Real-time Measurement of Aerospace Organic Coating Condition and Performance in Atmospheric Corrosion Conditions

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Paper No. C2024-20742

AMPP Conference 2024

Modernization of Corrosion and Coating Research

March 7th, 2024

Background

Introduction

- Aircraft corrosion costs the U.S. Department of Defense billions due to maintenance time and decreased aircraft availability

- Coatings are the first line of defense against corrosion, but they require further investigation to understand their service life

- A predictive coating condition model (PCCM) is needed to inform coating selection and corrosion management based on real-time measurements

Background

- Failure of a properly formulated and applied coating consists of two distinct processes: mechanical damage and inhibitor exhaustion

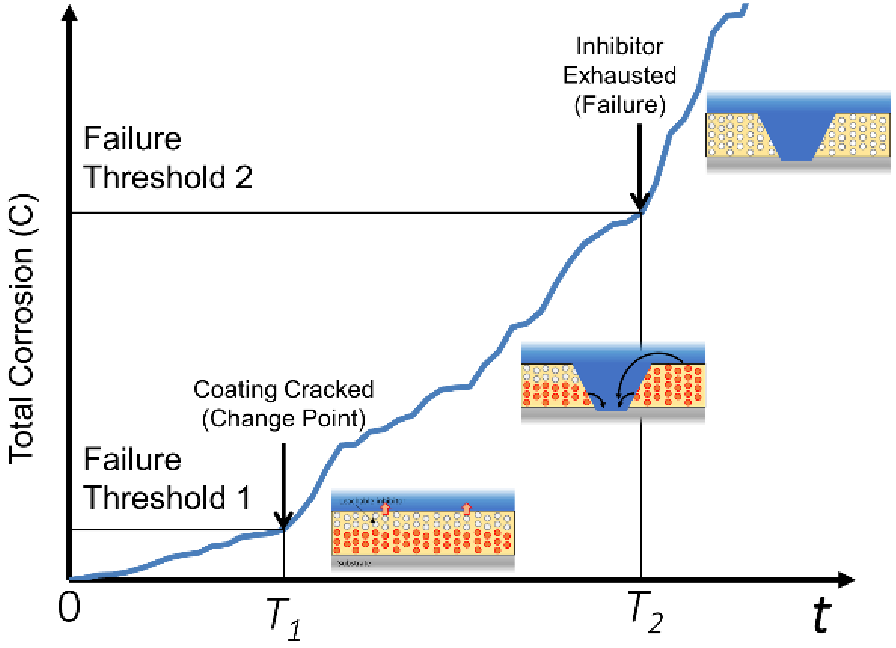
- Model development and validation are limited by the ability to accurately measure time to failure

- Want higher resolution of corrosion kinetics to better understand coating behavior

- Real-time evaluation of coating condition using advanced coating evaluation metrics can improve modeling efforts

Two Stages of Failure

$T_2 - T_1 >> T_1$



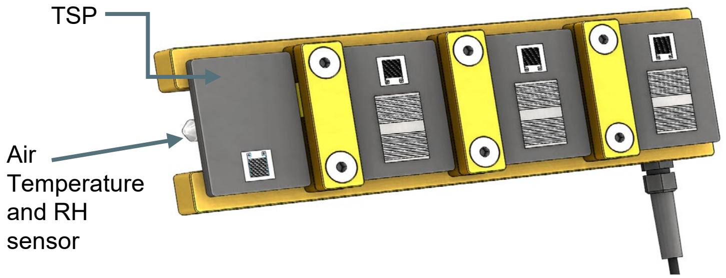
Goal

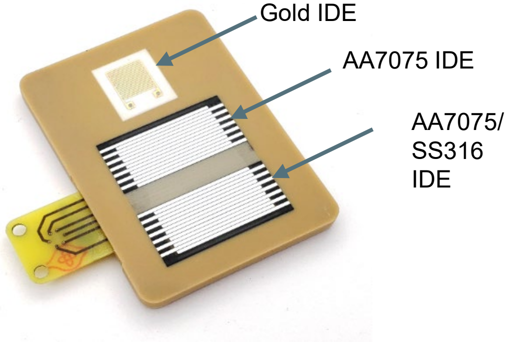
Develop a PCCM that leverages continuous galvanic corrosion measurements to define failure metrics and thresholds that characterize coating performance to predict service life

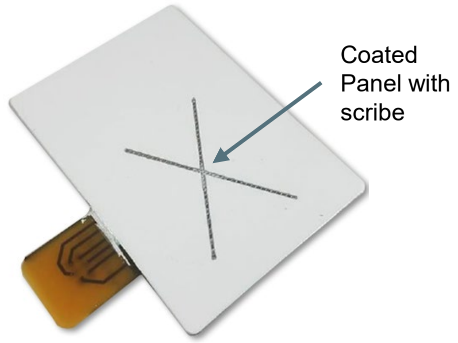
Collecting Real-Time Data
Test Set Up

Acuity CR Capabilities

- Multi-sensor panels (MSP) can be used bare or coated and scribed using traditional methods
- Measures up to three test panels at once
- Environmental severity measurements
  - RH
  - Air and panel temperature
  - Gold sensor conductance
    - contaminants or coating barrier properties
- Corrosivity measurements
  - Free corrosion (AA7075, impedance)
  - Galvanic corrosion (AA7075/SS316)
- Applicable for use in
  - Accelerated test chambers
  - Outdoor exposure sites







