Readiness- only 4 out of 49 aircraft types met their annual mission capable goal in 10 year period.
- 10+ years to deploy new coatings
- Environmental concerns, Health & Safety REACH, RoHS, OSHA – changing coatings

30% – 40% of corrosion costs can be eliminated in design.

The entire fuselage… was so riddled with corrosion, fatigue cracks, and repair patches… In some areas, nearly every rivet hole had a fatigue crack emanating from it.

USAF – we are continually fixing problems that ***should have been eliminated in design…***

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Corrosion Analysis – Impact of corrosion on Automotive Industry

Cost of corrosion remediation in the US alone is estimated at $23 billion annually. Impacts:

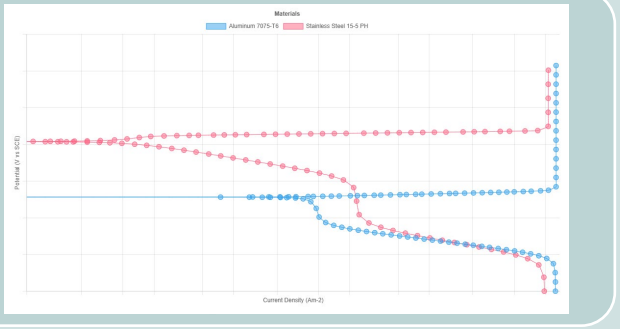
- Corrosion issues 15-20% of total vehicle maintenance cost
- Impacts vehicle downtime and reduced lifespan
- Brand reputation and warranty claims
- Environmental concerns, Health & Safety REACH, RoHS, OSHA – changing coatings

Unique Corrosion Issues with Electric Vehicles

- Battery casing & connectors
- Cooling systems
- Brake systems and undercarriage

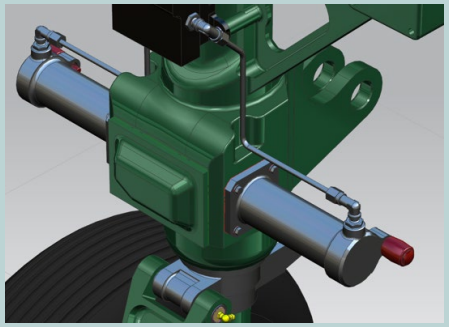
30% – 40% of corrosion costs can be eliminated in design.

3-Tier Analysis Workflow



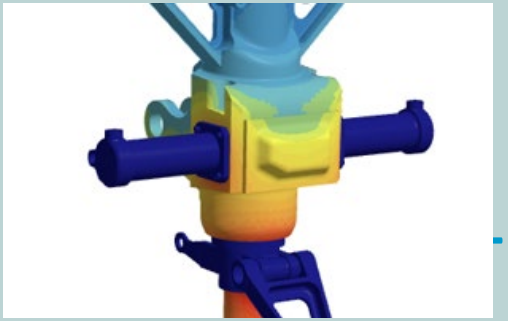
Djinn®

MIL-STD-889D Polarization



NX-CAD

MIL-STD-889D Automated



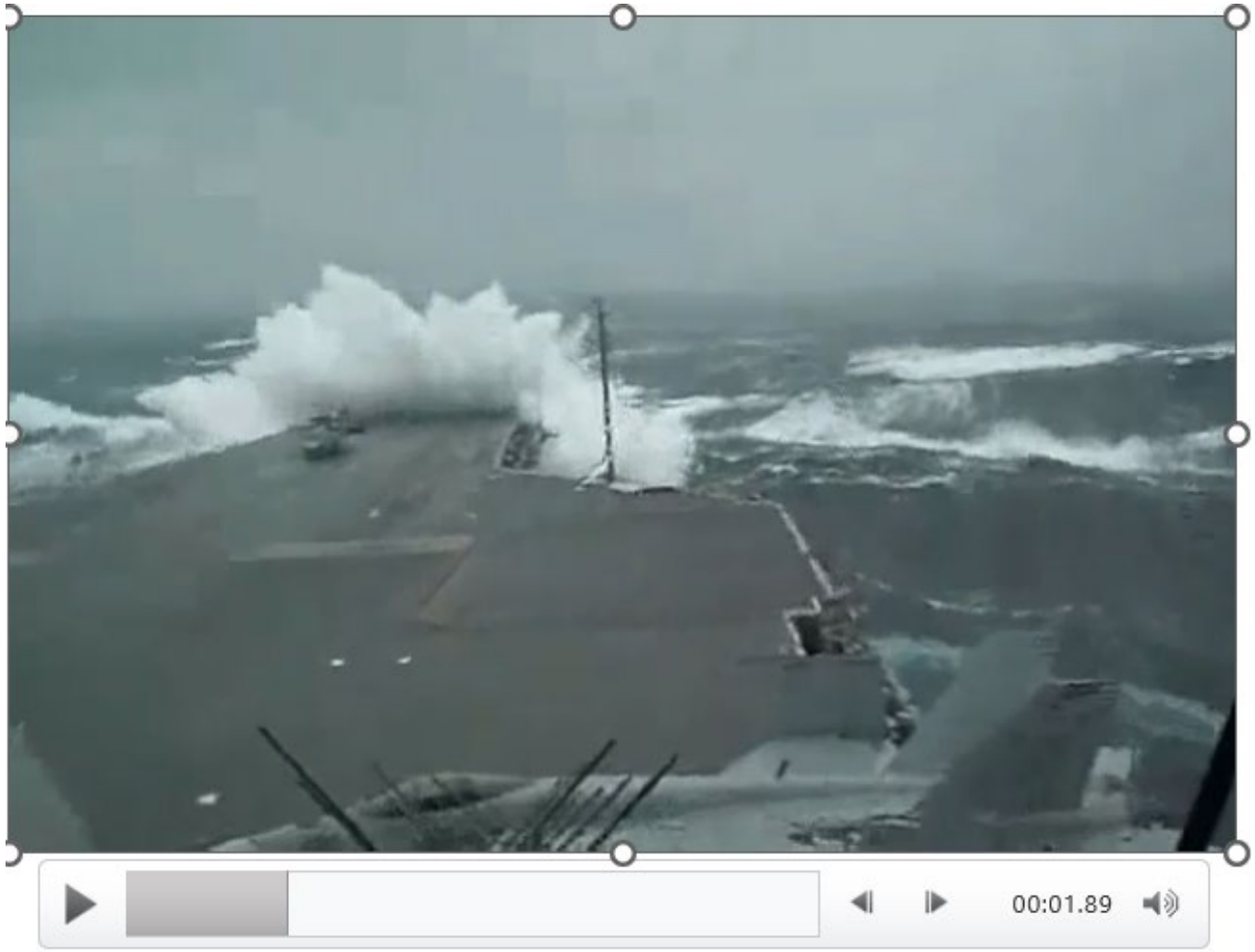
CAE

3D multi-physics solver

Catch >80% issues upfront

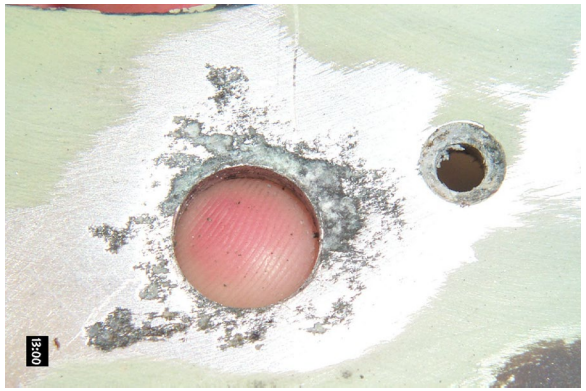
Aerospace

USS Kitty Hawk



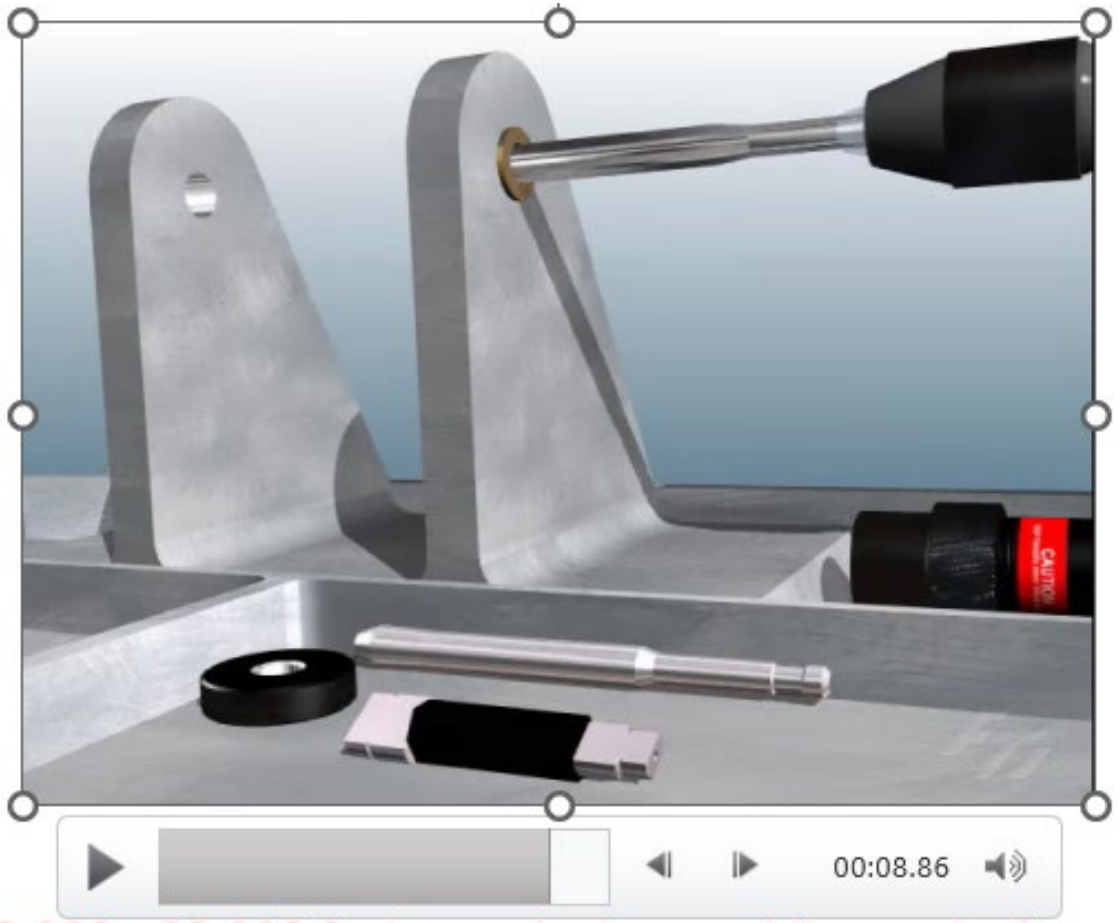
https://youtu.be/Z0Jzb8dfcC4

Annual Cost of Corrosion in the Department of Defense



24 million hours of downtime at $833 per hour

Bushing installation with Forcemate



20,000 - 22,000 fasteners just around the center barrel area !

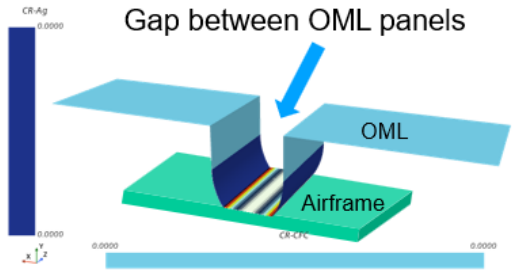
Corrosion Problems Persist in New Platforms

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

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

Use - Cases

- "I'll believe it if you can show it would have prevented the $200M+ F-22 gap filler corrosion problem" USAF WPAFB
- Corrdesa and USAF carried out analysis (using surrogate materials as the current gap filler is classified)



Scen #	1 Airframe	2 Gap filler	3 Skin	Min µm/yr	Max µm/yr
1	Al-Alodine 1200	Ag	CFC Unsanded	1,316	1,365
2	Al-Alodine 1200	Ag	CFC Sanded	2,689	2,930
3	Al-Alodine 1200	Insulator	CFC Unsanded	35	35
4	Al-Alodine 1200	Insulator	CFC Sanded	1,569	1,594
5	Al-Alodine 1200	Ti	CFC Unsanded	42	42
6	Al-Alodine 1200	Ti	CFC Sanded	1,576	1600
7	Al- Bare	Ag	CFC Unsanded	1,434	1,482
8	Al- Bare	Ag	CFC Sanded	3,024	3,094
9	Al- Bare	Ag	CFC Unsanded-Insulator (Prime+topcoat)	1,405	1,452
10	Al- Bare	Ag	CFC Sanded-Insulator (Prime+topcoat)	1,722	1,775
11	Al- Bare	Ag	CFC Unsanded-Prime	1,425	1,473
12	Al- Bare	Ag	CFC Sanded-Prime	1,881	1,936

Conclusions:

- Yes, using this technology would have prevented the gap filler problem.
- But changing the gap filler only **eliminates half of the problem**.
- **Half of the corrosion current is due to the carbon fiber composite skin - a common issue in composite-skinned aircraft**

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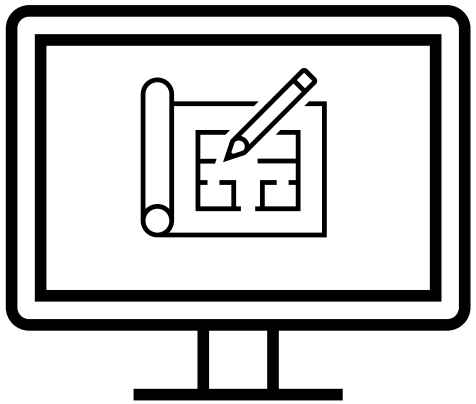
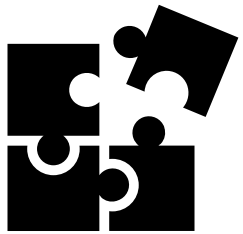
"The root cause of this problem lay within the galva couple between the conductive gap filler and aluminum skin panels." Daniel J Dunmire, Director, DoD Corrosion Policy and Oversight Office, reported in CorrdeDefense, Spring 2011, Vol7, Number 1

Corrosion Risks – Quick Solutions

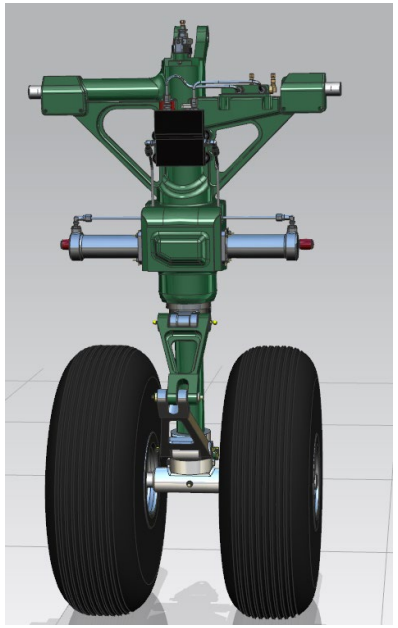


Siemens NX

+

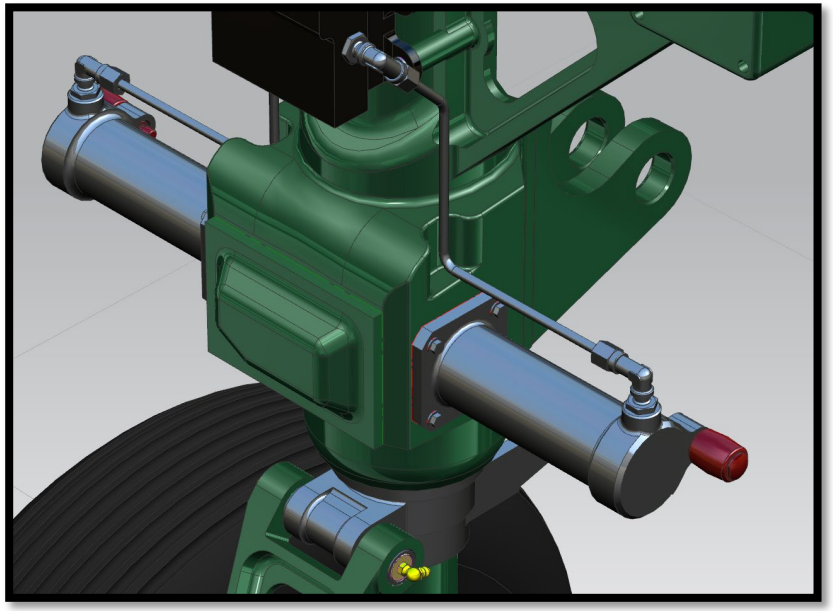


NX Corrosion Analysis Module NX30161



- Change materials, sealants, coatings
- Fix errors omissions

Risks highlighted



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457896 - Plain Washer Narrow, AM,M5		Steel (High Strength)_4340...	Stainless Steel_13-8 PH	4	202.3553522
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Provided by Siemens

