Air Force Research Laboratory

Integrity ★ Service ★ Excellence

Advanced Environmental Severity Index

7 December 2016

Douglas Dudis, DR IV
AFRL/RXSS
Air Force Research Laboratory

DISTRIBUTION A: Cleared for public release. Case 88ABW-2016-5944

Mission of the AFRL C-IPT

A Century of Scientific Excellence

"The C-IPT provides continuity of science and engineering-based corrosion expertise; plans and executes corrosion-centric research and development; and facilitates introduction of new and improved corrosion-fighting technologies, from any source, into Air Force weapon system acquisition and sustainment processes."

AFRL RX Corrosion IPT Charter, 2015

AFRL Corrosion IPT

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RX

C-Eng

ICMSE

RXA
- MIC research & field studies
- MIC remediation
- Mil-Std 1568 (lead; **Implemeted**)

RXC
- Sensor CONOPs
- AlLi Alloys
- Probabilistic Modeling

RQVS
- Sustainment S&T and Transition

711 HPW
- Human Interactions

RXSS (Corrosion)
- Cumulative Corrosion Damage Model
- Galvanic Engineering
- C5 IAT
- Scanning Kelvin Probe
- Building Block Test Specimens
- Combined Effects
- Mil-Std 889

RXSS (Corrosion)
- International Activities
- Non-Chrome

RXSS (Coatings)
- Coating Systems Support
- Non chrome Outdoor Test
- Combined Effects
- International Activities

RXSA
- Building Block Test Specimens
- Lessons Learned
- Airworthiness CET
- Mil-Std 1587
- Mechanical Test
- CPC Eval for Electrical
- AS 12500
- Mil-Std 889
- Combined Effects

RXSS (LO)
- Combined Effects
- Building Block Test Specimens
- Scanning Kelvin Probe

RXSC
- Co-Locates

AFRL Corrosion IPT Interactions

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AF, OSD, Navy, Army Academia, Industry Corrosion Community

AF Materials and Manufacturing Research

AFRL - CCEL

LOA IPT

ICMSE (modeling) IPT

60+ Participants
Many Organizations!

Corrosion Core Team
Dr. Dudis- Lead
~~Dr. Hunter~~ *M Hartshorne*
Dr. Juzukonis
Mr. Ron Pendleton
Dr. Nick Wilson

Aircraft Design and Life Management

Structures/Propulsion

AFMC
- **AF Life Cycle Management Center**
  - **Integrity Programs**
- **AF Sustainment Center**

Program Offices

AFRL Sustainment Tech Trans

AF Corrosion Program Office

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Five Key Elements

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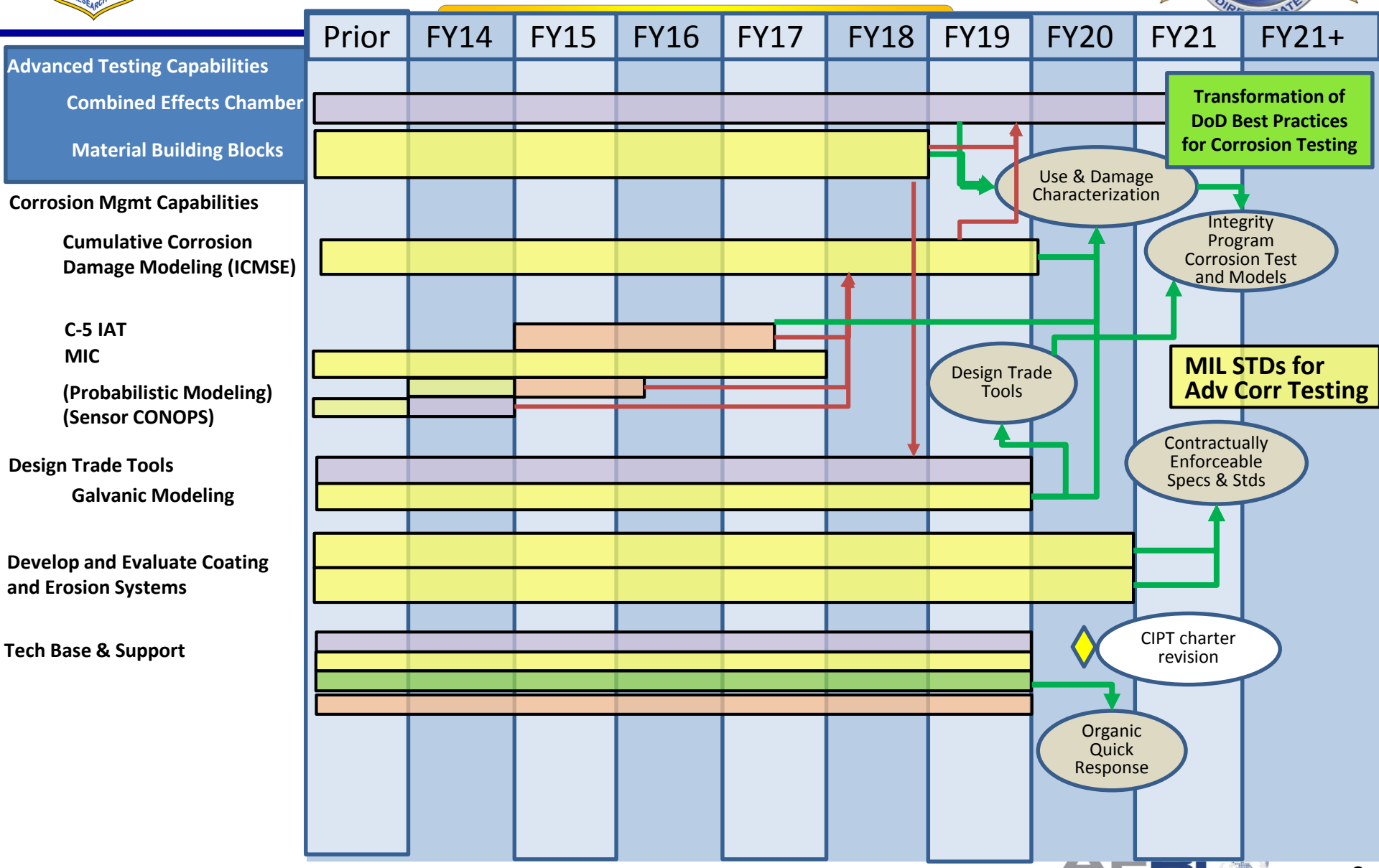
- ***Environment*:** Ability to realistically simulate any environment our assets might be deployed (weather, pollutants, static and dynamic mechanical loads).
- ***Specimen*:** Building Blocks that capture complex materials interactions.
- ***Framework*:** Scientifically sound model that captures essential factors for degradation of a material with use.
- ***Protocols:*** Experimentally verified and validated approaches connecting environment with degradation.
- ***Implementation*:** Feasible approaches for taking from laboratory to operational environments.

