Galvanic Compatibility Assessment: New Methodology and Standardization

March 26th, 2019

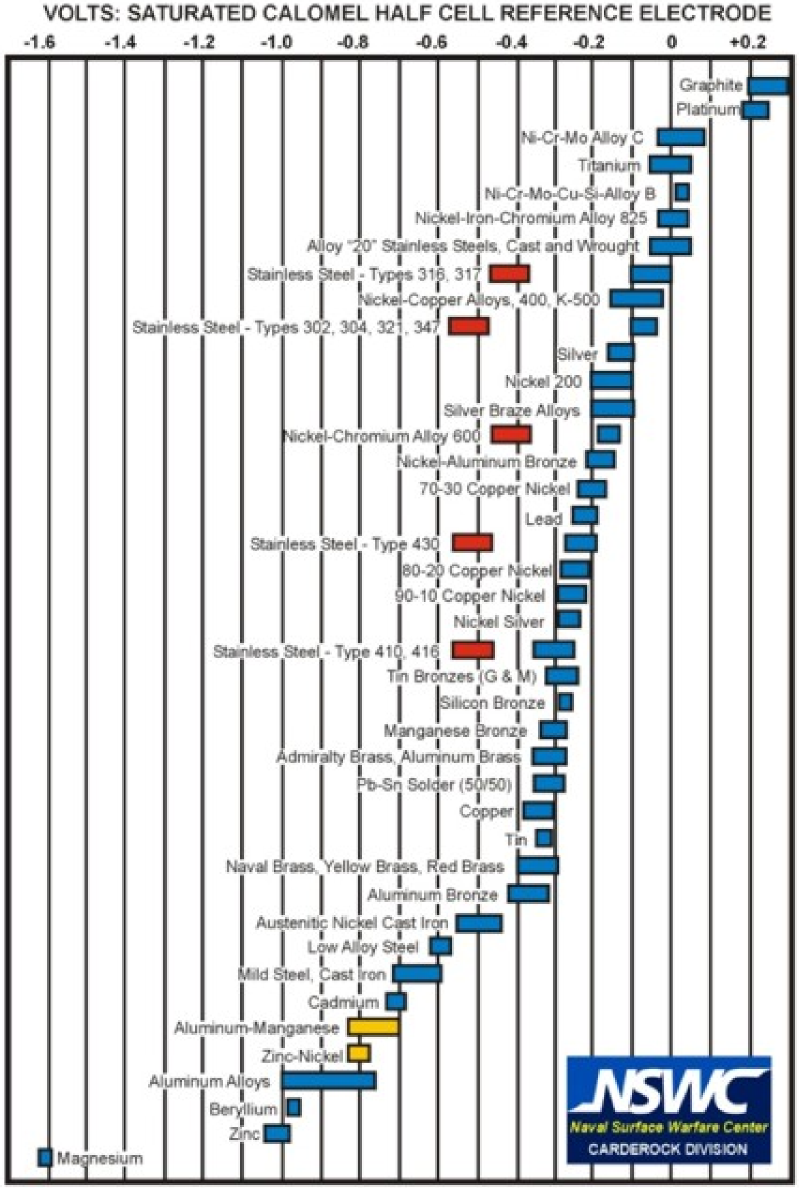
Presented to: NACE Corrosion 2019

Presented by: Steven Kopitzke,
on behalf of Victor Rodriguez-Santiago, Anna Safigan

MIL-STD-889: Dissimilar Metals

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

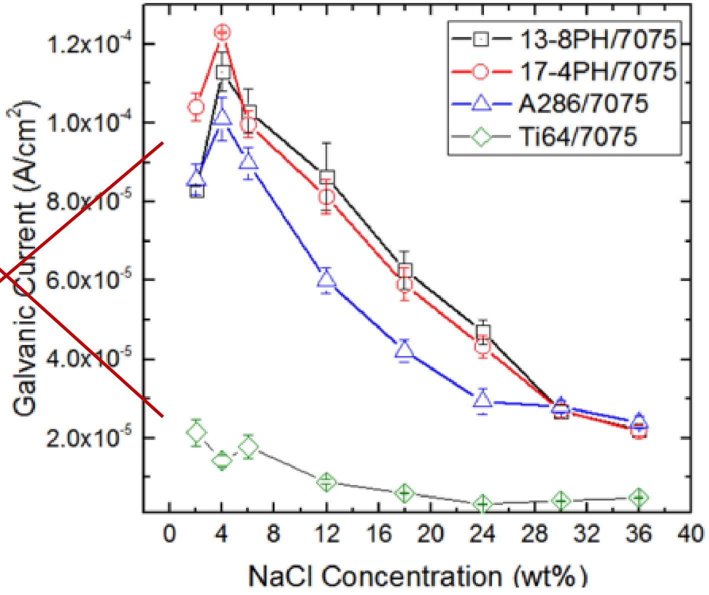
Wrong Compatibility Decisions are Possible



Titanium

Stainless Steels

Al Alloys



Based in the galvanic series, stainless steels are a better material choice than titanium when coupled to Al7075. However, titanium has almost an order of magnitude lower galvanic current.

Proposed Approach for Technical Revision

- **Aim:** Update MIL-STD-889C based on current density rather than ΔE, and to update the materials list.

- **Proposed Methods:**

Phase II

  - **Method 0:** Replace galvanic series with a similar table based on current density for equal areas, but using alloys rather than the generic materials in the current standard. Include simple ways of adjusting for relative areas and finishes. Galvanic current would be obtained from polarization data, and curve crossing.
    - **Task:** Define **methodology to acquire polarization data** in bulk electrolyte using flat cell -- this methodology will be based on a Best Practices Document for generating polarization curves.

Other Phases

  - **Method 1:** Define galvanic acceleration factors – corrosion testing such as weight loss.
  - **Method 2:** Define computational method using curve crossing.
  - **Method 3:** Define methodology for full FEA approach.

What do we need to accomplish?

Development of a Methodology for Generating Standardized Electrochemical Data

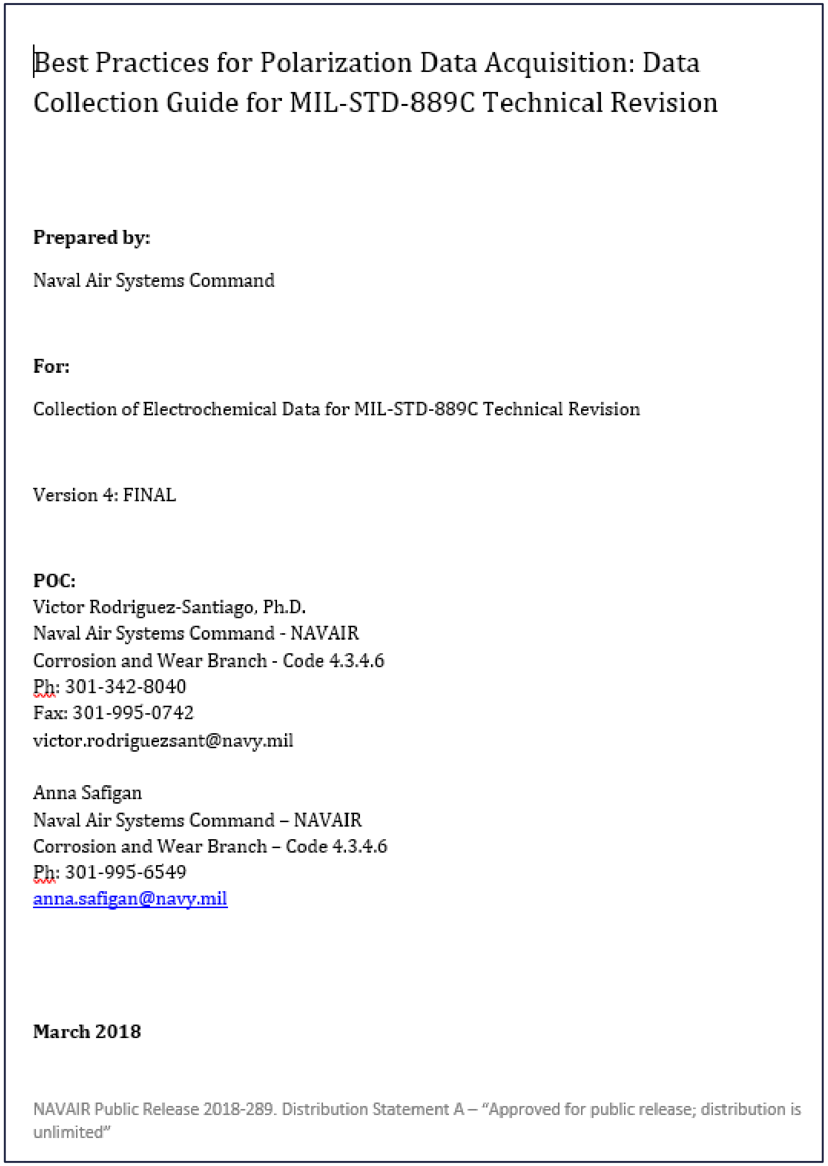
Development of a Deconvolution Approach for Analyzing the Data

Determining Galvanic Currents and Establishing Compatibility Thresholds

Round Robin for Developing a Test Methodology

- A methodology was established in order to obtain potentiodynamic polarization data. This methodology provides a best-practices approach in order to generate data across laboratories that is consistent and valid.
- Round robin testing was established encompassing academia, industry, and NAVAIR:
  - UVA (Kelly)
  - OSU (Frankel)
  - Corrdesa (Keith, Siva)
  - MSU (Swain)
  - NAVAIR (Safigan, Rodriguez)
  - UTRC (Jaworowski)
  - Safran
- The round robin was conducted and analyzed per **ASTM E691**.

Best Practices Document



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

Prepared by:

Naval Air Systems Command

For:

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

Version 4: FINAL

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March 2018

- **Best Practices document has been finalized and it is Distribution A.**

<table>
<tr><th>Item</th><th colspan="2">Notes</th></tr>
<tr><td>Equipment</td><td colspan="2">Flat cell.</td></tr>
<tr><td>Reference electrode</td><td colspan="2">SCE, Ag/AgCl, or other suitable electrode.</td></tr>
<tr><td>Electrolyte</td><td colspan="2">Artificial sea water per ASTM D1141 (2013) without heavy metals, 25 ±3° C, pH 8.2, vigorously aerated prior to testing, then quiescent condition (naturally aerated; no bubbling)</td></tr>
<tr><td>Working electrode</td><td colspan="2">Specimen to be tested. Stationary. Abraded with appropriate P800 or ANSI 400 grinding paper, cleaned with acetone then ethanol, and surface treated appropriately (if required).</td></tr>
<tr><td rowspan="3">OCP stabilization</td><td colspan="2">The surface should be stabilized in the electrolyte, but not for a time that causes the surface condition to change significantly (e.g. crevice or pitting):</td></tr>
<tr><td>MORE Noble (OCP > -200 mV vs SCE):</td><td>LESS Noble (OCP < -200 mV vs SCE):</td></tr>
<tr><td>24 hours in electrolyte prior to polarization measurement</td><td>4 hours in electrolyte prior to polarization measurement</td></tr>
<tr><td>Polarization curve</td><td colspan="2">• Anodic polarization: OCP to +0.7 V vs OCP, or when the anodic current density reaches a maximum of 10 mA/cm^2
• Cathodic polarization: OCP to -1.4 V vs REF, or when the cathodic current density reaches a maximum of 10 mA/cm^2
Note: Cathodic and anodic curves shall be obtained on separate specimens prepared according to section 3.1.</td></tr>
<tr><td>Sweep rate</td><td colspan="2">0.2 mV/s for entire potential range</td></tr>
<tr><td>IR correction</td><td colspan="2">The reference electrode should be placed >2x diameter of Luggin tip from the working electrode.</td></tr>
</table>

What do we need to accomplish?

Development of a Methodology for Generating Standardized Electrochemical Data

Development of a Deconvolution Approach for Analyzing the Data

Determining Galvanic Currents and Establishing Compatibility Thresholds

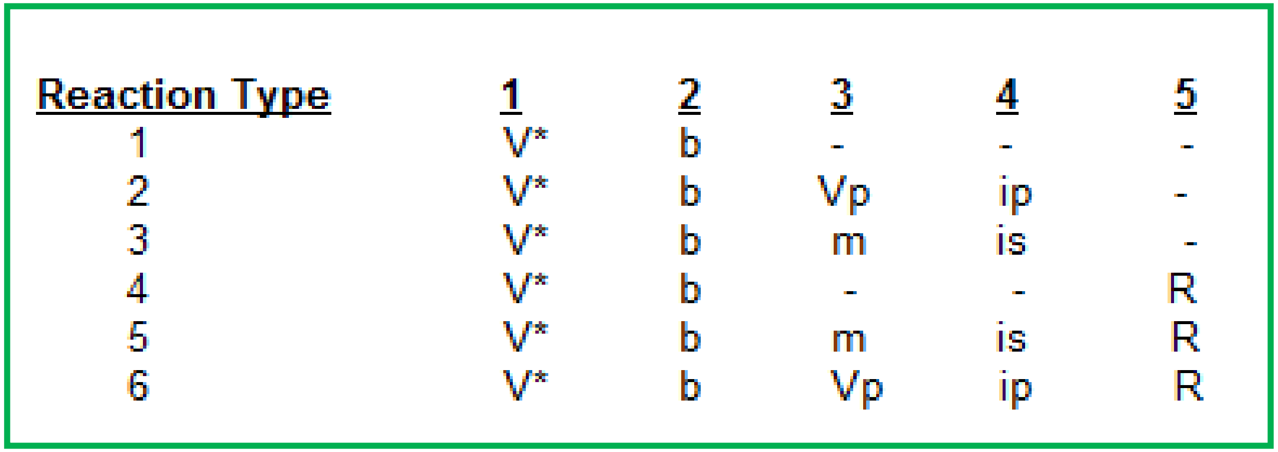
Deconvolution Approach: Reactions

- Semi-automated approach published by Yeum and Devereux:
  - K.S. Yeum and O.F. Devereux, "An Iterative Method for Fitting Complex Electrode Polarization Curves", Corrosion, Vol. 45, pp. 478-487 (1989).

1) Identify curve regions dominated by separate reactions
2) Classify those reactions into one of six types
3) Provide initial estimates for kinetic parameters
4) Operate software to obtain the best fit

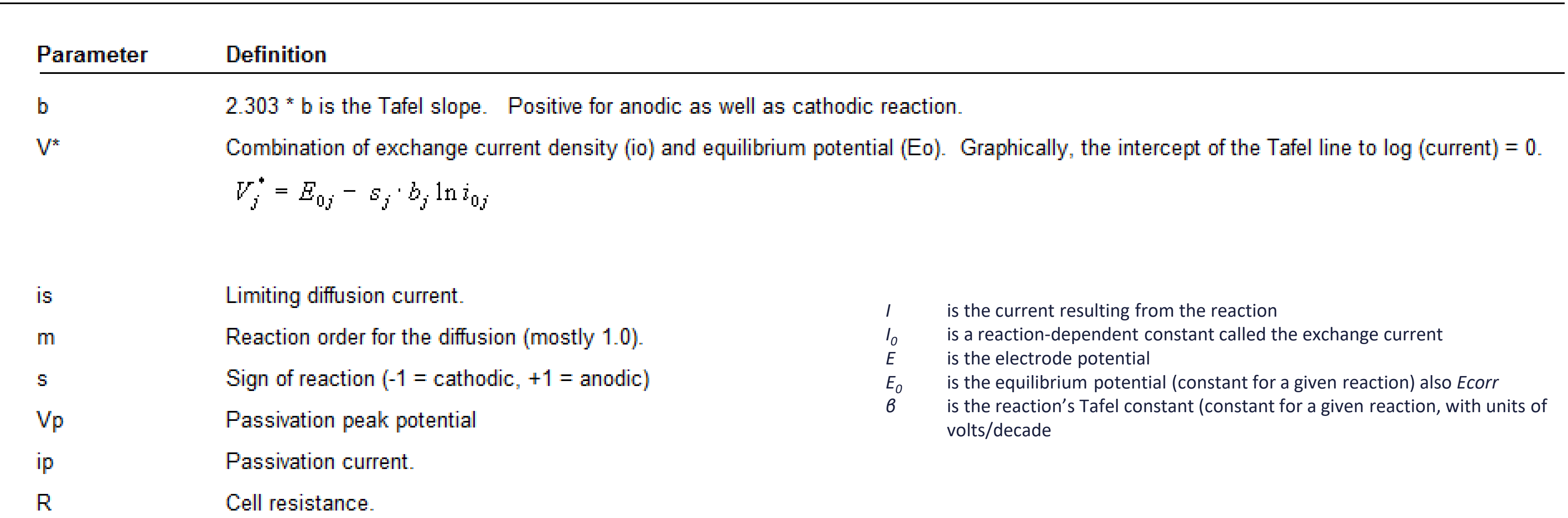
Reaction Type	Electron	Passivation	Diffusion	Ohmic-drop
1	x			
2	x	x		
3	x		x	
4	x			x
5	x		x	x
6	x	x		x

Deconvolution Approach: Parameters



Reaction Type	1	2	3	4	5
1	V*	b	-	-	-
2	V*	b	Vp	ip	-
3	V*	b	m	is	-
4	V*	b	-	-	R
5	V*	b	m	is	R
6	V*	b	Vp	ip	R