Further investigation
3D simulation with CCM+

3D Computational Corrosion Analysis

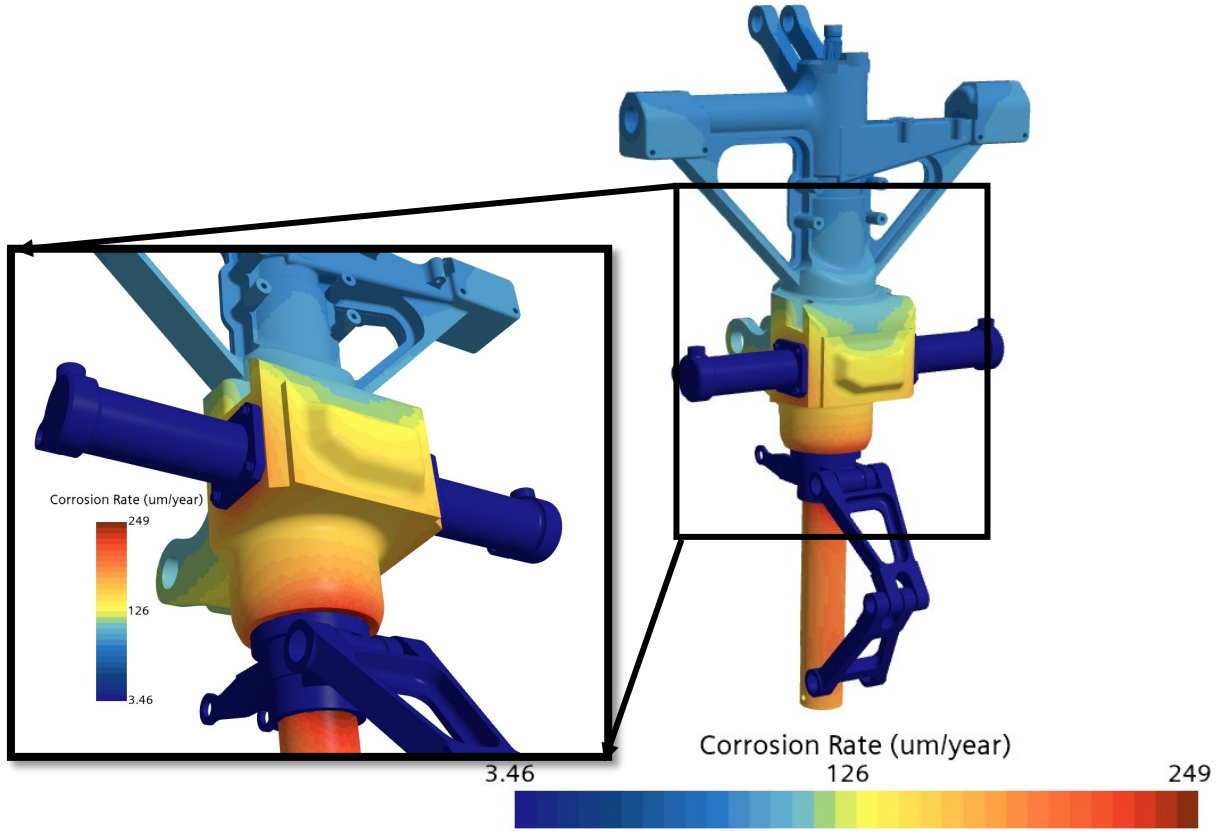
Siemens CCM+
2502

CEDBCCM

Corrdesa
Electrochemical
Database

CDSHP01

Customer Managed
Electrochemical
Data



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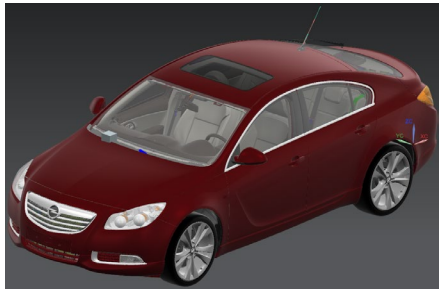
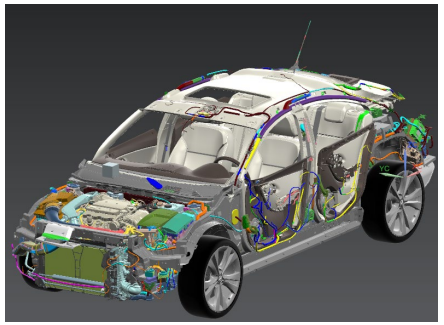
Automotive

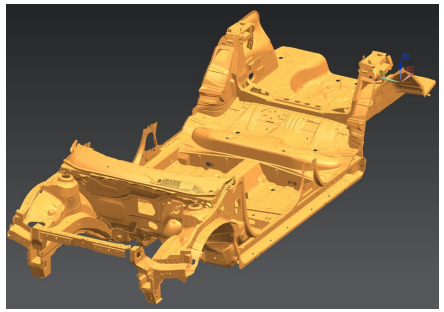
Corrosion Risks – resolve 80% issues upfront in NX

Siemens NX Designcenter

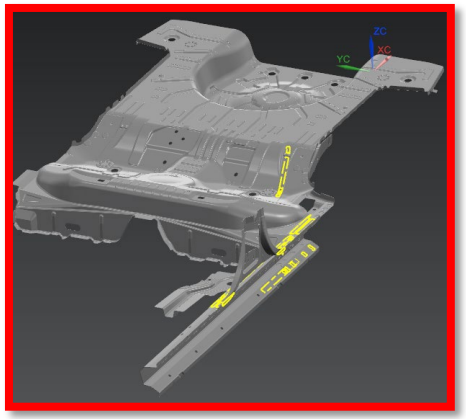
NX Corrosion Analysis Module NX30161







Risks highlighted



- Change materials, sealants, coatings
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Further investigation 3D simulation with CCM+

SIEMENS

3D Computational Corrosion Analysis

Siemens CCM+
2502

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Corrdesa
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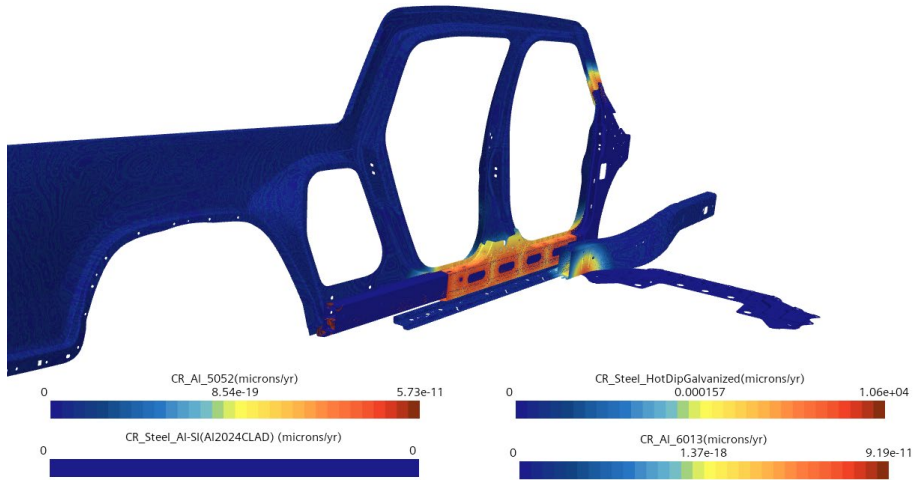

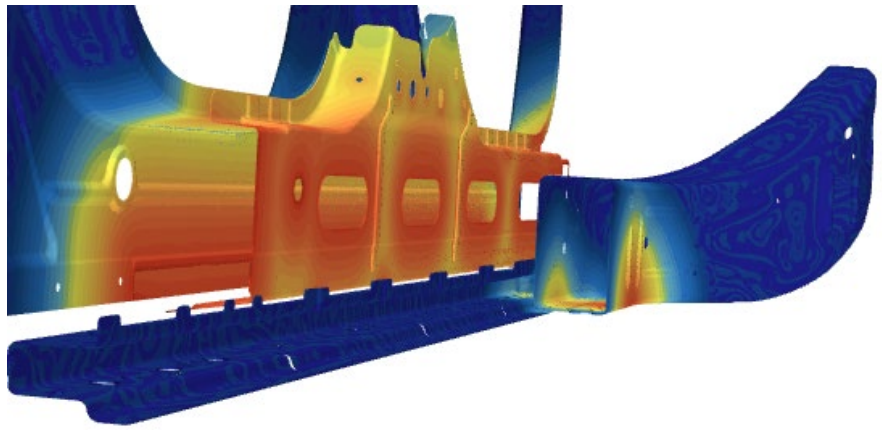

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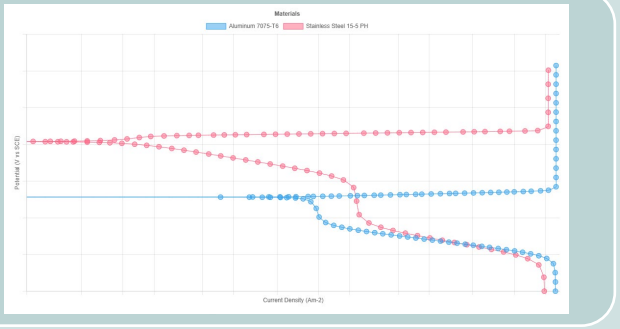
Computational Corrosion Analysis

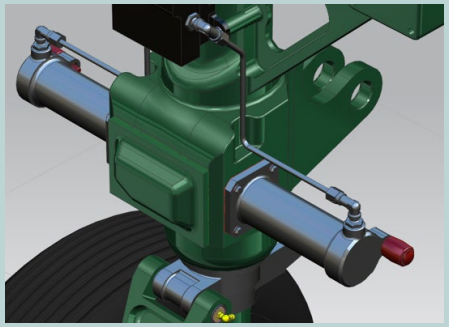
A 3-Tier Workflow

3-Tier Analysis Workflow



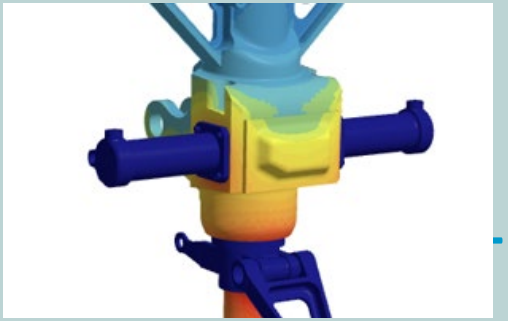
Djinn®

MIL-STD-889D Polarization



NX-CAD

MIL-STD-889D Automated

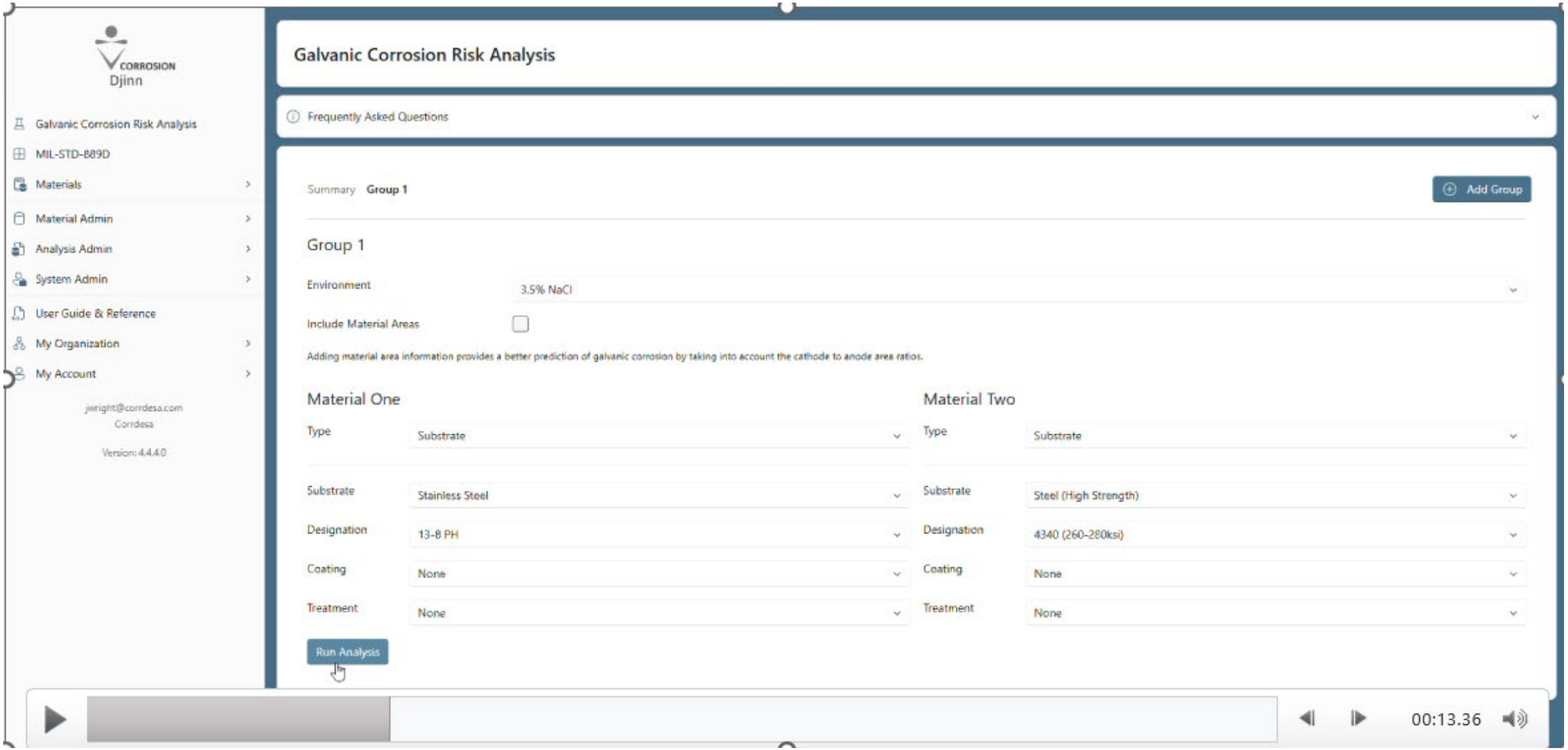


CAE

3D multi-physics solver

Catch >80% issues upfront

Tier-1 Analysis – Corrosion Djinn®



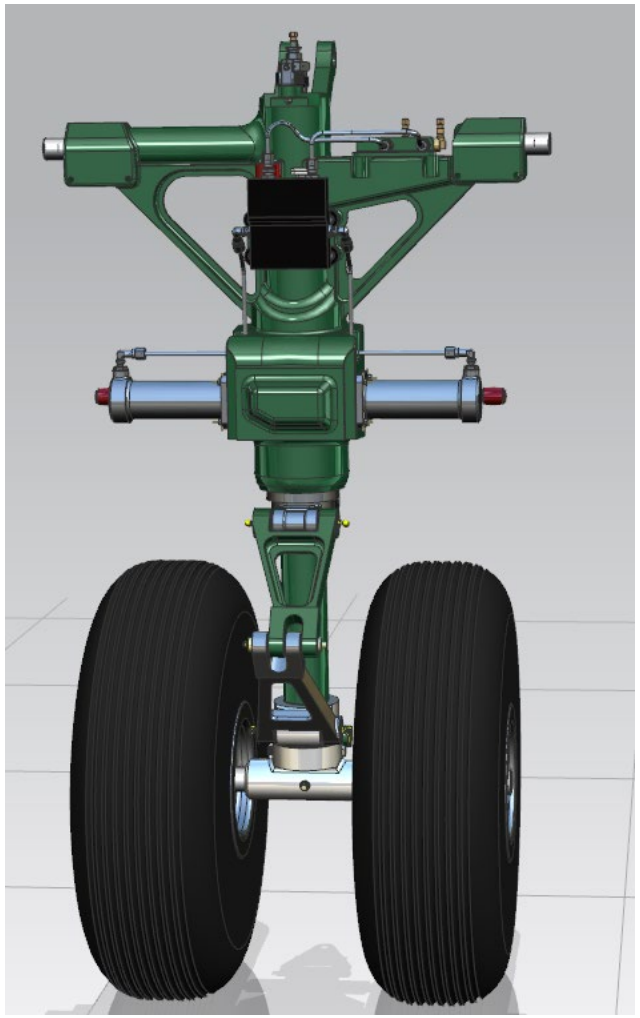
Summary Djinn® V4.4

Group	Material 1 - Anodic	Material 2 - Cathodic	Al corrosion rate 'class'	Quantified galvanic corrosion rate (mil/year)	Quantified galvanic corrosion rate (µm/year)
1	4340	Stainless Steel 13-8 PH	4	80	202
2	Stainless Steel 15-5 PH	Ti6Al4V	0	0.001	0

Galvanically Compatible:
0: <0.009 mil/year

Galvanically Incompatible:
1: 0.01-0.09 mil/year
2: 0.1-0.9 mil/year
3: 1-4.99 mil/year
4: 5-9.99 mil/year
5: 10-99.99 mil/year
6: > 100 mil/year

Tier-2 Analysis – NX Corrosion Indicator



What if… over time..

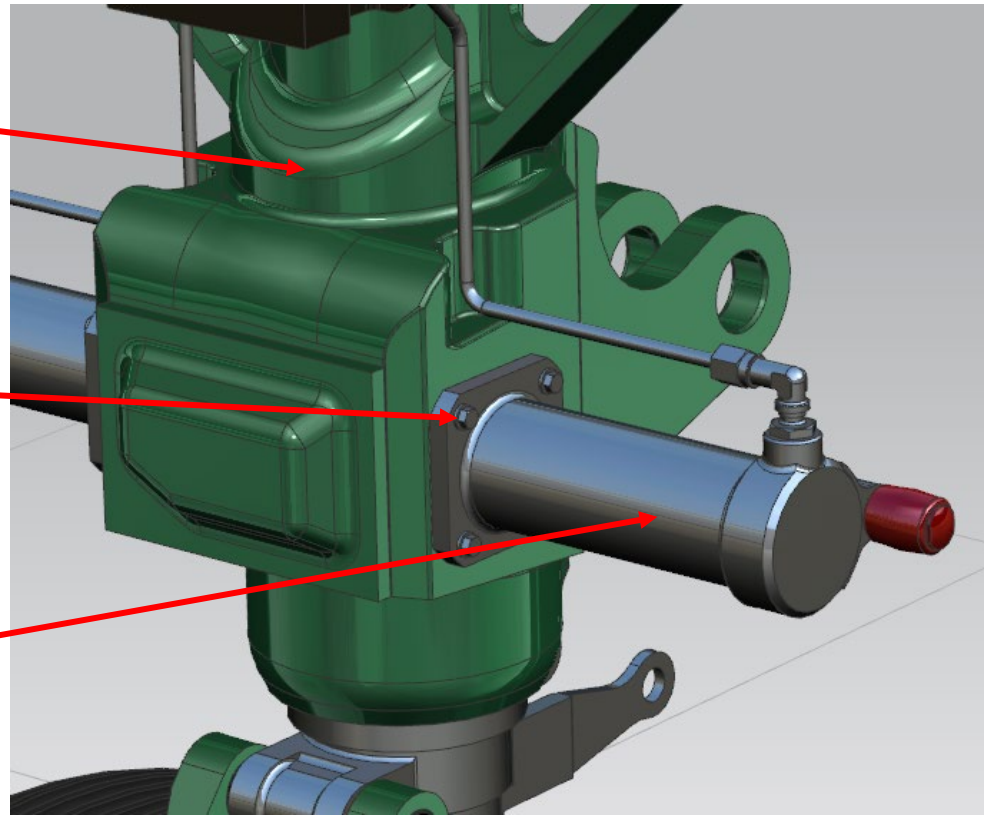
Deploy drop-in coating

Green areas are ZnNi coated

Aermet 100 plated with ZnNi.

