



Local Corrosivity Classification and Enhancement of Corrosion Rate via Environmental Modification

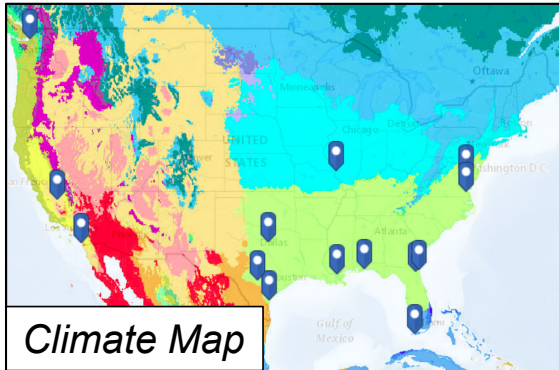
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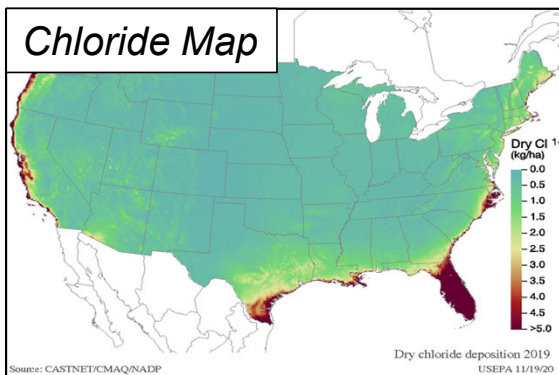
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Environmental Severity and Atmospheric Corrosion

Atmospheric exposure is complex and varies wildly from one location to the next



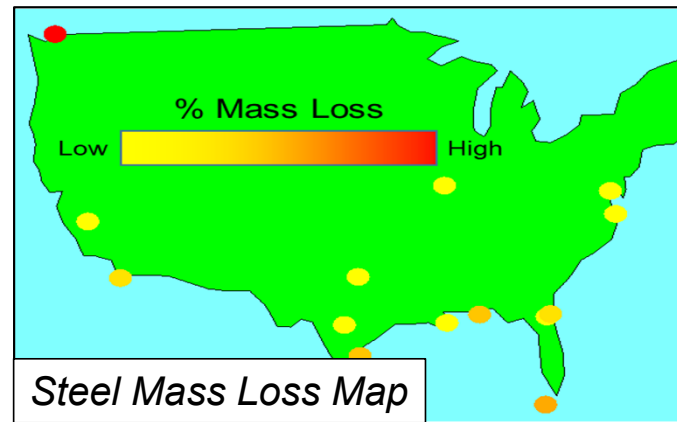
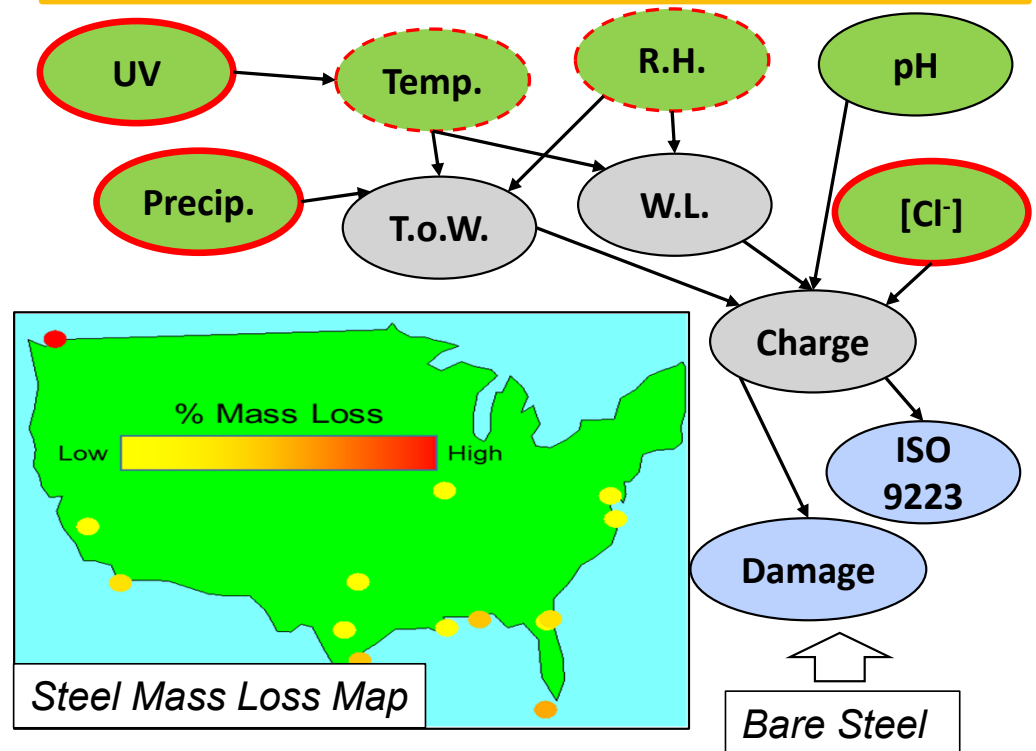
Climate Map



Chloride Map

What are some of the main, deterministic factors?:

- ▶ Temperature
- ▶ Relative Humidity
- ▶ Chloride Deposition
- ▶ Precipitation
- ▶ UV Radiation
- ▶ Sample



Steel Mass Loss Map

Bare Steel

Environmental Severity – Why Does It Matter?

U.S. Air Force TO 1-1-691

Table 3-1. Aircraft Wash Intervals

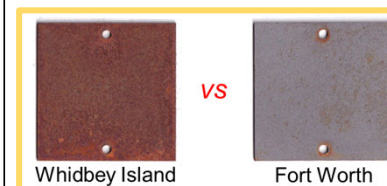
Air Base Name and Location * Asterisks before Air base Name and Location designates environments considered as SWA and fall under Chapter 9.	Wash Interval by Severity		
	Severe (30 Days)	Moderate (90 Days)	Mild (180 Day)
*Afghanistan (All Locations)			X
*Aj Taif, SA			X
*Al Dhafra UAE			X
*Al Jouf, SA			X
*Al Udeid AB QATAR			X
*Ali Al Salem Kuwait			X
Allen C. Thompson Fld.; Jackson, MS			X
Altus AFB, OK			X
Anderson AFB, GU	X		
Anchorage IAP, AK			X
Andrews AFB, MD (Washington DC)			X
*As Sulayyil, SA			X
Atlantic City, NJ			X
Aviano AB, IT			X
*Bahrain	X		
*Balad, Iraq			X



Intimidate Adversaries



Intimidate Corrosion



Has Real Consequences for Mission Readiness

Determines allocation of:

- Funds
- Personnel
- Resources
- Time

Can be mitigated through Environmental Modification:

- Rinsing
- Washing
- Covering

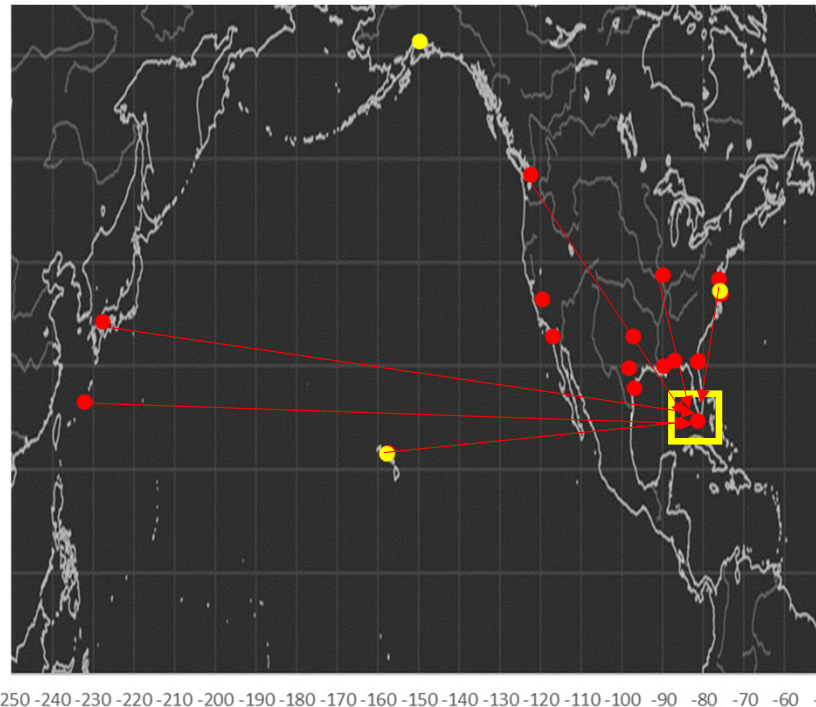
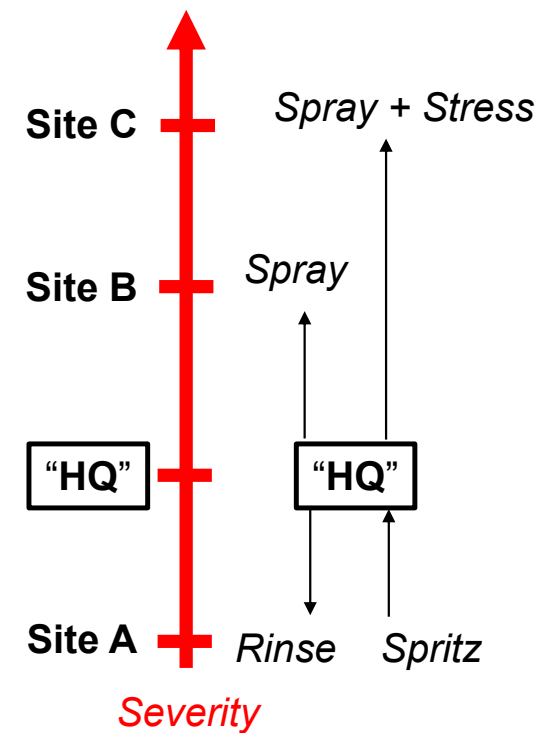
Goal: Favorably Modify the Environment
Means: Remove Corrosive Species

Objective

Phase I – Environmental Modification: 3-Month
Phase II – Environmental Modification: 12 Month
Phase III – Environmental Severity Correlation: 17-Site
Phase IV – Environmental Severity Correlation: 4-Site

First, modify the environment of a controlled test site to tune it to mimic other sites

