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Development of a Computational Framework for Prediction of Galvanic Corrosion for Automotive Applications

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George Mason University | Volgenau School of Engineering

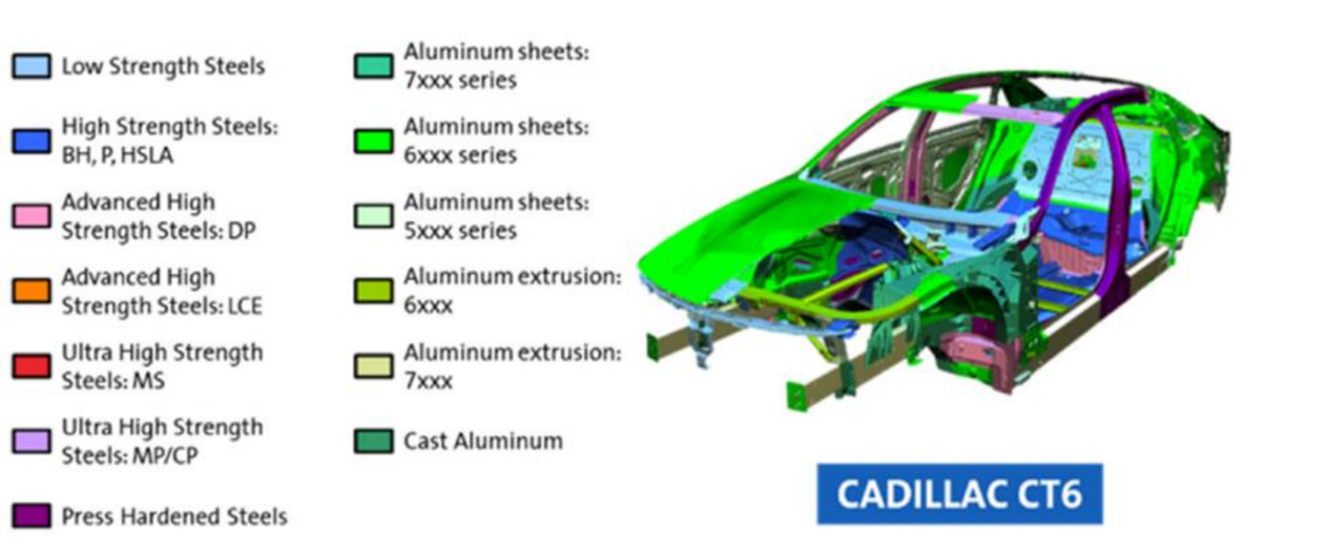
The Future of Engineering Is Here.

Outline

1. Introduction
2. Corrosion Modeling and Simulation
    1. Film thickness model
    2. Free corrosion model
    3. Galvanic corrosion simulation
3. Results
4. Conclusions
5. Future Steps

Introduction

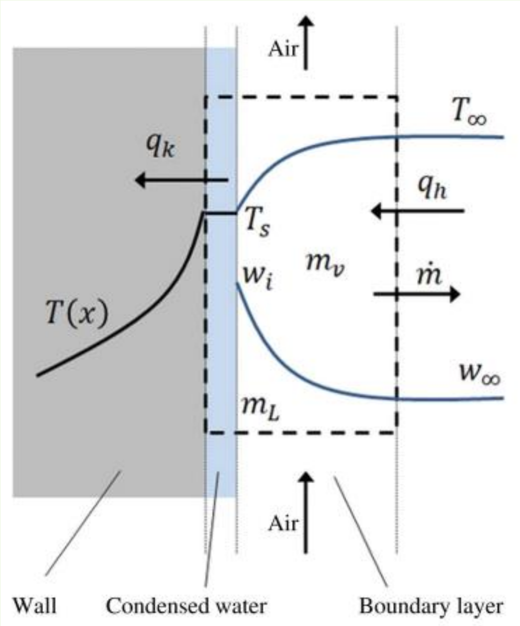
- NACE study estimated global cost of corrosion at $2.5 trillion, equivalent to 3.4 of the global Gross Domestic Product (GDP) (2013)
- Corrosion behavior (and galvanic corrosion behavior) will be complex due to
    - The electrochemical system and
    - The conductivity path constantly evolving/differing
- Parameters considered in our study:
    - Temperature, Relative humidity (RH), Salt load density



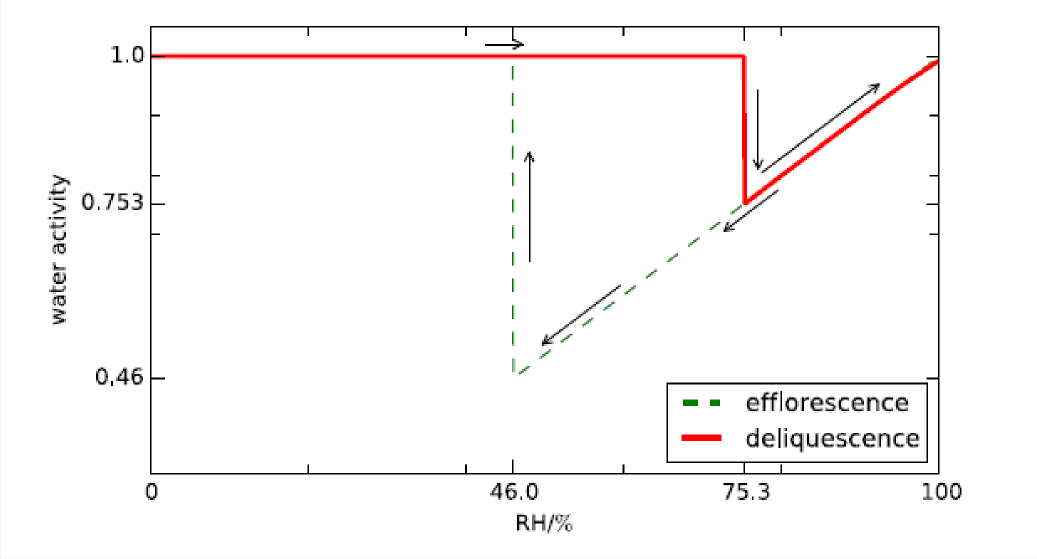
[Liu et al., 2018]

Corrosion Modeling
(Film Thickness)

- Surface temperature distribution
$$c_p \rho \frac{dT}{dt} = \nabla(-\mathrm{k}\nabla T)$$
- Mass balance equation
$$\dot{m} = k_m(w_\infty - w)$$
- Water activity
$$a_w = \frac{P}{P^s}$$
- Deliquescence RH (DRH)
$$DRH_{Nacl} = 75.3\%,$$
$$DRH_{MgCl_2} = 15\%$$
- Efflorescence RH (ERH)
$$ERH_{Nacl} = 46\%,$$
$$ERH_{MgCl_2} = 5\%$$



[Nickerson, Amiri, Iyyer, 2019]



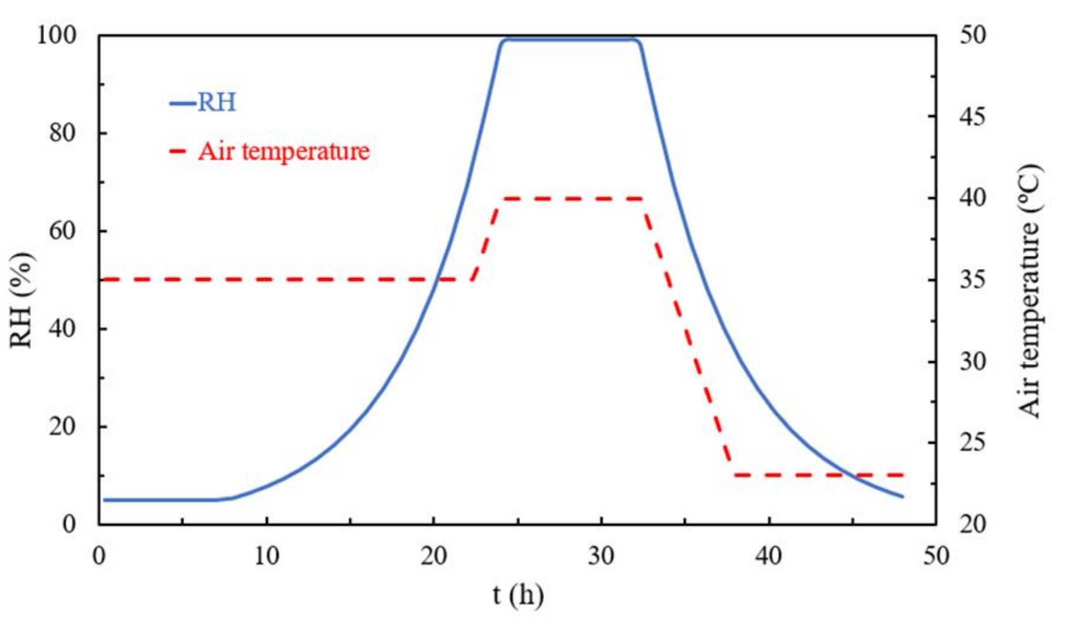
[Van den Steen et al., 2016]