Fastener and Washer 4340 (No Coating)

Stainless Steel 13-8 PH



Tier-2 Analysis – NX Corrosion Indicator

Classifies and ranks material pairs

MIL-STD-889D, 3.5%NaCl

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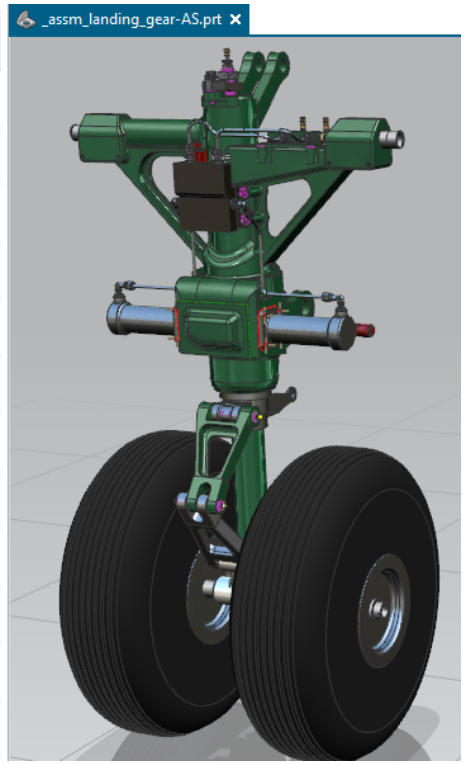
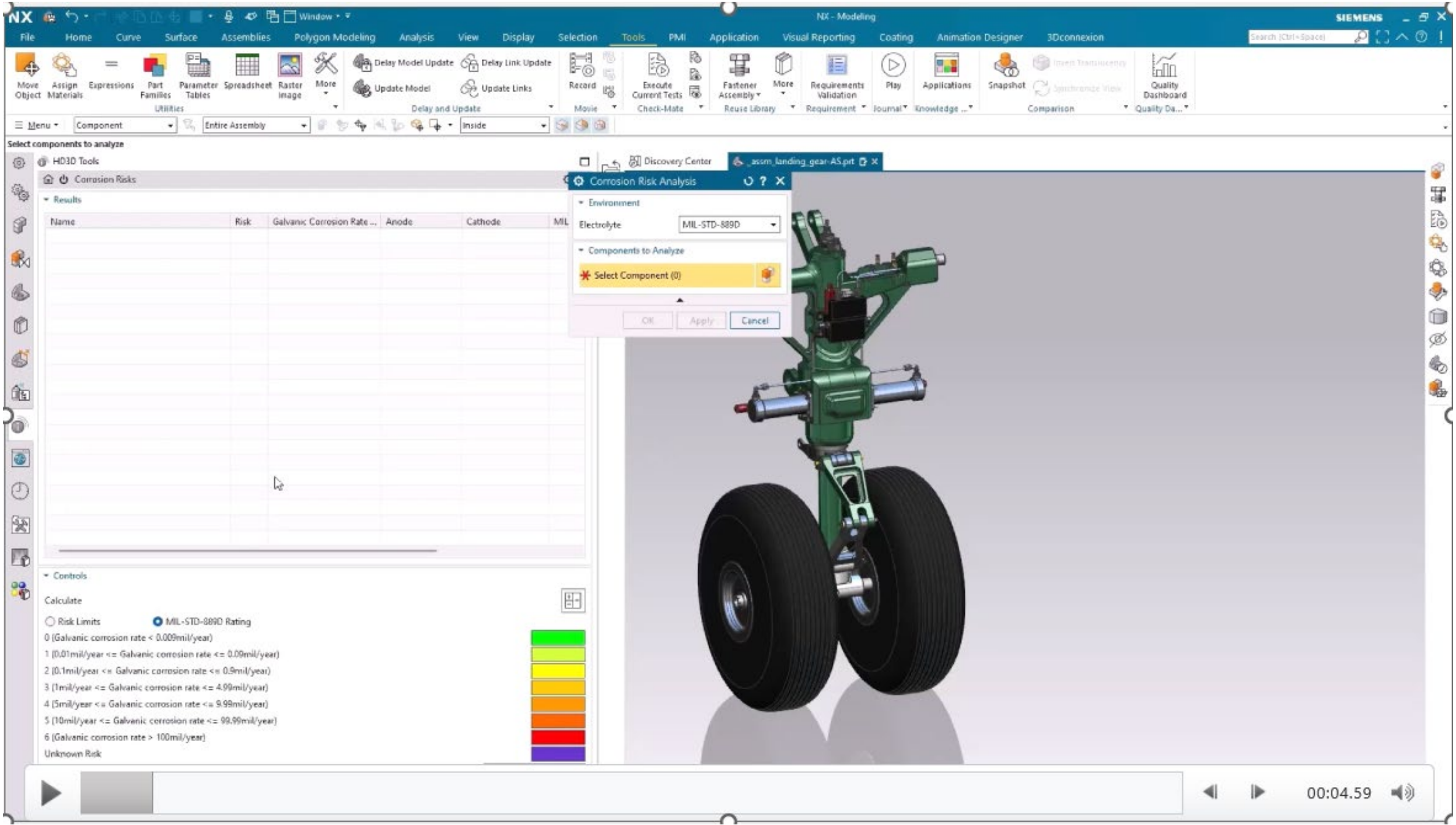
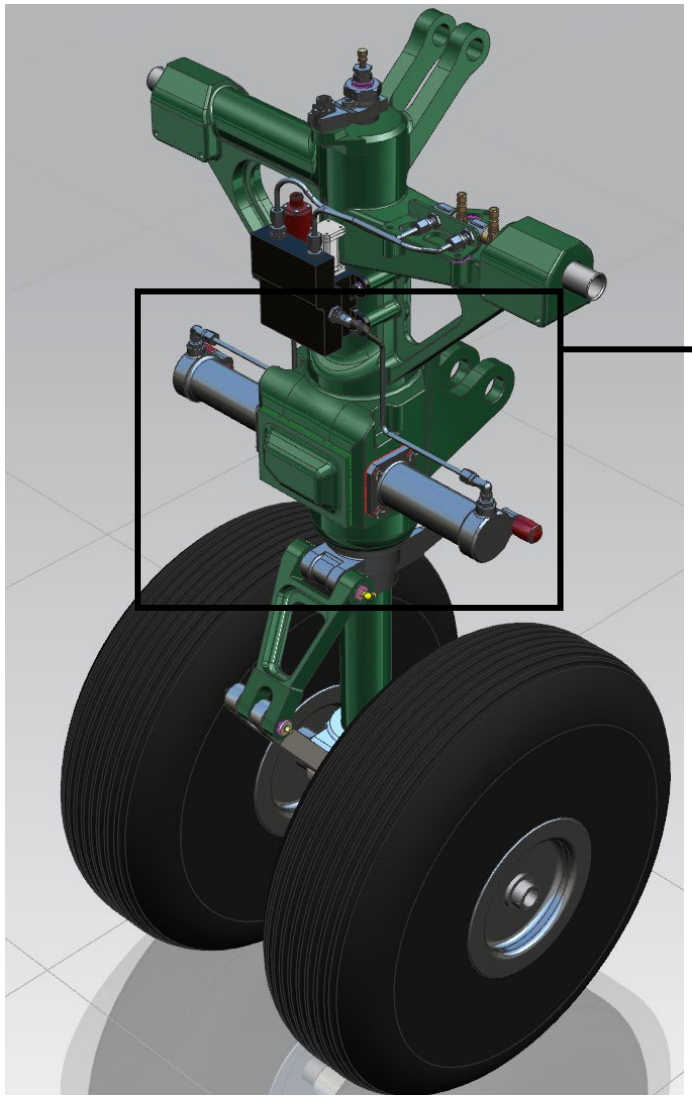
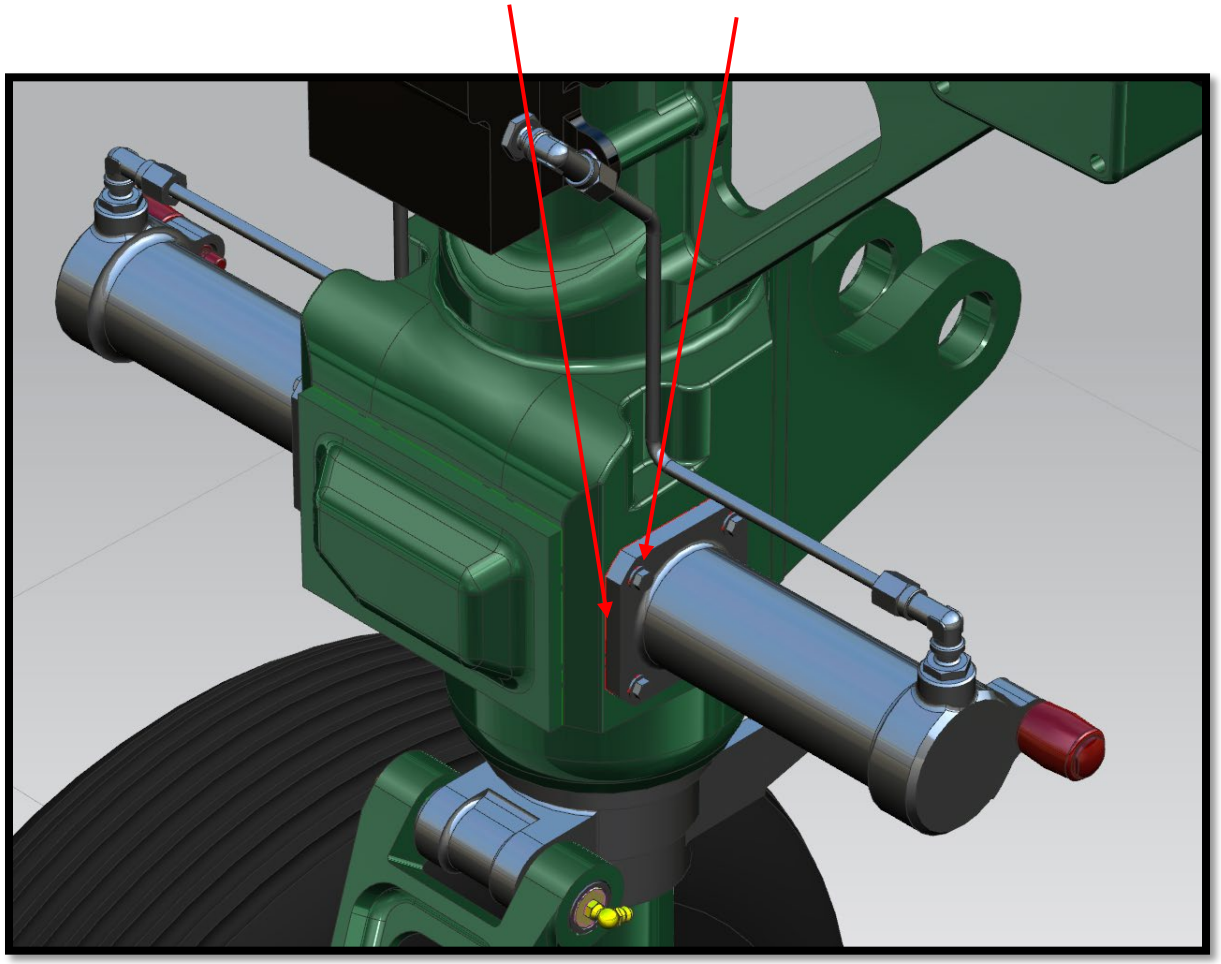



NX - Modeling
SIEMENS
File Home Curve Surface Assemblies Polygon Modeling Analysis View Display Selection Tools PMI Application Visual Reporting Coating Animation Designer 3Dconnexion
Move Object
Assign Materials
Expressions
Part Families
Parameter Tables
Spreadsheet
Raster Image
More
Utilities
Delay Model Update
Update Model
Delay Link Update
Update Links
Delay and Update
Record
Movie
Execute Current Tests
Check-Mate
Fastener Assembly
Reuse Library
Requirements Validation
Requirement
Play
Journal
Applications
Knowledge
Snapshot
Comparison
Quality Dashboard
Select components to analyze
HD3D Tools
Corrosion Risks
Results
Name
Risk
Galvanic Corrosion Rate ...
Anode
Cathode
Controls
Calculate
Risk Limits
MIL-STD-889D Rating
0 (Galvanic corrosion rate < 0.009mil/year)
1 (0.01mil/year <= Galvanic corrosion rate <= 0.09mil/year)
2 (0.1mil/year <= Galvanic corrosion rate <= 0.9mil/year)
3 (1mil/year <= Galvanic corrosion rate <= 4.99mil/year)
4 (5mil/year <= Galvanic corrosion rate <= 9.99mil/year)
5 (10mil/year <= Galvanic corrosion rate <= 99.99mil/year)
6 (Galvanic corrosion rate > 100mil/year)
Unknown Risk
Discovery Center
_assm_landing_gear-AS.prt
Corrosion Risk Analysis
Environment
Electrolyte
MIL-STD-889D
Components to Analyze
Select Component (0)
OK
Apply
Cancel
00:04.59

Tier-2 Analysis – NX Corrosion Indicator

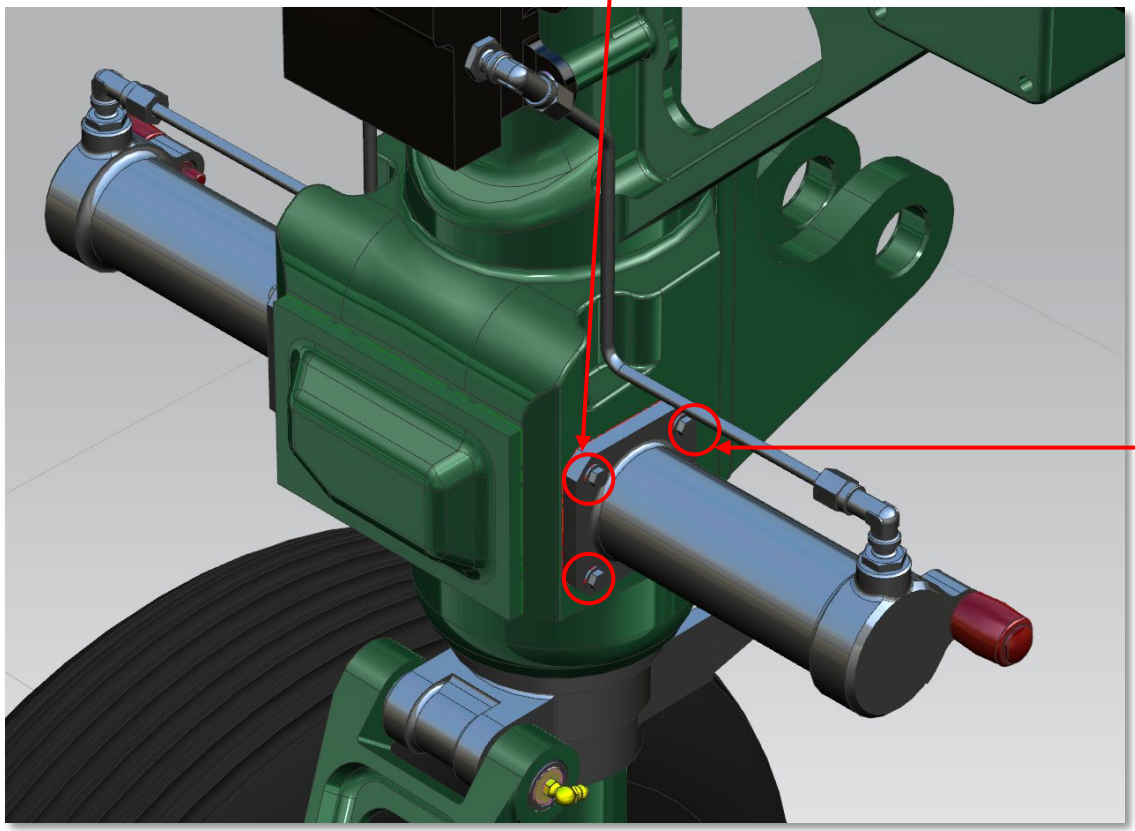


Interface colors based on risk value



Tier-2 Analysis – NX Corrosion Indicator

4340 Washers corroded by the pneumatic cylinder SS 13-8 PH



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457896 - Plain Washer Narrow, AM,M5		Steel (High Strength)_4340...	Stainless Steel_13-8 PH	4	202.3553522
457897 - Plain Washer Narrow, AM,M5		Steel (High Strength)_4340...	Stainless Steel_13-8 PH	4	202.3553522
457896 - Plain Washer Narrow, AM,M5		Steel (High Strength)_4340...	Stainless Steel_13-8 PH	4	202.3553522
457897 - Plain Washer Narrow, AM,M5		Steel (High Strength)_4340...	Stainless Steel_13-8 PH	4	202.3553522
457897 - Plain Washer Narrow, AM,M5		Steel (High Strength)_4340...	Stainless Steel_13-8 PH	4	202.3553522
457897 - Plain Washer Narrow, AM,M5		Steel (High Strength)_4340...	Stainless Steel_13-8 PH	4	202.3553522
0123456 - 457896		Zinc-Nickel LHE	Stainless Steel_13-8 PH	5	429.5537028
0123456 - 457897		Zinc-Nickel LHE	Stainless Steel_13-8 PH	5	429.5537028

ZnNi sacrificially protects the underlying material (Aermet 100) when in contact with Stainless Steel 13-8 PH