Corrosion S&T Capability



Accelerated Aging

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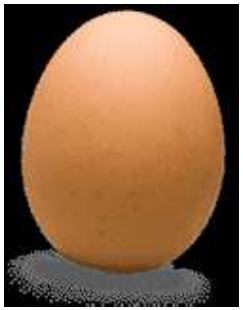
Accelerated aging should not change the target aging mechanism!

Long-term aging of an egg @ 80ºF



Accelerated aging @ 100ºF

Accelerated aging @ 212ºF

Slide courtesy Dr. Greg Schoeppner AFLCMC/EZFS.

Advanced Combined Effects Methodologies

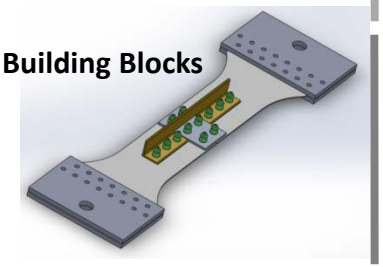
UDRI SERDP "Dynamic Multivariate Corrosion Test Protocol"

SMRC SBIR "Programmable Accelerated Environmental Test System"

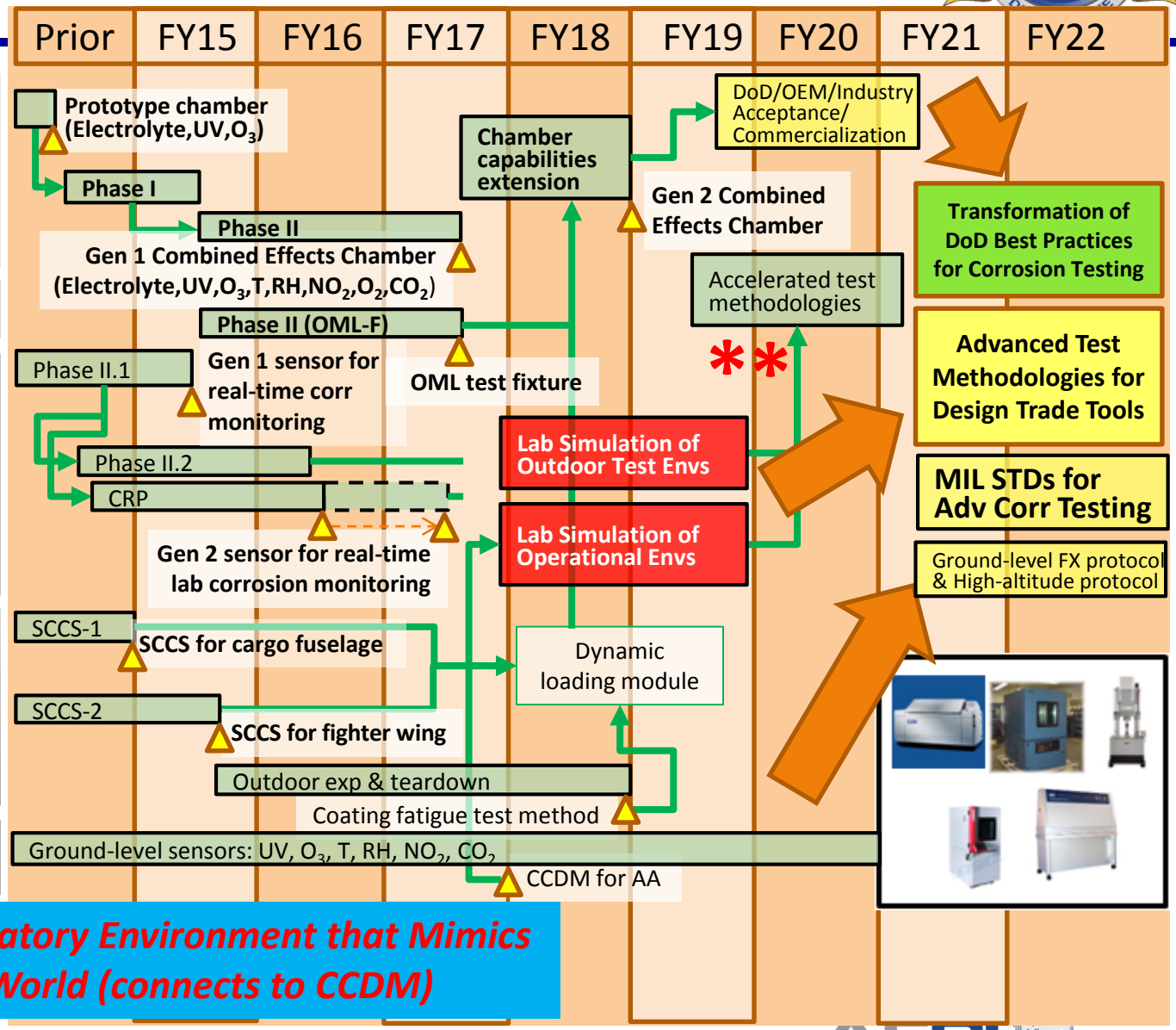
MAPS SBIR "Realistic Test Methods for A/C OML Treatment Materials"

