WP19-1017

An Experimental and Finite Element Modeling Approach to Determining of Aircraft Coating Systems

Steven A. Policastro

Center for Corrosion Science and Engineering, U.S. Naval Research Laboratory

4555 Overlook Avenue SW, Washington, DC 20375

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Steve Policastro
Carlos Hangarter
Rachel Anderson
Attilio Arcari
Erick Iezzi

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14. ABSTRACT
The technical objectives of this project are listed below:
- Develop an improved theoretical understanding of organic coating system deterioration due to exposure to environmental stressors.
- Quantify how static and dynamic environmental conditions influence coating system deterioration over the duration of laboratory aging conditions and outdoor exposures.

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corrosion, repair technologies, analysis of failure modes, computational methods and modeling

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Project Team

- Steven A. Policastro, Rachel M. Anderson, Carlos M. Hangarter, Attilio Arcari, and Erick Iezzi

- Center for Corrosion Science and Engineering, U.S. Naval Research Laboratory
- 4555 Overlook Avenue SW, Washington, DC 20375

Background

- Galvanic corrosion on airframes
  - ♦ Enormous cost to Naval air fleet
  - ♦ Coatings are first line of defense
- However, coating systems
  - ♦ Contain hazardous chemicals
  - ♦ Paint/Depaint actions expose workers and generate waste

Molent, L.; Wanhill, R. Management of Airframe In-Service Pitting Corrosion by Decoupling Fatigue and Environment. *Corros. Mater. Degrad.* **2021**, 2, 493-511.

Brandice J. O'Brien, Tinker Public Affairs

Technical Objectives

- Develop an improved theoretical understanding of organic coating system deterioration due to exposure to environmental stressors.
- Quantify how static and dynamic environmental conditions influence coating system deterioration over the duration of laboratory aging conditions and outdoor exposures.

Technical Approach

Task 1
Coating transport mechanisms under simulated field conditions

- Immersion testing
- Salt spray exposure
- Humidity cycling

Task 2
Loading coating systems under simulated field conditions

- Coating tensile testing
- Static load testing

Task 3
Finite element analyses of crack propagation and stress fields

- Stress state in coating systems
- Crack propagation in coating system

Task 4
Outdoor exposure testing and predictive model development

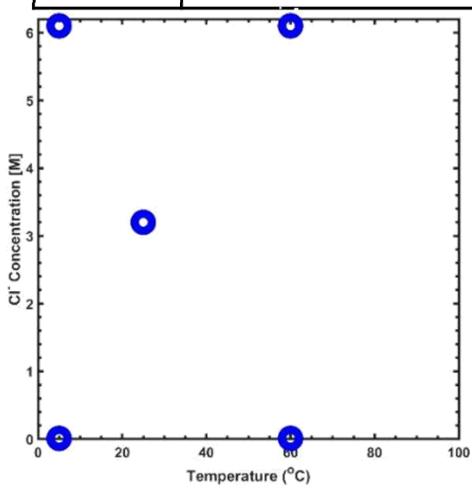
- Development of cumulative coating damage model
- Outdoor exposure and fatigue testing of coatings at C-CoAST facility

Results

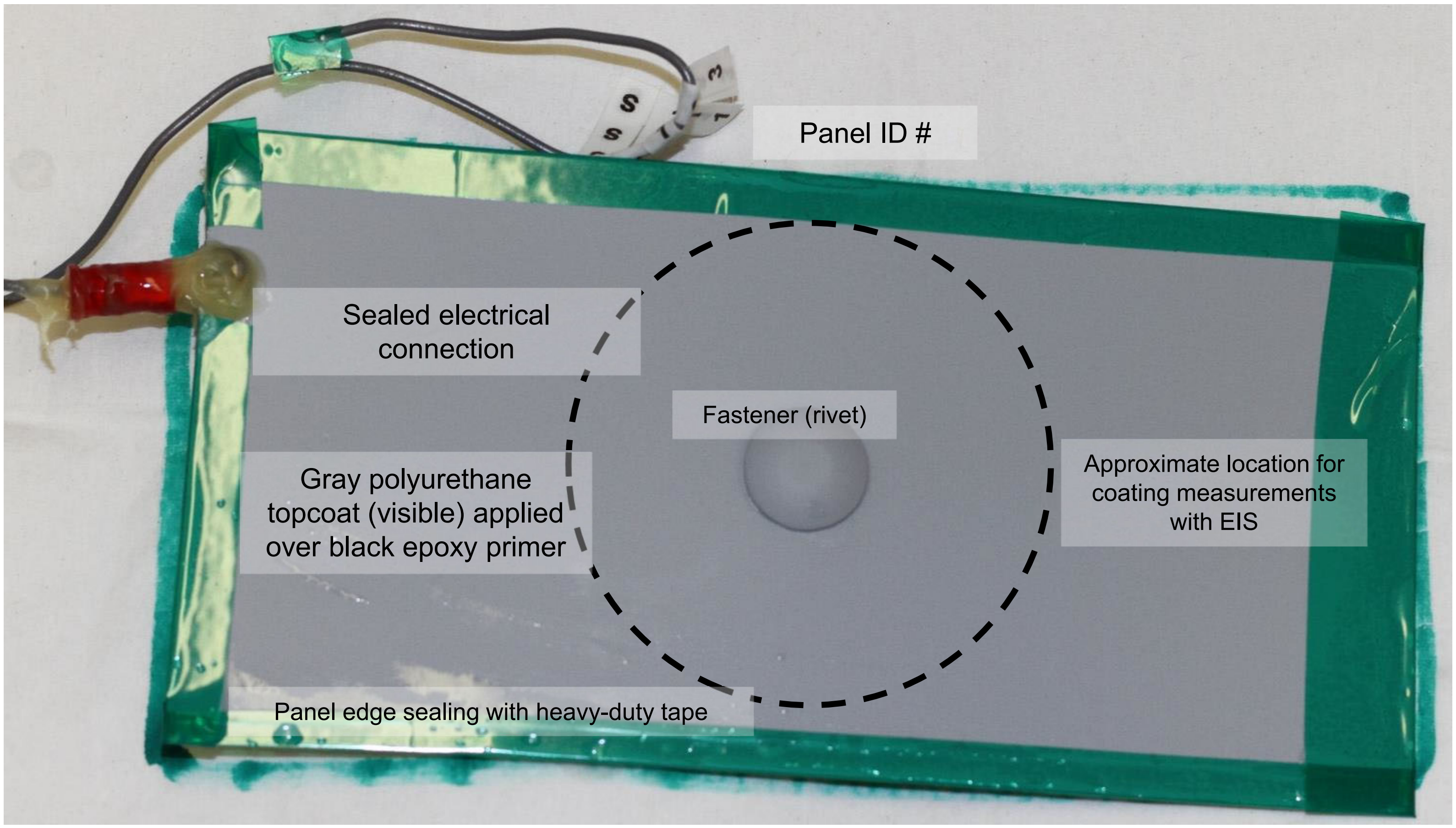
- Coating exposures under laboratory conditions
  - Immersion in NaCl solutions at different concentrations and temperatures
  - QUV and salt spray
- Develop of ML model to analyze EIS data
- Development of models for water uptake by polymers and physics-based models of equivalent circuits
- Measurements of mechanical properties of organic coatings – both newly cured and after outdoor exposures
- FEM of crack propagation in organic coatings
- Fatigue measurements of supported and unsupported coatings
- Comparison of predictions of color change due to exposure from EIS measurements – using models developed in SERDP Program PP1133

Task 1 - Coating Transport Mechanisms Under Simulated Field Conditions

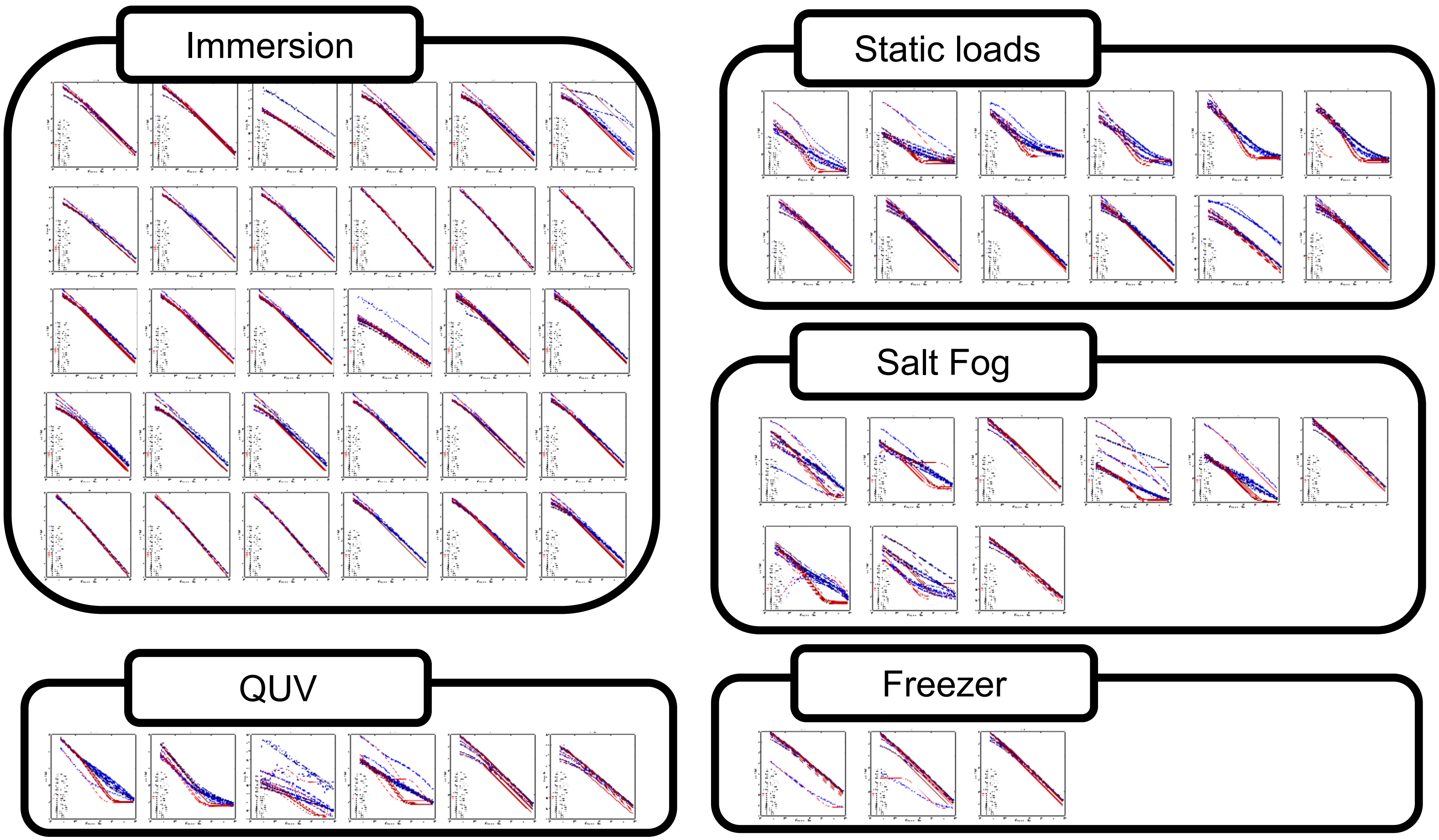
Task	Description	Factors	
		A	B
1	Coating System Immersion (3192 and 6840 h)	Temperature: 5°C, 25°C, 60°C	Cl^- concentration: 0.01 M, 3.2 M, 6.1 M



Representative Experimental Test Panel

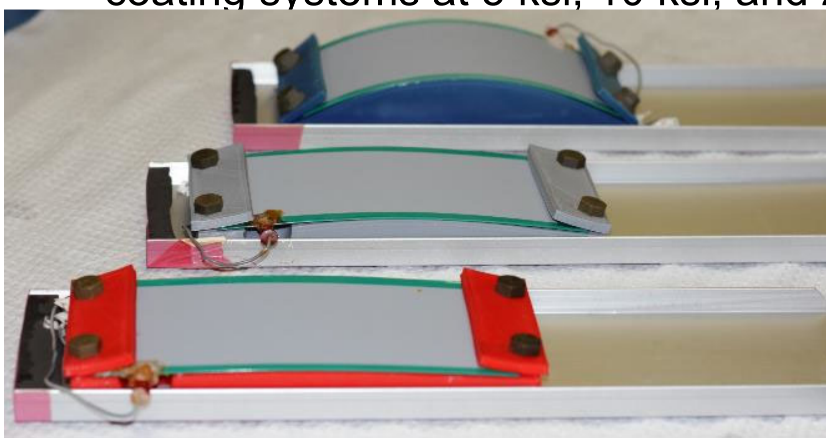


EIS Measurements of Laboratory Exposures

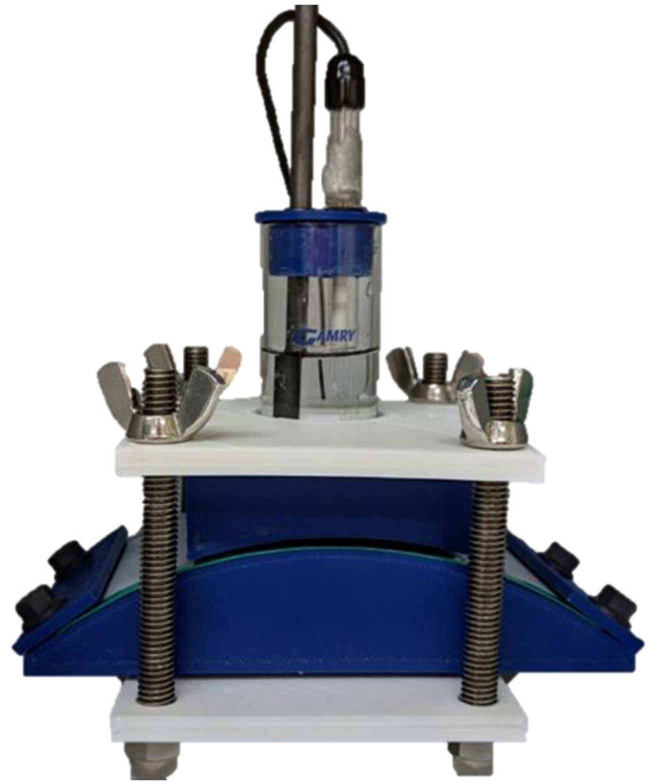


Task 2 - Loaded Coating Systems Under Simulated Field Conditions

- Simulation of coating system under ground / sea-level conditions
- Flat panels and bolt-on assemblies with static loads of coating systems at 5 ksi, 10 ksi, and 2% strain

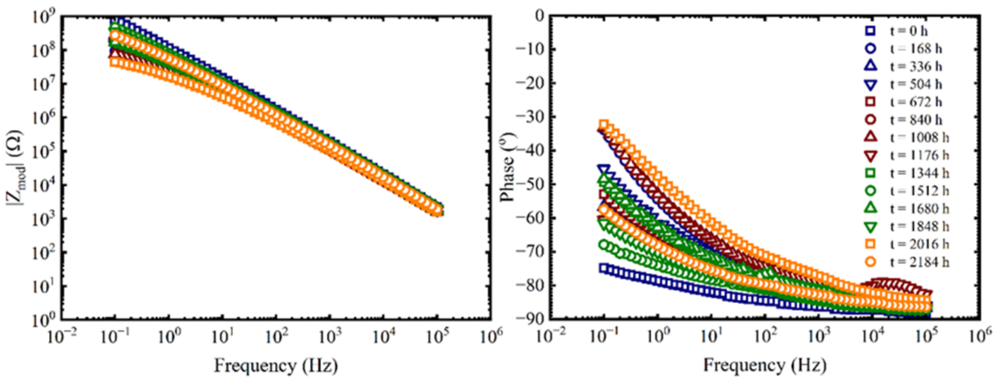


Panel mounts to apply static loads to the coating system. From bottom to top: 34.5 MPa load, 69 MPa load, 2% strain