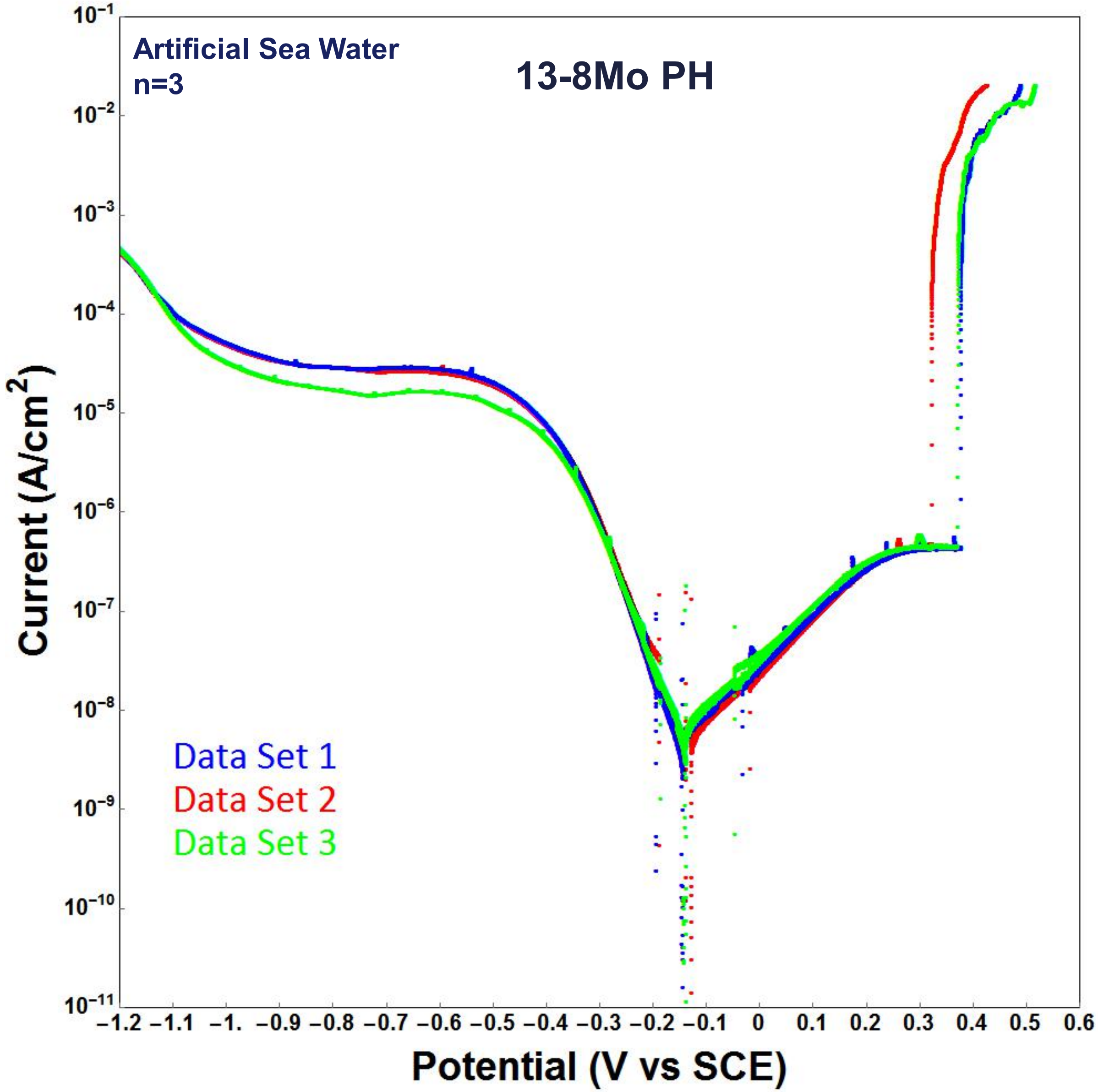
Definition of parameters



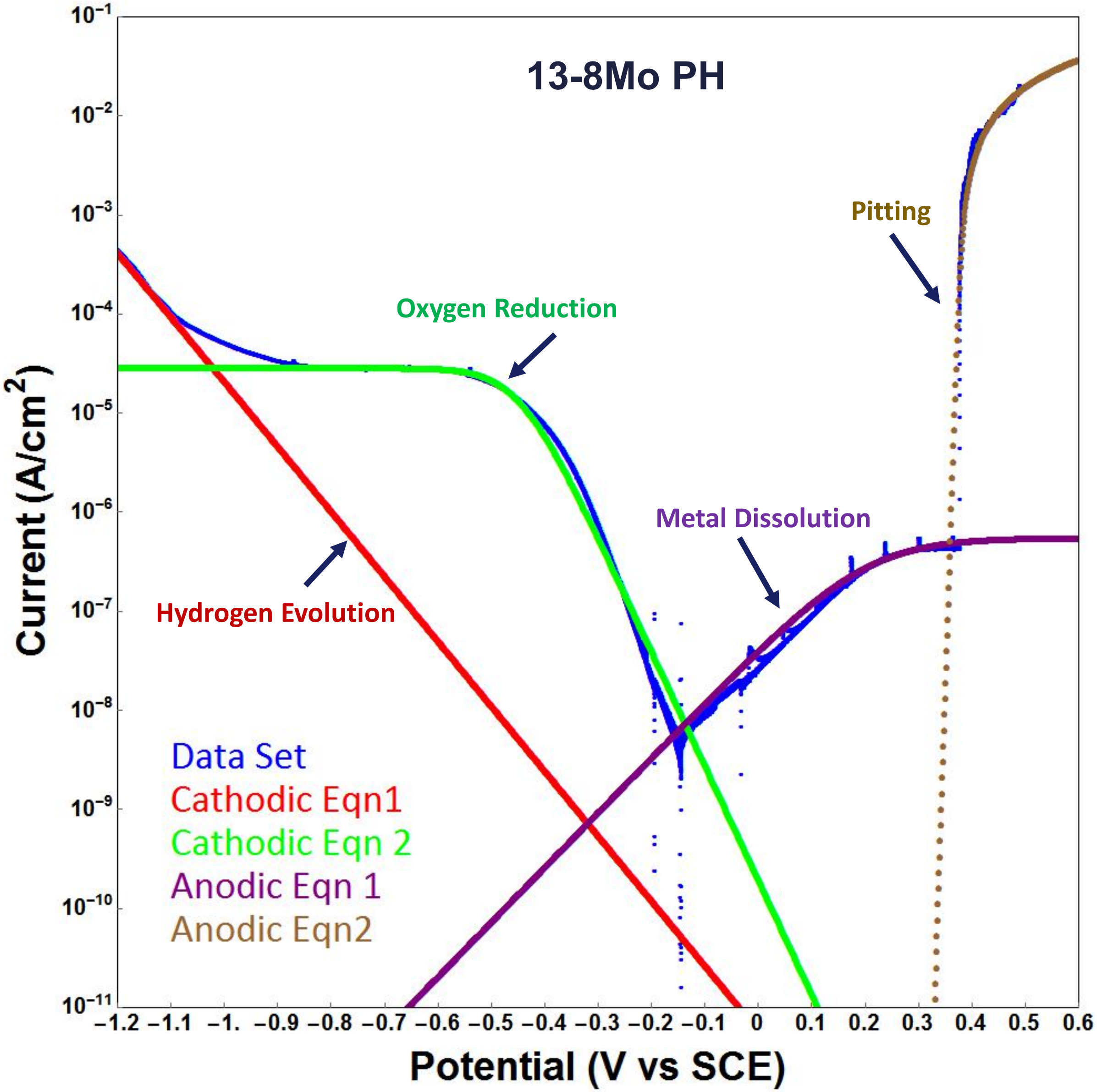
Parameter	Definition
b	2.303 * b is the Tafel slope. Positive for anodic as well as cathodic reaction.
V*	Combination of exchange current density (io) and equilibrium potential (Eo). Graphically, the intercept of the Tafel line to log (current) = 0. $V_j^* = E_{0j} - s_j \cdot b_j \ln i_{0j}$
is	Limiting diffusion current.
m	Reaction order for the diffusion (mostly 1.0).
s	Sign of reaction (-1 = cathodic, +1 = anodic)
Vp	Passivation peak potential
ip	Passivation current.
R	Cell resistance.

I	is the current resulting from the reaction
I_0	is a reaction-dependent constant called the exchange current
E	is the electrode potential
E_0	is the equilibrium potential (constant for a given reaction) also *Ecorr*
β	is the reaction's Tafel constant (constant for a given reaction, with units of volts/decade