Luna Innovations SBIR "Instrumented Test Coupons and Monitoring System for Improved Material Performance Evaluations" (AFLCMC)

Material Building Blocks



Cumulative Corrosion Damage Model / Env Characterization and Monitoring



Laboratory Environment that Mimics Real World (connects to CCDM)

Environmental Conditions Matrix *

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Counter indicated

Can do simultaneously

Potential interactions

Unknown

	Low Temp	High Temp	Humidity	Salt Spray	Arc	Ozone	NO_2	CO_2	SO_2
Low Temp		T vs.T	Ice	Ice	Ice	low%RH	95%RH		95%RH
High Temp			RH vs. T	RH vs. T	RH vs. T	low%RH	RH vs. T		RH vs. T
Humidity				95%RH	95%RH	low%RH	95%RH		95%RH
Salt Spray					95%RH	low%RH	95%RH		95%RH
Arc						Make O_3?	Chem?		Chem?
Ozone							low%RH?		low%RH?
NO_2									95%RH
CO_2									
SO_2									

* As dictated by the laws of physics

Fatigue Testing

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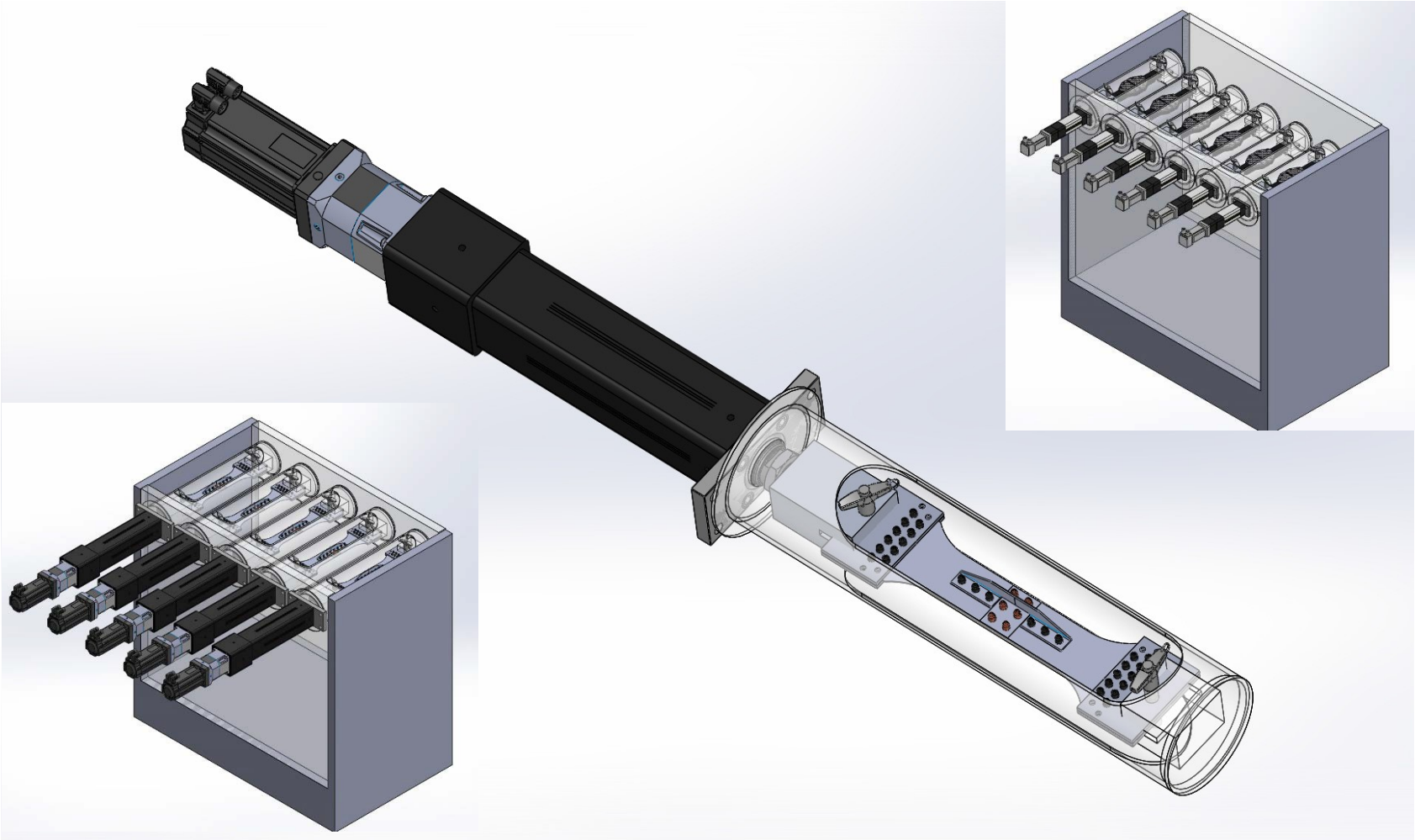

