ACUITY
corrosion technology

Atmospheric Environment Severity Monitoring for Corrosion Management

acuitycorrosion.com | sales@acuitycorrosion.com

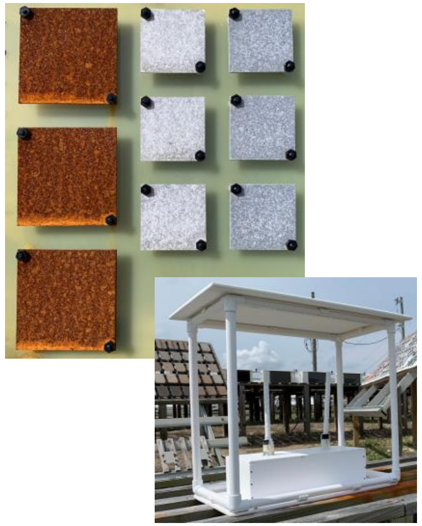
Outline

The problem:	Environment severity monitoring needs and challenges
A solution:	Standard processes for using corrosivity monitoring devices and data
An example:	Case study in continuous environment and corrosivity monitoring
One result:	Framework for severity classification with continuous data

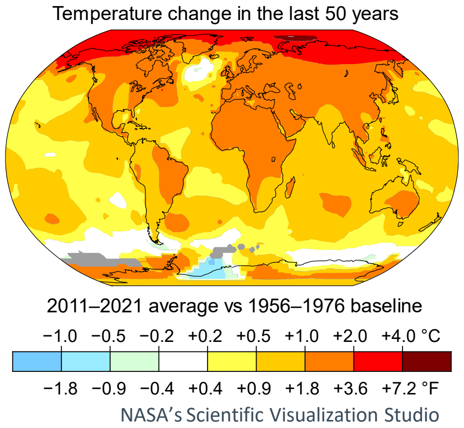
Need and challenges

- Many industries continue to use and add complex material systems that are susceptible to atmospheric corrosion, so relevant environments need to be characterized to understand and predict corrosion performance

Cost of deployment and laboratory analysis

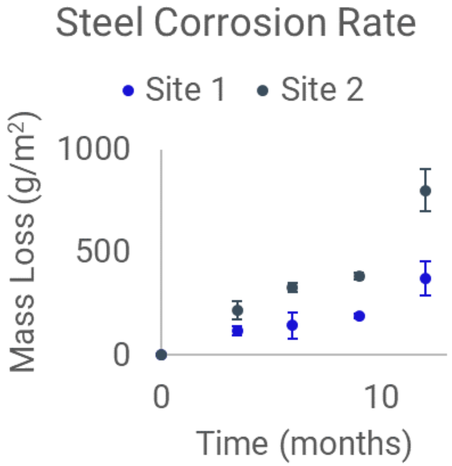


Industrial or climatic long-term trends



Seasonal variation

Sparseness of coupon data



Unique samples and exposure configurations result in siloed datasets

Ideal solution: efficient generation of standardized continuous environmental severity and corrosivity data for improved modeling of atmospheric corrosion and understanding of site severity

acuitycorrosion.com | sales@acuitycorrosion.com

Atmospheric environment severity solutions

AD HOC I-SC 07 - Environmental Spectra for Severity Classification

AMPP community seeking to standardize methodology to reduce data silos and improve collaboration

- Atmospheric environment and corrosivity monitoring sensors address some common severity monitoring challenges
- More continuous data for short-term and long-term trend analysis
- Can be standardized for collaboration
- Decreased laboratory work and cost

Gas sniffers / nephelometers

Galvanic corrosion sensors

Electrical resistance corrosion sensors

Time of wetness electrodes

Interdigitated electrode sensors

EIS-based corrosion sensors

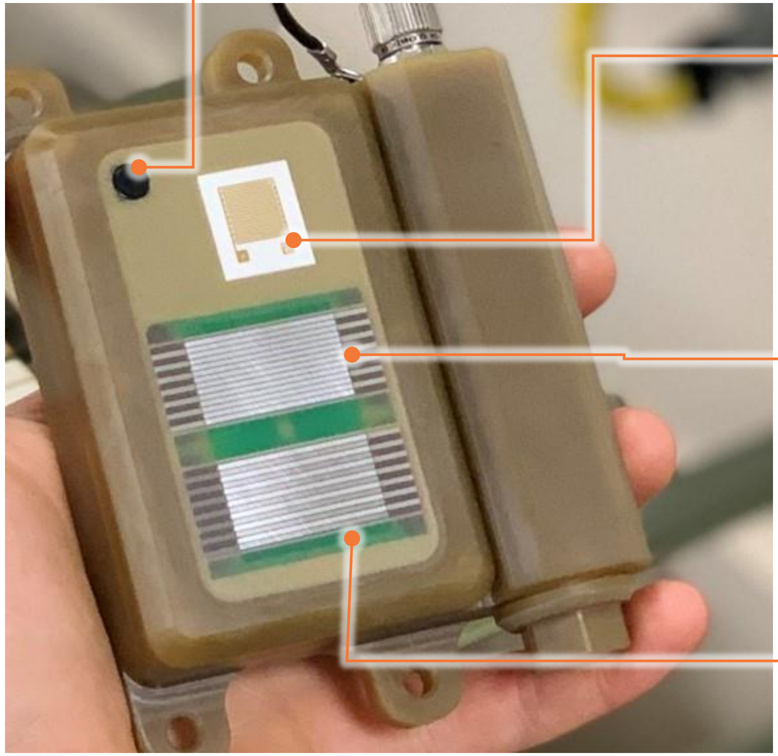
Climatic/weather data

Temp/RH data

UV light sensors

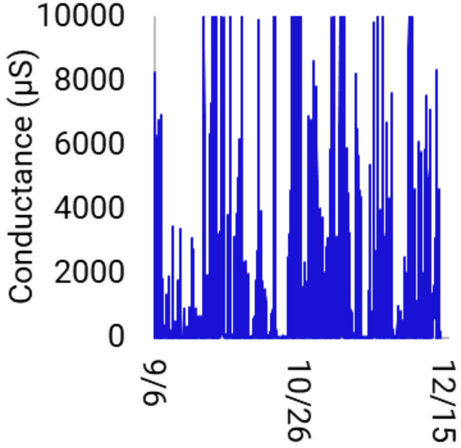
Where we are

We have developed a device to continuously monitor environmental and corrosion parameters with a small footprint to easily deploy and monitor any corrosive atmospheric location



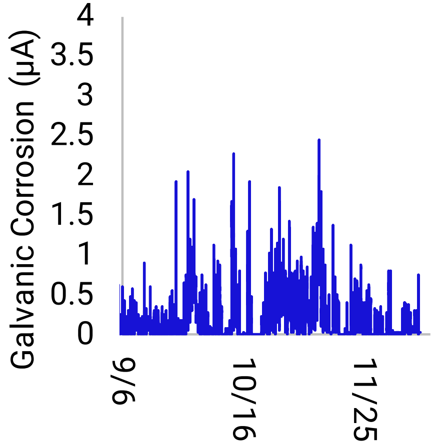
Air temperature & relative humidity

Conductance
- Gold
- 20 mV peak-to-peak
- 10 Hz and 25 kHz
- Conductance (μS)