Tier-2 Analysis – NX Corrosion Indicator

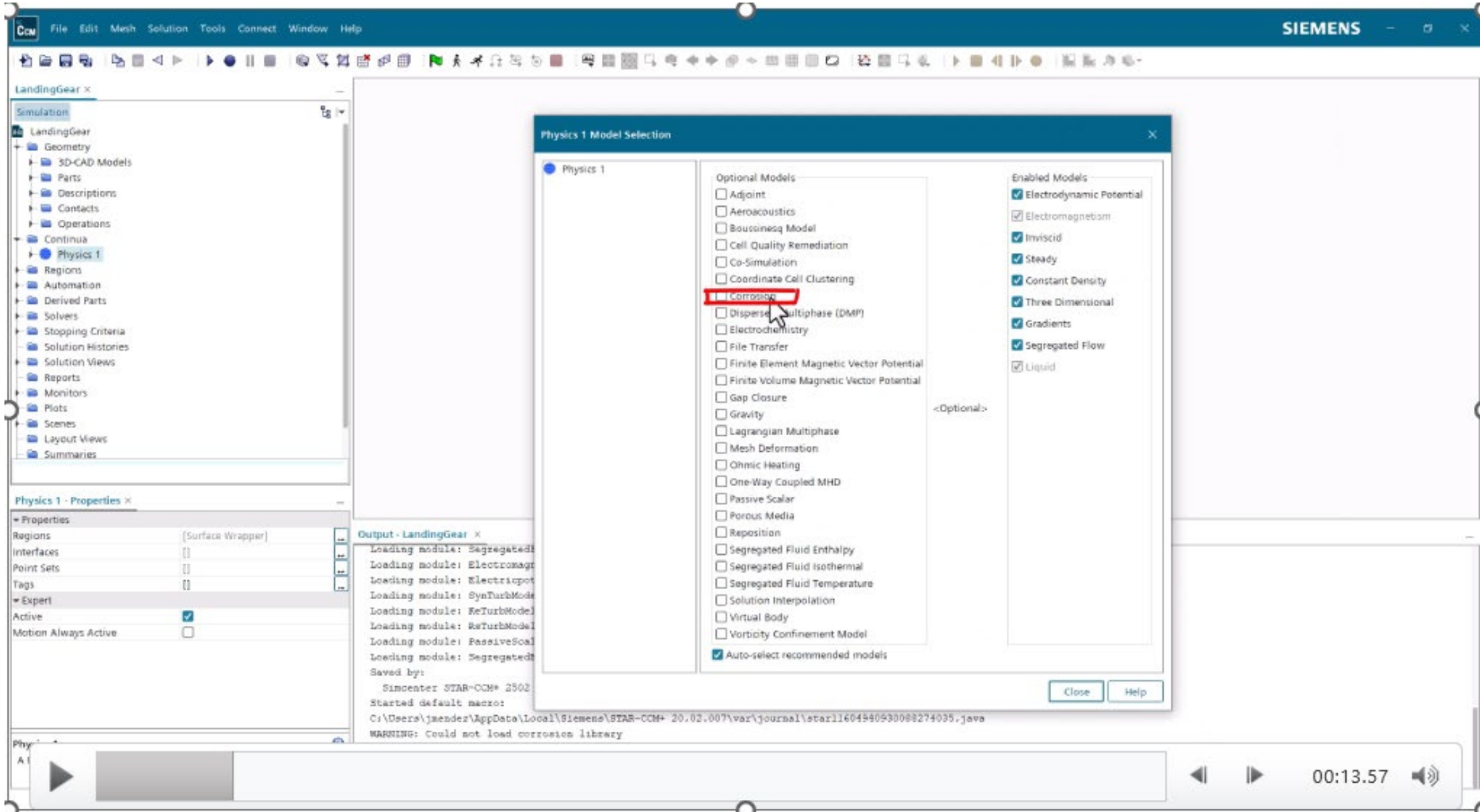
Name	Risk	Anode	Cathode	MIL-STD-889...	Galvanic Corrosion ...
126578 - 23452		Steel (High Strength)_4340...	Steel (High Strength)_4340...	0	0.0000000
126578 - 23452		Steel (High Strength)_4340...	Steel (High Strength)_4340...	0	0.0000000
457896 - Plain Washer Narrow, AM,M5		Steel (High Strength)_4340...	Stainless Steel_13-8 PH	4	202.3553522
457896 - Plain Washer Narrow, AM,M5		Steel (High Strength)_4340...	Stainless Steel_13-8 PH	4	202.3553522
457896 - Plain Washer Narrow, AM,M5		Steel (High Strength)_4340...	Stainless Steel_13-8 PH	4	202.3553522
457897 - Plain Washer Narrow, AM,M5		Steel (High Strength)_4340...	Stainless Steel_13-8 PH	4	202.3553522
457896 - Plain Washer Narrow, AM,M5		Steel (High Strength)_4340...	Stainless Steel_13-8 PH	4	202.3553522
457897 - Plain Washer Narrow, AM,M5		Steel (High Strength)_4340...	Stainless Steel_13-8 PH	4	202.3553522
457897 - Plain Washer Narrow, AM,M5		Steel (High Strength)_4340...	Stainless Steel_13-8 PH	4	202.3553522
457897 - Plain Washer Narrow, AM,M5		Steel (High Strength)_4340...	Stainless Steel_13-8 PH	4	202.3553522
0123456 - 457896		Zinc-Nickel LHE	Stainless Steel_13-8 PH	5	429.5537028
0123456 - 457897		Zinc-Nickel LHE	Stainless Steel_13-8 PH	5	429.5537028

To mitigate the risk, replace;

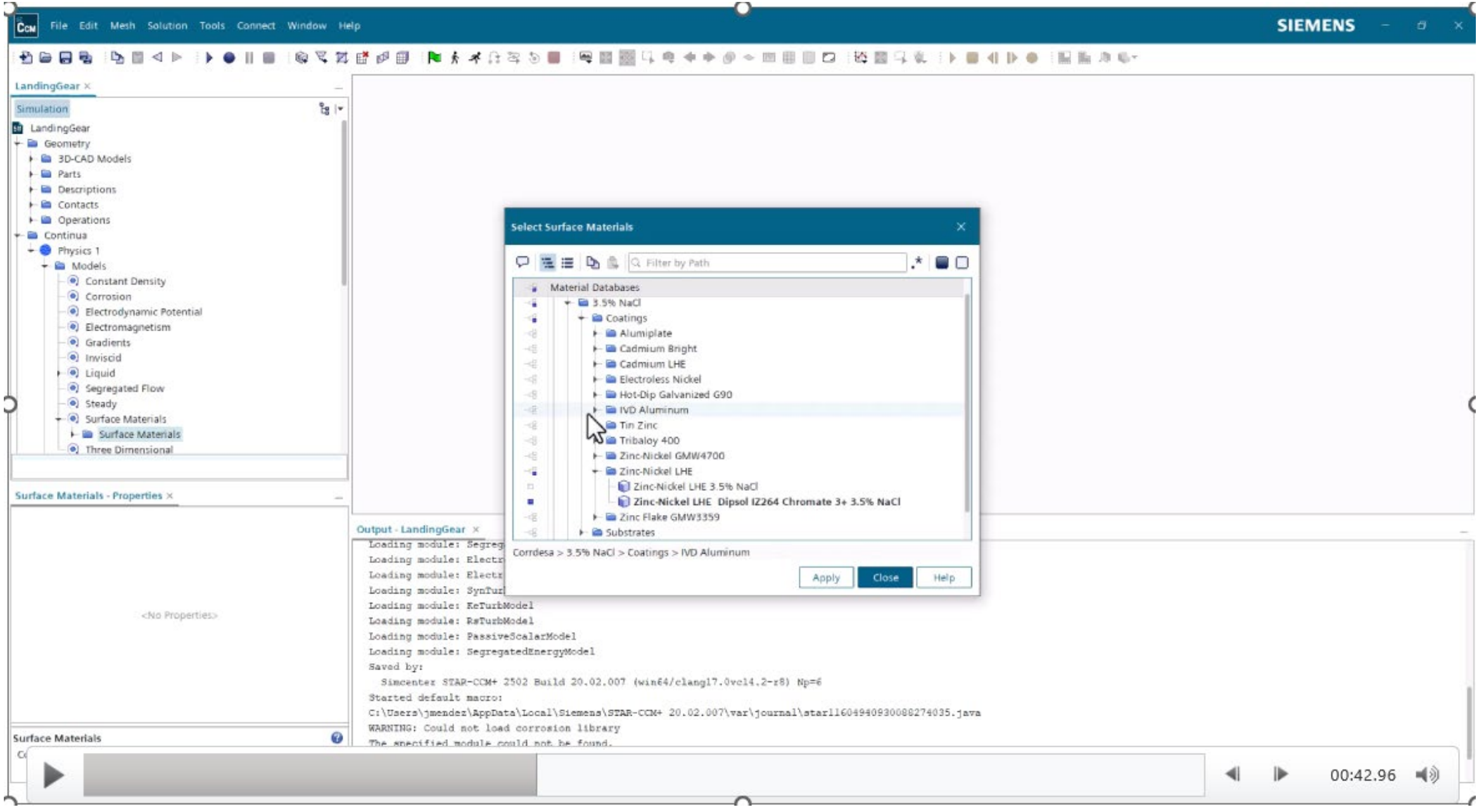
- 4340 fasteners & uncoated washers with Ti6Al4V
- 13-8 PH with passivated 15-5 PH

Name	Risk	Anode	Cathode	MIL-STD-889D Ra...	Galvanic Corrosion ...
126578 - 23452		Steel (High Strength)_4340 ...	Steel (High Strength)_4340 (260...	0	0.0000000
457896 - Plain Washer Narrow, AM,M5		Titanium_Ti6Al4V	Stainless Steel_15-5 PH/Passivat	0	0.0010837
457896 - Plain Washer Narrow, AM,M5		Titanium_Ti6Al4V	Stainless Steel_15-5 PH/Passivat	0	0.0010837
457896 - Plain Washer Narrow, AM,M5		Titanium_Ti6Al4V	Stainless Steel_15-5 PH/Passivat	0	0.0010837
457897 - Plain Washer Narrow, AM,M5		Titanium_Ti6Al4V	Stainless Steel_15-5 PH/Passivat	0	0.0010837
457896 - Plain Washer Narrow, AM,M5		Titanium_Ti6Al4V	Stainless Steel_15-5 PH/Passivat	0	0.0010837
457897 - Plain Washer Narrow, AM,M5		Titanium_Ti6Al4V	Stainless Steel_15-5 PH/Passivat	0	0.0010837
457897 - Plain Washer Narrow, AM,M5		Titanium_Ti6Al4V	Stainless Steel_15-5 PH/Passivat	0	0.0010837
457897 - Plain Washer Narrow, AM,M5		Titanium_Ti6Al4V	Stainless Steel_15-5 PH/Passivat	0	0.0010837
0123456 - 332345		Zinc-Nickel LHE	Zinc-Nickel LHE	0	0.0000000
0123456 - 457896		Zinc-Nickel LHE	Stainless Steel_15-5 PH/Passivat	4	182.3037742