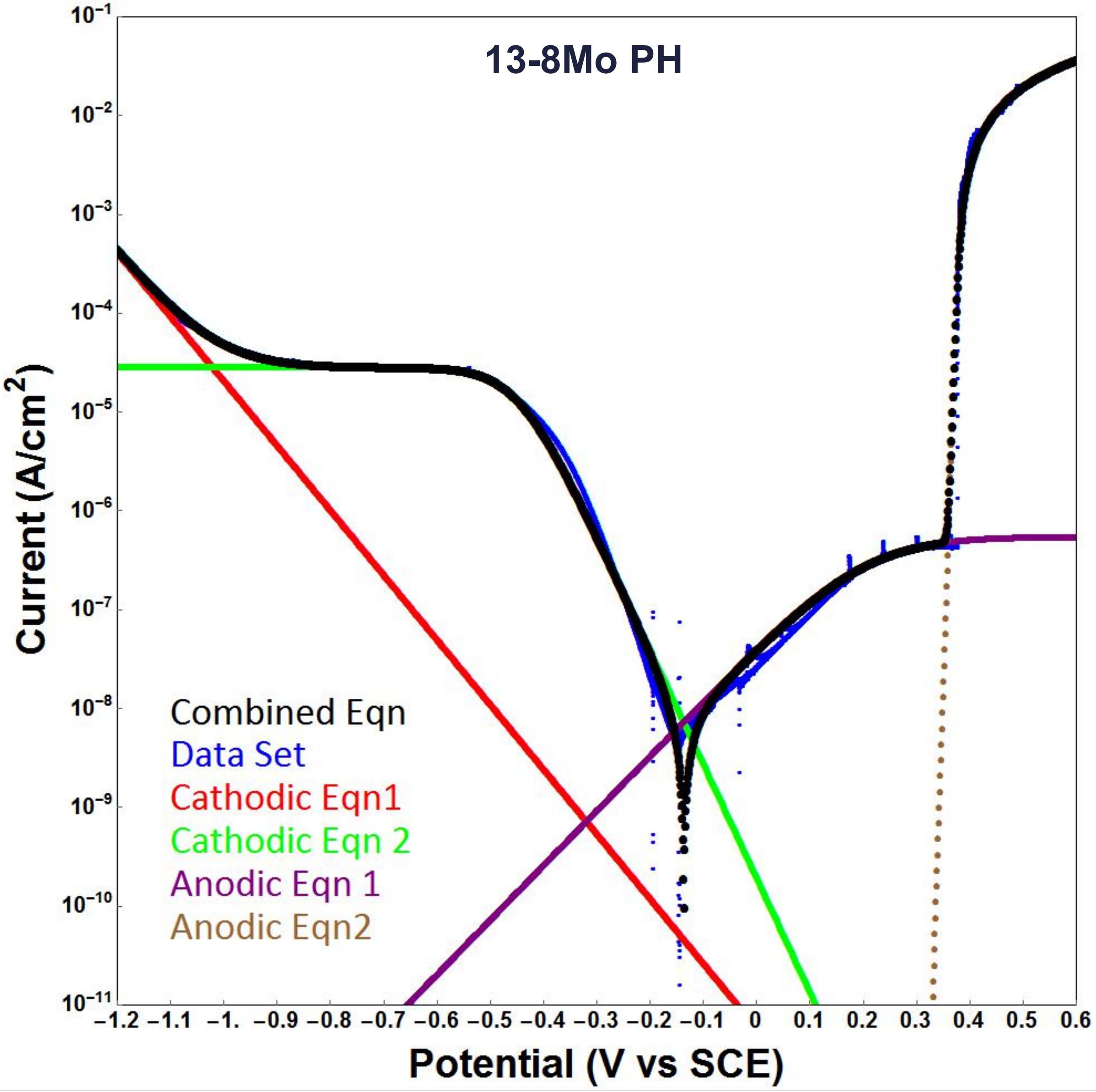
Raw Data 13-8Mo PH



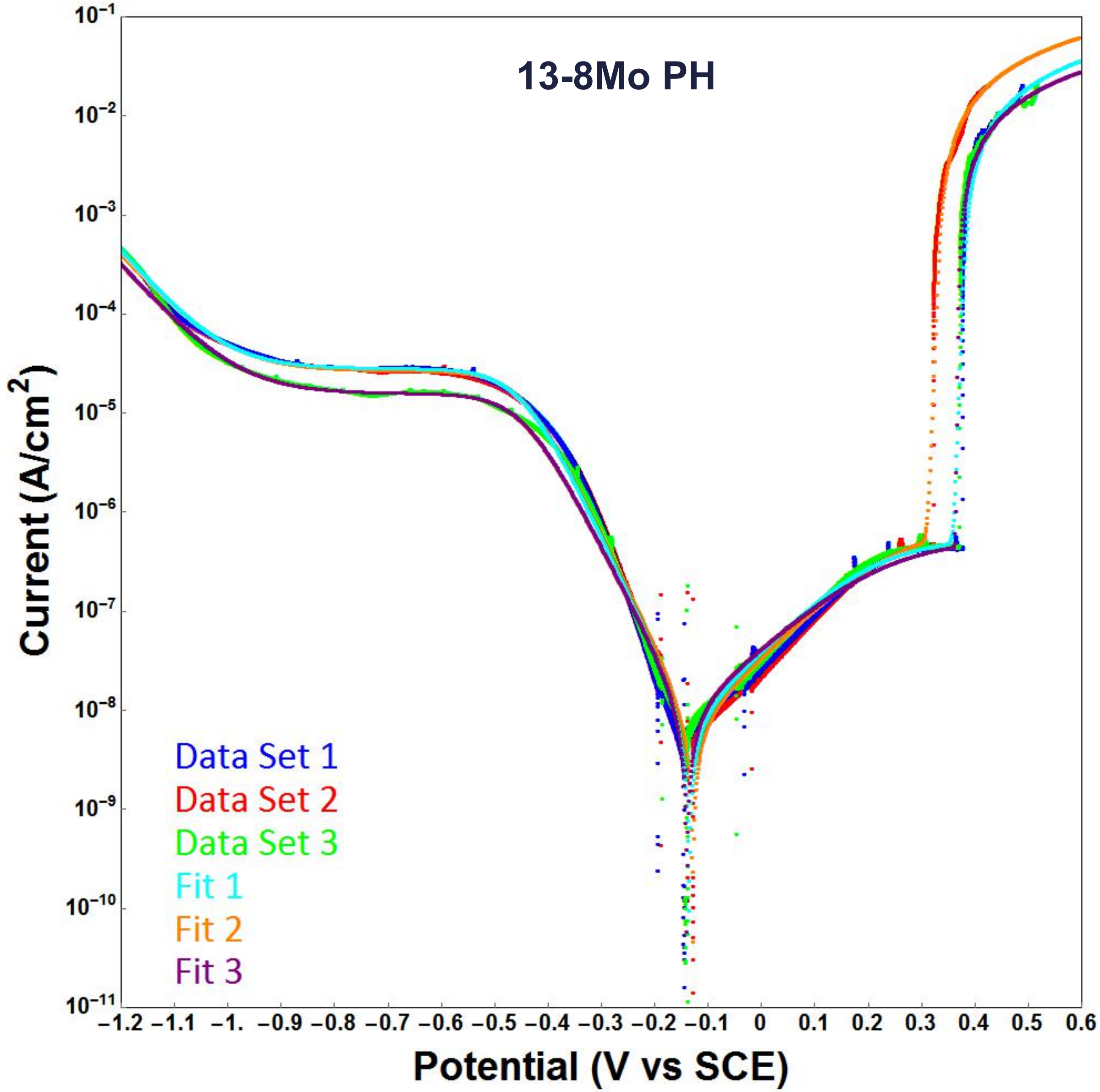
Deconvoluted Components



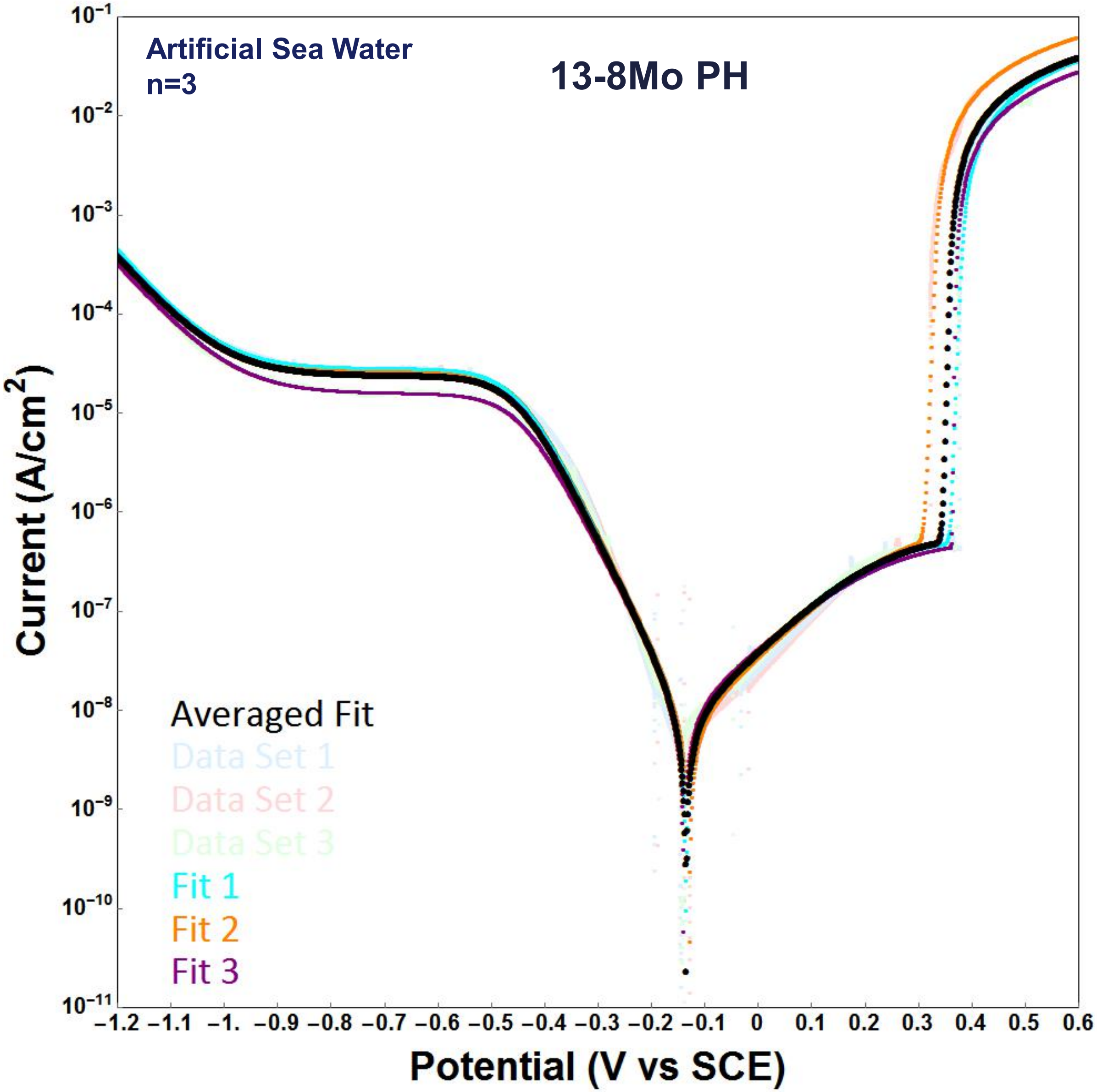
Fully Deconvoluted Curve



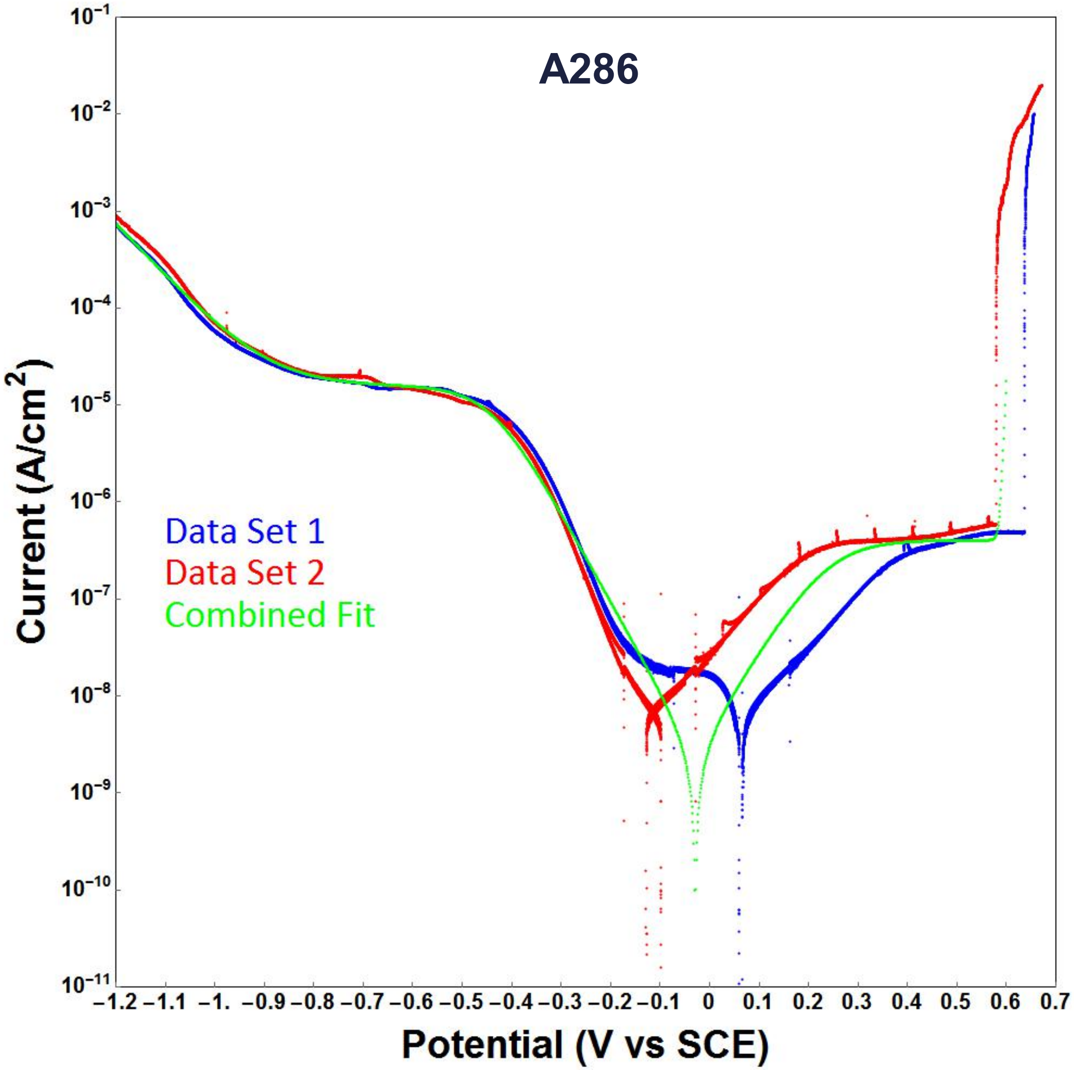
Raw and Deconvoluted



Average Deconvoluted Curve for All Data Sets



A286 Raw and Deconvoluted



- **Scattered data sets can be averaged and represented in one curve using individual fit parameters.**

What do we need to accomplish?

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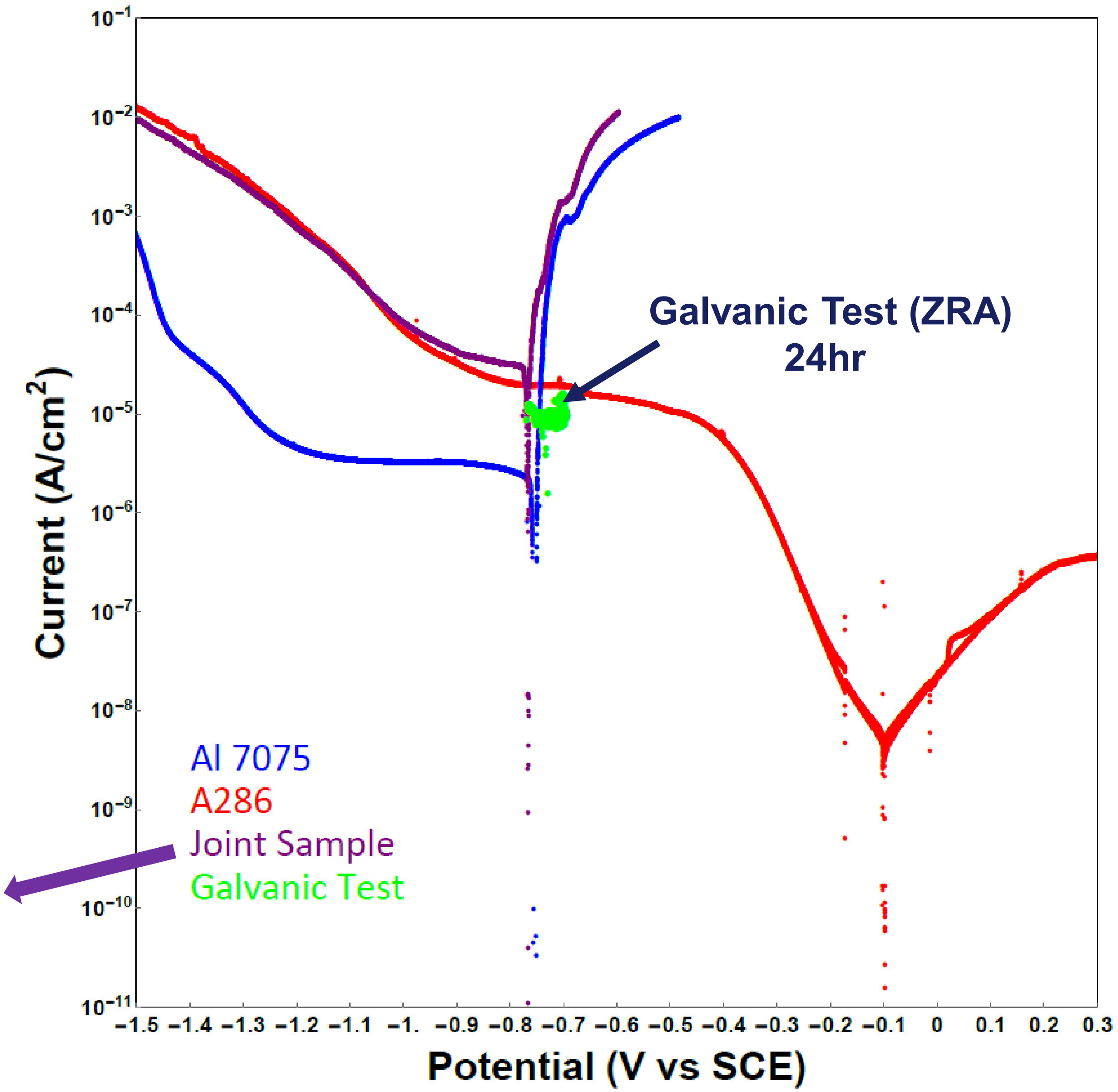
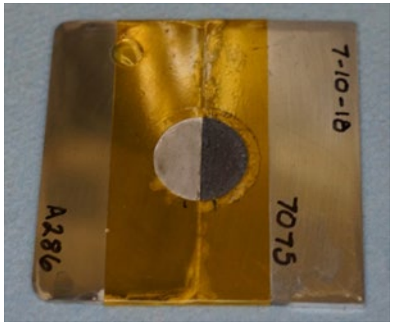
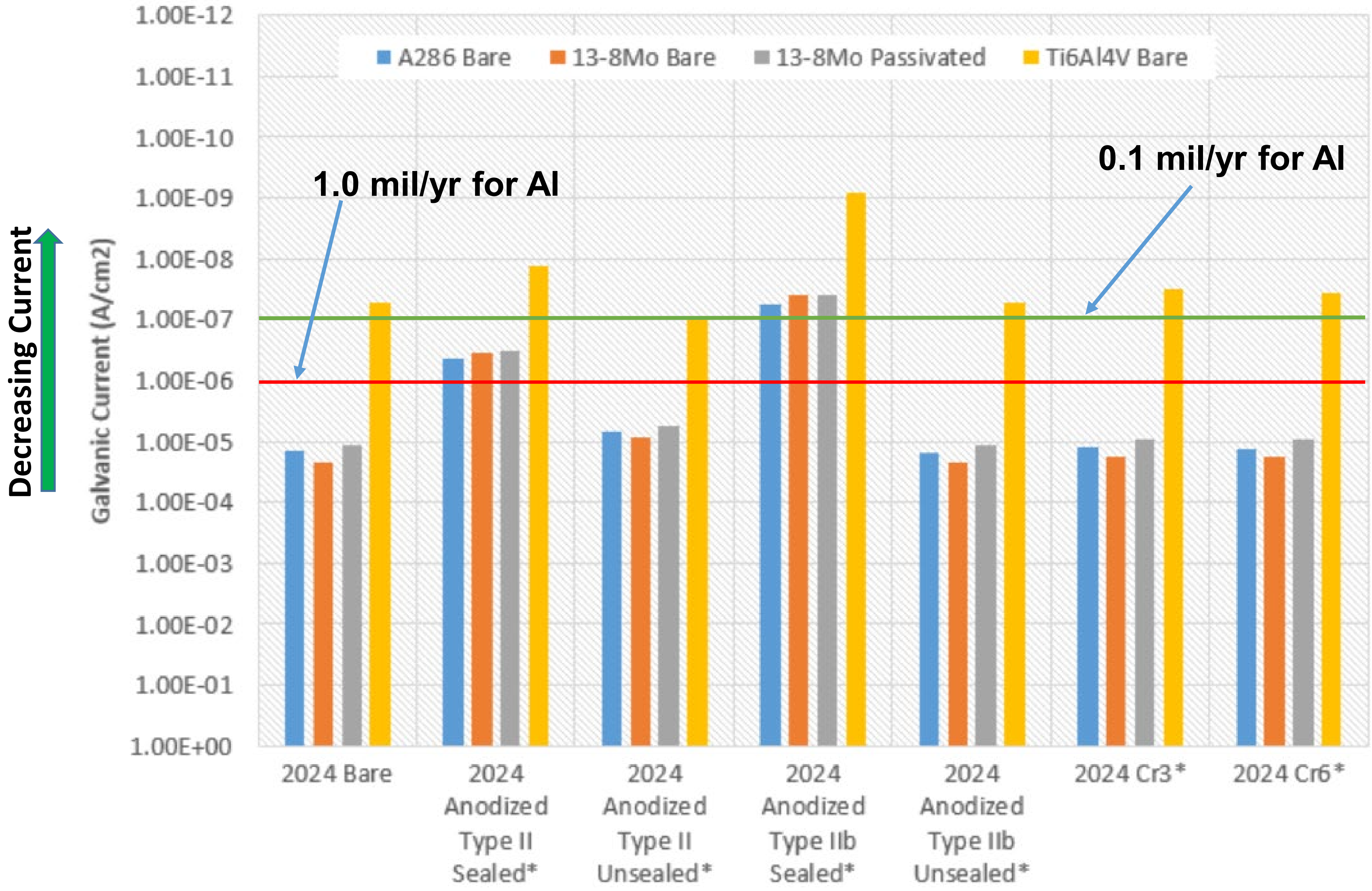
Verifying Mixed Potential Approach



**Galvanic Test (ZRA)
24hr**

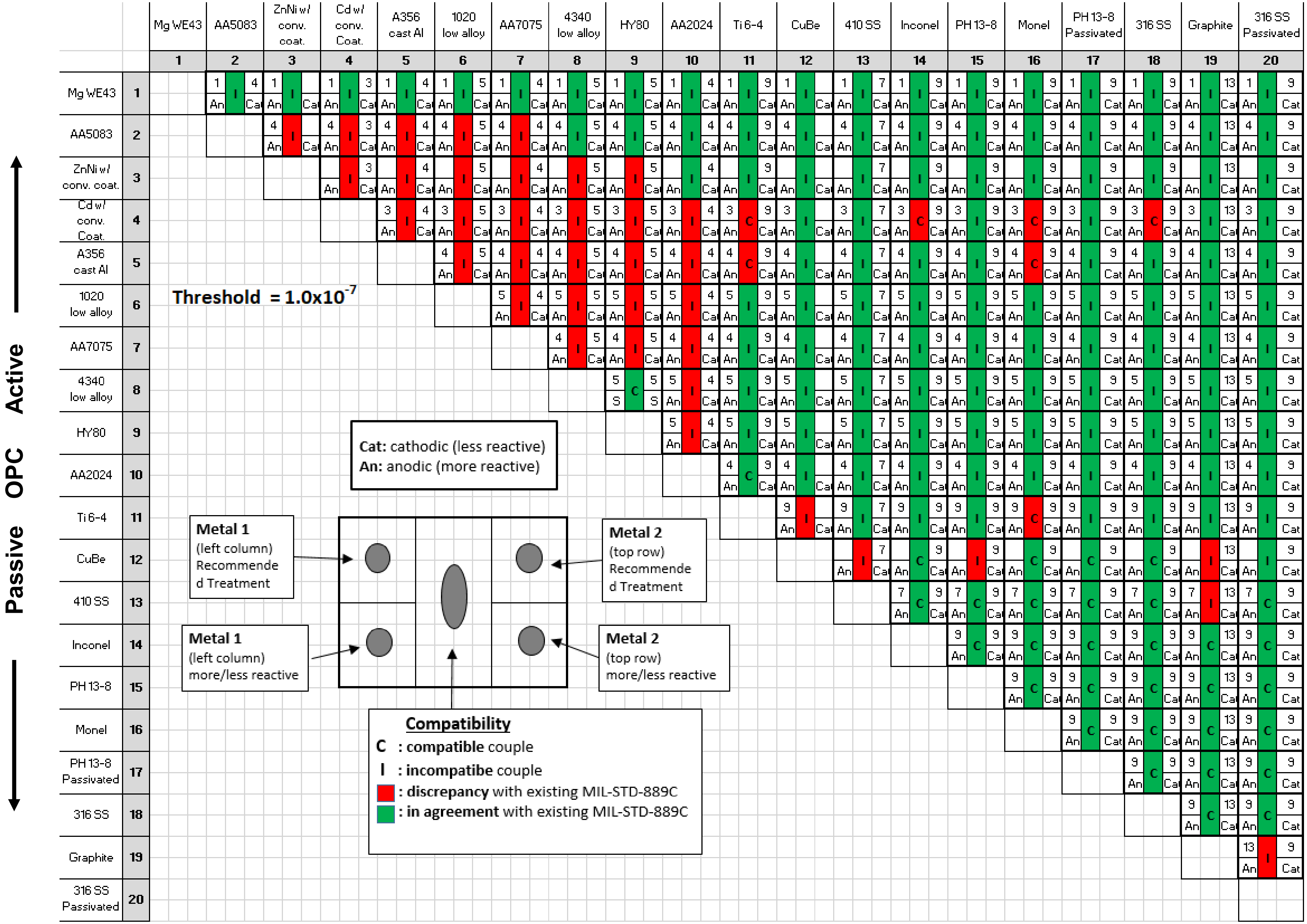


Galvanic Current of Several Couples



***Conversion coatings and anodization treatments will be attacked in a localized manner. All galvanic current will be concentrated in a small area.**

Galvanic Table – New Methodology (High)



