CORROSION
Djinn

Corrosion Djinn

User Guide & Reference

Corrdesa

Table of contents

1. Corrosion Djinn 3
  1.1 Executive Summary 3
  1.2 Quick Start Guide 4
  1.3 Features 12
  1.4 Self Hosted 17
2. Background & Theory 19
  2.1 Background & Theory 19
3. Simcenter Star CCM+ 25
  3.1 Overview 25
  3.2 Installation 26
  3.3 Running Analysis 28

1. Corrosion Djinn

1.1 Executive Summary

This document is the User Manual for Corrosion Djinn, a software package and SaaS tool, developed and released by Corrdesa LLC, for predicting the galvanic corrosion rates between mixed metals, alloys, and other conductive materials in electrolytes. Typically, the impact of galvanic corrosion is assessed on the basis of a galvanic series [1] which are cited in a number of proprietary guidelines or public/military standards, such as;

- ASM Metals Handbook 13A
- ASTM G82
- AD823185
- DEF-STAN 00-970
- MIL-STD-889 B & C & D
- MIL-STD-1250
- MIL-DTL-14072
- NASA/TM-2019-218194

This type of classification of metals and alloys, although it provides quite useful indication of general trend in galvanic corrosion, however it does not help much to understand the actual process of galvanic corrosion when dissimilar metals are coupled since the electrochemical potential series is obtained for individual metals under “uncoupled” condition [2][3][4]. The electrode potential on these galvanic series is a measure, under certain fixed conditions, of the thermodynamic tendency of a metal to undergo a corrosion reaction or lose an electron providing no information concerning the kinetics of the corrosion reaction. The magnitude of galvanic corrosion depends not only on the potential difference between dissimilar metals but also on the electrochemical kinetic parameters on each material, electrolyte composition and temperature when they are coupled together. In order to capture the kinetics, one would need the polarization behavior of each material involved. This is explained in the following sections. The military standard, MIL-STD-889C [5] has already started to recognize the shortfall of the present method. Appendix B of MIL-STD-889C states that the maximum corrosion current is identified by the crossing point of the material polarization curves. An issue however, is that the present form of MIL-STD-889C does not include polarization curve data. Indeed, the present standard does not even include galvanic potential data on many modern materials.

A revised version of the standard, MIL-STD-889D, was released in the first quarter of 2021 and ushered in a new era where galvanic corrosion risk will be assessed through the application of polarization data, consequently, the methodology employed in Djinn® is compliant with this revised military standard.

Corrosion Djinn addresses these issues by providing an easy to use, computerized method for determining the crossing points, together with a database of consistent, accurate, modern polarization curves – the data of which has been acquired by following a measurement protocol developed by NAVAIR. Consequently, the Djinn Platform can provide a more accurate insight into possible corrosion rate and consequent risk. The methodology used in this software is based on the mixed potential theory of electrochemistry that was first formulated 70 years ago and has been validated and used by electrochemists ever since. It is based on the principle that the common potential reached by two dissimilar materials in electrical contact, and the galvanic current between them is determined by the crossing points of their polarization curves.

1.1.1 References

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[1] Standard Guide for Development and Use of Galvanic Series for Predicting Galvanic Corrosion Performance. G82-98 (Reapproved 2014) ↩

[2] J.W. Oldfield, Electrochemical theory of galvanic corrosion, in: Harvey P. Hack (Ed.), Galvanic Corrosion, ASTM STP 978, ASTM, 1988, p 5-22. ↩

[3] F. Mansfeld, Corrosion, Vol. 27, 1971, p 436. ↩

[4] F. Mansfeld, Corrosion, Vol.29, 1973, p 403. ↩

[5] Mil-STD-889C, Department of Defense, Standard Practice, Dissimilar Metals, 22 August 2016.Naval Air Warfare Center Aircraft Division. ↩

1.2 Quick Start Guide

1.2.1 Quick Start Guide

Running a risk analysis

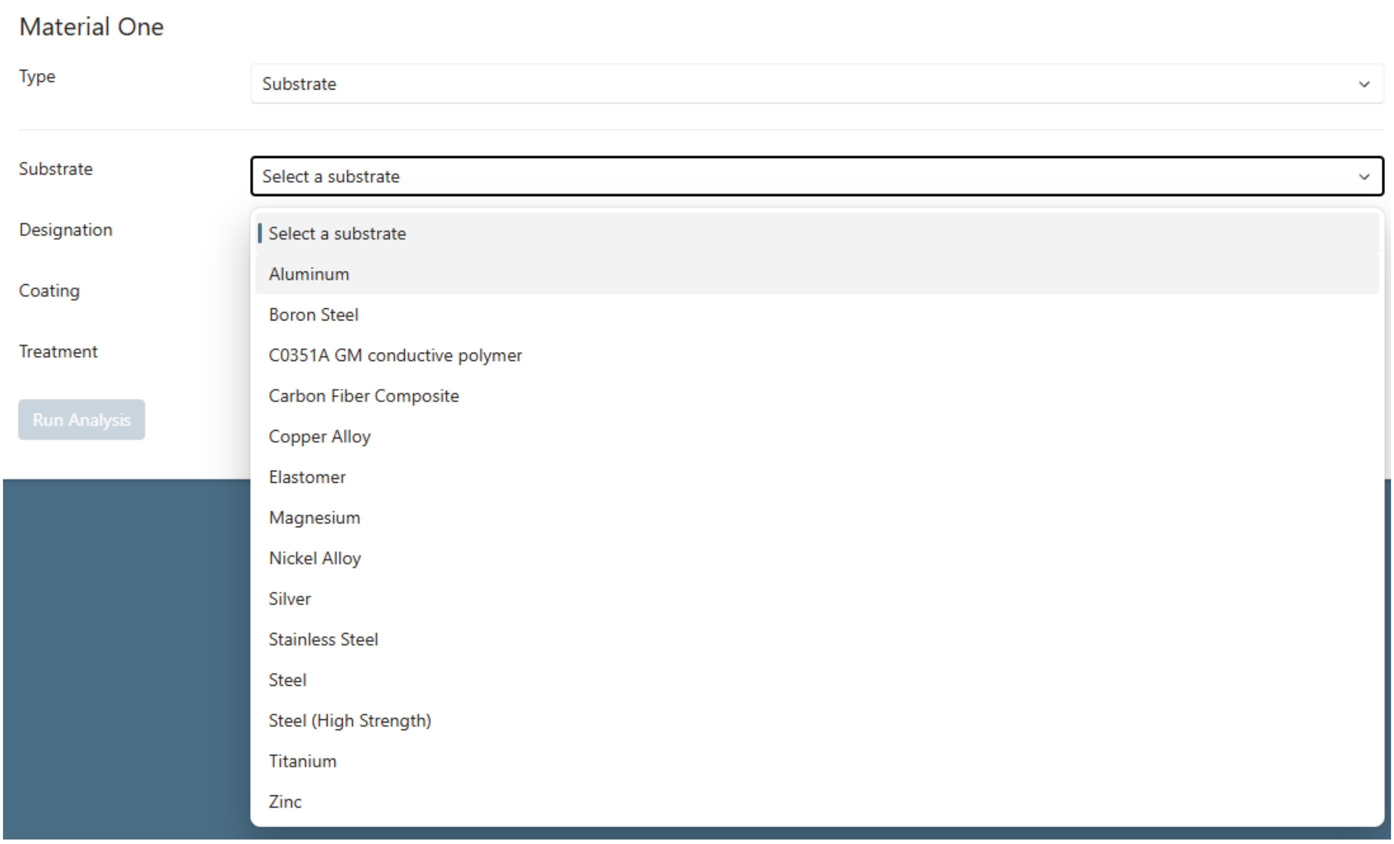
Assessing galvanic corrosion risk between material couples is quick and easy with Corrosion Djinn.

Go to the https://corrosiondjinn.com website. You can then create groups of material pairs for examination. So first you enter the environment, Figure 1, and then you create your first group by making your choices for the individual materials in the material pairs.

In Djinn, materials are defined by using four descriptors, so in this example if we want to examine the interface between an Aluminum alloy and a Stainless Steel we would make our choices as follows

- Substrate - Figure 2
- Designation - Figure 3
- Coating - Figure 4
- Treatment - Figure 5
- Choice of second material - Figure 6
- Results - Figure 7
- Adding further groups

Figure 1 - Choosing your Environment



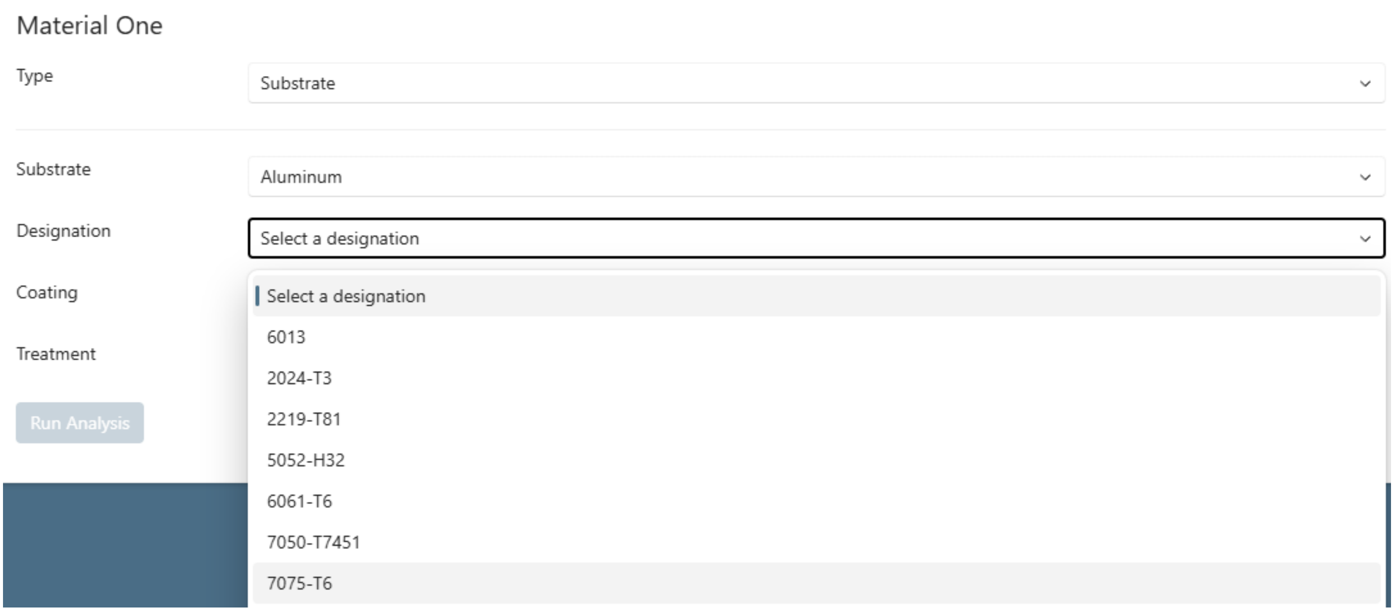
Material One

Type: Substrate

Substrate: Select a substrate

Figure 2 - Choosing your Substrate

By substrate we mean the underlying base material, which could be an element or alloy.



Material One

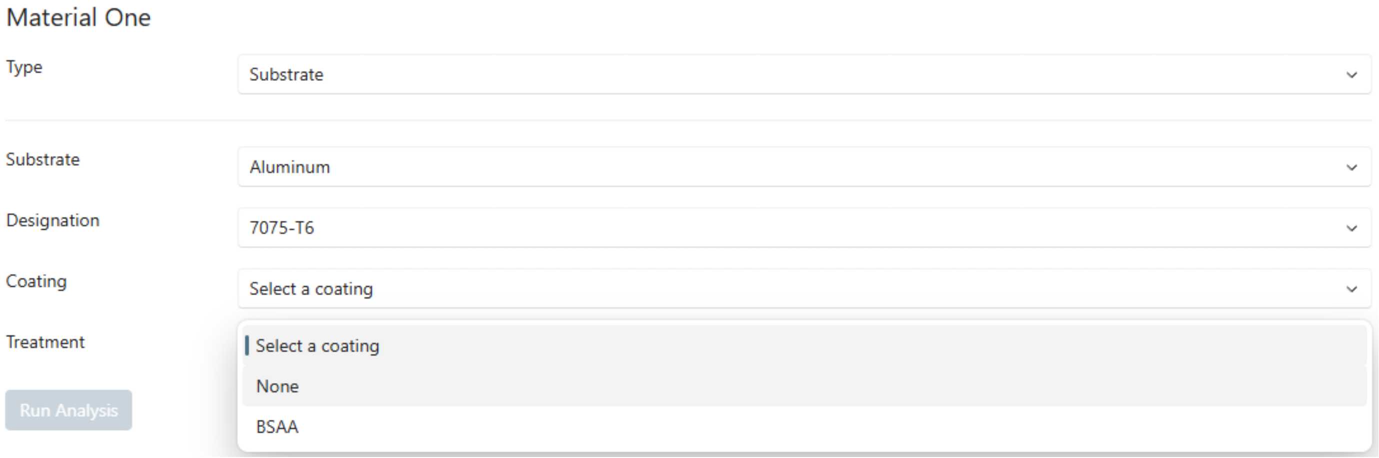
Type: Substrate

Substrate: Aluminum

Designation: Select a designation

Figure 3 - Choosing your Designation

If an alloy is being considered, for example, then designation allows the user to be a little more specific, permitting the user to specify a particular alloy series or heat treatment.



Material One

Type: Substrate

Substrate: Aluminum

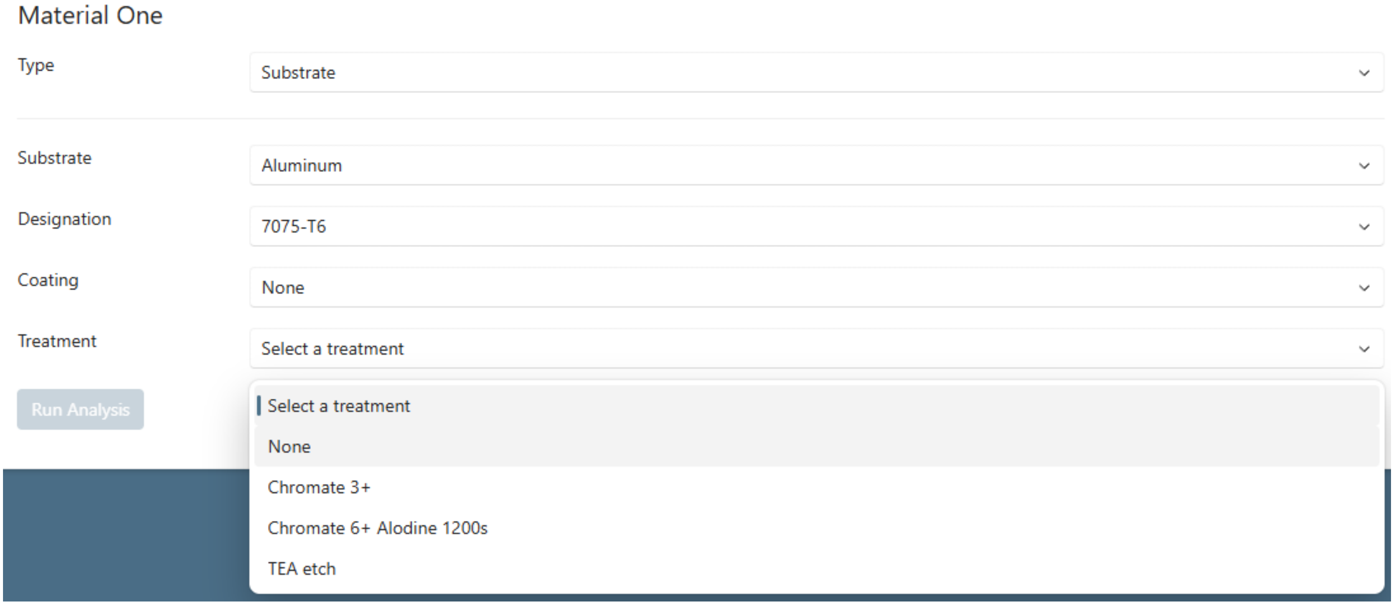
Designation: 7075-T6

Coating: Select a coating

Treatment

Figure 4 - Choosing your Coating

The user also has the opportunity to specify a coating, which, in the case of Figure 4, would allow the user to specify an anodized aluminum alloy.