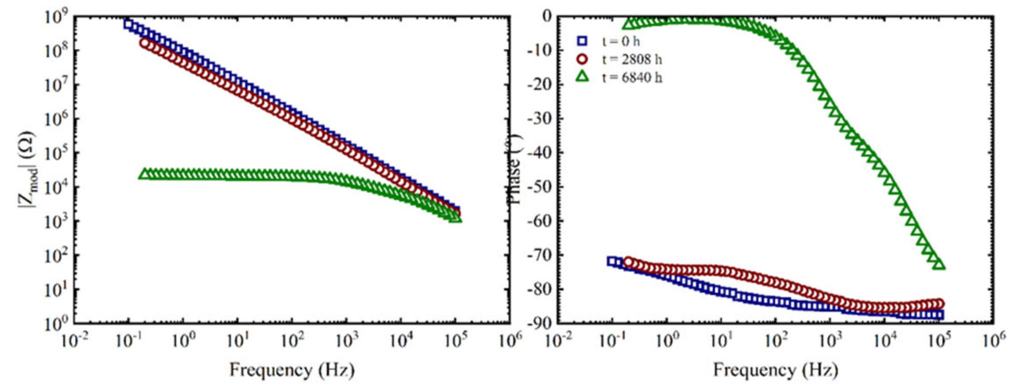


B117 - Salt Spray Testing

- Unstressed coating system aged in ASTM B117 salt spray



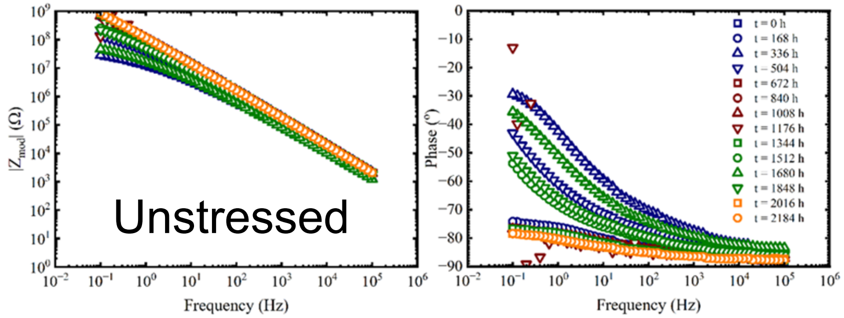
2184 h

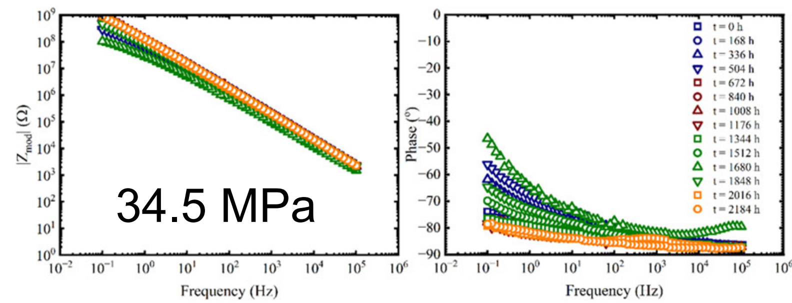


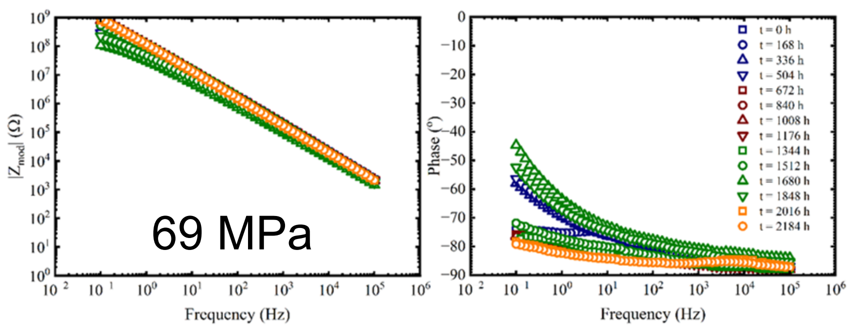
6840 h

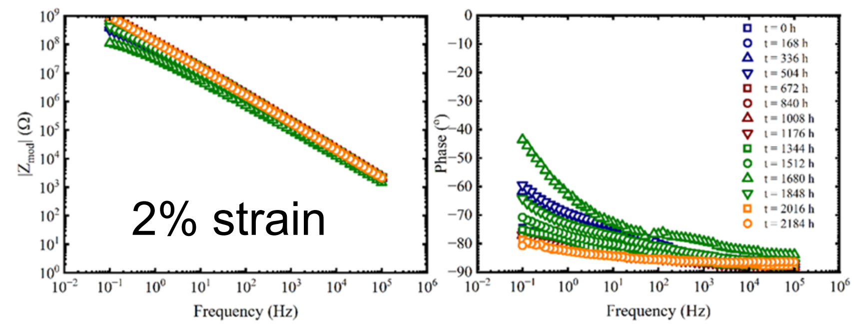
Stressed and Unstressed Panels – 2184 h

- Heated at 45°C for 3 hours in darkness, condensation from a deionized water mist for 9 hours at 45°C, followed by 12 hours of UV irradiance at an intensity of 1.46 W/m^2









Stressed and Unstressed Panels – 6840 h

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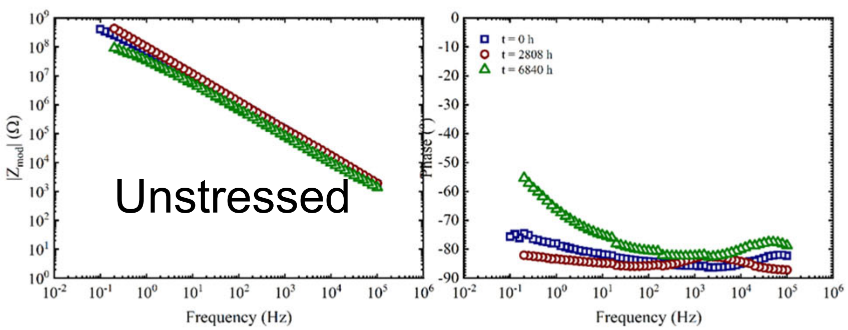
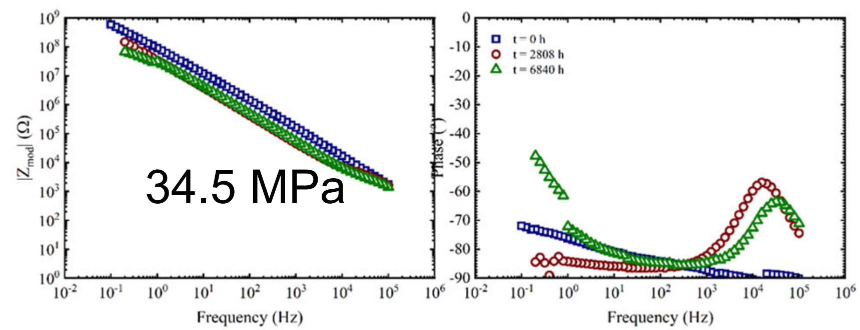
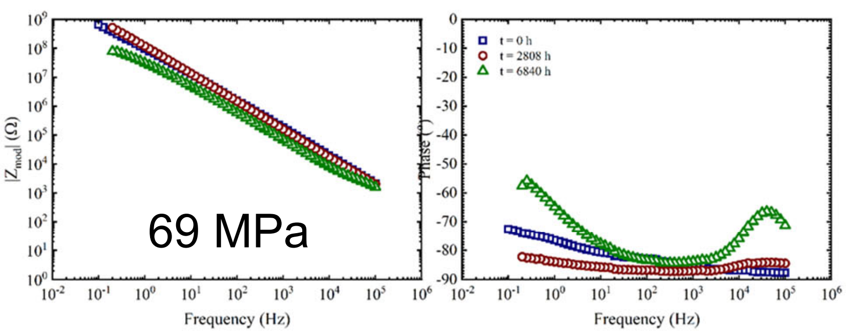
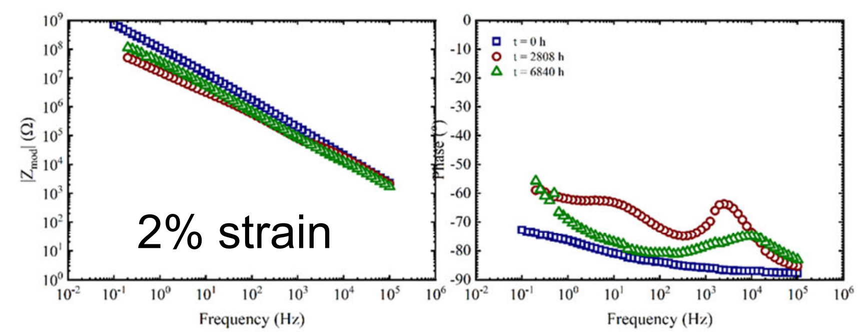


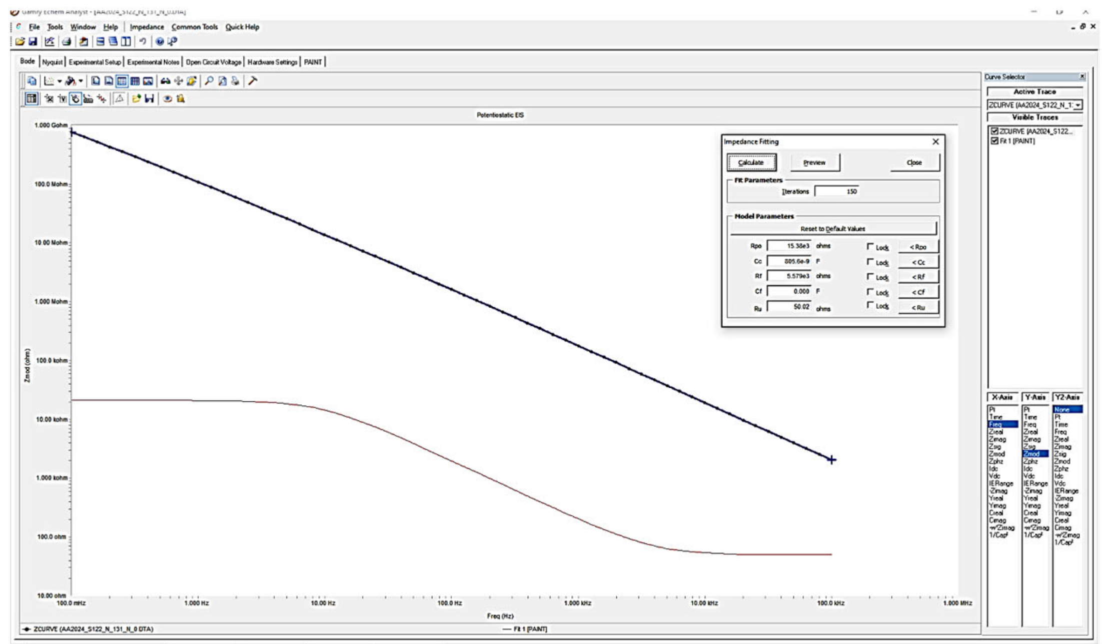






Challenge with EIS Data

- EIS data, on its own, presents an incomplete picture of the state of the coating system
- Equivalent circuit modeling of the system's impedance response can provide insight into the underlying mechanisms that give rise to the impedance
- Estimates of equivalent circuit parameters are obtained from nonlinear regression of model response to measured data
- Obtaining "good" fits can be challenging!



<u>Goal</u>: Inform initial guesses of parameter values using physics-based models

A Brief History of Equivalent Circuit Models for Coatings

- In the beginning….
- Coating as a resistive layer

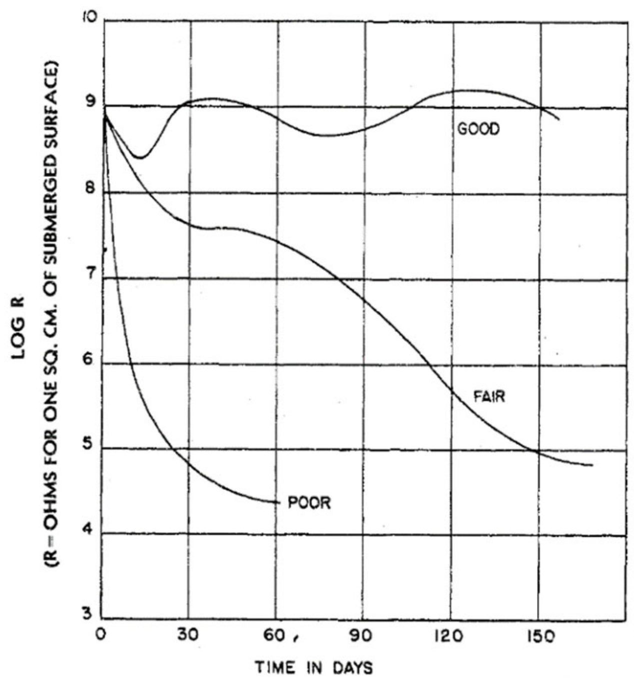


Figure 2. Schematic Resistance Behavior of Coatings on Immersed Metals

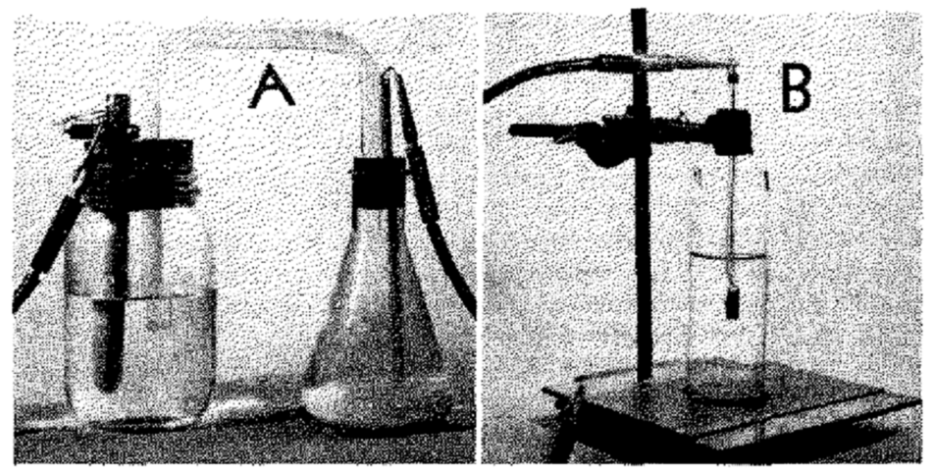
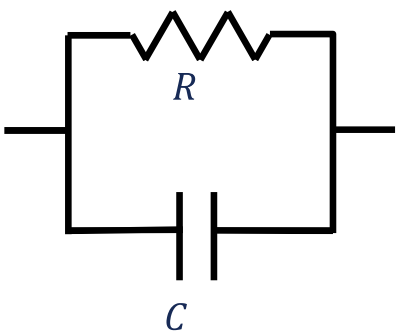


Figure 3. Test Cells

Bacon, R. C., Smith, J. J., Rugg, F. M., *Electrolytic Resistance in Evaluating Protective Merit of Coatings on Metals,* Ind. Eng. Chem. 1948, 40, 1, 161–167

Dielectric Properties of Coatings

- Water permeation changes the film capacitance



$$X_v = \frac{\ln \frac{C_t}{C_0}}{\ln \epsilon_{H_2O}}$$

Brasher, D.M. and Kingsbury, A.H. (1954), *Electrical measurements in the study of immersed paint coatings on metal. I. Comparison between capacitance and gravimetric methods of estimating water-uptake*. J. Appl. Chem., 4: 62-72

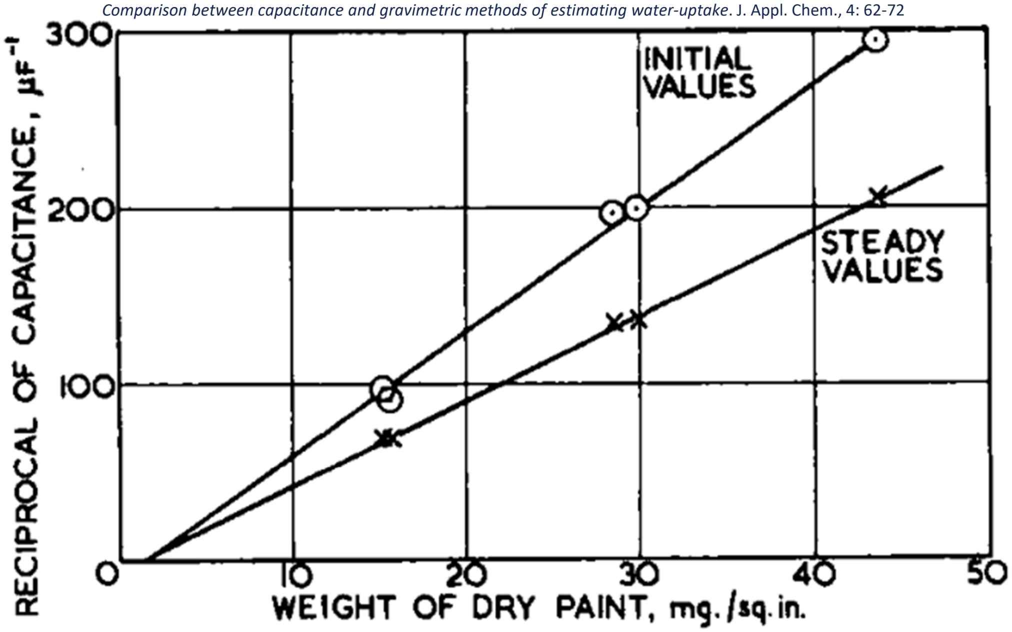
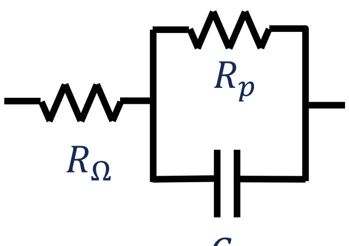