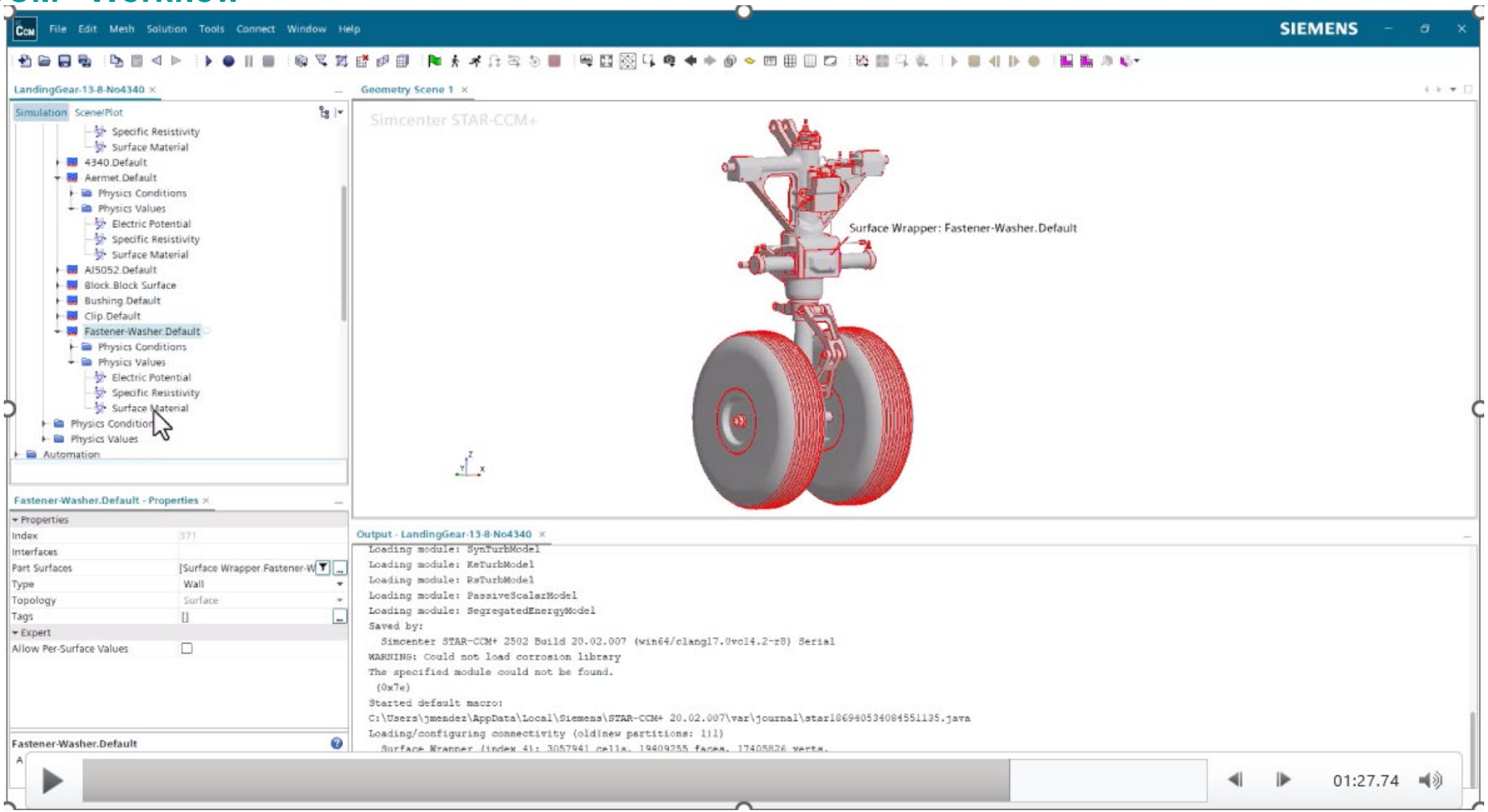
CCM+ Workflow



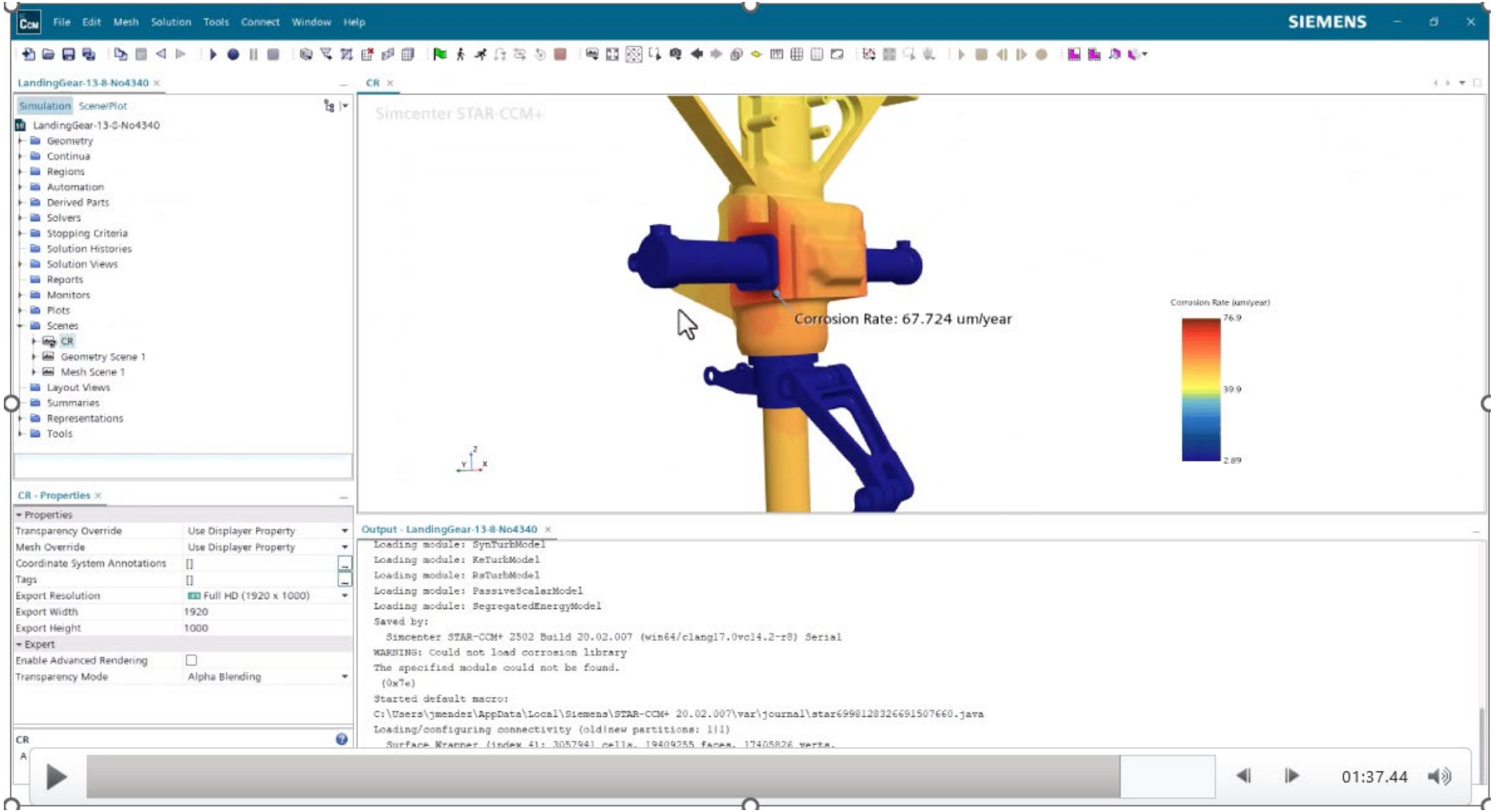
CCM+ Workflow



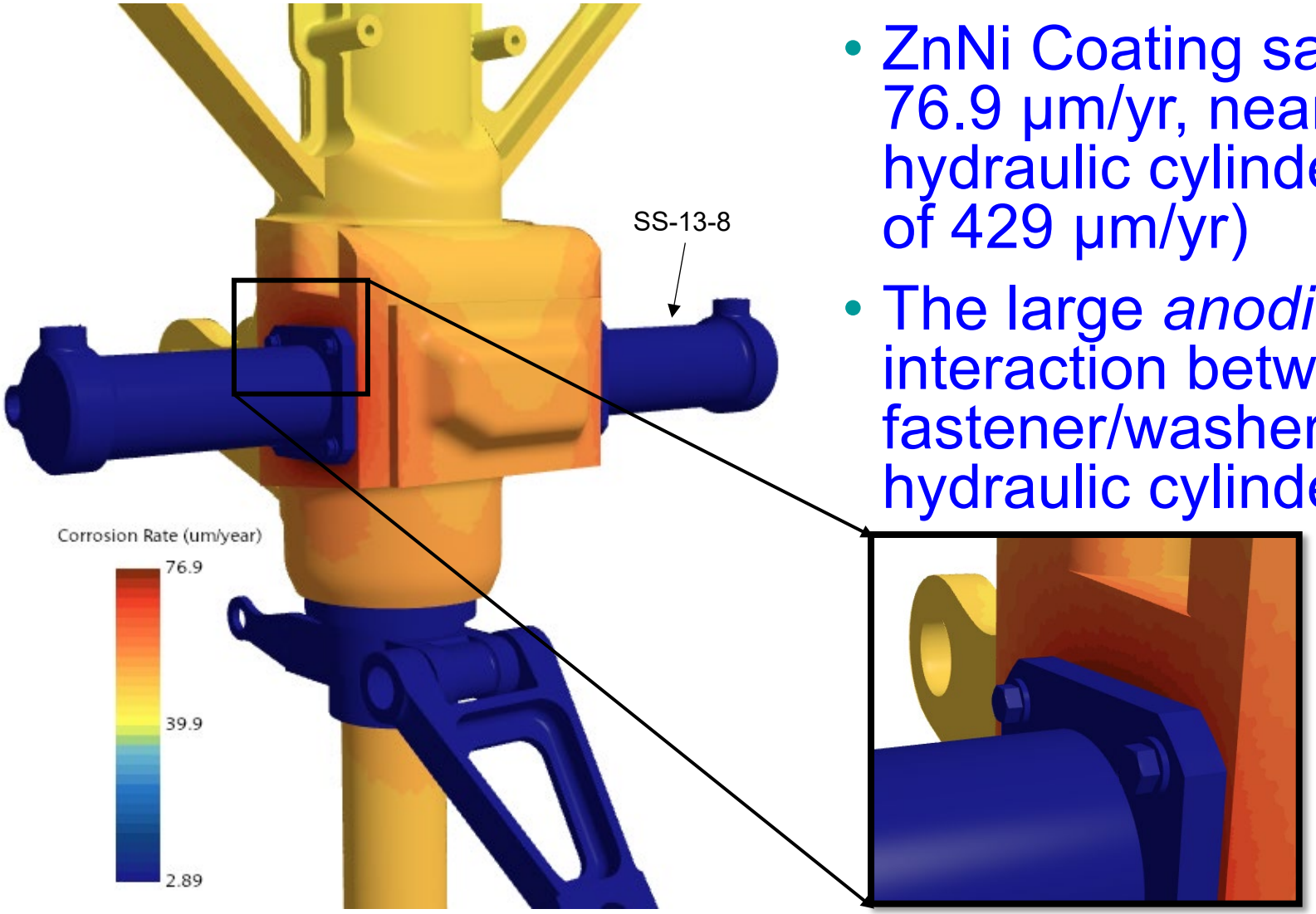
CCM+ Workflow



CCM+ Workflow



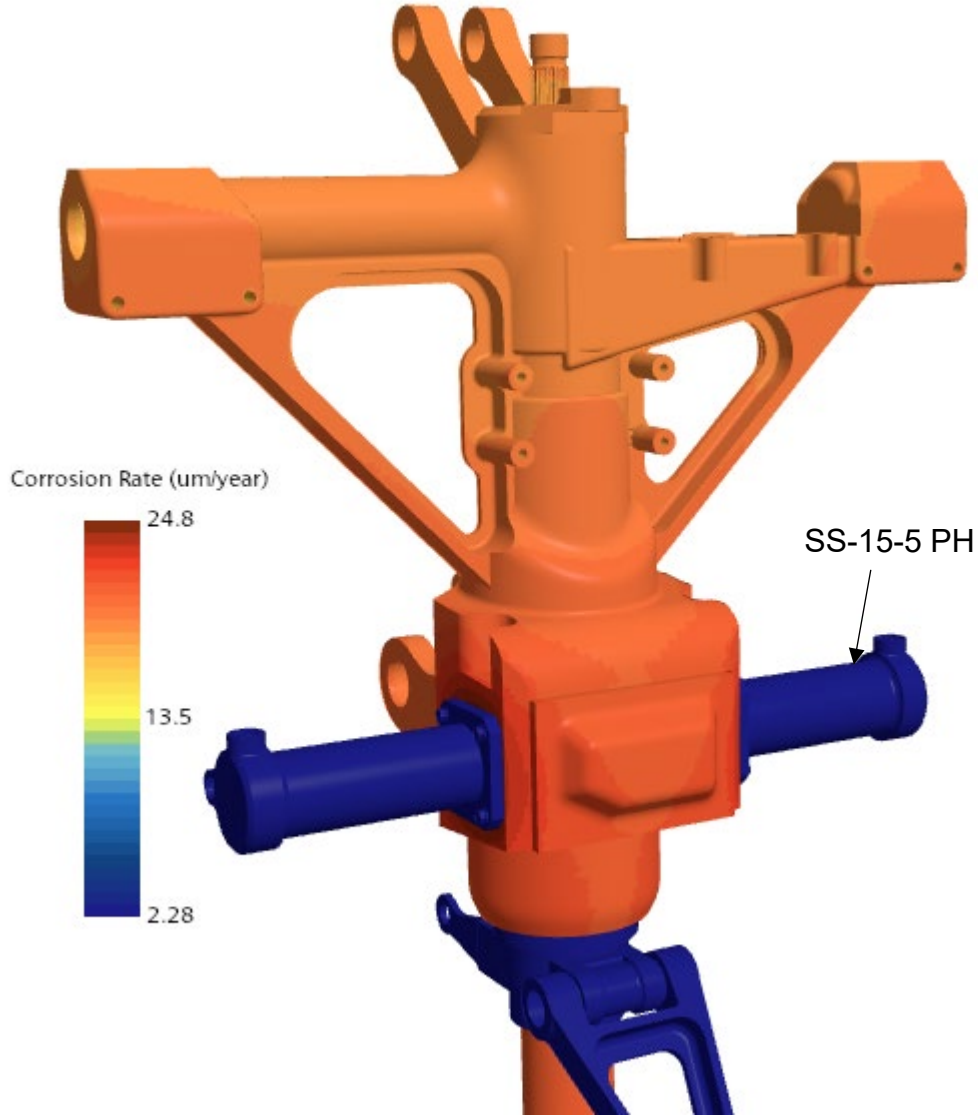
Tier-3 Analysis – Star-CCM+, Higher Fidelity 3D



- ZnNi Coating sacrificially corroding at 76.9 µm/yr, near the SS 13-8 PH hydraulic cylinder (quick Tier-1 result of 429 µm/yr)
- The large *anodic* LG swamps interaction between the fastener/washer and the SS 13-8 PH hydraulic cylinder - no corrosion.

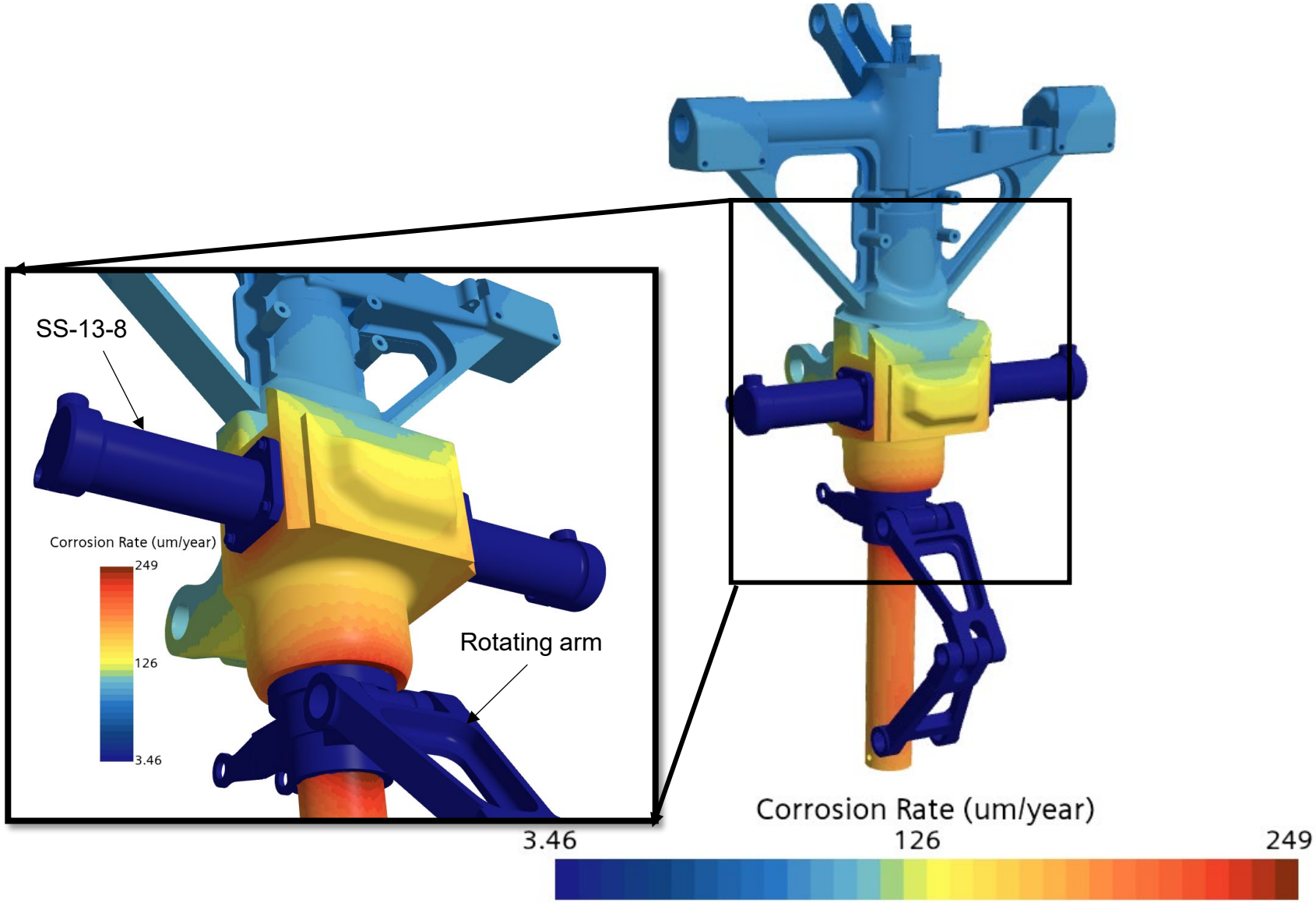
Tier-3 Analysis – Star-CCM+, Higher Fidelity 3D

- Replace the 13-8 PH with passivated 15-5 PH.
- Reducing maximum corrosion rate from 77 µm/yr to 24.8 µm/yr year, thereby extending the life span of the ZnNi coating.

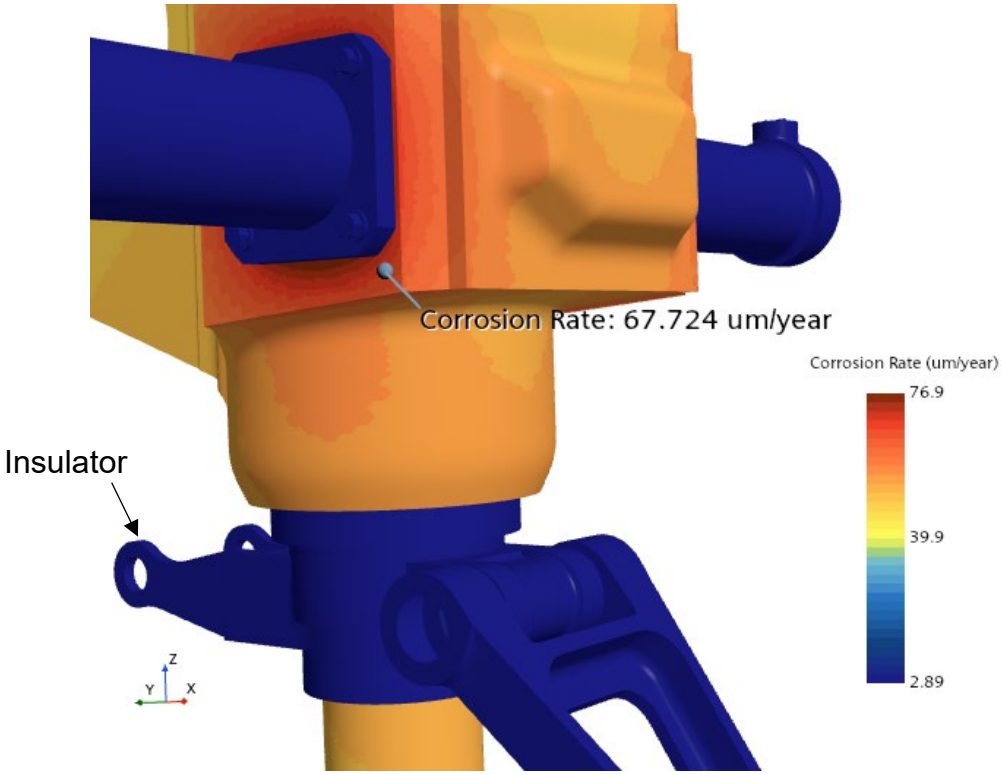


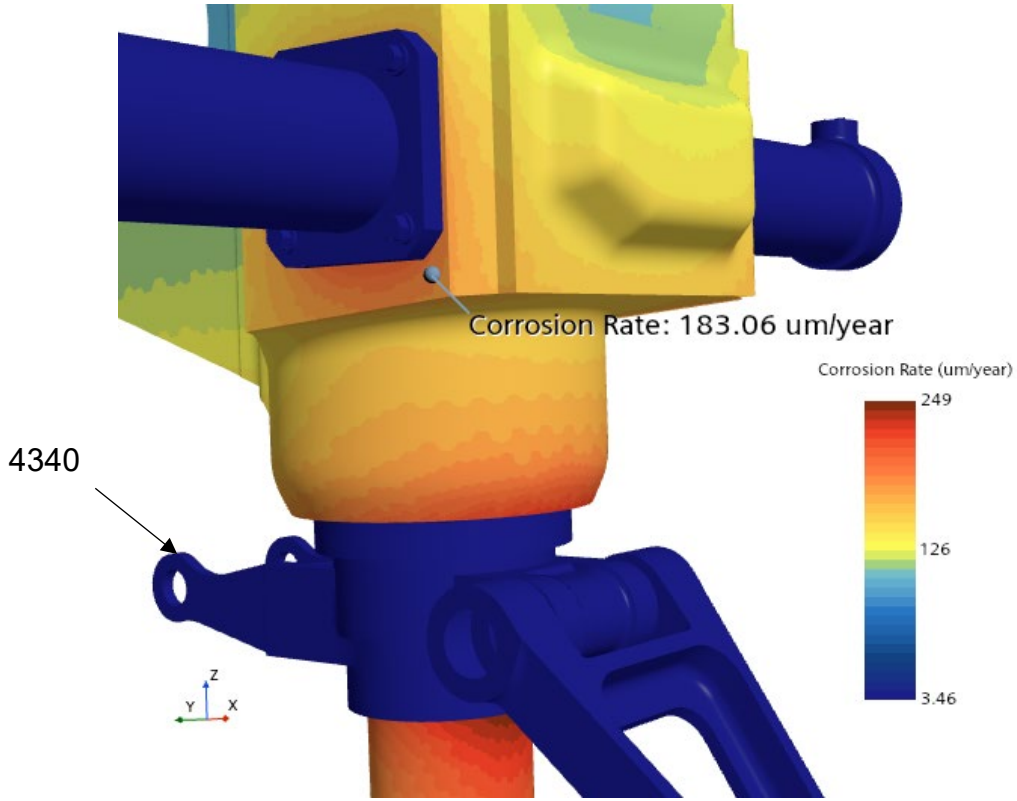
Tier-3 Analysis – Star-CCM+, Higher Fidelity 3D

corrosion rate near hydraulic cylinder impacted by distant rotating arm



Tier-3 Analysis – Star-CCM+, Higher Fidelity 3D



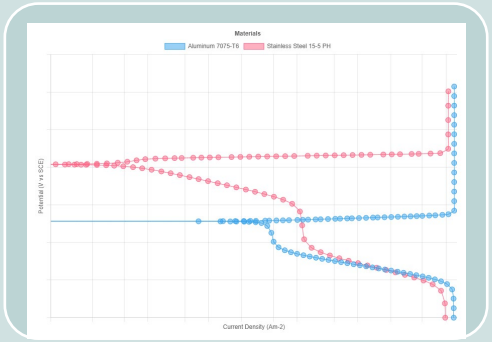


By *Activating* the Lower Rotating Arm (4340) we can see its impact on the corrosion rate near hydraulic cylinder

Corrdesa Corrosion Toolset

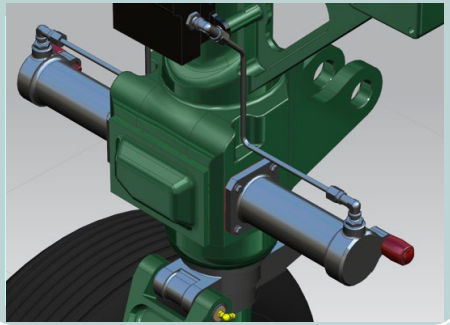
Templated analysis in PLM Environment for M&P Engineers, Considering Geometry