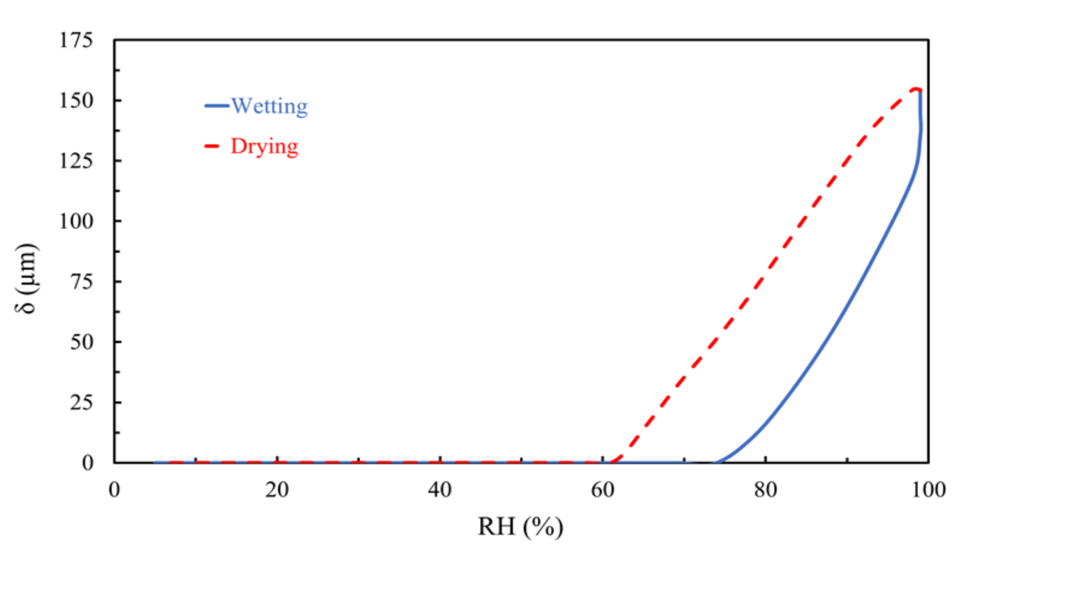
Corrosion Modeling
(Film Thickness)

- The lumped capacitance:
  - $T = (T_0 - T_\infty)\exp\left(\frac{-2h_{air}t}{\rho c_p d}\right) + T_\infty$
- Dynamic film thickness:

$$\delta(t) = \int_{t'=0}^{t} \dot{\delta}\, dt'$$

- The film thickness is calculated for saturated solution*, δ_{sat}.



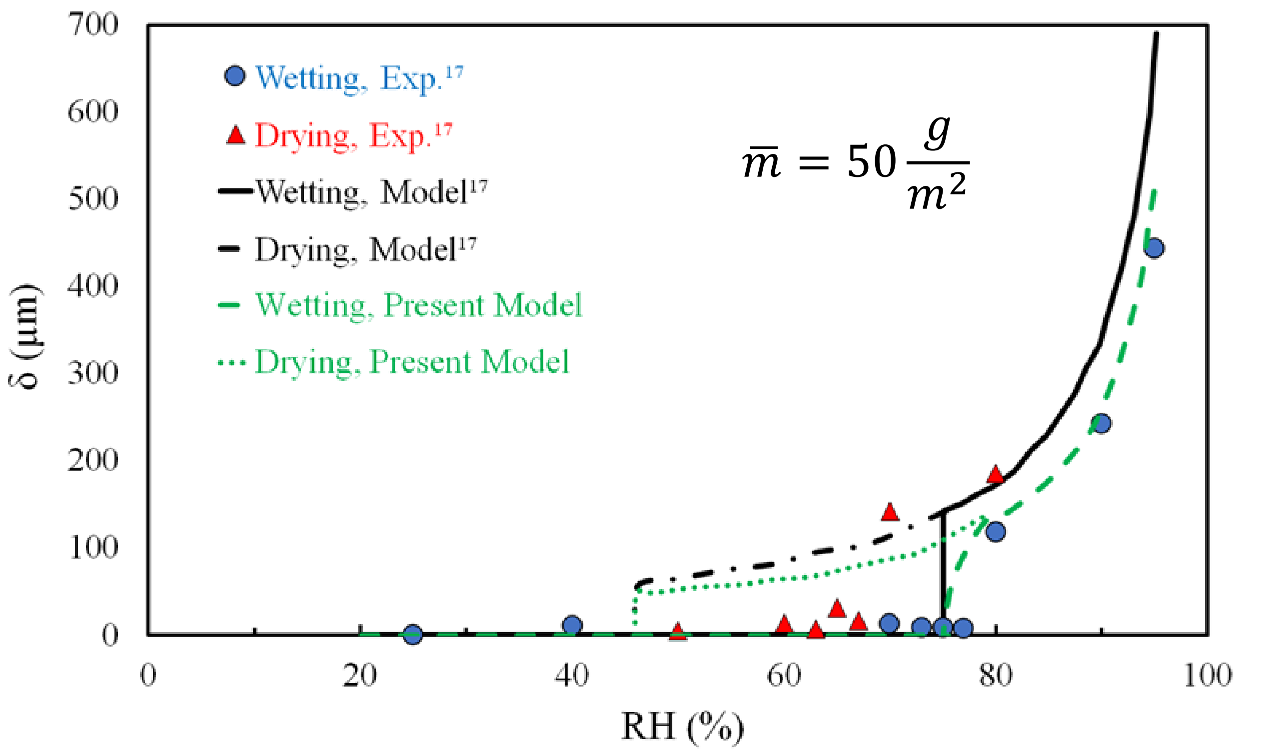


*A saturated solution is a chemical solution containing the maximum concentration of a solute dissolved in the solvent.

[Saberi, Amiri, 2021]

Corrosion Modeling
(Film Thickness)

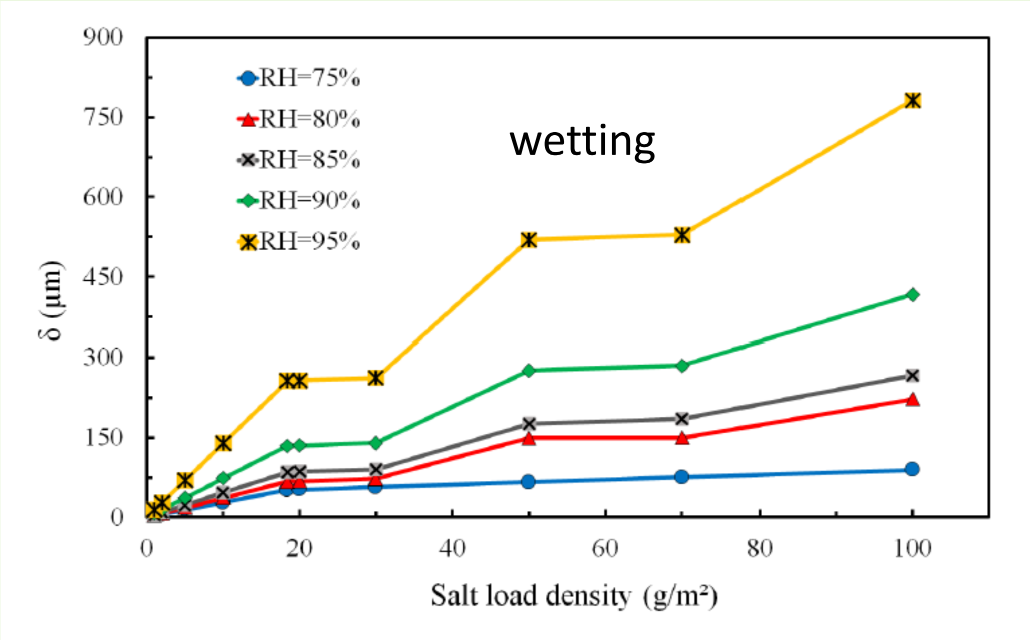
- $\delta(RH) = \begin{cases} \left(\frac{\overline{m}}{M}\right)\delta_{sat}(RH) & , \ \overline{m} < M \\ p\delta_{sat}(RH) + \frac{q}{\rho_{salt}}, & \overline{m} > M \end{cases}$
- where $\overline{m}$ is the salt load density,
- M is the amount of salt needed to form a saturated solution,
- ρ_{salt} is the salt density,
- p and q are calculated based on $\overline{m}$ and M as:
  - p is the smallest integer number for which we have $p \geq \overline{m}/2M$, and $q = \overline{m} - pM$

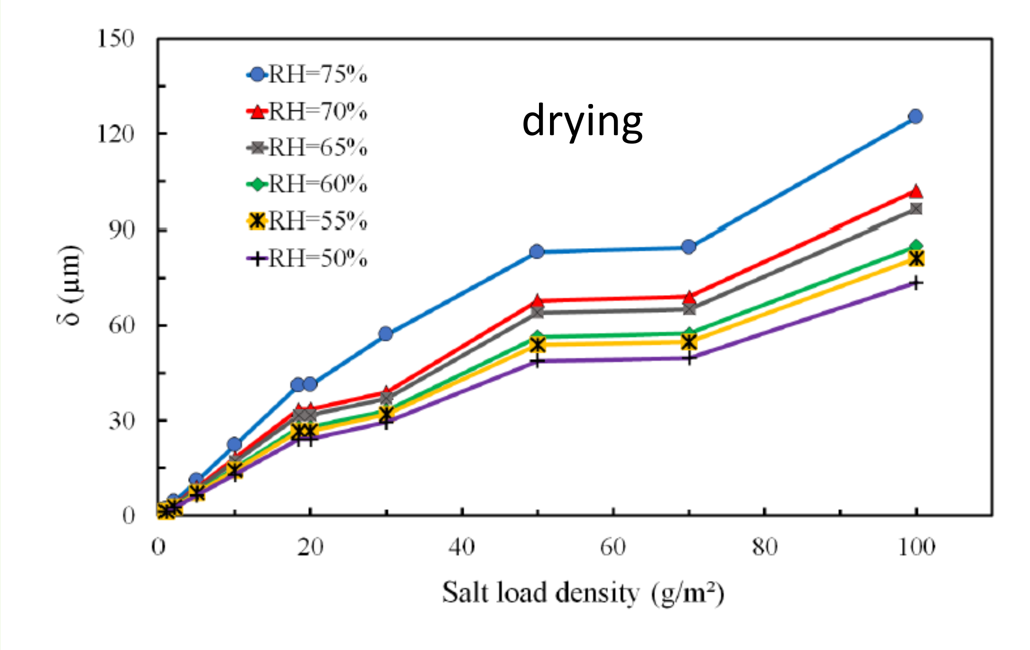


[Saberi, Amiri, 2021]
[Van den Steen et al., 2016]

Corrosion Modeling
(Film Thickness)

- Effect of salt load density on film thickness
- As the salt load density increases, the film thickness increases for a given relative humidity.