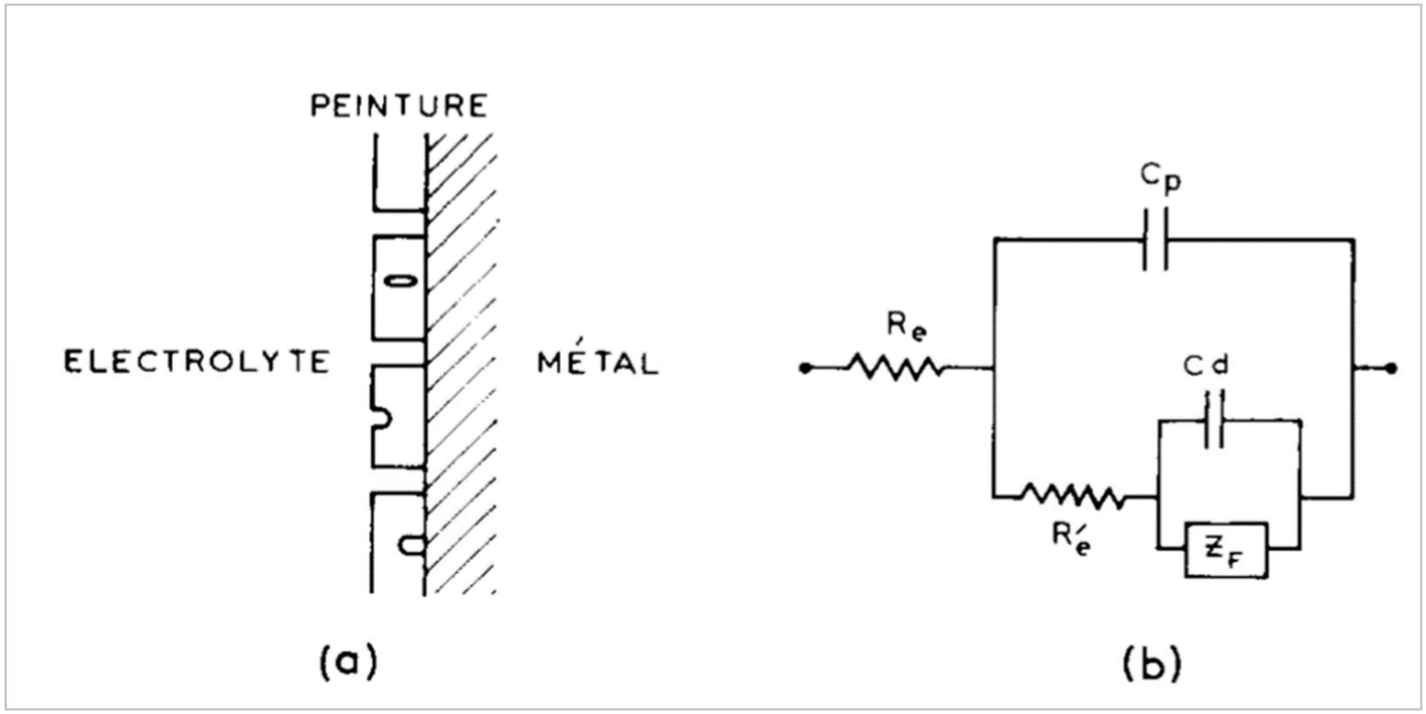
FIG. 1. *Reciprocal of capacitance against thickness (weight per unit area) of paint*

Incorporating Coating Flaws Into Impedance Models

- Ideal coating:
  - ♦ R_{Ω} = electrolyte resistance
  - ♦ R_p = coating resistance
  - ♦ C_p = polymer capacitance



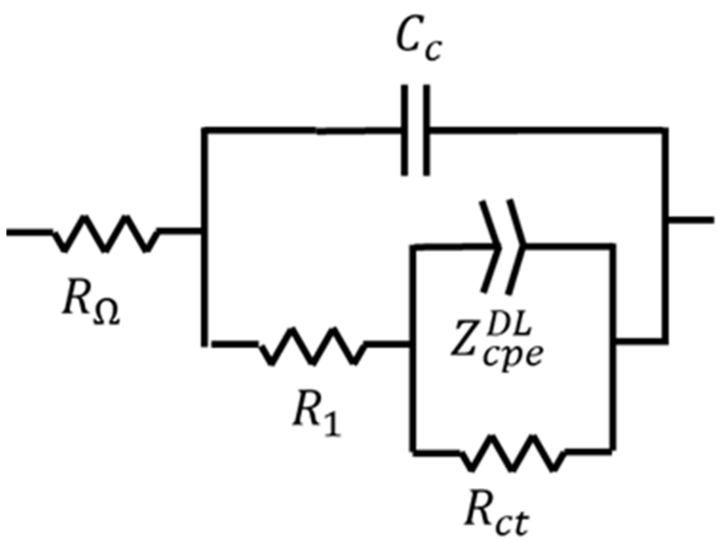
- Coating with flaws:



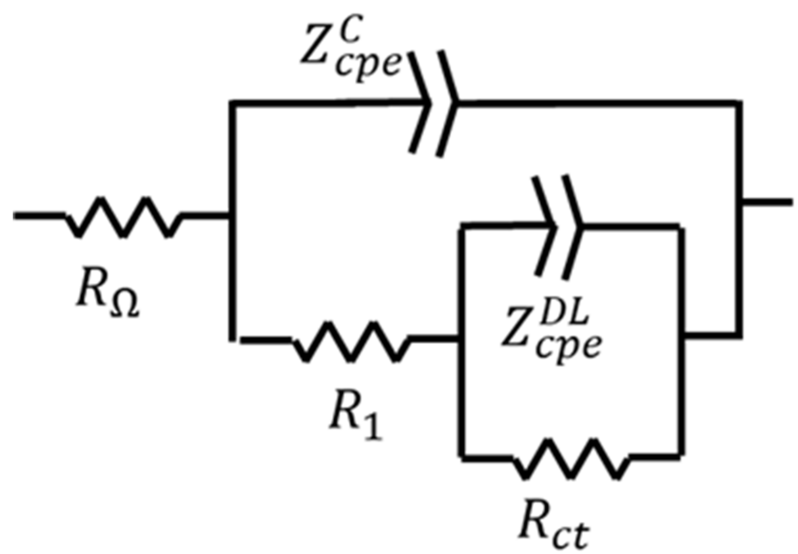
L. Beaunier, I. Epelboin, J.C. Lestrade, H. Takenouti, *Etude electrochimique, et par microscopie electronique a balayage, du fer recouvert de peinture*, Surface Technology, 4 (1976), 3, 237-254,

Refinements: Non-ideal Capacitor Behavior

- REAP and siblings



Kendig, M.W., Jeanjaquet, S. L., Brown, R., and Thomas, F., *Rapid electrochemical assessment of paint,* Journal of Coatings Technology, 68 (1996), 39-47



S Duval, Y Camberlin, M Glotin, M Keddam, F Ropital, H Takenouti, *Characterisation of organic coatings in sour media and influence of polymer structure on corrosion performance*, Progress in Organic Coatings, 39 (2000), 1,15-22,

Parameter Estimation for a Nonlinear System

- How to obtain parameters for the equivalent circuit model fits?
- Non-linear regression analysis
  - Gauss-Newton algorithm
  - Levenberg-Marquardt algorithm
- Iterate until convergence criteria met
- Approach:
- $Z^M(\omega_i, \theta_j) = y(\omega_1, \omega_2, \ldots \omega_N;\ \theta_1, \theta_2, \ldots \theta_k,)$
- Objective function:
- $\epsilon_i = Z^D(\omega_i) - Z^M(\omega_i, \theta_j)$
- $S(\theta) = \sum_{i=0}^{N-1} (\epsilon_i)^2$

$$\theta_i = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{bmatrix}$$

$$J = \begin{bmatrix} \frac{\partial S(\omega_0)}{\partial \theta_1} & \cdots & \frac{\partial S(\omega_0)}{\partial \theta_k} \\ \vdots & \ddots & \vdots \\ \frac{\partial S(\omega_{N-1})}{\partial \theta_1} & \cdots & \frac{\partial S(x_{N-1})}{\partial \theta_k} \end{bmatrix}$$

$$(J^T J + \lambda \times diag(J^T J))p = J^T [Z^D - Z^M]$$

$$p = \frac{J^T [F(y, \hat{y})]}{J^T J + \lambda \times diag(J^T J)}$$

$$\theta_{k+1,j} = \theta_{k,j} + p$$

$$\lambda_0 \approx 0.01$$

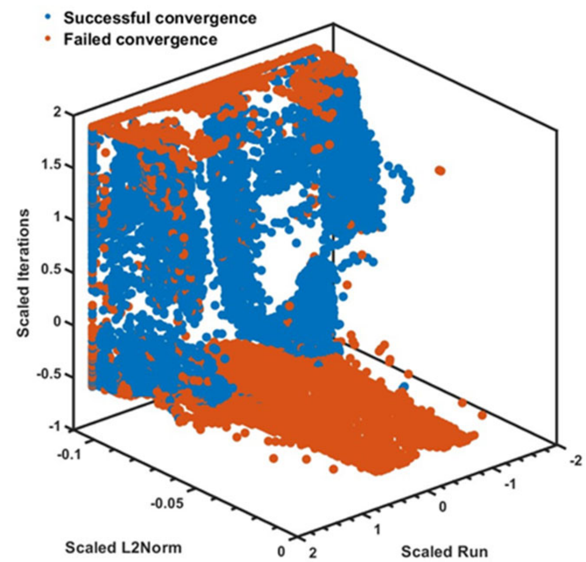
- Approach for performing this matrix operation: $Ax = b$

$$S(\theta_{i+1,k}) \leq S(\theta_{i,k})$$

$$\left| \frac{p(\theta_i)}{\theta_i + \tau} \right| \leq \delta$$

Construct Datasets for ML Training - Convergence

- Featured of the datasets for ML model training
  - ♦ Run parameter – specified how the initial parameters for the fit were determined
  - ♦ L^2-norm of the fit
  - ♦ Number of iterations
- Features were scaled
  - ♦ $X' = \frac{X-\mu}{\sigma}$
  - ♦ X = standard value,
  - ♦ μ = mean,
  - ♦ σ = standard deviation



Successful and unsuccessful convergence as functions of the scaled features for the C0.8 training set. Initial estimates that established large L^2- norm values generally failed to converge

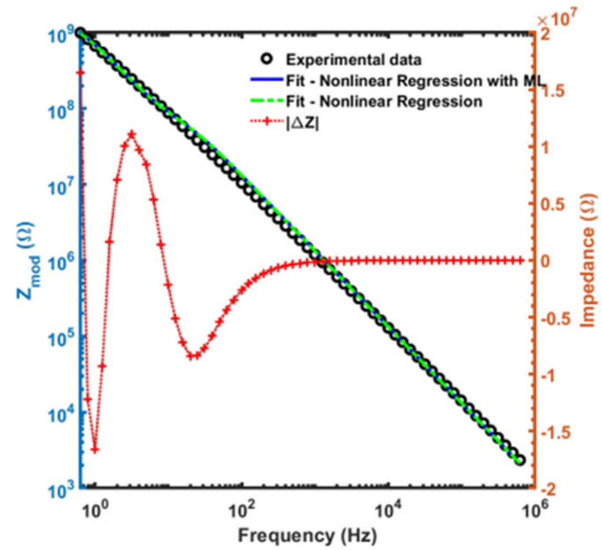
Trainer Evaluation – Convergence

- Binary Classification
  - Logistic regression
  - Support vector machines
  - Gradient boosted algorithms
- Best option:
  - Gradient boosting decision tree trainer: LightGBM

	Testing Set					
Training Set	**F**	**Q**	**U**	**S**	**I**	**C0.2**
F	1.00	0.93	0.93	0.92	0.94	-
Q	0.97	0.99	0.95	0.93	0.93	-
U	0.96	0.93	0.99	0.93	0.92	-
S	0.96	0.93	0.94	0.99	0.95	-
I	0.97	0.91	0.92	0.92	0.98	-
C0.8	0.97	0.95	0.96	0.96	0.95	0.97

Comparison

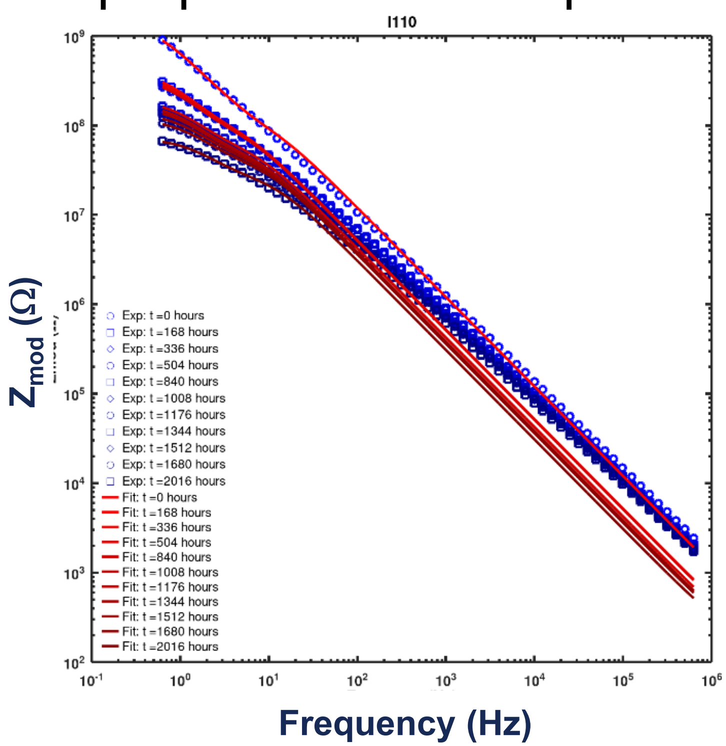
- Use of ML models decreased execution time:
  - Compared 740 individual EIS measurements
    - Submitted to original algorithm and algorithm with both ML models
  - Using the ML models: t = 87 s
  - Classical algorithm: t = 4657s.
  - ML models offered ~53x improvement (execution time)
- Difference between model impedance that did converge and the one that did not roughly 1.7%.

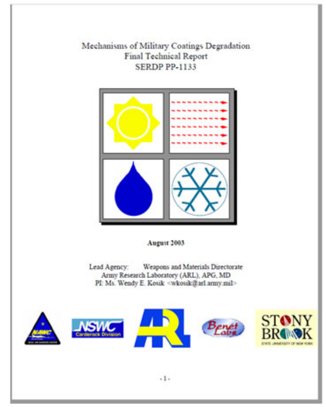


Z_{mod} vs. frequency data overlaid with equivalent circuit models on the left axis. One fit algorithm used the ML models to provide the initial estimate, and the other fit algorithm did not. The difference between the two fits as a function of frequency is shown on the right axis

Initial Approach

- Attempt to model changes in coating properties with simple diffusion model




Mechanisms of Military Coatings Degradation
Final Technical Report
SERDP PP-1133

August 2003

Lead Agency: Weapons and Materials Directorate
Army Research Laboratory (ARL), APG, MD
PI: Ms. Wendy E. Kosik <wkosik@arl.army.mil>

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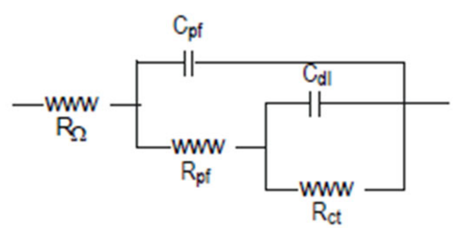
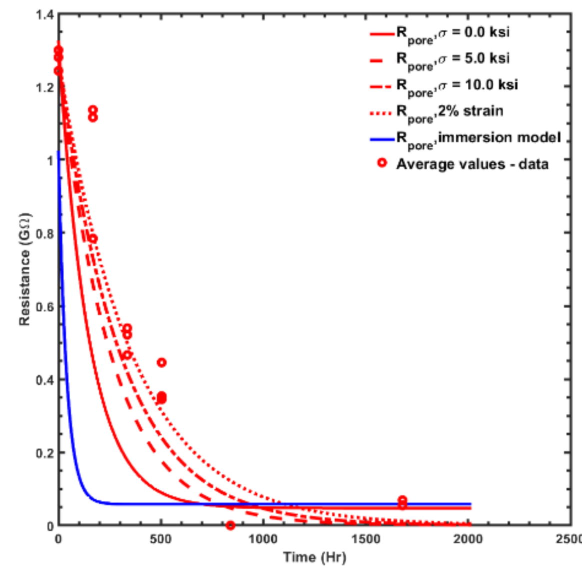
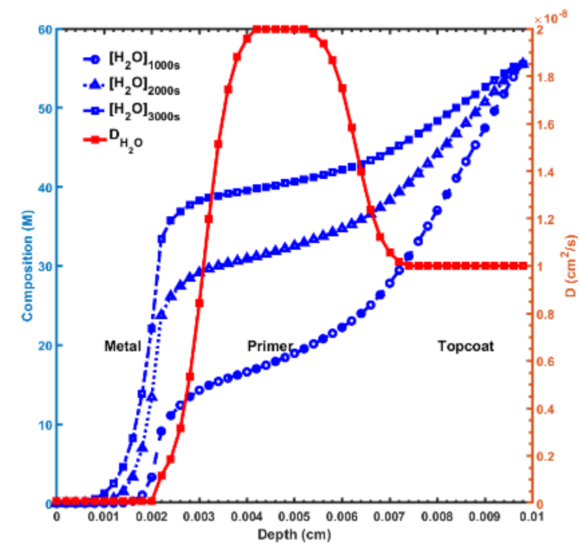