3-Tier Analysis Workflow



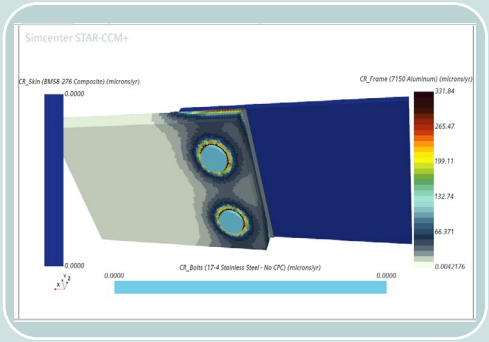
Djinn®

MIL-STD-889D Polarization



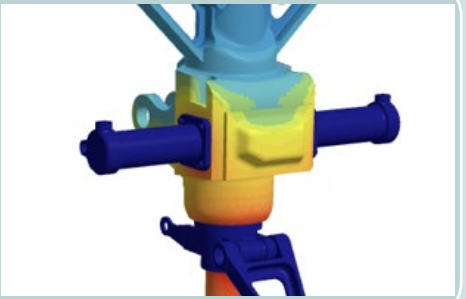
CAD

Automated MIL-STD-889D



Templates

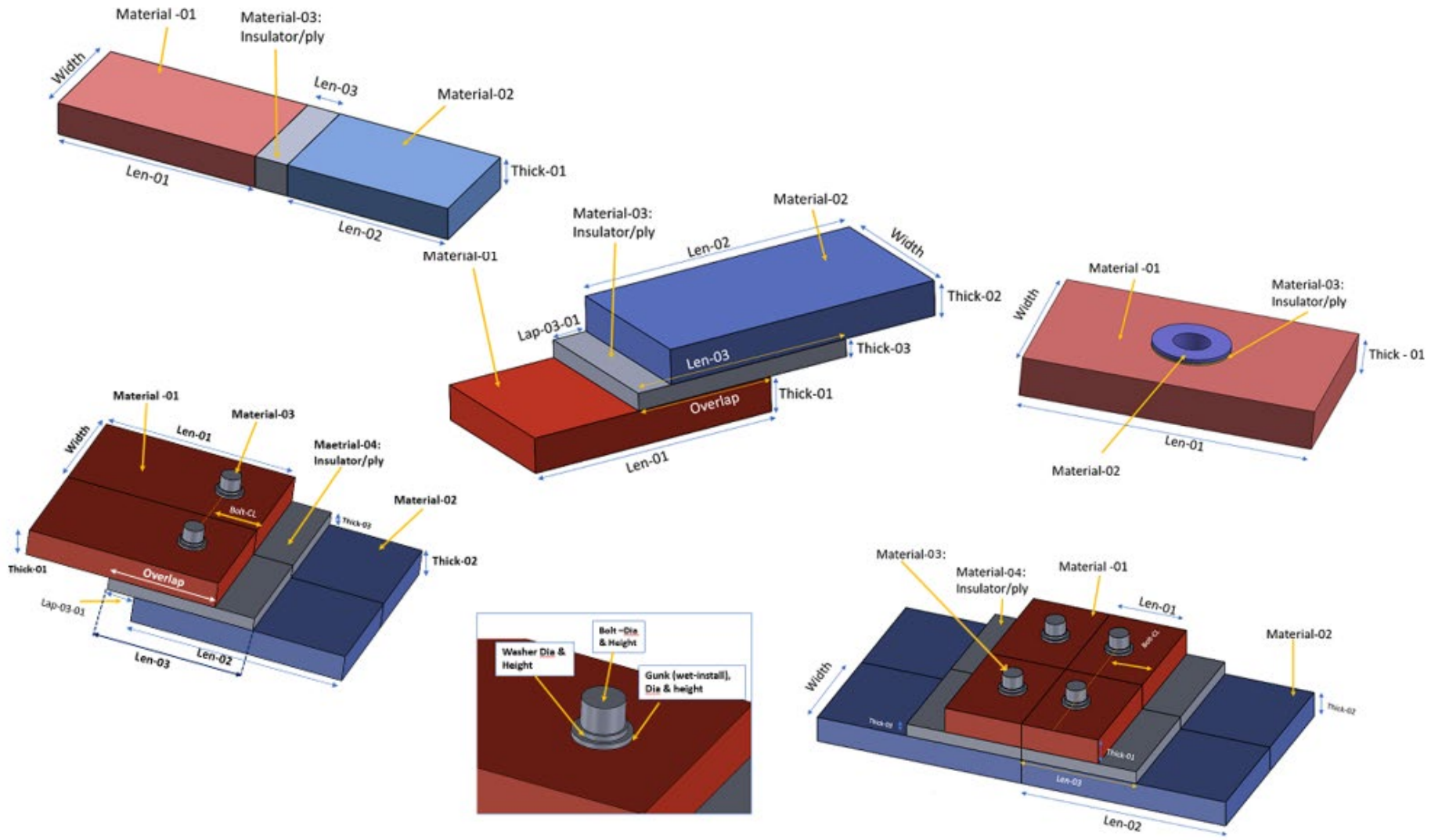
3D multi-physics solver



Full CAD

3D multi-physics solver

Standard templates



Parameterized dimensions set up 3D Commercial CFD software

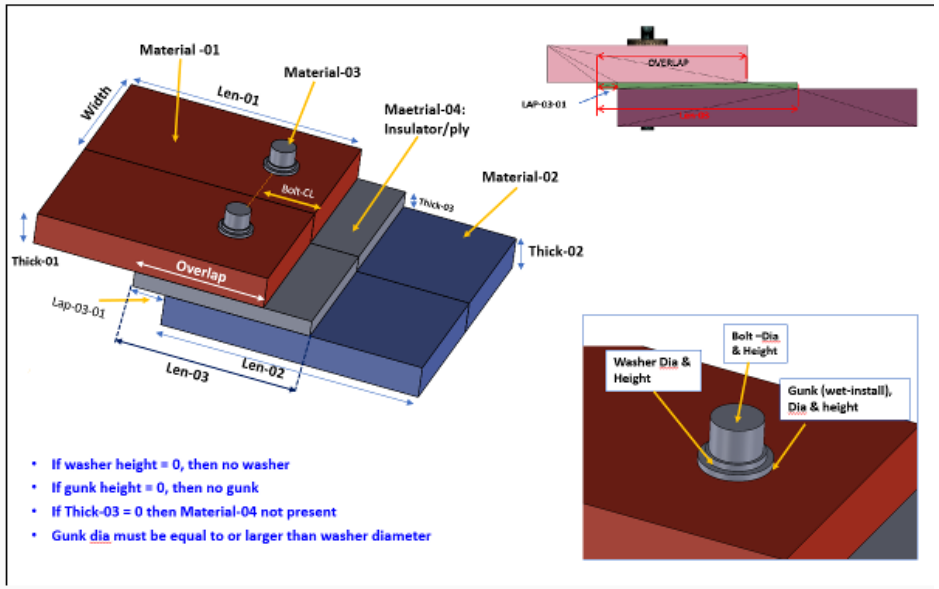
Corrosion Modeling Interface

Corrosion Modeling Interface v1.0

Project Name	Project Name
Geometry Type	03_LapJoint_Bolted
CAD Directory	Browse...

Design Parameters

Length-01	3.0 in	Thick-01	0.09 in
Length-02	3.0 in	Thick-02	0.25 in
Length-03	1.125 in	Thick-03	0.01 in
Overlap	1.0 in	Lap-03-01	0.06 in
Width	1.0 in	Bolt Dia.	0.375 in
Bolt-CL	0.5 in	Bolt Top Height	0.0625 in
Washer OD	0.45 in	Washer Thick	0.015 in
Gunk OD	0.0 mm	Gunk Thick	0.0 mm
Bush OD	0.0 mm	Bush ID	0.0 mm
Bush Flange Thick	0.0 mm	Bush Flange Dia.	0.0 mm



- If washer height = 0, then no washer
- If gunk height = 0, then no gunk
- If Thick-03 = 0 then Material-04 not present
- Gunk dia must be equal to or larger than washer diameter

Fluid Domain Type	○ BULK ◉ FLUID FILM
Fluid Film Thickness	0.1 mm

Material-01

Name	Skin (CFC Composite)
Polarization Curve	posite-Prepreg-None-Outer Surface Unsanded.csv ...

Material-02

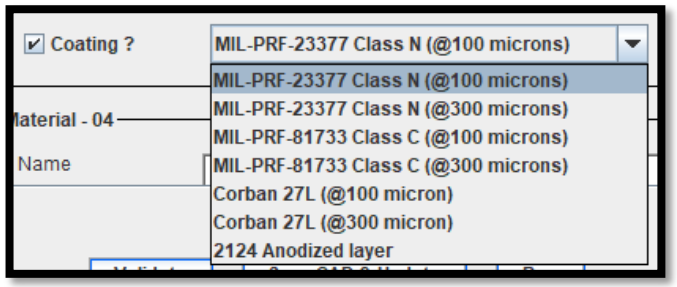
Name	Frame (7150 Aluminum)
Polarization Curve	Corrdesa)-Aluminum-7150-T7751-None-None.csv ...

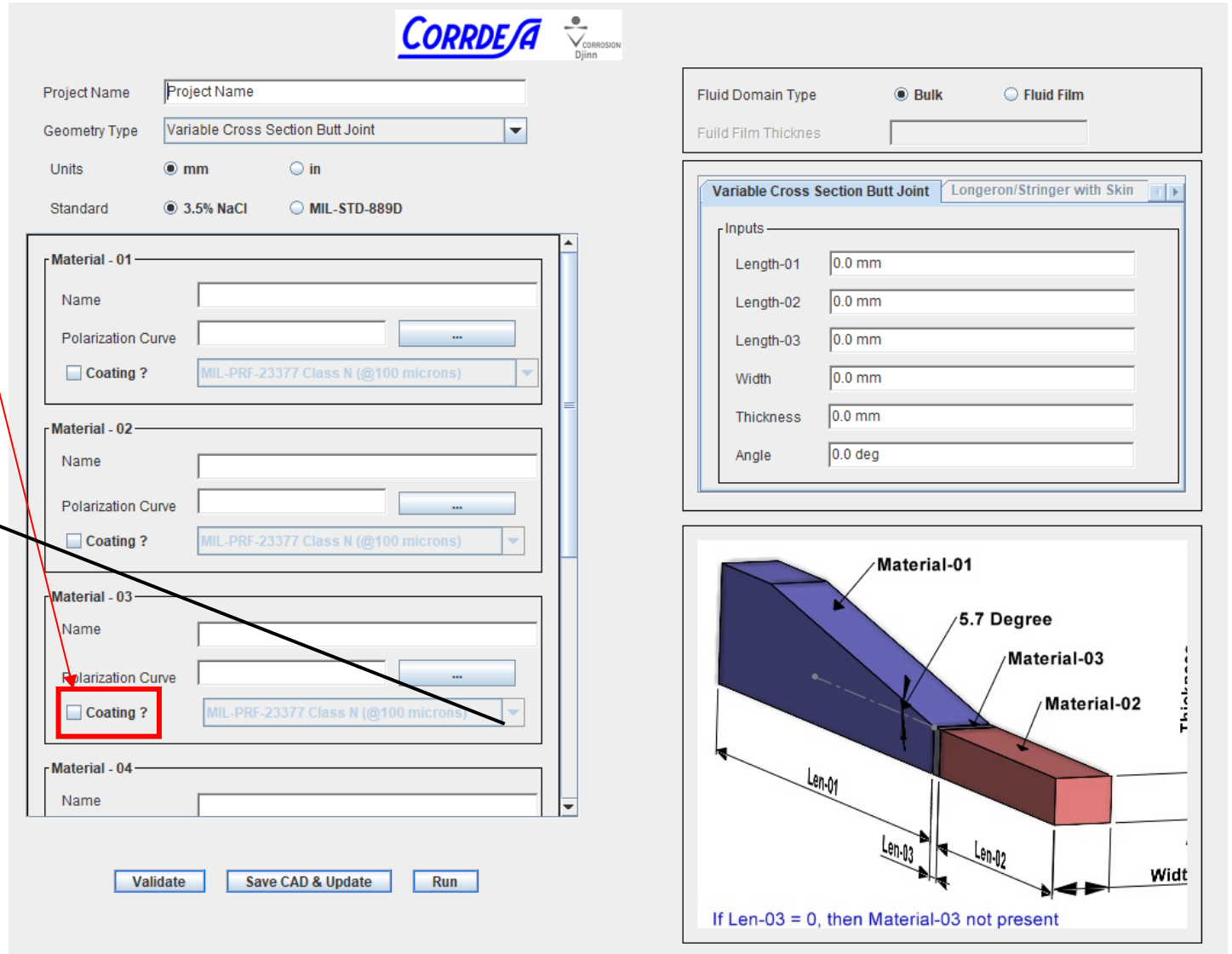
Material-03

Name	Bolts (17-4 SS)
Polarization Curve	-STD-889D-Stainless Steel-17-4 PH-None-None.csv ...

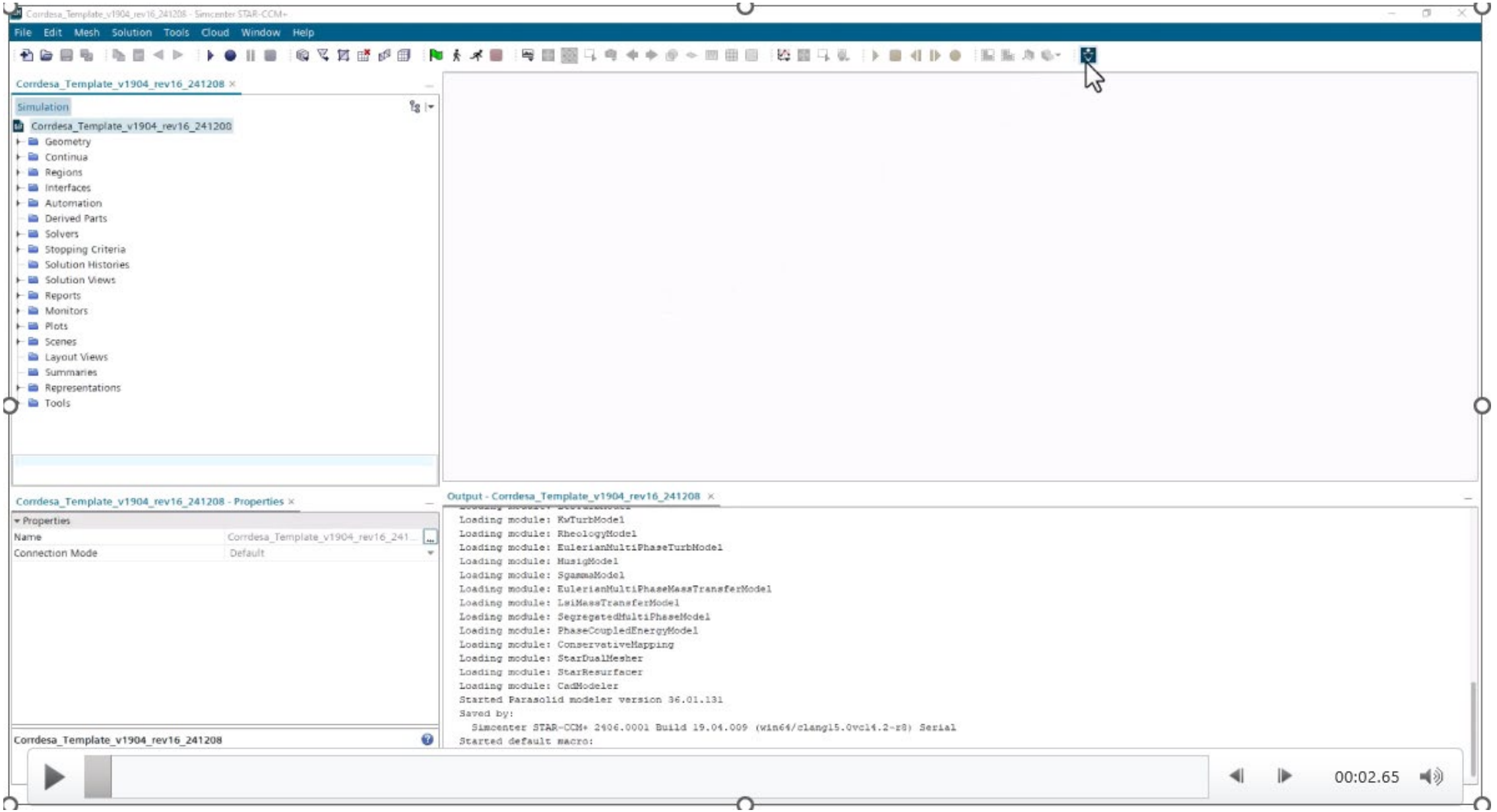
Corrosion Toolset

The user can incorporate the coating's effect on the corrosion rate calculation by ticking the "Coating" box. If selected, this opens a new menu with the list of coatings from our database.