Material One

Type: Substrate

Substrate: Aluminum

Designation: 7075-T6

Coating: None

Treatment: Select a treatment

Figure 5 - Choosing your Treatment

Finally, the user also has an opportunity to specify a treatment. For example, in the case of an anodized aluminum alloy, treatment allows the user to specify the final “finish” to the anodized layer such as chromate or hot water seal etc. The user then makes selections for the Second Material of the couple. Figure 6 shows selections for the second material Stainless Steel 15-5 PH which is coupled to bare Aluminum alloy 7075-T6. When satisfied with the materials selections for the first group the user then clicks *Run Analysis*.

Material Two

Type	Substrate
Substrate	Stainless Steel
Designation	15-5 PH
Coating	None
Treatment	None

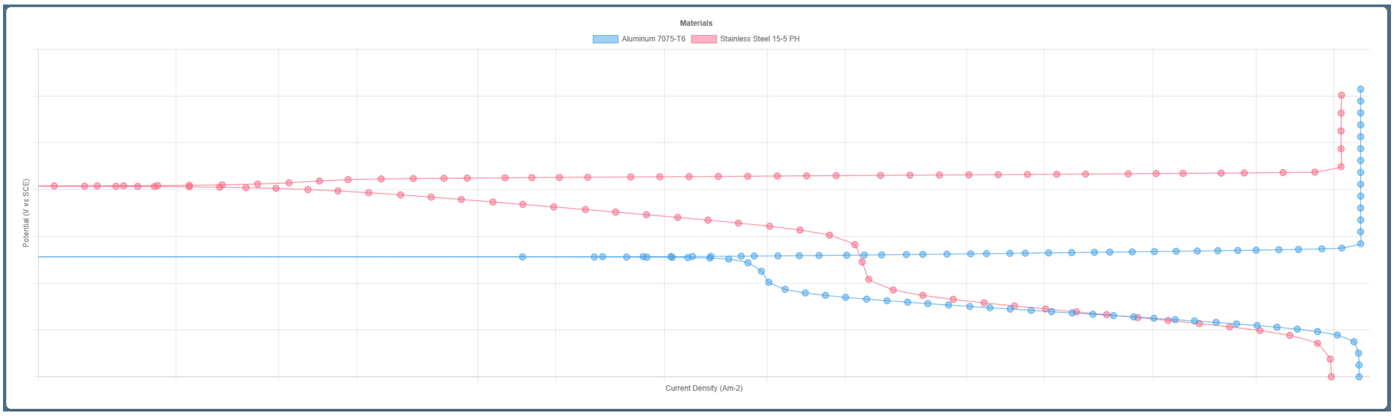
Figure 6 - Choices for second material in Group 1

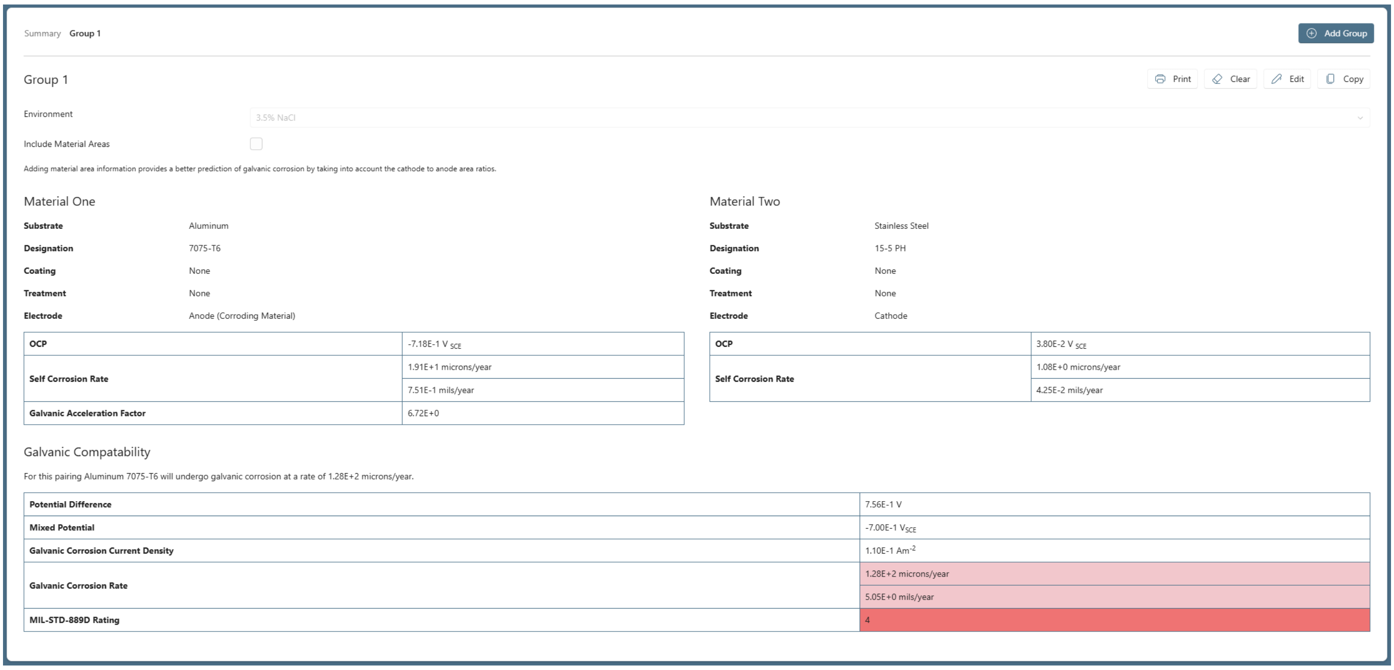
The user now chooses the option to *Run Analysis*, which provides a plot of the material polarization curves and a summary table of the material compatibility results for this particular couple, see Figure 7. Djinn annotates each material in the couple as anode and cathode according to their relative OCPs (Open Circuit Potentials), anodic materials having a more negative OCP.

The Djinn electrochemical database also contains material self-corrosion rates and these can be seen for each material, the bare Al-7075 T6 having a self-corrosion rate of 19.1 microns per year compared to the stainless steel 15-5 PH which only has a self-corrosion rate of 1.08 micron/year which is essentially negligible. However, there is a galvanic impact resulting from these particular materials being adjacent to one another, this is reflected in the galvanic corrosion rate, of 128 microns/year shown in the summary portion of the table. The inference is that although the aluminum alloy has a self-corrosion rate of 19.1 microns/year, this is accelerated when in galvanic contact with the 15-5 PH stainless steel to 128 microns/year. This is captured in the reported Galvanic Acceleration Factor of 6.7. A summary report can be printed to file using the ‘print’ button.

Adding more groups

More material pairs (groups) can be added for comparison by clicking the Copy button. This copies the current group and gives it the next sequential Group #. After making any changes, clicking the *Run Analysis* button saves it to the next group. Any number of additional groups can be added in this way.





Group 1

Environment: 3.5% NaCl

Include Material Areas ☐

Adding material area information provides a better prediction of galvanic corrosion by taking into account the cathode to anode area ratios.

Material One

Substrate	Aluminum
Designation	7075-T6
Coating	None
Treatment	None
Electrode	Anode (Corroding Material)

OCP	-7.18E-1 V_{SCE}
Self Corrosion Rate	1.91E+1 microns/year
	7.51E-1 mils/year
Galvanic Acceleration Factor	6.72E+0

Material Two

Substrate	Stainless Steel
Designation	15-5 PH
Coating	None
Treatment	None
Electrode	Cathode

OCP	3.80E-2 V_{SCE}
Self Corrosion Rate	1.08E+0 microns/year
	4.25E-2 mils/year

Galvanic Compatability

For this pairing Aluminum 7075-T6 will undergo galvanic corrosion at a rate of 1.28E+2 microns/year.

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	1.28E+2 microns/year
	5.05E+0 mils/year
MIL-STD-889D Rating	4

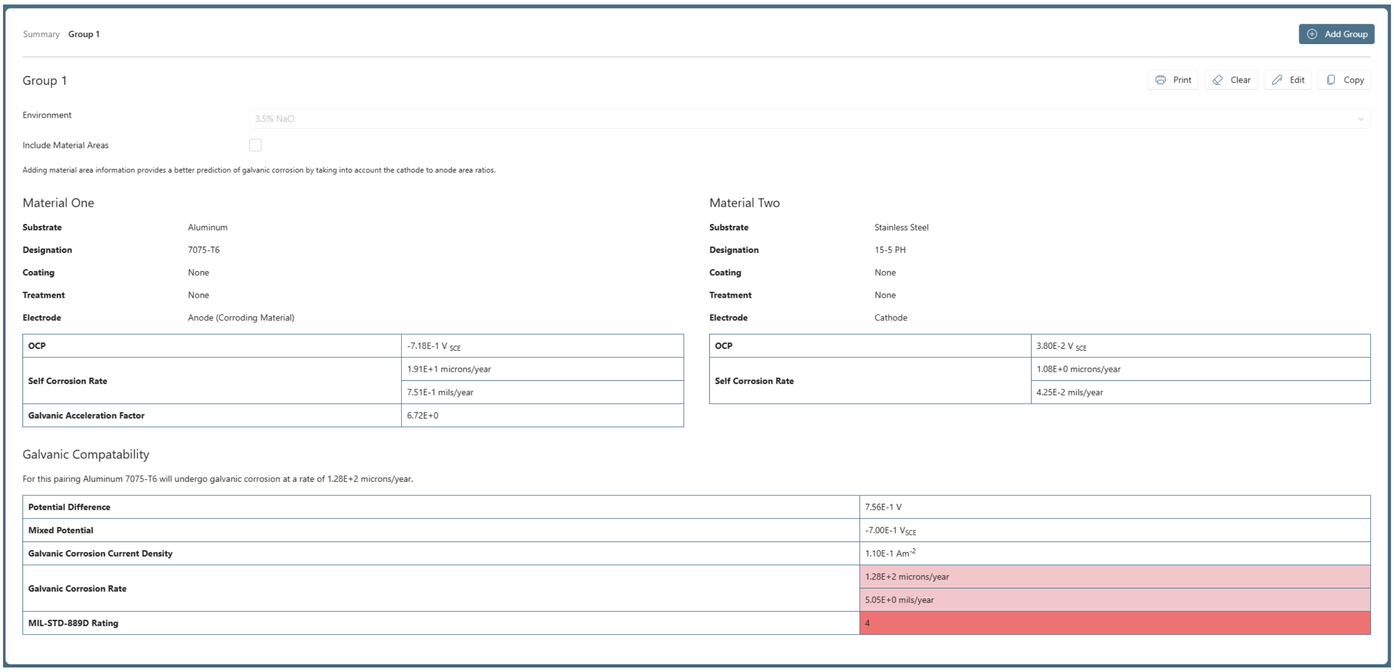
Figure 7 - Group 1 Results

1.2.2 Example Use Case

Choosing Materials

The Quick Start Guide showed how a user could quickly examine the galvanic impact of a dissimilar material couple. In this section we will build upon the first material couple and illustrate how a user can make informed choices of materials, coatings and treatments in order to mitigate corrosion risks.

For demonstration purposes let's imagine a scenario where an engineer has to specify a material for bushings to be used in an airframe repair. Over time, fixture systems (bolts, fasteners, etc) connecting components to airframes may cause the airframe to corrode. The repair procedure would comprise the removal of corroded material and restoring the fixture hole diameter by use of a bushing. The material choice for the bushing is very important as a poor material choice may lead to galvanic corrosion risk.



Group 1

Environment: 3.5% NaCl

Include Material Areas ☐

Adding material area information provides a better prediction of galvanic corrosion by taking into account the cathode to anode area ratios.

Material One

Substrate	Aluminum
Designation	7075-T6
Coating	None
Treatment	None
Electrode	Anode (Corroding Material)

OCP	-7.18E-1 V_{SCE}
Self Corrosion Rate	1.91E+1 microns/year
	7.51E-1 mils/year
Galvanic Acceleration Factor	6.72E+0

Material Two

Substrate	Stainless Steel
Designation	15-5 PH
Coating	None
Treatment	None
Electrode	Cathode

OCP	3.80E-2 V_{SCE}
Self Corrosion Rate	1.08E+0 microns/year
	4.25E-2 mils/year

Galvanic Compatability

For this pairing Aluminum 7075-T6 will undergo galvanic corrosion at a rate of 1.28E+2 microns/year.

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	1.28E+2 microns/year
	5.05E+0 mils/year
MIL-STD-889D Rating	4

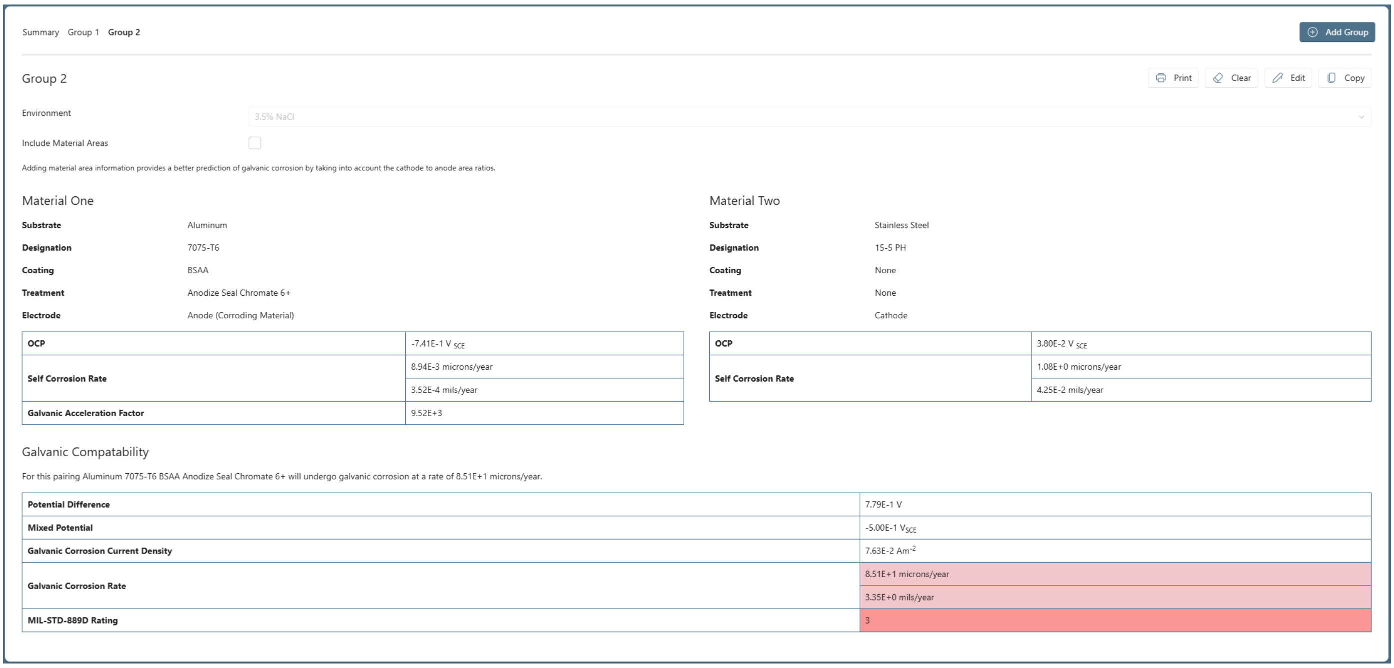
Figure 1 - Group 1 Results

Our first group, already examined corresponds to the proposed use of Stainless Steel 15-5 PH bushings in an airframe structure comprising Aluminum 7075-T6.