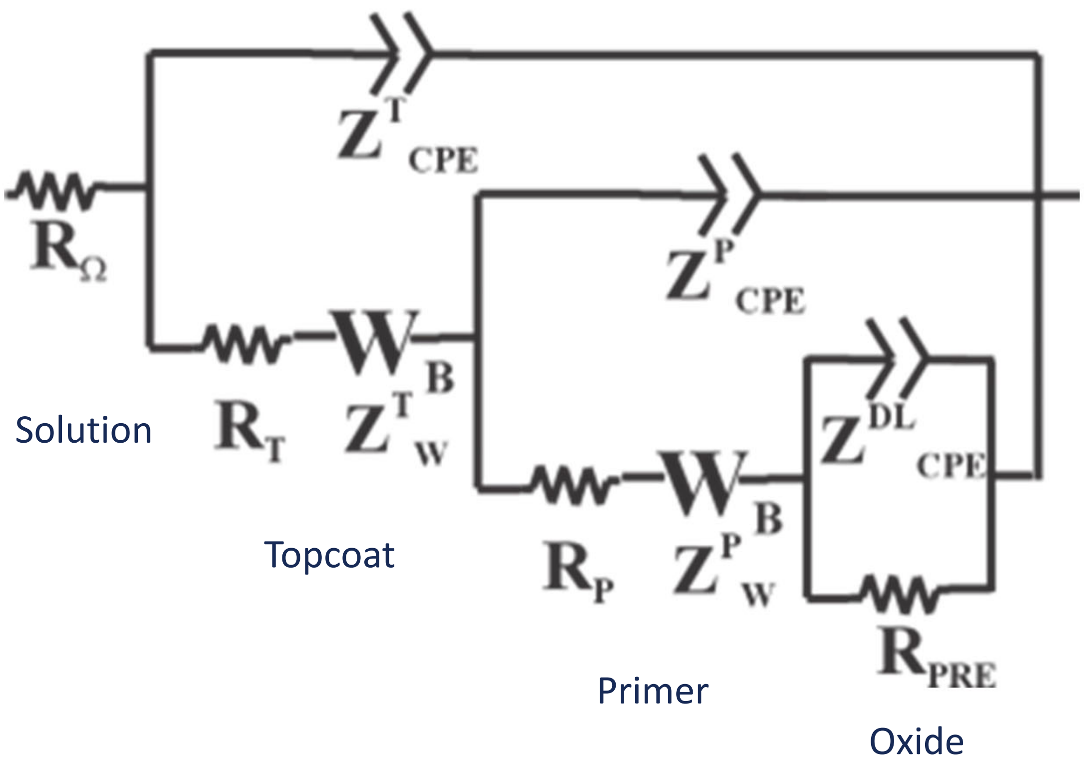
Figure 2. 5-Element Equivalent Circuit model





Extended Modified REAP Circuit

- Capture behavior from two organic coating layers



$$\begin{bmatrix} A_{00} & A_{01} & A_{02} & A_{03} \\ A_{10} & A_{11} & A_{12} & A_{13} \\ A_{20} & A_{21} & A_{22} & A_{23} \\ A_{30} & A_{31} & A_{32} & A_{33} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \end{bmatrix} = \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix}$$

$$A_{00} = Z_{R_\Omega} + Z_{R_t} + Z_W^t + Z_{R_p} + Z_W^p + Z_{R_{pre}}$$

$$A_{11} = Z_{R_\Omega} + Z_{R_t} + Z_W^t + Z_{R_p} + Z_W^p + Z_{\text{cpe}}^{\text{pre}}$$

$$A_{22} = Z_{R_\Omega} + Z_{R_t} + Z_W^t + Z_{cpe}^p$$

$$A_{33} = Z_{R_\Omega} + Z_{cpe}^t$$

$$A_{01} = A_{10} = Z_{R_\Omega} + Z_{R_t} + Z_W^t + Z_{R_p} + Z_W^p$$

$$A_{02} = A_{20} = A_{21} = A_{12} = Z_{R_\Omega} + Z_{R_t} + Z_W^t$$

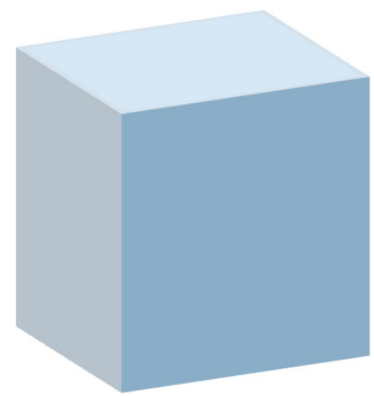
$$A_{03} = A_{30} = A_{13} = A_{31} = A_{23} = A_{32} = Z_{R_\Omega}$$

Resistance Models

- Resistance and resistivity
- $Z_R = R = \frac{\rho l}{A}$

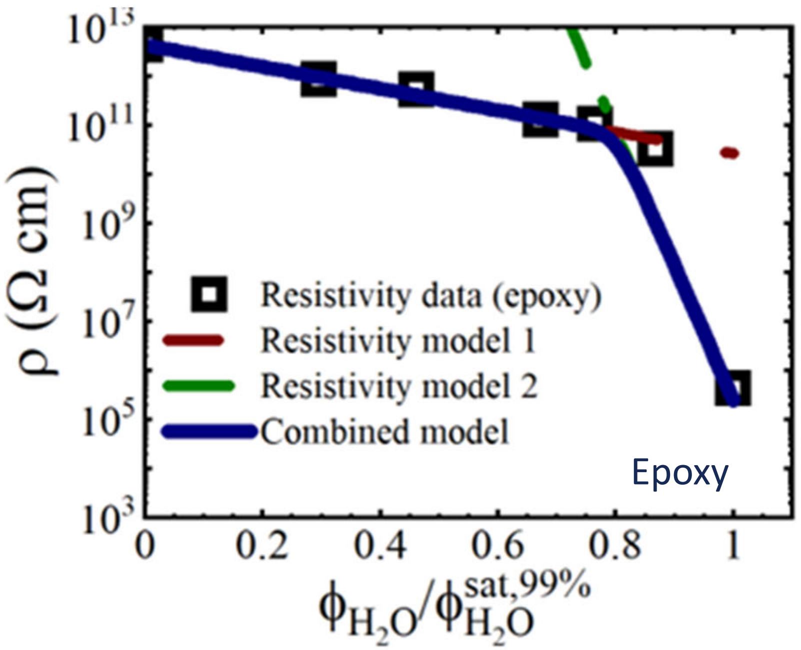
Polymer resistance

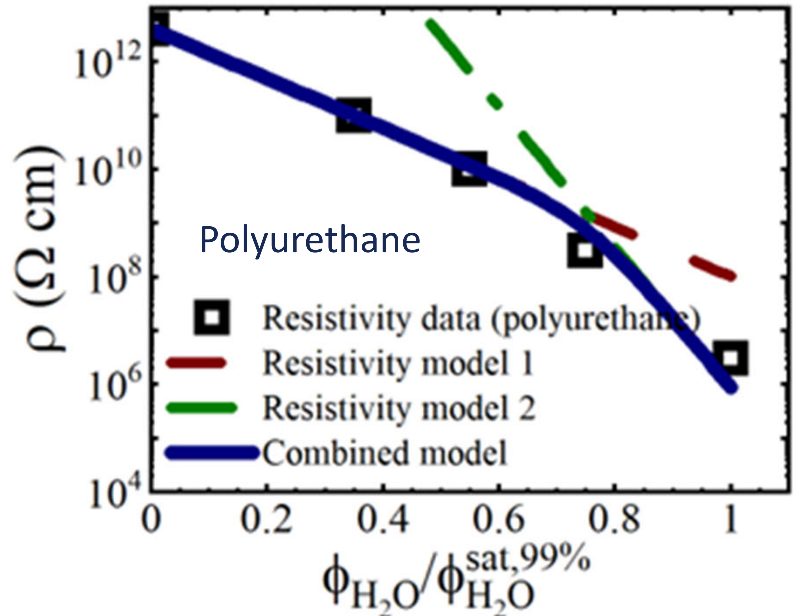
$$R_{t,p} = \frac{\rho_e d_e}{A} + \frac{\rho_p d_d}{A}$$



- Solution Resistance
- $R_\Omega = \frac{\rho c_{Cl^-} l}{A}$
- $\rho_{[Cl^-]} = \left[\frac{(0.0480+0.0034T)+(6.7545+0.2392T)[Cl^-]}{1.0+(0.2065+0.0013T)[Cl^-]}\right]^{-1}$

Polymer Resistivity





- Model of the change in the polymer resistivity as a function of time of exposure to a 99% RH environment
- $\rho = \frac{(c_1 e^{c_2 \phi})}{a_1 e^{-a_2 \phi} + e^{-b\phi}}$

Capacitance and CPE Models

- Capacitance of polymers dependent on the dielectric constant of the material

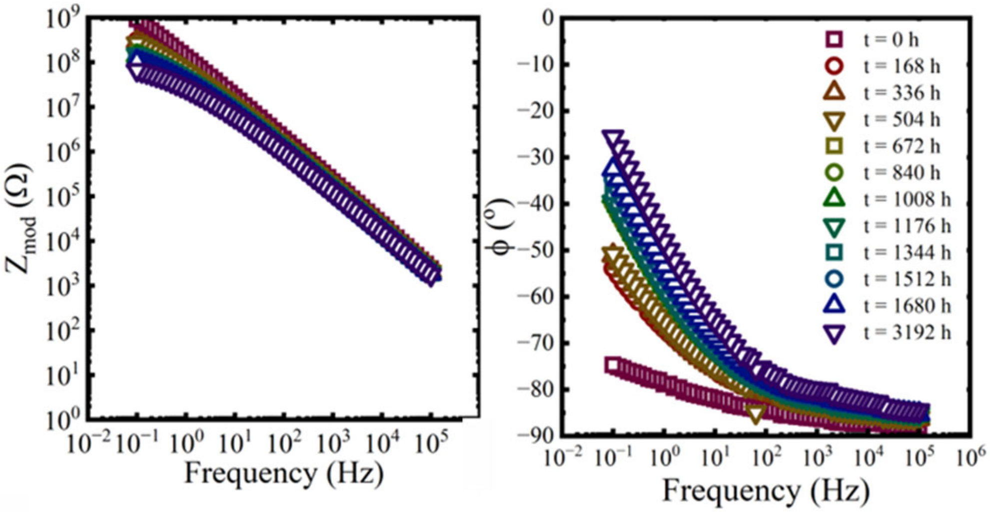
$$C = \frac{\epsilon_i \epsilon_0 A}{d} \qquad Z_c(\omega) = \frac{1}{Cj\omega}$$

$$\xi = \frac{(CR_1)^\alpha}{R_1} \qquad Z_{cpe}(\omega) = \frac{1}{\xi(j\omega)^\alpha}$$

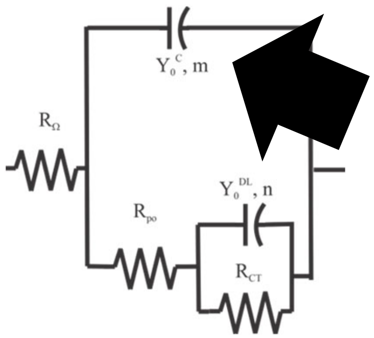
Material	**ϵ**
Water	80.1
Hydrated Al_2O_3	11.5
Epoxy	3.6
Polyurethane	5.1-6.2

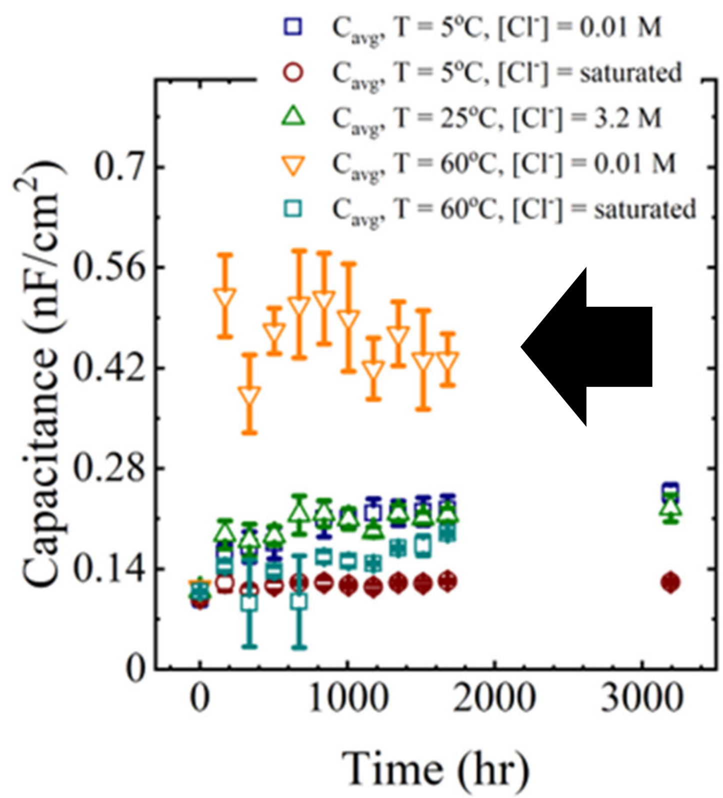
How does the dielectric constant of polymer change during immersion?

Changing capacitances as a function of immersion time



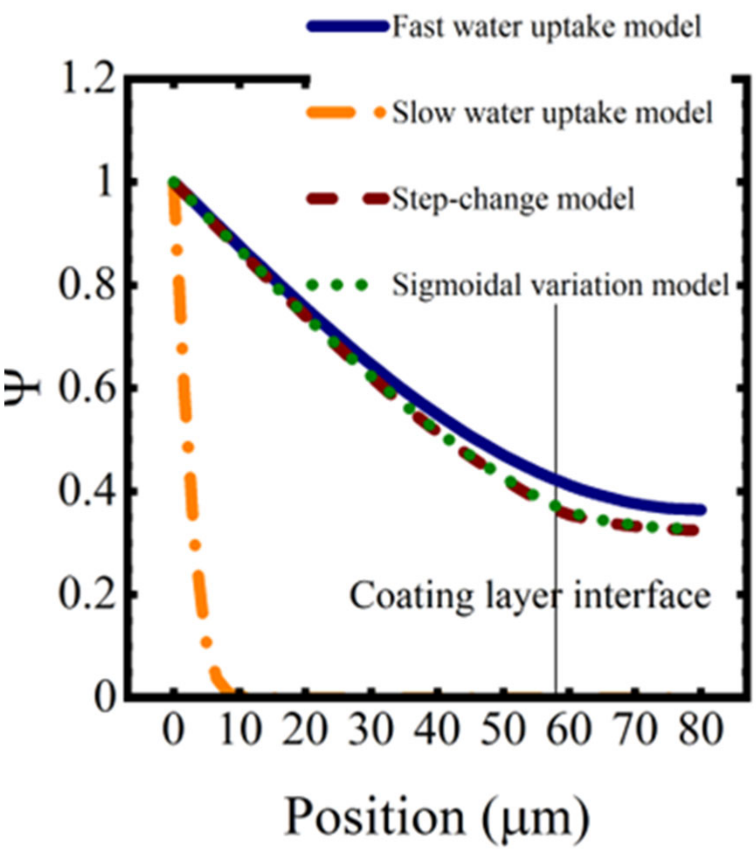
Bode representation of EIS data for a coated panel immersed in a 0.01 M NaCl solution at 5°C for 3192 h.