Second, collect atmospheric corrosion data to determine environmental severity correlation



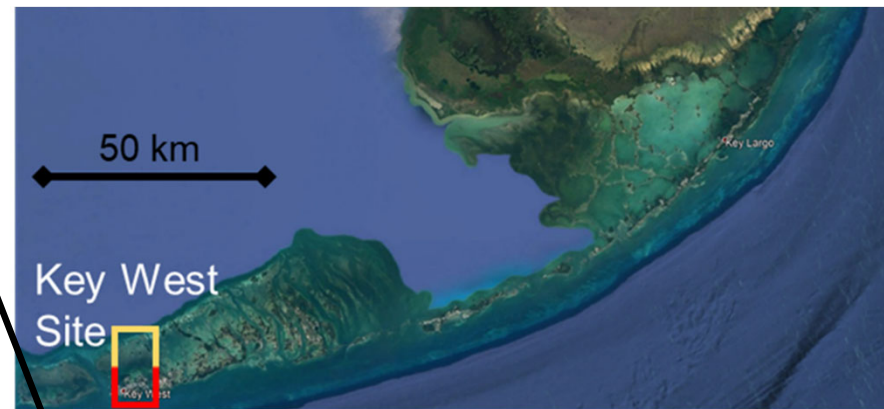
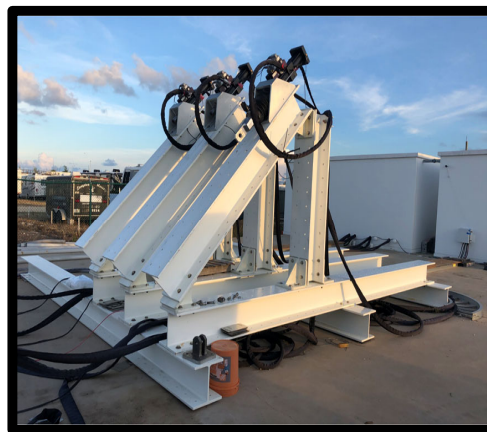
If Successful, It will:

- Demonstrate a correct understanding of environmental parameters and atmospheric corrosion
- Enable more flexibility in executing research
- Allow for correlation of results from controlled site to multiply sites of interest

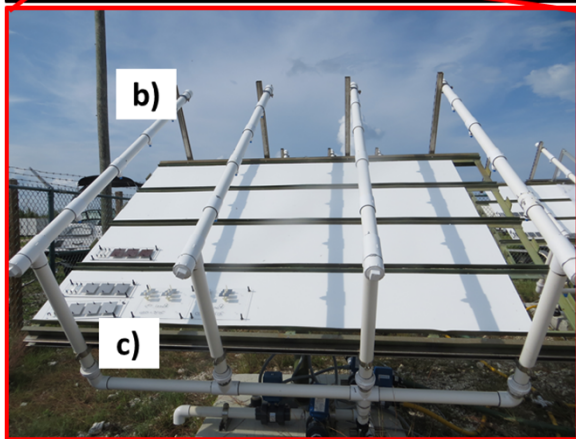
U.S. Naval Research Laboratory Key West Test Facility “Headquarters”

Stable and Measurable Conditions

- ✓ Meteorology
- ✓ Oceanography
- ✓ Research Infrastructure
- ✓ NRL Facility
- ✓ Aerosol Instrumentation
- ✓ Historical Baseline



Key West Environmental Modification (Phase I & II) Glossary



- a) Spray racks (programmable for CWR or sea spray, variable schedule and duration)
- b) Spray nozzles (CW and/or NSW)
- c) Samples
- d) Sea water tank (refreshed twice weekly)
- e) Aircraft cover (note sample shading)
- f) Ambient exposure racks

Ambient: Natural, unaltered environment

Clear Water Rinse (CWR): Short, Periodic rinsing with clear water

Clear Water (CW): Purified water like tap, drinking, potable, fresh, etc.

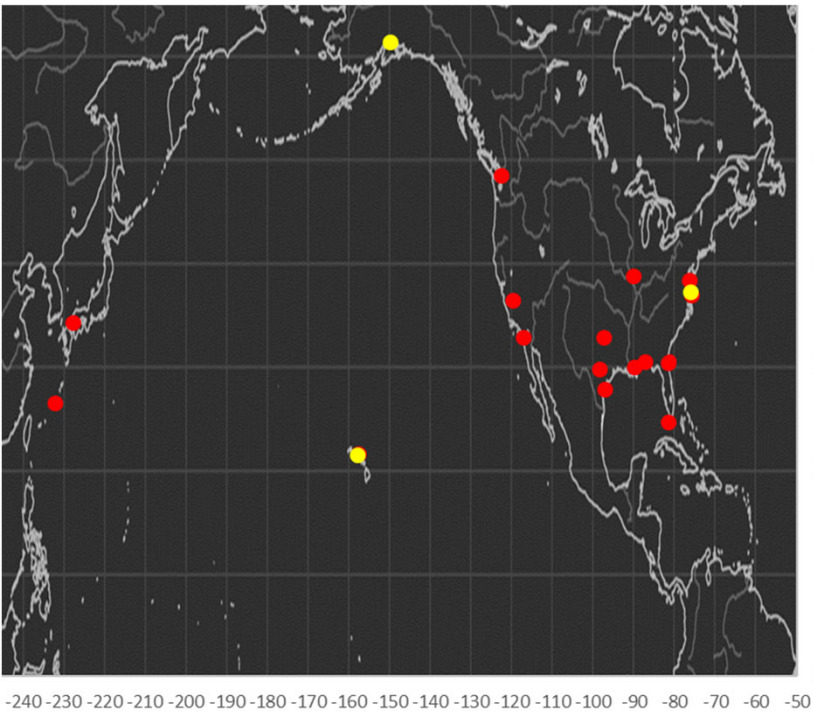
Natural Sea Water (NSW): water sourced straight from the ocean

Cover: Open-ended plasticized tension fabric tent

Baseline Condition	No Rinse	Once Weekly Rinse	Multi-Weekly Rinse
Ambient (No Spray)	[A]	[A1]	[A2]
Covered (No Spray, No Rain, No Sun)	[C]	[C1]	[C2]
Daily NSW Spray	[S]	[S1]	[S3]
Twice Daily NSW Spray	[X]	[X1]	[X3]

Environmental Severity Campaigns

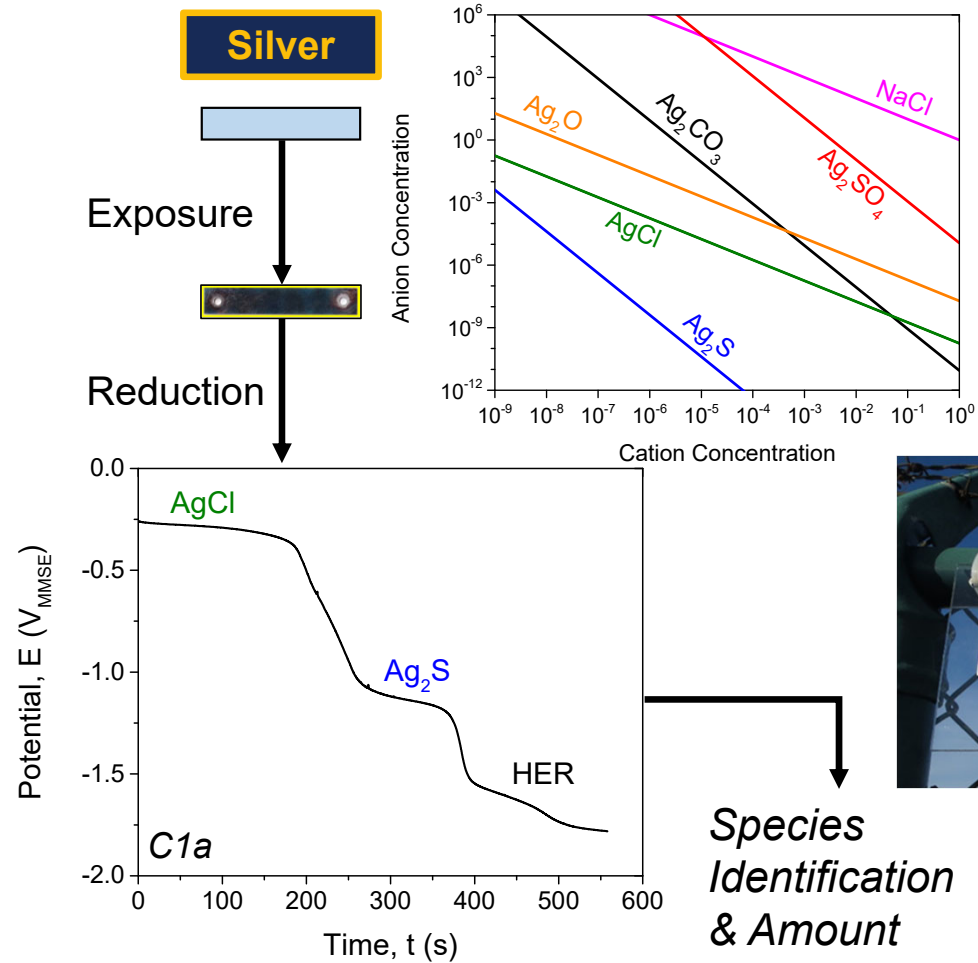
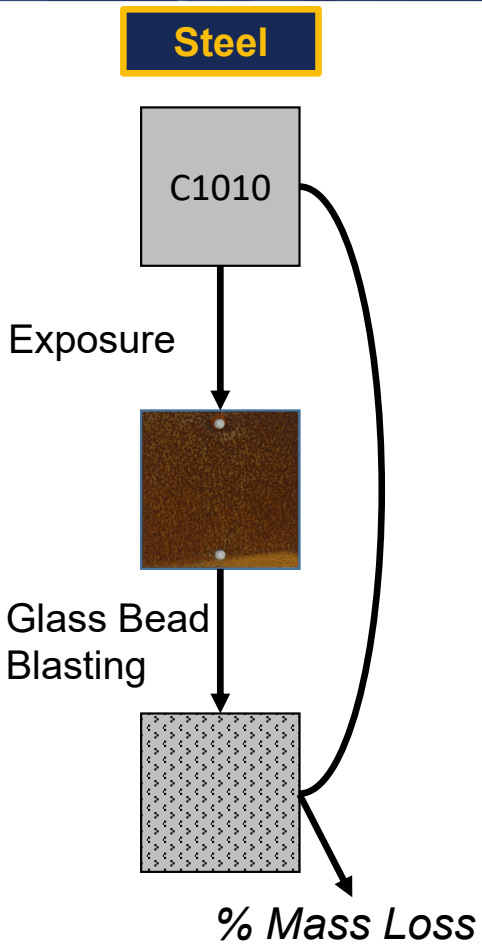
Phase III – 17 Site Assessment
 Phase IV – 4 Site Assessment