Free corrosion rate
- Single engineering alloy
- Linear polarization resistance
- 20 mV peak-to-peak, 0.5 Hz
- Current (μA)

Galvanic corrosion rate
- Two dissimilar materials
- Zero resistance ammeter
- Current (μA)



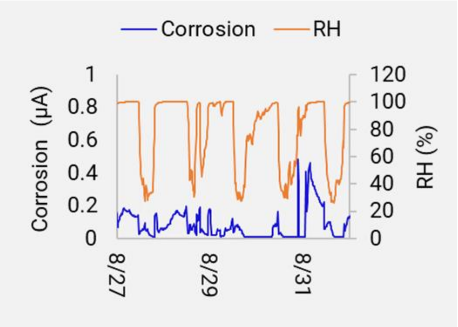
acuitycorrosion.com | sales@acuitycorrosion.com

How atmospheric corrosivity sensors have been used

Monitor accelerated corrosion test cycle conditions

Inform predictions of corrosion under atmospheric conditions1,2

Characterize on-asset environments3



Understand environmental factors affecting corrosion rate4

Evaluate aerospace coating corrosion inhibition5

Monitor shipboard environments6

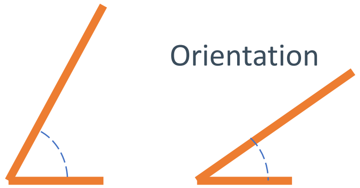
acuitycorrosion.com | sales@acuitycorrosion.com

Corrosivity sensor challenges

- Challenges have been identified in these use cases – some traditional challenges of data-centric solutions and some unique to corrosion sensing

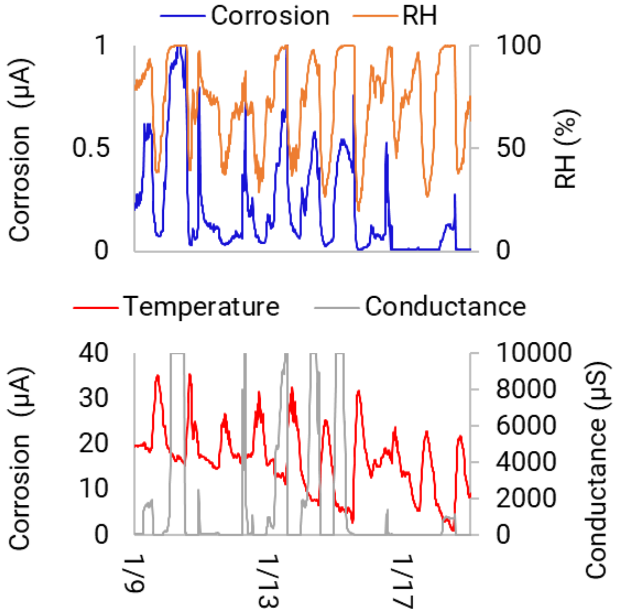
- Typical data-centric solution challenges:
- Irrelevant data, needs cleaning
- Large quantity of data, different formats
- Data corruption
- Data 'tagging' / metadata / record keeping

- Additional corrosivity sensor specific challenges
- Finite sensing element life
- Faulty sensor measurements
- Interpretation of (novel) measurements, conclusions



Tagging/metadata

Large, complex datasets



Finite life

Heavily corroded, exhausted sensing element (7075/CFRP)

acuitycorrosion.com | sales@acuitycorrosion.com

Outline

The problem:	Environment severity monitoring needs and challenges
A solution:	Standard processes for using corrosivity monitoring devices and data
An example:	Case study in continuous environment and corrosivity monitoring
One result:	Framework for severity classification with continuous data

acuitycorrosion.com | sales@acuitycorrosion.com

Solution – environment and corrosivity data processes

- How can we more efficiently generate continuous corrosivity data for understanding environment severity and managing corrosion?

↓

- Clearly-defined processes for environment and corrosivity data acquisition, review, analysis, and reporting

(1) Acquisition → (2) Review → (3) Analysis → (4) Reporting →

(1) Acquisition	(2) Review	(3) Analysis	(4) Reporting
Deployment conditions Metadata / tagging Design of experiment	Cleaning Range constraints Data-type constraints Consistency	Time-based analysis Aggregations Statistics Relationships	Relation to other datasets Comparative conclusions Metrics and insights Severity indices

- Standardized data and collaboration
- Continuous data
- Trends (long and short term)
- Efficient deployment and analysis
- Actionable conclusions and ESI

acuitycorrosion.com | sales@acuitycorrosion.com

Outline

The problem:	Environment severity monitoring needs and challenges
A solution:	Standard processes for using corrosivity monitoring devices and data
An example:	Case study in continuous environment and corrosivity monitoring
One result:	Framework for severity classification with continuous data

acuitycorrosion.com | sales@acuitycorrosion.com

(1) Corrosivity data acquisition

- Consider material selection
  - Environment severity and longevity
  - Available datasets for comparison
  - Relevant structural and galvanic materials

- Consider deployment
  - Conditions –orientations, durations, recording interval for comparison with available datasets
  - Preparation – sensor surface prep, shipment, mounting

- Metadata and tagging

Design of experiment

Factor	Levels	# of levels
Location	• Daytona, FL Ocean • Daytona, FL Intracoastal (IC) • El Segundo, CA • Whidbey Island, WA	4
Galvanic couple	• AA7075-T6/CFRP • AA7075-T6/A286 • AA7075-T6/T-6Al-4V	3
Replicates	1, 2, 3	3
	TOTAL	36 galvanic data streams

Example details to record for device deployment

Test name, Device Type, Serial Number, Galvanic Alloys, Free Corrosion Alloy, Data Owner, Data Distribution, Exposure Type (On Asset, Outdoors, Laboratory), Asset Type, Asset Identifier, Position on Asset, Exposure Location, Sheltered? (Y/N), Orientation (angle above horizontal), Standard Test Method, Coated? (Y/N), Pretreatment, Primer, Topcoat, Exposure Notes, Exposure Start Date.

acuitycorrosion.com | sales@acuitycorrosion.com

Case study – acquisition conditions

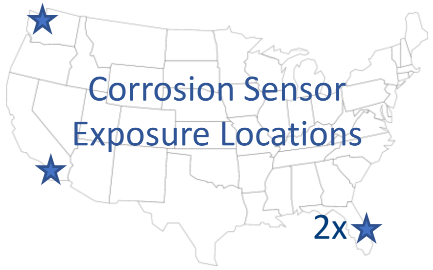
Locations

Daytona, FL

- Ocean
- Intracoastal site (IC), 800 meters inland

El Segundo, CA

Whidbey Island, WA



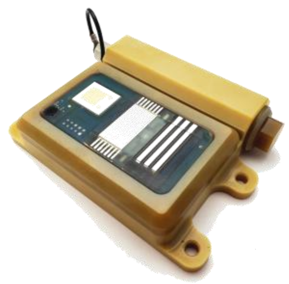
Materials

Galvanic corrosion couples

- A286/AA7075
- CFRP/AA7075
- Ti-6-4/AA7075

Free corrosion

- AA7075



Overview

Location	Start Date	Available data
Daytona, FL (Ocean)	12/21/2021	12 months
Daytona, FL (Intracoastal)	12/21/2021	12 months
El Segundo, CA	01/11/2022	9 months
Whidbey Island, WA	04/29/2022	6 months

acuitycorrosion.com | sales@acuitycorrosion.com

(2) Corrosivity data review

The data needs to be reviewed and cleaned before any analysis steps occur

≈800,000 measurement records (7 measurements in each record)

Relevance / data trimming

- E.g., prior to and after the useful range of data

Sensor longevity

E.g., exhaustion of corrosion sensing elements

Range constraints

E.g., any measurement that has a value outside of its specified operational range.