Acuity CR Measurand	Symbol	Range		Units	Sensor Excitation
		Min	Max		
Air Temperature	T_a	-40	+85	°C	-
Relative Humidity	RH	0	100	% RH	-
Surface Temperature	T_s	-40	+85	°C	DC Current
Conductance, Low Freq	G_L	0.005	1	µS	20 mV_{pp}, 10 Hz
Conductance, High Freq	G_H	5	10,000	µS	20 mV_{pp}, 25 kHz
Free Corrosion	I_C	0.005	100	µA	20 mV_{pp}, 0.5 Hz
Galvanic Corrosion	I_G	0.005	100	µA	ZRA

Coating Systems

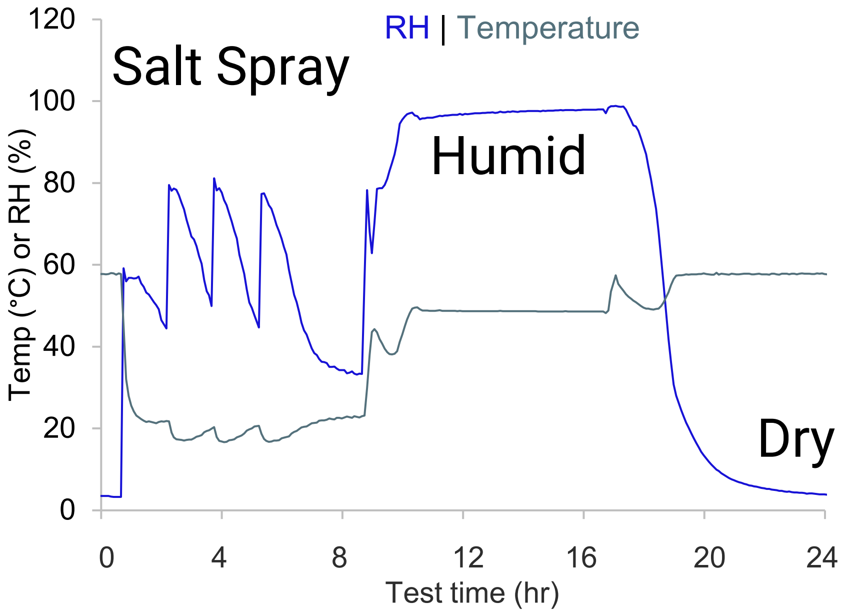
- Two aerospace coating systems
  - Chromate
  - Non-chrome
- MSP coated and scribed across the interdigitated electrodes

Pretreatment	Primer	Topcoat
Organic film-former	Solvent Borne Chromate+|	Polyurethane Topcoat*
Organic film-former	Water Borne Non-chrome^	Polyurethane Topcoat*

+ MIL-PRF-23377 Ty I Class C2
^ MIL-PRF-85582 Ty I Class N
* MIL-PRF-25285 Ty I

Laboratory Test Conditions

- Coatings tested in GMW 14872
  - 24-hour cycle
  - 4 salt sprays over 8 hours at ambient
  - 8 hours of high humidity
  - 8 hours of high-temperature dry



- Samples racked at 20° from vertical during testing to allow for solution runoff

- Samples exposed for 2000 to 3000 hours

- Photos were captured weekly to document the visual blistering progression

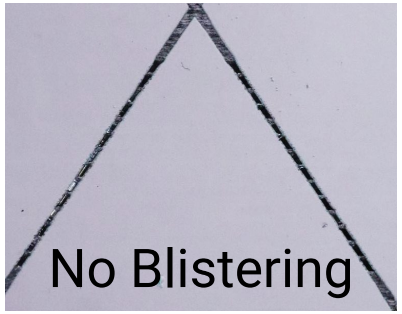
Outdoor Test Conditions

- Triplicate chromate and non-chrome samples were exposed outdoors at the Florida Materials Research Facility at Daytona Beach, Fl
- Samples were exposed for 6 months starting in March 2023
- Platforms were angled 45° from vertical and oriented toward the coast to maximize salt deposition
- Photos were captured bi-weekly to document the visual blistering progression