Adding a Coating

> **Question**
>
> What would be the impact of anodizing the Aluminum 7075-T6, but staying with the bushing material of Stainless Steel 15-5 PH?

To examine this the user simply clicks 'Copy' and a second group is created as a second 'TAB' with the same materials pre-populated. The user then changes the selections for the Aluminum 7075-T6, assigning an anodize (BSAA) for the coating and an 'Anodize Seal Chromate 6+' for the treatment, see Figure 2.



Group 2

Environment: 3.5% NaCl

Include Material Areas ☐

Adding material area information provides a better prediction of galvanic corrosion by taking into account the cathode to anode area ratios.

Material One

Substrate	Aluminum
Designation	7075-T6
Coating	BSAA
Treatment	Anodize Seal Chromate 6+
Electrode	Anode (Corroding Material)

OCP	-7.41E-1 V_{SCE}
Self Corrosion Rate	8.94E-3 microns/year
	3.52E-4 mils/year
Galvanic Acceleration Factor	9.52E+3

Material Two

Substrate	Stainless Steel
Designation	15-5 PH
Coating	None
Treatment	None
Electrode	Cathode

OCP	3.80E-2 V_{SCE}
Self Corrosion Rate	1.08E+0 microns/year
	4.25E-2 mils/year

Galvanic Compatability

For this pairing Aluminum 7075-T6 BSAA Anodize Seal Chromate 6+ will undergo galvanic corrosion at a rate of 8.51E+1 microns/year.

Potential Difference	7.79E-1 V
Mixed Potential	-5.00E-1 V_{SCE}
Galvanic Corrosion Current Density	7.63E-2 Am^{-2}
Galvanic Corrosion Rate	8.51E+1 microns/year
	3.35E+0 mils/year
MIL-STD-889D Rating	3

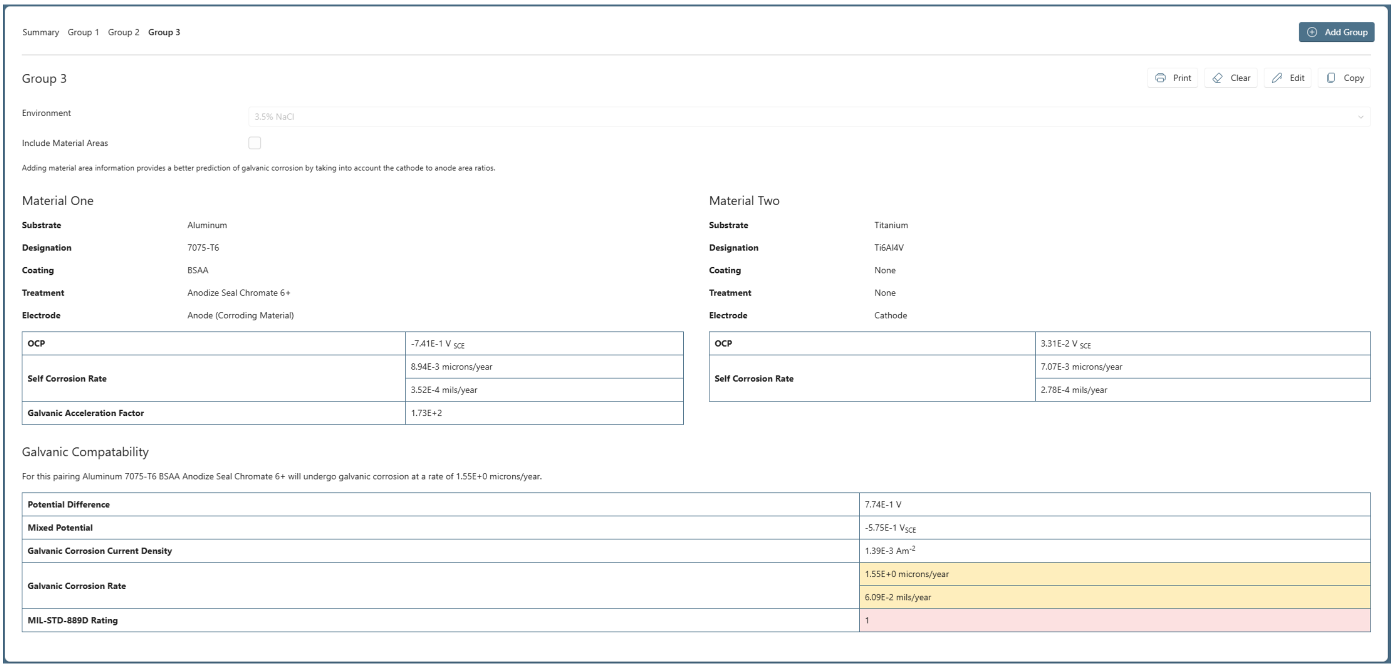
Figure 2 - Group 2 Results - Showing the impact of anodizing the Al-7075-T6

As expected, anodizing dramatically drops the self-corrosion rate of the Aluminum 7075-T6 to fractions of a micron per year. However, when coupled to the Stainless Steel 15-5 PH the galvanic corrosion rate is still high, at a value of 85.1 microns/year.

So, anodizing the anodic member of this particular couple has had little impact on galvanic corrosion. Another approach would be to consider treatments for the cathodic member, in this scenario, the Stainless Steel bushing.

Alternative Material Choices

So, while on the Group 2 TAB, we click ‘Copy’ to create Group 3 and change the Material 2 descriptors to a Titanium, Ti6Al4V when done, click 'Run Analysis', the results are shown in Figure 3.



Group 3

Environment: 3.5% NaCl

Include Material Areas ☐

Adding material area information provides a better prediction of galvanic corrosion by taking into account the cathode to anode area ratios.

Material One

Substrate	Aluminum
Designation	7075-T6
Coating	BSAA
Treatment	Anodize Seal Chromate 6+
Electrode	Anode (Corroding Material)

OCP	-7.41E-1 V_{SCE}
Self Corrosion Rate	8.94E-3 microns/year
	3.52E-4 mils/year
Galvanic Acceleration Factor	1.73E+2

Material Two

Substrate	Titanium
Designation	Ti6Al4V
Coating	None
Treatment	None
Electrode	Cathode

OCP	3.31E-2 V_{SCE}
Self Corrosion Rate	7.07E-3 microns/year
	2.78E-4 mils/year

Galvanic Compatability

For this pairing Aluminum 7075-T6 BSAA Anodize Seal Chromate 6+ will undergo galvanic corrosion at a rate of 1.55E+0 microns/year.

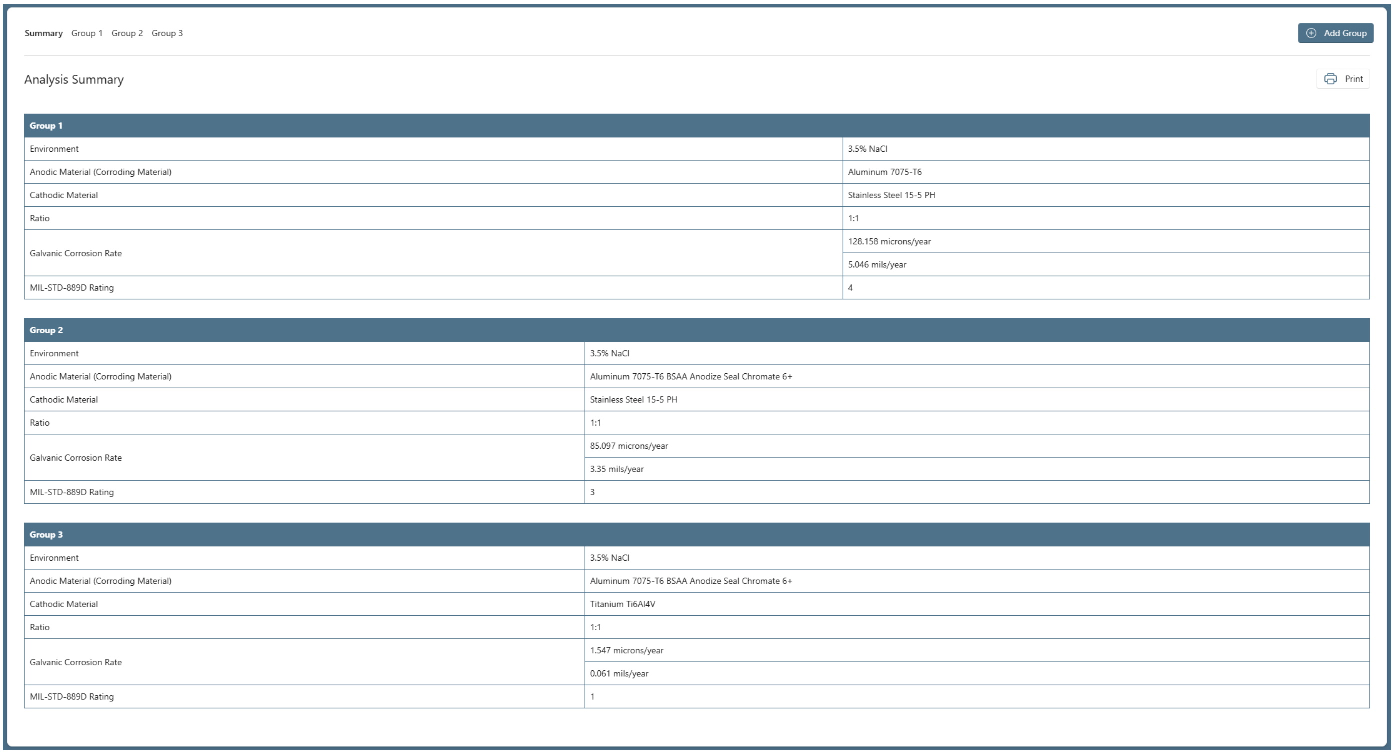
Potential Difference	7.74E-1 V
Mixed Potential	-5.75E-1 V_{SCE}
Galvanic Corrosion Current Density	1.39E-3 Am^{-2}
Galvanic Corrosion Rate	1.55E+0 microns/year
	6.09E-2 mils/year
MIL-STD-889D Rating	1

Figure 3 - Group 3 results - Showing the impact of choosing a titanium alloy for the bushing

The use of the Titanium, Ti6Al4V results in a significantly lower Galvanic Corrosion Rate of 1.55 microns/year, despite the similar potential differences between the material couples.

Analysis Summary

A summary of the Analysis can be seen in Figure 4 which shows the change in Galvanic Corrosion Rate as we updated our material choices.



Analysis Summary

Group 1	
Environment	3.5% NaCl
Anodic Material (Corroding Material)	Aluminum 7075-T6
Cathodic Material	Stainless Steel 15-5 PH
Ratio	1:1
Galvanic Corrosion Rate	128.158 microns/year
	5.046 mils/year
MIL-STD-889D Rating	4

Group 2	
Environment	3.5% NaCl
Anodic Material (Corroding Material)	Aluminum 7075-T6 BSAA Anodize Seal Chromate 6+
Cathodic Material	Stainless Steel 15-5 PH
Ratio	1:1
Galvanic Corrosion Rate	85.097 microns/year
	3.35 mils/year
MIL-STD-889D Rating	3

Group 3	
Environment	3.5% NaCl
Anodic Material (Corroding Material)	Aluminum 7075-T6 BSAA Anodize Seal Chromate 6+
Cathodic Material	Titanium Ti6Al4V
Ratio	1:1
Galvanic Corrosion Rate	1.547 microns/year
	0.061 mils/year
MIL-STD-889D Rating	1

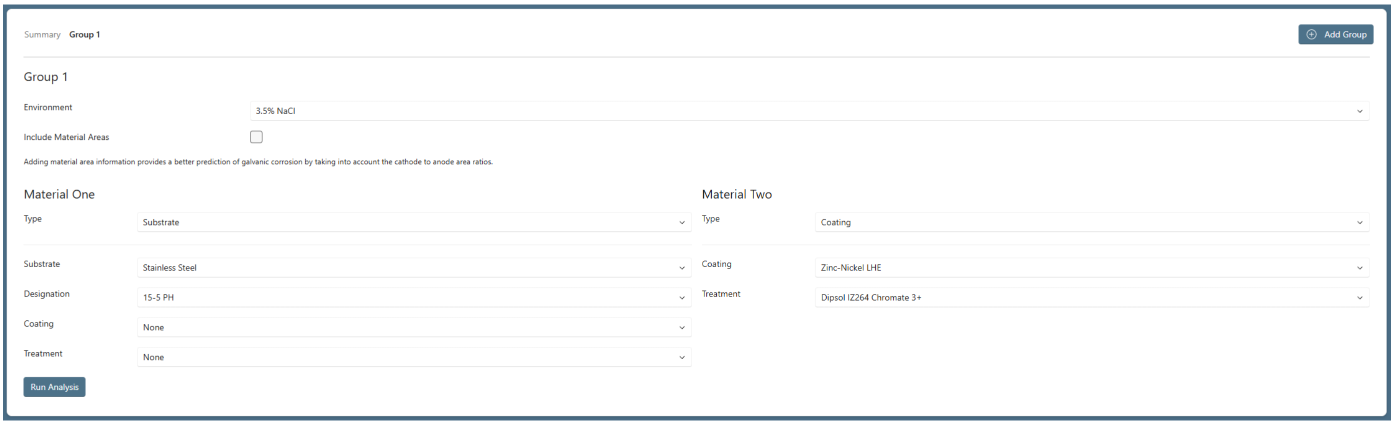
Figure 4 - Analysis Summary

1.3 Features

1.3.1 Coatings (such as electroplates)

In Djinn it is considered that a coating entirely covers the substrate, so we assume that with respect to the measured polarization data of the coating, it does not matter what the substrate is, as it will not be adjacent to the electrolyte. With this in mind, in order to choose a coating, we simply have to select a *Type* of **Coating**.

Figure 1 shows the choices to analyze the galvanic couple between Stainless Steel 15-5 PH and a Zinc-Nickel LHE coating.



Group 1

Environment	3.5% NaCl
Include Material Areas	☐

Adding material area information provides a better prediction of galvanic corrosion by taking into account the cathode to anode area ratios.