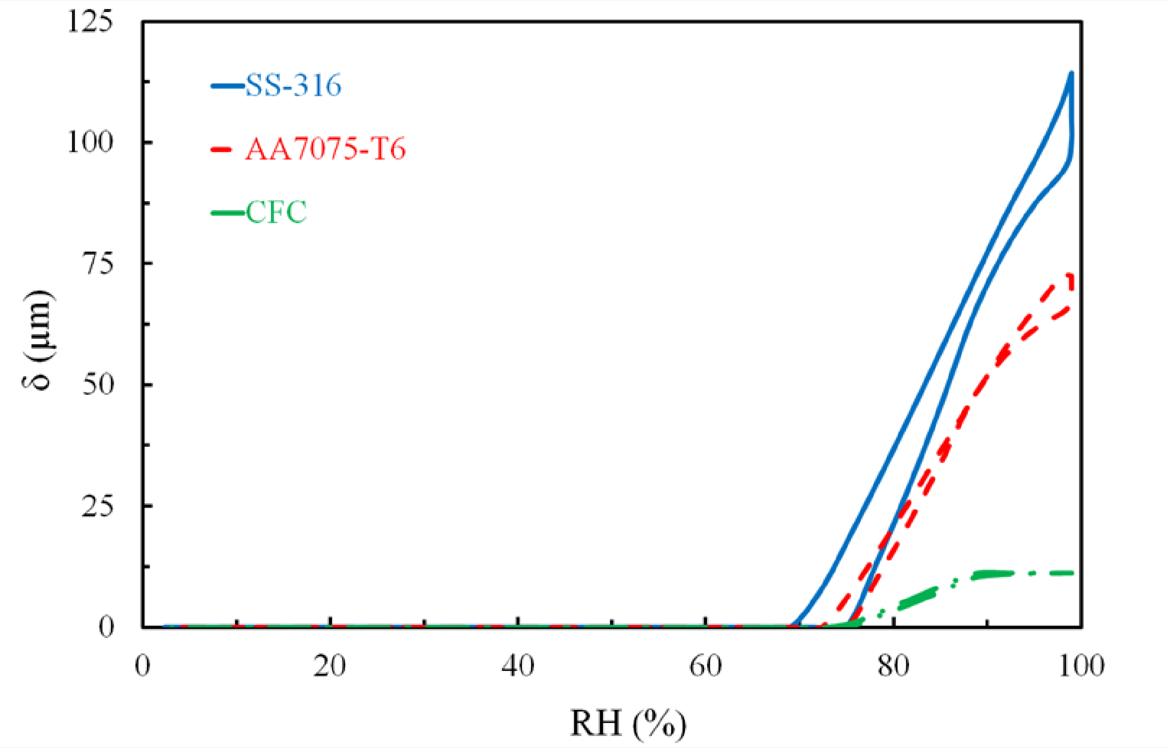




[Saberi, Amiri, 2021]

Corrosion Modeling
(Film Thickness)

- Effect of substrate:
  - SS316, AA7075-T6, Chlorofluorocarbon (CFC)
- Roughness & contact angle ignored
- It is concluded that substrates with higher value of ρc_p form thicker film due to higher maximum water mass flux and Time of Wetness (TOW).



$$T = (T_0 - T_\infty)\exp\left(\frac{-2h_{air}t}{\rho c_p d}\right) + T_\infty$$

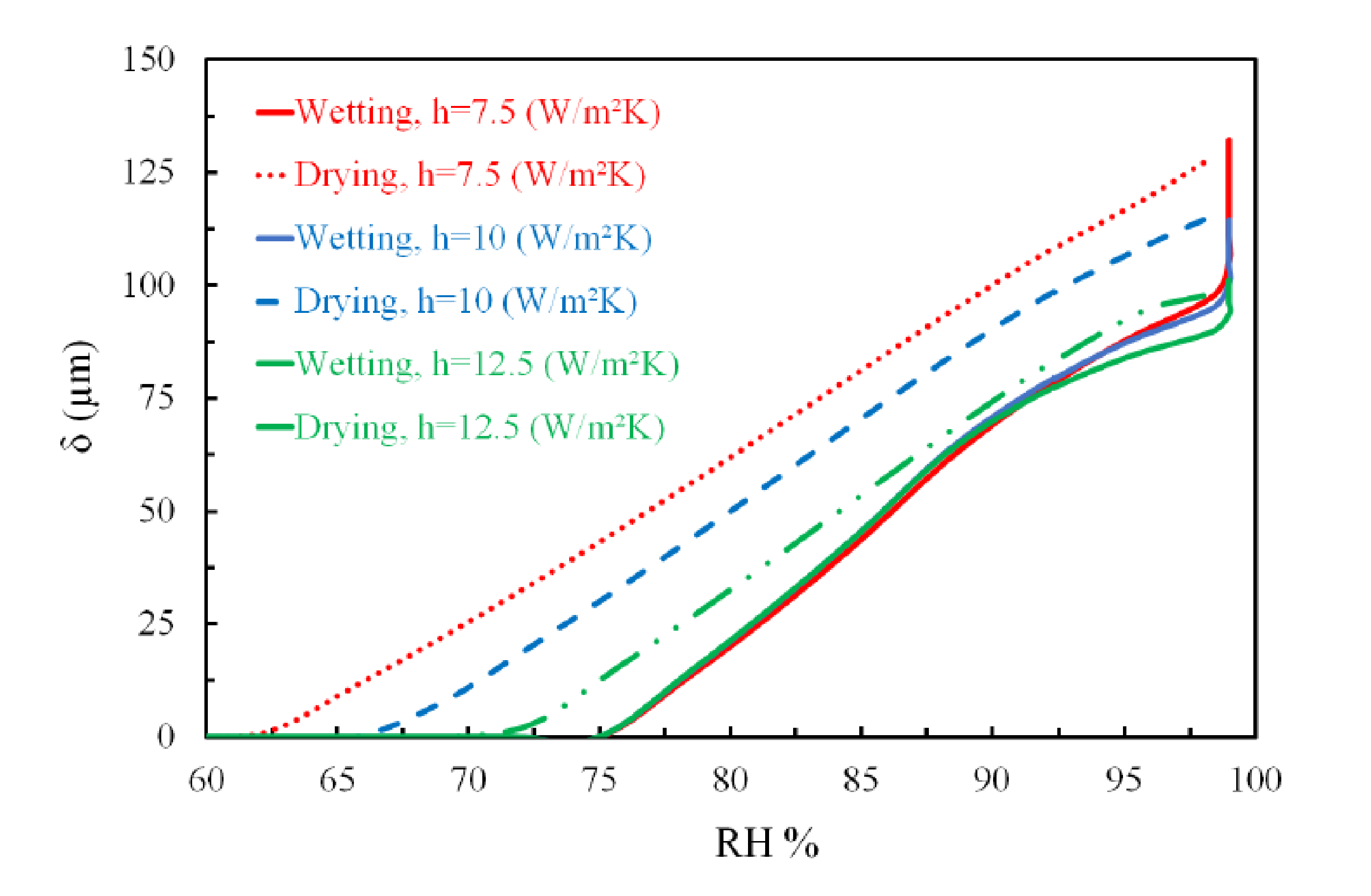
Table I. Density and specific heat of SS316, AA7075-T6, CFC.

Substrate	SS316	AA7075-T6	CFC
ρ (kg m^{-3})	7878	2810	1529
c_p (J Kg^{-1} K^{-1})	490	960	598
$\boxed{\rho c_p \text{ (J m}^{-3}\text{K}^{-1})}$	3.86×10^6	2.69×10^6	0.91×10^6
δ_{max} (μm)	114.45	72.47	11.15
$\dot{m}_{max}$ (kg m^{-2}s^{-1})	2.98×10^{-5}	2.17×10^{-5}	0.46×10^{-5}
Time of reaching δ_{max}	27: 45′: 47″	26: 15′: 28″	23: 54′: 58″

[Saberi, Amiri, 2021]

Corrosion Modeling
(Film Thickness)

- The effect of heat transfer coefficient, *h*
- The higher values of *h* result in smaller maximum film thickness because the time response to reach steady-state temperature is shorter for higher *h* which, in turn, results in smaller film thickness.