Active

OPC

Passive

		Mg WE43	AA5083	ZnNi w/ conv. coat.	Cd w/ conv. Coat.	A356 cast Al	1020 low alloy	AA7075	4340 low alloy	HY80	AA2024	Ti 6-4	CuBe	410 SS	Inconel	PH 13-8	Monel	PH 13-8 Passivated	316 SS	Graphite	316 SS Passivated
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Mg WE43	1		1 An 🟩 I 4 Cat	1 An 🟩 I Cat	1 An 🟩 I 3 Cat	1 An 🟩 I 4 Cat	1 An 🟩 I 5 Cat	1 An 🟩 I 4 Cat	1 An 🟩 I 5 Cat	1 An 🟩 I 5 Cat	1 An 🟩 I 4 Cat	1 An 🟩 I 9 Cat	1 An 🟩 I Cat	1 An 🟩 I 7 Cat	1 An 🟩 I 9 Cat	1 An 🟩 I 9 Cat	1 An 🟩 I 9 Cat	1 An 🟩 I 9 Cat	1 An 🟩 I 9 Cat	1 An 🟩 I 13 Cat	1 An 🟩 I 9 Cat
AA5083	2			4 An 🟥 I Cat	4 An 🟥 I 3 Cat	4 An 🟥 I 4 Cat	4 An 🟥 I 5 Cat	4 An 🟥 I 4 Cat	4 An 🟩 I 5 Cat	4 An 🟩 I 5 Cat	4 An 🟩 I 4 Cat	4 An 🟩 I 9 Cat	4 An 🟩 I Cat	4 An 🟩 I 7 Cat	4 An 🟩 I 9 Cat	4 An 🟩 I 9 Cat	4 An 🟩 I 9 Cat	4 An 🟩 I 9 Cat	4 An 🟩 I 9 Cat	4 An 🟩 I 13 Cat	4 An 🟩 I 9 Cat
ZnNi w/ conv. coat.	3				An 🟥 I 3 Cat	An 🟥 I 4 Cat	An 🟥 I 5 Cat	An 🟥 I 4 Cat	An 🟥 I 5 Cat	An 🟥 I 5 Cat	An 🟩 I 4 Cat	An 🟩 I 9 Cat	An 🟩 I Cat	An 🟩 I 7 Cat	An 🟩 I 9 Cat	An 🟩 I 9 Cat	An 🟩 I 9 Cat	An 🟩 I 9 Cat	An 🟩 I 9 Cat	An 🟩 I 13 Cat	An 🟩 I 9 Cat
Cd w/ conv. Coat.	4					3 An 🟥 I 4 Cat	3 An 🟥 I 5 Cat	3 An 🟥 I 4 Cat	3 An 🟥 I 5 Cat	3 An 🟥 I 5 Cat	3 An 🟥 I 4 Cat	3 An 🟥 C 9 Cat	3 An 🟩 I Cat	3 An 🟩 I 7 Cat	3 An 🟥 C 9 Cat	3 An 🟩 I 9 Cat	3 An 🟥 C 9 Cat	3 An 🟩 I 9 Cat	3 An 🟥 C 9 Cat	3 An 🟩 I 13 Cat	3 An 🟩 I 9 Cat
A356 cast Al	5						4 An 🟥 I 5 Cat	4 An 🟥 I 4 Cat	4 An 🟥 I 5 Cat	4 An 🟥 I 5 Cat	4 An 🟥 I 4 Cat	4 An 🟥 C 9 Cat	4 An 🟩 I Cat	4 An 🟩 I 7 Cat	4 An 🟩 I 9 Cat	4 An 🟩 I 9 Cat	4 An 🟥 C 9 Cat	4 An 🟩 I 9 Cat	4 An 🟩 I 9 Cat	4 An 🟩 I 13 Cat	4 An 🟩 I 9 Cat
1020 low alloy	6							5 An 🟥 I 4 Cat	5 An 🟥 I 5 Cat	5 An 🟥 I 5 Cat	5 An 🟥 I 4 Cat	5 An 🟩 I 9 Cat	5 An 🟩 I Cat	5 An 🟩 I 7 Cat	5 An 🟩 I 9 Cat	5 An 🟩 I 9 Cat	5 An 🟩 I 9 Cat	5 An 🟩 I 9 Cat	5 An 🟩 I 9 Cat	5 An 🟩 I 13 Cat	5 An 🟩 I 9 Cat
AA7075	7								4 An 🟥 I 5 Cat	4 An 🟥 I 5 Cat	4 An 🟥 I 4 Cat	4 An 🟩 I 9 Cat	4 An 🟩 I Cat	4 An 🟩 I 7 Cat	4 An 🟩 I 9 Cat	4 An 🟩 I 9 Cat	4 An 🟩 I 9 Cat	4 An 🟩 I 9 Cat	4 An 🟩 I 9 Cat	4 An 🟩 I 13 Cat	4 An 🟩 I 9 Cat
4340 low alloy	8									5 S 🟩 C 5 S	5 An 🟥 I 4 Cat	5 An 🟩 I 9 Cat	5 An 🟩 I Cat	5 An 🟩 I 7 Cat	5 An 🟩 I 9 Cat	5 An 🟩 I 9 Cat	5 An 🟩 I 9 Cat	5 An 🟩 I 9 Cat	5 An 🟩 I 9 Cat	5 An 🟩 I 13 Cat	5 An 🟩 I 9 Cat
HY80	9										5 An 🟥 I 4 Cat	5 An 🟩 I 9 Cat	5 An 🟩 I Cat	5 An 🟩 I 7 Cat	5 An 🟩 I 9 Cat	5 An 🟩 I 9 Cat	5 An 🟩 I 9 Cat	5 An 🟩 I 9 Cat	5 An 🟩 I 9 Cat	5 An 🟩 I 13 Cat	5 An 🟩 I 9 Cat
AA2024	10											4 An 🟩 C 9 Cat	4 An 🟩 I Cat	4 An 🟩 I 7 Cat	4 An 🟩 I 9 Cat	4 An 🟩 I 9 Cat	4 An 🟩 I 9 Cat	4 An 🟩 I 9 Cat	4 An 🟩 I 9 Cat	4 An 🟩 I 13 Cat	4 An 🟩 I 9 Cat
Ti 6-4	11												9 An 🟥 I Cat	9 An 🟩 I 7 Cat	9 An 🟩 I 9 Cat	9 An 🟩 I 9 Cat	9 An 🟥 C 9 Cat	9 An 🟩 I 9 Cat	9 An 🟩 I 9 Cat	9 An 🟩 I 13 Cat	9 An 🟩 I 9 Cat
CuBe	12													An 🟥 I 7 Cat	An 🟩 C 9 Cat	An 🟥 I 9 Cat	An 🟩 C 9 Cat	An 🟩 C 9 Cat	An 🟩 C 9 Cat	An 🟥 I 13 Cat	An 🟩 I 9 Cat
410 SS	13														7 An 🟩 C 9 Cat	7 An 🟩 C 9 Cat	7 An 🟩 C 9 Cat	7 An 🟩 C 9 Cat	7 An 🟩 C 9 Cat	7 An 🟥 I 13 Cat	7 An 🟩 C 9 Cat
Inconel	14															9 An 🟩 C 9 Cat	9 An 🟩 C 9 Cat	9 An 🟩 C 9 Cat	9 An 🟩 C 9 Cat	9 An 🟩 C 13 Cat	9 An 🟩 C 9 Cat
PH 13-8	15																9 An 🟩 C 9 Cat	9 An 🟩 C 9 Cat	9 An 🟩 C 9 Cat	9 An 🟩 C 13 Cat	9 An 🟩 C 9 Cat
Monel	16																	9 An 🟩 C 9 Cat	9 An 🟩 C 9 Cat	9 An 🟩 C 13 Cat	9 An 🟩 C 9 Cat
PH 13-8 Passivated	17																		9 An 🟩 C 9 Cat	9 An 🟩 C 13 Cat	9 An 🟩 C 9 Cat
316 SS	18																			9 An 🟩 C 13 Cat	9 An 🟩 C 9 Cat
Graphite	19																				13 An 🟥 I 9 Cat
316 SS Passivated	20																				

Threshold = 1.0×10^{-7}

Cat: cathodic (less reactive)
An: anodic (more reactive)

Metal 1
(left column)
Recommended Treatment

Metal 2
(top row)
Recommended Treatment

Metal 1
(left column)
more/less reactive

Metal 2
(top row)
more/less reactive

Compatibility

- **C** : **compatible** couple
- **I** : **incompatibe** couple
- 🟥 : **discrepancy** with existing MIL-STD-889C
- 🟩 : **in agreement** with existing MIL-STD-889C

Galvanic Table – New Methodology (Low)

Active

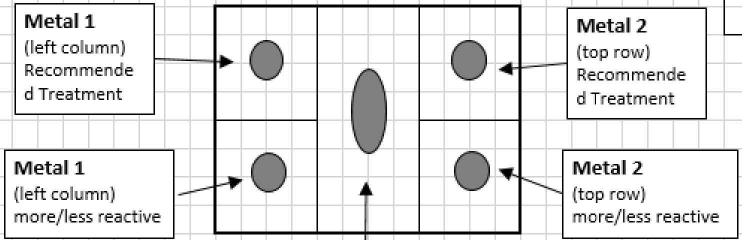
OPC

Passive

		Mg WE43	AA5083	ZnNi w/ conv. coat.	Cd w/ conv. coat.	A356 cast Al	1020 low alloy	AA7075	4340 low alloy	HY80	AA2024	Ti 6-4	CuBe	410 SS	Inconel	PH 13-8	Monel	PH 13-8 Passivated	316 SS	Graphite	316 SS Passivated
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Mg WE43	**1**		1 An 🟩 I 4 Ca	1 An 🟩 I Ca	1 An 🟩 I 3 Ca	1 An 🟩 I 4 Ca	1 An 🟩 I 5 Ca	1 An 🟩 I 4 Ca	1 An 🟩 I 5 Ca	1 An 🟩 I 5 Ca	1 An 🟩 I 4 Ca	1 An 🟩 I 9 Ca	1 An 🟩 I Ca	1 An 🟩 I 7 Ca	1 An 🟩 I 9 Ca	1 An 🟩 I 9 Ca	1 An 🟩 I 9 Ca	1 An 🟩 I 9 Cat	1 An 🟩 I 9 Ca	1 An 🟩 I 13 Ca	1 An 🟥 C 9 Cat
AA5083	**2**			4 An 🟥 I Ca	4 An 🟥 I 3 Ca	4 An 🟩 C 4 Ca	4 An 🟥 I 5 Ca	4 An 🟥 I 4 Ca	4 An 🟩 I 5 Ca	4 An 🟩 I 5 Ca	4 An 🟩 I 4 Ca	4 An 🟥 C 9 Ca	4 An 🟩 I Ca	4 An 🟩 I 7 Ca	4 An 🟩 I 9 Ca	4 An 🟩 I 9 Ca	4 An 🟩 I 9 Ca	4 An 🟩 I 9 Cat	4 An 🟩 I 9 Ca	4 An 🟩 I 13 Ca	4 An 🟩 I 9 Cat
ZnNi w/ conv. coat.	**3**				An 🟥 I 3 Ca	An 🟩 C 4 Ca	An 🟥 I 5 Ca	An 🟥 I 4 Ca	An 🟥 I 5 Ca	An 🟥 I 5 Ca	An 🟩 I 4 Ca	An 🟩 I 9 Ca	An 🟩 I Ca	An 🟩 I 7 Ca	An 🟩 I 9 Ca	An 🟩 I 9 Ca	An 🟥 C 9 Ca	An 🟩 I 9 Cat	An 🟩 I 9 Ca	An 🟩 I 13 Ca	An 🟩 I 9 Cat
Cd w/ conv. Coat.	**4**					3 An 🟥 I 4 Ca	3 An 🟥 I 5 Ca	3 An 🟩 C 4 Ca	3 An 🟥 I 5 Ca	3 An 🟥 I 5 Ca	3 An 🟥 I 4 Ca	3 An 🟥 C 9 Ca	3 An 🟩 I Ca	3 An 🟥 C 7 Ca	3 An 🟥 C 9 Ca	3 An 🟩 I 9 Ca	3 An 🟥 C 9 Ca	3 An 🟥 C 9 Cat	3 An 🟥 C 9 Ca	3 An 🟩 I 13 Ca	3 An 🟩 I 9 Cat
A356 cast Al	**5**						4 An 🟥 I 5 Ca	4 An 🟥 I 4 Ca	4 An 🟥 I 5 Ca	4 An 🟥 I 5 Ca	4 An 🟥 I 4 Ca	4 An 🟥 C 9 Ca	4 An 🟩 I Ca	4 An 🟩 I 7 Ca	4 An 🟩 I 9 Ca	4 An 🟩 I 9 Ca	4 An 🟥 C 9 Ca	4 An 🟩 I 9 Cat	4 An 🟩 I 9 Ca	4 An 🟩 I 13 Ca	4 An 🟩 I 9 Cat
1020 low alloy	**6**							5 An 🟥 I 4 Ca	5 An 🟥 I 5 Ca	5 An 🟥 I 5 Ca	5 An 🟥 I 4 Ca	5 An 🟥 C 9 Ca	5 An 🟩 I Ca	5 An 🟩 I 7 Ca	5 An 🟩 I 9 Ca	5 An 🟩 I 9 Ca	5 An 🟩 I 9 Ca	5 An 🟩 I 9 Cat	5 An 🟩 I 9 Ca	5 An 🟩 I 13 Ca	5 An 🟩 I 9 Cat
AA7075	**7**								4 An 🟥 I 5 Ca	4 An 🟥 I 5 Ca	4 An 🟥 I 4 Ca	4 An 🟥 C 9 Ca	4 An 🟩 I Ca	4 An 🟩 I 7 Ca	4 An 🟩 I 9 Ca	4 An 🟩 I 9 Ca	4 An 🟩 I 9 Ca	4 An 🟩 I 9 Cat	4 An 🟩 I 9 Ca	4 An 🟩 I 13 Ca	4 An 🟩 I 9 Cat
4340 low alloy	**8**									5 S 🟩 C 5 S	5 An 🟥 I 4 Ca	5 An 🟥 C 9 Ca	5 An 🟩 I Ca	5 An 🟩 I 7 Ca	5 An 🟩 I 9 Ca	5 An 🟩 I 9 Ca	5 An 🟩 I 9 Ca	5 An 🟩 I 9 Cat	5 An 🟩 I 9 Ca	5 An 🟩 I 13 Ca	5 An 🟩 I 9 Cat
HY80	**9**										5 An 🟥 I 4 Ca	5 An 🟥 C 9 Ca	5 An 🟩 I Ca	5 An 🟩 I 7 Ca	5 An 🟩 I 9 Ca	5 An 🟩 I 9 Ca	5 An 🟩 I 9 Ca	5 An 🟩 I 9 Cat	5 An 🟩 I 9 Ca	5 An 🟩 I 13 Ca	5 An 🟩 I 9 Cat
AA2024	**10**											4 An 🟩 C 9 Ca	4 An 🟩 I Ca	4 An 🟩 I 7 Ca	4 An 🟩 I 9 Ca	4 An 🟩 I 9 Ca	4 An 🟩 I 9 Ca	4 An 🟩 I 9 Cat	4 An 🟩 I 9 Ca	4 An 🟩 I 13 Ca	4 An 🟩 I 9 Cat
Ti 6-4	**11**												9 An 🟩 C Ca	9 An 🟥 C 7 Ca	9 An 🟥 C 9 Ca	9 An 🟥 C 9 Ca	9 An 🟥 C 9 Ca	9 An 🟥 C 9 Cat	9 An 🟥 C 9 Ca	9 An 🟥 C 13 Ca	9 An 🟥 C 9 Cat
CuBe	**12**													An 🟩 C 7 Ca	An 🟩 C 9 Ca	An 🟥 I 9 Ca	An 🟩 C 9 Ca	An 🟩 C 9 Cat	An 🟩 C 9 Ca	An 🟥 I 13 Ca	An 🟩 I 9 Cat
410 SS	**13**														7 An 🟩 C 9 Ca	7 An 🟩 C 9 Ca	7 An 🟩 C 9 Ca	7 An 🟩 C 9 Cat	7 An 🟩 C 9 Ca	7 An 🟥 I 13 Ca	7 An 🟩 C 9 Cat
Inconel	**14**															9 An 🟩 C 9 Ca	9 An 🟩 C 9 Ca	9 An 🟩 C 9 Cat	9 An 🟩 C 9 Ca	9 An 🟩 C 13 Ca	9 An 🟩 C 9 Cat
PH 13-8	**15**																9 An 🟩 C 9 Ca	9 An 🟩 C 9 Cat	9 An 🟩 C 9 Ca	9 An 🟩 C 13 Ca	9 An 🟩 C 9 Cat
Monel	**16**																	9 An 🟩 C 9 Cat	9 An 🟩 C 9 Ca	9 An 🟩 C 13 Ca	9 An 🟩 C 9 Cat
PH 13-8 Passivated	**17**																		9 An 🟩 C 9 Ca	9 An 🟩 C 13 Ca	9 An 🟩 C 9 Cat
316 SS	**18**																			9 An 🟩 C 13 Ca	9 An 🟩 C 9 Cat
Graphite	**19**																				13 An 🟩 C 9 Cat
316 SS Passivated	**20**																				

Threshold = 1.0×10^{-6}

Cat: cathodic (less reactive)
An: anodic (more reactive)



Metal 1
(left column)
Recommended Treatment

Metal 1
(left column)
more/less reactive

Metal 2
(top row)
Recommended Treatment

Metal 2
(top row)
more/less reactive

Compatibility

- **C** : **compatible** couple
- **I** : **incompatibe** couple
- 🟥 : **discrepancy** with existing MIL-STD-889C
- 🟩 : **in agreement** with existing MIL-STD-889C

Summary

- Galvanic current is a better assessment metric than galvanic potential for determining galvanic compatibility.
- A methodology was created to generate polarization data sets. The methodology was validated through a round robin test.
- A deconvolution approach was used to analyze the polarization data sets.
- The mixed potential approach to determine galvanic current is valid.
- A ranking for galvanic compatibility will be created.

Development and Validation of a Cyclic Humidity Corrosion Test

March 26th, 2019

Presented to NACE Corrosion 2019

Presented by Steven Kopitzke
on behalf of Victor Rodriguez-Santiago, Alex Lilly

Traditional ACT Fails to Replicate Representative Corrosion Severity

- What do we know?
  - Current accelerated corrosion tests (ACT) fail to replicate damage observed in field environments (e.g., ASTM B117, ASTM G85, MIL-STD-810, GMW14872, etc.).
  - In addition, current ACT is well known for chamber inconsistencies, which can be more pronounced during cyclic tests.
  - Recent studies indicate that controlling relative humidity is crucial to replicating damage, which is NOT accurately specified in current ACT.
- What can we do?
  - Better understand the individual and combined effects of environmental factors and solution chemistry on the mechanisms and severity of corrosion.
  - Better understand environment dynamic changes in order to quantify environmental severity.

Dynamic Monitoring of Corrosive Environments is Critical to Understand Corrosion Evolution

- Environmental exposure sites provide the closest correlation between corrosion degradation and damage experienced in-service, but:
  - Time-consuming
  - Not widely accessible
  - Provides cumulative data only
  - No dynamic monitoring

Outdoor Exposure of Samples by W.H. Abbott at Battelle Columbus Operations.[1]

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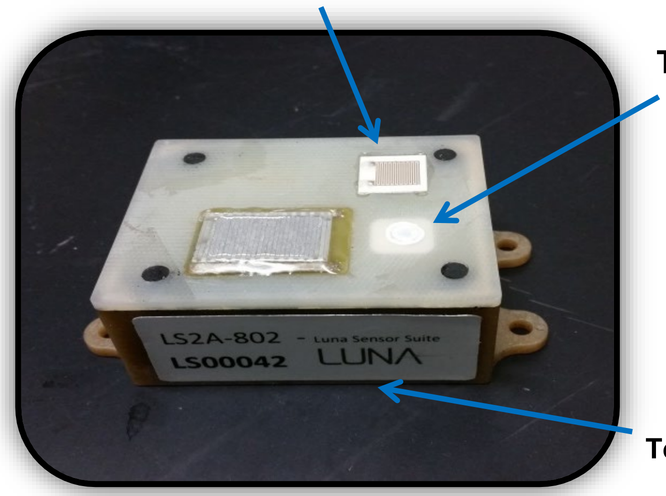
[1] *W.H. Abbott, "A Decade of Corrosion Monitoring in the World's Military Operating Environments: A Summary of Results," DoD CorrDefense, 2008.*

Dynamic Environmental Monitoring Devices Allow Correlation Between Environmental Conditions and Corrosion Severity

- Monitor environment through dynamic capture of temperature, relative humidity, and solution resistance across a gold interdigitated electrode
- No information of the sample's surface condition is necessary, i.e. salt concentration, surface contaminants, etc.
- Environmental data and statistical analysis can be used to develop an accelerated test better representative of exposure data



Gold interdigitated electrode

Air Temperature; Relative Humidity

Surface Temperature

Multi-sensor device measuring temperature, relative humidity, and solution resistance across gold interdigitated electrode.