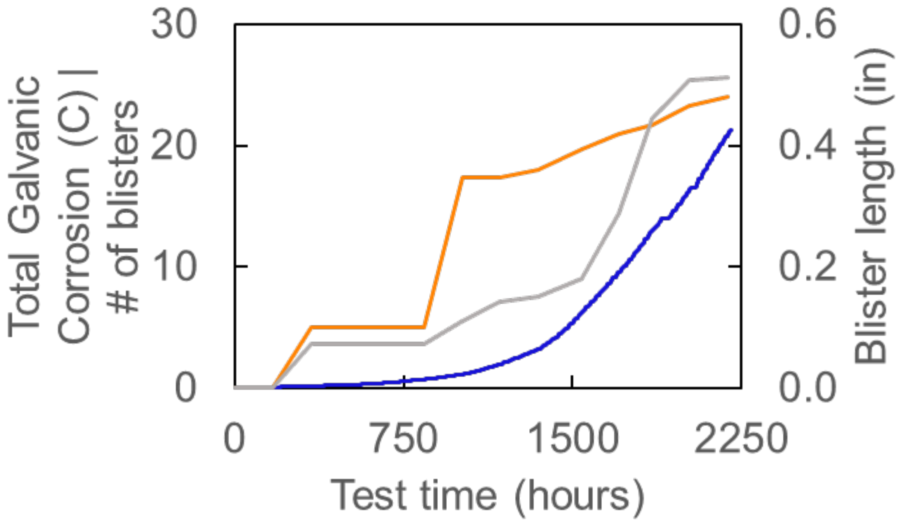
Extracting Parameters

Blister Observations

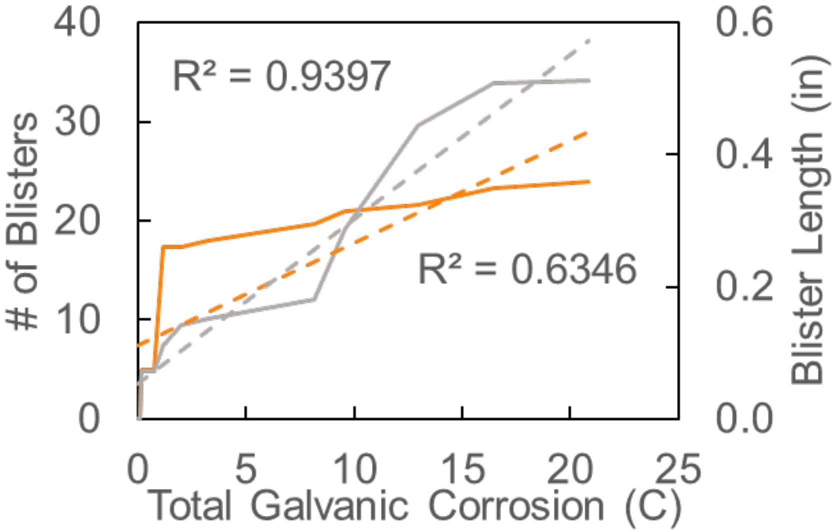
- Analysis of the images revealed 2 blistering stages: initiation and propagation



- To quantify the blister progression the number of blisters and maximum blister length were determined for each image each week for the non-chrome samples
  - Blister length displayed a better correlation to total galvanic corrosion