[Saberi, Amiri, 2021]

Corrosion Modeling
(Corrosion rate)

- Corrosion rate based on the electrolyte film thickness

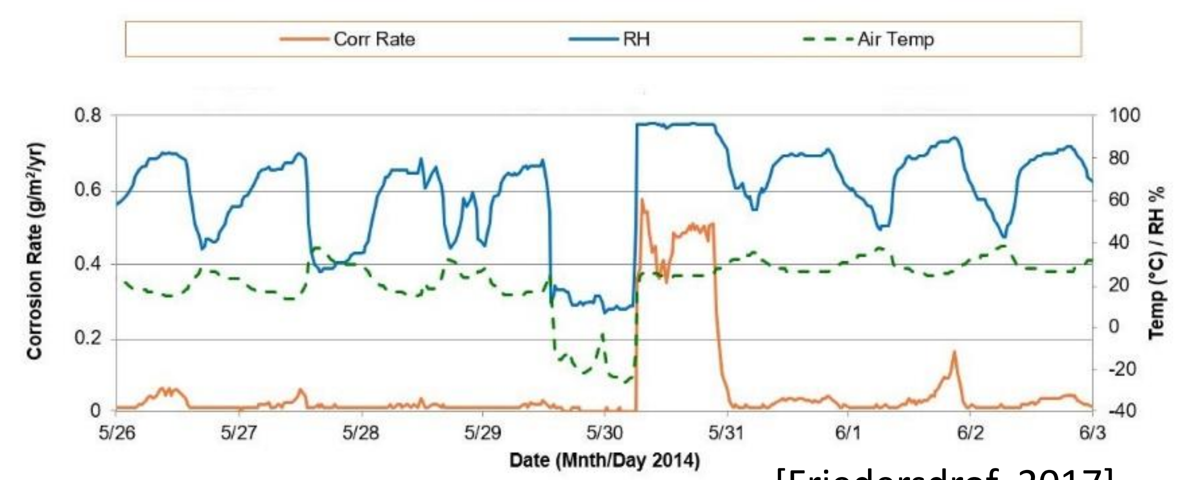
$$j(\delta) = \begin{cases} \dfrac{nFD_{O_2}C_{O_2}^{bulk}}{\delta_{nc}} & \delta \geq \delta_{nc} \\ \dfrac{nFD_{O_2}C_{O_2}^{bulk}}{\delta} & \beta \leq \delta < \delta_{nc} \\ \dfrac{nFD_{O_2}C_{O_2}^{bulk}}{\beta^2}\delta & \delta < \beta \end{cases}$$

D_{O_2}: the diffusion coefficient of oxygen,

β: the film thickness for which the current density is maximum,

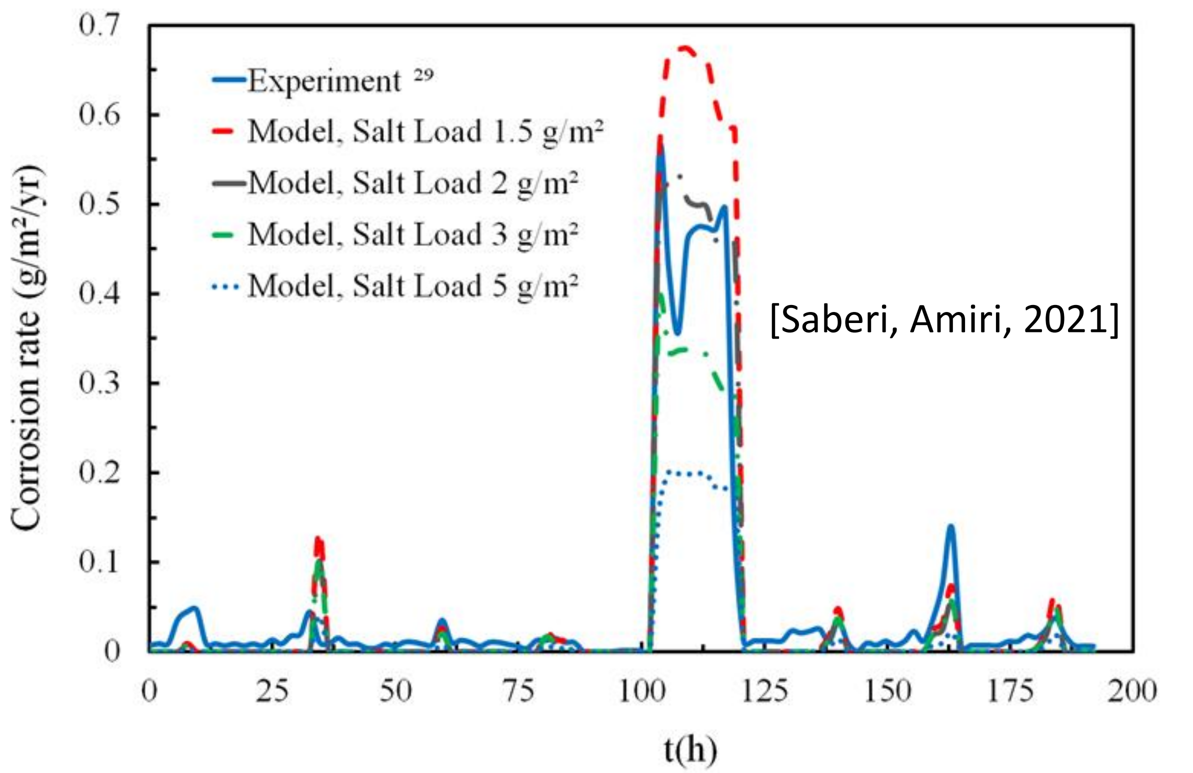
$C_{O_2}^{bulk}$: the bulk concentration of oxygen,

δ_{nc}: the maximum of film thickness after which the current density is assumed to be constant



[Friedersdrof, 2017]

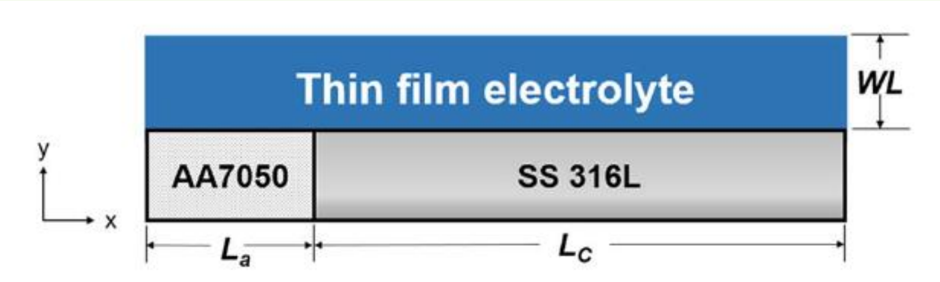
AA7075-T6

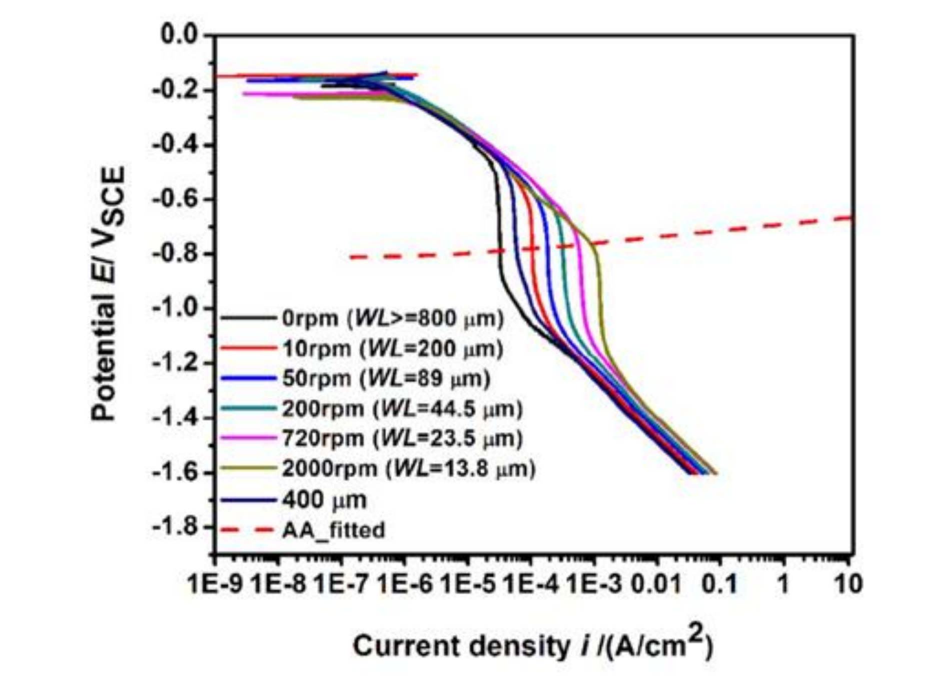


[Saberi, Amiri, 2021]

Corrosion Simulation
(Galvanic corrosion)

- Film thickness, δ, affects the:
  - Cathode equilibrium potential
  - Cathode equilibrium current density
  - Cathode Tafel slope
- Anode:
  - Equilibrium potential
  - Equilibrium current density
  - Tafel slope
- Anode limiting current density obtained from $j(\delta)$ model