Material One

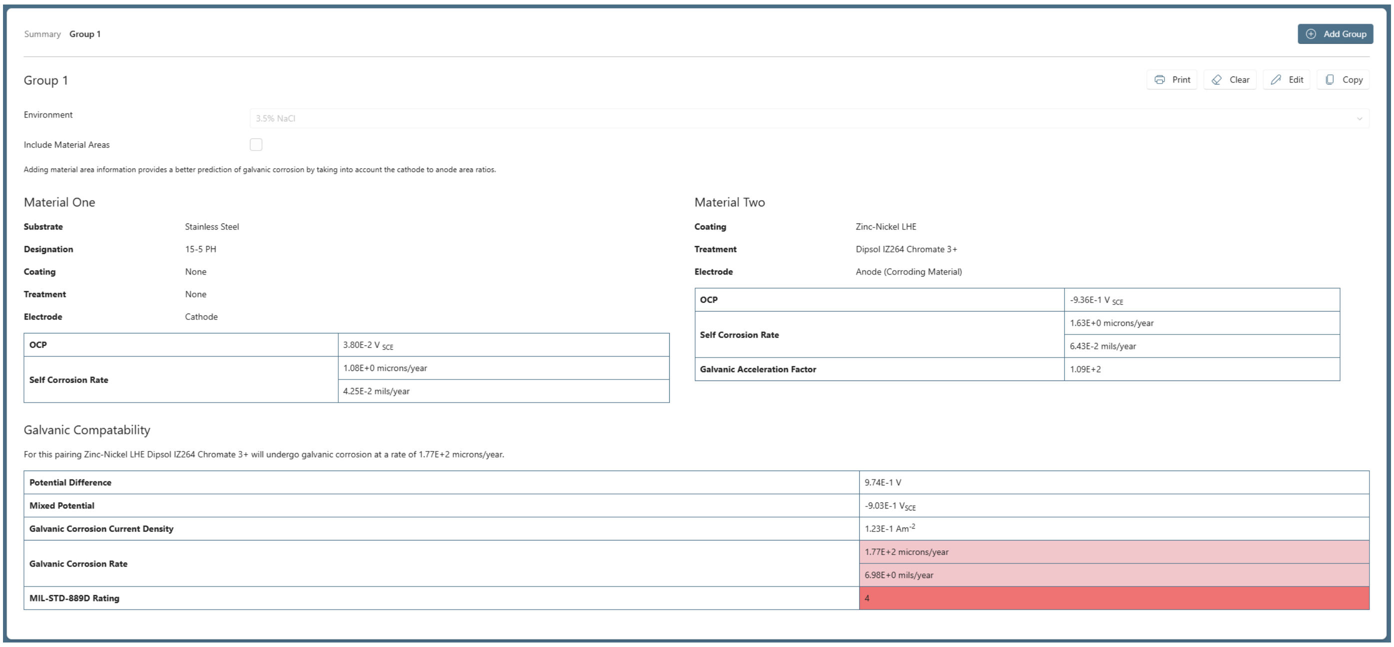
Type	Substrate
Substrate	Stainless Steel
Designation	15-5 PH
Coating	None
Treatment	None

Material Two

Type	Coating
Coating	Zinc-Nickel LHE
Treatment	Dipsol IZ264 Chromate 3+

Figure 1 - Choices for comparing Stainless Steel 15-5 PH with a Zinc-Nickel LHE coating

Figure 2 shows the results of the analysis between the stainless steel and the Zinc-Nickel LHE coating. The Zinc-Nickel is clearly more active, as would be expected of Zinc-Nickel coatings, which are often used for sacrificial protection.



Group 1

Environment	3.5% NaCl
Include Material Areas	☐

Adding material area information provides a better prediction of galvanic corrosion by taking into account the cathode to anode area ratios.

Material One

Substrate	Stainless Steel
Designation	15-5 PH
Coating	None
Treatment	None
Electrode	Cathode

OCP	3.80E-2 V $_{SCE}$
Self Corrosion Rate	1.08E+0 microns/year
	4.25E-2 mils/year

Material Two

Coating	Zinc-Nickel LHE
Treatment	Dipsol IZ264 Chromate 3+
Electrode	Anode (Corroding Material)

OCP	-9.36E-1 V $_{SCE}$
Self Corrosion Rate	1.63E+0 microns/year
	6.43E-2 mils/year
Galvanic Acceleration Factor	1.09E+2

Galvanic Compatability

For this pairing Zinc-Nickel LHE Dipsol IZ264 Chromate 3+ will undergo galvanic corrosion at a rate of 1.77E+2 microns/year.

Potential Difference	9.74E-1 V
Mixed Potential	-9.03E-1 V$_{SCE}$
Galvanic Corrosion Current Density	1.23E-1 Am^{-2}
Galvanic Corrosion Rate	1.77E+2 microns/year
	6.98E+0 mils/year
MIL-STD-889D Rating	4

Figure 2 - Results for comparing Stainless Steel 15-5 PH with a Zinc-Nickel LHE coating.

1.3.2 Material Area Ratios

Work In Progress

Content coming soon.

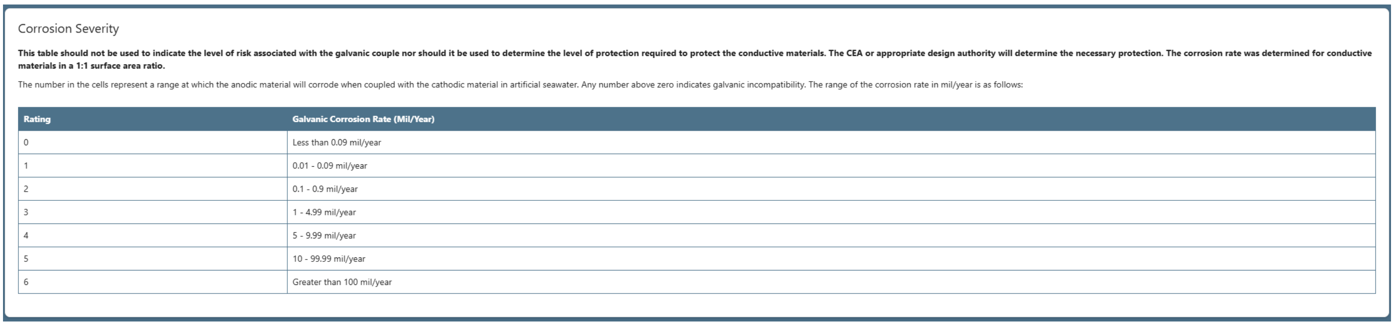
1.3.3 Corrosion Severity

Question

What should be the target corrosion rate?

This really depends on the situation at hand, for example, in aircraft we would want to keep this very low, especially in areas that cannot be easily inspected. Consequently, in the Corrosion Severity section of the results output, the user can set the lower and upper limits for the color coding used in the results table – so this could be set according to the advice of your organization materials engineers or proprietary guidelines and standards.

Additionally the MIL-STD-889D defines a rating system for galvanic corrosion rate with a rating between 0 and 6 with 0 being 'galvanically compatible', note the scale for this result is not linear, as seen in Figure 1.



Corrosion Severity

This table should not be used to indicate the level of risk associated with the galvanic couple nor should it be used to determine the level of protection required to protect the conductive materials. The CEA or appropriate design authority will determine the necessary protection. The corrosion rate was determined for conductive materials in a 1:1 surface area ratio.

The number in the cells represent a range at which the anodic material will corrode when coupled with the cathodic material in artificial seawater. Any number above zero indicates galvanic incompatibility. The range of the corrosion rate in mil/year is as follows:

Rating	Galvanic Corrosion Rate (Mil/Year)
0	Less than 0.09 mil/year
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	Greater than 100 mil/year

Figure 1 - MIL-STD-889D Corrosion Severity Guidance

1.3.4 MIL-STD-889D

What is MIL-STD-889D?

The MIL-STD-889D is a standard practice document for handling the galvanic compatibility of electrically conductive materials published by the Department of Defense (DoD).[1]

The MIL-STD-889D specification can be downloaded for free here, alternatively our free tool provides a simple user interface for comparing material pairs.

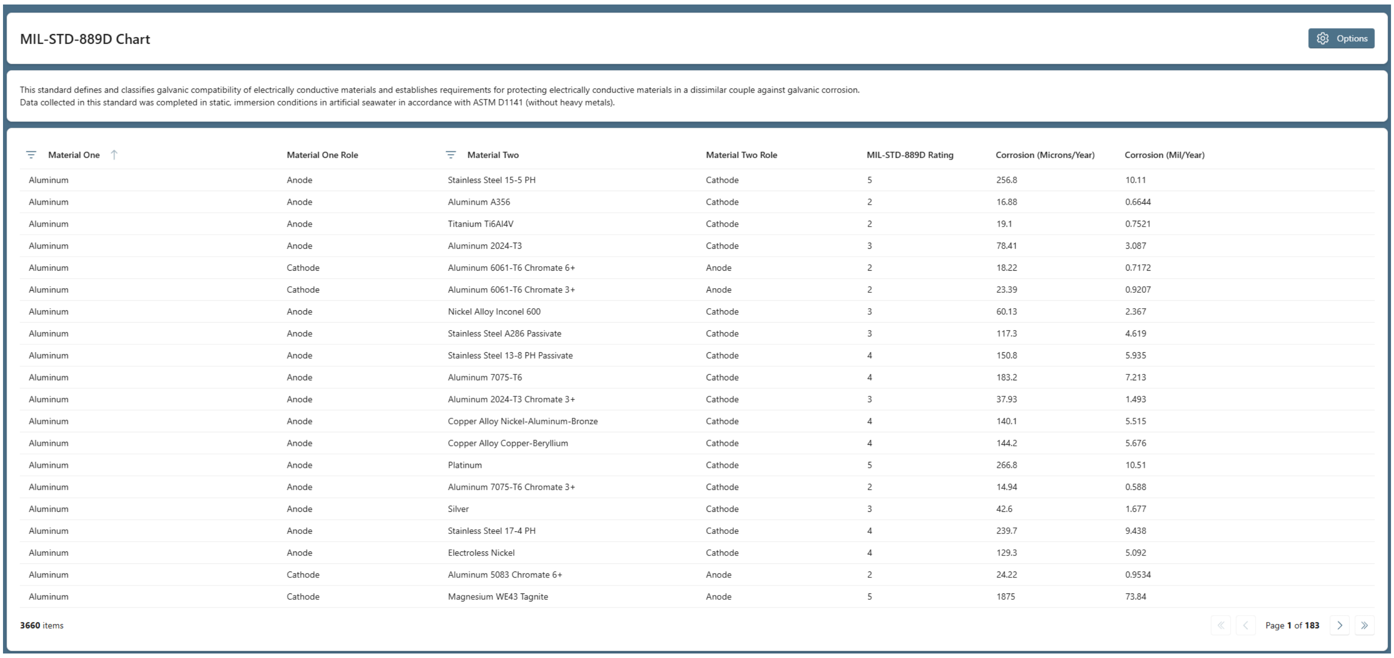
The MIL-STD-889D Table

Corrdesa provides a free public tool for users to quickly compare materials in a table format rather than using the mileage chart provided in the MIL-STD-889D documentation.

The feature is free to all users and can be accessed here: https://corrosiondjinn.com/MIL-STD-889D/

MIL-STD-889D

The table shows all possible material combinations that are present in MIL-STD-889D, showing the anodic and cathodic members in each pair, the MIL-STD-889D rating, and Corrosion Rate in μpy (Microns Per Year) and mpy (Mils Penetration Per Year), as can be seen in Figure 1.



MIL-STD-889D Chart

This standard defines and classifies galvanic compatibility of electrically conductive materials and establishes requirements for protecting electrically conductive materials in a dissimilar couple against galvanic corrosion.
Data collected in this standard was completed in static, immersion conditions in artificial seawater in accordance with ASTM D1141 (without heavy metals).

Material One ↑	Material One Role	Material Two	Material Two Role	MIL-STD-889D Rating	Corrosion (Microns/Year)	Corrosion (Mil/Year)
Aluminum	Anode	Stainless Steel 15-5 PH	Cathode	5	256.8	10.11
Aluminum	Anode	Aluminum A356	Cathode	2	16.88	0.6644
Aluminum	Anode	Titanium Ti6Al4V	Cathode	2	19.1	0.7521
Aluminum	Anode	Aluminum 2024-T3	Cathode	3	78.41	3.087
Aluminum	Cathode	Aluminum 6061-T6 Chromate 6+	Anode	2	18.22	0.7172
Aluminum	Cathode	Aluminum 6061-T6 Chromate 3+	Anode	2	23.39	0.9207
Aluminum	Anode	Nickel Alloy Inconel 600	Cathode	3	60.13	2.367
Aluminum	Anode	Stainless Steel A286 Passivate	Cathode	3	117.3	4.619
Aluminum	Anode	Stainless Steel 13-8 PH Passivate	Cathode	4	150.8	5.935
Aluminum	Anode	Aluminum 7075-T6	Cathode	4	183.2	7.213
Aluminum	Anode	Aluminum 2024-T3 Chromate 3+	Cathode	3	37.93	1.493
Aluminum	Anode	Copper Alloy Nickel-Aluminum-Bronze	Cathode	4	140.1	5.515
Aluminum	Anode	Copper Alloy Copper-Beryllium	Cathode	4	144.2	5.676
Aluminum	Anode	Platinum	Cathode	5	266.8	10.51
Aluminum	Anode	Aluminum 7075-T6 Chromate 3+	Cathode	2	14.94	0.588
Aluminum	Anode	Silver	Cathode	3	42.6	1.677
Aluminum	Anode	Stainless Steel 17-4 PH	Cathode	4	239.7	9.438
Aluminum	Anode	Electroless Nickel	Cathode	4	129.3	5.092
Aluminum	Cathode	Aluminum 5083 Chromate 6+	Anode	2	24.22	0.9534
Aluminum	Cathode	Magnesium WE43 Tagnite	Anode	5	1875	73.84

3660 items

Page **1** of **183**

Figure 1 - MIL-STD-889D Table

Filtering & Sorting

It is possible to filter the material pairs to reduce number of entries in the table, this allows the user to choose a 'primary' material and then see possible combinations that are related to the chosen material. In addition to filtering you can also sort the data on the following columns; Materials, MIL-STD-889D Rating, Corrosion Rate μpy (Microns Per Year), and Corrosion Rate in mpy (Mils Penetration Per Year).

An example of filtering data can be seen in Figure 2 where Material One is filtered to *Aluminum* & *Aluminum 2024-T3*, with sorted results shown in Figure 3 this table is sorted to highest Corrosion Rate in μpy (Microns Per Year).