Traditional Environmental Severity Classification Methods Fail to Reliably Classify Corrosion Severity

- ISO 9223:2012[2]
  - Classification of the corrosion severity of atmospheres on the basis of three key factors:
    - TOW (time of wetness)
      - Temperature > 0 °C
      - Relative humidity > 80%
    - Deposition rate of chlorides
    - Sulfur dioxide concentration
  - Five corrosivity classes: C1 to C5

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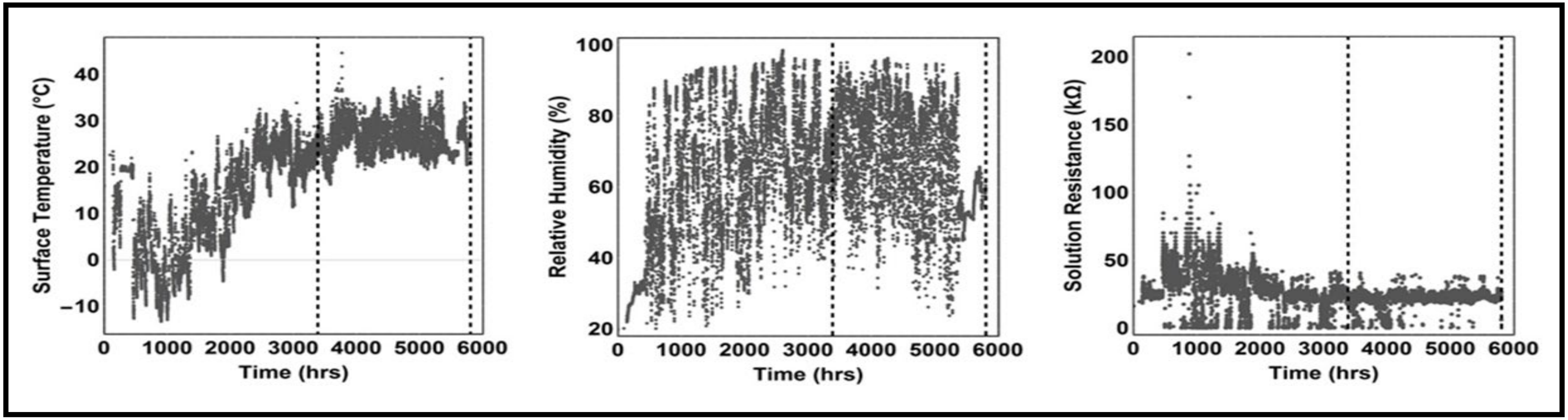
[2] ***ISO 9223, "Corrosion of Metals and Alloys – Corrosivity of Environments – Classification, Determination and Estimation" (Geneva, Switzerland: ISO, 2012).***

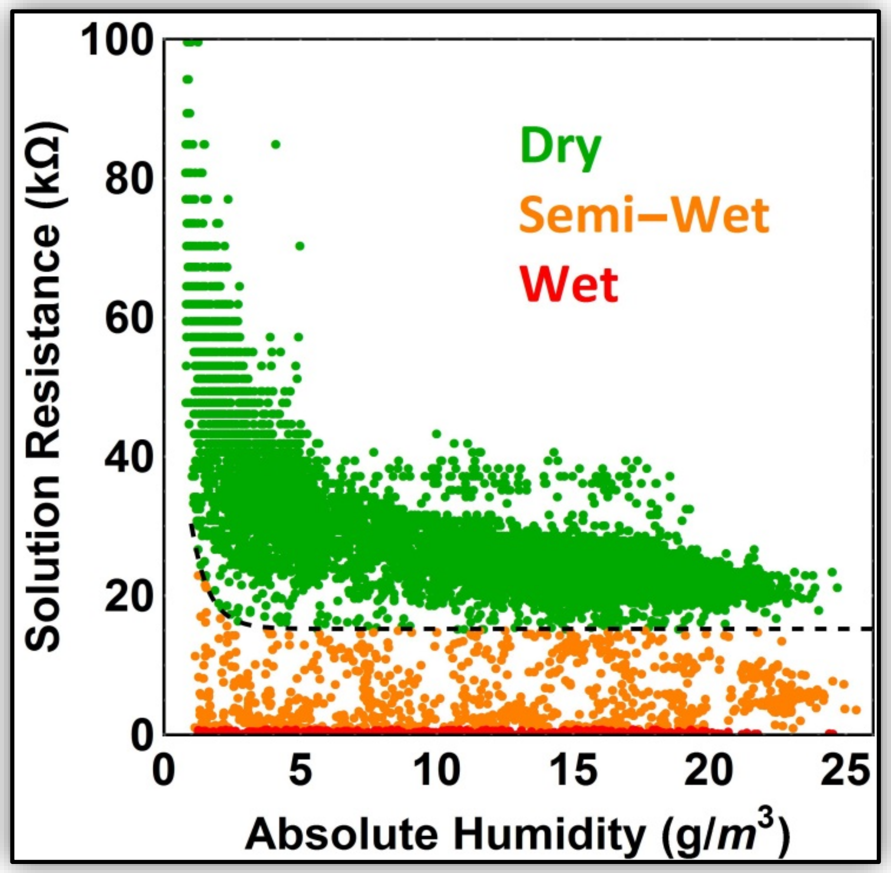
Dynamic Environmental Monitoring Allows Correlation Between Environmental Conditions and Corrosion Severity



Variables of interest are plotted as a function of time showing the oscillatory surface temperature and relative humidity behavior expected due to day/night cycles. Changes in average temperature behave as expected due to changes in seasons. Solution resistance is measured across a broad range of values. Dashed lines represent data retrieval and therefore mass loss measurements.

Statistical Methodologies Allow Correlation of Environmental Variables to Corrosion Severity

- Data collected on-board USS Wasp over 9 months.[3]
- All data falling below 819 Ω will be considered 'wet' while data contained between 819 Ω and the 'dry' solution resistance limit are considered 'semi-wet'
- From these data, number of wetness and semi-wetness events can be determined, as well as their average duration



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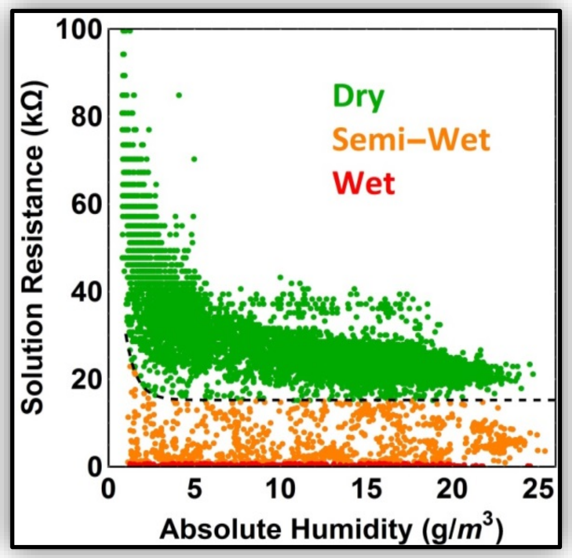
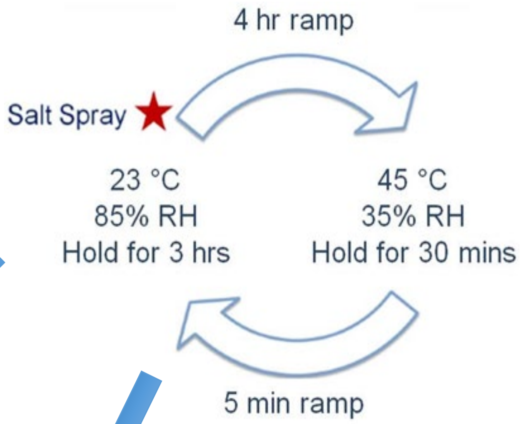
[3] *Cosima Boswell-Koller, Victor Rodriguez-Santiago, Statistical Analysis of Environmental Parameters: Correlations between Time of Wetness and Corrosion Severity, CORROSION.*

Environmental Monitoring Allows the Development of Effective Accelerated Corrosion Methods





Salt Spray ★

4 hr ramp

23 °C
85% RH
Hold for 3 hrs

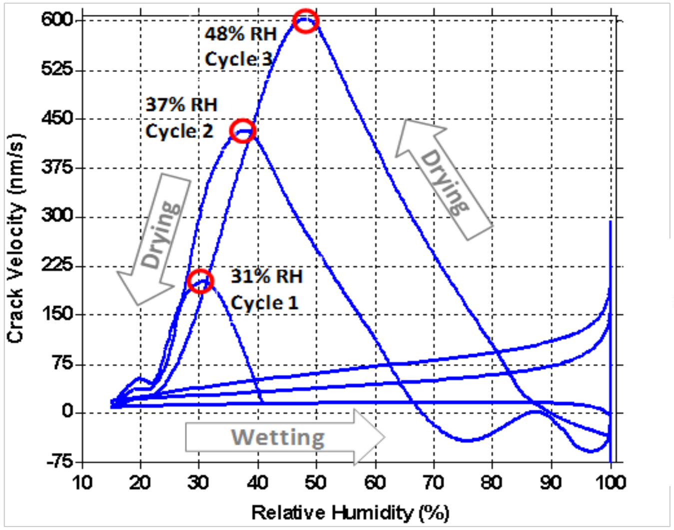
45 °C
35% RH
Hold for 30 mins

5 min ramp

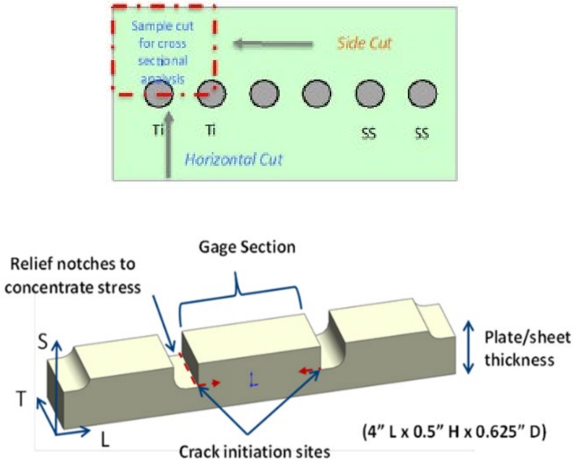
	Actual (g)	Predicted (g)	Comparison to Environmental Exposure
Al 7075	0.0044 g	0.0038 g	4/9 mass loss in 1/30 time
1020 CS	0.1457 g	0.15 g	1/4 mass loss in 1/30 time

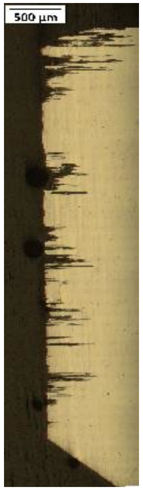
Lessons Learned: Relative Humidity and Solution Chemistry Control Corrosion Severity and Mechanism

- The proposed methodology was developed through SERDP WP-1673.[4]
- ***Main concept*: Relative humidity (RH) cycling is a major factor in controlling corrosion damage and mechanism.**



Sensitized AA5083 in modified ASTM G85-A5.





Pt. Judith
7075-T6
Al/SS
12 months

G85-A5
7075-T6
Al/SS
1,000 hrs

Experiment 1
7075-T6
Al/SS
1,000 hrs

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[4] ***James Dante, Accelerated Dynamic Corrosion Test Method Development, SERDP Project WP-1673.***

Degradation Mechanisms are Dependent on Relative Humidity Cycling

Accelerated Test Cycle Conditions

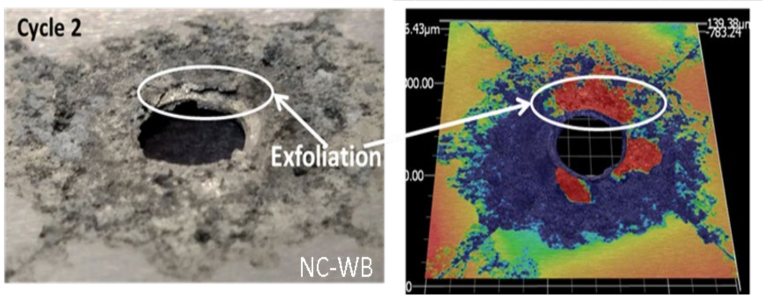
- **T = 49° C**
- **TOW = 67% of total exposure time**
- **Salt deposition: 0.6M NaCl, pH = 3, salt dip = 15 min**

	Cycle 1	Cycle 2	Cycle 3
Max RH	90%	90%	90%
Min RH	40%	65%	40%
Max RH Time (hr)	2	2	8
Min RH Time (hr)	1	1	4
Salt Dip Frequency (per wk)	1	1	1

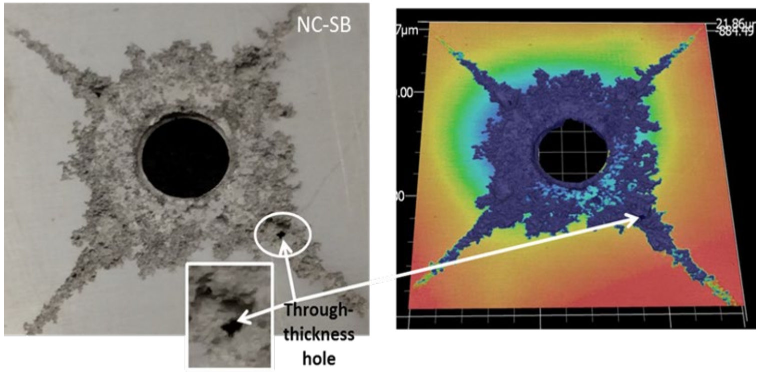
Effect of degree of drying

Effect of frequency of cycles and high RH dwell time

- **Cycle 1:** Very shallow damage restricted to the uppermost surface layer.
- **Cycle 2:** Exfoliation, extensive coating delamination and material volume loss.



- **Cycle 3:** Deep corrosion trenches along fastener and significant pitting.



Technical Approach: Specific Variables Allow for Tunable Environmental Corrosion Severity

- Main parameters affecting corrosion:
  - **Relative Humidity** – defines periods when active electrolyte exists
  - **Relative Humidity Duty Cycle** – determines attack morphology
  - **Electrolyte chemistry and deposition rate** – determines degree of attack

- The innovative aspect of this methodology is the control of cyclic variation of relative humidity and the periodic salt deposition of salt solution within each cycle.

- Traditional cyclic tests do not include this degree of control, limiting their usefulness and introducing a high degree of variation in test results.

- The degree of detail in knowledge of the role of humidity cycling control has been gained only within the last 5 years.

Task 1: Optimization of Cycle Period

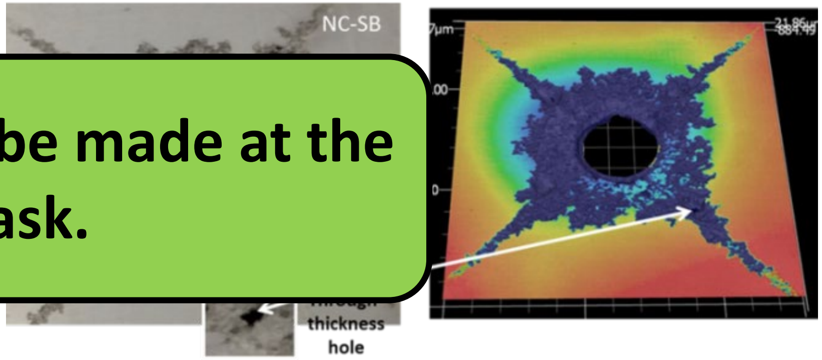
- **2 chemistries and 3 RH cycles will be tested.**

Proposed Chemistries*

Reagent	g/L (Reagent) NE#1	g/L (Reagent) NE#2
NaCl	24.53	22.26
$MgCl_2.6H_2O$	11.10	11.10
Na_2SO_4	4.00	4.00
$NaNO_3$	0	
HCl (1N)	(1	

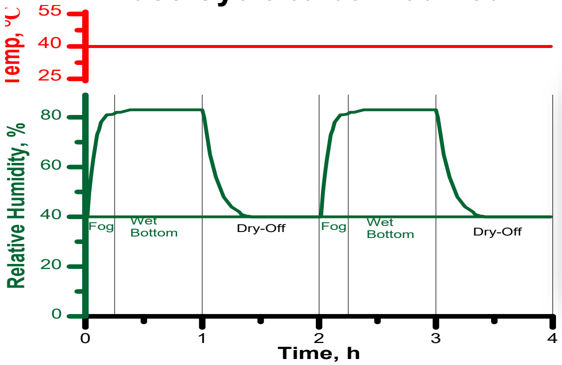
***Normalized to ionic stren**

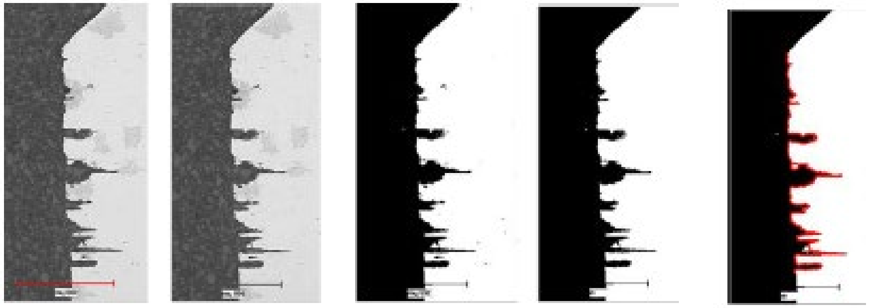
- **Ordinal rankings of coating performance and environmental severity will generated through image analysis of 3-D optical images.**



Go/No-Go decision will be made at the end of this task.