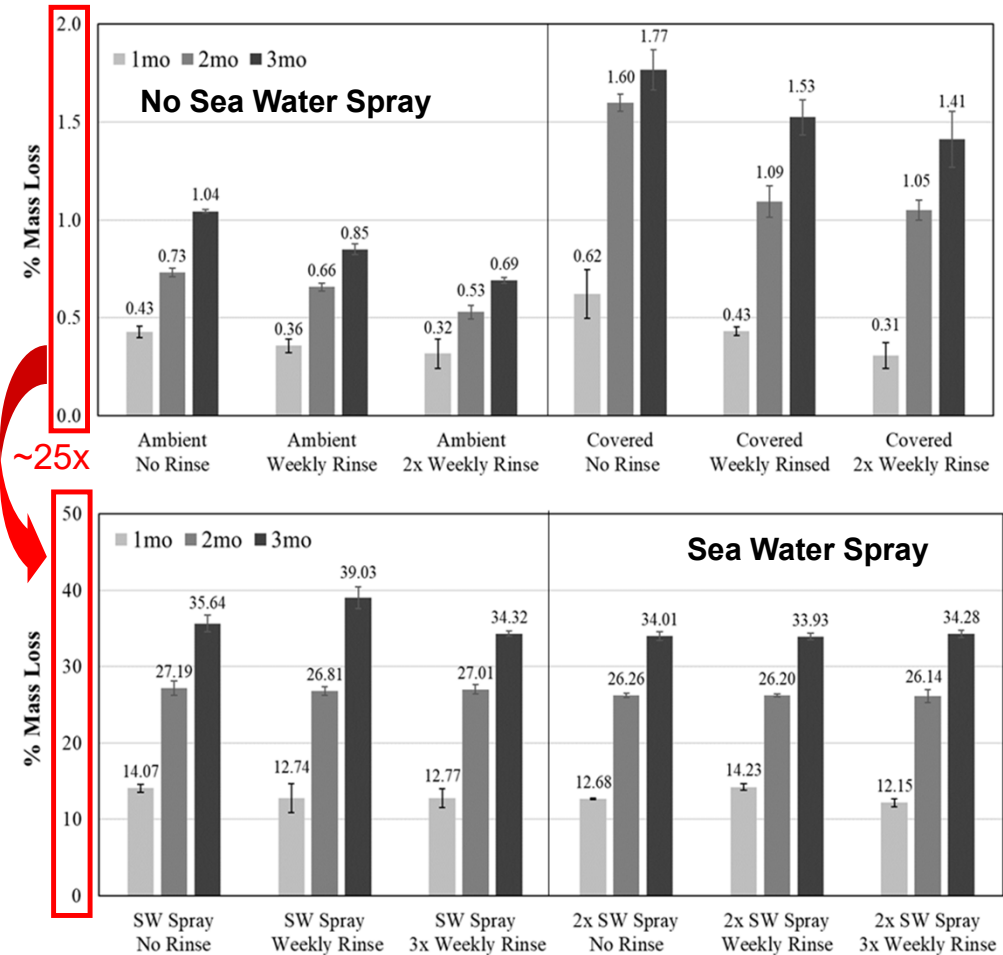
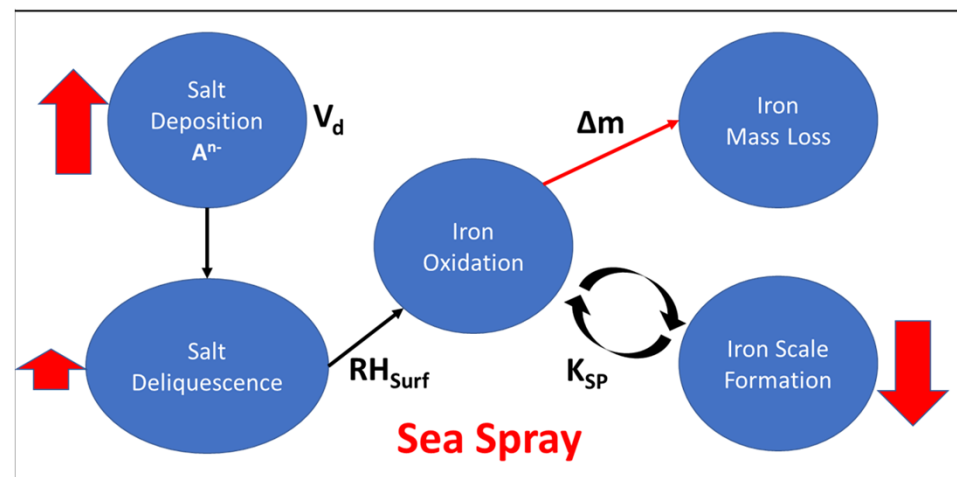
<i>Site (Alphabetical)</i>	<i>Site ID</i>	<i>Köppen Code</i>	<i>Exposure Start</i>
NAS Corpus Christi	CC	Cfa	21DEC2020
NAS Ft. Worth	FW	Cfa	17DEC2020
MCAS Iwakuni	Iw	Cfa	01DEC2020
NAS Jacksonville	Ja	Cfa	17DEC2020
MCAS Kaneohe Bay	KB	Aw	30NOV2020
NRL Key West	KW	Aw	14DEC2020
NAS Lemoore	Le	BSk	23DEC2020
NS Mayport	Ma	Cfa	14DEC2020
NAS New Orleans	NO	Cfa	15DEC2020
NAS North Island	NI	Csa / BSk	04FEB2021
NAS Oceana	Oc	Cfa	17DEC2020
MCAS Futenma, Okinawa	Ok	Cfa	31DEC2020
NAS/NAVAIR Patuxent River	PAX	Cfa	16DEC2020
NAS Pensacola	Pe	Cfa	14JAN2021
Boeing, St. Louis	SL	Cfa	13JAN2021
JB San Antonio	SA	Cfa	17DEC2020
NAS Whidbey Island	WI	Csb	14DEC2020
Elmendorf AFB	Elmo	Dsc	23FEB2021
Hickam AFB	Hick	Aw	26FEB2021
NAS Key West	KW	Aw	17FEB2021
Langley AFB	Lang	Cfa	17MAR2021

Test Coupons

Bare, witness coupons
No Coatings were tested!



Phase I Environmental Modification Effect of Natural Sea Water Spray



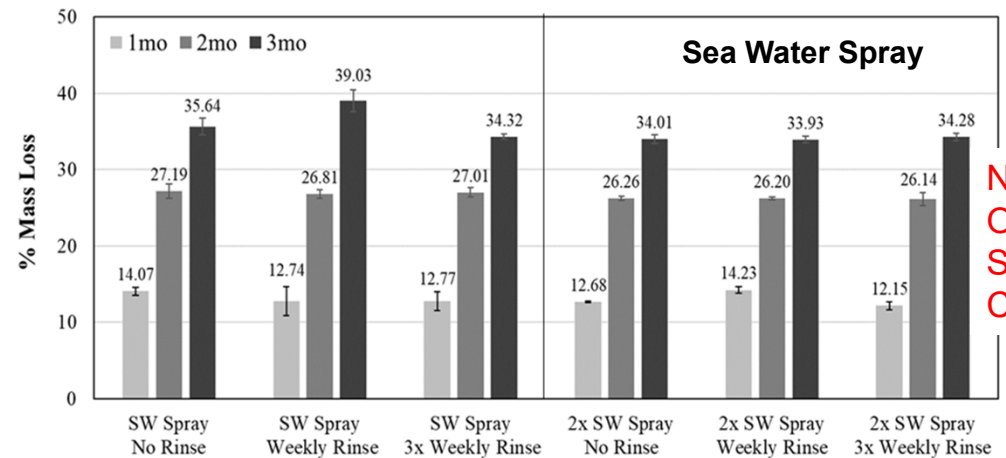
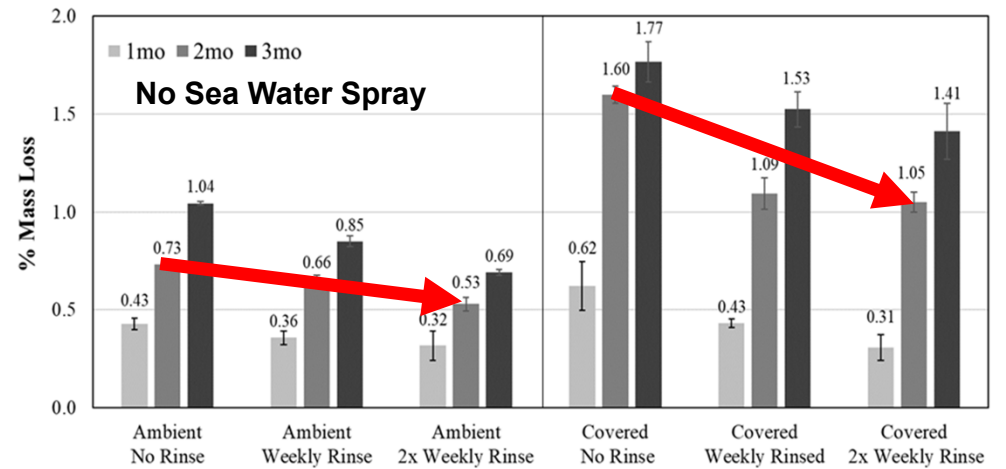
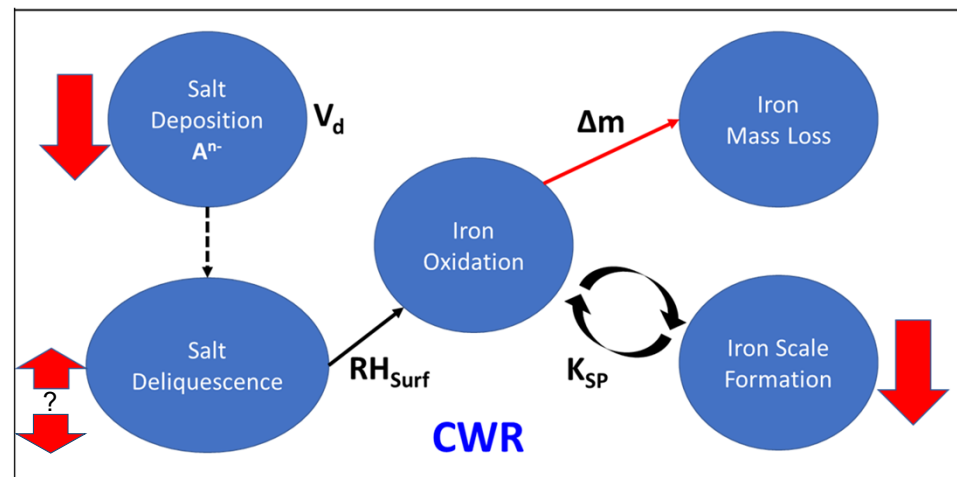
Spraying greatly increases salt accumulation on the surface

Spraying prolongs the amount of time in the wet condition

Spraying may limit iron scale formation

Generally, greatly increase steel corrosion(!)