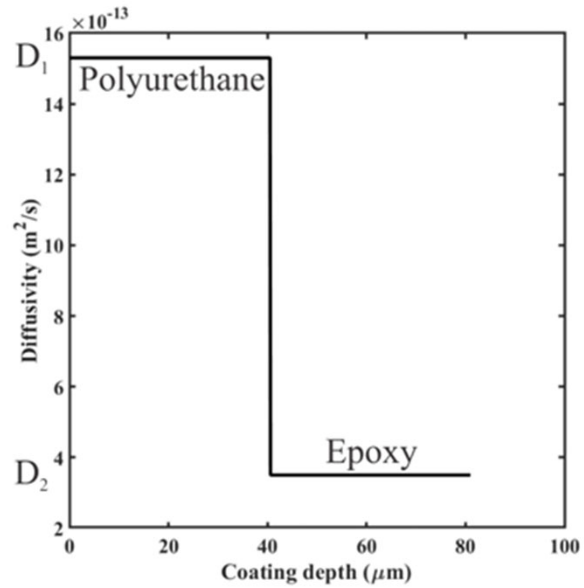


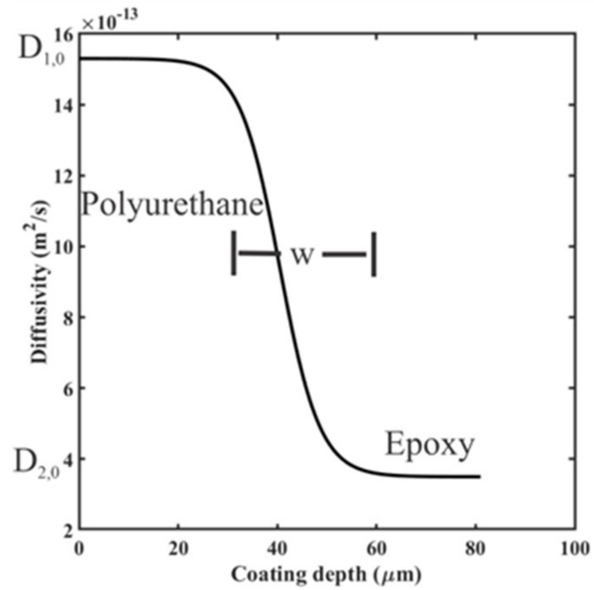


Average coating capacitance values for all aging conditions.

Modeling water sorption in polymers - I







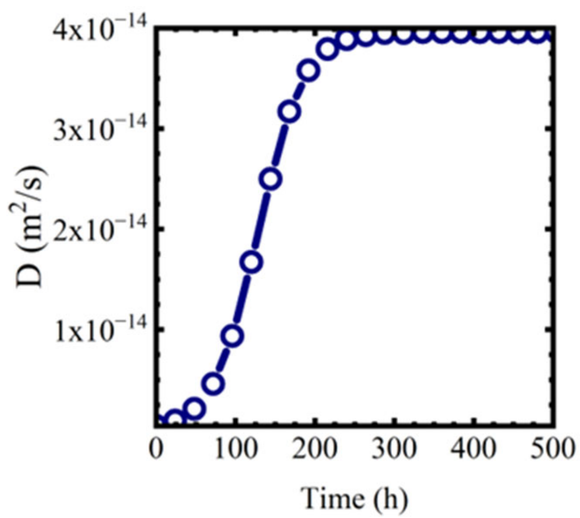
$$\Psi(t) = \frac{\phi(t)}{\phi_s} = \frac{\ln\left(\frac{C_c(t)}{C_c^0}\right)}{\ln\left(\frac{C_c^s}{C_c^0}\right)}$$

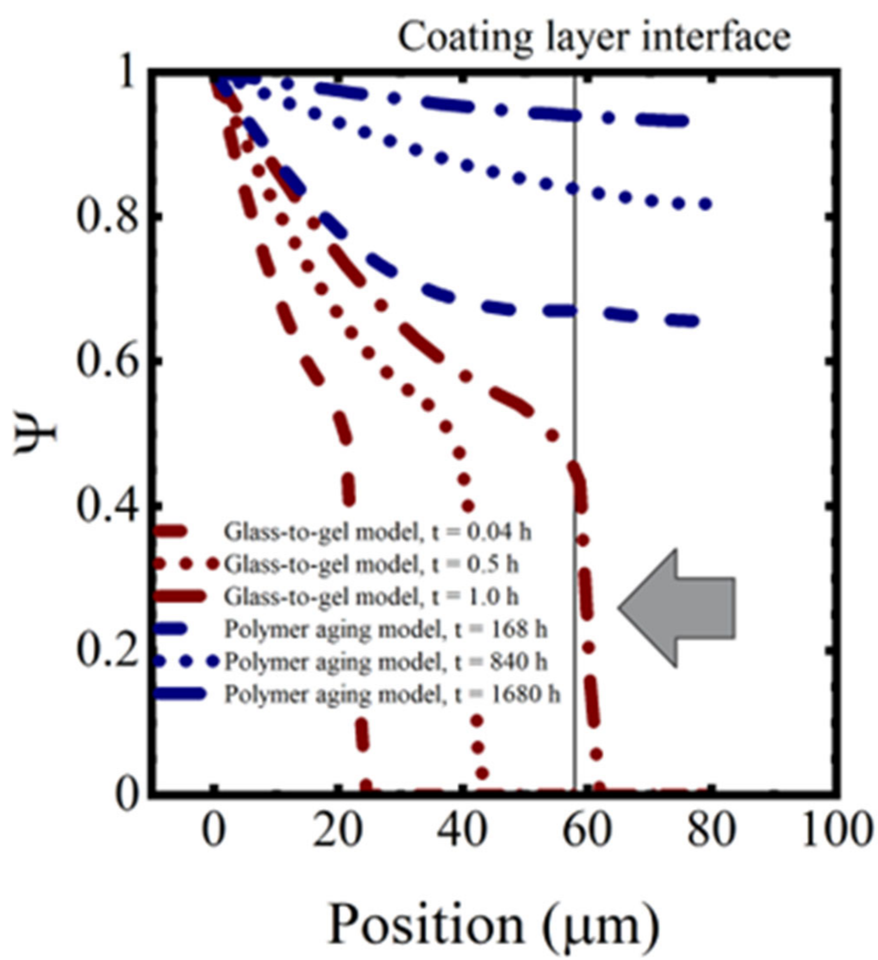
$$\frac{\partial \Psi(x,t)}{\partial t} = \frac{\partial}{\partial x}\left(D\,\frac{\partial \Psi(x,t)}{\partial x}\right)$$

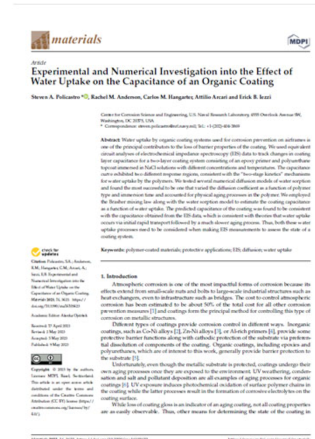
Modeling water sorption in polymers - II

- Glass-to-gel transition model
- Polymer aging model

$$D_i(t) = \frac{D_i^{age}}{\left[\frac{\left(D_i^{age} - D_{i,0}\right)}{D_{i,0}} * e^{-D_i^{age}\frac{t}{\tau}}\right] + 1},$$





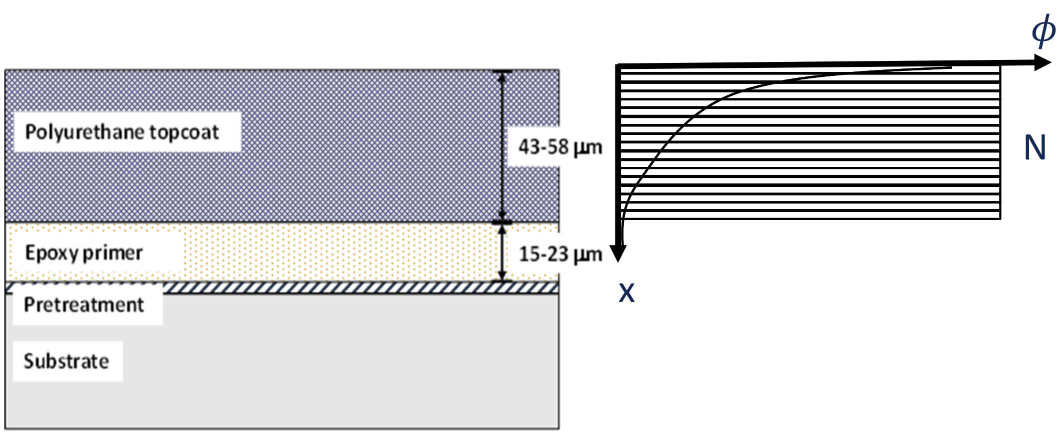

materials

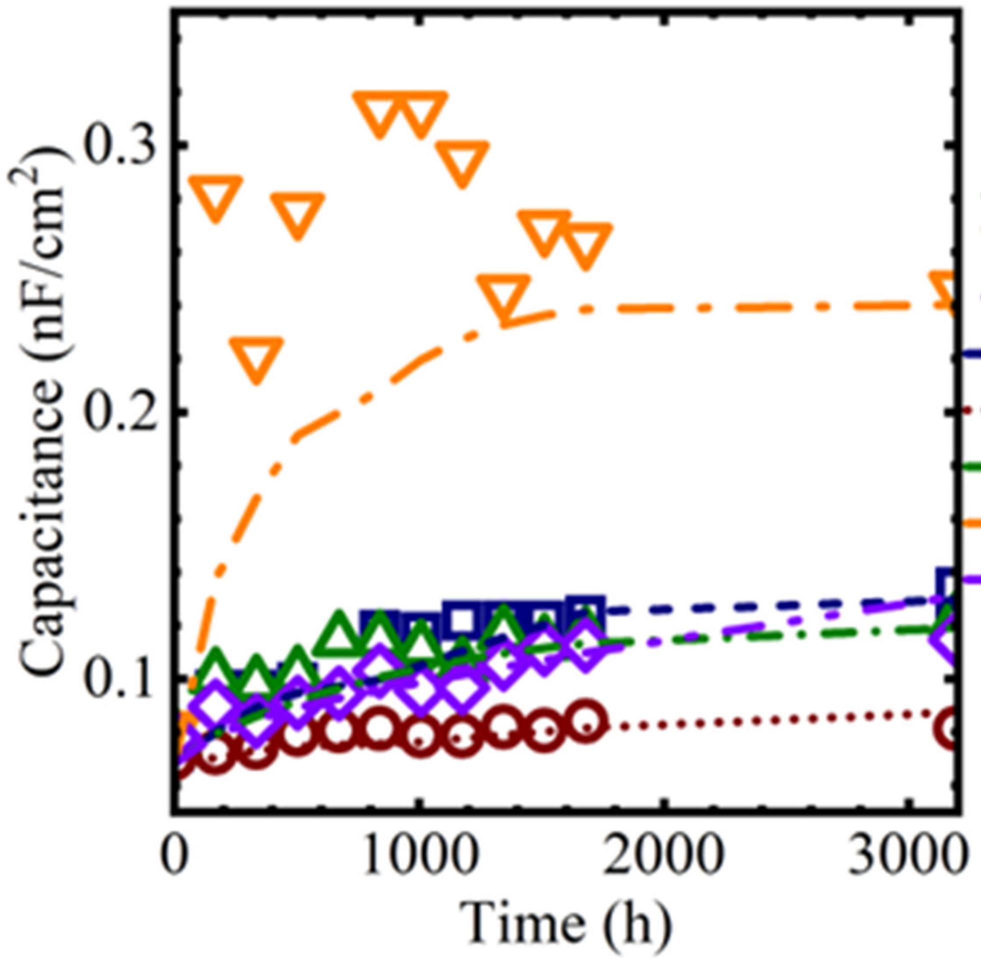
Experimental and Numerical Investigation into the Effect of Water Uptake on the Capacitance of an Organic Coating

Dielectric Properties

- Assume contributions to the dielectric constant at that node follow the Brasher mixing law

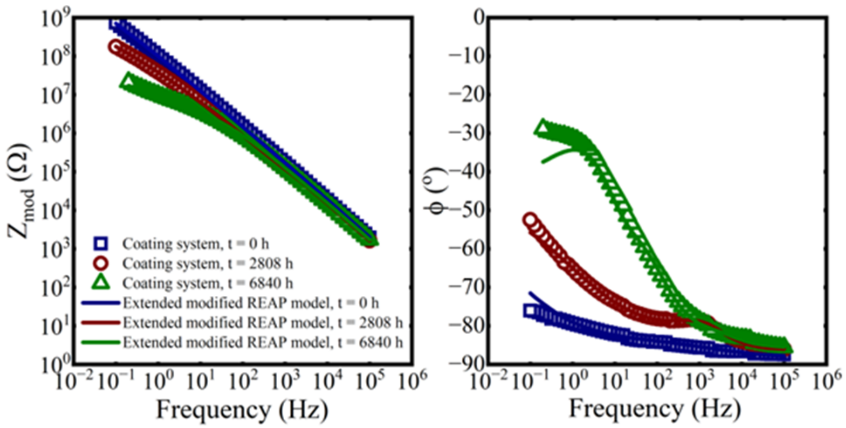
$$\frac{1}{C_c(t)} = \frac{1}{\epsilon_0 A \sum_{n=1}^{N} \frac{\left(e^{\phi(x)\ln \epsilon_{H_2O}} + e^{(1-\phi(x))\ln \epsilon_c}\right)}{\Delta x}}$$





Extended Modified REAP Predictions I

$T = 5^oC, [Cl^-] = 0.01\ M$

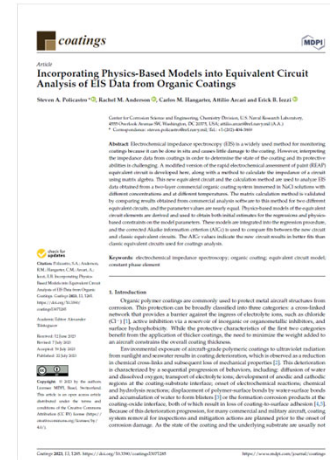


$$v_1 = i_1(R_\Omega + R_1) + i_2 R_\Omega,$$

$$v_2 = i_1 R_\Omega + i_2(R_\Omega + Z_{cpe}).$$

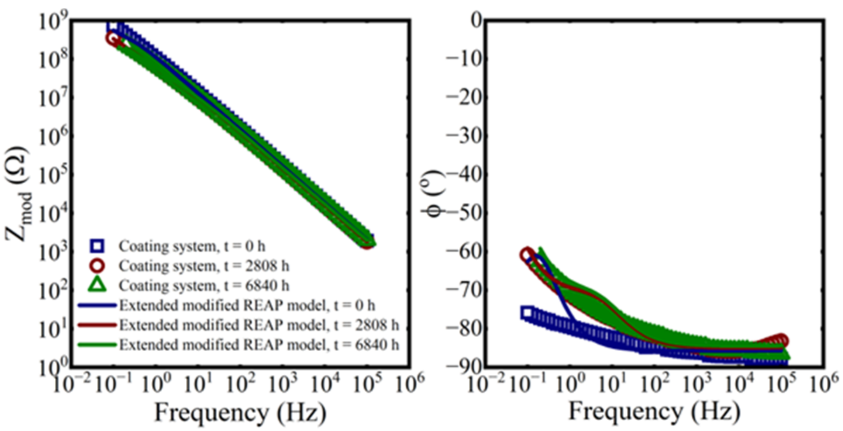
$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \begin{bmatrix} R_\Omega + R_1 & R_\Omega \\ R_\Omega & R_\Omega + Z_{cpe} \end{bmatrix}$$

$$\boldsymbol{i} = Z^{-1}\boldsymbol{v}$$



- Regression to minimize objective function, simplex method

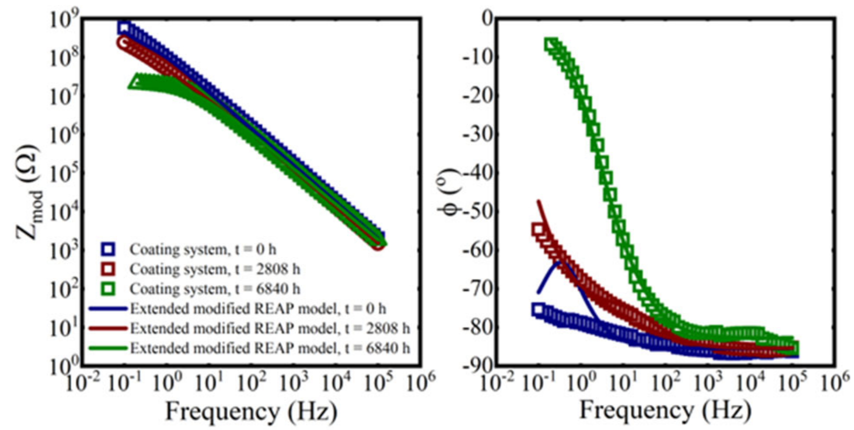
$$MSE = \frac{\left[\sum_{i=1}^{N}\left(\left(\frac{u_i - x_i}{x_i}\right)^2 + \left(\frac{v_i - y_i}{y_i}\right)^2\right)\right]}{N-k}$$