Notional Test Sequence

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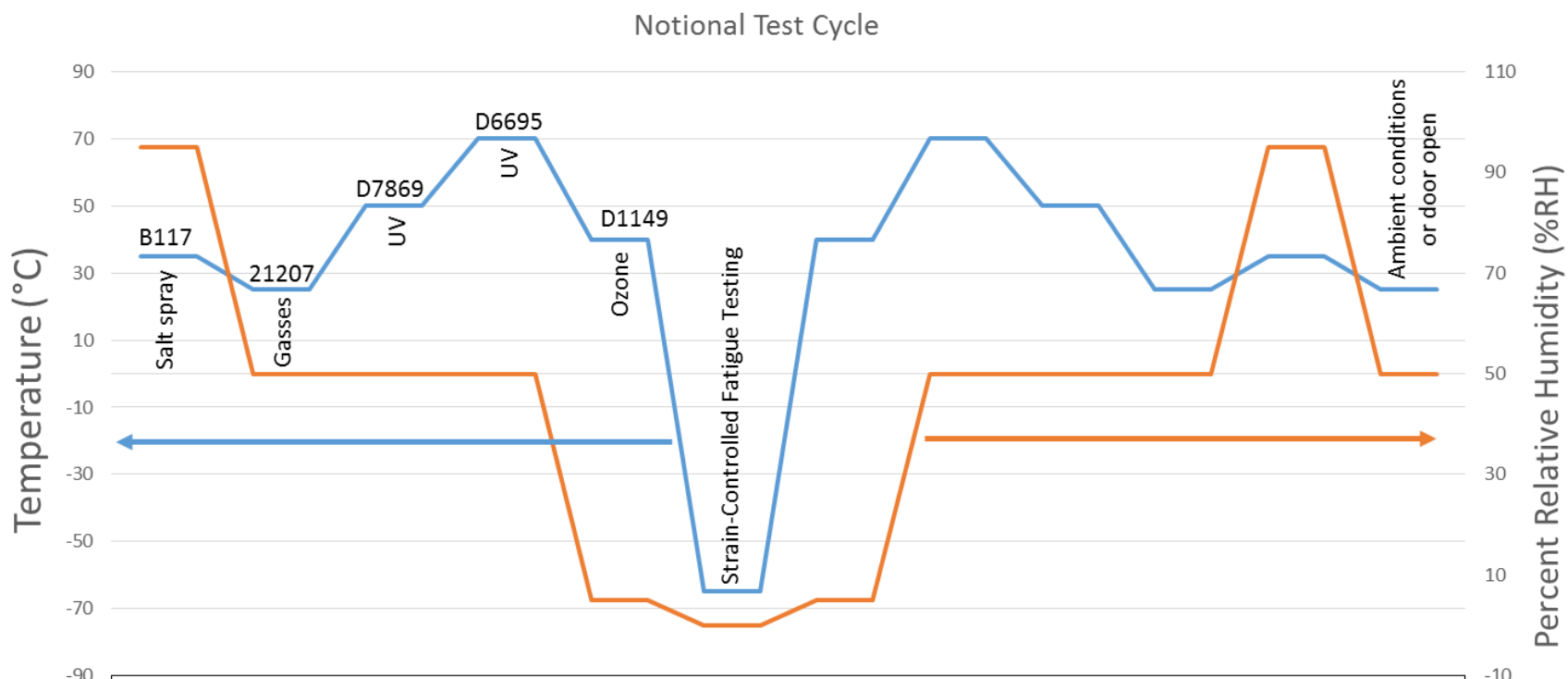