Phase I Environmental Modification Effect of Clear Water Rinsing



No Effect On Sea Spray Condition

Rinsing greatly reduces salt accumulation on the surface

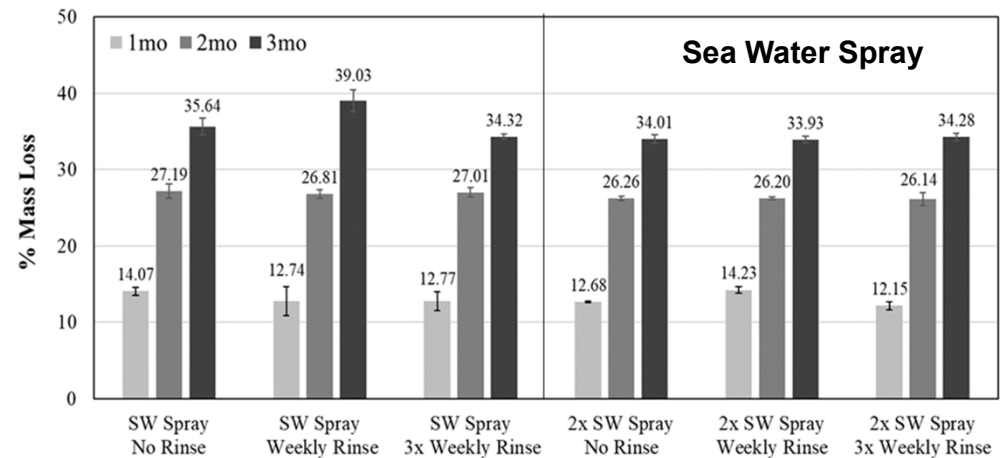
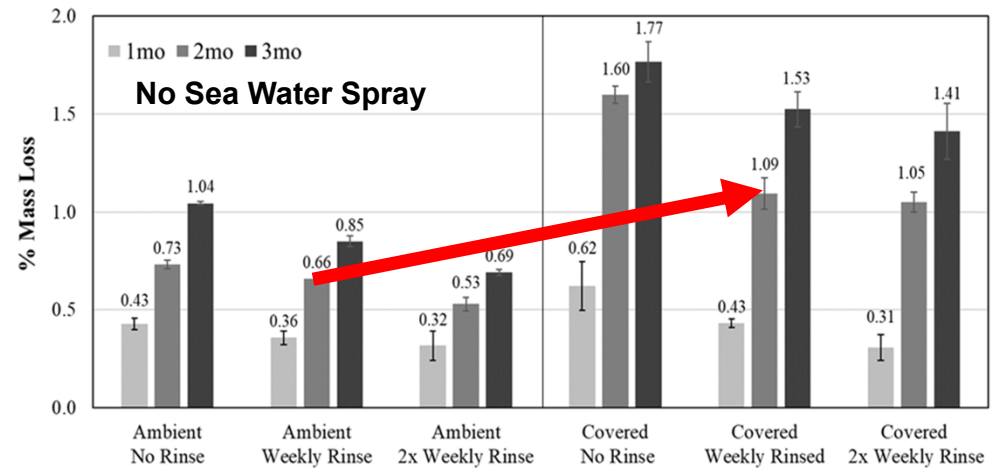
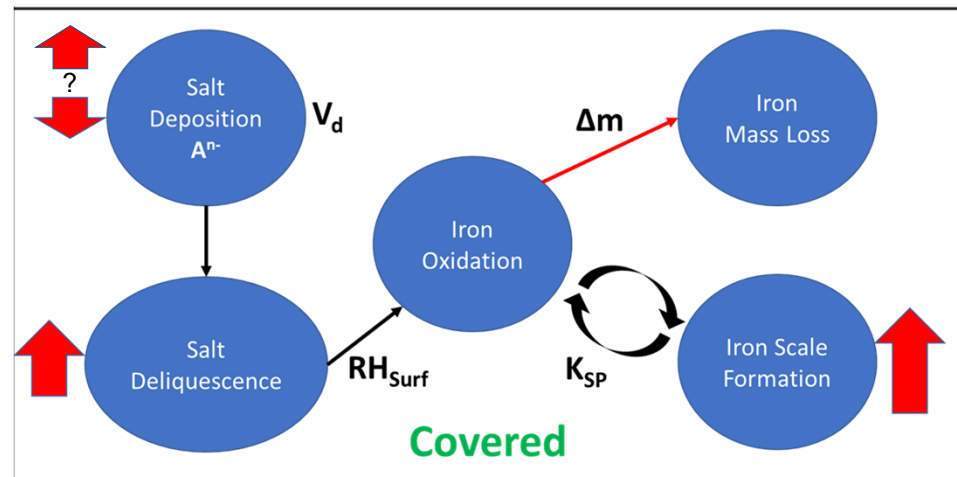
Rinsing, does it prolong wet time during rinses or decrease wet time by removing salt

Rinsing may limit iron scale formation

Rinsing is overwhelmed by spraying

Generally, reduces steel corrosion

Phase I Environmental Modification Effect of Covering



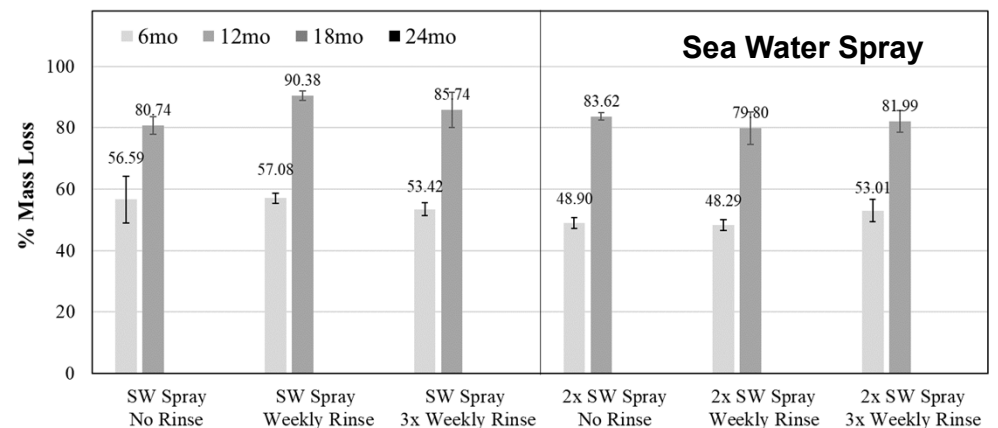
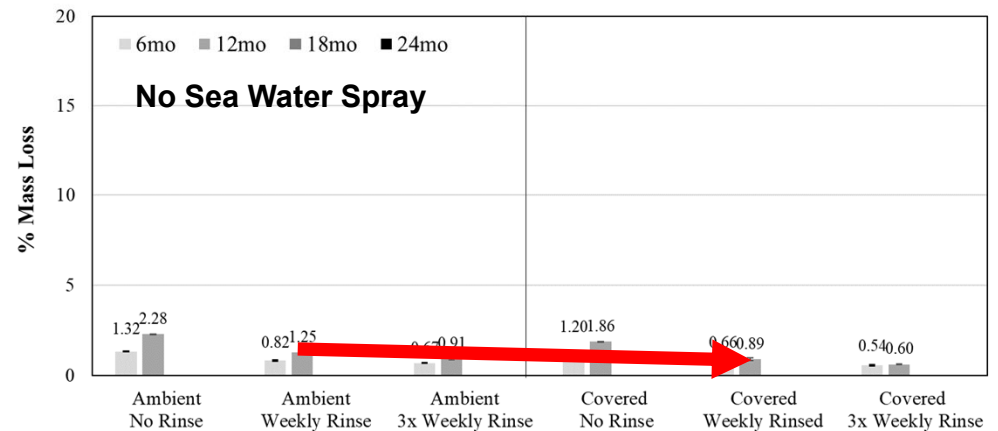
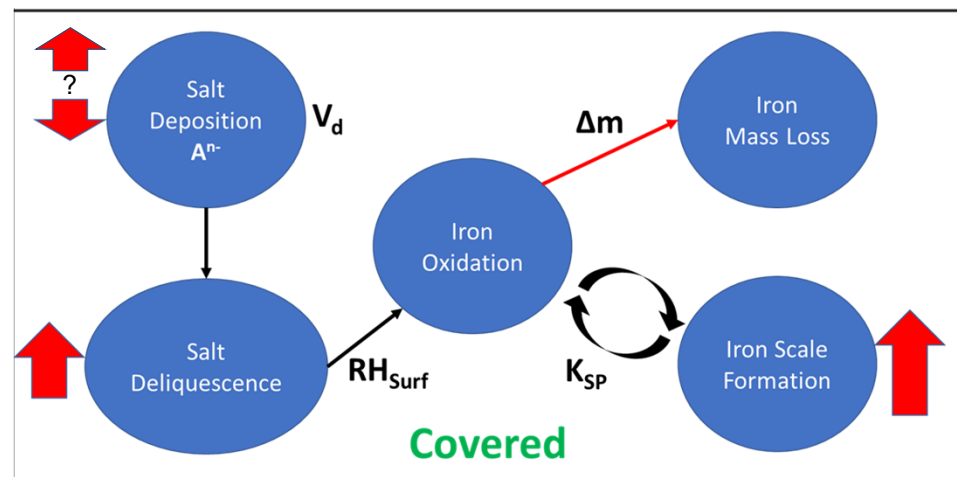
Covering may slow salt accumulation on the surface but may prevent salt removal by rain

Covering may prolong wet time by blocking solar radiation

Covering may promote iron scale formation

Generally, increases steel corrosion(?)