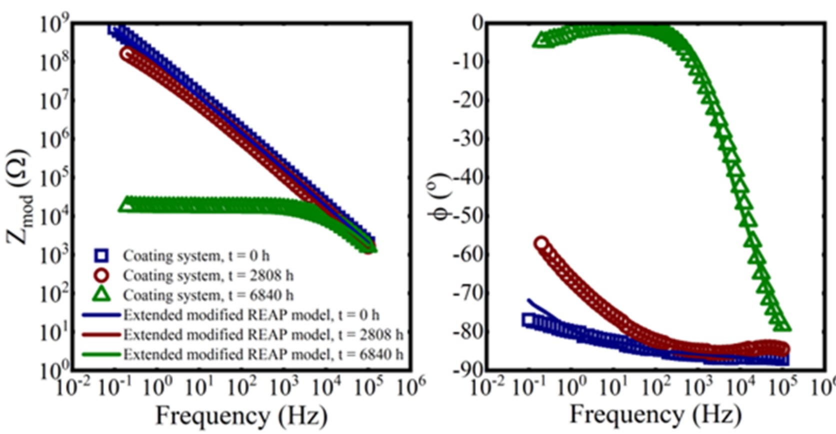
$T = 5^oC, [Cl^-] = 6.1\ M$

Extended Modified REAP Predictions II

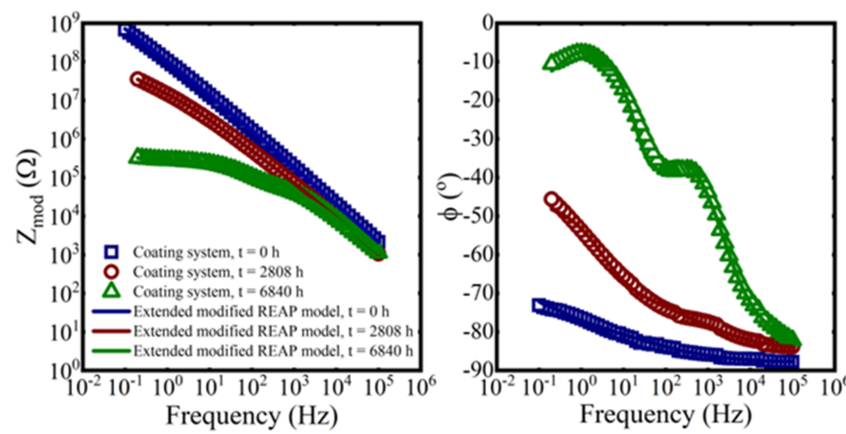
$T = 25^{o}C, [Cl^{-}] = 3.2\ M$



$T = 60^{o}C, [Cl^{-}] = 6.1\ M$



$T = 60^{o}C, [Cl^{-}] = 0.01\ M$

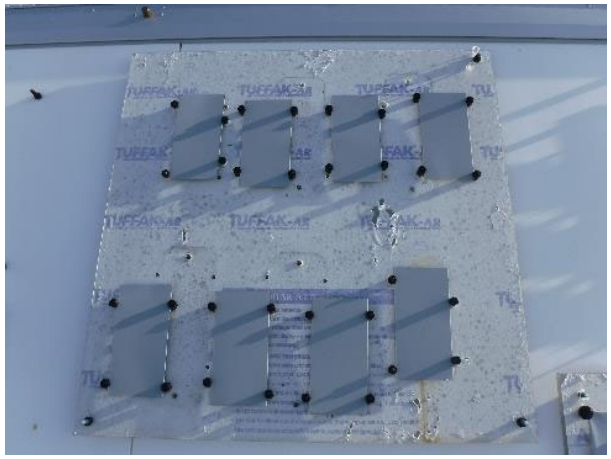


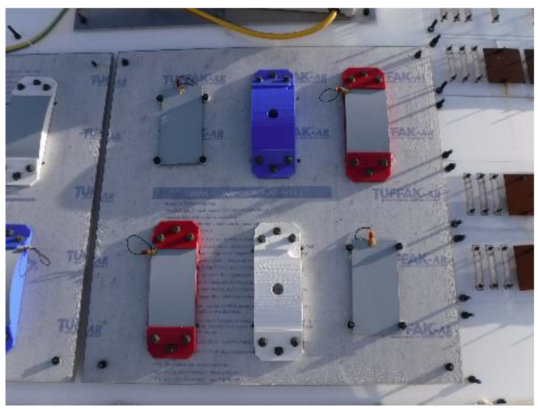
Task 4 - Outdoor Exposure Testing

- Tests performed at NRL's C-CoAST facility for exposure in a service relevant environment
- Outdoor exposure testing to be used to calibrate cumulative damage model

Outdoor Exposures and Dynamic Loading

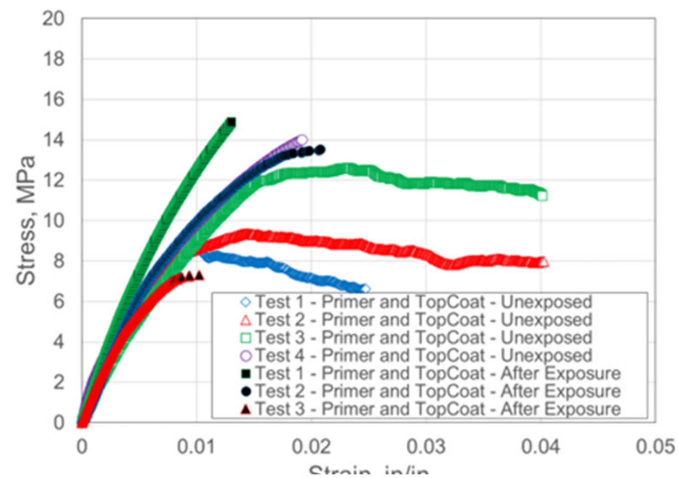
- Coating systems emplaced at NRL-KW for 3, 6, 9 months
- Free films, unloaded, statically loaded, and fatigued samples

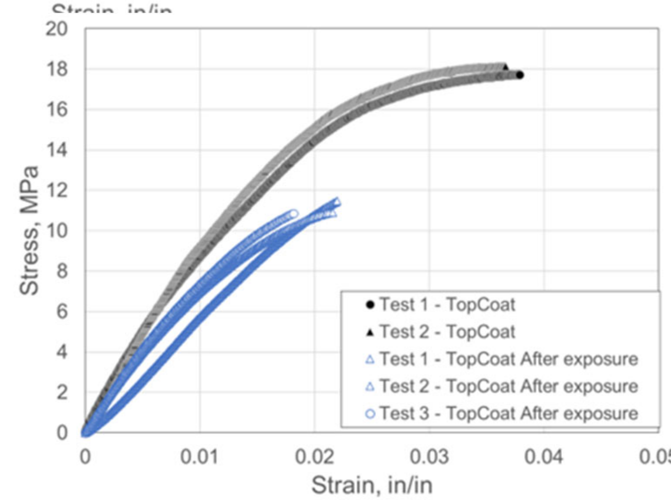




Elastic Properties of the Coating System

- Tensile tester was set up to allow the gripping of 2.54 cm wide strips of the materials
- Applied loads and displacements measured during the test

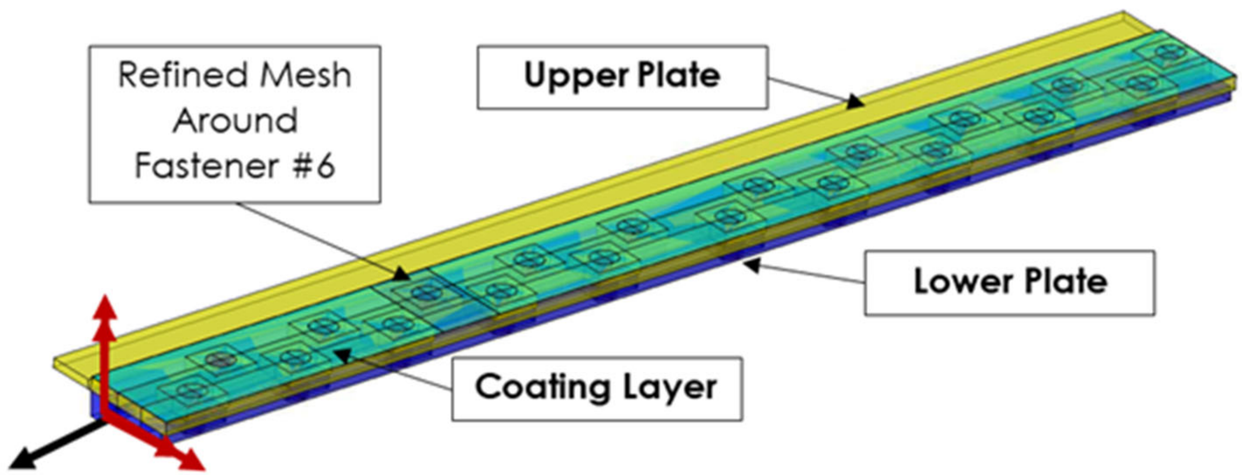




	Elastic Modulus (MPa)	Fracture Strain (%)
Primer and Topcoat	1,028.6	3.5
Topcoat	846.0	3.8
Primer (estimated)	3,102.7	-

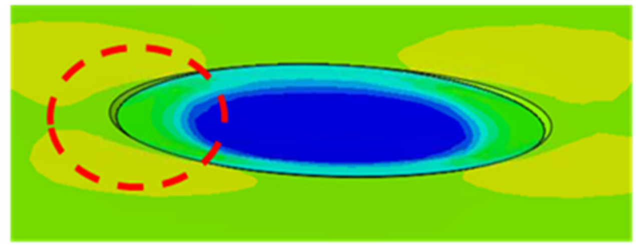
Task 3 - Modeling Coating System Stress Fields and Crack Propagation

- FE analysis of a sub-component that explicitly includes the substrate-primer-topcoat interfaces and the geometry underneath
- This allows the identification of critical locations for the coating
- Sub-modeling of identified critical locations enables to study the stress-strain state locally and its variation over time (fatigue cycles)

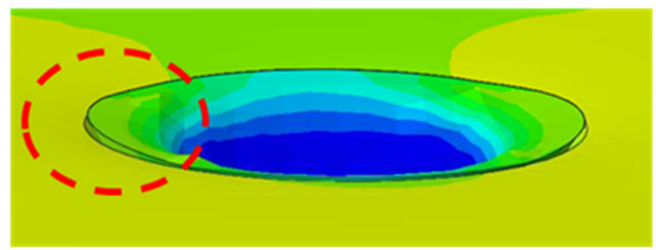


Modeling Dynamic Loading II

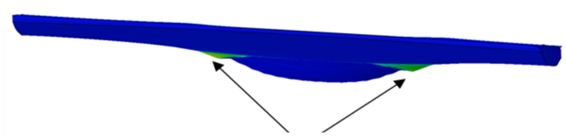
- Coating follows the relative movement of the fastener and skin
  - ♦ Coating is constrained to fastener and skin
- Relative displacements in y-direction
  - ♦ Fastener: -0.01 mm
  - ♦ Skin: 0.0035 mm



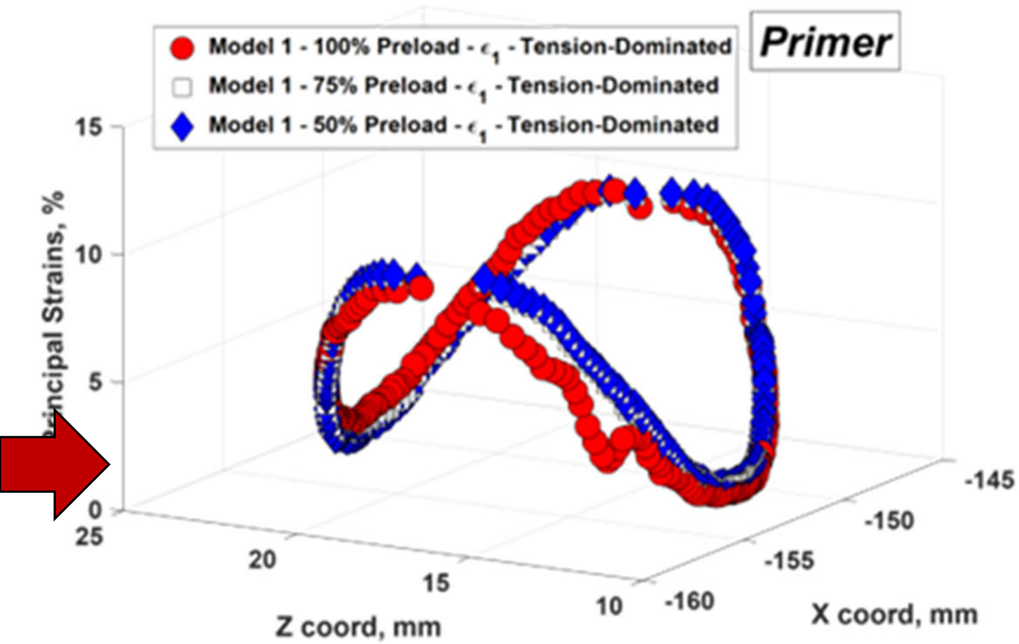
Severe Load Case

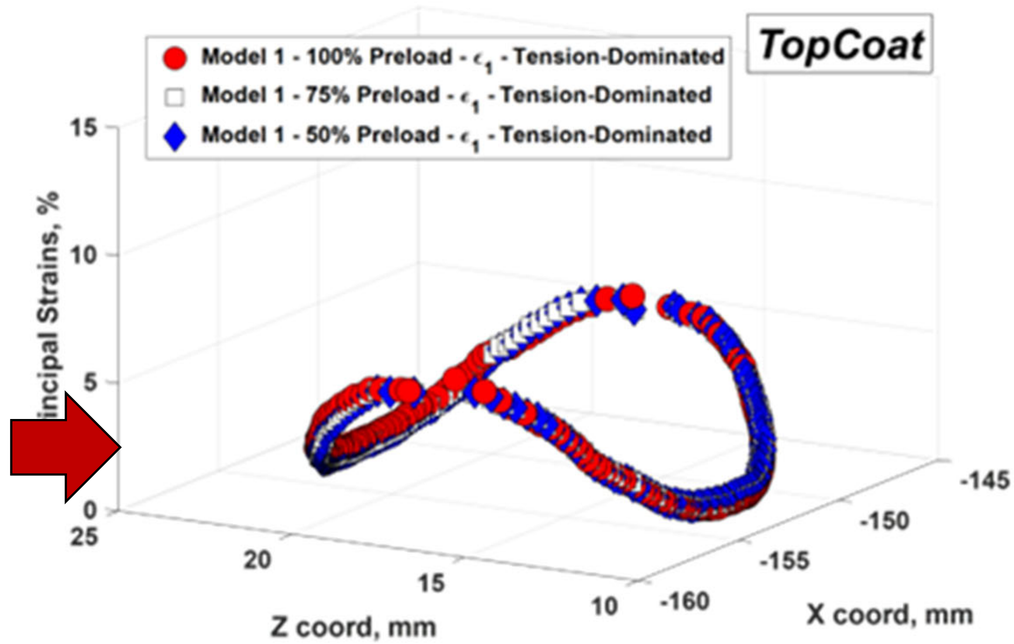


b) Intermediate Load Case



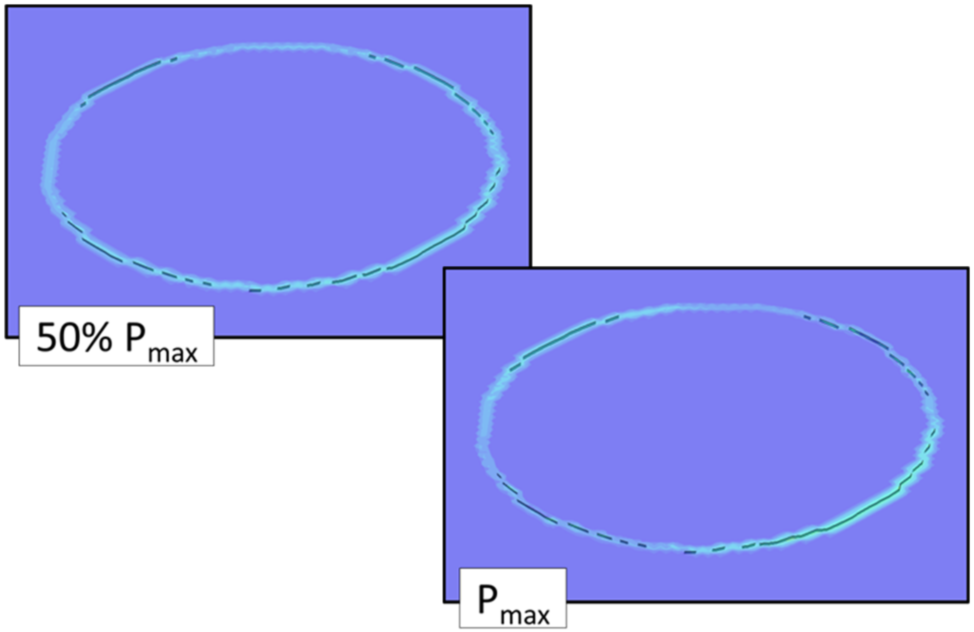
Modeling Dynamic Loading III





= max static strain used in laboratory exposure testing

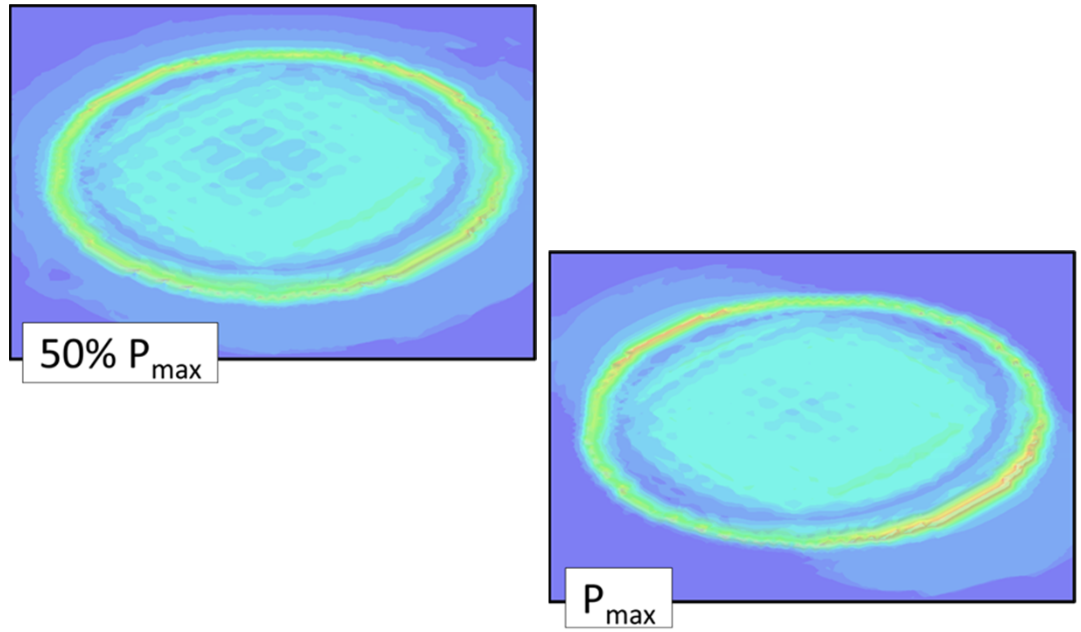
Modeling Crack Propagation – Fresh Coating