Time (hours)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Temperature (°C)	35	35	25	25	50	50	70	70	40	40	-65	-65	40	40	70	70	50	50	25	25	35	35	25	25
%RH	95	95	50	50	50	50	50	50	5	5	0	0	5	5	50	50	50	50	50	50	95	95	50	50

Building Block Approach to Specimens

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Feasibility Study

- Early concepts
- Gen I Designs
- Establish fatigue and interrogation methods, procedures
- ASTM B-117 study

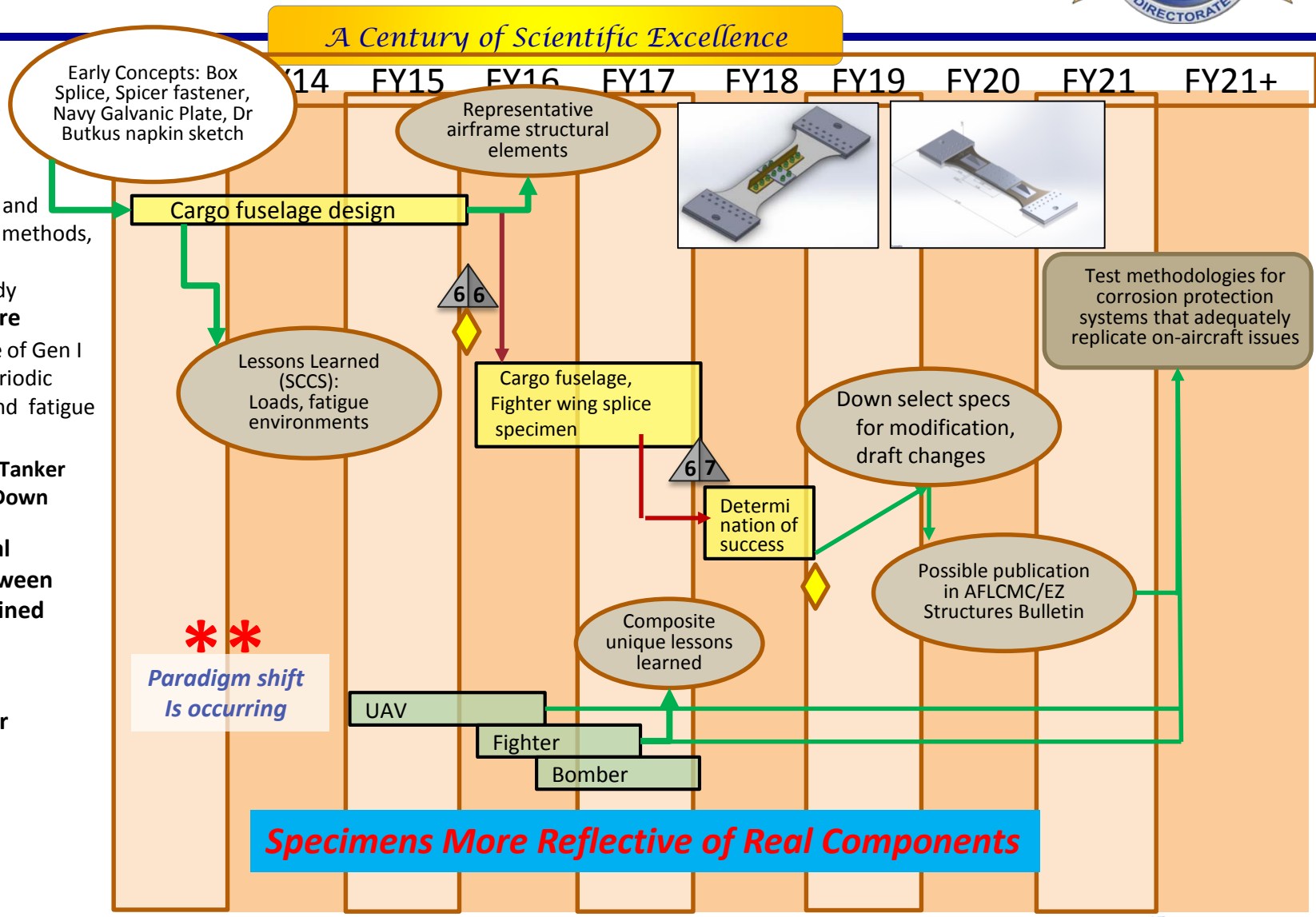
Outdoor Exposure

- Beach Exposure of Gen I designs with periodic interrogation and fatigue cycling