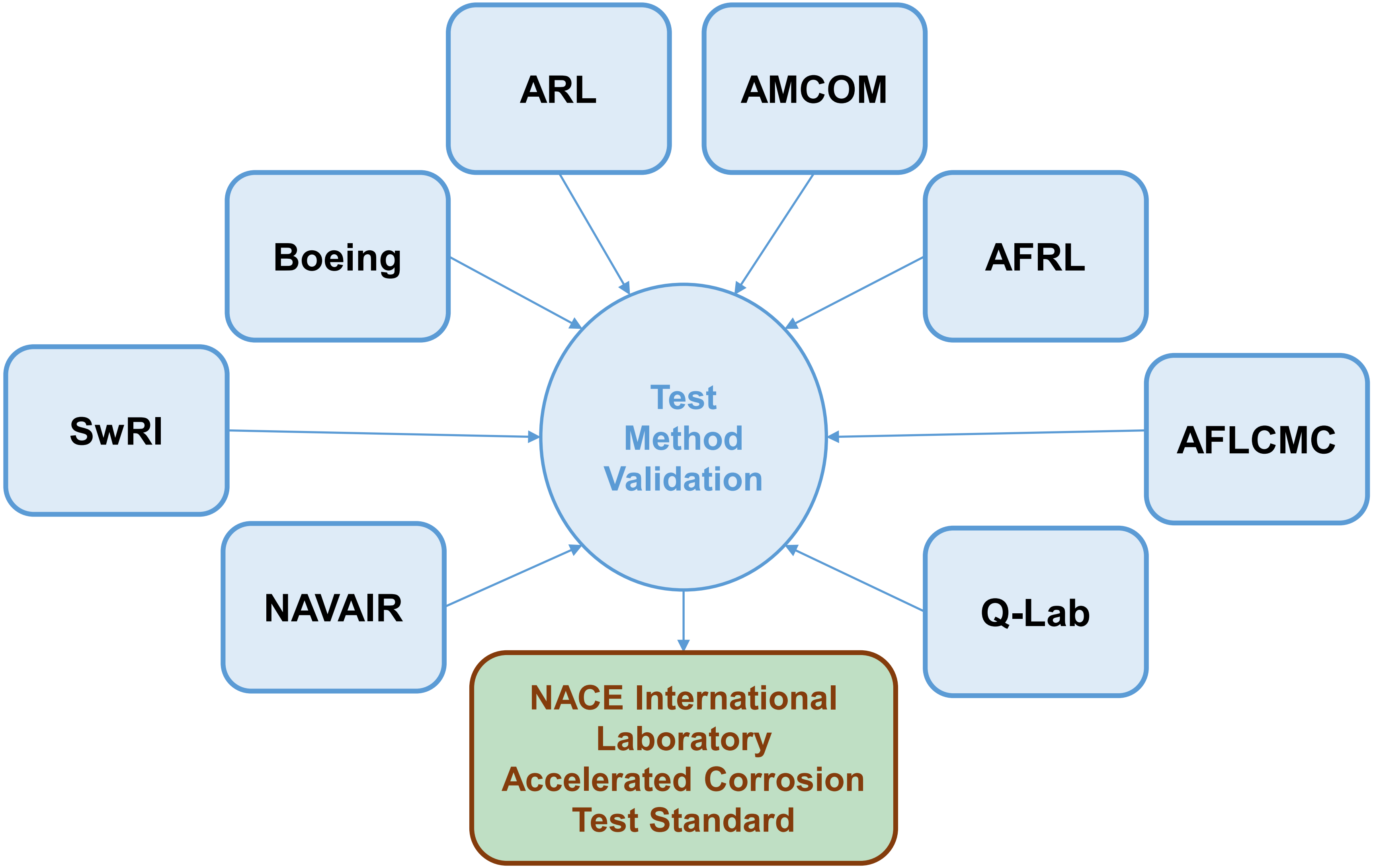
Base Cycle to be Modified





Original Image | Grayscale | Threshold applied | Unconnected areas removed | Border detected

Task 2: Round Robin Testing



ARL

AMCOM

Boeing

AFRL

SwRI

Test Method Validation

AFLCMC

NAVAIR

Q-Lab

NACE International Laboratory Accelerated Corrosion Test Standard

Task 3: Standard Development & Acceptance

- The **objective** of this task is to **formalize** the test procedure into a NACE International laboratory accelerated corrosion **test standard**.
- A society standard offers several advantages over a MIL-STD:
  - OEMs can participate in development and drafting of the standard, thus reducing resistance to acceptance.
  - Society standards require revisions every three to five years. This means the standard can be updated as new technical developments are made.
  - If DoD components wanted a MIL-STD version, it is easier to convert a pre-vetted standard.
- The approach is to create a NACE Task Group (TG) within STG 41 (Electric Utility Generation, Transmission, and Distribution) to drive the development of the specification.
- Victor Rodriguez-Santiago (PI, NAVAIR), Sean Fowler (Q-Lab), James Dante (SwRI, PI from WP-1673) and Kris Williams (Boeing, Key personnel on WP-2521) will serve on the TG as representatives from this ESTCP effort.
- The front end of the specification will define the overall testing approach.
- Specific environmental test cycles will be included within the annex section of the specification.
- Because of the flexible nature of the specification, additional annexes can be created to include other types of environments

Summary

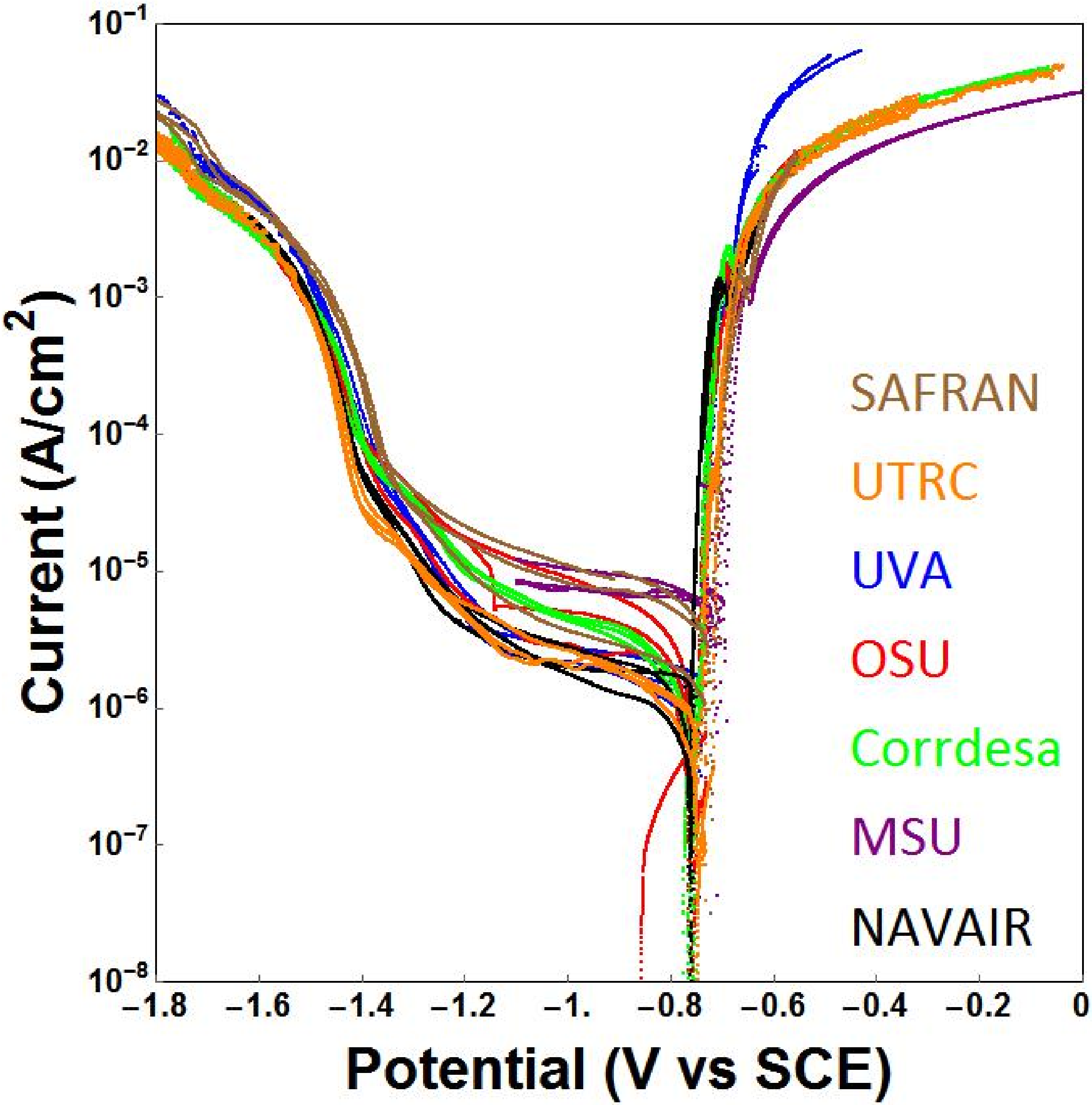
- Dynamic environmental monitoring devices and subsequent data analysis methodologies allow correlation between environmental conditions and corrosion severity.
- Dynamic environmental monitoring allows for development of effective accelerated corrosion test methodologies which replicate corrosion severity of outdoor field exposures.
- The combination of effects observed from varying solution chemistries, time of wetness, and drying to wetting time ratios may allow for full tunable corrosion severity.
- Corrosion severity and mechanisms will be quantified using 3-D image analysis.
- The present work aims to develop a more representative and repetitive accelerated corrosion test standard through inter-laboratory collaboration.

References

1. W.H. Abbott, “A Decade of Corrosion Monitoring in the World’s Military Operating Environments: A Summary of Results,” DoD CorrDefense, 2008.
2. ISO 9223, “Corrosion of Metals and Alloys – Corrosivity of Environments – Classification, Determination and Estimation” (Geneva, Switzerland: ISO, 2012).
3. Cosima Boswell-Koller, Victor Rodriguez-Santiago, Statistical Analysis of Environmental Parameters: Correlations between Time of Wetness and Corrosion Severity, CORROSION.
4. James Dante, Accelerated Dynamic Corrosion Test Method Development, SERDP Project WP-1673.

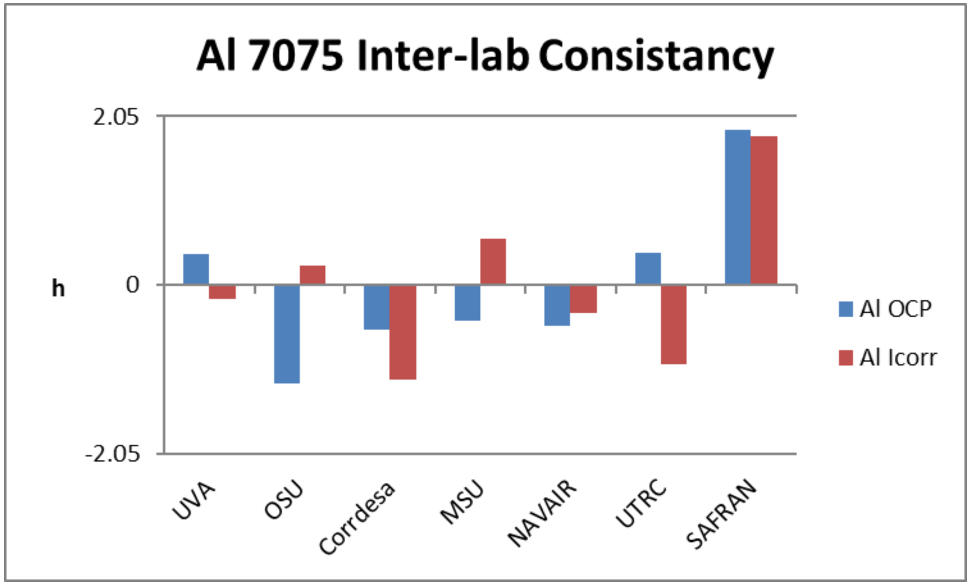
Backup Slides

Round Robin: Combined Al 7075

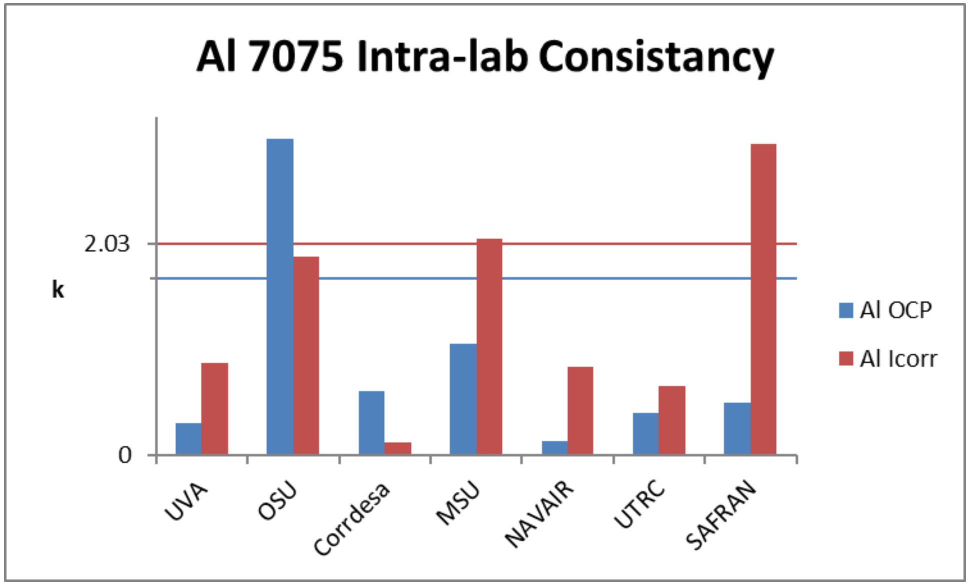


Round Robin Statistics: Al7075

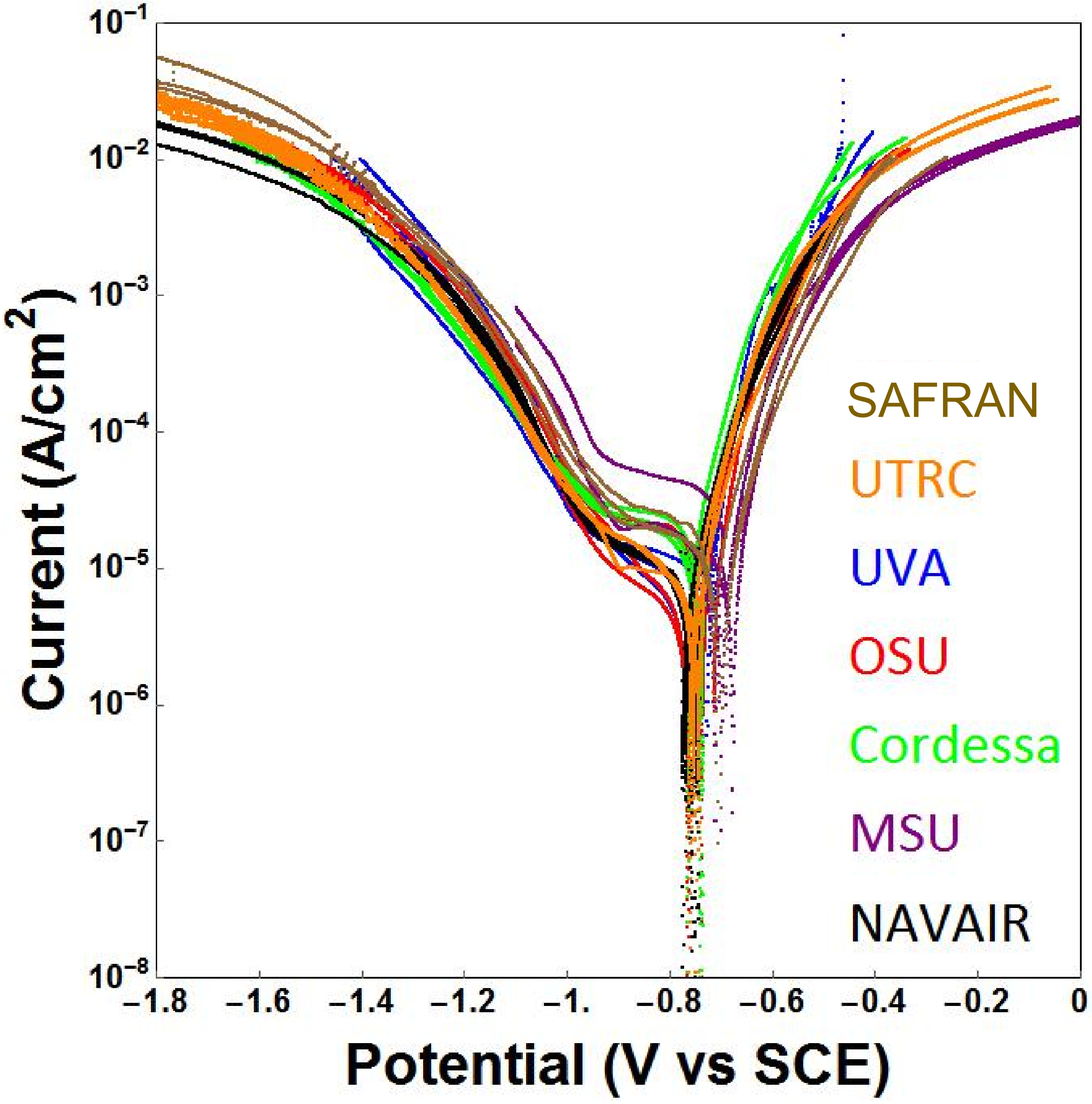
Inter-lab statistics: indicator of how one laboratory's cell average, for a particular material, compares with the average of the other laboratories (n = 7).



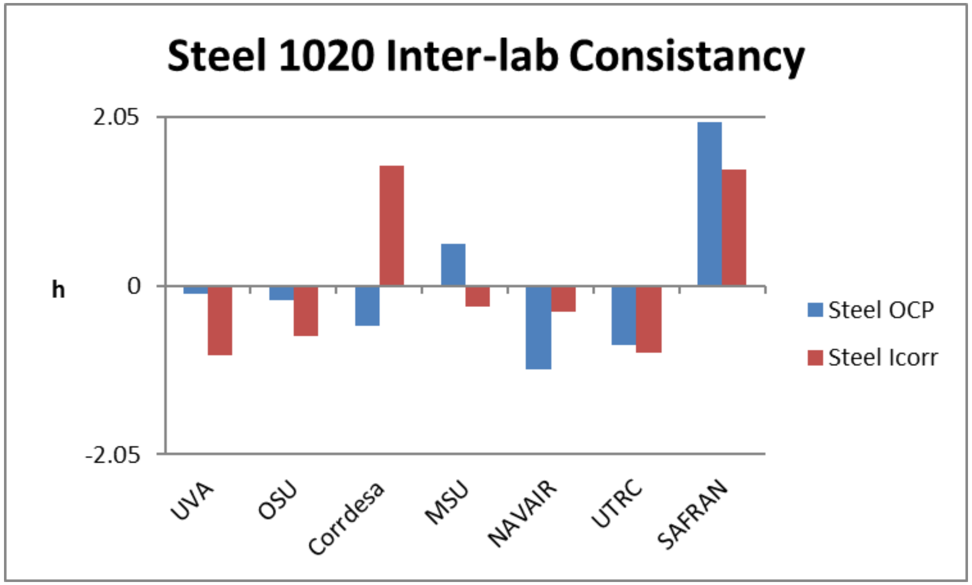
Intra-lab statistics: an indicator of how one laboratory's within-laboratory variability, under repeatability conditions (n = 3), on a particular material, compares with all of the laboratories combined (n = 7).