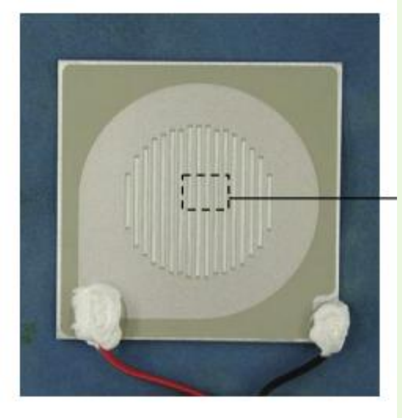


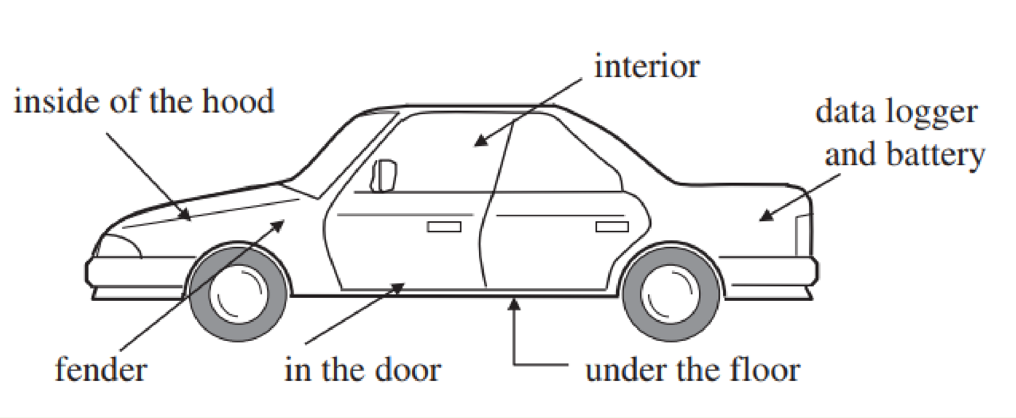


[Liu, Srinivasan, Kelly, 2017]

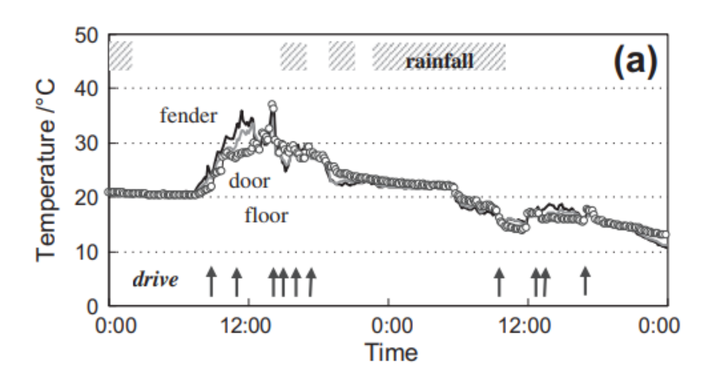
Corrosion Simulation
(Galvanic corrosion)

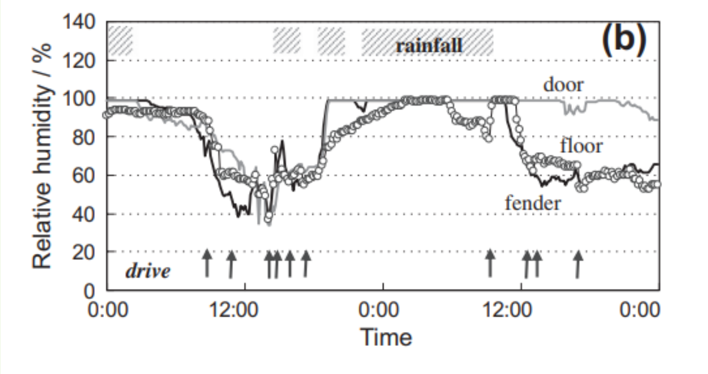
- The atmospheric corrosion monitor (ACM) sensor to measure Temp., RH, corrosion current
- Coupons:
  - cold rolled steel
  - Zn coated steel
  - Thickness 0.8 mm
- We used experimental measurements to validate our galvanic simulations

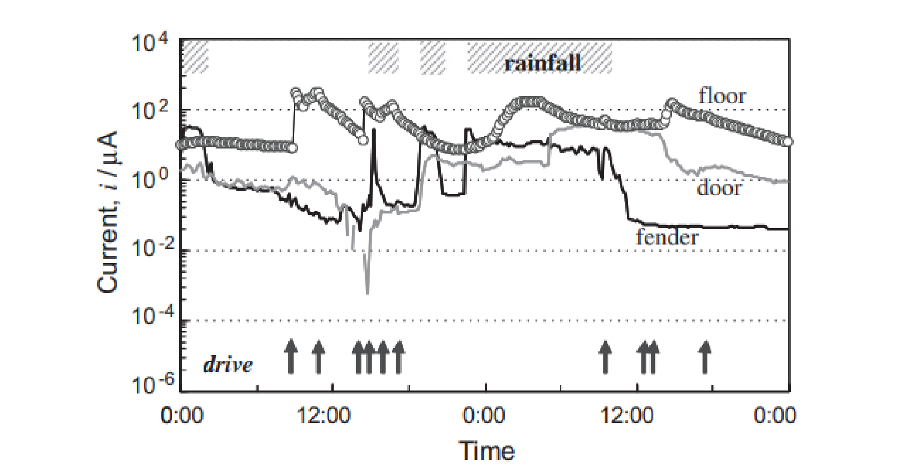




[Mizuno et al., 2014]