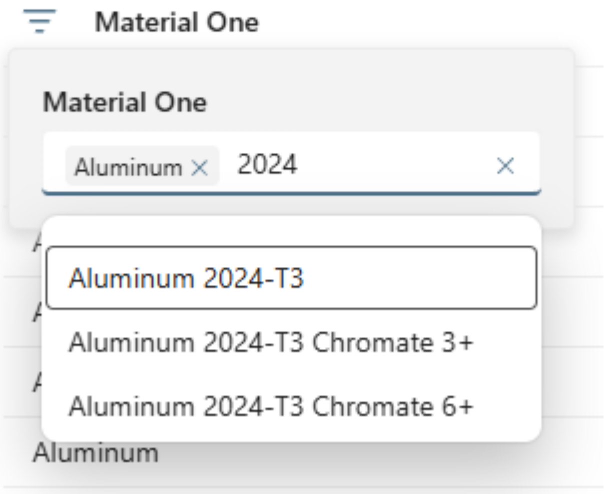
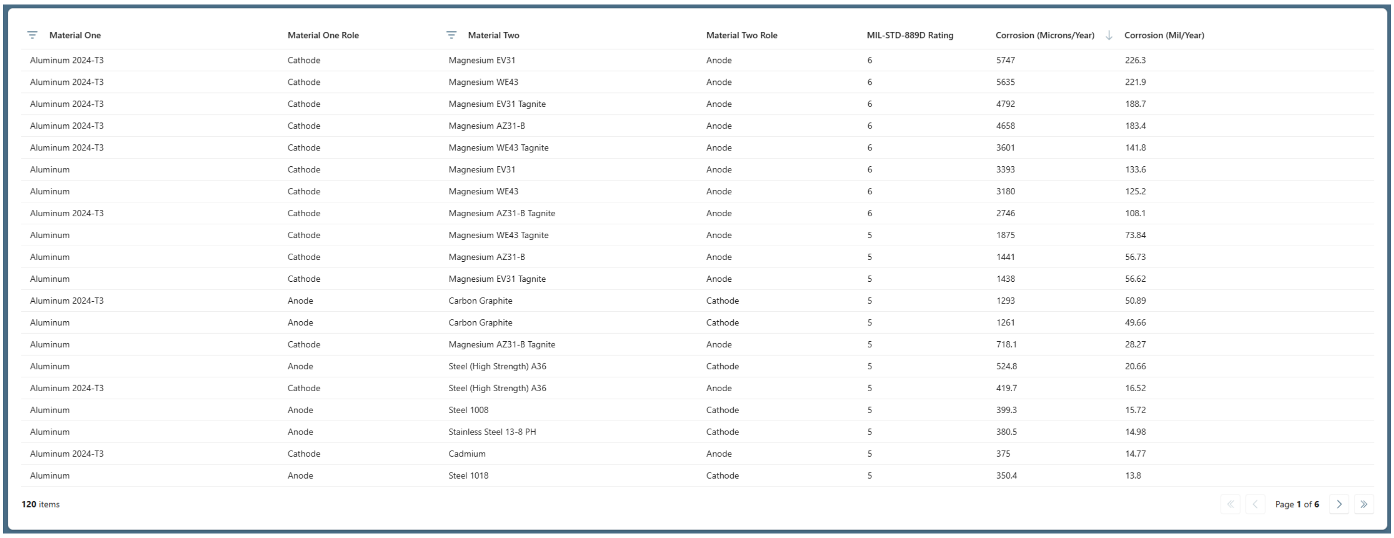


Figure 2 - Filtering Material One



Material One	Material One Role	Material Two	Material Two Role	MIL-STD-889D Rating	Corrosion (Microns/Year) ↓	Corrosion (Mil/Year)
Aluminum 2024-T3	Cathode	Magnesium EV31	Anode	6	5747	226.3
Aluminum 2024-T3	Cathode	Magnesium WE43	Anode	6	5635	221.9
Aluminum 2024-T3	Cathode	Magnesium EV31 Tagnite	Anode	6	4792	188.7
Aluminum 2024-T3	Cathode	Magnesium AZ31-B	Anode	6	4658	183.4
Aluminum 2024-T3	Cathode	Magnesium WE43 Tagnite	Anode	6	3601	141.8
Aluminum	Cathode	Magnesium EV31	Anode	6	3393	133.6
Aluminum	Cathode	Magnesium WE43	Anode	6	3180	125.2
Aluminum 2024-T3	Cathode	Magnesium AZ31-B Tagnite	Anode	6	2746	108.1
Aluminum	Cathode	Magnesium WE43 Tagnite	Anode	5	1875	73.84
Aluminum	Cathode	Magnesium AZ31-B	Anode	5	1441	56.73
Aluminum	Cathode	Magnesium EV31 Tagnite	Anode	5	1438	56.62
Aluminum 2024-T3	Anode	Carbon Graphite	Cathode	5	1293	50.89
Aluminum	Anode	Carbon Graphite	Cathode	5	1261	49.66
Aluminum	Cathode	Magnesium AZ31-B Tagnite	Anode	5	718.1	28.27
Aluminum	Anode	Steel (High Strength) A36	Cathode	5	524.8	20.66
Aluminum 2024-T3	Cathode	Steel (High Strength) A36	Anode	5	419.7	16.52
Aluminum	Anode	Steel 1008	Cathode	5	399.3	15.72
Aluminum	Anode	Stainless Steel 13-8 PH	Cathode	5	380.5	14.98
Aluminum 2024-T3	Cathode	Cadmium	Anode	5	375	14.77
Aluminum	Anode	Steel 1018	Cathode	5	350.4	13.8

120 items

Page **1** of **6**

Figure 3 - Filtered & Sorted MIL-STD-889D Table

References

1. MIL-STD-889D, GALVANIC COMPATIBILITY OF ELECTRICALLY CONDUCTIVE MATERIALS, Department of Defense. https://corrdesa.com/wp-content/uploads/2024/04/MIL-STD-889D-2021-Release.pdf ↩

1.4 Self Hosted

1.4.1 Adding Materials

Work In Progress

Content coming soon.

1.4.2 Adding Polarization Data

Work In Progress

Content coming soon.

2. Background & Theory

2.1 Background & Theory

“Corrosion Djinn”, has been developed by Corrdesa LLC under SBIR funding from the Office of Naval Research. Corrosion Djinn is software designed to calculate the corrosion current across an interface between two galvanically different materials, from which we can estimate the corrosion rate of the more anodic (less noble) material.

2.1.1 Galvanic Corrosion

Galvanic corrosion is an electrochemical process in which an oxidation-reduction reaction occurs. The anode is the electrode where the oxidation half of the oxidation-reduction reaction takes place. Similarly, the reduction half of the reaction takes place at the cathode. In principle, galvanic corrosion is characterized by localization of the anodic and cathodic processes in different regions. These different regions can be found on the same metal surface between different microscopic phases, as well as between two dissimilar materials electrically in contact with each other in the presence of conductive electrolyte. The direction of the electrochemical process between two dissimilar metals or phases depends on the difference between the two Gibbs free energies, ${\Delta}G$ [2].

The tendency for a bimetallic couple to corrode can be expressed in terms of thermodynamic parameter, the electromotive force ${\text{(EMF)}}$ or the static corrosion potential of the corrosion cell [3]. The polarity and direction of galvanic current flow between two connected bare materials is determined by the thermodynamic reversible potentials of the materials. The material which has a higher reversible potential in the electromotive force ${\text{(EMF)}}$ series or galvanic series is the cathode in the galvanic couple. The relation between ${\Delta}G$ and ${\text{EMF}}$ is defined by:

$$\tag{1} {\Delta}({\Delta}{G}) = -{\Delta}E.n.F$$

where

- n = Number of electrons taking place in the reaction
- ${\Delta}E = {\text{EMF}}$ (difference between the EMFs of the two members of the ion couple)
- F = Faraday’s constant

The principal phases in the operation of a galvanic corrosion cell are illustrated in Figure 1 in chloride ions containing electrolyte. When galvanic corrosion takes place, the less noble metal acts as the anode and is oxidized according to:

$$\tag{2} \underbrace{M}_{\text{atom in metal surface}} \to \underbrace{M^{n+}}_{\text{ion in solution}} + \underbrace{ne^-}_{\text{electrons in metal}}$$

The cathodic process in galvanic corrosion in near-neutral electrolyte is often stated in terms of the oxygen reduction reaction [4]

$$\tag{3} \underbrace{O_2 + 2H_2O}_{\text{adsorbed on metal surface}} + \underbrace{4e^-}_{\text{in metal}} \to \underbrace{4OH}_{\text{in solution}}$$

Equations (4) and (5) represent corrosion processes taking place in the acidic environments encountered in industrial processes or for the confined volumes (pits, crevices) where the pH can reach acidic values because of hydrolysis reactions.

$$\tag{4} {O^2} + {4H^+} + {4e^-} \to {2H_2O}$$
$$\tag{5} {2H^+} + {2e^-} \to {H_2}$$

In a galvanic system, current flow between anode and cathode either on a single material or between two different materials will take place by the movement of electrons from anodic to cathodic regions and in the solution by movement of cations from the anodic to the cathodic regions and movement of anions in the opposite direction. In Figure 1, we consider the case of an iron-copper galvanic couple in an aqueous solution. The dissolution (oxidation) of the iron results in a loss of electrons which travel through the metallic members (current in the opposite direction by definition), ie LEO, acronym for Lose Electron = Oxidation. The ferrous ions are then mobile in the electrolyte layer. Meanwhile, on the copper side of the couple, the excess of electrons on the copper surface combine with the water and oxygen (reduction) in the aqueous solution resulting in hydroxyl ions, ie, GER, as an acronym for, Gain Electron = Reduction.

The material effect of galvanic corrosion will therefore appear principally on the anodes. On the cathodically acting areas there will be no appreciable loss of metal. Galvanic corrosion can occur on the macroscopic level or/and on the microscopic level. On the macroscopic level, dissimilar materials comprise of at least one anode and one cathode. On the microscopic level, inhomogeneity within a single material due to alloying elements, causes different microstructural features to act as local anode and cathode.

From Ohm's Law, we learn that potential is the product of current and resistance. From this perspective we can consider the electrical circuit to comprise a number of potential drops, or iR drops. In the metals the iR drop will be very low, since metals have a very high conductivity (equivalent to reciprocal of resistivity). Whereas, the iR drop in the electrolyte depends on the combining effect of the physical electrical conductivity of the solution along with the resistance experienced at the metallic/electrolyte interface due to the reactions and varying mobilities of the ions. This latter effect is captured and referred to as polarization effects and can be measured with respect to a reference potential. Consequently, if we know the polarization curves for the materials under consideration, for that particular environment, then we can quantify the galvanic current and hence the galvanic corrosion.

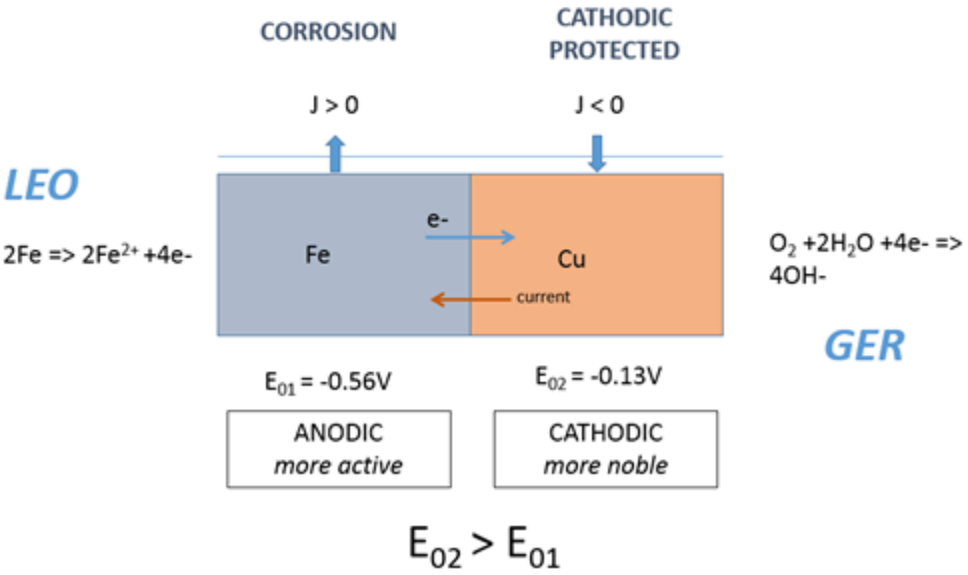


Figure 1 - Schematic electrical circuit depicting galvanic corrosion

Even though MIL-STD-889C, like many other similar standards and proprietary guidelines, suggests that the magnitude of the difference in galvanic potential between two dissimilar materials is an indication of corrosion risk, the standard does recognize that this is an over-simplification, as we expand upon in the next section.

2.1.2 Polarization Curve

The combined experimental measurement of potential and current relationships \(({E} \space {\text{vs}} \log(I))\) for an operating corrosion cell over a wide range of oxidizing conditions results in polarization curves that describe the complete electrochemical behavior of a material, see Figure 2. The curve on the blue and the green region represents the involved anodic and cathodic reactions of the material respectively. In a polarization curve, the current represents the rate with which the anodic or cathodic reactions are taking place on a material surface. Typically, the current is expressed in terms of the current per unit area of the exposed surface, or the current density. The electrochemical interactions between two dissimilar materials typically involve metal pitting and dissolution, oxidation, and hydrogen evolution reactions, all of which must remain in balance so that the anodic currents on the anode equal the cathodic currents on the cathode [5]. Many variables will influence the rate of a given electrochemical reaction, including the temperature, the surface condition of the surface being interrogated, as well as the chemical environment in which the experiment is performed.

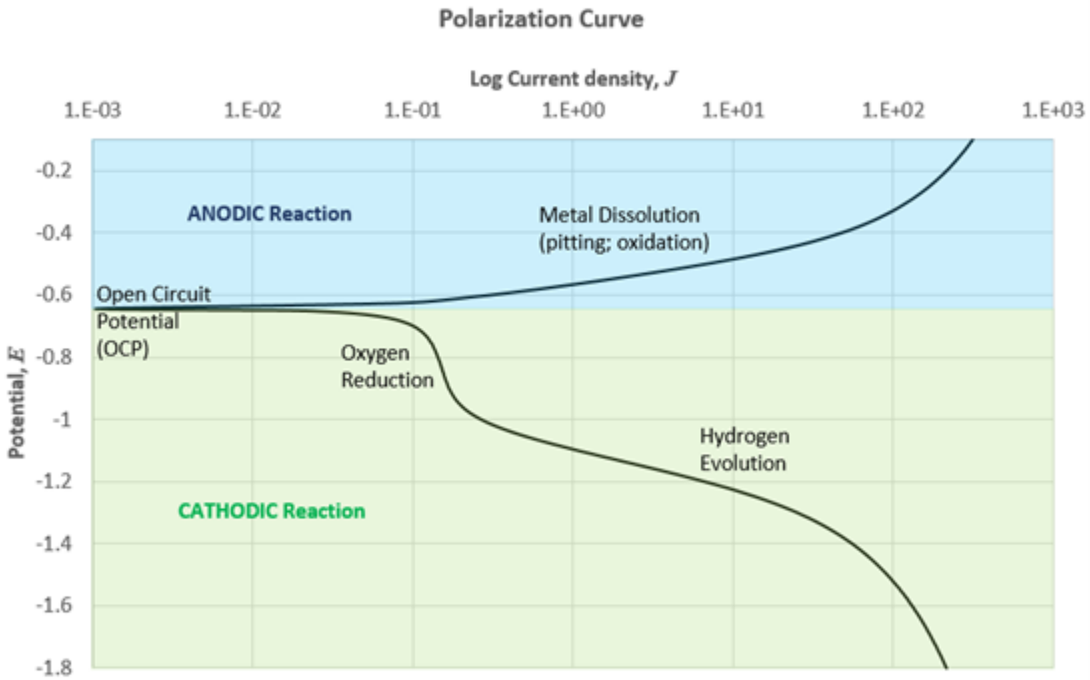


Figure 2 - Example of complete polarization curve showing both anodic and cathodic reactions indicating individual partial reaction components

Given sufficient quantitative information from the polarization curve about the electrochemical processes occurring on a material, mixed potential theory can be used to predict a corrosion rate.

2.1.3 Mixed potential and polarization curve-crossing

Corrosion Djinn is based on the well established fundamental electrochemical principle of mixed potentials, first elucidated by Wagner and Traud [6] in 1938 based on two simple hypotheses. First, any electrochemical reaction can be divided into two or more oxidation or reduction reactions, and secondly, there can be no net accumulation of electrical charge during an electrochemical reaction i.e. the polarization curve.

The equilibrium potential given in a typical galvanic series MIL-STD-889 is also referred to as mixed-potential of the particular material when it’s cathodic and anodic currents are equal in that specific environment. The same applies to galvanic corrosion between two different materials. When two different materials are electrically coupled in the same electrolyte, both materials are polarized to a new potential lying in between the two-uncoupled corrosion potentials which can be explained by mixed potential theory.

This can be illustrated by plotting the current produced as a function of applied potential, called a polarization curve. The magnitude of current flow and the increase in corrosion rate due to this coupling are determined by the tendency of each of the materials in the couples to deliver current when its potential is forced to change, called polarization. If a material delivers little current for a large change in potential, it is said to have a large polarization resistance, while if it can deliver a large current for a small enforced potential change, it is said to have a small polarization resistance. The latter is often the case with e.g. aerospace aluminum alloys when they are anodically polarized.