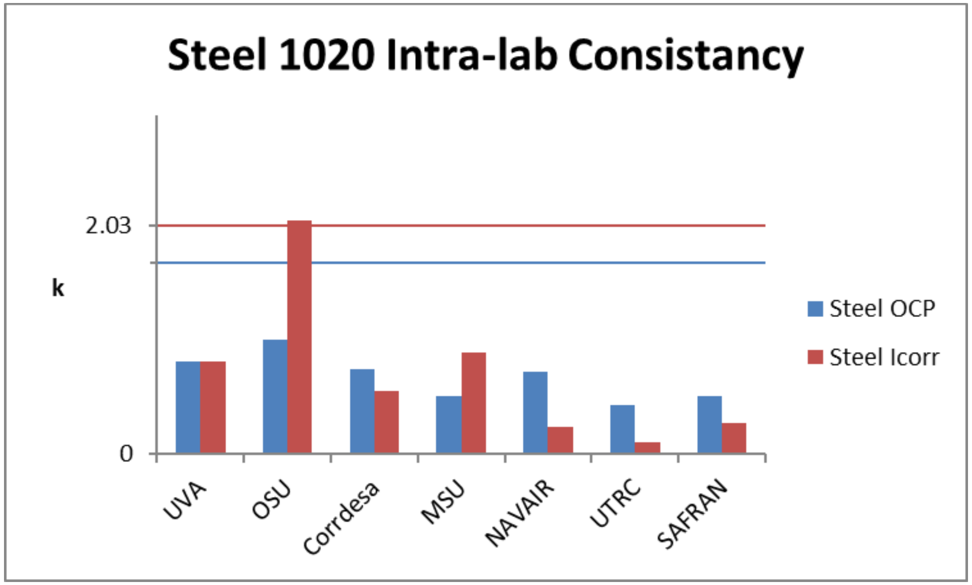


Round Robin: Combined Steel 1020

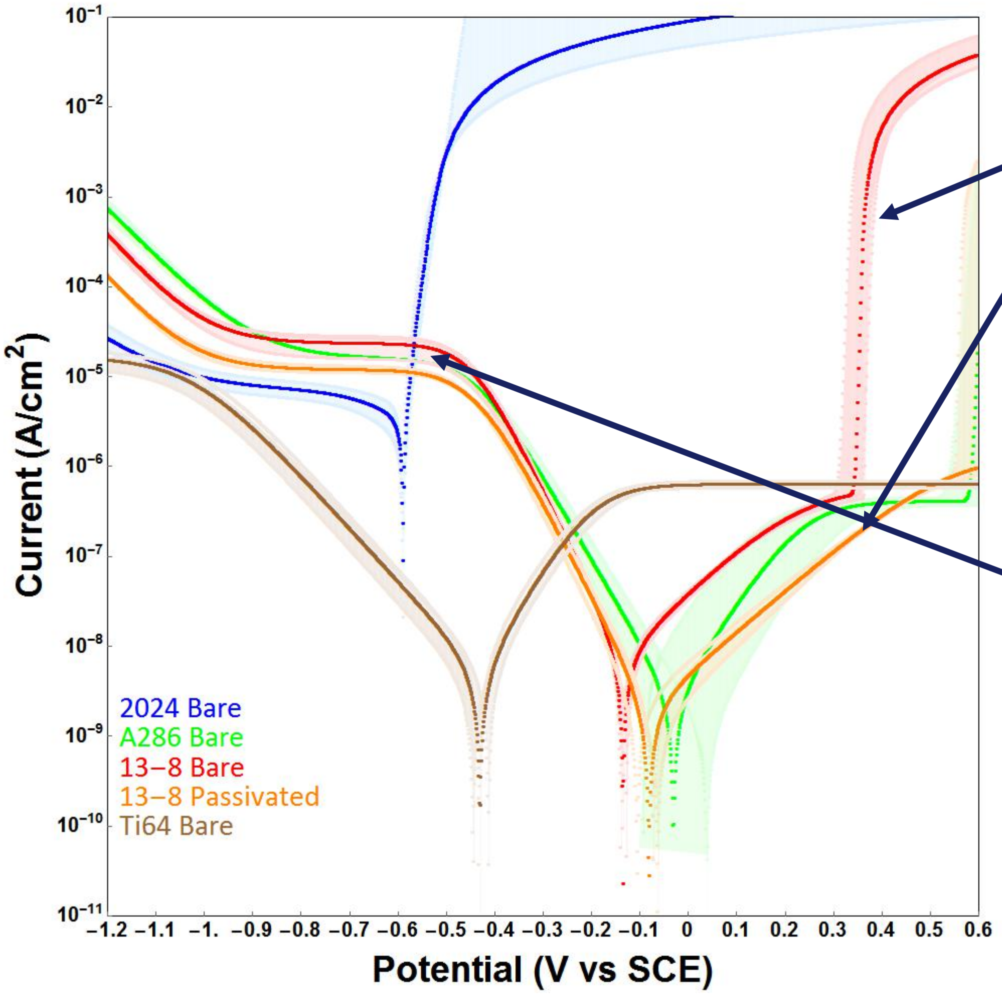


Round Robin Statistics: Steel 1020





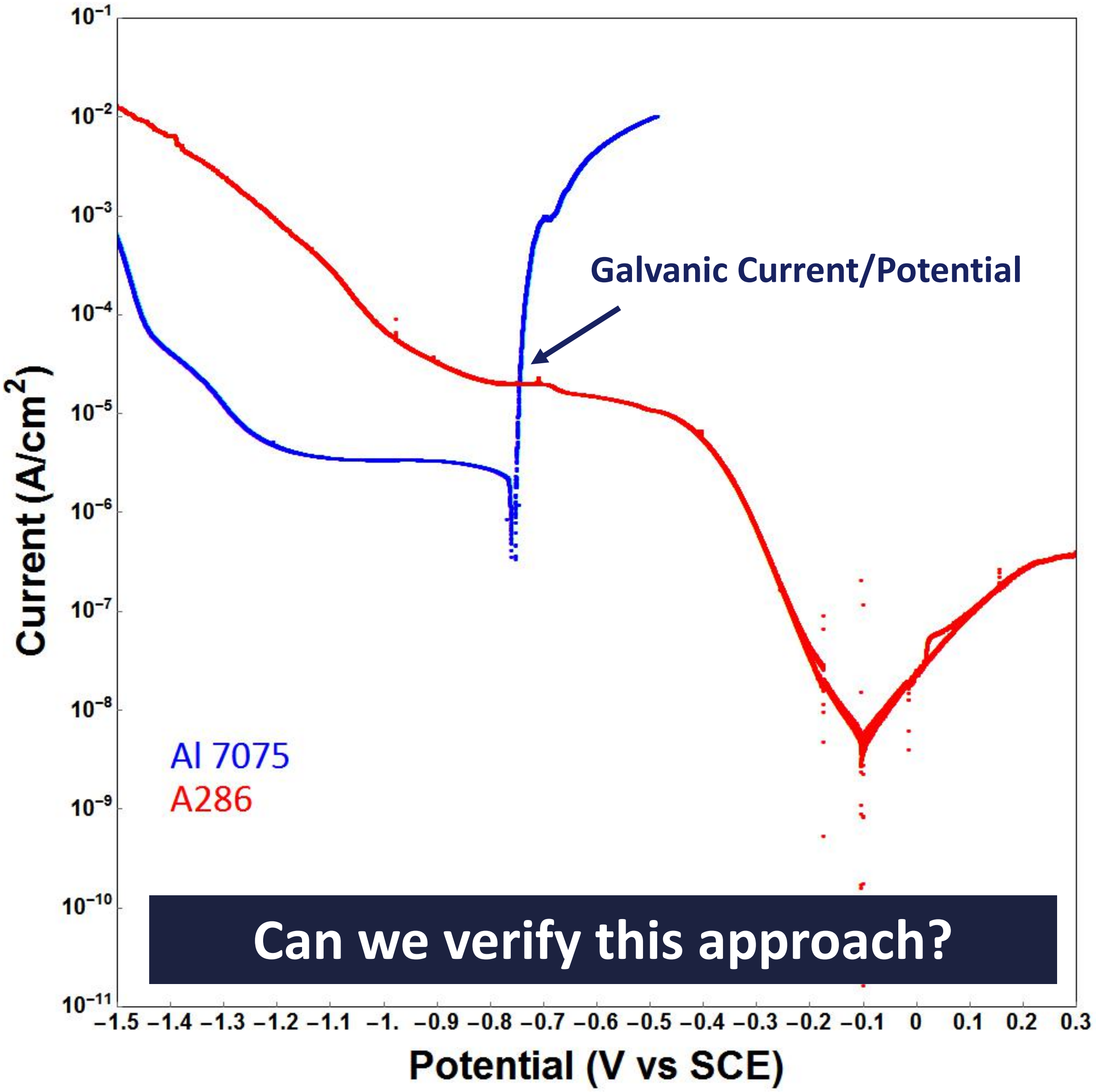
Mixed Potentials with Data Variation



Passivation helps with the self corrosion and anodic behavior but…..

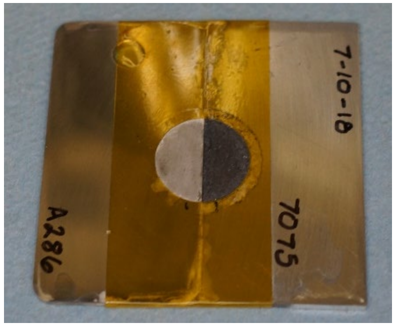
…it does not hinder cathodic behavior.

Mixed Potential Approach to Galvanic Current

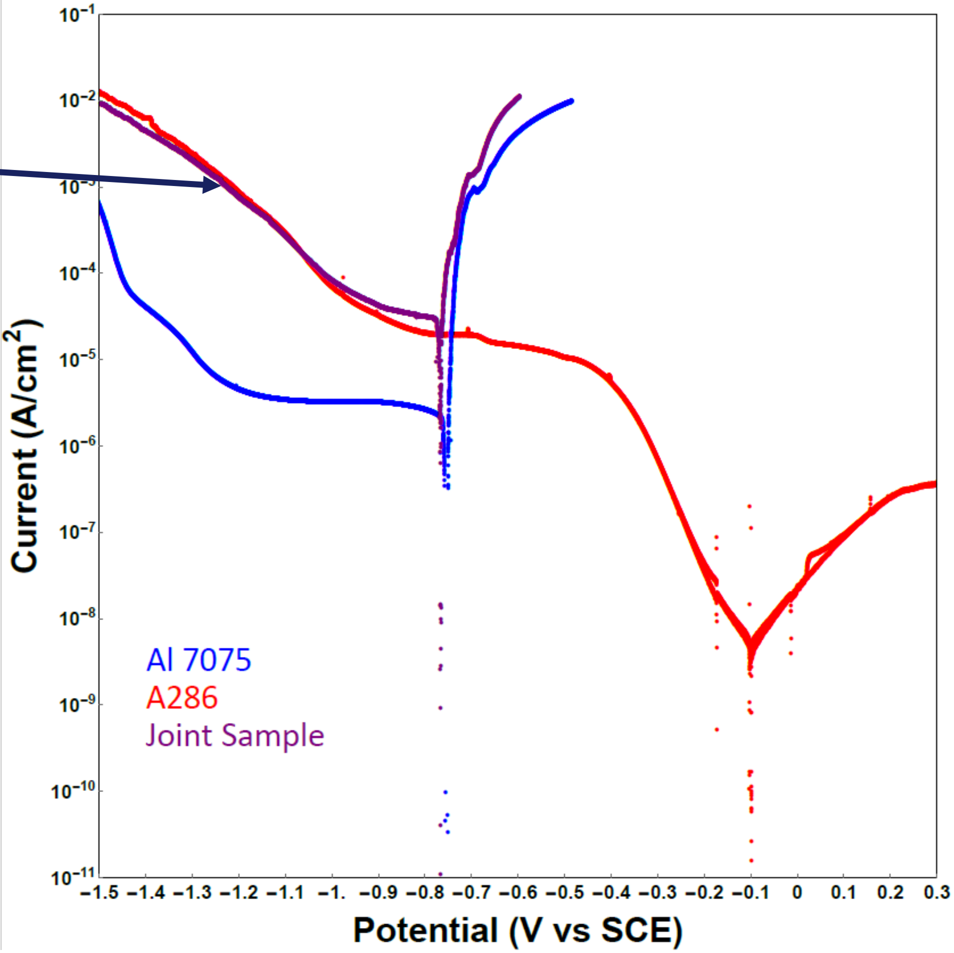


Can we verify this approach?

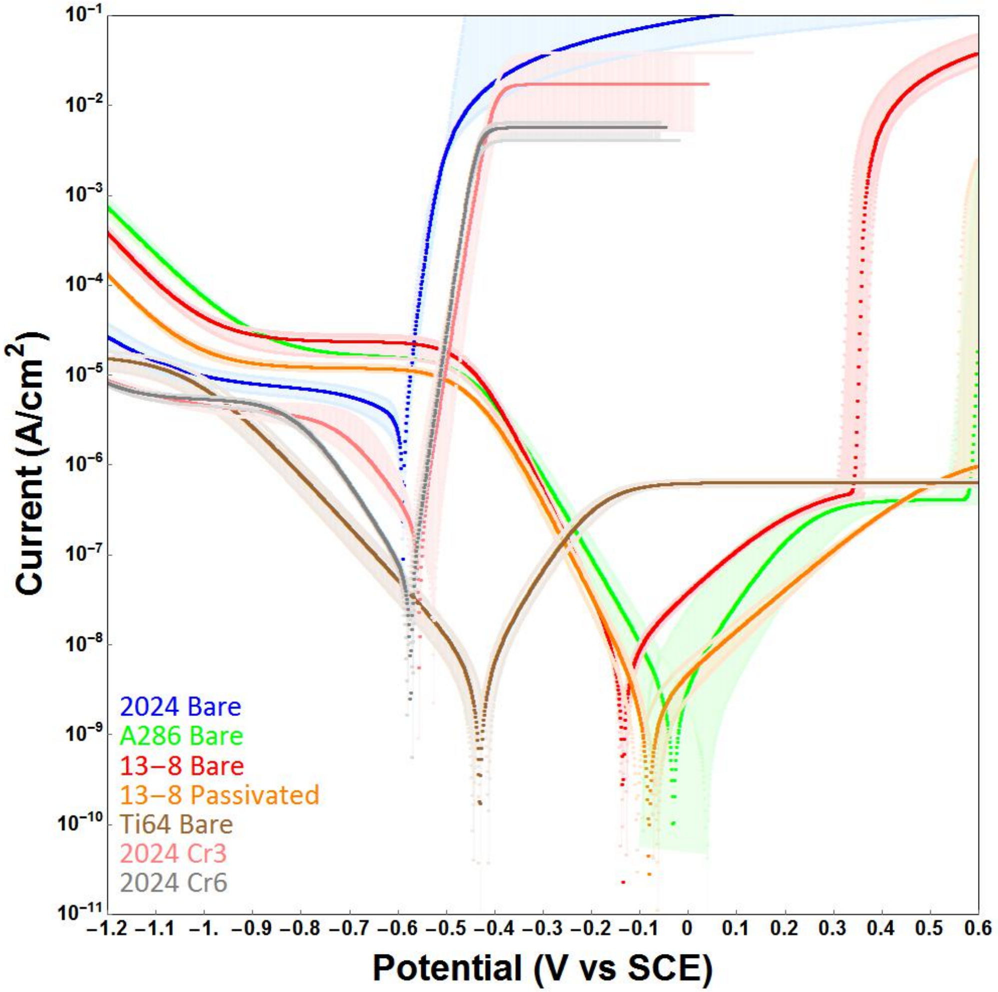
Validating Mixed Potential Approach



Joint sample gives mixed potential curve.



Effect of Conversion Coating



Conversion coatings do not offer a galvanic benefit but can cause severe localized damage when breached. The same applies to anodization.

Galvanic Table – New Methodology (Mid)