Erroneous data detection

- Timestamp is out of sequence or clearly erroneous
- Known faults: E.g., Relative humidity and temperature sensor measurement is: -45 °C and 12% RH for the devices used in this test

Consistency

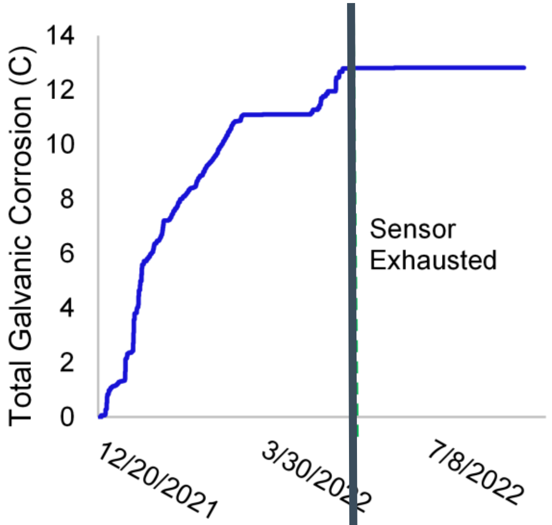
Is this reasonable given coincident measurements or historic data?

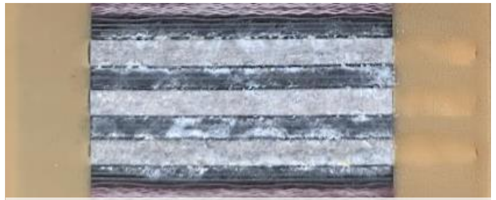
acuitycorrosion.com | sales@acuitycorrosion.com

Sensor longevity

Sensor exhaustion is highly dependent on aggressiveness of the couple and environment

Total galvanic corrosion



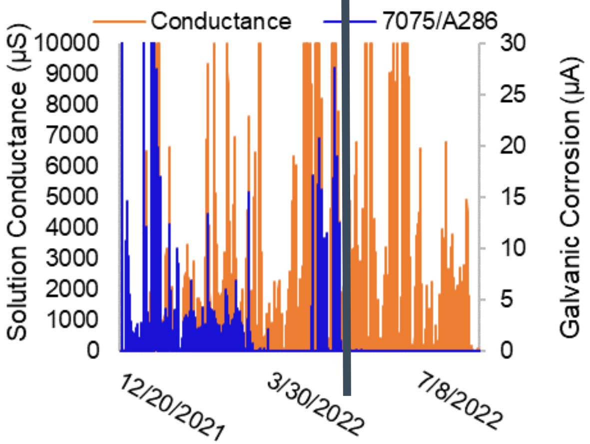


Heavily corroded, exhausted sensing element (7075/CFRP)

Corroding sensor elements have a finite lifetime

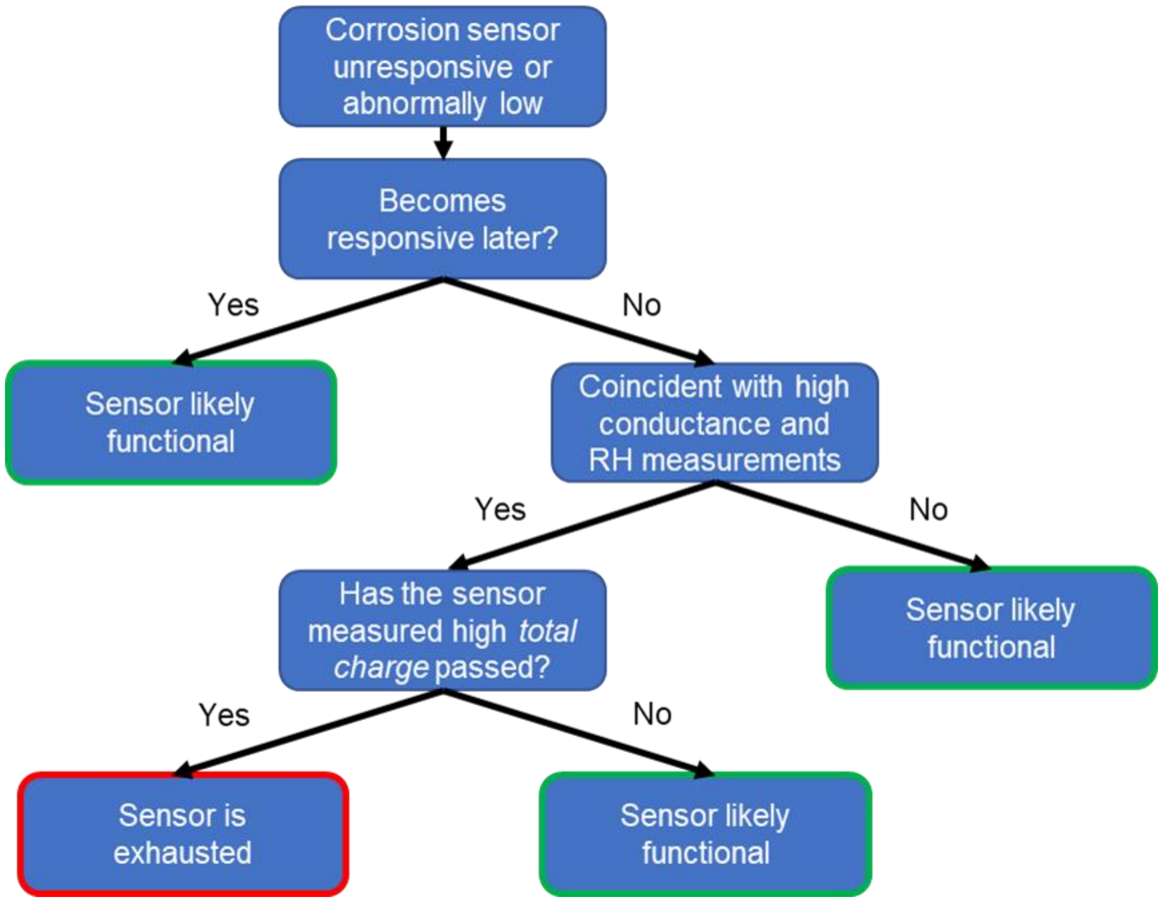
Data collected after sensor exhaustion must be removed