Phase II Environmental Modification Effect of Covering



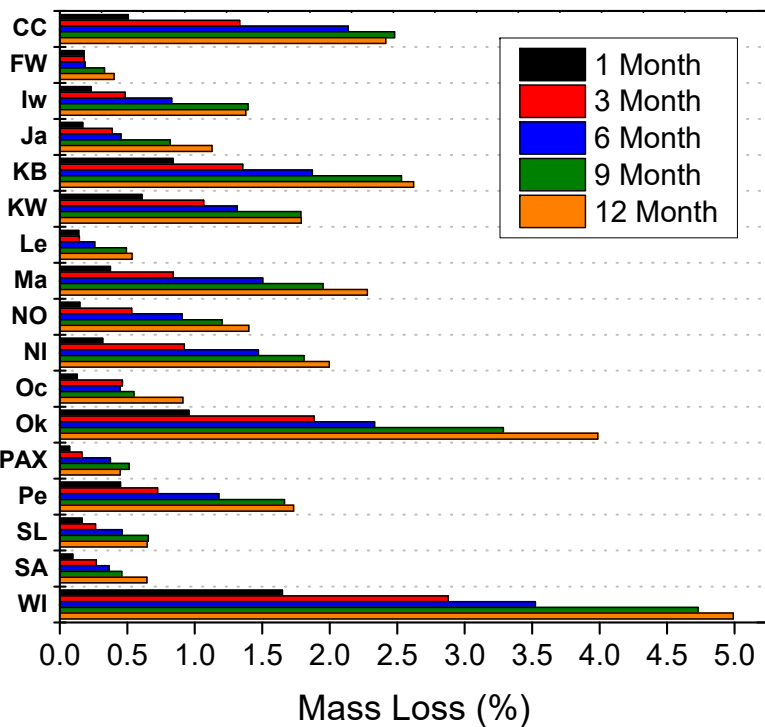
Covering may slow salt accumulation on the surface but may prevent salt removal by rain

Covering may prolong wet time by blocking solar radiation

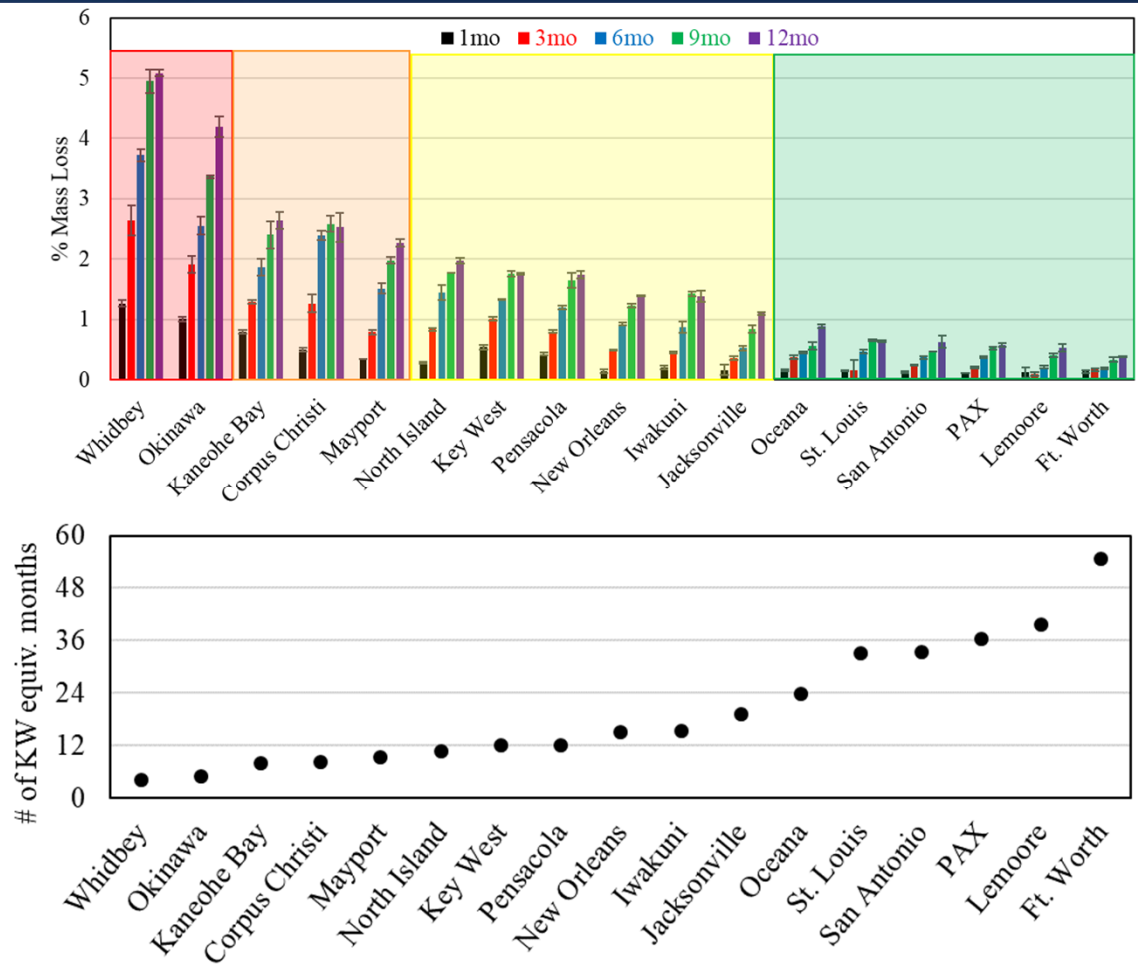
Covering may promote iron scale formation

Decreases steel corrosion(?)

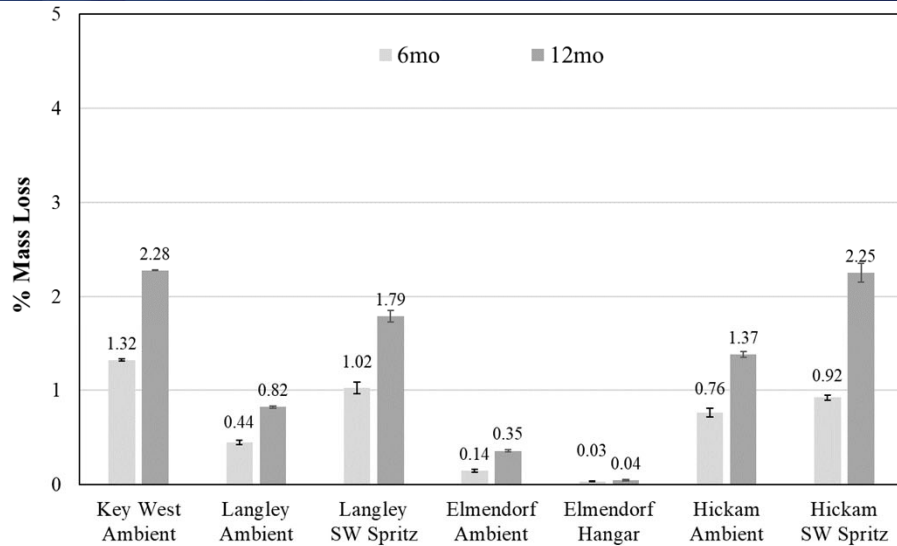
Phase III Environmental Severity Results



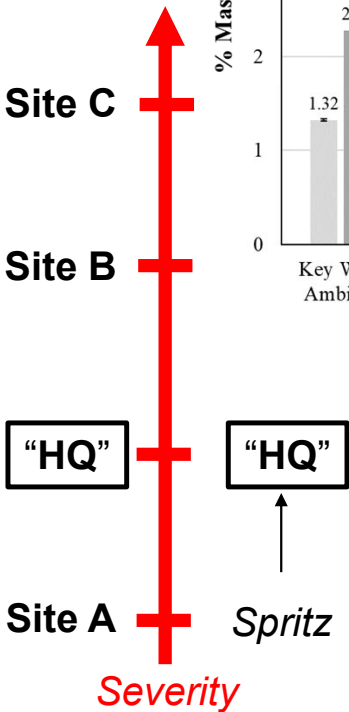
Sites were ranked and sorted by severity and normalized against KW to determine equivalent time for 1 year mass loss



Phase IV Environmental Severity Results

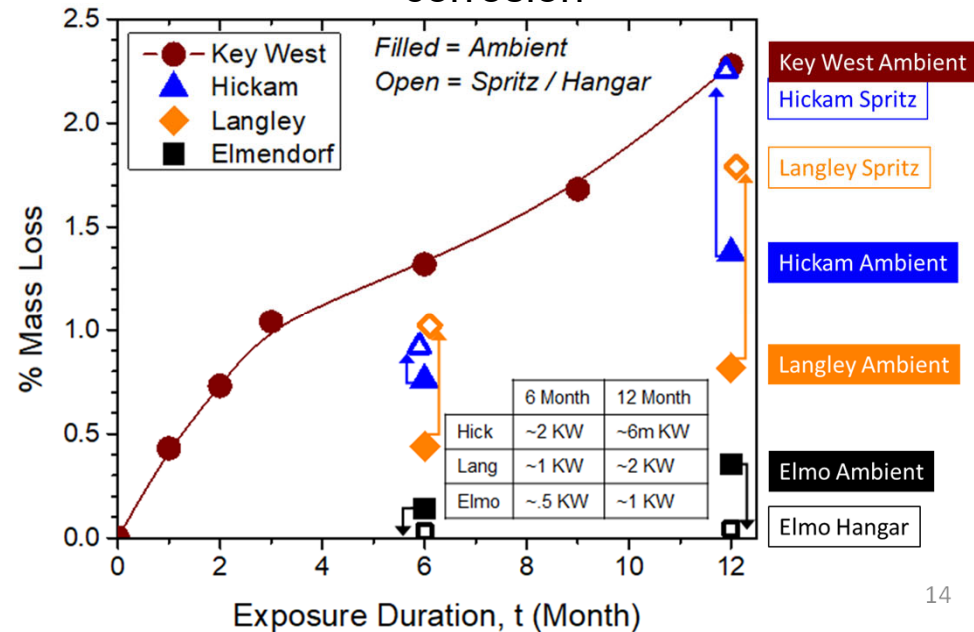


Site ranking is:
 Elmendorf < Langley <
 Hickam < Key West

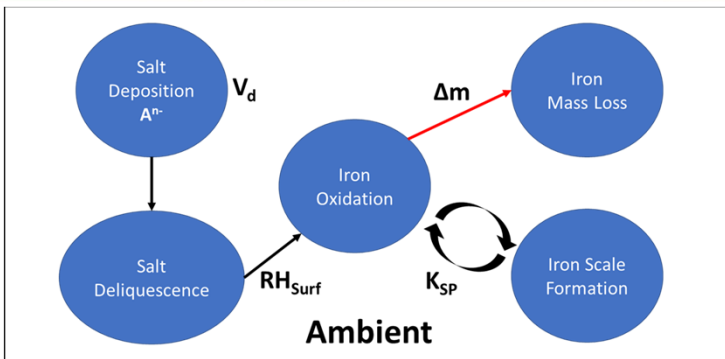


Natural Sea Water Spritzing at Langley and Hickam increase the severity. Hickam tuned to match 12-month Key West Mass Loss