		Mg WE43	AA5083	ZnNi w/ conv. coat.	Cd w/ conv. coat.	A356 cast Al	1020 low alloy	AA7075	4340 low alloy	HY80	AA2024	Ti 6-4	CuBe	410 SS	Inconel	PH 13-8	Monel	PH 13-8 Passivated	316 SS	Graphite	316 SS Passivated
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Mg WE43	1		1 An – I 🟩 – 4 Cat	1 An – I 🟩 – Cat	1 An – I 🟩 – 3 Cat	1 An – I 🟩 – 4 Cat	1 An – I 🟩 – 5 Cat	1 An – I 🟩 – 4 Cat	1 An – I 🟩 – 5 Cat	1 An – I 🟩 – 5 Cat	1 An – I 🟩 – 4 Cat	1 An – I 🟩 – 9 Cat	1 An – I 🟩 – Cat	1 An – I 🟩 – 7 Cat	1 An – I 🟩 – 9 Cat	1 An – I 🟩 – 9 Cat	1 An – I 🟩 – 9 Cat	1 An – I 🟩 – 9 Cat	1 An – I 🟩 – 9 Cat	1 An – I 🟩 – 13 Cat	1 An – C 🟥 – 9 Cat
AA5083	2			4 An – I 🟥 – Cat	4 An – I 🟥 – 3 Cat	4 An – I 🟥 – 4 Cat	4 An – I 🟥 – 5 Cat	4 An – I 🟥 – 4 Cat	4 An – I 🟩 – 5 Cat	4 An – I 🟩 – 5 Cat	4 An – I 🟩 – 4 Cat	4 An – I 🟩 – 9 Cat	4 An – I 🟩 – Cat	4 An – I 🟩 – 7 Cat	4 An – I 🟩 – 9 Cat	4 An – I 🟩 – 9 Cat	4 An – I 🟩 – 9 Cat	4 An – I 🟩 – 9 Cat	4 An – I 🟩 – 9 Cat	4 An – I 🟩 – 13 Cat	4 An – I 🟩 – 9 Cat
ZnNi w/ conv. coat.	3				An – I 🟥 – 3 Cat	An – I 🟥 – 4 Cat	An – I 🟥 – 5 Cat	An – I 🟥 – 4 Cat	An – I 🟥 – 5 Cat	An – I 🟥 – 5 Cat	An – I 🟩 – 4 Cat	An – I 🟩 – 9 Cat	An – I 🟩 – Cat	An – I 🟩 – 7 Cat	An – I 🟩 – 9 Cat	An – I 🟩 – 9 Cat	An – C 🟥 – 9 Cat	An – I 🟩 – 9 Cat	An – I 🟩 – 9 Cat	An – I 🟩 – 13 Cat	An – I 🟩 – 9 Cat
Cd w/ conv. Coat.	4					3 An – I 🟥 – 4 Cat	3 An – I 🟥 – 5 Cat	3 An – I 🟥 – 4 Cat	3 An – I 🟥 – 5 Cat	3 An – I 🟥 – 5 Cat	3 An – I 🟥 – 4 Cat	3 An – C 🟥 – 9 Cat	3 An – I 🟩 – Cat	3 An – I 🟩 – 7 Cat	3 An – C 🟥 – 9 Cat	3 An – I 🟩 – 9 Cat	3 An – C 🟥 – 9 Cat	3 An – C 🟥 – 9 Cat	3 An – C 🟥 – 9 Cat	3 An – I 🟩 – 13 Cat	3 An – I 🟩 – 9 Cat
A356 cast Al	5						4 An – I 🟥 – 5 Cat	4 An – I 🟥 – 4 Cat	4 An – I 🟥 – 5 Cat	4 An – I 🟥 – 5 Cat	4 An – I 🟥 – 4 Cat	4 An – C 🟥 – 9 Cat	4 An – I 🟩 – Cat	4 An – I 🟩 – 7 Cat	4 An – I 🟩 – 9 Cat	4 An – I 🟩 – 9 Cat	4 An – C 🟥 – 9 Cat	4 An – I 🟩 – 9 Cat	4 An – I 🟩 – 9 Cat	4 An – I 🟩 – 13 Cat	4 An – I 🟩 – 9 Cat
1020 low alloy	6							5 An – I 🟥 – 4 Cat	5 An – I 🟥 – 5 Cat	5 An – I 🟥 – 5 Cat	5 An – I 🟥 – 4 Cat	5 An – I 🟩 – 9 Cat	5 An – I 🟩 – Cat	5 An – I 🟩 – 7 Cat	5 An – I 🟩 – 9 Cat	5 An – I 🟩 – 9 Cat	5 An – I 🟩 – 9 Cat	5 An – I 🟩 – 9 Cat	5 An – I 🟩 – 9 Cat	5 An – I 🟩 – 13 Cat	5 An – I 🟩 – 9 Cat
AA7075	7								4 An – I 🟥 – 5 Cat	4 An – I 🟥 – 5 Cat	4 An – I 🟥 – 4 Cat	4 An – C 🟥 – 9 Cat	4 An – I 🟩 – Cat	4 An – I 🟩 – 7 Cat	4 An – I 🟩 – 9 Cat	4 An – I 🟩 – 9 Cat	4 An – I 🟩 – 9 Cat	4 An – I 🟩 – 9 Cat	4 An – I 🟩 – 9 Cat	4 An – I 🟩 – 13 Cat	4 An – I 🟩 – 9 Cat
4340 low alloy	8									5 S – C 🟩 – 5 S	5 An – I 🟥 – 4 Cat	5 An – C 🟥 – 9 Cat	5 An – I 🟩 – Cat	5 An – I 🟩 – 7 Cat	5 An – I 🟩 – 9 Cat	5 An – I 🟩 – 9 Cat	5 An – I 🟩 – 9 Cat	5 An – I 🟩 – 9 Cat	5 An – I 🟩 – 9 Cat	5 An – I 🟩 – 13 Cat	5 An – I 🟩 – 9 Cat
HY80	9										5 An – I 🟥 – 4 Cat	5 An – C 🟥 – 9 9	5 An – I 🟩 – Cat	5 An – I 🟩 – 7 Cat	5 An – I 🟩 – 9 Cat	5 An – I 🟩 – 9 Cat	5 An – I 🟩 – 9 Cat	5 An – I 🟩 – 9 Cat	5 An – I 🟩 – 9 Cat	5 An – I 🟩 – 13 Cat	5 An – I 🟩 – 9 Cat
AA2024	10											4 An – C 🟩 – Cat	4 An – I 🟩 – Cat	4 An – I 🟩 – 7 Cat	4 An – I 🟩 – 9 Cat	4 An – I 🟩 – 9 Cat	4 An – I 🟩 – 9 Cat	4 An – I 🟩 – 9 Cat	4 An – I 🟩 – 9 Cat	4 An – I 🟩 – 13 Cat	4 An – I 🟩 – 9 Cat
Ti 6-4	11												9 An – C 🟩 – Cat	9 An – I 🟩 – 7 Cat	9 An – I 🟩 – 9 Cat	9 An – I 🟩 – 9 Cat	9 An – C 🟥 – 9 Cat	9 An – I 🟩 – 9 Cat	9 An – I 🟩 – 9 Cat	9 An – I 🟩 – 13 Cat	9 An – I 🟩 – 9 Cat
CuBe	12													An – C 🟩 – 7 Cat	An – C 🟩 – 9 Cat	An – I 🟥 – 9 Cat	An – C 🟩 – 9 Cat	An – C 🟩 – 9 Cat	An – C 🟩 – 9 Cat	An – I 🟥 – 13 Cat	An – I 🟩 – 9 Cat
410 SS	13														7 An – C 🟩 – 9 Cat	7 An – C 🟩 – 9 Cat	7 An – C 🟩 – 9 Cat	7 An – C 🟩 – 9 Cat	7 An – C 🟩 – 9 Cat	7 An – I 🟥 – 13 Cat	7 An – C 🟩 – 9 Cat
Inconel	14															9 An – C 🟩 – 9 Cat	9 An – C 🟩 – 9 Cat	9 An – C 🟩 – 9 Cat	9 An – C 🟩 – 9 Cat	9 An – C 🟩 – 13 Cat	9 An – C 🟩 – 9 Cat
PH 13-8	15																9 An – C 🟩 – 9 Cat	9 An – C 🟩 – 9 Cat	9 An – C 🟩 – 9 Cat	9 An – C 🟩 – 13 Cat	9 An – C 🟩 – 9 Cat
Monel	16																	9 An – C 🟩 – 9 Cat	9 An – C 🟩 – 9 Cat	9 An – C 🟩 – 13 Cat	9 An – C 🟩 – 9 Cat
PH 13-8 Passivated	17																		9 An – C 🟩 – 9 Cat	9 An – C 🟩 – 13 Cat	9 An – C 🟩 – 9 Cat
316 SS	18																			9 An – C 🟩 – 13 Cat	9 An – C 🟩 – 9 Cat
Graphite	19																				13 An – C 🟩 – 9 Cat
316 SS Passivated	20																				

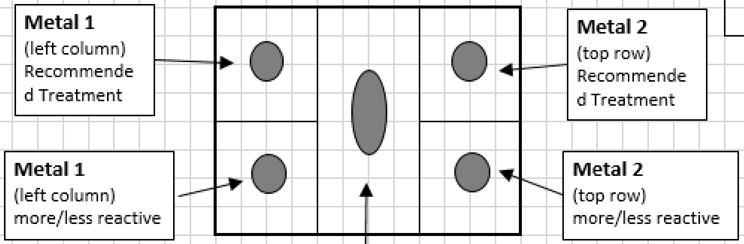
Active

OPC

Passive

Threshold $= 5.0\text{x}10^{-7}$

Cat: cathodic (less reactive)
An: anodic (more reactive)



Metal 1
(left column)
Recommended Treatment

Metal 2
(top row)
Recommended Treatment

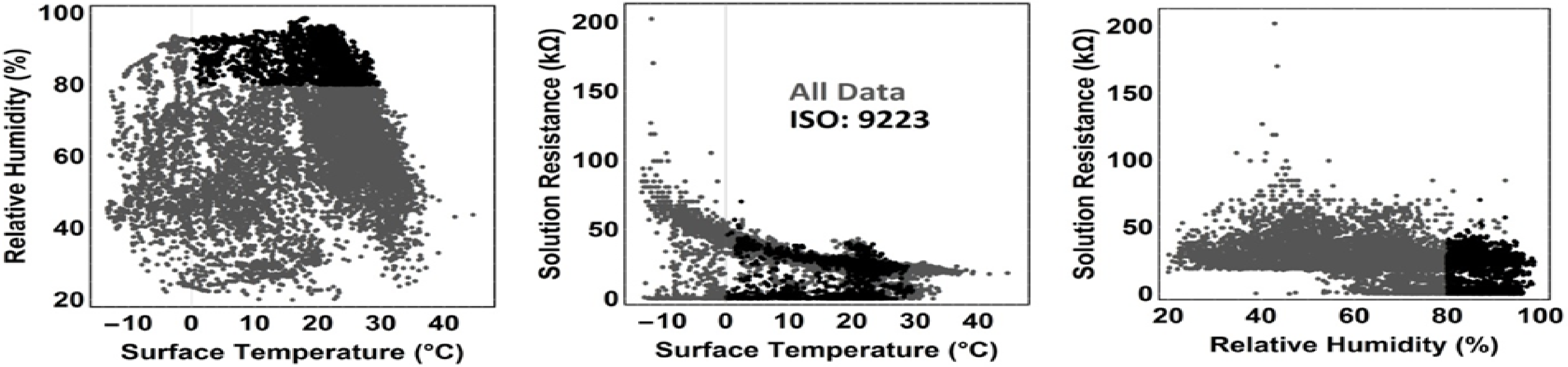
Metal 1
(left column)
more/less reactive

Metal 2
(top row)
more/less reactive

Compatibility

- **C** : **compatible** couple
- **I** : **incompatibe** couple
- 🟥 : **discrepancy** with existing MIL-STD-889C
- 🟩 : **in agreement** with existing MIL-STD-889C

ISO Classification vs. SR Classification



The complete data set is shown in dark gray, while those data points consistent with ISO 9233 (T > 0 ° C and RH > 80%) are shown in black. The ISO data points are found to vary over a broad range of solution resistance values, while being expected to be found at low SR values, due to an increased conductivity.

Absolute Humidity Calculation

- Ideal gas law: $PV=nRT$
- Apply ideal gas law to a water vapor system:

$$e_v V = m_v R_v T,$$

e_v is the vapor pressure
V is the unit volume of air
m_v is the mass of water vapor
R_v is the specific gas constant of water vapor
T is the absolute temperature

- Define the relative (H_R) and absolute (H) humidity:

$$H_R = \frac{e_v}{e_s} \qquad H = \frac{m_v}{V},$$

e_s is the saturation vapor pressure

- Rearranging: $H = \frac{1}{R_v} \cdot H_R \cdot \frac{e_s}{T}$

- Goff-Gratch equation: temperature dependent saturation vapor pressure over liquid water (valid over temperature range of -50 to 100 °C) [5]:

$$\mathrm{Log}_{10}\, e_s = -7.90298\,(373.16/T-1) + 5.02808\,\mathrm{Log}_{10}(373.16/T) - 1.3816\;10^{-7}\,(10^{11.344\,(1-T/373.16)} -1) + 8.1328\;10^{-3}\,(10^{-3.49149\,(373.16/T-1)} -1) + \mathrm{Log}_{10}(1013.246)$$

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[4] ***O.O. Parish and T.W. Putnam, (1977), Equations for the Determination of Humidity from Dewpoint and Psychrometric Data, NASA Technical Note D-8401.***

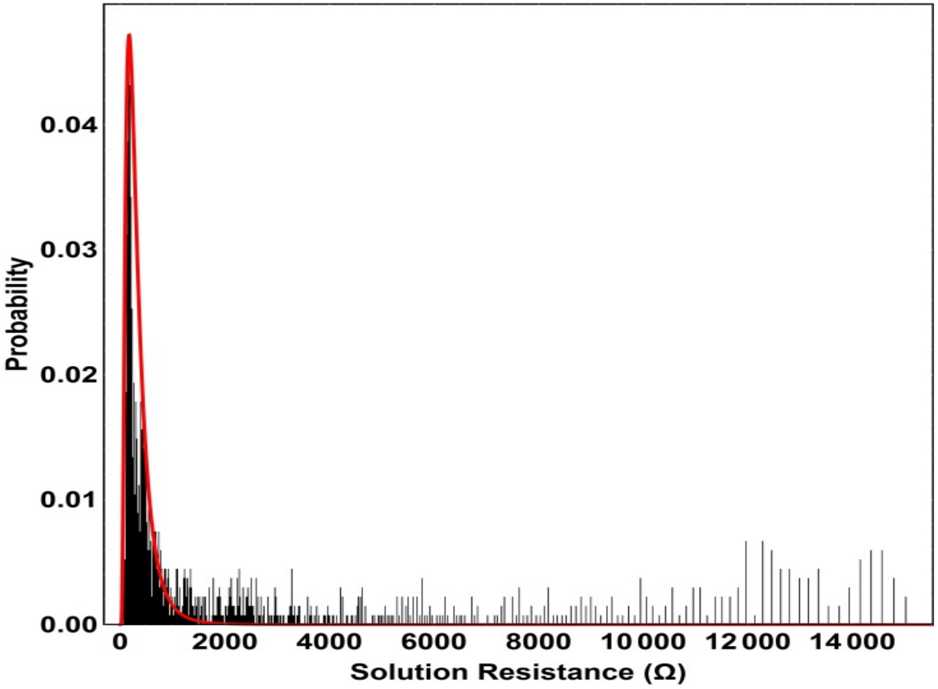
[5] **Goff, J. A., and S. Gratch (1946), Low-pressure properties of water from -160 to 212 ° F, Transactions of the Amer. Society of Heating and Ventilating Engineers, pp 95-122.**

Data Analysis: Wet Data

- Plot histogram of the 'non-dry' solution resistances
- Bin width optimization:

  bin width = 19 Ω
- Log-normal distribution function fit to probability density of the data
- Upper SR limit is determined that captures 95% of the data cumulative distribution function

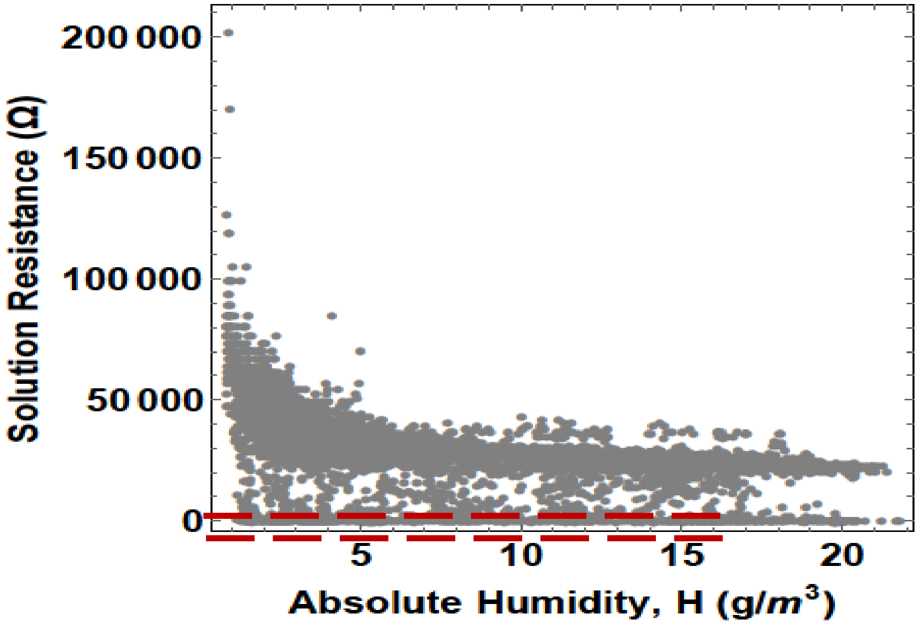
  Upper SR limit = 819 Ω



Probability histogram of 'non-dry' data (bin width = 19 Ω). Log normal distribution function fit shown in red. 95% of area under curve found at SR-values less than 819 Ω.

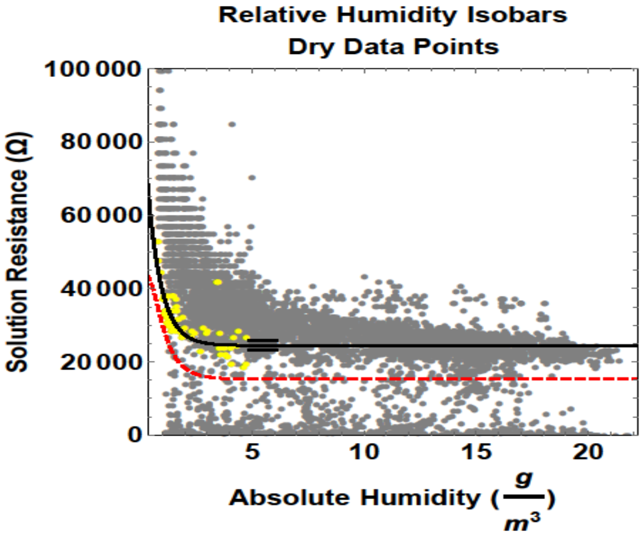
Data Analysis

- All collected data were transformed to absolute humidity scale to simultaneously take into account both temperature and relative humidity
- Again, three distinct regimes are visible
- Further analysis will consider 'dry', 'semi-wet', and 'wet' solution resistance readings



Collected data set has been transformed to absolute humidity plotted vs solution resistance.

Data Analysis



- Lowest RH readings: 20-25 %
- Initial value:

  $\{H^{init}, SR^{init}\} = \{4.88224\ g/m^3, 24{,}497\ \Omega\}$

- Fit data to exponential function:

  $$SR(H) = c + a\, e^{-k\,H}$$

- Line of best fit:

  $$SR(H) = 24{,}469 + 76{,}014.6\, e^{-1.61963\,H}$$

- 95% confidence interval band
- All data falling below the dashed line are now considered 'non-dry'

Mass Loss Prediction Calculations: 1020 Steel

- Assumptions:
  - Witness coupons experience nominally **same environment** as sensor
  - Steel corrodes **uniformly** [6,7]
  - Mass loss calculated by **product** of time of wetness, corrosion rate, and area of the sample (19.34 cm^2)
- Three cases:
  1. All data satisfying the ISO requirement considered wet
  2. ISO constraints applied to the above described ‘wet’ and ‘semi-wet’ data
  3. Mass loss calculated without the ISO constraint

Mass loss predictions of SAE-1020

	Retrieval #1	Retrieval #2
Actual	0.37 g	0.65 g
1. ISO 9223 (wet)	0.54 g (46%)	1.1 g (67%)
2. ISO 9223 (wet + semi-wet)	0.19 g (-49%)	0.23 g (-65%)
3. This study	0.42 g (14%)	0.49 g (-25%)

$$CR_W = 12.7 * 10^{-9}\ g/cm^2s$$
$$CR_{SW} = 3.29 * 10^{-9}\ g/cm^2s$$

[6] *E.C. Rios, A.M. Zimer, E.C. Pereira, L.H. Mascaro, (2014), Analysis of AISI 1020 steel corrosion in seawater by coupling …, Electrochimica Acta, 124, 211-217.*

[7] *J.S. Lee, R.I. Ray, E.J. Lemieux, A.U. Falster and B.J. Little, (2004), An Evaluation of Carbon Steel Corrosion under Stagnant Seawater Conditions, Biofouling, 20 (4/5), 237-247.*