Comparison with Tanker and Fighter Tear Down Reports

Define functional relationship between specs and Combined Effects Chamber

Unique Customer Requirements



Time/Corrosion Severity Model

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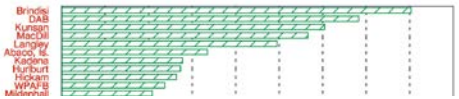
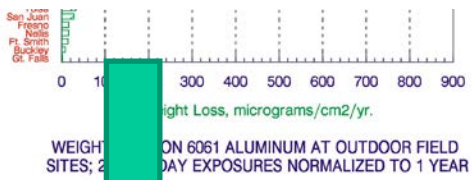
AFCPCO Base Rates

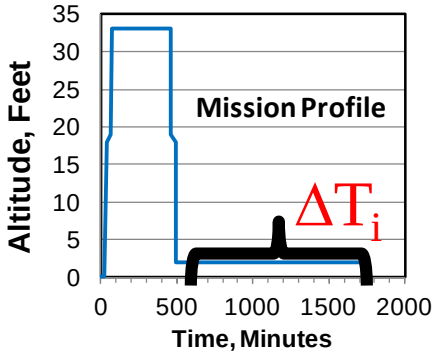


R_i = relative severity at base
Mass loss rates exists for 3 Al Alloys, Copper and Steel at world wide locations



ΔT_i = Locations and Time on ground for every flight for every aircraft

$$D_{A/C_j} = \sum_{i=1}^{n} R_i \Delta T_i$$



$D_{A/Cj}$ = damage Incurred by Aircraft j
R_i = Severity Rate for Base i
ΔT_i = Time on Ground at Base i
n = number of flights

The Time/Corrosion Severity model is a first order approximation selected for its computational simplicity. This effort will verify the model against existing maintenance data.

Environmental Severity Index

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ESI (Location) x Time at ACTUAL Location = Corrosion Cost

Discrepancies limits effectiveness
Additional work required

Inaccurate Data:
Has been/can be addressed

MX vs. Eng Data:
Additional analysis required

Path forward:

- **ESI is AVERAGE for Location (all factors rolled into ESI)**
- **Maturation Effort for Individual Aircraft Tracking**

The CBM+ Approach has adopted this tact – use the actual location of the A/C.

Cumulative Corrosion Damage Model

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Problem: Current environmental severity assessment methods do not provide the fidelity needed to accurately predict corrosion damage.

Customer: AFLCMC/EZP, CBM+

The CCDM is a more rigorous, time-dependent, extensible, and implementable approach and portends a transformational change in corrosion management.

Work Accomplished, Ongoing, and Future:

- Established calibration/validation sites
- Final model was validated for 1010 steel using data from seven sites in four climate zones
- Model optimization through DoD high performance computing simulation approach
- Extend and leverage model to military aerospace alloys & develop advanced outdoor test capabilities
- Extend and leverage CCD model to military aerospace alloys & develop advanced outdoor test capabilities

Impact

- Transformation change in the ability to prevent, predict, detect, & manage corrosion
- Measurably improved corrosion engineering decisions in acquisition and sustainment

Contains Relevant
- Chemistry
- Environment
- Time (by hour)

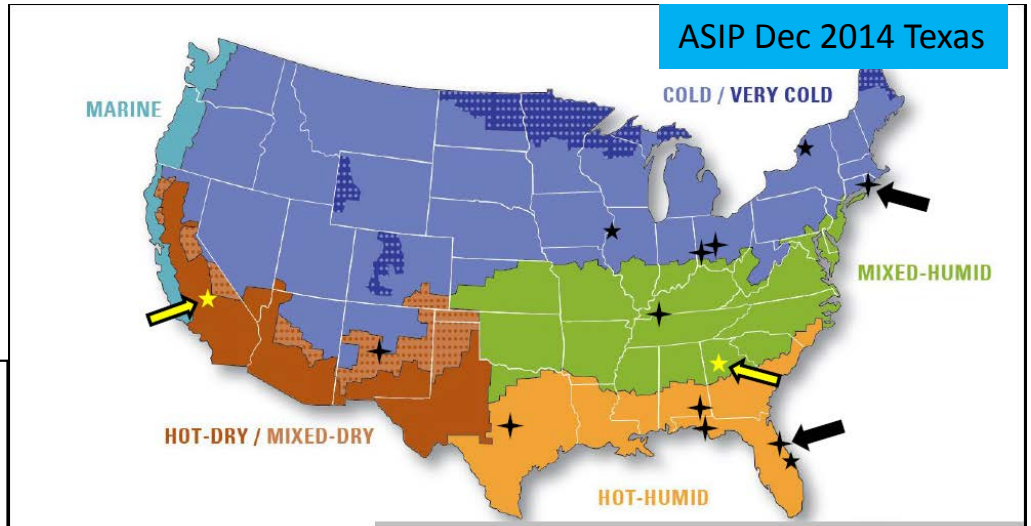
Material Reactivity (kinetics) | Chloride Reaction | Sulfur Dioxide Reaction

$$K_t = \exp\left(\frac{\Delta H}{kT}\right)\left[A_{CL}T^{\alpha CL} f_{CL}(T,RH) f(T,Cl) + A_{SO2}T^{\alpha SO2} f_{SO2}(T,RH) f(T,SO_2) + A_{O3}T^{\alpha O3} f_{O3}(T,RH) f(T,O_3)\right]$$