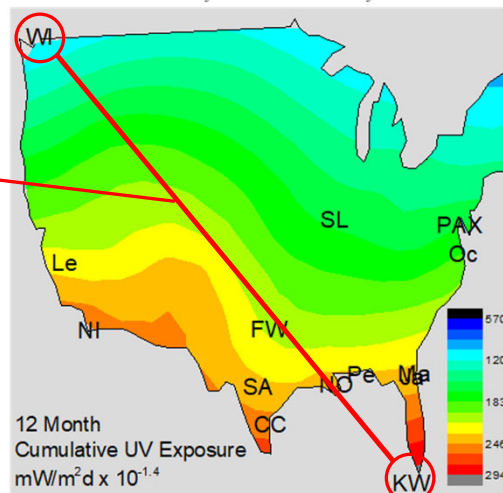
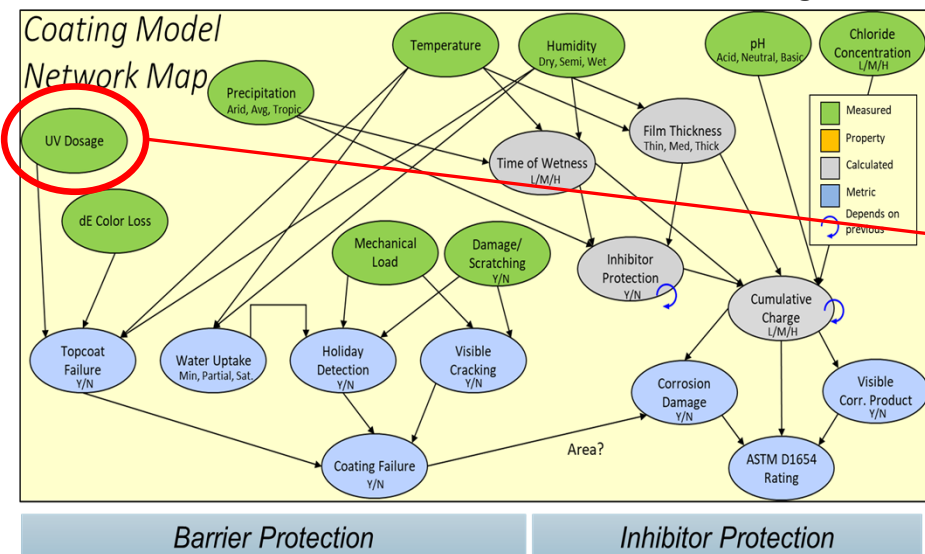
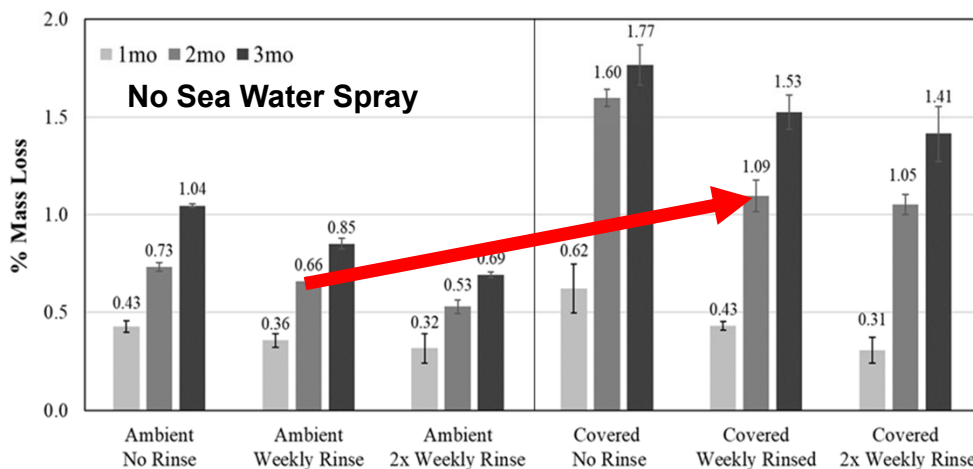
Hangar at Elmendorf decreases steel corrosion



A Word about the Steel Mass Loss Results in a Covered Environment



Low Carbon Steel Corrosion
Vs
Coating Degradation



Larger Context is Needed, Coatings have Different Degradation Mechanism

Covering might vary for location and material

Environmental Modification and Severity Indexing

Mass loss results often follow a power law form of function vs time.

Square root function ($n=0.5$) seems to fit well for atmospheric conditions.

$$M = \beta t^n$$

Where:

M = Mass density

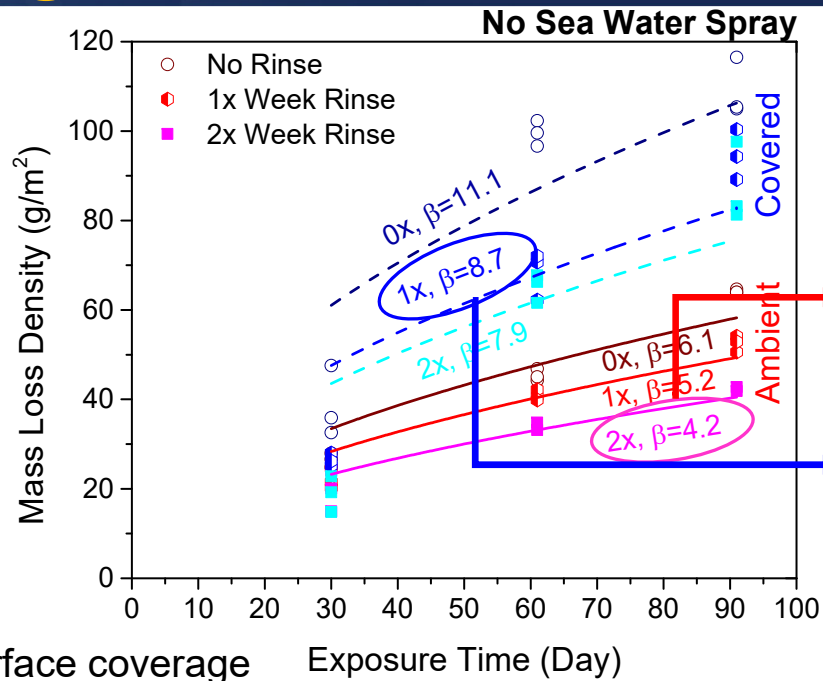
t = days of exposure

β = related to site severity

n = related to scale formation/surface coverage

N = 0.5 good for non-accelerated conditions

Empirical comparison can be made



KW can be Tuned to Mimic Corpus Christi, Iwakuni, New Orleans, Hickam, etc.

Condition	β (g/m ² /d)
Key West Ambient and Bi-Weekly Rinse	4.24
Hickam Ambient	4.17
New Orleans Ambient	4.26
Iwakuni Ambient	4.31
Key West Covered and Weekly Rinse	8.69
Corpus Christi Ambient	8.56
Kaneohe Bay Ambient	8.79

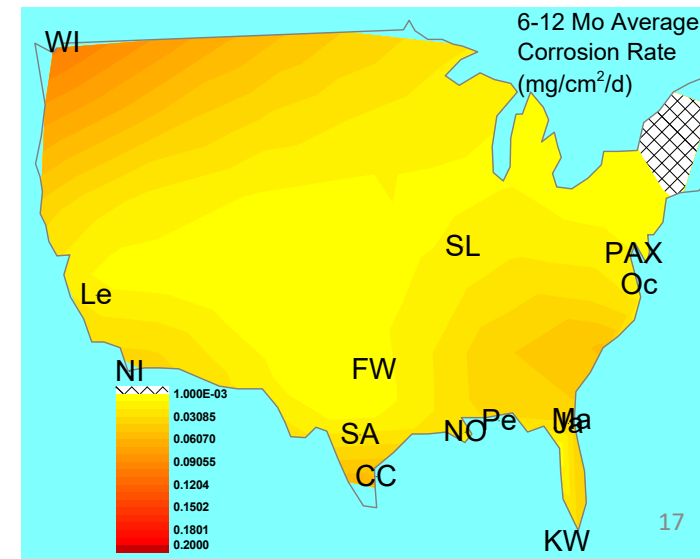
Bi-Weekly Rinse

Site	M.A.T., °C	M.A.P., mm
KW	25.4	997
Iw	15.8	1700
NO	20.1	1560

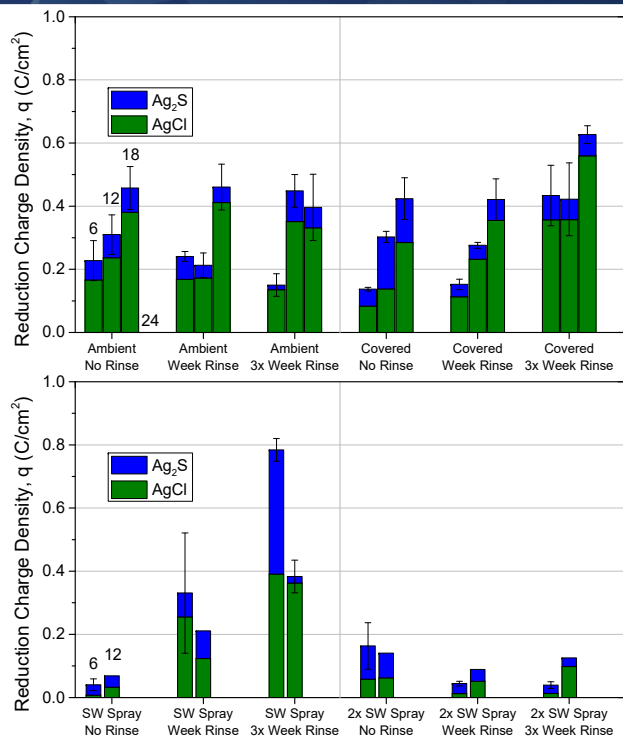
Does Rinsing Simulate Precipitation?