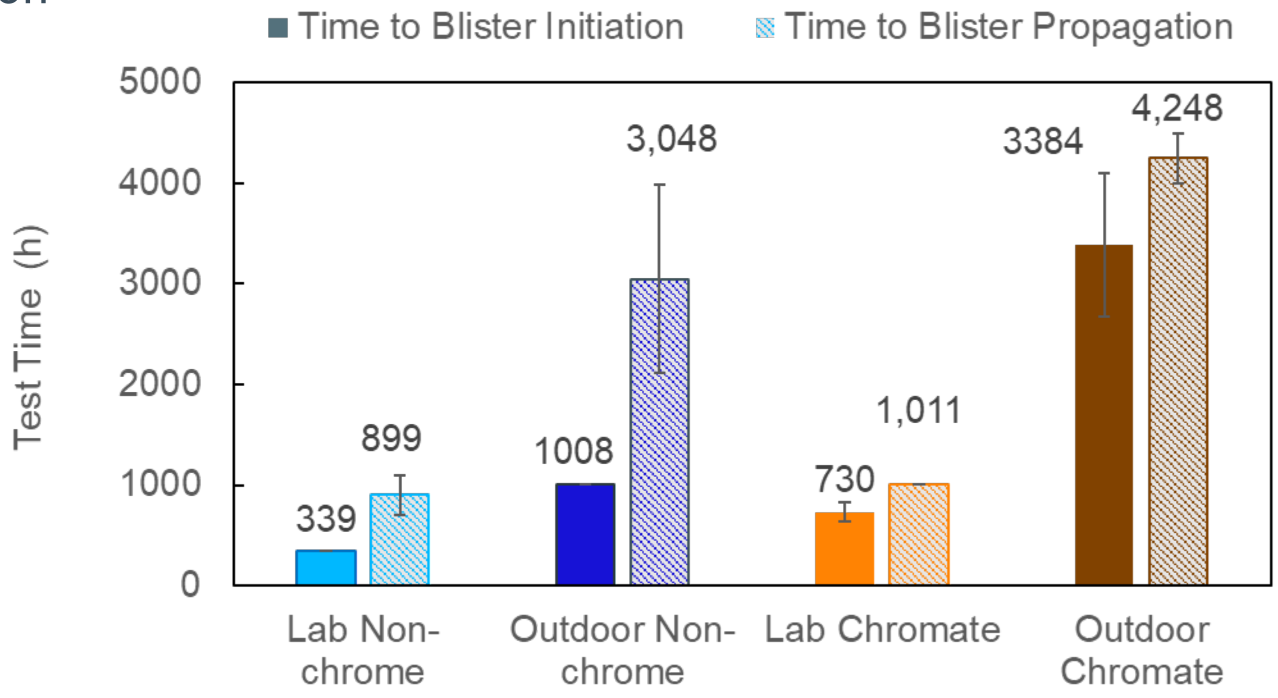


Total Galvanic Corrosion
Number of Blisters
Blister Length



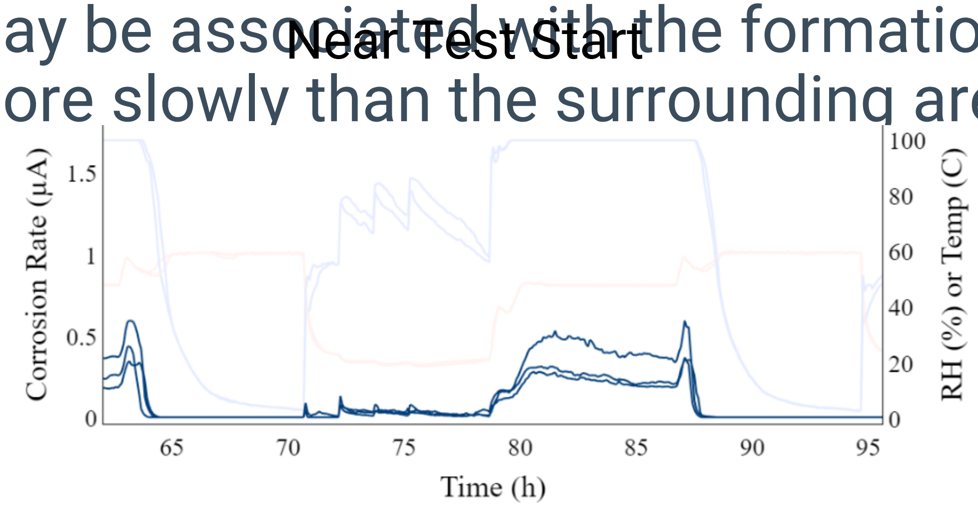
Establishing an observation-based metric

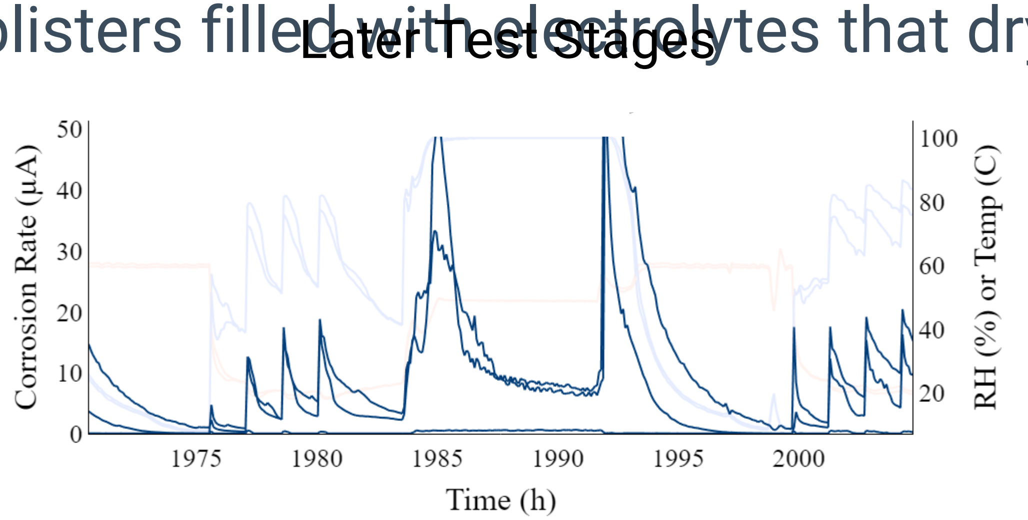
- Given the correlation between the blistering and the collected corrosion measurements it was decided to use the times to the two stages of coating failure as a benchmark for the modeling efforts
- Times reflect when changes were first noticed in images for triplicate samples
- Revealed that while non-chrome begins blistering sooner, chromate transitions more quickly from initiation to propagation



Real-Time Measurement of Galvanic Corrosion Protection

- Similar trends in galvanic corrosion current versus time at scribe for all coating systems
- Coating behavior shifted as the test progressed
  - Start of test (no blisters) – directly correlated to RH and returned to baseline current during dry conditions
  - Later stages (initiation/propagation) – maximum current during wetting and drying transitions and no longer returned to baseline current during dry conditions
- May be associated with the formation of blisters filled with electrolytes that dry more slowly than the surrounding area