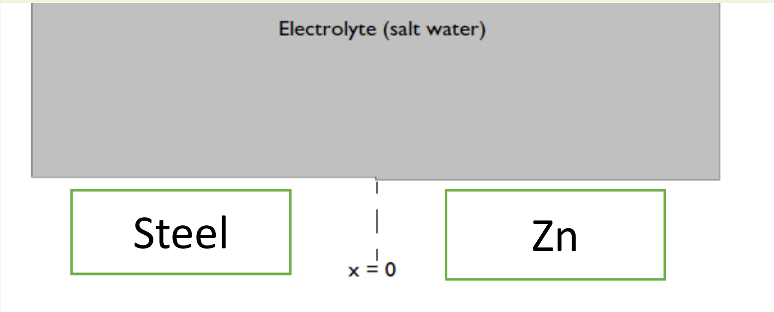


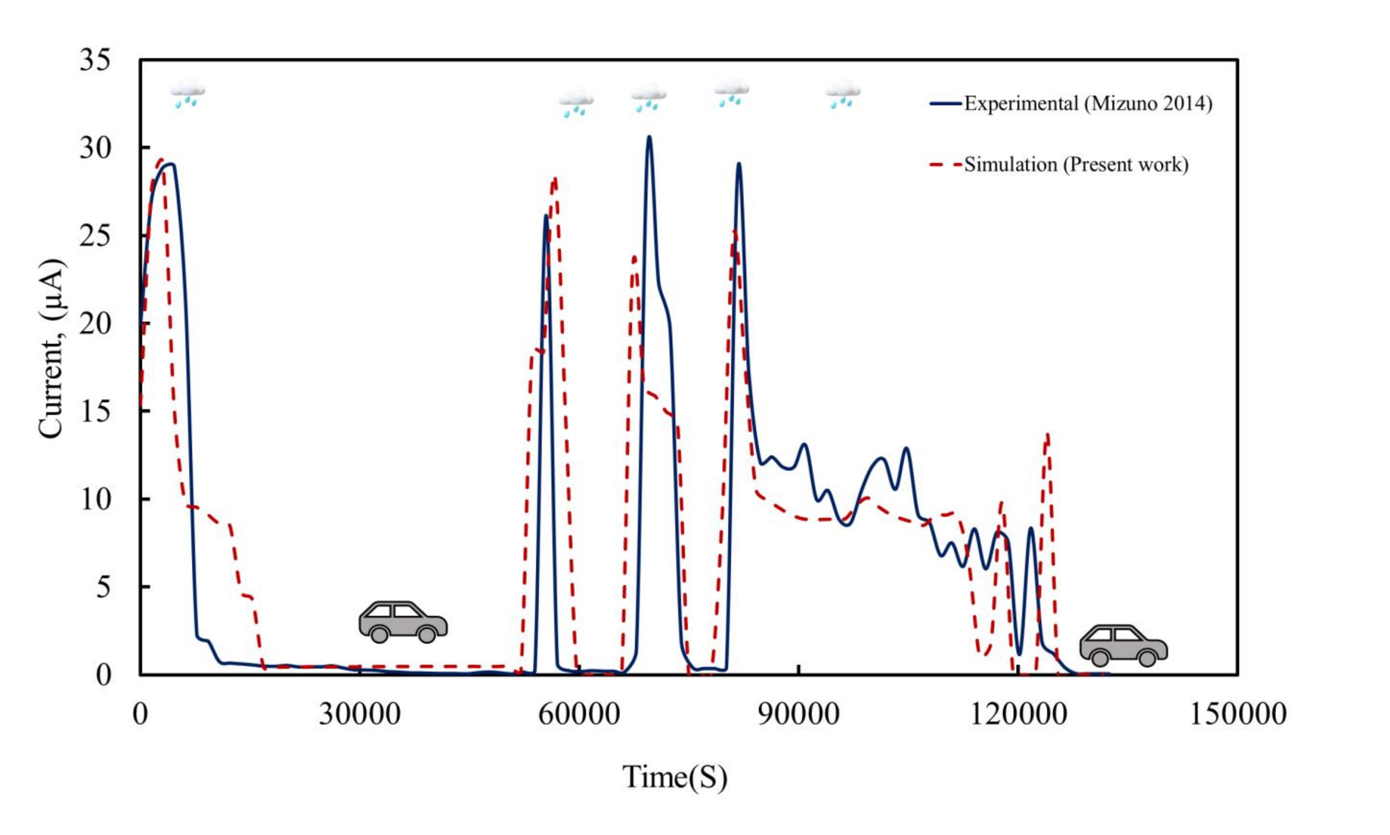




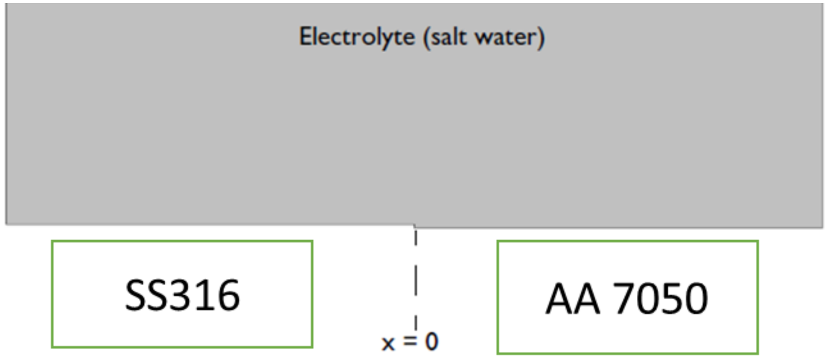
Corrosion Simulation
(Galvanic corrosion)

- Simulations for fender
- Data extracted from Steel-Zn polarization curve
- Assumptions:
  - For rainfalls:
    - $\delta = constant$
  - For driving:
    - $\delta \cong 0$
  - Salt load density $2\ g/m^2$
  - The effect of gravity on fender is ignored
- The model is capable of capturing the trend of corrosion rate for a given relative humidity and temperature history



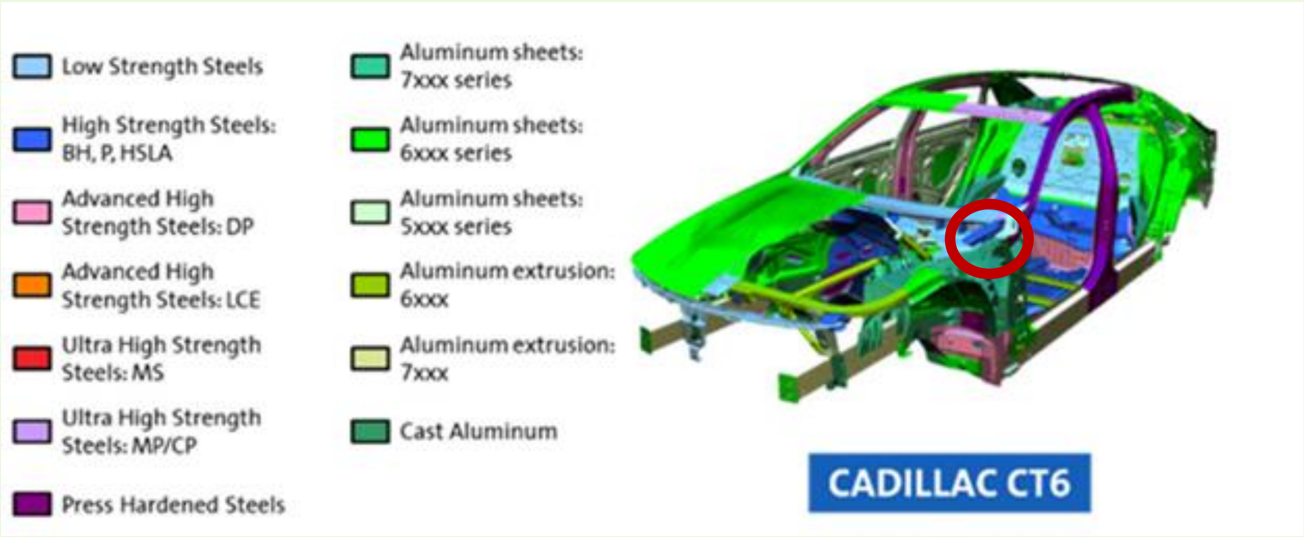


Corrosion Simulation
(Galvanic corrosion)

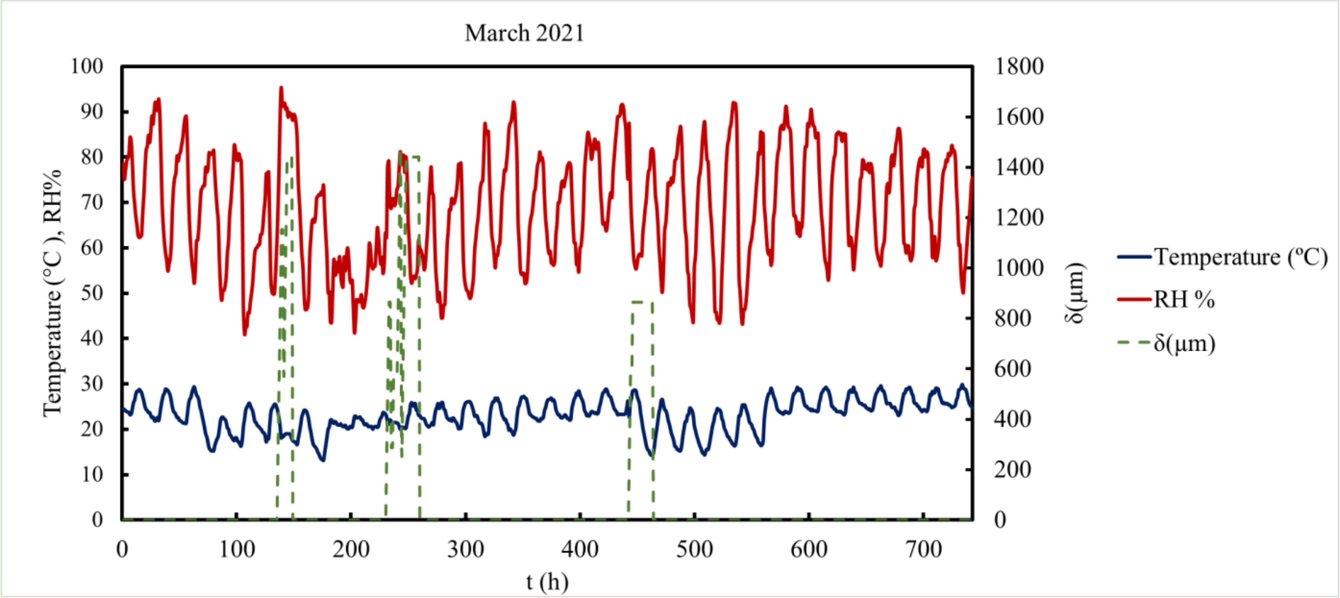


- Weather data* for Miami Beach for 2021
- The effects of gravity, wind, sun light are ignored
- No driving history
- Salt load density of $2g/m^2$

*https://www.visualcrossing.com/weather-data

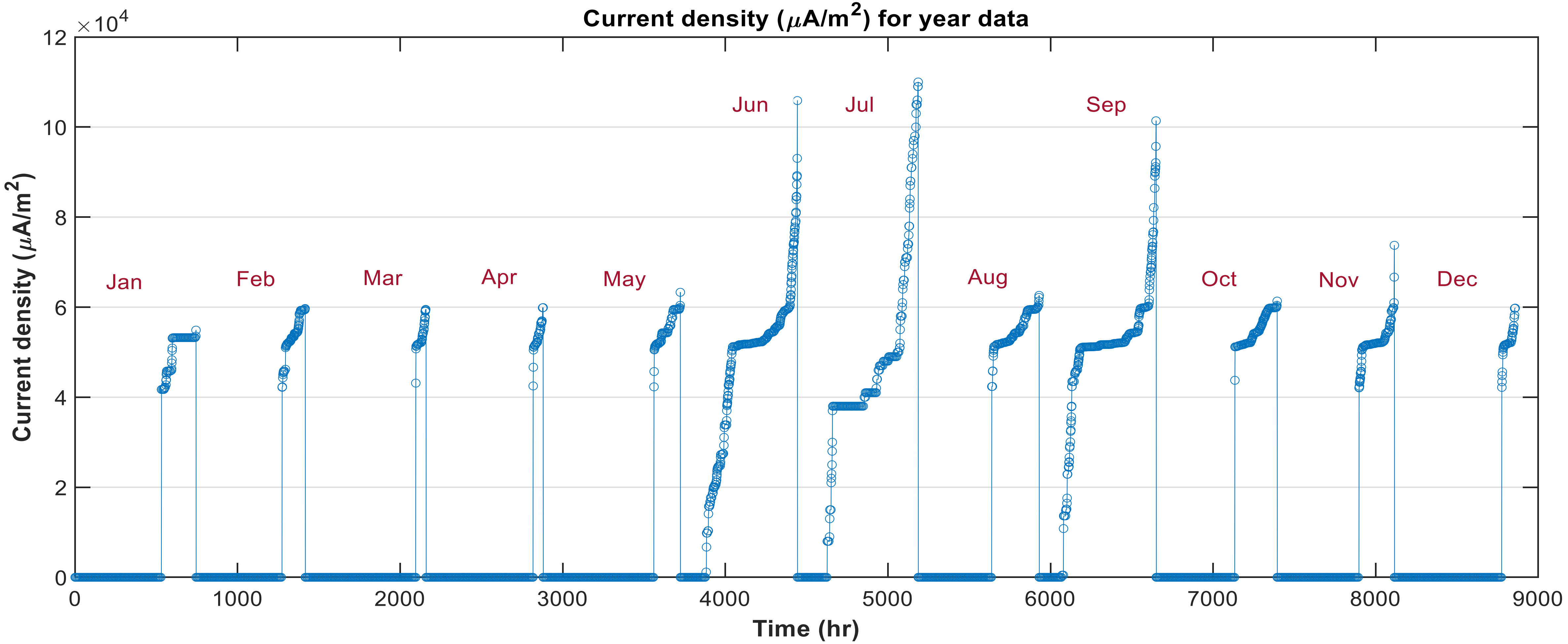


[Liu et al., 2018]