Summary

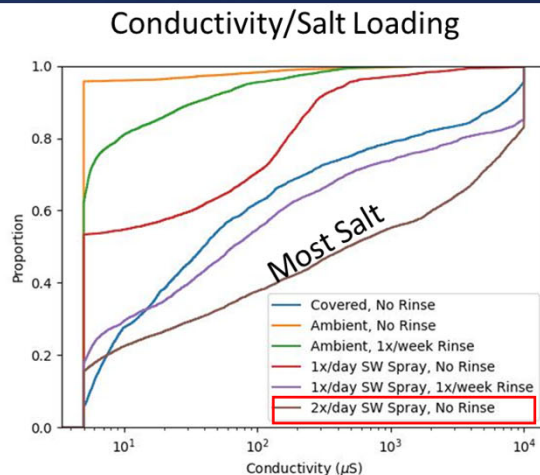
- Understanding environmental severity and environmental modifications is important
- CWR reduces corrosion, but can be overwhelmed by competitive salt deposition
- Covering had mixed results but has the risk of increasing steel corrosion. Results must be balanced against application for different materials and different locations
- Coastal sites tended to be more severe due to the prevalence of chloride from sea spray aerosol deposition
- A database of environmental severity was initiated
- The KW environment was modified to mimic the environmental severity of other DoD installations



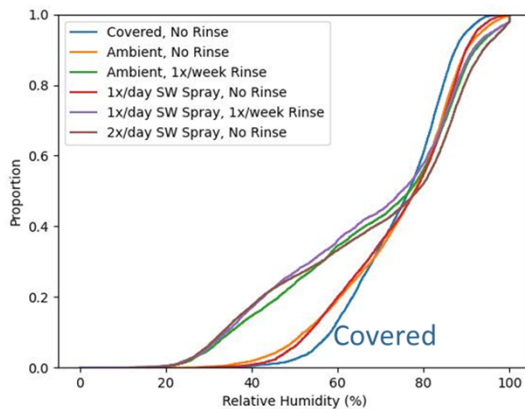
On-Going Work - Testing



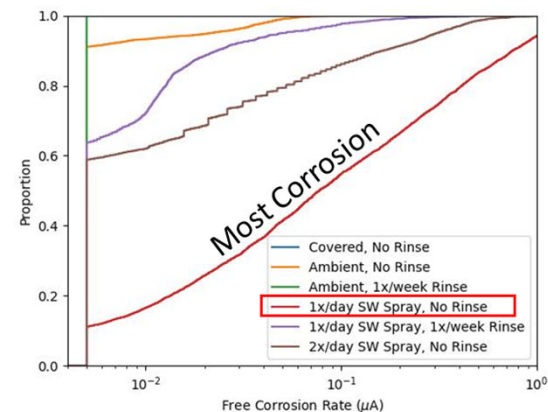
Phases II & IV testing still underway for longer exposure times. NSW Spray was discontinued after 1 year due to excessive damage



Relative Humidity



Free Corrosion



Corrosion sensors are being used to confirm mechanism and supplement data collection

New sensor data confirms that the covering results in wetter, cooler conditions

Future Work

Multi-site analysis of tap water chemistry regarding oxidation power and purity

Improve standardization for atmospheric exposure to determine environmental severity.
Continue to collaborate across organizations to build existing database.

Develop deeper understanding of why each site performed the way they did based on factors like environment and geography

Investigation of aerosolized sea water aging effects

Cross-referencing of findings to other alloy systems and weather/corrosion sensors

Add mechanical stress as an environmental modification

Further tuning of CWR & NSW Spray frequency, durations, and timing



Acknowledgments

- **F-22 Program Office** – Program Management, Funding, Base Support

- Primary POC:

Joseph Solomon

NDI Manager & ASIP Corrosion Projects Engineer



- **Naval Air Systems Command (NAVAIR)** – Financial and Collaborative Support

- Primary POCs:

Fred Lancaster

Steven Kopitzke, Ph.D.

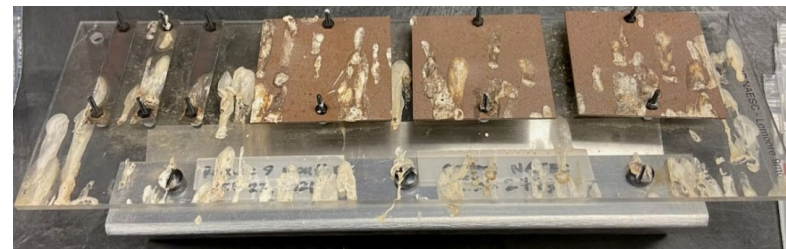
S&T Team Lead

Materials Protection Technology Branch, NAWCAD



“Hall of Fame”

- Partially Missing Samples – AWOL
- Samples mailed while wet
- Avian Deposition
- Arachnid Stowaways
- Mouse Final Resting Place
- Building Demolition – Samples Deserted
- Two Panels were Exposed Backwards
- Datalogger lost
- Sensors installed backwards/upside down
- Datalogger battery connection cut by ground’s crew



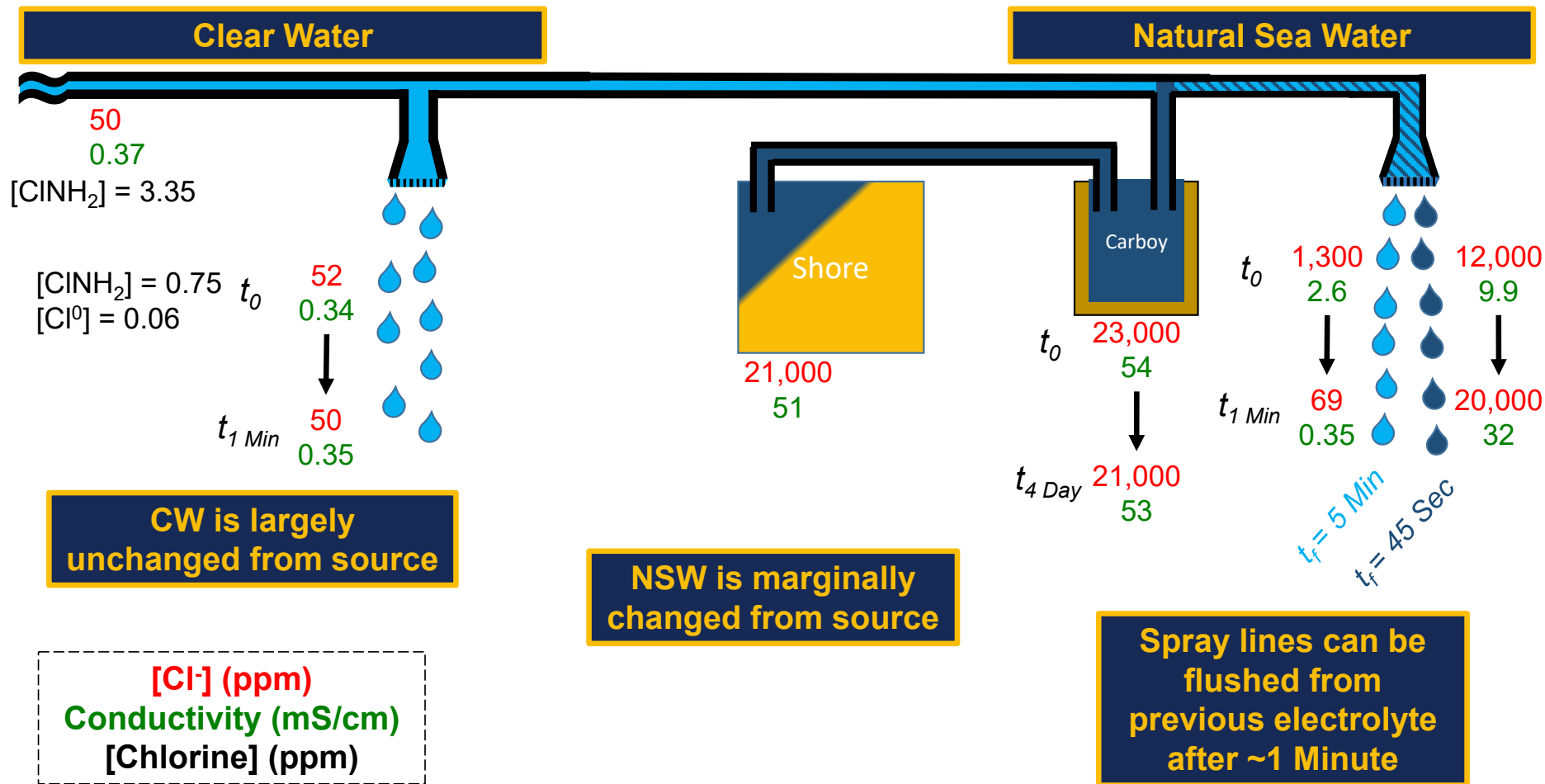


Environmental Modification Set-Up

Baseline Condition	No Rinse	Once Weekly Rinse	Multi-Weekly Rinse
Ambient (No Spray)	[A]	[A1]	[A2]
Covered (No Spray, No Rain, No Sun)	[C]	[C1]	[C2]
Daily NSW Spray	[S]	[S1]	[S3]
Twice Daily NSW Spray	[X]	[X1]	[X3]