For galvanic corrosion, the curve-crossing or intersection of an anodic curve of a less noble metal of the couple with a cathodic curve of a more noble metal gives the galvanic current and potential of the couple for equal surface areas. This is depicted in Figure 3 showing anodic and cathodic polarization curves which are used to visualize the polarization within a galvanic couple. In this case the iron is the anode and copper is the cathode in the couple. The solid lines represent experimental polarization curves of copper and iron. The dashed lines represent the polarization curves for the half cell reactions defining the uncoupled corrosion potentials, \({E\text{corr}}\) for anode and cathode, respectively. The mixed potential or couple potential, \({E\text{couple}}\) is established where anode and cathode are polarized to potentials by the same galvanic current, \({I\text{couple}}\).

Reduction reactions on the anode metal are assumed to be very small compared to such reactions on the cathode, shown in Figure 3. That is, \({I\text{couple}}\) >> \({I\text{corr.A}}\). The galvanic current \({I\text{couple}}\) which essentially translates to the rate of galvanic attack on the anodic metal is a more accurate way to assess galvanic corrosion susceptibility of a bimetallic couple since it is a measure of corrosion kinetics. Corrosion Djinn calculates and reports the galvanic current, mixed potential values on the fly once the user has made the material selection for assessment.

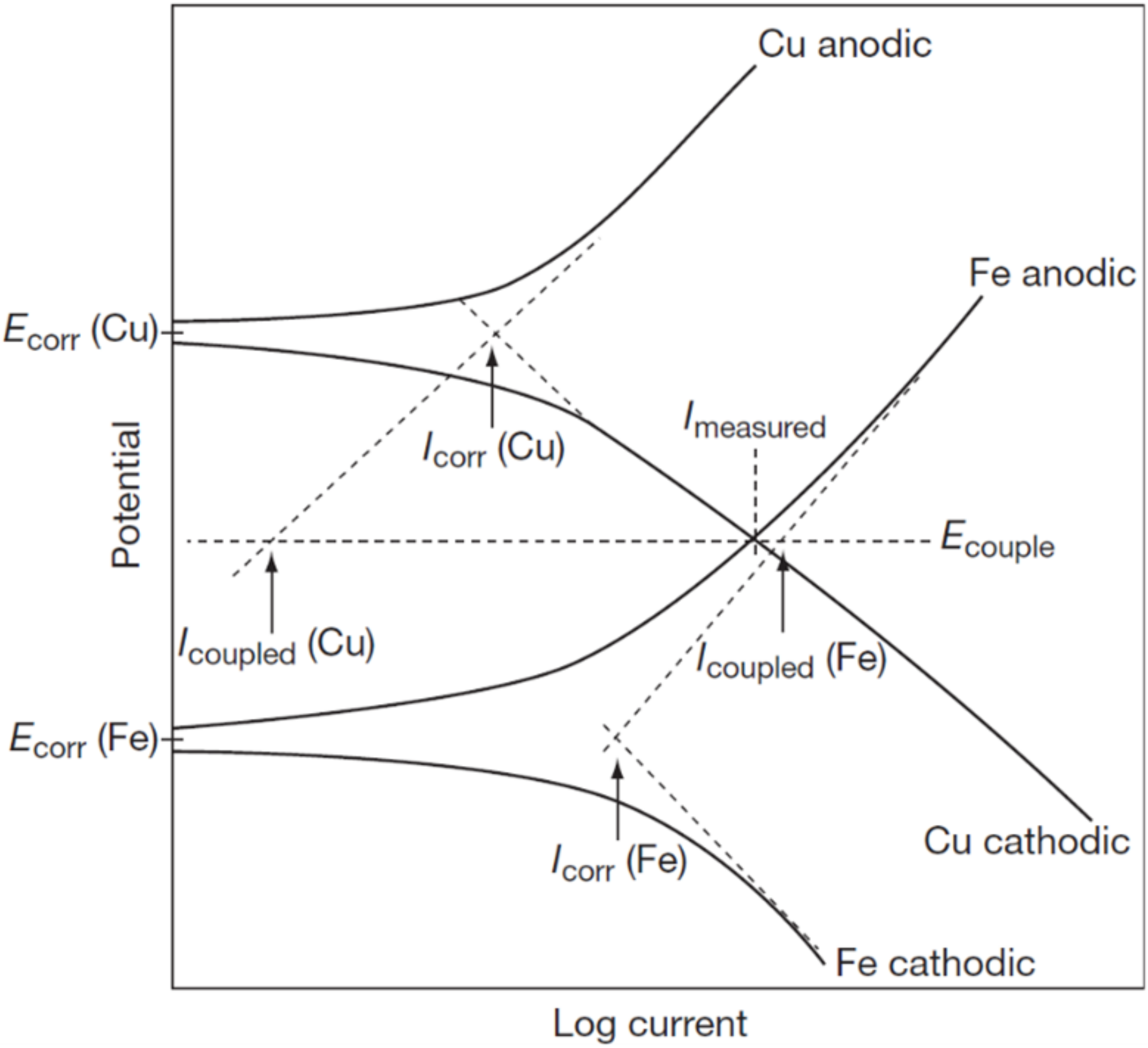


Figure 3 - Polarization curve-crossing between active material (anode) and less active material (cathode)

7

Galvanic coupling current divided by the anode area gives the average anode current density which is proportional to average corrosion or penetration rate. One key assumption of this approach is that there is no ohmic resistance between anode and cathode. Such a condition may occur when e.g. two dissimilar materials are in direct/electrical contact immersed in a very conductive electrolyte e.g. seawater with very low ohmic drop in the electrolyte.

Additionally, a distinction is made between anodic polarization (displacement of the anodic potential in the positive direction) and cathodic polarization (displacement of the cathodic potential in the negative direction). The extent of the electrode activity can be judged by the amount of potential shift. The kinetics of the process can consequently be determined from the relationship between the shift in electrode potential and the current density. This dependence can be seen in Figure 4.

When polarization occurs mostly at the anodes, the corrosion reaction is said to be anodically controlled. Under anodic control, the corrosion potential is close to the thermodynamic potential of the cathode. When polarization occurs mostly at the cathode, the corrosion rate is said to be cathodically controlled. The corrosion potential is then near the thermodynamic anode potential. Resistance control occurs when the electrolyte resistance (due to low ionic concentrations) is so high that the resultant current is not sufficient to appreciably polarize anodes or cathodes. An example occurs with a porous insulating coating covering a metal surface. The corrosion current is then controlled by the IR drop through the electrolyte in pores of the coating. It is common for polarization to occur in some degree at both anodes and cathodes. This situation is described as mixed control. The extent of polarization depends not only on the nature of the metal and electrolyte, but also on the actual exposed area of the electrode.

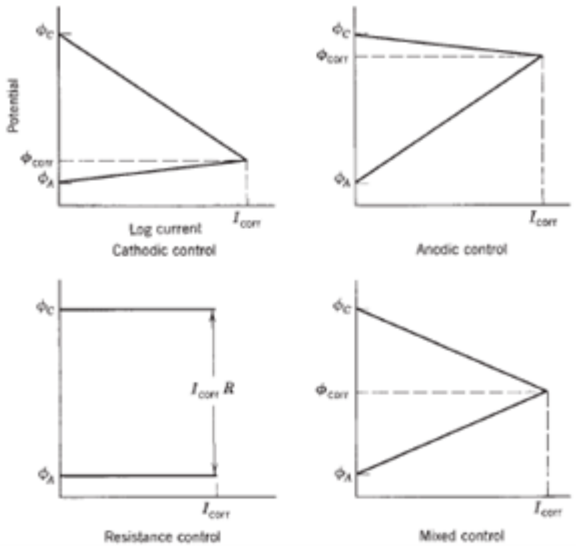


Figure 4 - Types of polarization control

1

In particular, the kinetics of cathodic control could be further categorized into three main regions in the polarization curves. Firstly, cathodic control due to charge transfer limitation which occurs at low current density near open circuit potential region and derives from the slowness (irreversibility) of the reactions taking place on the surface of the electrodes. The charge transfer reaction depends on the nature of the electrode materials, reactant activities, electrolyte, electrochemical mediators, electrode microstructure and operational conditions such as temperature, pressure, concentration and flow condition. Next, the cathodic reaction could be under mass transport limitation which results from the changes in concentration of the reactants (or products) at the interface between electrode surface region and bulk electrolyte; this limitation is prevalent at relatively high current densities if the reactants cannot be supplied to the electrode reaction zones at the rate required to sustain the generation of current. The presence of high concentrations of product species can also lead to the reduction of transport of reactants to where they are needed. Mass transfer derived overpotentials are affected by the geometry and the structure of electrodes, the nature of the electrolyte, and the products that are present. Finally, cathodic reaction under mixed diffusion meaning the cathodic current is influenced by both charge transfer kinetics and mass transport.

Common anodic materials are aluminum and magnesium alloys, and sacrificial coatings such as zinc and cadmium. Common cathodic materials include stainless steels, titanium, and the carbon in carbon fiber composites (CFCs). Placing an anodic material such as 2024 aluminum next to a cathodic material such as stainless steel (which is commonly done with bushings in air structures) in a humid, chloride salt (NaCl) containing environment results in rapid corrosion and pitting of the aluminum at a rate of about 55 μm (0.002”) per year.

MIL-STD-889C defines standard practice for classifying dissimilar metals and establishes requirements for protecting coupled dissimilar metals against corrosion. The standard is applicable to all military equipment parts, components and assemblies. Although the standard proposes the use of a galvanic series to assess material compatibility it does state that ‘compatibility does not indicate complete freedom from galvanic action’. The standard continues to warn that the degree of corrosion is influenced by kinetic factors such as polarization effects. The reader is referred to the Appendix B of the standard which states;

electrode polarization behavior is a means by which the compatibility of coupled dissimilar metals in solution can be established…

… The limiting current corresponds with the intersection of the polarization curves. This is a maximum current obtainable in the system if constant conditions are maintained.

Corrosion Djinn is a simulation software tool that reports the intersection point between polarization curves of different materials to determine the maximum corrosion current as MIL-STD-889C suggests. When the user enters two materials of a galvanic couple on the data entry page of Corrosion Djinn the software takes the polarization curve data of the two materials (including their coatings and surface treatments) from its internal electrochemical database and finds the intersection point, by overlaying the cathodic curve of the nobler material with the anodic curve of the more active material. This point defines the mixed potential and the corrosion current. From data entered for each curve in the database Djinn also calculates the galvanic corrosion rate reports the self-corrosion rate.

In order to help the user understand the impact of the material choices we have defined a metric that we call the Galvanic Acceleration Factor;

$$\text{Galvanic Acceleration Factor} = \frac {\text{Galvanic Corrosion Current}} {\text{Self Corrosion Current}}$$

The galvanic acceleration factor (GAF), essentially measures the multiplying factor by which galvanic corrosion exceeds self-corrosion. All of this information, together with the polarization curves, is output to the user.

2.1.4 Djinn electrochemical database

The key for the Djinn software is the electrochemical database of qualified polarization curves for various materials in order to be able to predict galvanic corrosion between different materials, coatings, and treatments. Corrdesa together with NAVAIR, academic, and commercial organizations' team of experts has developed a set of Best Practices for acquiring the necessary electrochemical polarization data to ensure that all of the data are consistent and of high quality. So, the polarization data stored in the Djinn electrochemical database has all been gathered using this standard [8][10] to ensure robust and consistent data.

2.1.5 Corrosion rate calculation

Along with this data, using standard methods [9] the equivalent weights of all the alloys is also stored, thereby allowing calculation of corrosion rate, which is reported in microns per year and mils per year. The equation used in essentially Faraday's law adjusted for the particular units employed in this application, that is, corrosion rate in microns per year per $1 A/m^2$;

$$\text{Corrosion rate} = 327 . \frac {(\text{Equivalent Weight})} {(\text{Material Density})}$$

Where the units are shown in Table 1.

Parameter	Units
Corrosion Rate	Microns per Year
Equivalent Weight	Grams
Material Density	Grams per Cubic Centimeter

Table 1 Units employed in annual corrosion rate calculation (per A/m^2)

2.1.6 References

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1. Standard Guide for Development and Use of Galvanic Series for Predicting Galvanic Corrosion Performance. G82-98 (Reapproved 2014) ↩
2. A. de Rooij, Bimetallic compatible couples, ESA Journal, Vol. 13 (1989), p 199-209. ↩
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8. Best Practices for Polarization Data Acquisition: Data Collection Guide for MIL-STD-889C Technical Revision. Prepared by Naval Air Systems Command. Version 4 FINAL. 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 ↩
9. Standard Practice for Calculation of Corrosion Rates and Related Information from Electrochemical Measurements. ASTM G102-89 (reapproved 2105) ↩
10. AMPP TM21510, Potentiodynamic Scans: Material Preparation, Data Acquisition and Analysis (www.ampp.org) ↩

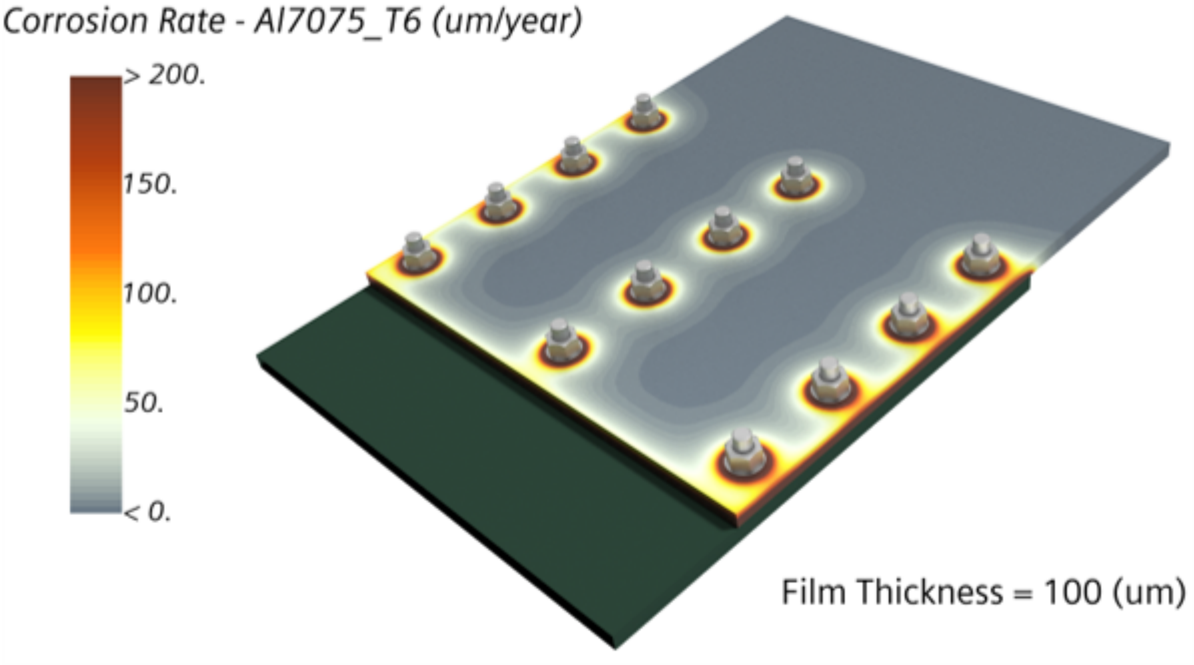
3. Simcenter Star CCM+

3.1 Overview

Corrosion is a pervasive issue across many industries, leading to significant maintenance costs and equipment downtime. Traditional analysis tools often fail to predict the onset and progression of corrosion effectively, leading to unexpected failures.

Simcenter STAR-CCM+ 2502 integrates Corrdesa’s Corrosion Djinn Database for advanced corrosion analysis. High-quality polarization data describes the relationship between the potential drop at the material interface and the specific electric current and are important inputs to the Electrodynamic Potential solver of Simcenter STAR-CCM+. The Corrdesa Corrosion Djinn material database hosts collection of data, including surface polarization, derived through rigorous experimental quantification.