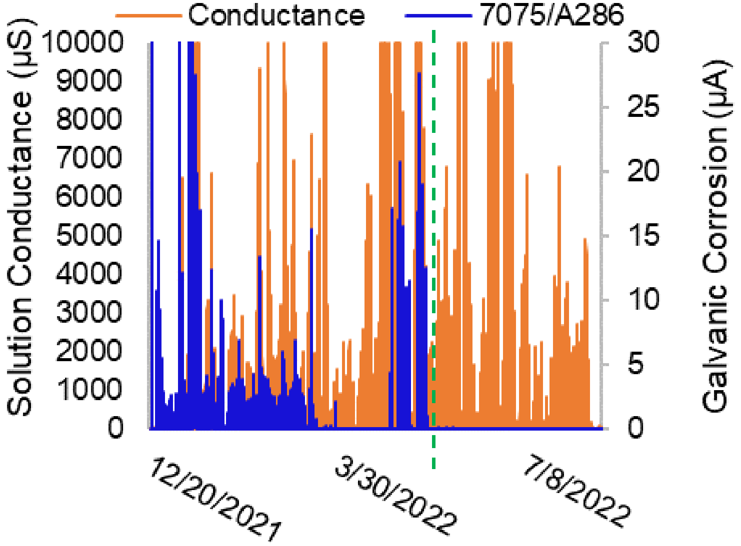
Galvanic corrosion rate

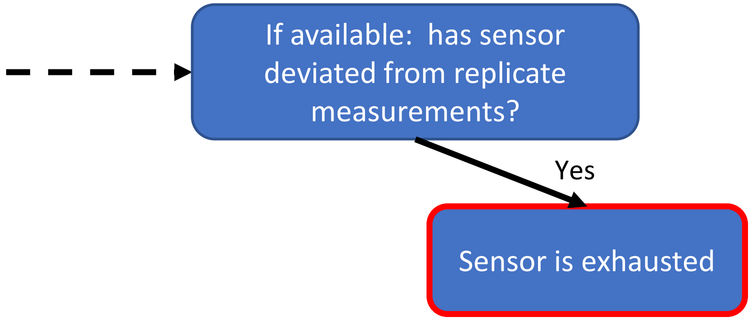


How is exhaustion detected?

Detecting sensor exhaustion

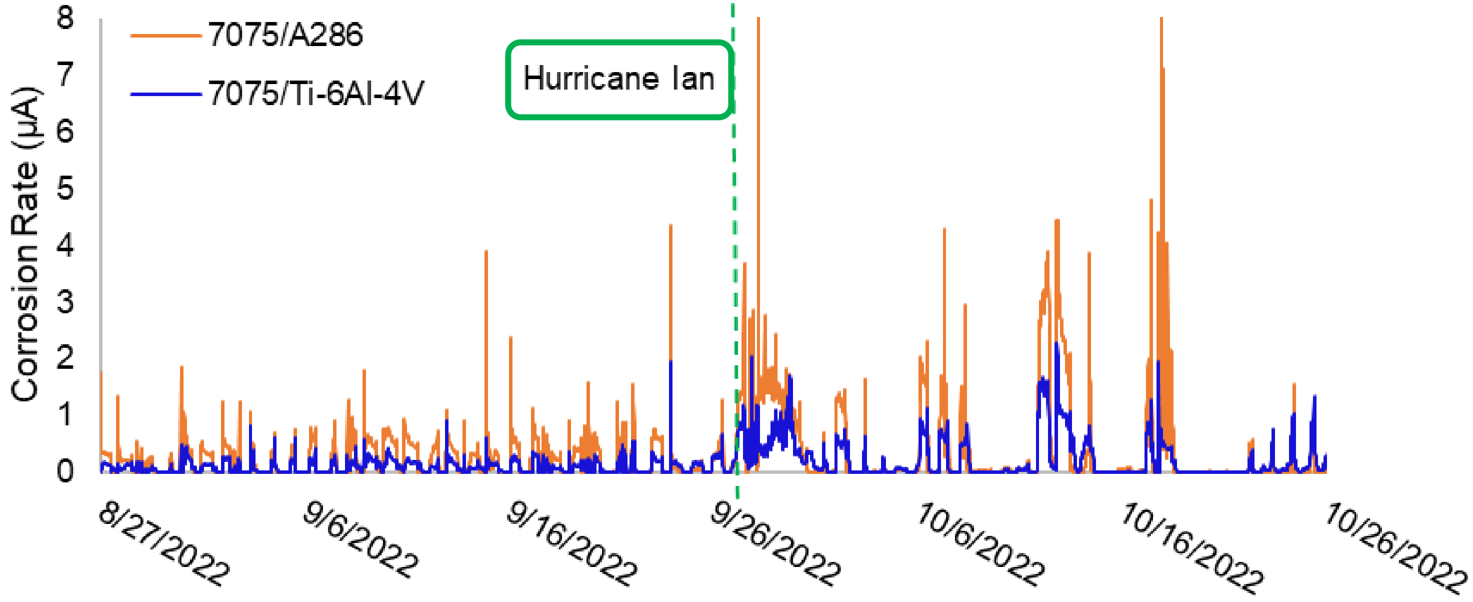


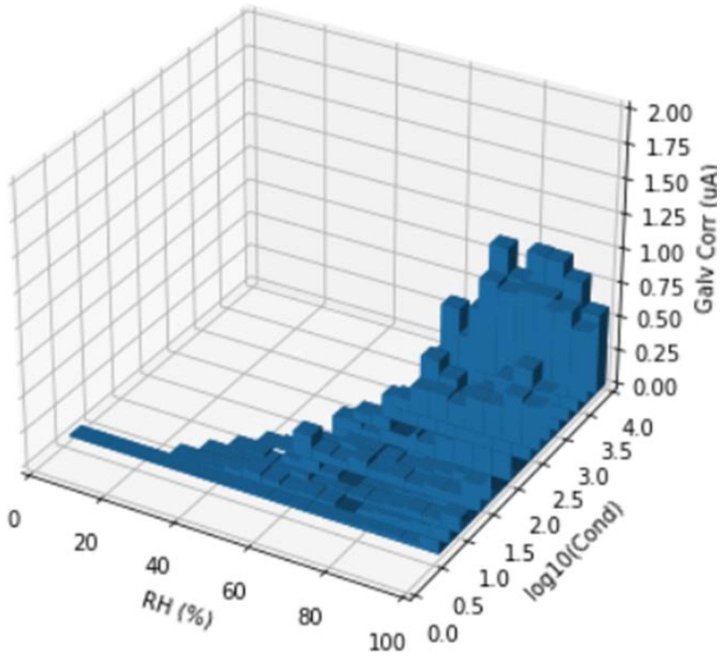




(3) Corrosivity data analysis

After data review is complete and datasets are clean, different analyses can be used depending on the need





- Time-based analysis can require significant hands-on investigation to identify relationships and the significance of responses to a particular study or need
- Causality and correlations can be determined where it would be difficult using only coupon data with sparse datapoints