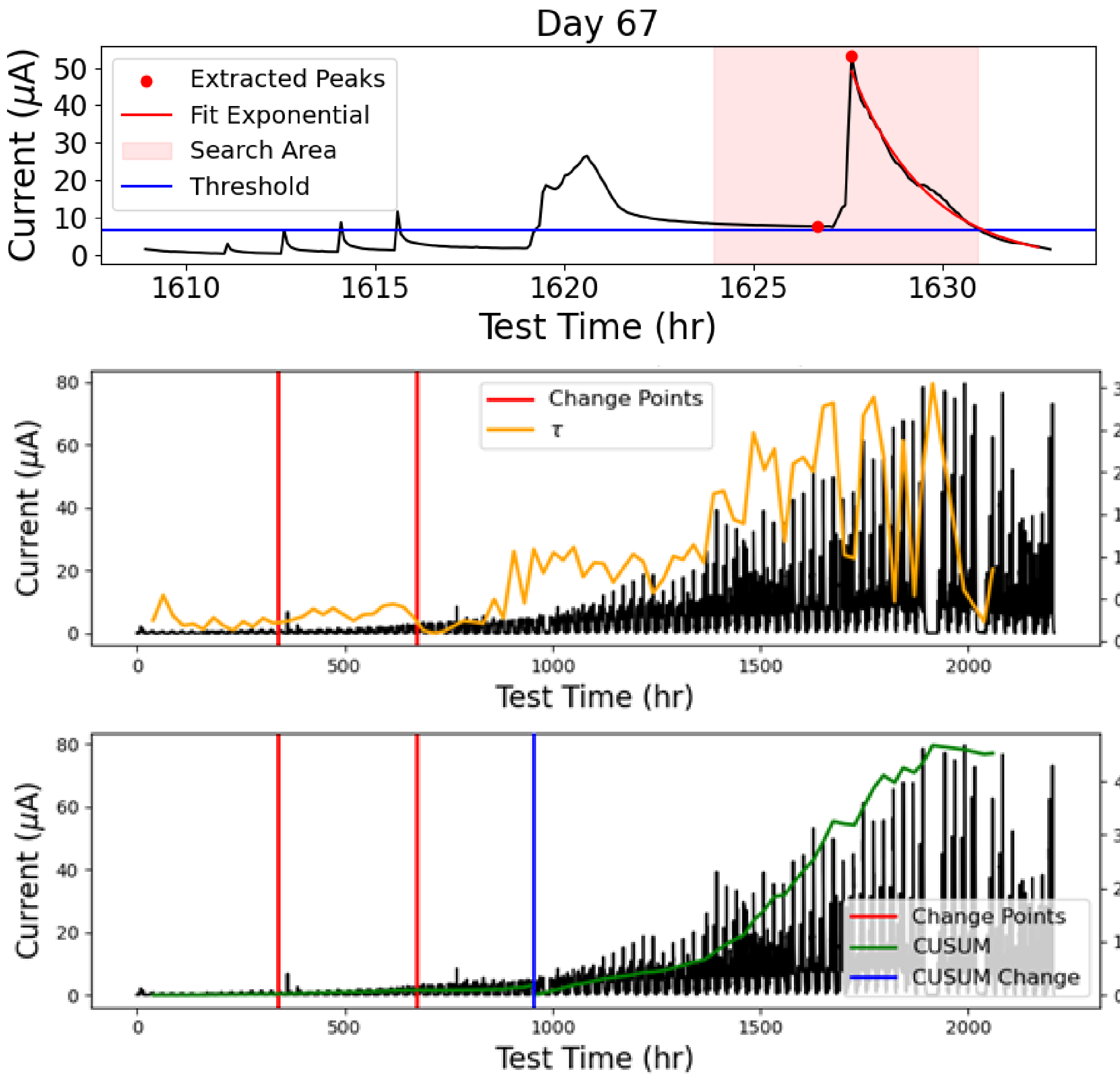




Defining Failure Thresholds

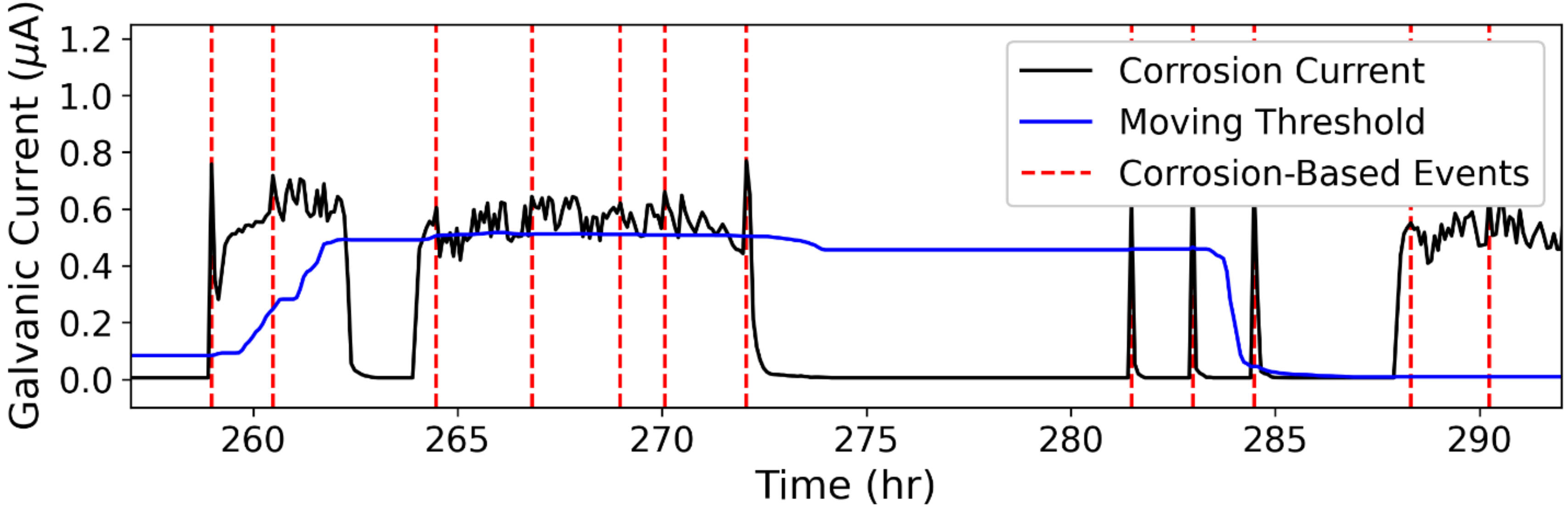
Decay Parameter

- An exponential decay parameter (τ) was defined to capture the change in behavior during drying associated with blister formation and propagation
- This parameter was extracted from each daily cycle by establishing a search window to find the peak current value
- A cumulative sum approach was used to establish a threshold indicating a change in the behavior of τ