Ozone Reaction

Form based on Eyring equation describing the variance of the rate of a chemical reaction with temperature

ASIP Dec 2014 Texas



Corrosion tests were conducted at these sites under an AFRL and SERDP sponsored effort supported by UDRI and under earlier Battelle efforts sponsored by various DoD organizations

Illustration of Cumulative Predictions

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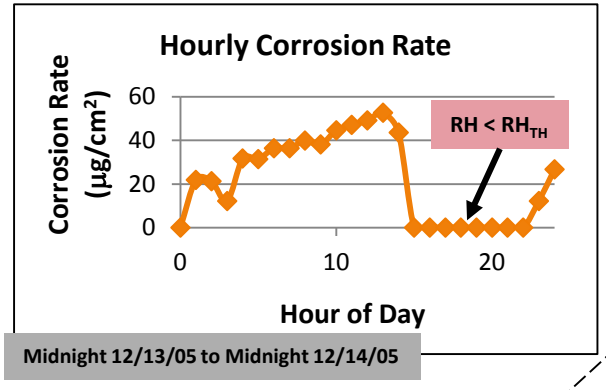

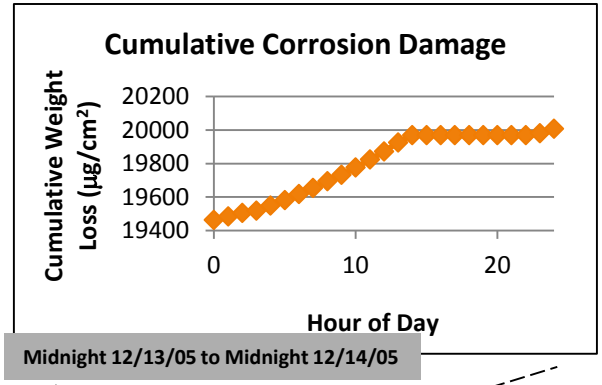

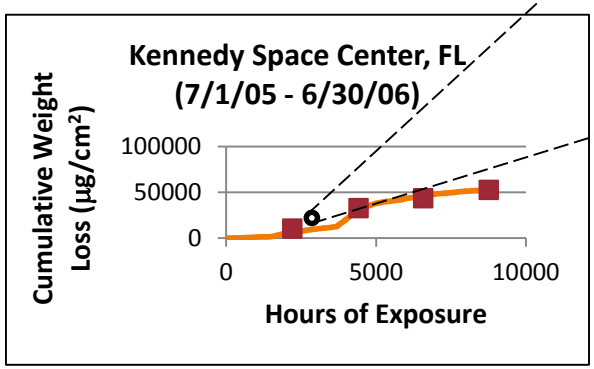

The magnitude of the hourly increments of damage are dependent upon environmental conditions.

- **The methodology is analogous to certain types of random amplitude fatigue models**
- **Equal environmental conditions will always lead to the same predicted hourly mass loss**

Final Proof-of-Concept CCDM

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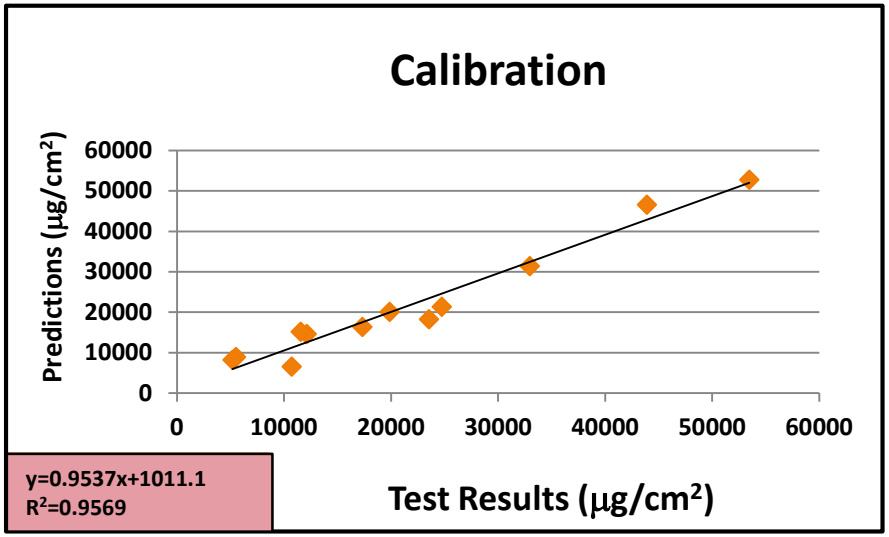
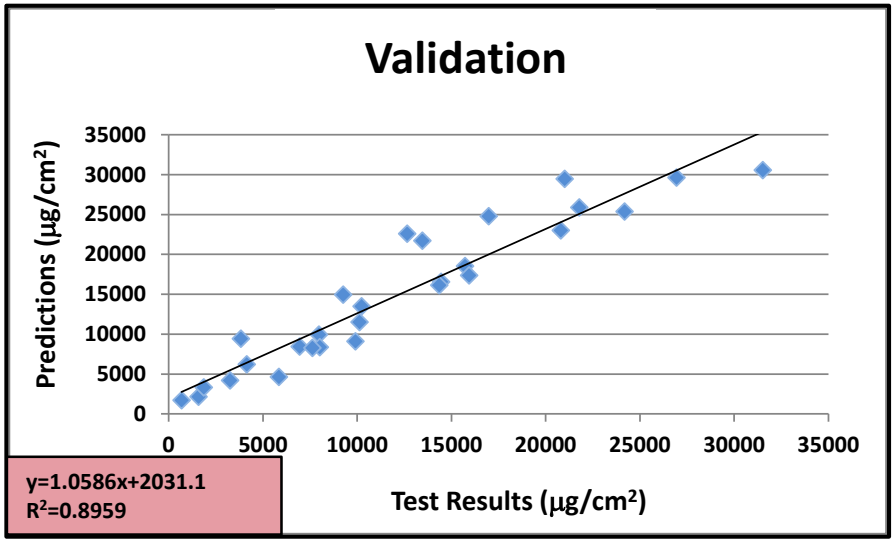
Results from Proof-of-Concept 1010 Steel Model