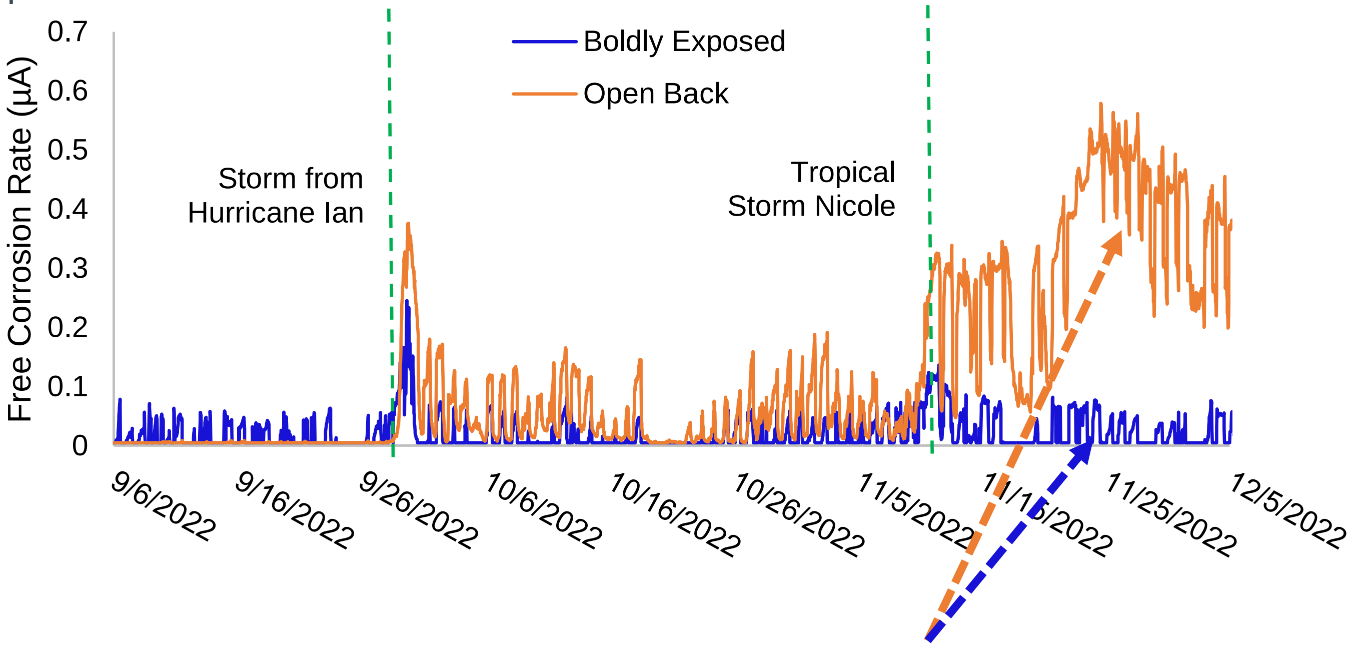
Multiple parameter investigations can reveal correlations useful in characterizing environments for modeling of atmospheric corrosion

Time-based investigative analysis

- Additional sensors in Simulated Aircraft Structure (SAS) boxes were placed at the Daytona, FL Intracoastal site

‘Open back’ – sheltered condition

Boldly exposed condition



Storms clearly affect the free corrosion rate, likely resulting from both high salt deposition rates and moisture

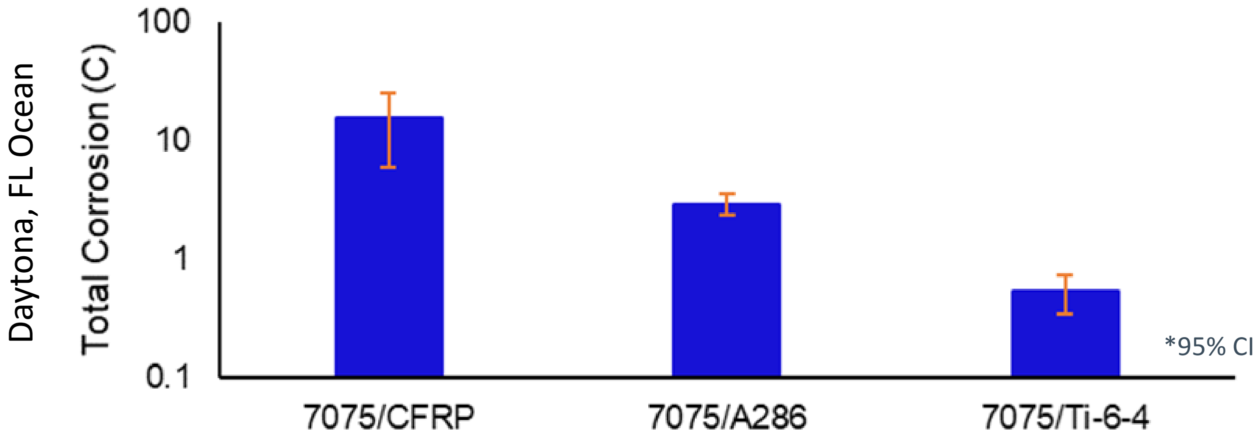
Continuous corrosion monitoring enables correlation of weather, maintenance, or other events with corrosion

The sheltered condition results in a lack of rinsing that enables salt contaminant accrual higher than the boldly exposed surface, resulting in drastically higher corrosion rates

acuitycorrosion.com | sales@acuitycorrosion.com

Cumulative effect of corrosion

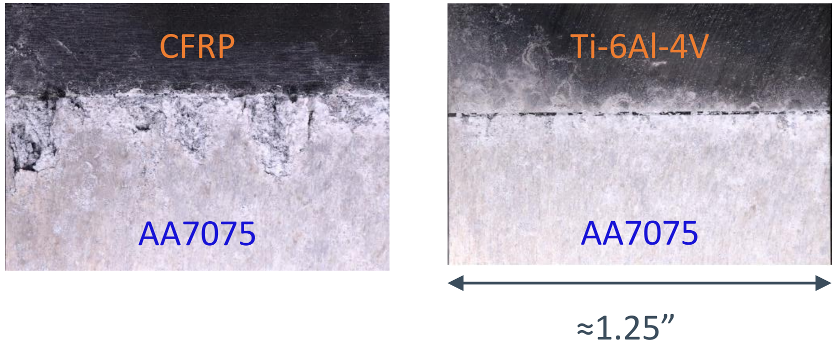
- Continuous measurements can be easily summarized for comparison of conditions
  - **Total** corrosion is calculated as the integral of the corrosion rates over time



Quantified effect of this environment on galvanically coupled AA7075

CFRP › A286 › Ti-6Al-4V

Co-located galvanic witness coupons (6 mo.)



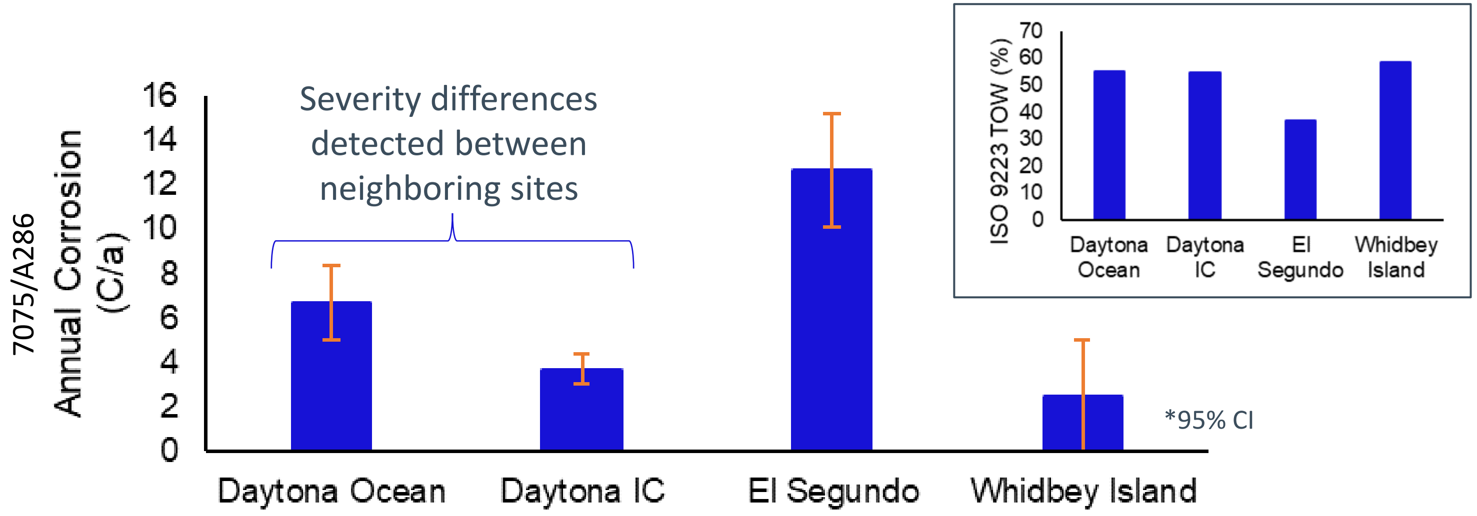
These observations inform ongoing atmospheric predictive galvanic corrosion modeling work for aerospace applications