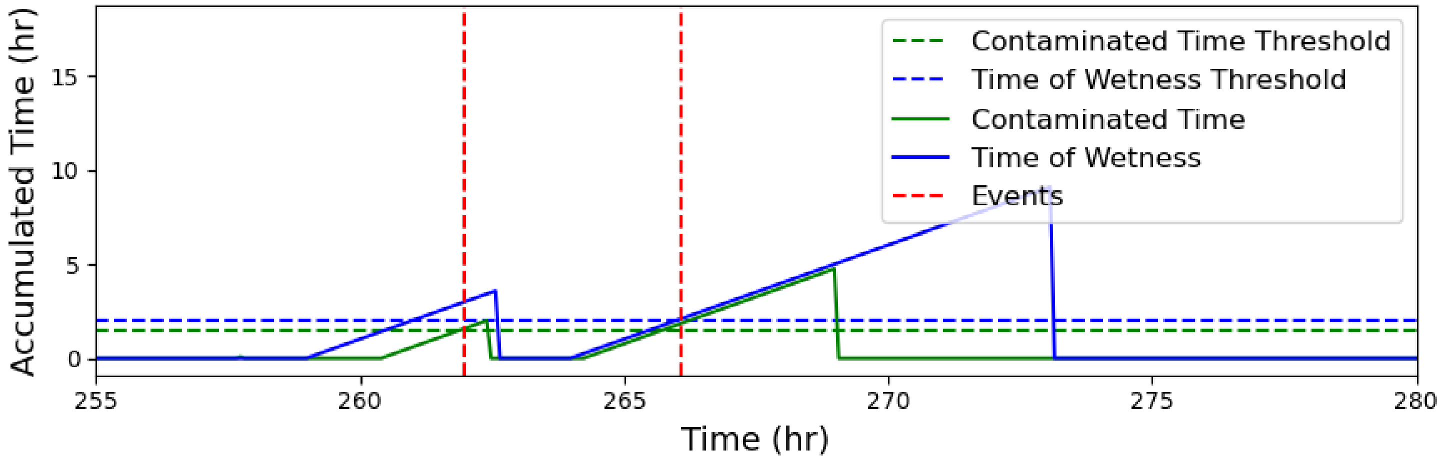
Corrosion Events

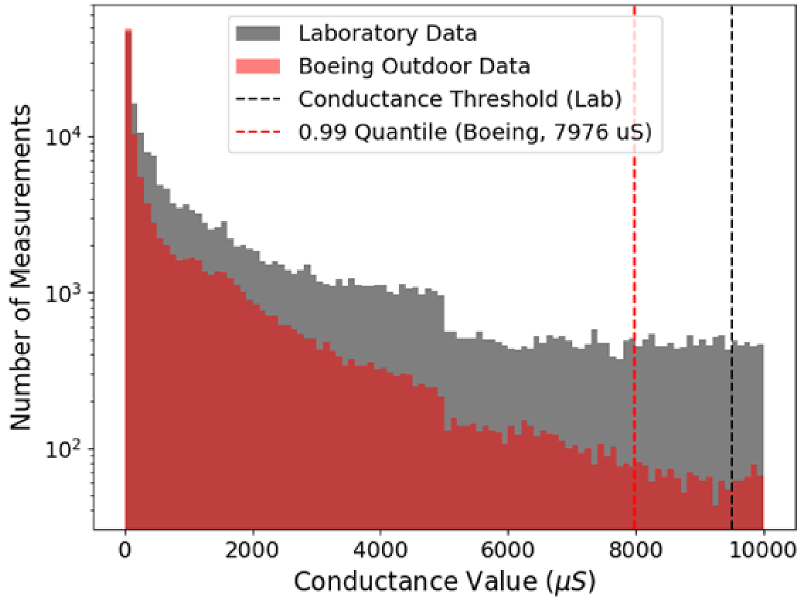
- Assumes that high corrosion events, rather than average corrosion behavior, predict time to failure
- Periods of high-corrosion self-perpetuate and cause damage to the coating
- High corrosion events defined using a moving average threshold and extracting local maxima
- Events extracted with this technique were used in subsequent stochastic modeling



Environmental Events

- Outdoor conditions don't have the same consistent daily cycles as the laboratory data so knowing when to look for τ can be difficult
- An environmental event occurs when both conditions are met:
  - RH ≥ 70 % for 2 hours
  - Conductance ≥ 9,500 μS for 0.5 hours
    - This threshold was lowered for outdoor conditions to approximately 8000 μS due to fewer contaminants on the surface