Primer

Crack propagation through the primer along the critical path of highest strain –

a. 50% maximum load

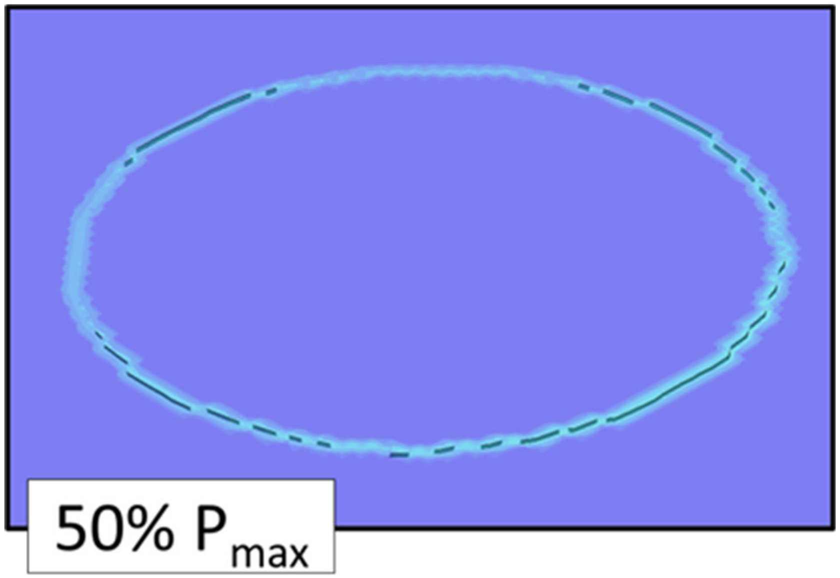


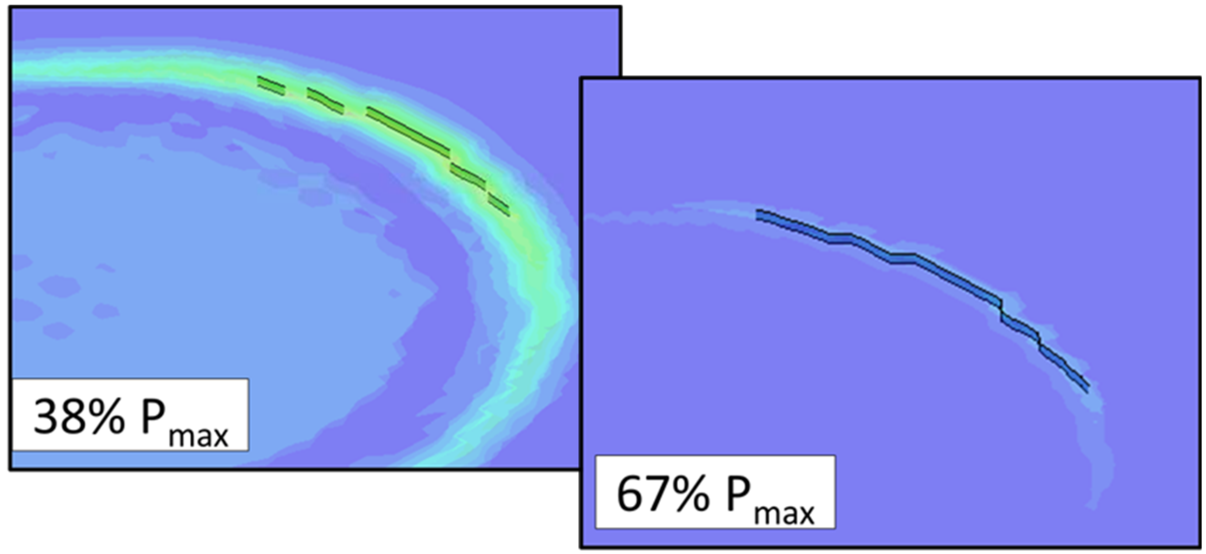
Topcoat

Cracking of topcoat by propagation of primer crack

a. 38% maximum load
b. 67% maximum load

Modeling Crack Propagation – Aged Coating





Primer

Crack propagation through the primer along the critical path of highest strain –

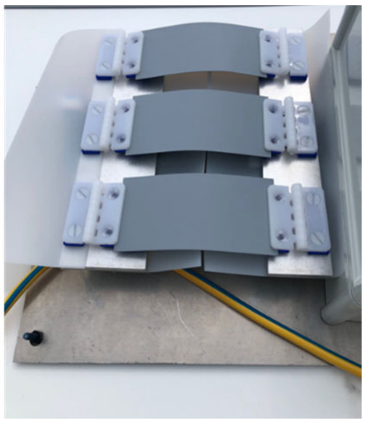
a. 50% maximum load

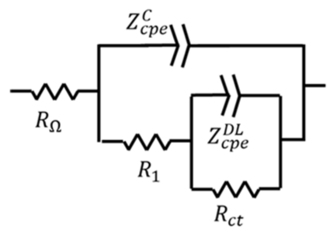
Topcoat

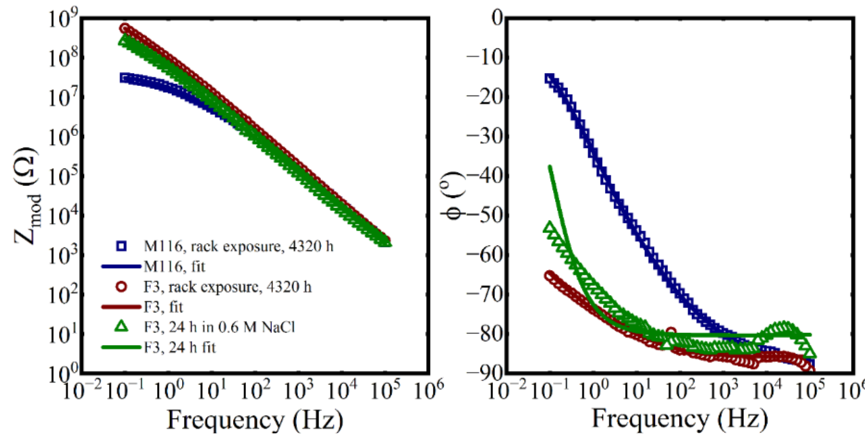
Cracking of topcoat by propagation of primer crack –

a. 38% maximum load
b. 67% maximum load

EIS of Fatigued Panels







Sample ID and Exposure Time (h)

Parameter	M116		N119		I118
	0	**4320**	**0**	**10272**	**3120**
R_{Ω} (Ω)	4	4	4	4	4
R_{po} (GΩ)	5.7	0.04	4.8	2570	0.78
R_{ct}(MΩ)	9.15	0.02	0.019	207	0.82
$Y_0^{DL}(nF \cdot s^{n-1})$	1.48	12.9	2.37	1.01	5.35
m	0.562	0.537	0.589	0.602	0.594
$Y_0^{C}(nF \cdot s^{n-1})$	2.28	1.05	1.23	1.77	1.78
n	0.950	0.978	0.968	0.950	0.958

With and without sea spray

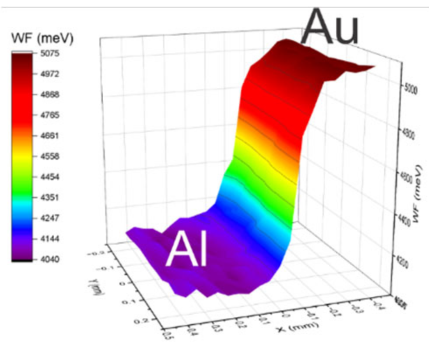
Sample ID and Exposure Time (h)

Parameter	F3		I118
	4320	**24***	**3120**
R_{Ω} (Ω)	4	4	4
R_{po} (GΩ)	15.4	3.16×10^{-5}	0.78
R_{ct}(MΩ)	30.4	404	0.82
$Y_0^{DL}(nF \cdot s^{n-1})$	1.32	283	5.35
m	0.561	0.747	0.594
$Y_0^{C}(nF \cdot s^{n-1})$	1.40	3.37	1.78
n	0.952	0.892	0.958

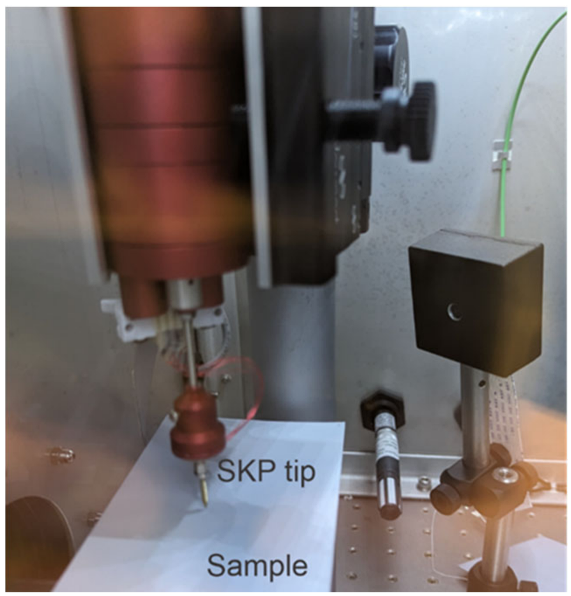
Fatigue

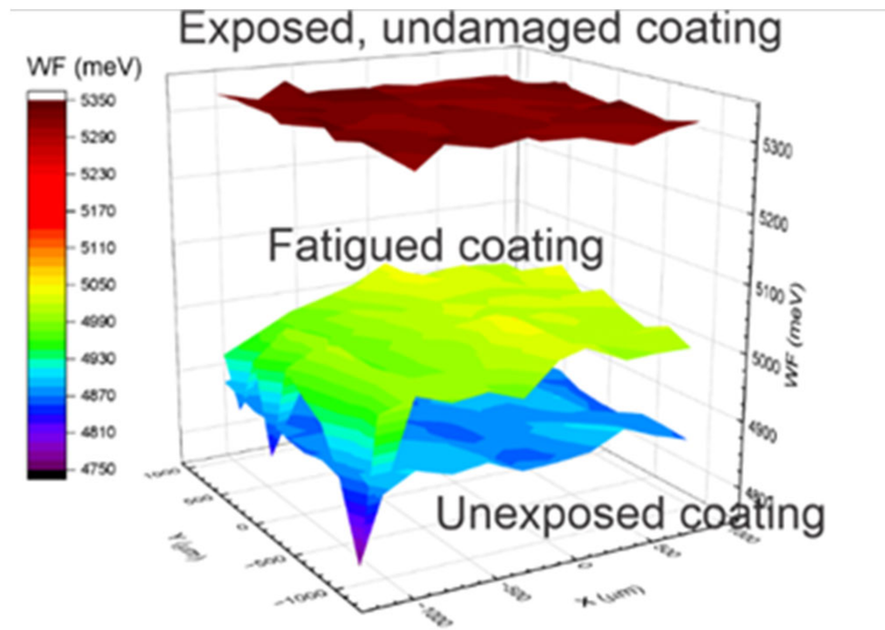
Scanning Kelvin Probe Analysis

- No coating cracks identified in SEM…
- Comparison of SKP results suggest fatigue damaged coating



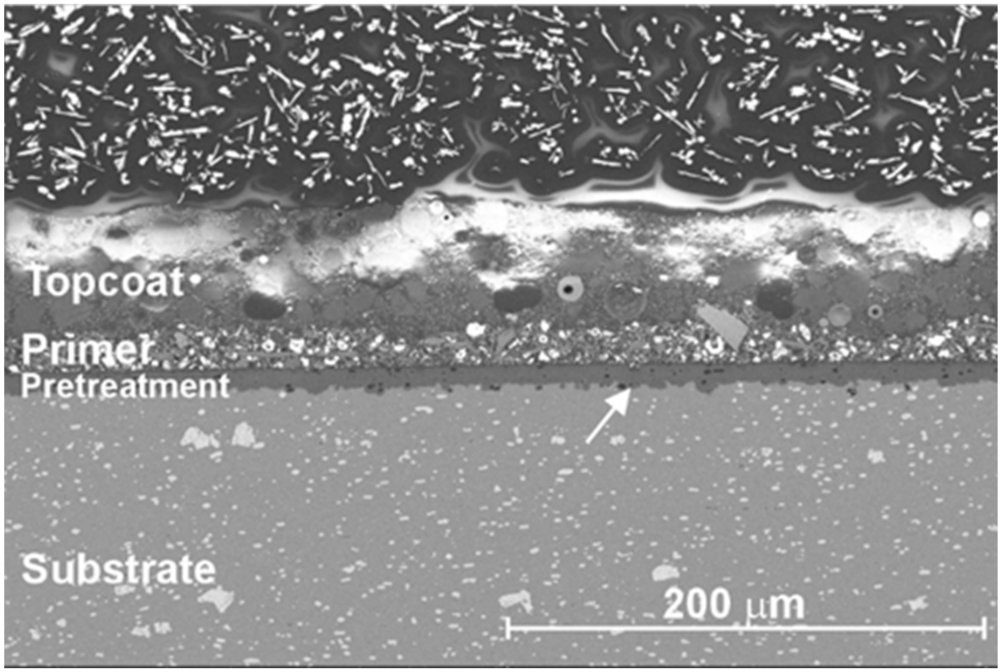
1 mm x 0.5 mm area scan across the interface on the Au-Al SKP calibration standard



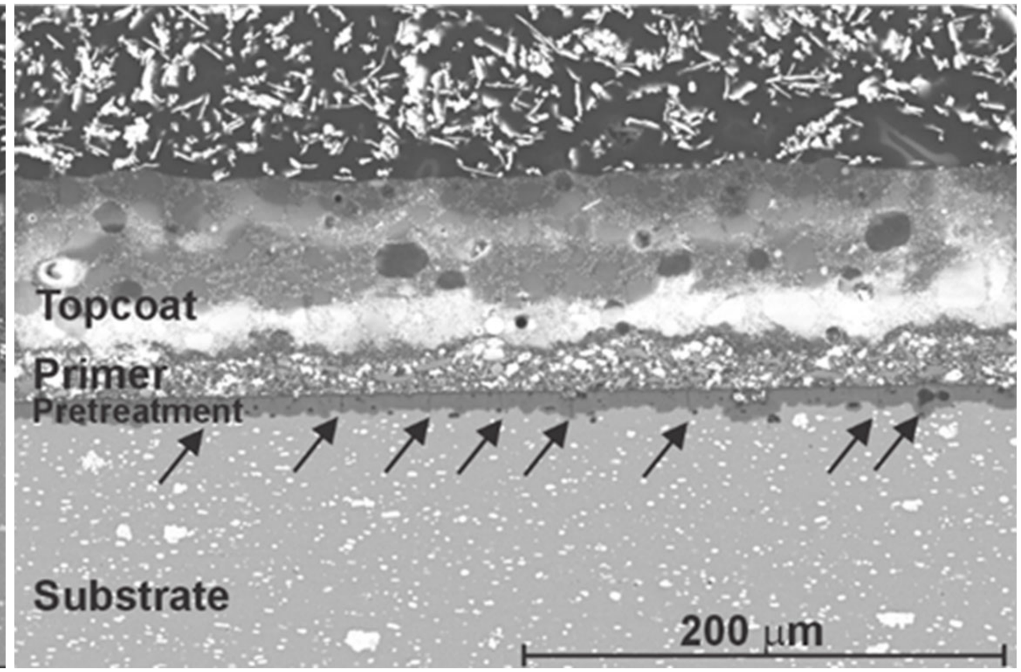


2 mm x 2 mm area scans at the center of the coating systems for: 1. a fatigued coating in the outdoor environment for 4320 h, 2. An exposed, but mechanically undamaged coating in the outdoor environment for 4320 h, and 3. a coating applied at the same time as the other samples but stored for the same duration.