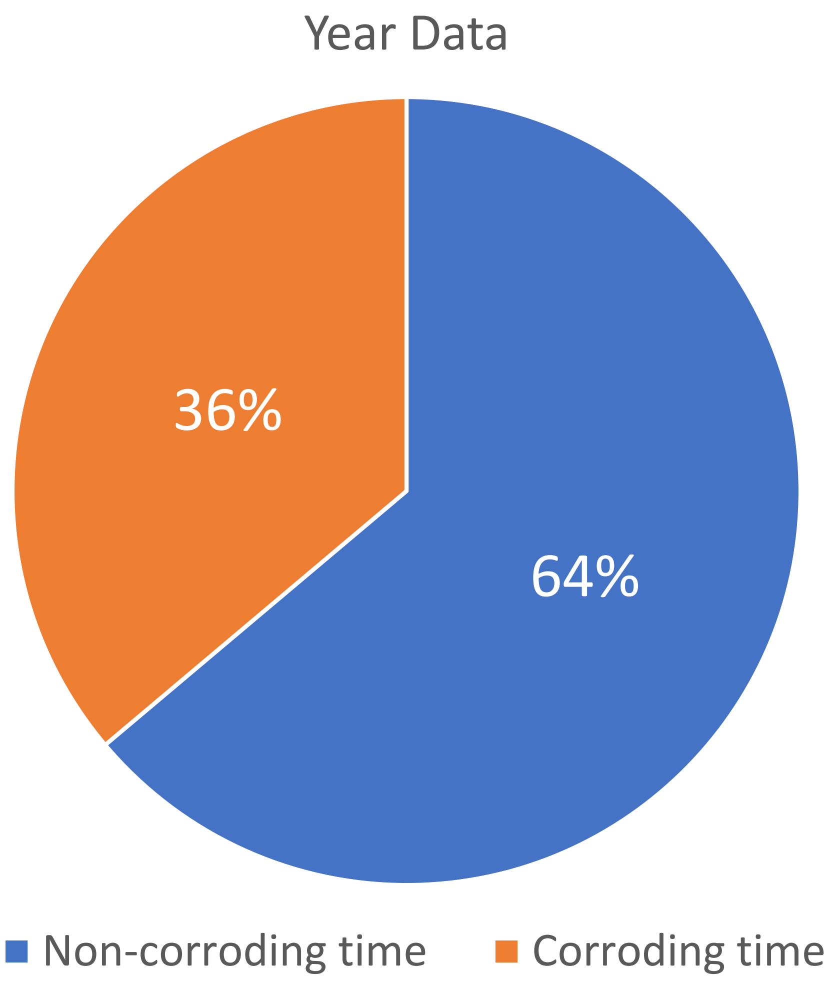


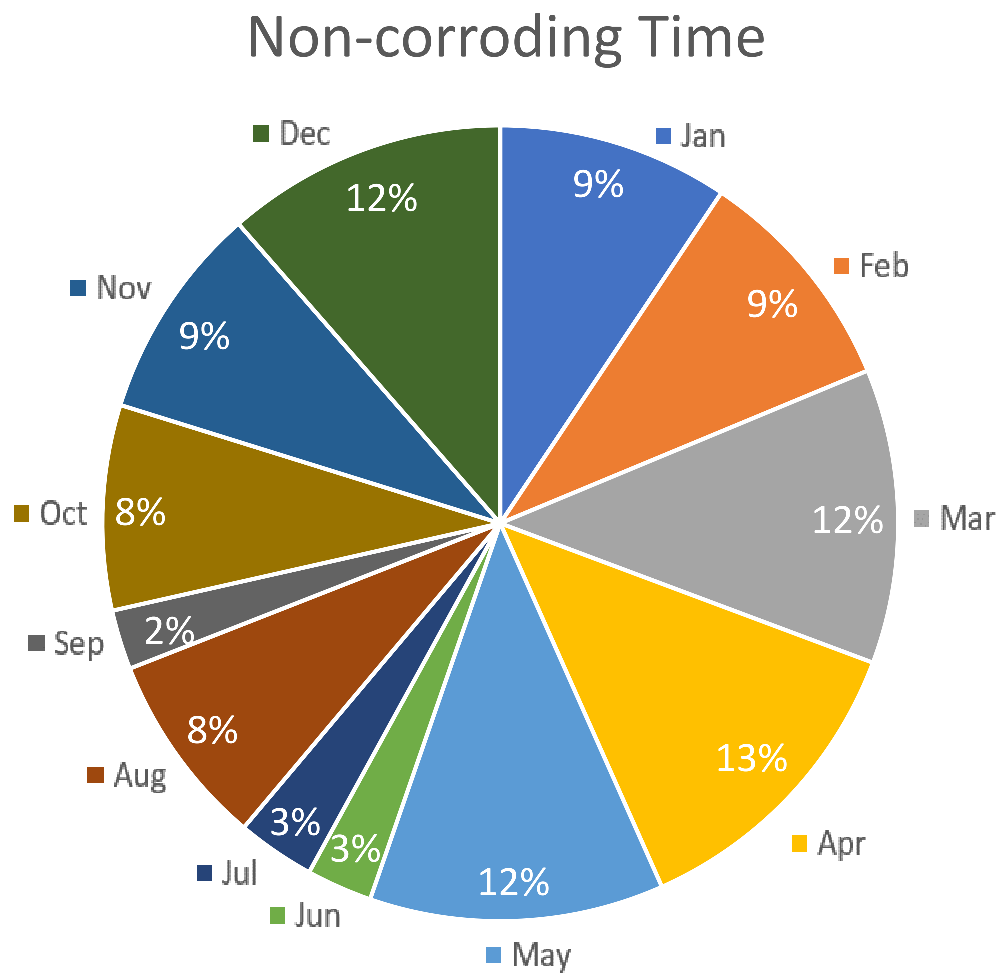
Corrosion Simulation (Galvanic corrosion)

- Sorted data



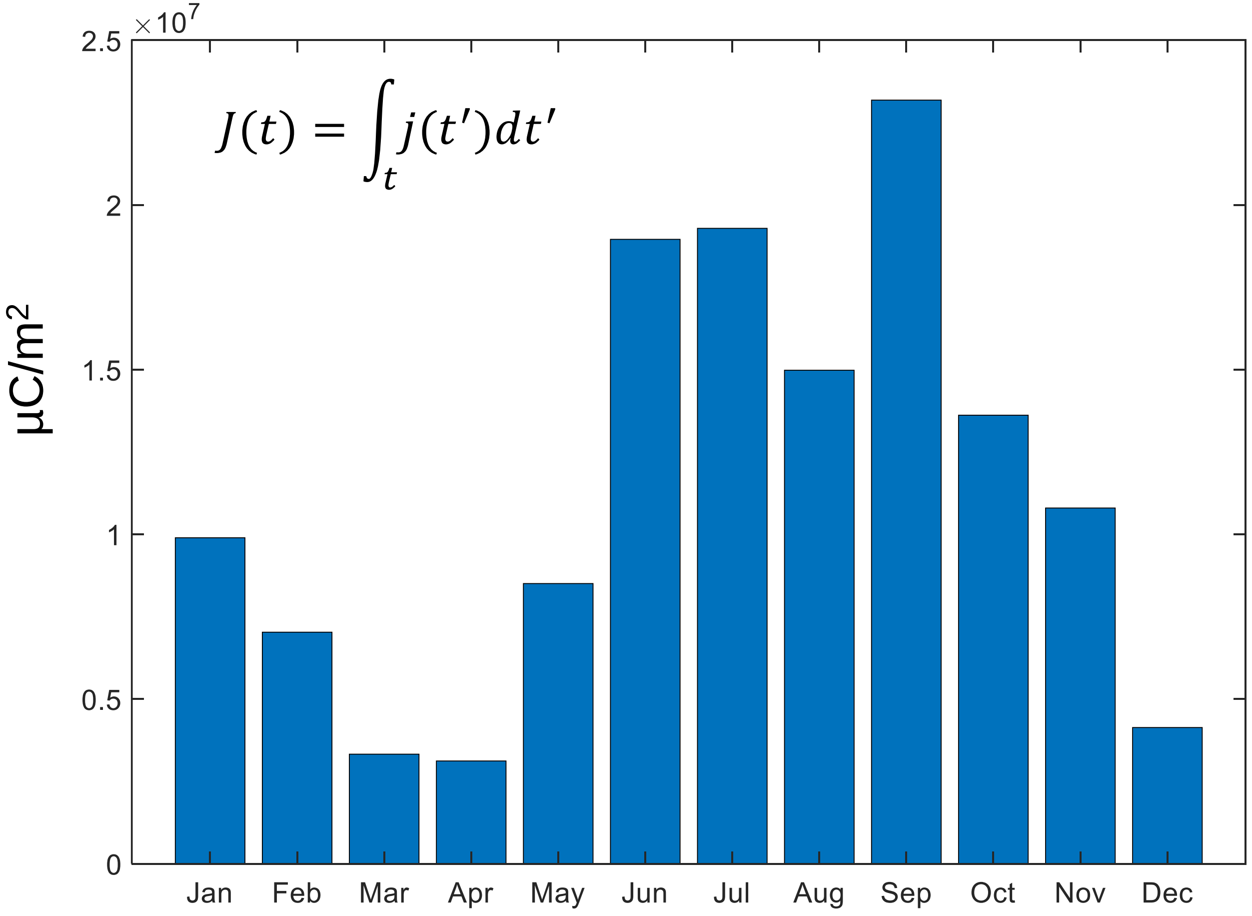
Corrosion Simulation (Galvanic corrosion)