This feature offers engineers robust tools to simulate and predict corrosion under various environmental conditions, using high-fidelity data. As a result, industries can proactively design out potential corrosion issues, extend equipment lifespan, and significantly reduce maintenance costs.



Simcenter STAR-CCM+ Galvanic Corrosion Analysis

3.2 Installation

3.2.1 Dependencies

- Simcenter STAR-CCM+ 2502

3.2.2 Installation Files

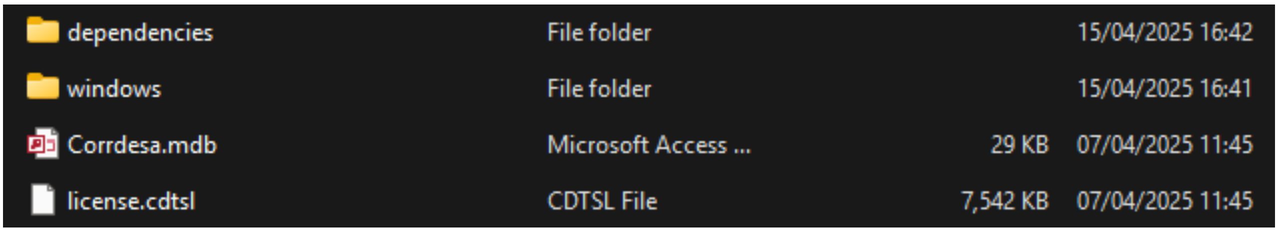
`license.cdtsl`

The Corrosion Djinn Toolset License file (`license.cdtsl`) contains the polarization data for the Corrosion Djinn database and any custom polarization data that has been created in Corrosion Djinn Standalone.

`Corrdesa.mdb`

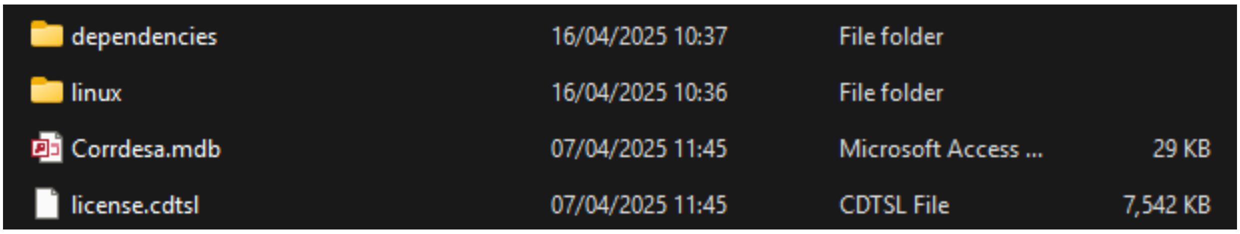
The `Corrdesa.mdb` file contains the material details that are used inside of STAR-CCM+ to display the list of material options available under the Surface Materials section.

The 2502 installation comes with a MDB file for our data already that is located at.



dependencies	File folder		15/04/2025 16:42
windows	File folder		15/04/2025 16:41
Corrdesa.mdb	Microsoft Access ...	29 KB	07/04/2025 11:45
license.cdtsl	CDTSL File	7,542 KB	07/04/2025 11:45

Windows Installation Files



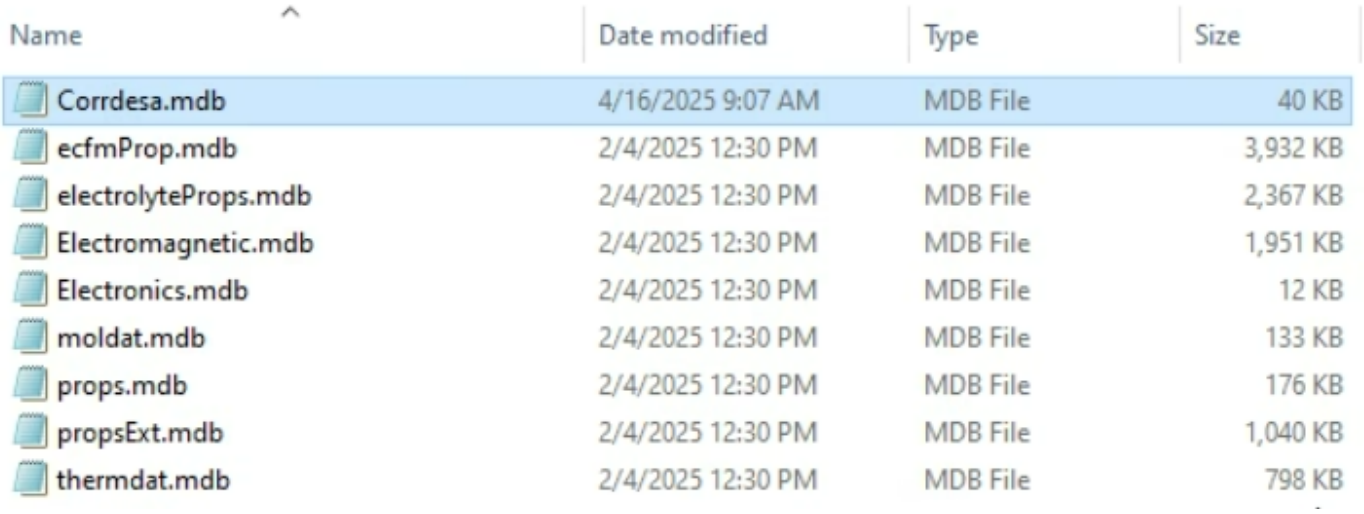
dependencies	16/04/2025 10:37	File folder	
linux	16/04/2025 10:36	File folder	
Corrdesa.mdb	07/04/2025 11:45	Microsoft Access ...	29 KB
license.cdtsl	07/04/2025 11:45	CDTSL File	7,542 KB

Linux Installation Files

Replacing the MDB file

- Location: [CCM+ Install Location]/star/data/

If you have any custom data or have an update for the file this need to be updated/replaced.



Name	Date modified	Type	Size
Corrdesa.mdb	4/16/2025 9:07 AM	MDB File	40 KB
ecfmProp.mdb	2/4/2025 12:30 PM	MDB File	3,932 KB
electrolyteProps.mdb	2/4/2025 12:30 PM	MDB File	2,367 KB
Electromagnetic.mdb	2/4/2025 12:30 PM	MDB File	1,951 KB
Electronics.mdb	2/4/2025 12:30 PM	MDB File	12 KB
moldat.mdb	2/4/2025 12:30 PM	MDB File	133 KB
props.mdb	2/4/2025 12:30 PM	MDB File	176 KB
propsExt.mdb	2/4/2025 12:30 PM	MDB File	1,040 KB
thermdat.mdb	2/4/2025 12:30 PM	MDB File	798 KB

Simcenter-STAR CCM+ Data Files

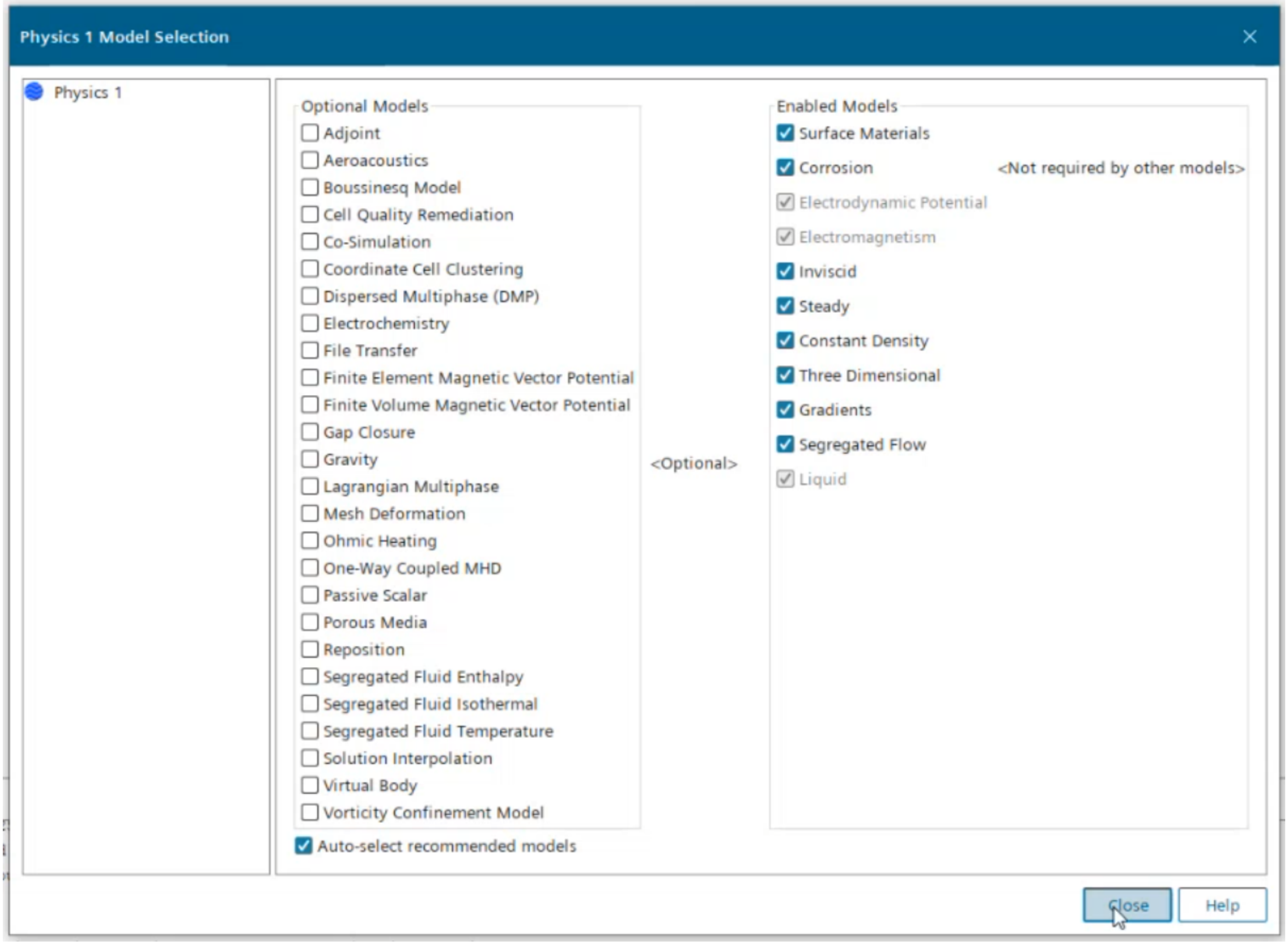
3.3 Running Analysis

3.3.1 Setting Up The Continua

Bulk Solution

- Material: Liquid
- Flow: Segregated Flow
- Axis: Three Dimensional
- Equation of State: Constant Density
- Time: Steady
- Viscous Regime: Inviscid
- Optional Models: Electromagnetism
- Electromagnetism: Electrodynamic Potential
- Optional Models: Corrosion

> **Note**
>
> Surface Materials & Gradients will be enabled automatically.



Optional Models
☐ Adjoint
☐ Aeroacoustics
☐ Boussinesq Model
☐ Cell Quality Remediation
☐ Co-Simulation
☐ Coordinate Cell Clustering
☐ Dispersed Multiphase (DMP)
☐ Electrochemistry
☐ File Transfer
☐ Finite Element Magnetic Vector Potential
☐ Finite Volume Magnetic Vector Potential
☐ Gap Closure
☐ Gravity
☐ Lagrangian Multiphase
☐ Mesh Deformation
☐ Ohmic Heating
☐ One-Way Coupled MHD
☐ Passive Scalar
☐ Porous Media
☐ Reposition
☐ Segregated Fluid Enthalpy
☐ Segregated Fluid Isothermal
☐ Segregated Fluid Temperature
☐ Solution Interpolation
☐ Virtual Body
☐ Vorticity Confinement Model

☑ Auto-select recommended models

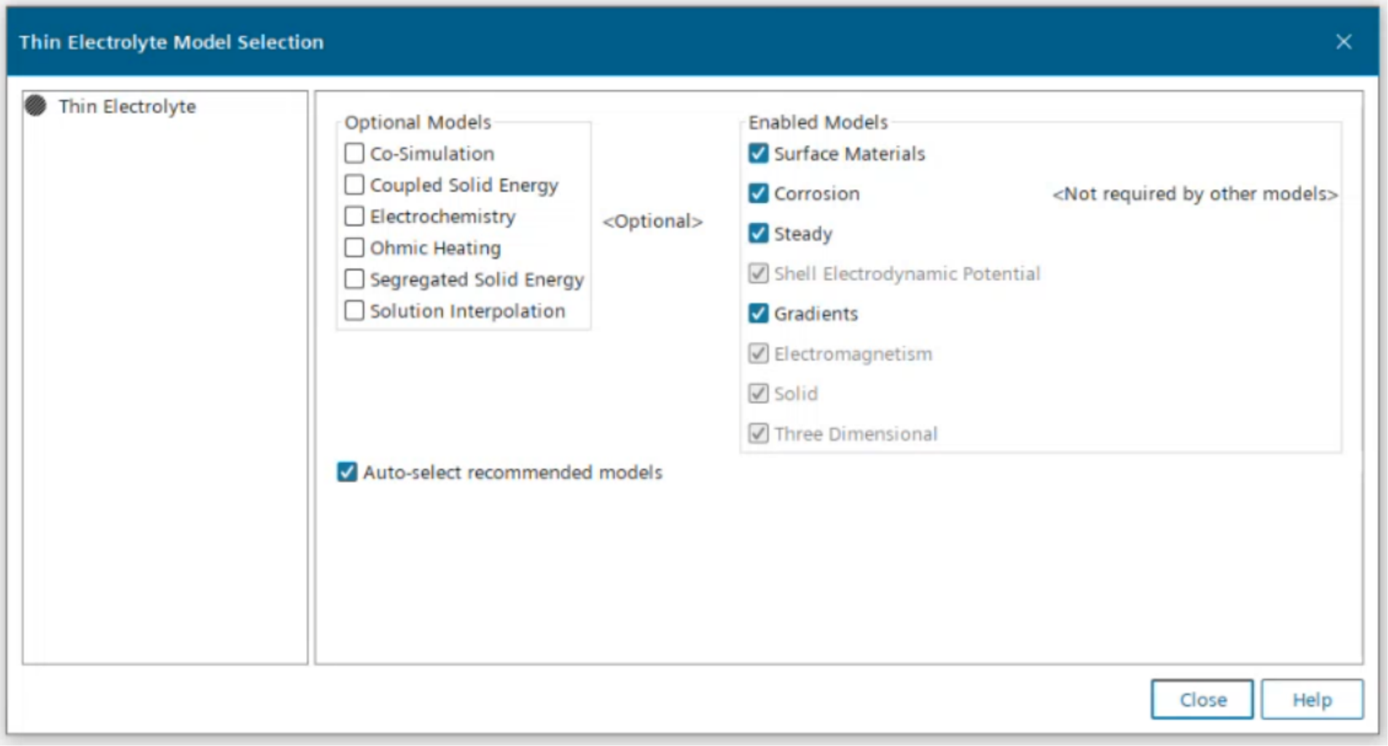
Enabled Models
☑ Surface Materials
☑ Corrosion <Not required by other models>
☑ Electrodynamic Potential
☑ Electromagnetism
☑ Inviscid
☑ Steady
☑ Constant Density
☑ Three Dimensional
☑ Gradients
☑ Segregated Flow
☑ Liquid

Bulk Continua Configuration

Thin Electrolyte Solution

- Space: Three Dimensional
- Material: Solid
- Optional Models: Electromagnetism
- Electromagnetism: Shell Electrodynamic Potential
- Time: Steady
- Optional Models: Corrosion

> **Note**
>
> Surface Materials & Gradients will be enabled automatically.