Predicting Events and Determining Failure Windows

Modeling Process

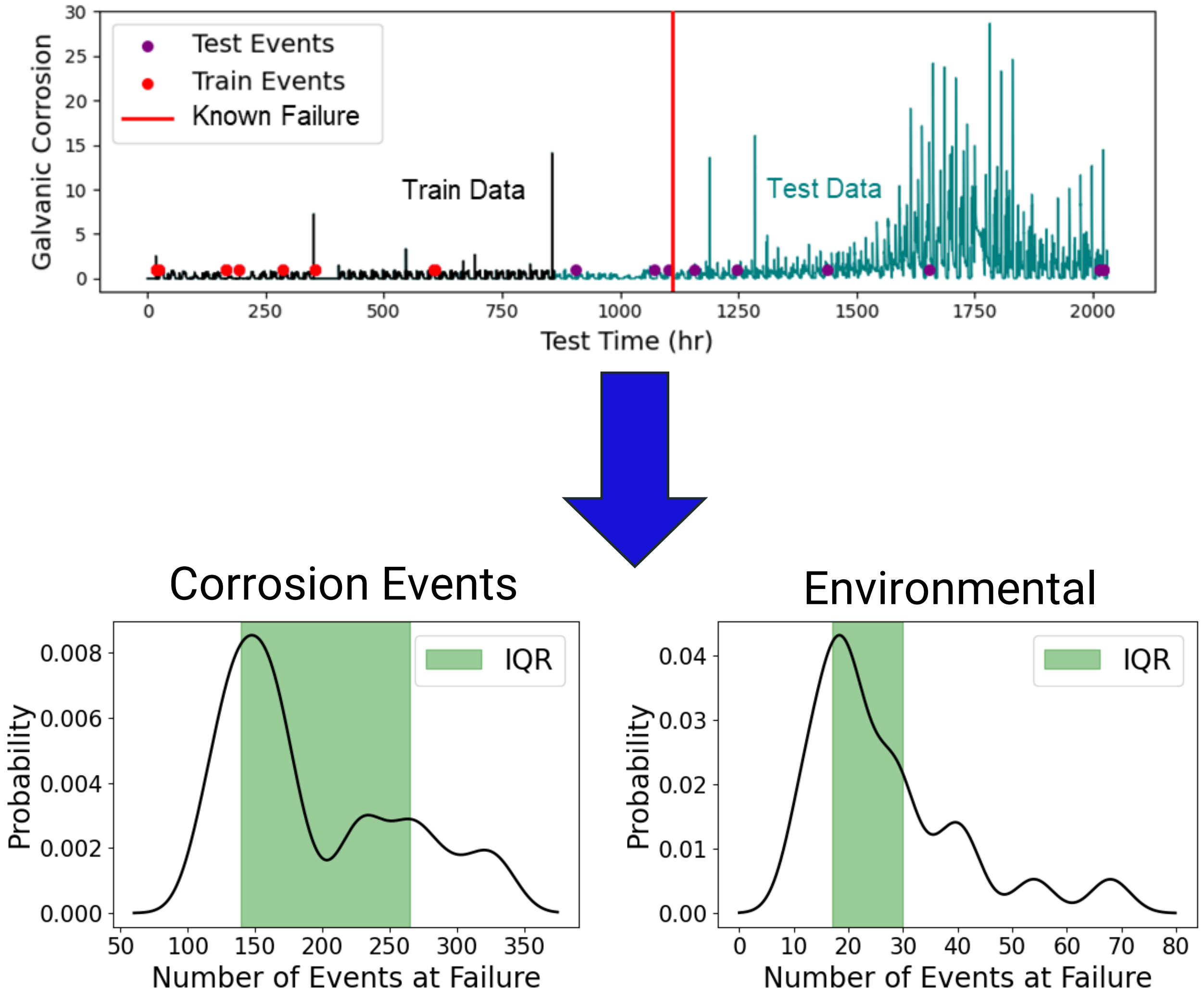
$$\lambda(t|\mathcal{H}_t) = \alpha \cdot \mu(t) + \omega \sum_{\{i\,:\,t_i \in \mathcal{H}_t\}} m_i \cdot \beta \cdot exp\left(-\beta(t - t_i)\right)$$

$\mathcal{H}_t$: history of degradation events
t_i: time of the event
m_i: magnitude of the event
$\mu(t)$: background intensity
β: self-excitation on influence decay
α and ω: relative impact of background and self excitation

A Hawkes Process was used to predict corrosion and environmental events

- Trained on ¼ of devices to develop the relationship between number of events and failure
- Coefficients (β, α and ω) for the Hawkes Process were optimized through maximum likelihood estimation
- Inputs from all sensors were then used to predict the time for the highest probability of failure
- A failure prediction window was established based on the interquartile range

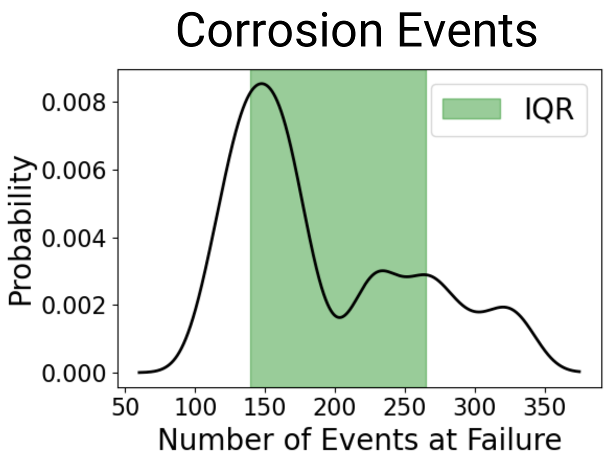
Implementation

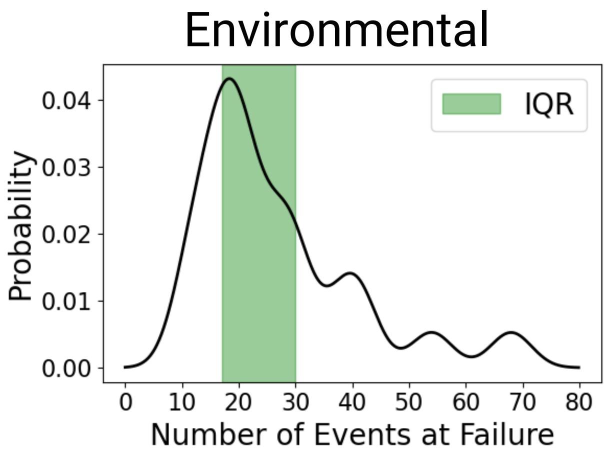


- Train the model to detect events
- Test event detection
- Apply to remaining sensors
- Determine the number of events before coating failure