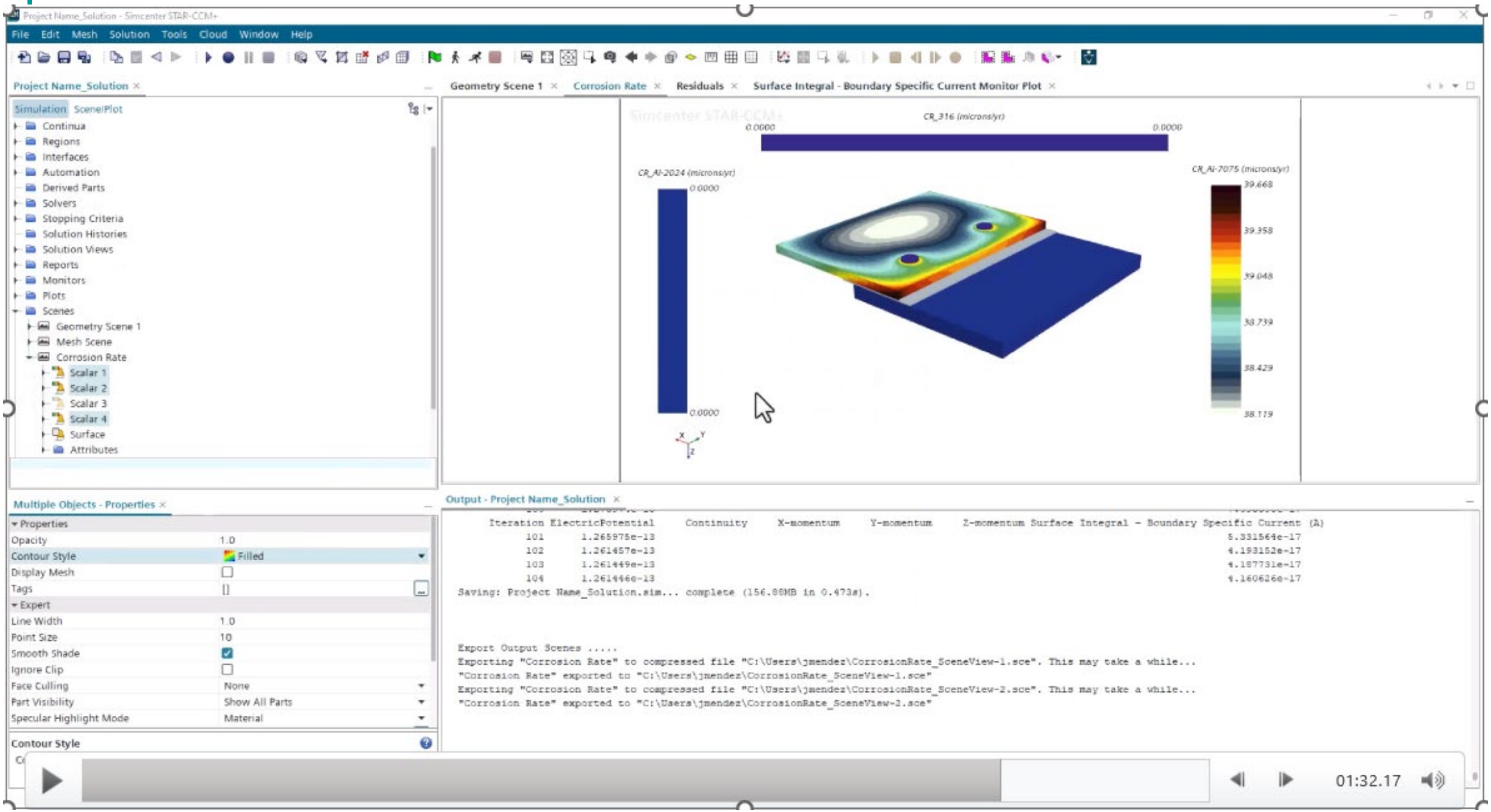




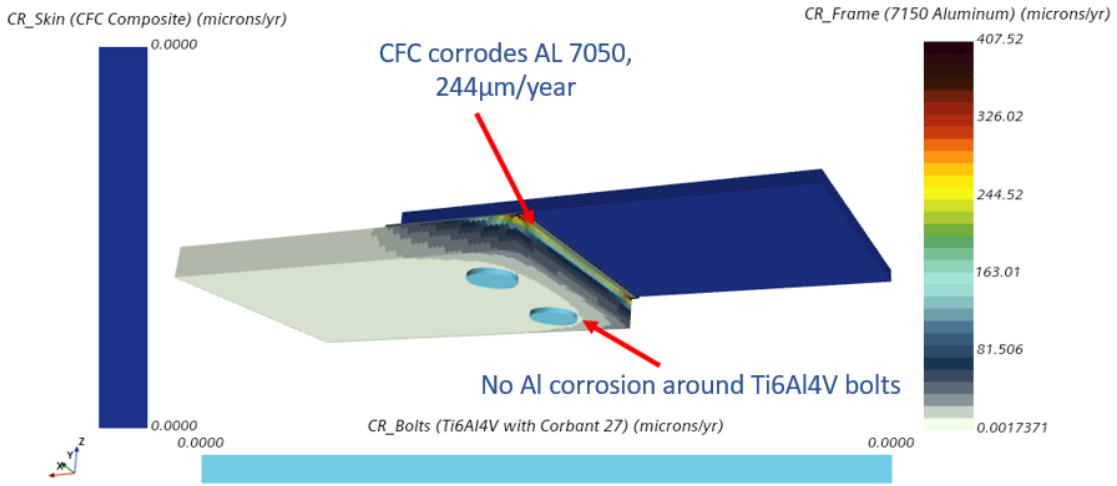
Templates Workflow

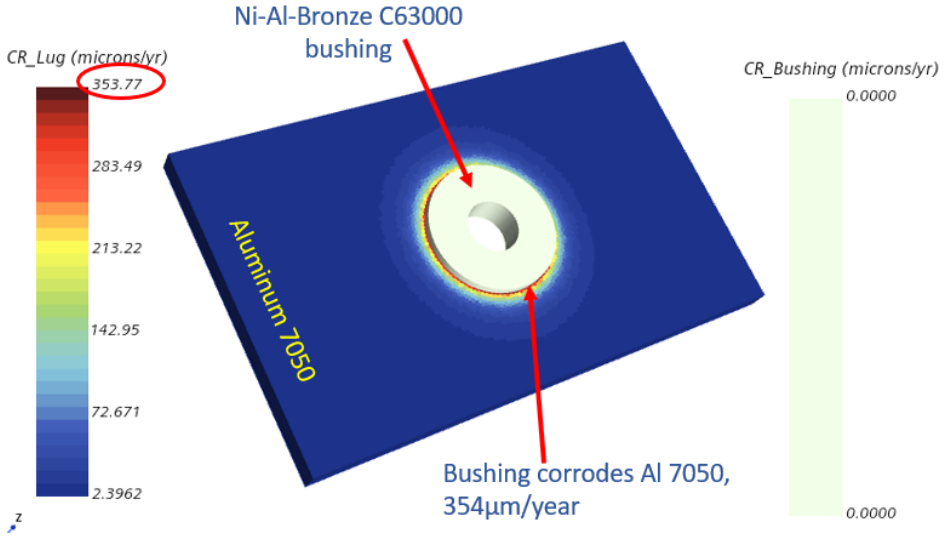


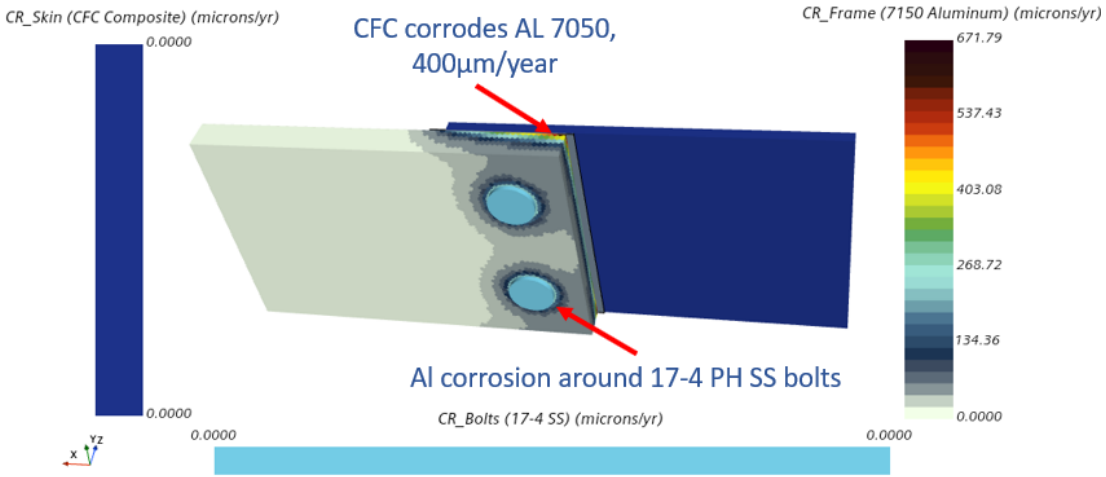
Templates Workflow

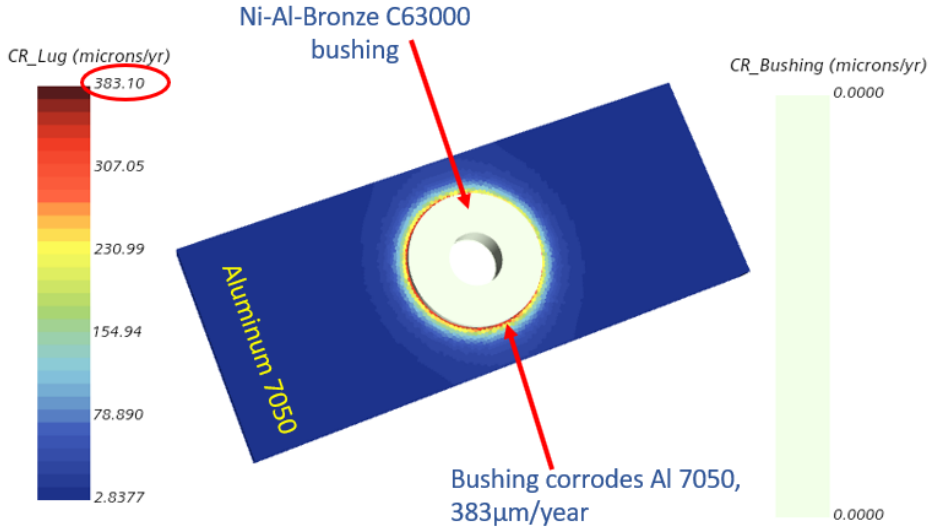


Quick Assessment by M&P Engineers









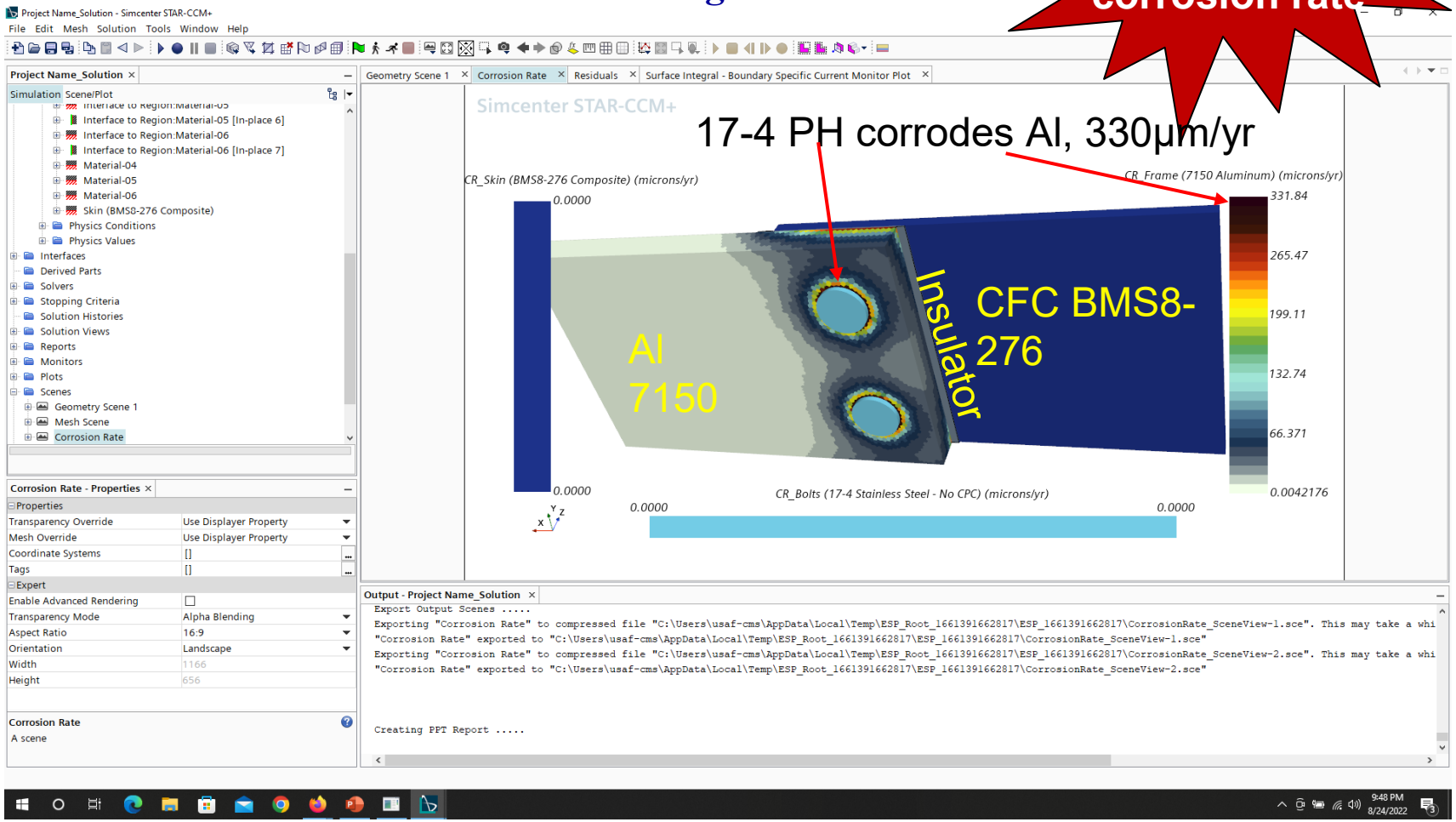
Corrosion Modeling Tool Set

- The full 3D calculation completes automatically
- You can then examine the assembly from any angle
- Change materials, coatings, dimensions to alleviate the problem

Bolted Lap Joint Model

- 17-4Ph Fasteners no CPC Applied
- Corrosion location and rate changed

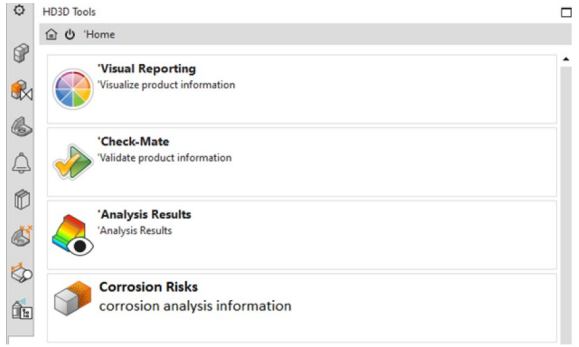
50X increase in corrosion rate

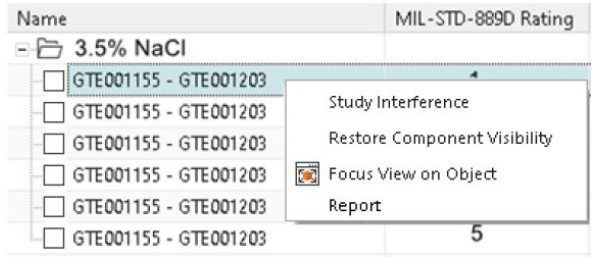


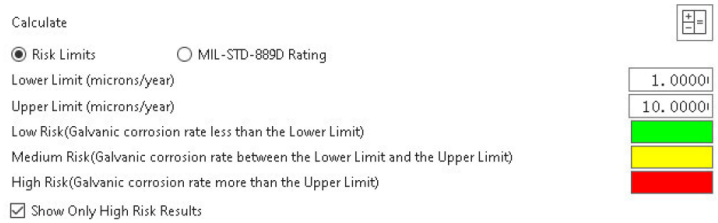
NX Corrosion Analysis Indicator

A new NX checking function to assess the galvanic corrosion risk of a designed assembly.

- Determines the components in contact with one another where corrosion is most likely.
- Works with standard material libraries including NX and IMM.
- Evaluates the impact of assigned coatings.
- Choice of environmental condition to evaluate within.
- Uses the latest galvanic corrosion assessment method provided by Corrdesa Djinn adheres to MIL-STD-889D
- Performs ‘what if’ analysis of different material combinations.
- Provides results in MIL standard or user defined ranges.
- Color coded graphic feedback for easy visualization.
- Delivers detailed result information.







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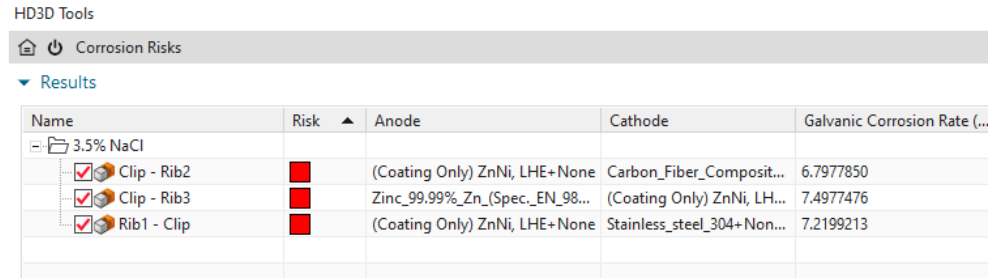
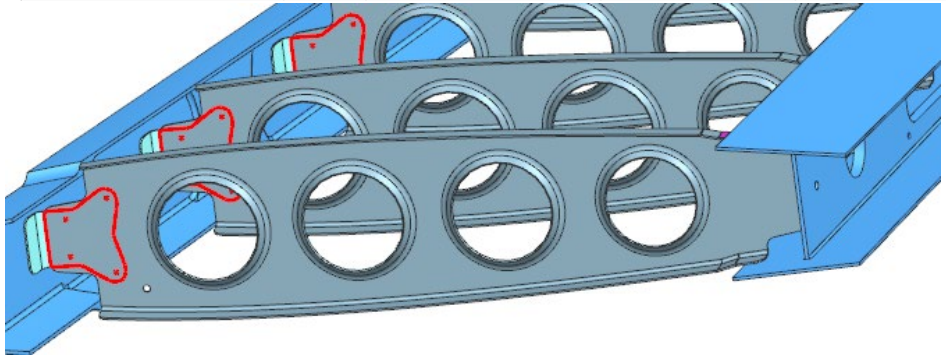
Key benefits of NX Corrosion Analysis

Running corrosion risk assessment during the design phase prior to release is extremely beneficial.