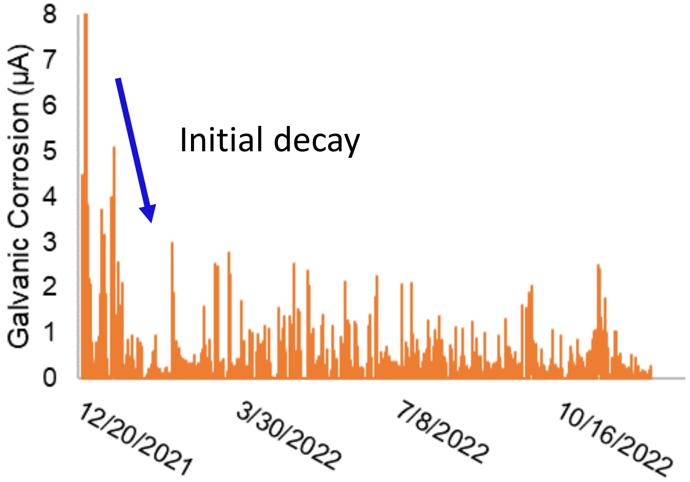
acuitycorrosion.com | sales@acuitycorrosion.com

Cumulative effect of corrosion

- **Annualized** corrosion enables clear comparison between datasets of different durations

With triplicate measurements, significant differences in galvanic corrosion severity between these sites are measured





Should consider the effect of initial corrosion rate decay when using annualized metrics

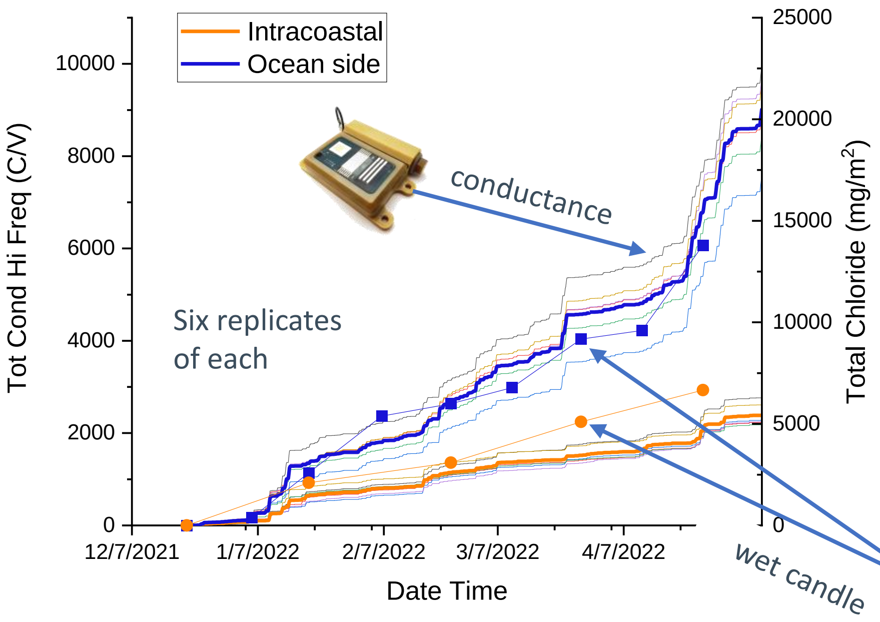
Could be extended to severity comparison on assets

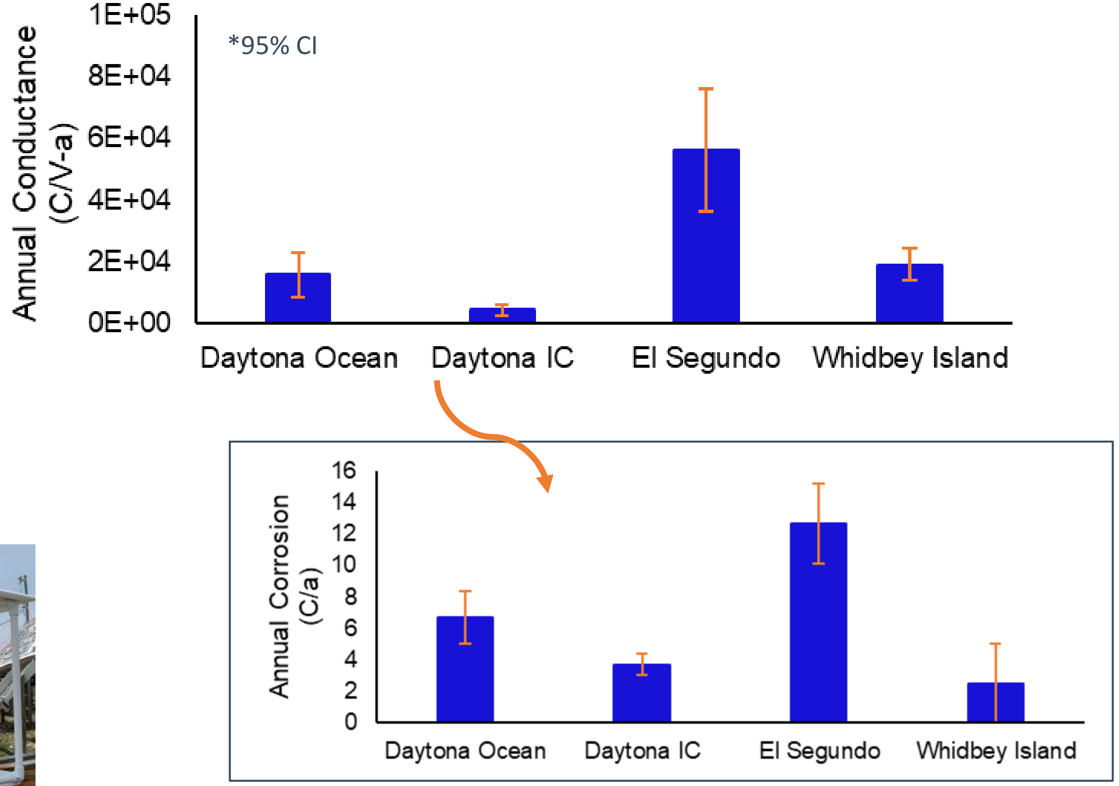
acuitycorrosion.com | sales@acuitycorrosion.com