- Determined probability of failure depending on the number of events
- Established probability of failure window based on the Interquartile Range (IQR)

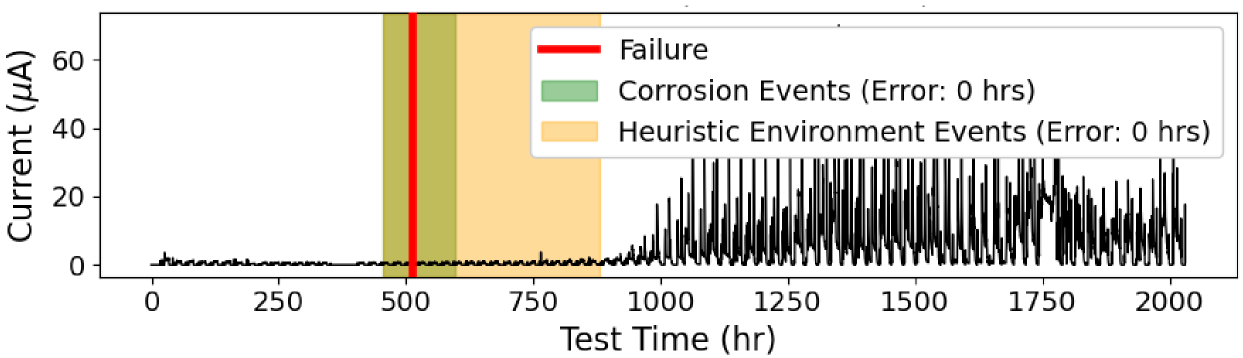
Implementation

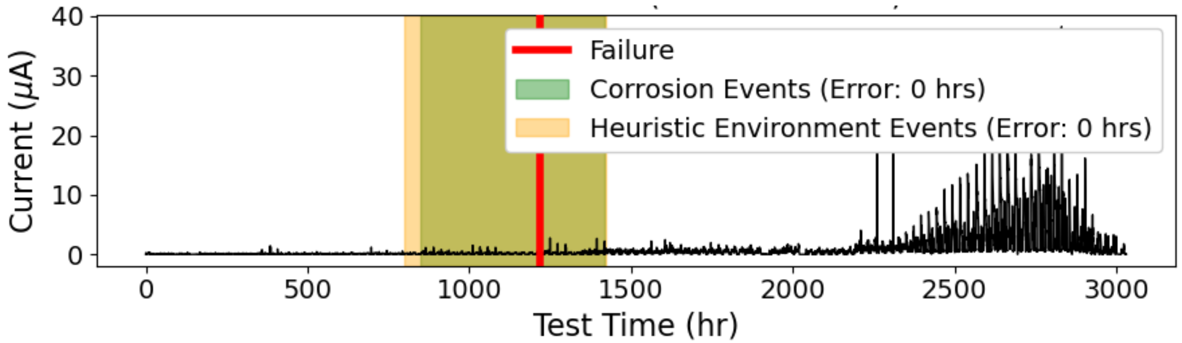




- Determined probability of failure depending on the number of events
- Established probability of failure window based on the Interquartile Range (IQR)

- The windows are applied to the remaining data sets





Results

Laboratory Model Results

- The model based on corrosion events was better able to predict the true failure
- The environmental events resulted in a larger time window

Type of samples	Number of samples	Percentage of true failure within prediction window		Avg. prediction window size [hrs]	
		Corrosion-event model	*Environmental-event model*	*Corrosion-event model*	*Environmental-event model*
Validation-only (chromate & non-chromate)	6	67%	17%	225	327
All non-chromate	15	60%	33%	195	241
All chromate	9	44%	44%	257	530
All samples (chromate & non-chromate)	24	54%	38%	218	350

Outdoor Model Results

- Only the environmental events were used to predict windows for the outdoor samples, the corrosion events do not account for the dynamic environment
- Larger prediction windows are a reflection of the larger time scales observed for outdoor testing
- Only 6 samples were available so additional optimization and validation are required, the current model failed to predict an accurate failure window for the chromate samples

Type of samples	Number of samples	Percentage of true failure within prediction window	Avg. prediction window size [hrs]	Avg. time interval of missed failure [hrs]
All non-chromate	3	100%	916	N/A
All chromate	3	0%	924	950
All samples (chromate & non-chromate)	6	50%	920	475

Conclusions

Conclusions

- A novel statistical modeling framework to predict coating failure was developed from real-time electrochemical monitoring and visual inspection during laboratory testing and indicating viability when extending to other coatings and outdoor testing measurements
- Two types of discrete events leading to coating failure were identified, a corrosion-current-based event and an environmental condition-based event
- Coating failure predictions during laboratory testing provided narrow failure prediction windows while accurately capturing failure, independent of coating type (chromate or non-chromate)

Acknowledgements

- This material is based upon work supported by the SERDP Program under WP19-1168. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the project sponsors.

- Thank you to Georgia Tech for all their modeling efforts and our collaborators SwRI and Boeing.

Questions?

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