SEM Imaging and Analysis II

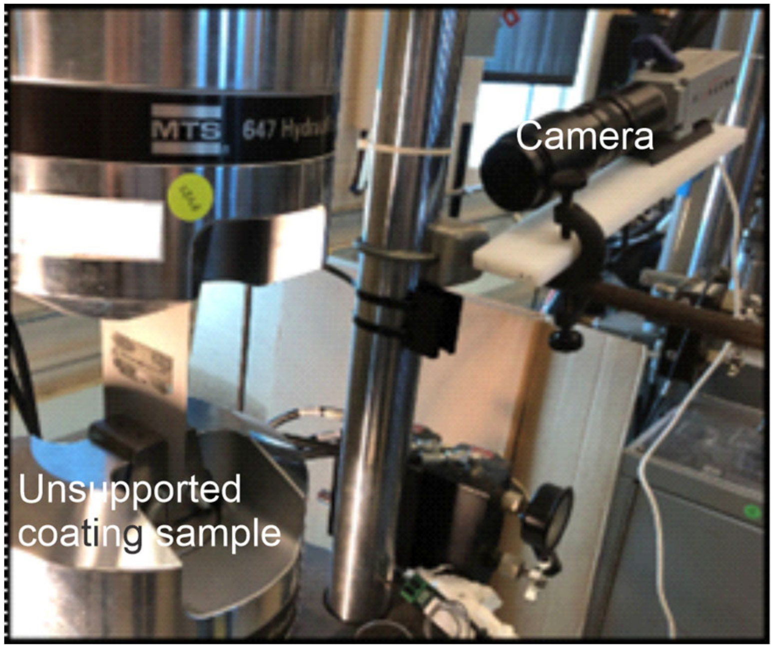


Cross-section images of an unstressed coating system

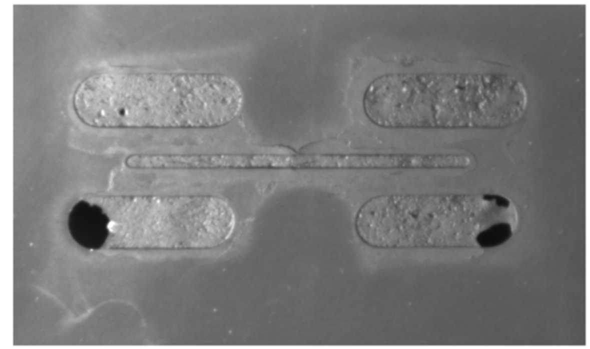


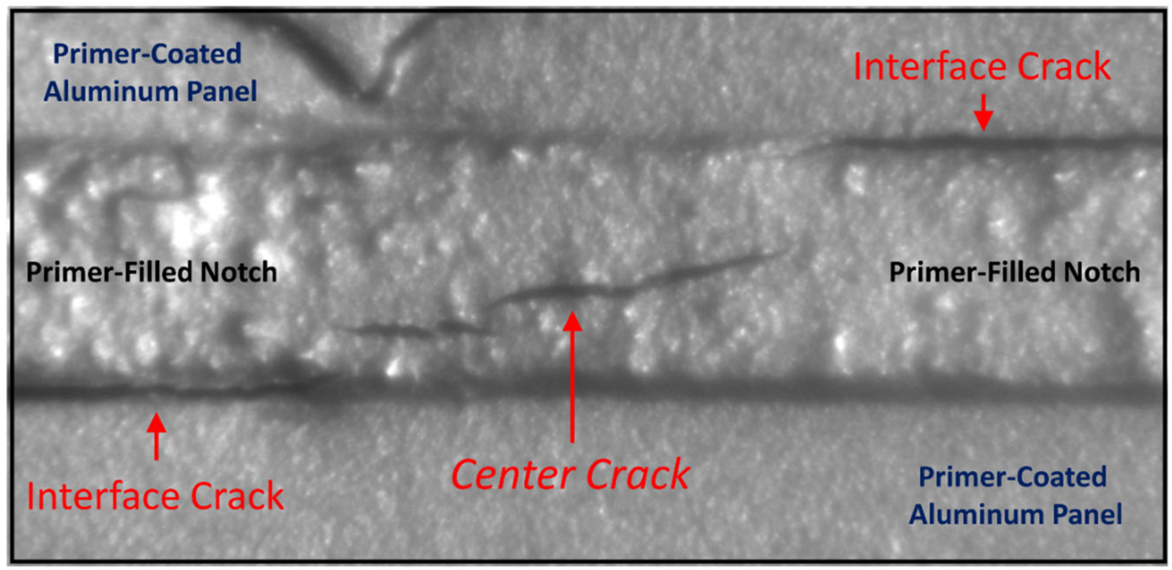
Cross-section images of a fatigued coating system. Arrows indicate the presence of through-thickness cracks in the pretreatment layer.

Fatigue of Unsupported Coating



Coating fatigue test panel developed to measure fatigue life of primer. Test setup using a digital camera scope to observe crack propagation.





Higher magnification image of the center notch of the coated aluminum panel tested in fatigue in this work. The epoxy primer initiated a fatigue crack for an applied maximum strain of 0.4% and minimum strain of 0.13%.

Color Change

- Color change as a result of the laboratory ageing was determined using the change in the CIELAB color space calculation:

$$\Delta E^* = \sqrt{(\boldsymbol{L_0^*} - \boldsymbol{L_1^*})^{\boldsymbol{2}} + (\boldsymbol{a_0^*} - \boldsymbol{a_1^*})^2 + (\boldsymbol{b_0^*} - \boldsymbol{b_1^*})^{\boldsymbol{2}}}$$

- ΔE^* = ASTM D2244-21 color difference
- L_i^* = distance along lightness axis
- a_i^* = distance along green-red axis
- b_i^* = distance along blue-yellow axis.

Color Change Values

Exposure conditions		CIELAB values			
	Time (h)	L_i^*	a_i^*	b_i^*	ΔE^*
All	0	67.95	-2.22	-3.59	-
Unstressed, UV and condensation	1176	67.19	-2.24	-3.50	0.760
	2184	67.07	-2.26	-3.52	0.877
Stressed, UV and condensation	1176	67.19	-2.23	-3.42	0.774
	2184	67.06	-2.25	-3.42	0.897
Salt spray	1176	67.73	-2.22	-3.63	0.223
	2184	67.60	-2.22	-3.64	0.350

Model Comparisons

- Arizona Model

$$\Delta E^* = \alpha_0 + \alpha_1 R_1 + \alpha_2 C_c$$

- Florida Model

$$\Delta E^* = \alpha_0 + \alpha_1 R_1 + \alpha_2 C_c + \alpha_3 C_c$$

Conditions	$\Delta E^*_{measured}$	$\Delta E^*_{Arizona}$	$\Delta E^*_{Florida}$
Unstressed, UV and condensation	0.00	0.00	0.00
	0.76	2.77	4.23
	0.88	3.24	0.85
Stressed, UV and condensation	0.00	0.00	0.00
	0.77	3.50	0.97
	0.90	7.65	2.83
Salt spray	0.00	0.00	0.00
	0.22	0.97	0.83
	0.35	1.04	1.09

Next Steps

- While the project execution plan is fully complete, the following research directions would be useful:
- <u>Model Development</u> – Synthesis of the environmental exposure data, particular water and pollutant accumulation and exposure to UV radiation with the new models for the rate of water saturation of organic polymers; and the effect of cyclic and high stress loads on the coating system is
  - Such a full-state model is necessary to be able to accurately predict the state of the coating along with the underlying substrate.
- <u>Implementation</u> – Once full state model validated, an *in-situ* EIS measurement device, coupled with aircraft sensors to detect local corrosive environments and aircraft loads, would be able to provide the maintainer with an accurate assessment of the state of the coating system.
  - Such output could be in the form of red/yellow/green assessment, as was suggested by the interim rating scheme, but the red/yellow/green categories would then be founded on a stronger physics basis than simply the coating impedance at 0.1 Hz.

Technology Transfer

- Presented results from this project:
  - SERDP and ESTCP Symposium
  - AMPP Annual Conference and Expo
  - DoD Corrosion Prevention Technology and Innovation Symposium
- Developed white paper proposal with Tom Curtin at *Beasy* to transition physics-based models of coating deterioration processes to the *Beasy* coating model software
  - Working to find a funding sponsor
- Goal is to stay engaged with NAVAIR and NAWCAD, who could use these results for the air fleet

Key Points

- Scientific Impact – Formulated mathematical description for saturation of organic polymer that predicts dielectric property changes over very long duration exposures
- Scientific Impact – Developed physics-based models for equivalent circuit parameters that model EIS responses of coatings
- Scientific Impact – Developed FEM of crack propagation in multi-layer coating system in response to external flight loads
- Technical Impact – Proposed method for measuring fatigue properties of unsupported organic coatings
- Navy/Service Impact – Measured and reported changes in mechanical and barrier properties of aircraft coating system as a result of environmental stressors.

BACKUP SLIDES

Publications

Journal Articles

1. Arcari, A.; Anderson, R.M.; Hangarter, C.M.; Iezzi, E.B.; Policastro, S.A. *Tensile Properties of Aircraft Coating Systems and Applied Strain Modeling*. Coatings 2024, 14, 91.
2. Policastro, S. A.; Anderson, R. M.; Hangarter, C. M.; Arcari, A.; Iezzi, E. B., *Incorporating Physics-Based Models into Equivalent Circuit Analysis of EIS Data from Organic Coatings*. Coatings 2023, *13* (7), 1285.
3. Policastro, S. A.; Anderson, R. M.; Hangarter, C. M.; Arcari, A.; Iezzi, E. B., *Experimental and Numerical Investigation into the Effect of Water Uptake on the Capacitance of an Organic Coating*. Materials 2023, *16* (10), 3623.
4. Arcari, A.; Anderson, R. M.; Hangarter, C. M.; Iezzi, E. B.; Policastro, S.A. *Deformation of Aircraft Coating Systems at Fastener-Skin Interfaces*. JDR&E, 2022, *5* (2) 1-13. [Distro D]

Proceedings

1. Arcari, A.; Policastro, S.A.; Anderson, R. M.; Hangarter, C. M.; Iezzi, E. B. *Effects of Environmental Exposure on Mechanical and Barrier Properties of an Aircraft Coating System*. AMPP Annual Conference + Expo, New Orleans, LA, USA, March 2024.
2. Policastro, S. A.; Arcari, A.; Hangarter, C. M.; Iezzi, E. B.; Anderson, R. M. *Relating Changes in Electrochemical Properties to Barrier Property Changes of an Organic Coating System*. Conference Proceeding, AMPP Annual Conference + Expo, Denver, Colorado, USA, March 2023., Paper Number: AMPP-2023-19314, Published: March 19, 2023.
3. Policastro, S. A.; Arcari, A.; Hangarter, C. M.; Iezzi, E. B.; Anderson, R. M. *Using Machine Learning Techniques to Estimate Initial Model Parameters*. Conference Proceeding, 2023 DoD Corrosion Prevention Technology and Innovation Symposium.

Presentations

1. Policastro, S. A.; Anderson, R. M.; Hangarter, C. M.; Arcari, A.; Iezzi, E. B. *Using Machine Learning Techniques to Estimate Initial Model Parameters*. 2023 DoD Corrosion Prevention Technology and Innovation Symposium, 14-17, August 2023.

2. Policastro, S. A.; Anderson, R. M.; Hangarter, C. M.; Arcari, A.; Iezzi, E. B. *Relating Changes in Electrochemical Properties to Barrier Property Changes of an Organic Coating System*, AMPP Annual Conference and Expo 2023, 19-23 March, 2023.

3. Policastro, S. A.; Anderson, R. M.; Hangarter, C. M.; Arcari, A.; Iezzi, E. B.; *Assessing Electrolyte Transport through an Aircraft Coating System using EIS*, 2022 SERDP/ESTCP Symposium, Arlington, VA, December 2nd, 2022.

4. Policastro, S. A.; Anderson, R. M.; Hangarter, C. M.; Arcari, A.; Iezzi, E. *B Assessing Electrolyte Transport through an Aircraft Coating System Using EIS*, 242nd Electrochemical Society Conference 9-13 October 2022.

5. Policastro, S.A.; Anderson, R.M.; Hangarter, C.M.; Arcari, A.; Iezzi, E.*; Levenberg-Marquardt Estimation of Nonlinear Parameters in EIS Analysis of Coated Aluminum Panels*, 240th ECS conference 10-14 October 2021

6. Policastro, S.A.; Anderson, R.M.; Arcari, A.; Iezzi, E.; *Using Machine Learning Techniques to Estimate Initial Model Parameters* SERDP-ESTCP Symposium, 29 November 2021 - 3 December 2021.

7. Policastro, S.A.; Anderson, R.M.; Hangarter, C.M.; Arcari, A.; Iezzi, E.; *Measuring and modeling aircraft coating degradation,* 2021 SERDP/ESTCP Webinar Series - 04 November 2021

8. Policastro S. A.; Anderson R. M.; Hangarter C. M.; Arcari, A.; Iezzi E. Modeling *Coating System Degradation*. Presented at a virtual project In Progress Review. September 11, 2021. Virtual Meeting.

9. Policastro S. A.; Arcari, A.; Anderson R. M. Hangarter C. M.; Iezzi E. *An experimental and finite element modeling approach to determining degradation of aircraft coating systems.* Presented at the SERDP Spring In Progress Review. April 20-23, 2021. Virtual Meeting.

10. Policastro, S.A.; Iezzi, E.; Hangarter C. M.; Anderson R. M.; Arcari, A.; Strom, M.J.; *An Experimental and Finite Element Modeling Approach to Determining Degradation of Aircraft Coating Systems*. FY 20 IPR, Washington, DC, 5 February 2020

WP19-1017: An experimental and finite element modeling approach to determining degradation of aircraft coating systems

Performers: Steven A. Policastro, Rachel M. Anderson, Carlos M. Hangarter, Attilio Arcari, and Erick Iezzi, Center for Corrosion Science and Engineering, U.S. Naval Research Laboratory 4555 Overlook Avenue SW, Washington, DC 20375

Technology Focus

- *Coating systems contain hazardous chemicals and paint/depaint actions expose workers and generate waste. However, coatings are first line of defense against corrosion. Need to reduce frequency of these operations to only necessary instances.*

Research Objectives

- *Develop an improved theoretical understanding of organic coating system deterioration due to exposure to environmental stressors.*
- *Quantify how static and dynamic environmental conditions influence coating system deterioration over the duration of laboratory aging conditions and outdoor exposures*

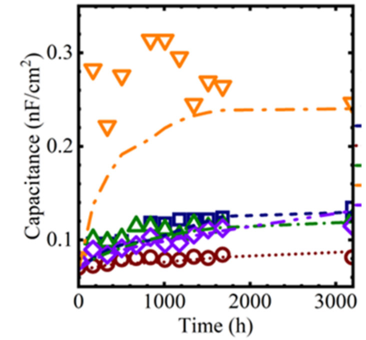
Project Progress and Results

- *Formulated mathematical description for saturation of organic polymer that predicts dielectric property changes over very long duration exposures and developed physics-based models for equivalent circuit parameters that model EIS responses of coatings*
- *Developed FEM of crack propagation in multi-layer coating system in response to external flight loads*
- *Navy/Service Impact – Measured and reported changes in mechanical and barrier properties of aircraft coating system as a result of environmental stressors.*

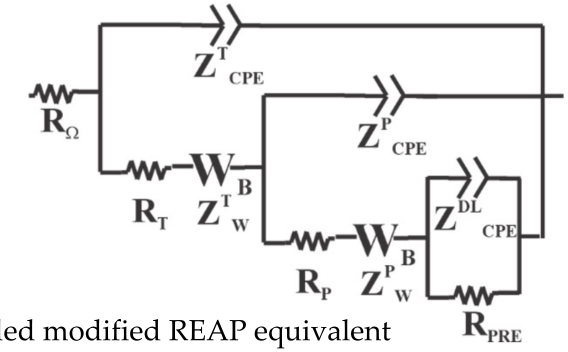
Technology Transition

- *Transition physics-based models of coating barrier and mechanical property changes because of exposure to commercial modeling software to leverage their installed user base so fleet maintenance decisions can benefit from this data*

Coating capacitance values obtained from equivalent circuit fits compared to values obtained from the polymer aging and Brasher-mixing model.



Deployment of apparatus for flexing coated aluminum 2024-0 alloy panels during outdoor exposure on 45º inclined exposure rack on Fleming Key, FL.



Extended modified REAP equivalent circuit model.