Conductance relation to electrolyte properties

Conductance relates to salt accumulation on the surface, so it responds like wet candle Cl^- deposition measurements at the Ocean and Intracoastal Daytona sites

- Electrolyte conductivity, thickness, and distribution all affect the conductance measurement – helping to determine electrolyte properties for physics-based corrosion modeling





* Wet candle depends only on deposition

Outline

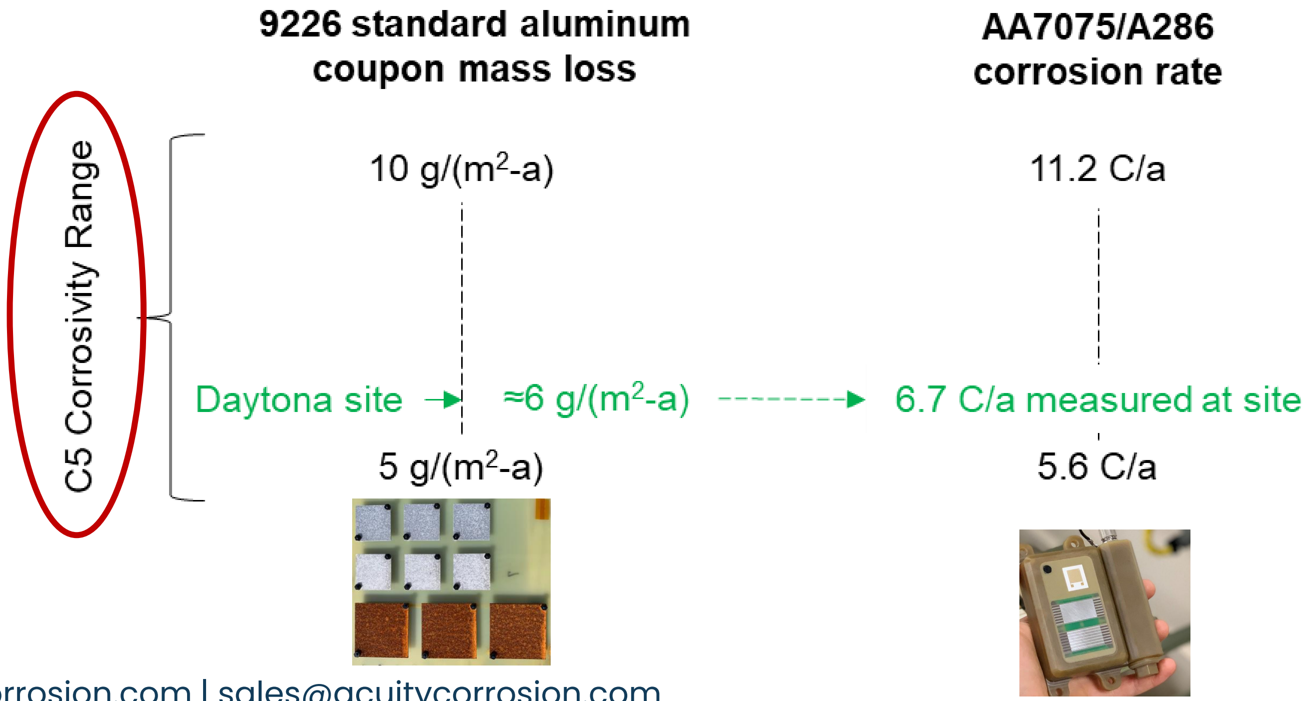
The problem:	Environment severity monitoring needs and challenges
A solution:	Standard processes for using corrosivity monitoring devices and data
An example:	Case study in continuous environment and corrosivity monitoring
One result:	Framework for severity classification with continuous data

acuitycorrosion.com | sales@acuitycorrosion.com

Environmental severity classification framework

- With standardized processes, ESI rankings could be obtained with continuous monitoring corrosivity devices
- To demonstrate, measurements of annual galvanic corrosion were mapped onto ISO 9223 corrosivity categories

- Based on historic data, the corrosivity at the Daytona, FL Ocean site was assumed to be on the low end of the ISO C5 corrosivity range:



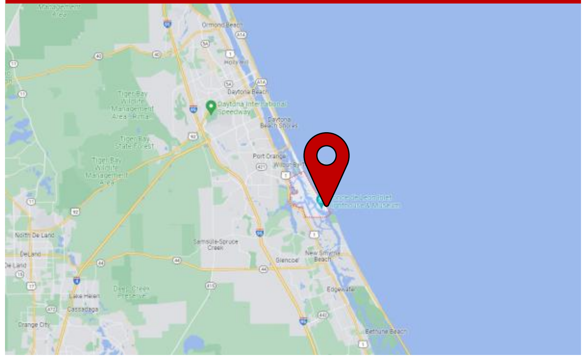
Assumed that galvanic couple corrosion is proportional to aluminum coupon corrosion rate

This is an empirical relationship based on historic site data and the continuous corrosion data

acuitycorrosion.com | sales@acuitycorrosion.com

Environmental severity classification framework

Daytona Beach, FL Ocean – C5



Used Daytona Ocean as a baseline condition for C5

ISO 9223 Category	Aluminum (g/(m^2-a))	7075 / A286 (C/a)
C1	negligible	r ≤ 0.03
C2	r ≤ 0.6	0.03 < r ≤ 0.7
C3	0.6 < r ≤ 2	0.7 < r ≤ 2.2
C4	2 < r ≤ 5	2.2 < r ≤ 5.6
C5	5 < r ≤ 10	5.6 < r ≤ 11.2
CX	R > 10	11.2 < r

Assumed a linear relationship between mass loss rates and corrosion measurements for the other categories

Environmental severity classification framework

- Extended the same method to the other sensor materials to determine corrosion rate measurement ranges that correspond to ISO corrosivity categories

ISO 9223 Category	ISO 9226 Corrosion Rates (r)		Continuous Monitored Annual Corrosion (r)			
	Carbon steel (g/(m²-a))	Aluminum (g/(m²-a))	7075 / CFRP (C/a)	7075 / A286 (C/a)	7075 / Ti-6-4 (C/a)	7075 (C/a)
C1	r ≤ 10	negligible	r ≤ 0.2	r ≤ 0.03	r ≤ 0.02	r ≤ 0.03
C2	10 < r ≤ 200	r ≤ 0.6	0.2 < r ≤ 3.5	0.03 < r ≤ 0.7	0.02 r ≤ 0.4	0.003 r ≤ 0.06
C3	200 < r ≤ 400	0.6 < r ≤ 2	3.5 < r ≤ 11.7	0.7 < r ≤ 2.2	0.4 < r ≤ 1.3	0.06 < r ≤ 0.2
C4	400 < r ≤ 650	2 < r ≤ 5	11.7 < r ≤ 29.2	2.2 < r ≤ 5.6	1.3 < r ≤ 3.2	0.2 < r ≤ 0.5
C5	650 < r ≤ 1500	5 < r ≤ 10	29.2 < r ≤ 58.4	5.6 < r ≤ 11.2	3.2 < r ≤ 6.4	0.5 < r ≤ 1.01
CX	1500< r ≤ 5500	R > 10	58.4 < r	11.2 < r	6.4 < r	1.01 < r