● Thin Electrolyte

Optional Models
☐ Co-Simulation
☐ Coupled Solid Energy
☐ Electrochemistry
☐ Ohmic Heating
☐ Segregated Solid Energy
☐ Solution Interpolation

<Optional>

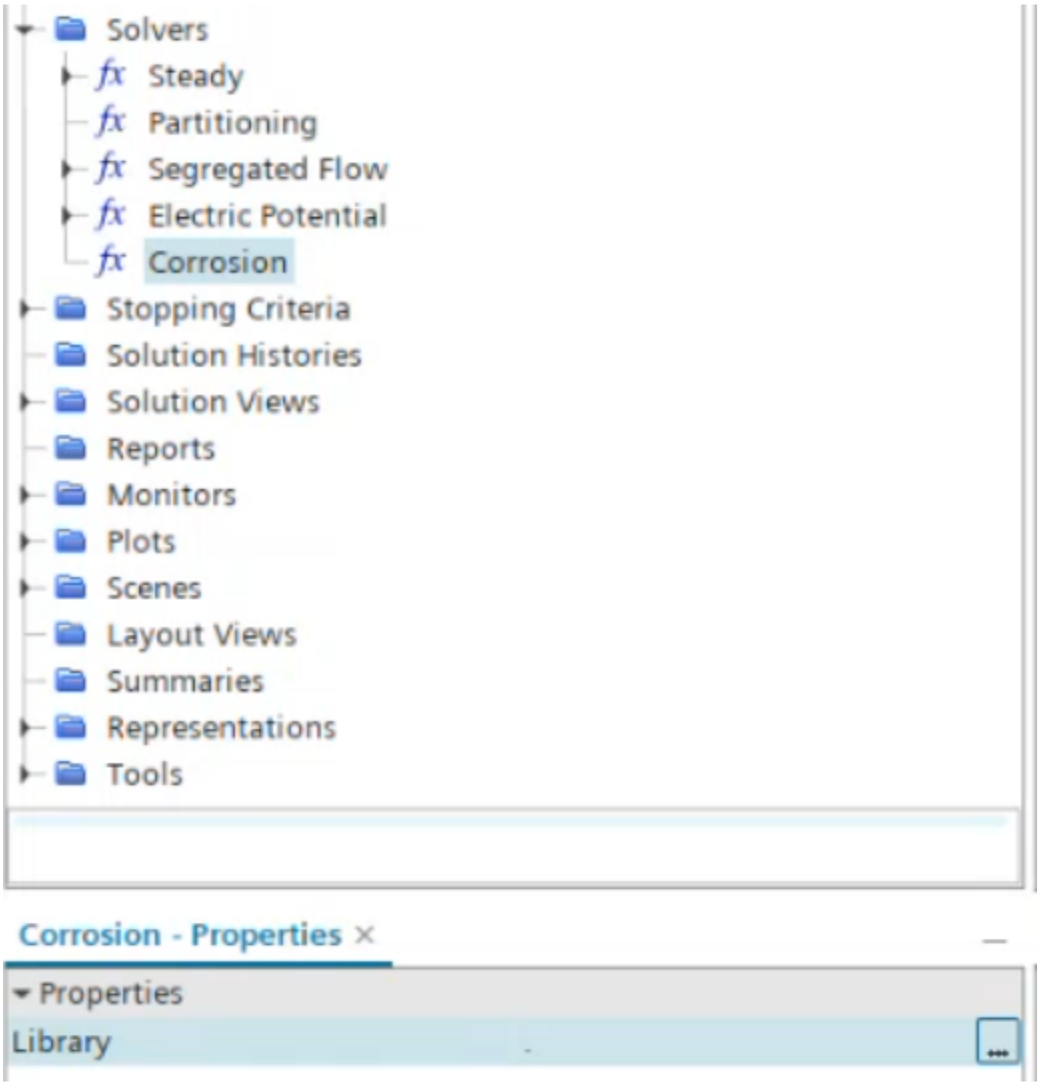
Enabled Models
☑ Surface Materials
☑ Corrosion <Not required by other models>
☑ Steady
☑ Shell Electrodynamic Potential
☑ Gradients
☑ Electromagnetism
☑ Solid
☑ Three Dimensional

☑ Auto-select recommended models

Thin Film Continua Configuration

3.3.2 Loading the Library

In order to perform analysis you need to ensure that the library is loaded into STAR-CCM+. Once you have setup the Corrosion module you next need to load the library into CCM+ this can be done under Solvers -> Corrosion -> Corrosion - Properties.



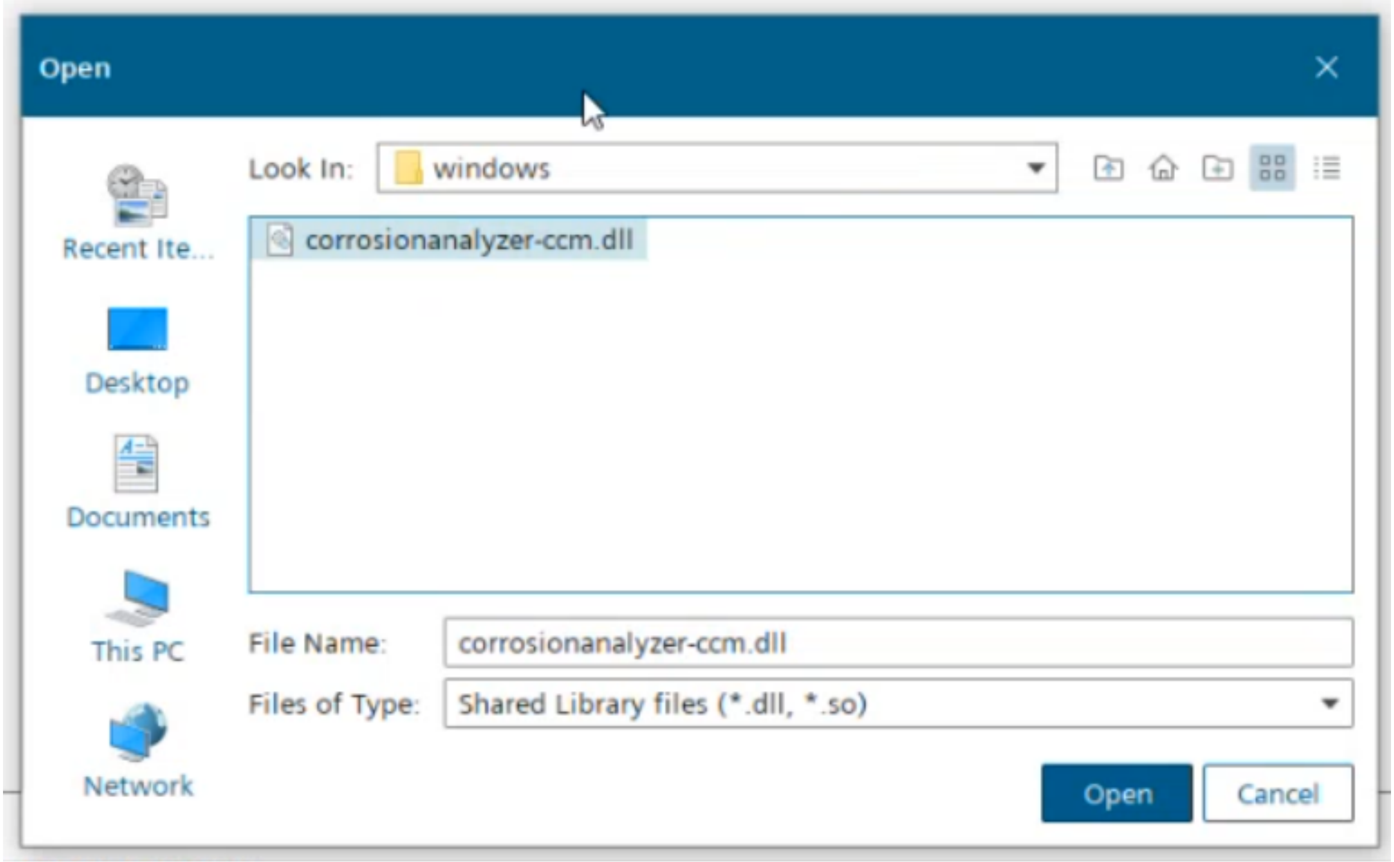
Setting up the library

Clicking the 3 dots will let you select a library to load into CCM+.

Navigate to the install files and select the file as below in the Windows/Linux folder you have been provided.

Note

- For Windows the file is `corrosionanalyzer-ccm.dll` .
- For Linux the file is `corrosionanalyzer-ccm.so` .



Look In: windows

corrosionanalyzer-ccm.dll

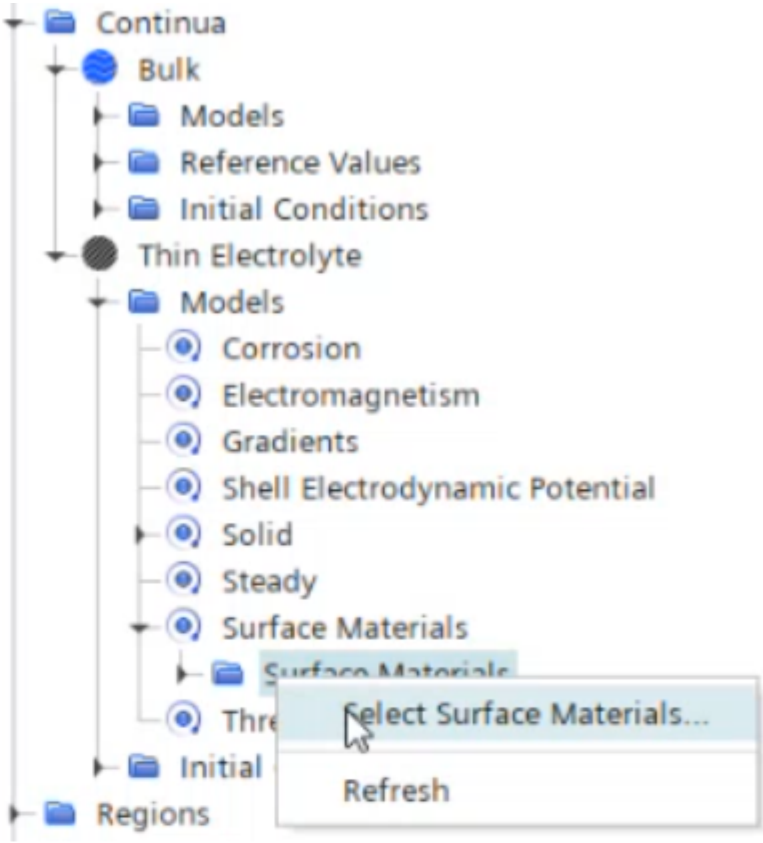
File Name: corrosionanalyzer-ccm.dll

Files of Type: Shared Library files (*.dll, *.so)

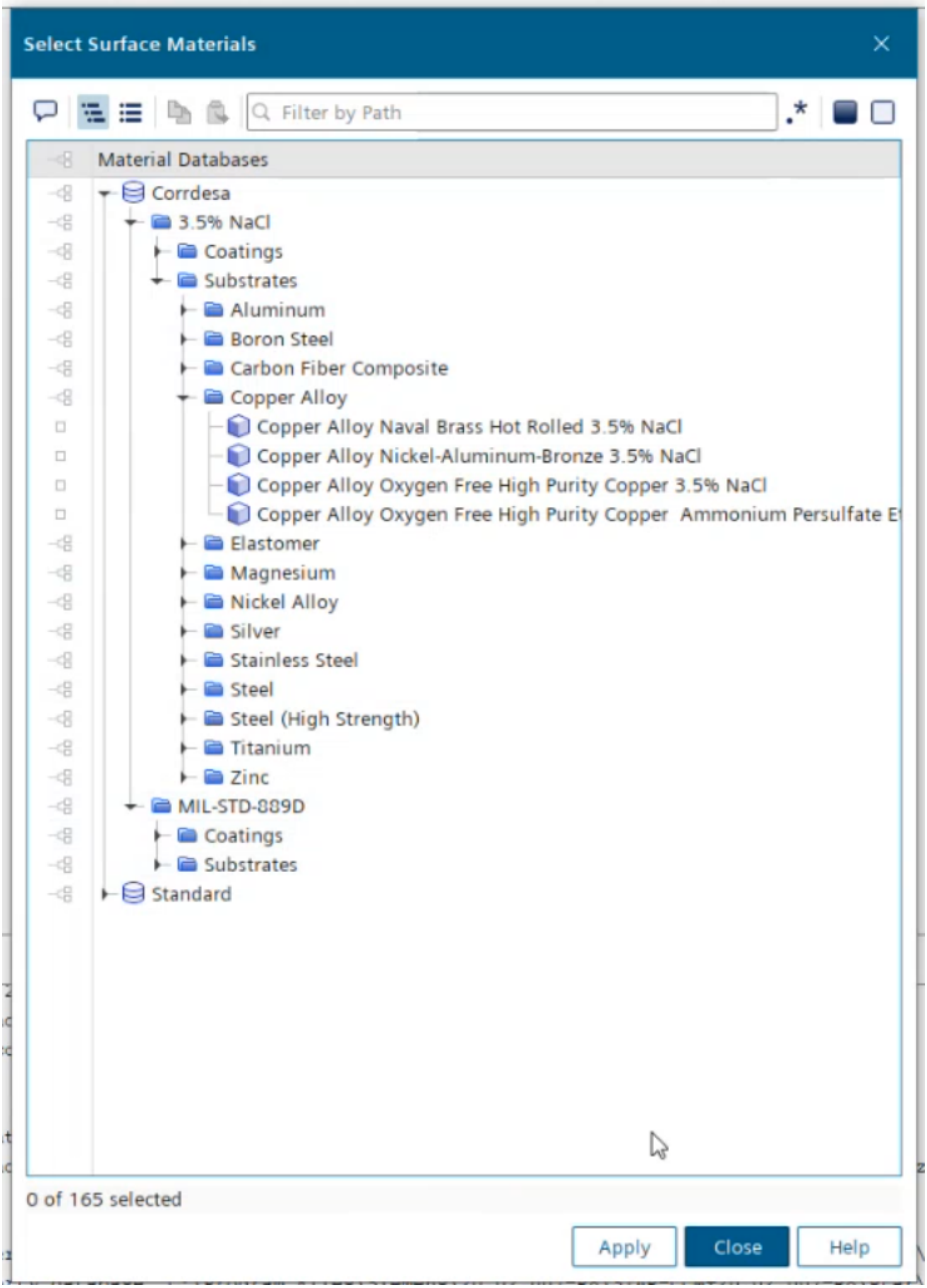
Corrosion Analyzer CCM Library Selected

3.3.3 Surface Materials

Selecting Surface Materials



Selecting Surface Materials



Material Databases

- Corrdesa
  - 3.5% NaCl
    - Coatings
    - Substrates
      - Aluminum
      - Boron Steel
      - Carbon Fiber Composite
      - Copper Alloy
        - ☐ Copper Alloy Naval Brass Hot Rolled 3.5% NaCl
        - ☐ Copper Alloy Nickel-Aluminum-Bronze 3.5% NaCl
        - ☐ Copper Alloy Oxygen Free High Purity Copper 3.5% NaCl
        - ☐ Copper Alloy Oxygen Free High Purity Copper Ammonium Persulfate E
      - Elastomer
      - Magnesium
      - Nickel Alloy
      - Silver
      - Stainless Steel
      - Steel
      - Steel (High Strength)
      - Titanium
      - Zinc
  - MIL-STD-889D
    - Coatings
    - Substrates
- Standard

0 of 165 selected