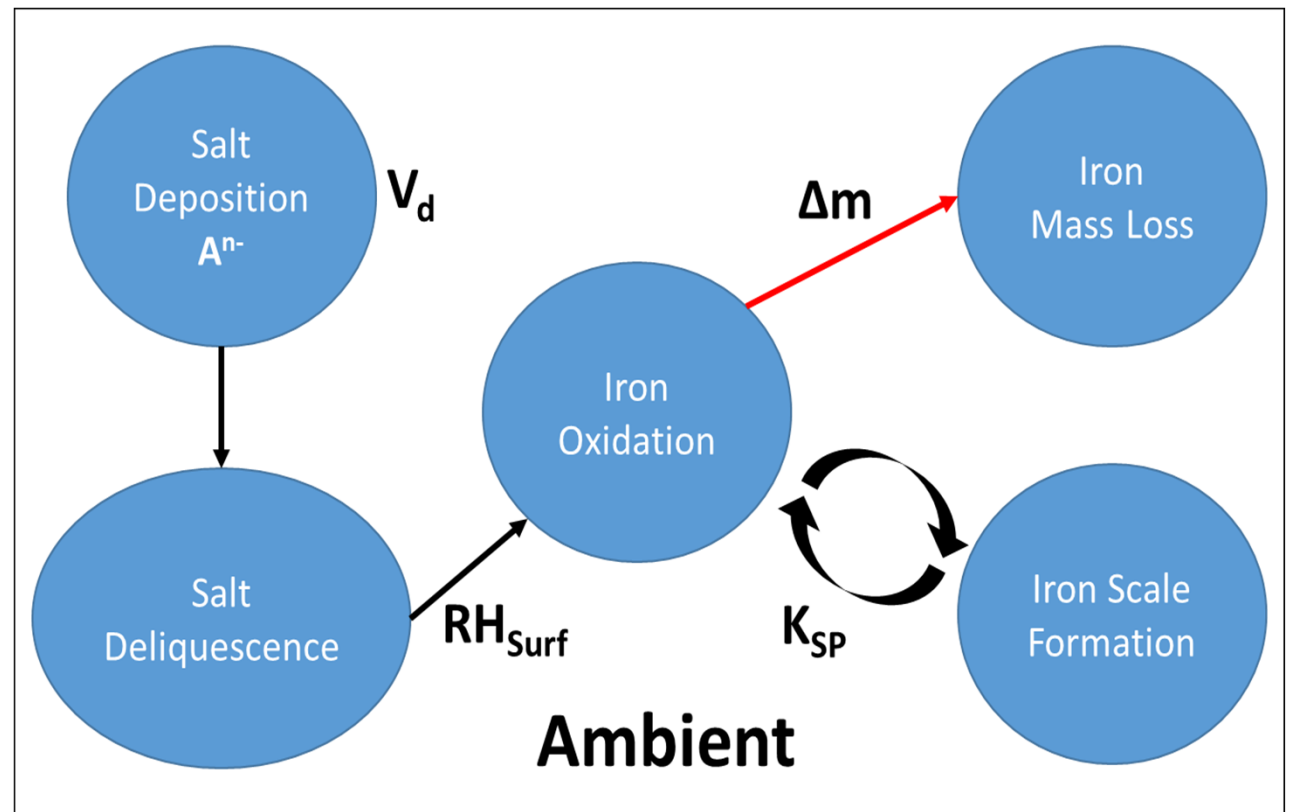
Rinse and Spray Schedule with Durations (s)												
Time	[A]	[A1]	[A2]	[C]	[C1]	[C2]	[S]	[S1]	[S3]	[X]	[X1]	[X3]
0700										45 D		
0800											45 D	
0900							45 D					45 D
1000								45 D				
1100									45 D			
1200											600 M	
1230		600 M	600 T-F		600 M	600 T-F						
1300												600 M-W-F
1400								600 M		45 D		
1500									600 M-W-F		45 D	
1600												45 D
1700												
	CW Rinse	NSW Spray					D = Daily	M = Monday	T = Tuesday	W = Wednesday	F = Friday	

Clear Water and Natural Sea Water



Process of Low-Carbon Steel Atmospheric Corrosion

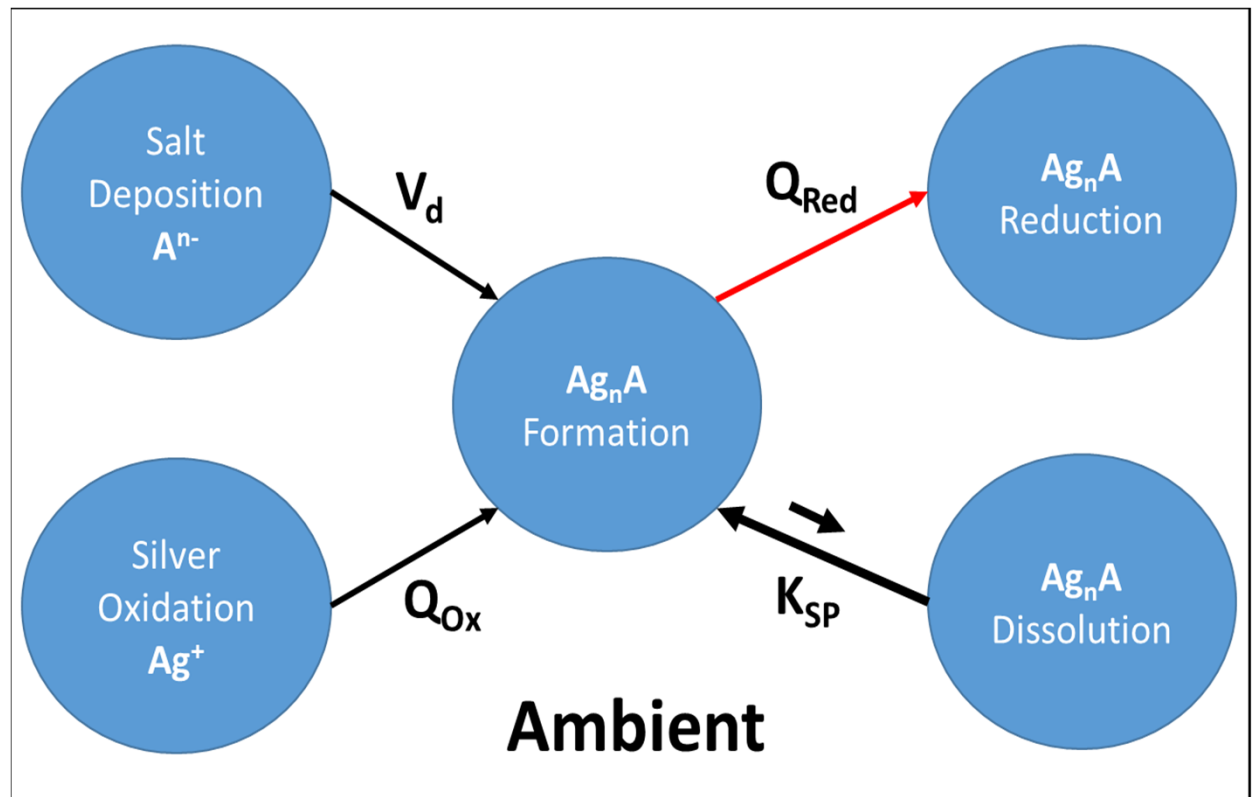
- Atmospheric deposition introduces salt
- Salt deliquescence at sufficiently high relative humidity
- Iron oxidation supported by oxygen reduction
- Oxidized iron measured via coupon mass loss
- Oxidized iron may remain on surface as a product or dissolve into solution



As always, a process can only proceed as quickly as the rate limiting step allows

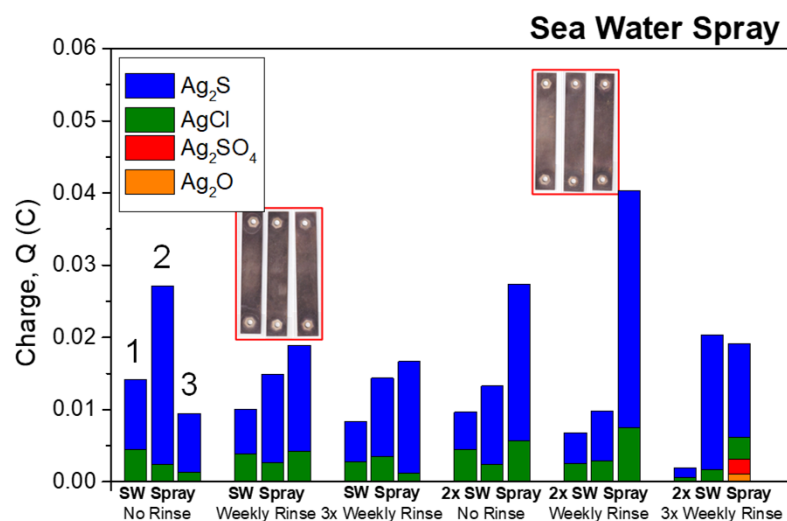
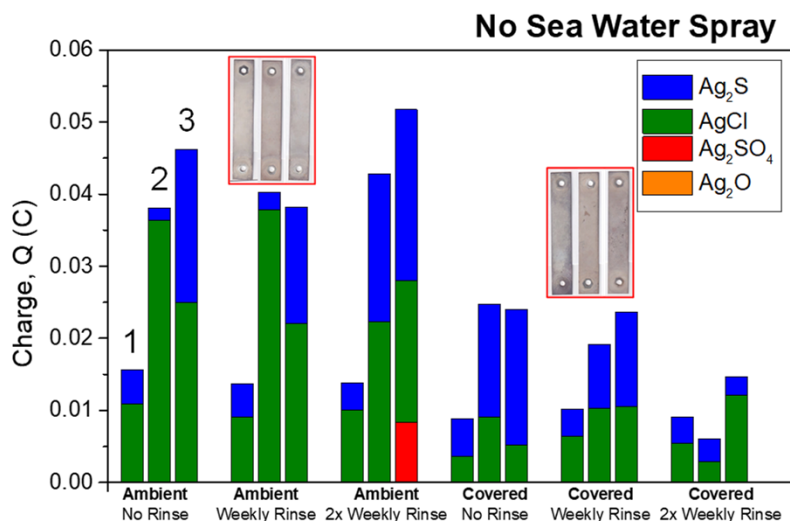
Process of Silver Atmospheric Corrosion

- Atmospheric deposition introduces contaminant
- Silver oxidation supported by UV/Ozone
- Formation of silver products
- Dissolution of silver products into solution
- Galvanostatic Reduction of silver yields information on silver product chemistry



As always, a process can only proceed as quickly as the rate limiting step allows

Chemical Trapping of Corrosive Species: O^{2-} , SO_4^{2-} , Cl^- , S^{2-}



Non-sea water spray exposures has higher AgCl content than sea water spray exposures

AgCl:Ag₂S content is related to the appearance of the sample surface

There are slightly more species retained on the surface of the non-sea water spray samples

And what about overall total charge?....