- Identify potential corrosion issues due to incompatible materials touching.
- Perform ‘what if’ analysis on different material combinations from results dialog
- Identify lack of coating or material specification in the CAD model.
- Indicate where the use of corrosion barriers may be needed.
- Provides detailed information to designers educating them on material compatibility.
- Identify areas in a design that a material analyst may need to do further detail studies by using Star CCM+





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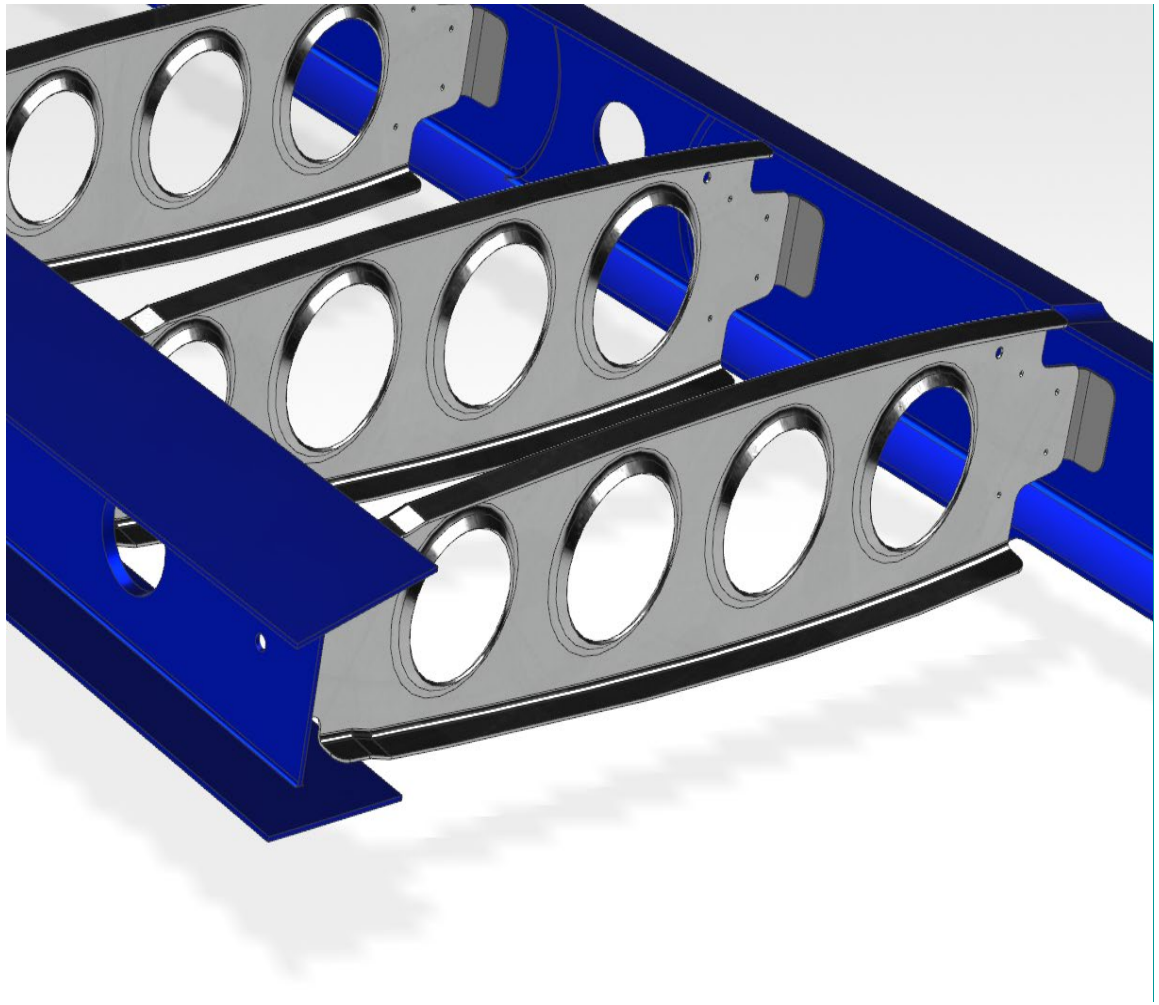
Technical information

NX Corrosion Analysis Indicator

Product ID: NX30161

Prerequisite: NX Design Solution

License: perpetual, HSaaS, VBL



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NX Corrosion Analysis benefits

Drastically reduce time it takes to evaluate potential corrosion problems prior to releasing design.

Identify any missing material or coating areas on your design.

Adhere to government mandates of corrosion modelling.

#NXMakesItReal

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Disclaimer

Subject to changes and errors. The information given in this document only contains general descriptions and/or performance features which may not always specifically reflect those described, or which may undergo modification in the course of further development of the products. The requested performance features are binding only when they are expressly agreed upon in the concluded contract.

Contact

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MIL-STD-889D Analysis Software

Digital version of MIL-STD-889D, mixed potential, CAD agnostic

Standards provide guidance – and work together

MIL-STD-1568D

4.4.1 **Modeling** and validation testing **shall be** performed to identify **corrosion-prone locations**

4.4.1 **Testing** shall include selected materials assembly techniques, and corrosion protection schemes in relevant environments and in-service loadings.

4.5.4 Galvanically dissimilar materials. Calling out **MIL-STD-889** (latest release by inference, rev D Summer 2021)

MIL-STD-889D

In revision D, **galvanic corrosion current** between two dissimilar materials will be used to determine galvanic compatibility.

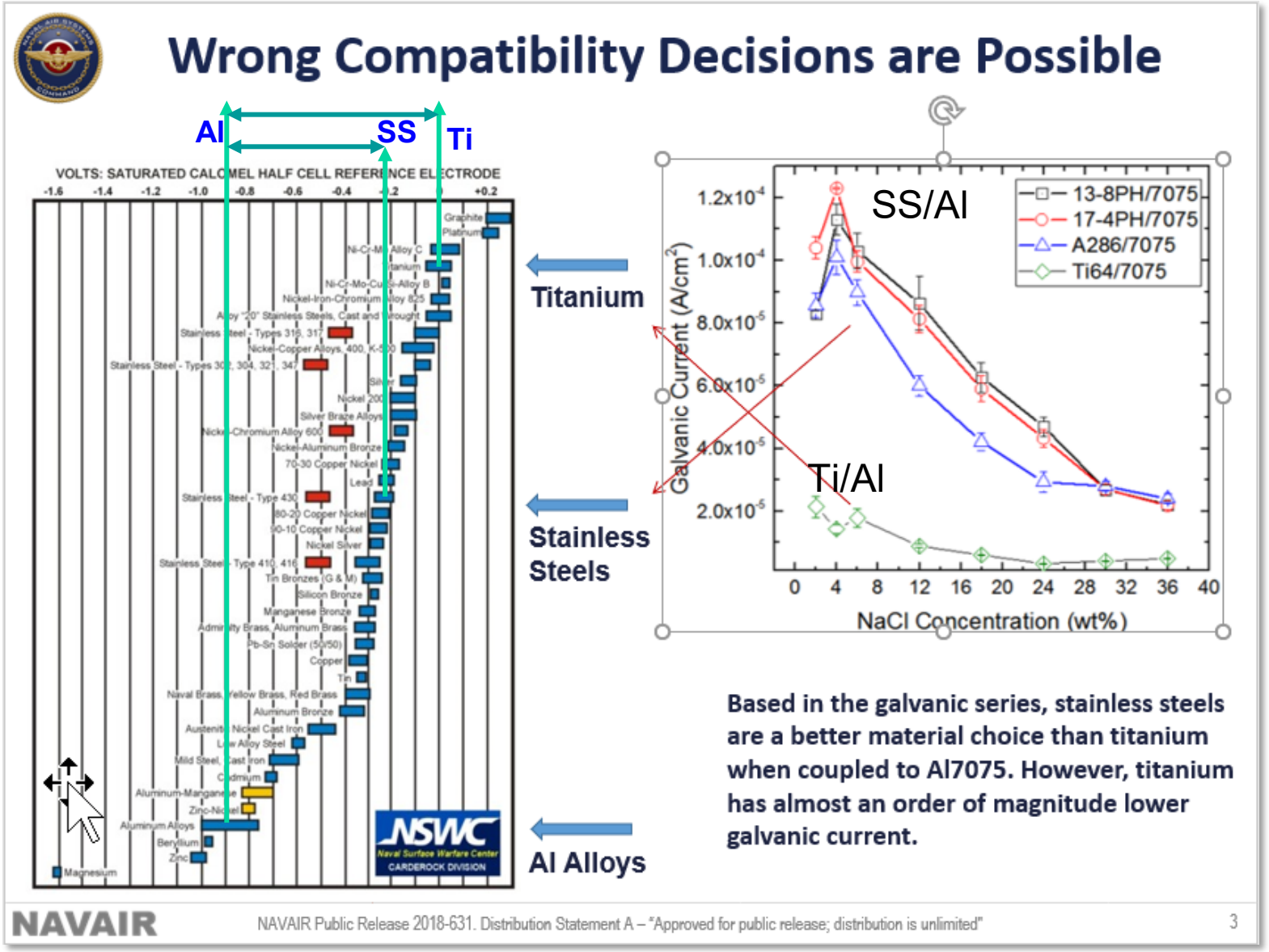
This new methodology is based on the mixed potential theory… the galvanic current, is determined by the crossing points of the **polarization curves**.

This galvanic current is then used to calculate the galvanic corrosion rate between any two materials.

NAVAIR briefing on MIL-STD-889 change

Victor Rodriguez-Santiago, ASETSDefense Workshop 2018

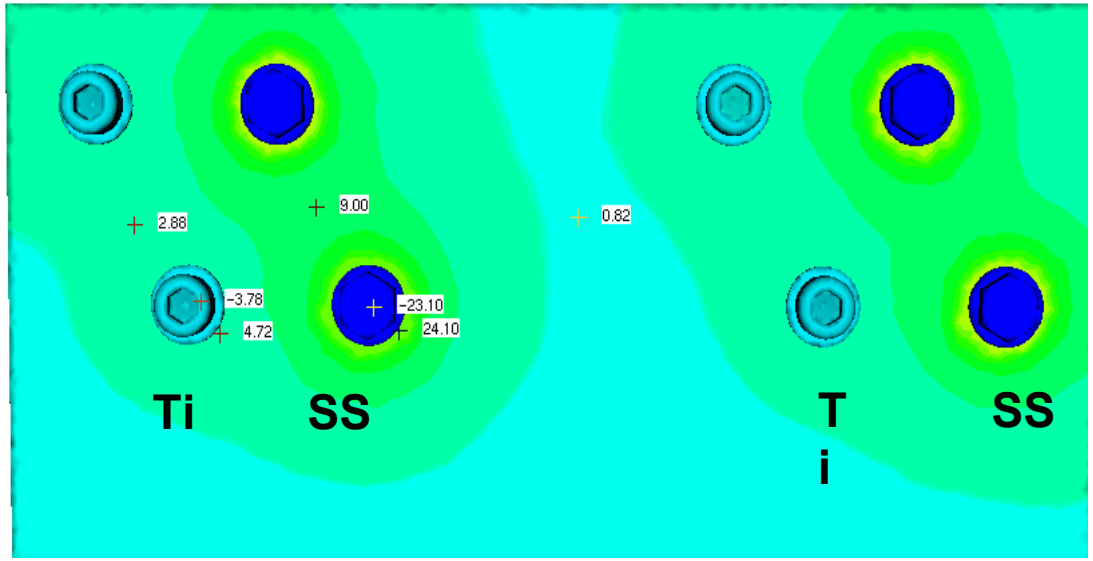
- “Galvanic Compatibility Assessment: New Methodology and Standardization”
- **MIL-STD-889D intended in 2020**



Old standards “not entirely” correct!

Corrosion Reality

Corrosion Prediction



Revised MIL-STD-889 ”D”, no longer used *potential* but requires calculation of *current*

Requiring the use of data known as “Polarization Curves”

Title change from ‘Dissimilar Metals’

DEPARTMENT OF DEFENSE

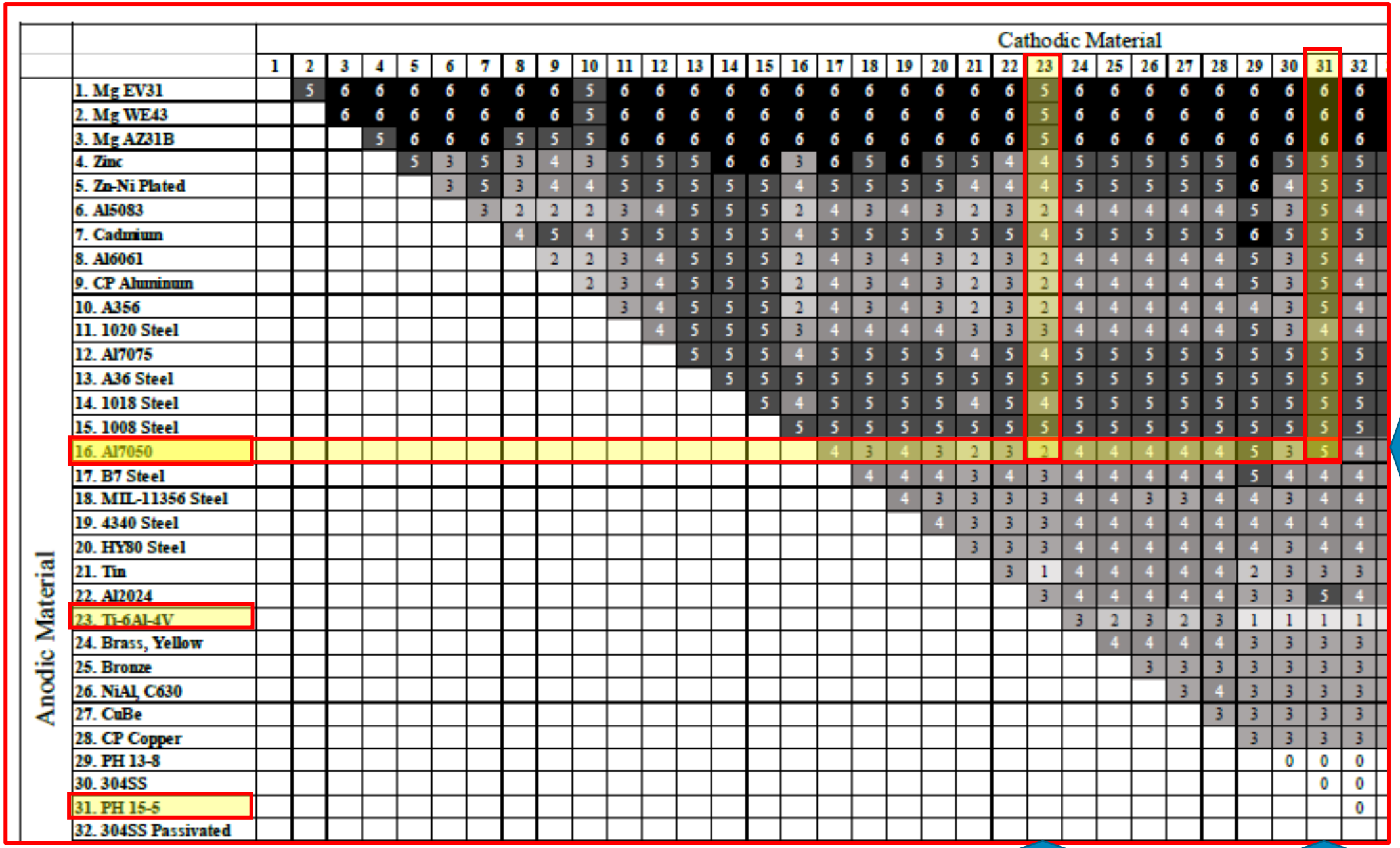
STANDARD PRACTICE

GALVANIC COMPATIBILITY OF ELECTRICALLY CONDUCTIVE MATERIALS

This change instantly impacts a much wider community and many new materials.

No longer just basic metals and alloys, but every material you use –

alloys, composites, conductive gaskets, sealants, gap fillers, and every coating and treatment (bare, chromated, trivalent passivated, BSAA anodized).



Anodic Material \ Cathodic Material	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1. Mg EV31		5	6	6	6	6	6	6	6	5	6	6	6	6	6	6	6	6	6	6	6	6	5	6	6	6	6	6	6	6	6	6
2. Mg WE43			6	6	6	6	6	6	6	5	6	6	6	6	6	6	6	6	6	6	6	6	5	6	6	6	6	6	6	6	6	6
3. Mg AZ31B				5	6	6	6	5	5	5	6	6	6	6	6	6	6	6	6	6	6	6	5	6	6	6	6	6	6	6	6	6
4. Zinc					5	3	5	3	4	3	5	5	5	6	6	3	6	5	6	5	5	4	4	5	5	5	5	5	6	5	5	5
5. Zn-Ni Plated						3	5	3	4	4	5	5	5	5	5	4	5	5	5	5	4	4	4	5	5	5	5	5	6	4	5	5
6. Al5083							3	2	2	2	3	4	5	5	5	2	4	3	4	3	2	3	2	4	4	4	4	4	5	3	5	4
7. Cadmium								4	5	4	5	5	5	5	5	4	5	5	5	5	5	5	4	5	5	5	5	5	6	5	5	5
8. Al6061									2	2	3	4	5	5	5	2	4	3	4	3	2	3	2	4	4	4	4	4	5	3	5	4
9. CP Aluminum										2	3	4	5	5	5	2	4	3	4	3	2	3	2	4	4	4	4	4	5	3	5	4
10. A356											3	4	5	5	5	2	4	3	4	3	2	3	2	4	4	4	4	4	4	3	5	4
11. 1020 Steel												4	5	5	5	3	4	4	4	4	3	3	3	4	4	4	4	4	5	3	4	4
12. Al7075													5	5	5	4	5	5	5	5	4	5	4	5	5	5	5	5	5	5	5	5
13. A36 Steel														5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
14. 1018 Steel															5	4	5	5	5	5	4	5	4	5	5	5	5	5	5	5	5	5
15. 1008 Steel																5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
16. Al7050																	4	3	4	3	2	3	2	4	4	4	4	4	5	3	5	4
17. B7 Steel																		4	4	4	3	4	3	4	4	4	4	4	5	4	4	4
18. MIL-11356 Steel																			4	3	3	3	3	4	4	3	3	4	4	3	4	4
19. 4340 Steel																				4	3	3	3	4	4	4	4	4	4	4	4	4
20. HY80 Steel																					3	3	3	4	4	4	4	4	4	3	4	4
21. Tin																						3	1	4	4	4	4	4	2	3	3	3
22. Al2024																							3	4	4	4	4	4	3	3	5	4
23. Ti-6Al-4V																								3	2	3	2	3	1	1	1	1
24. Brass, Yellow																									4	4	4	4	3	3	3	3
25. Bronze																										3	3	3	3	3	3	3
26. NiAl, C630																											3	4	3	3	3	3
27. CuBe																												3	3	3	3	3
28. CP Copper																													3	3	3	3
29. PH 13-8																														0	0	0
30. 304SS																															0	0
31. PH 15-5																																0
32. 304SS Passivated																																

Galvanically Compatible:
0: <0.009 mil/year

Galvanically Incompatible:
1: 0.01-0.09 mil/year
2: 0.1-0.9 mil/year
3: 1-4.99 mil/year
4: 5-9.99 mil/year
5: 10-99.99 mil/year
6: > 100 mil/year

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Ti6Al4V

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