Current standardized mass loss

Proposed framework for mapping continuous measurements to standardized corrosivity

Color coded by ideal case for a material couple

acuitycorrosion.com | sales@acuitycorrosion.com

Environmental severity classification

- Using this framework, the ISO corrosivity category for each site was determined from continuous data
  - For each site, the various material couples produced very similar estimates for corrosivity

Location	ISO Categorization (C1, C2, C3, C4, C5, CX)				
	7075-T6 / CFRP	7075-T6 / A286	7075-T6 / Ti-6Al-4V	7075-T6	MODE
Daytona, FL (Ocean)	35.0	6.7	3.8	0.60	C5
Daytona, FL (Intracoastal)	30.5	3.7	2.2	0.48	C4
El Segundo, CA	115.3	12.7	4.0	1.45	CX
Whidbey Island, WA	14.9	2.5	1.8	0.79	C4

Baseline → Daytona, FL (Ocean)

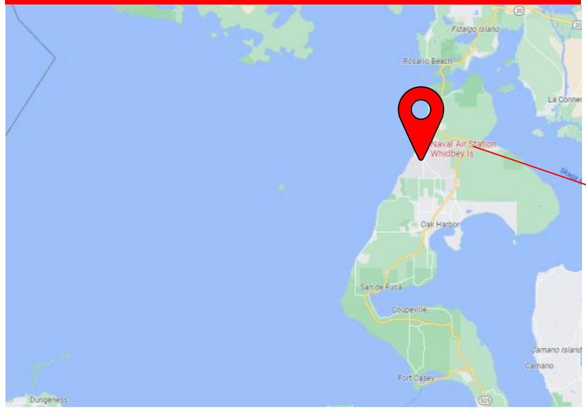
*(C/a)

Continuous measurements can be mapped to corrosivity standards for rapid deployment and determination of corrosion severity, using different material couples depending on structural relevance and environment

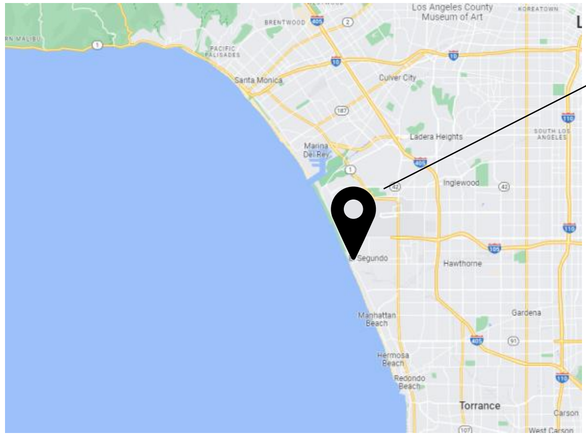
acuitycorrosion.com | sales@acuitycorrosion.com

Environment severity classification

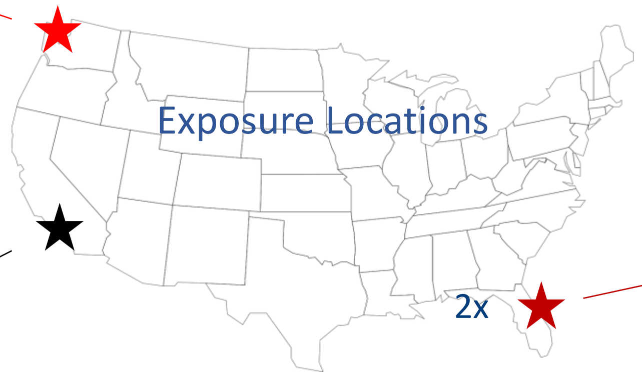
Whidbey Island, WA – C4



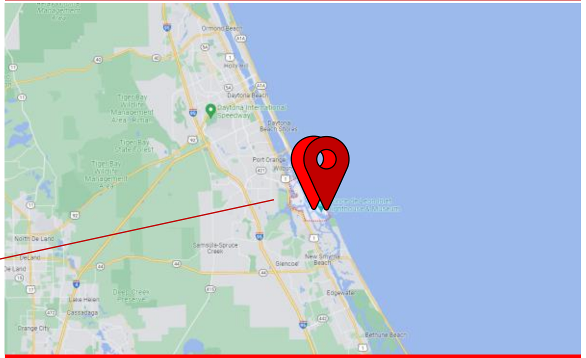
El Segundo, CA – CX



Site severity category determined with continuous measurements



Daytona Beach, FL Ocean – C5



Daytona Beach, FL Intracoastal waterway – C4

To refine the proposed model, simultaneous standardized coupons should be collocated with monitoring devices

acuitycorrosion.com | sales@acuitycorrosion.com

Conclusions

- Continuous atmospheric corrosion monitoring produces efficient characterization of environment severity to inform asset corrosion management
    - Further refinement of the ESI framework with continuous data is needed
    - Standardization, verification & validation will improve confidence in conclusions

- Well-defined processes for corrosivity sensor use result in environment severity data that could directly inform corrosion management practices through severity classifications and comparisons

- Corrosion monitoring data demonstrated clear differences in structural alloy corrosion at different sites, consistent with environmental effects such as salt deposition rates.

acuitycorrosion.com | sales@acuitycorrosion.com

Future work

- Continued refinement and standardizing of processes for acquisition, review, and analysis of continuous corrosion monitoring data (through efforts like the SC07 Ad Hoc – Environmental Spectra for Severity Classification)

- Development of data management tools to make the above processes easier and more efficient

- Continued research with corrosivity devices for condition-based corrosion management, monitoring local environments, and on-asset monitoring

- Use of the data for modeling purposes, relating conductance and corrosion measurements to electrolyte properties that can be used to model and predict corrosion degradation on assets or components

acuitycorrosion.com | sales@acuitycorrosion.com

References

1. Adey, R., A. Peratta, J. Baynham, and T. Curtin, "Predicting Cumulative Galvanic Corrosion Damage in Aircraft Structures STO-MP-AVT-303" (NATO, n.d.).
2. Pei, Z., D. Zhang, Y. Zhi, T. Yang, L. Jin, D. Fu, X. Cheng, H.A. Terryn, J.M.C. Mol, and X. Li, Corrosion Science 170 (2020): p. 108697.
3. L't Hoen-Velterop, "Helicopter Corrosion Maintenance Prediction Using Environmental Sensors NLR-TP-2015-440" (NLR, 2015).
4. Pei, Z., X. Cheng, X. Yang, Q. Li, C. Xia, D. Zhang, and X. Li, Journal of Materials Science & Technology 64 (2021): pp. 214–221.
5. V. Avance, B. Clark, L. Agnew, and F. Friedersdorf, "Predictive Coating Condition Model for Coating Lifetime Under Environmental Stressors," AMPP Annual Conference, (San Antonio, TX: AMPP 2022).
6. Tagert, J., D.C. Sanders, J. Easterday, P. Slebodnick, E. Lemieux, B. Kogler, and L. Erickson, "Corrosion Control for Navy Ships (CCNS): Improving the Performance of Protective Coatings" (Naval Research Laboratory, 2020).

ACUITY corrosion technology

Thank You

Questions?

www.acuitycorrosion.com
sales@acuitycorrosion.com