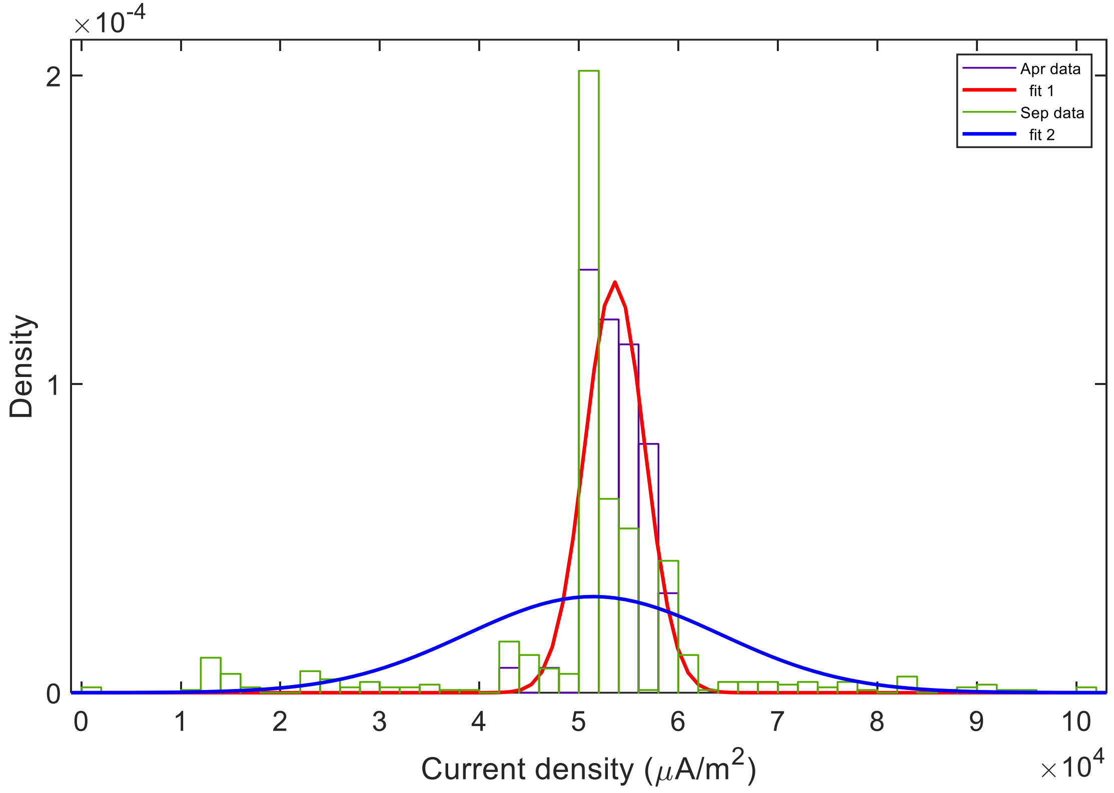


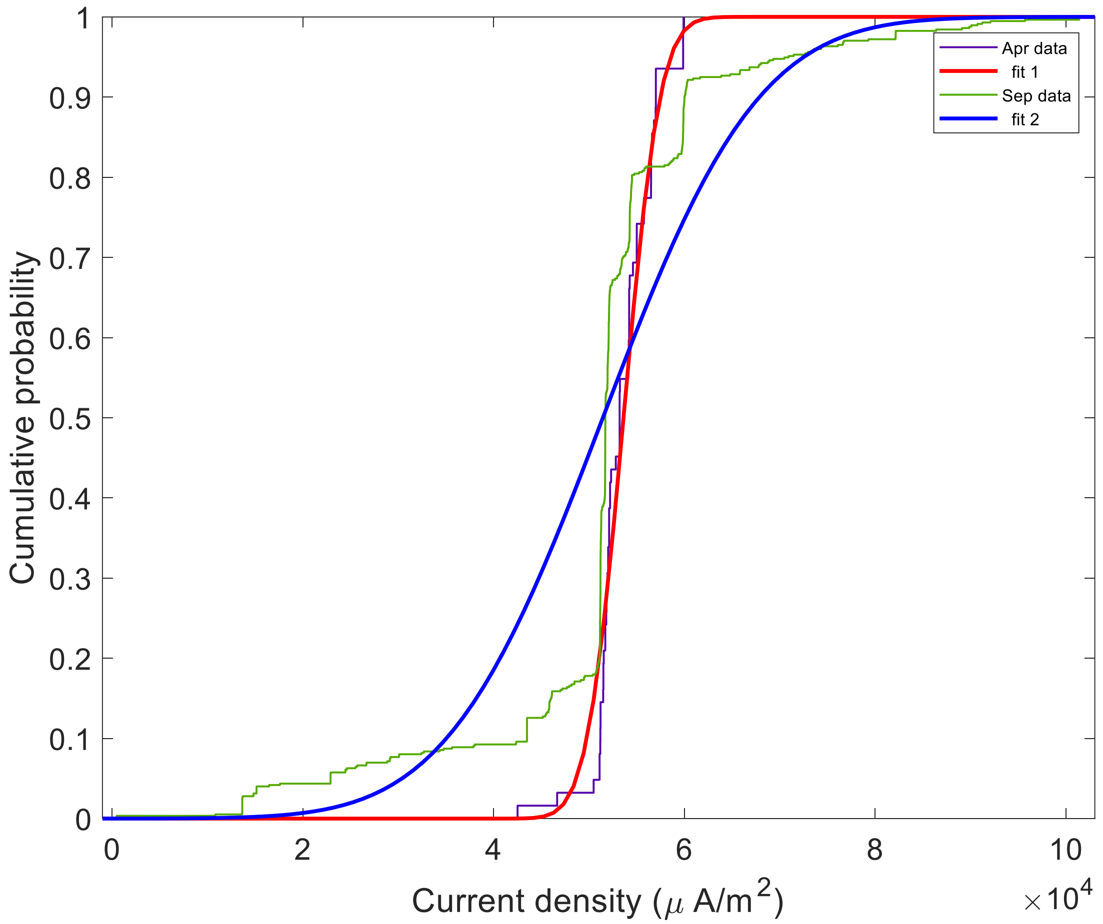
Corrosion Simulation (Galvanic corrosion)

- Magnitude of the corrosion current density and its time duration are both determining factors in overall corrosion
- Monthly integration of the current density over time is shown below



Corrosion Simulation (Galvanic corrosion)



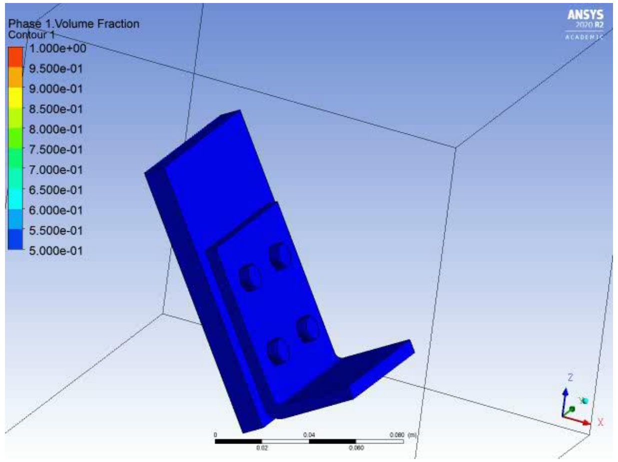


Conclusions

- The developed modeling and simulation is capable of capturing the trend of corrosion rate for a given relative humidity and temperature history.
- The model takes weather data as inputs and predicts corrosion rate
- To match the magnitude of the model prediction, the model parameters need to be calibrated.
- The model work for free corrosion and galvanic corrosion

Model Enhancement (Future Works)

- Several other factors such as part orientation, coatings, and other environmental factors must be accounted for (need for finite element simulations for film thickness)



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https://www.visualcrossing.com/weather-data

Thank you

Questions