- The fit of the final 1010 steel model to its calibration and independent validation data is quite good, but only when used within the bounds set by the calibration data
  - Humid locations that are five or more miles inland from coastal surf zones
- Preliminary models for copper and 2024, 6061, and 7075 aluminum alloys were created using the same approach but the results were far from satisfactory
- Work is needed to improve model accuracy, extend it to additional materials and broader environments, and make the approach practical!

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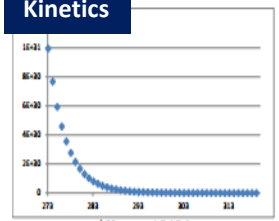
Comparison of CCDM to Observations

CCDM employs multiple (calibrated) functions multiplied against each other

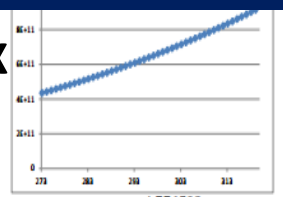
Kinetics



$$e^{\frac{\Delta H}{kT}} = e^{\frac{19496}{T}}$$

X

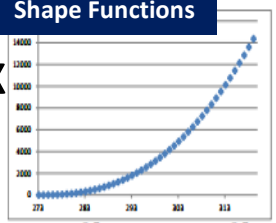
Temperature Adjustment



$$T^{a_{Cl}} = T^{4.776592}$$

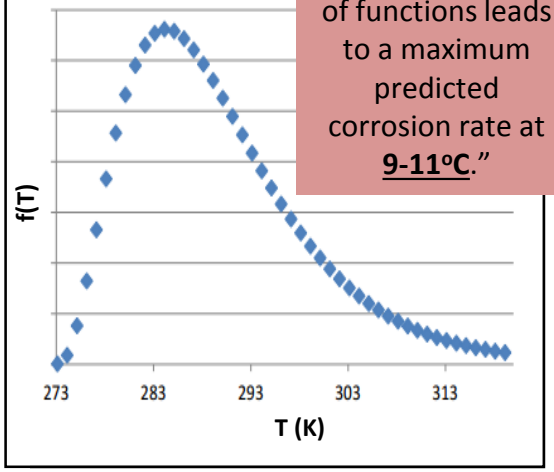
X

Shape Functions



$$(T-k)^{2.5} = (T-273.15)^{2.5}$$

=



The combination of functions leads to a maximum predicted corrosion rate at **9-11°C**."

Illustration of the chloride reaction (not scaled)

What effects are observed under actual atmospheric exposure conditions?

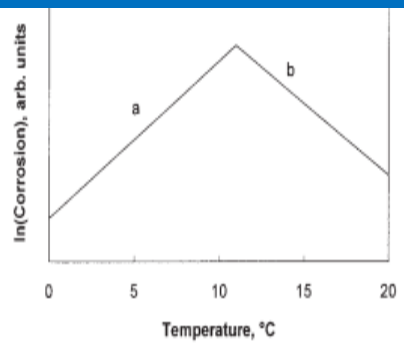
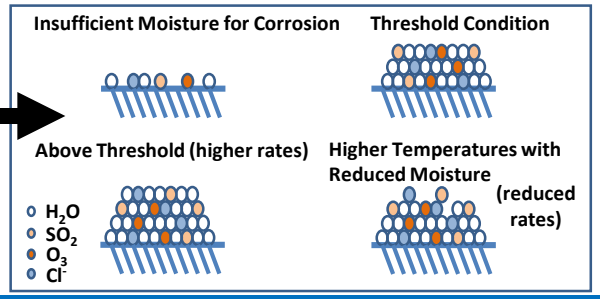


Figure 1. Schematic representation of the observed temperature dependence for many materials: a) increase of corrosion with temperature in the low temperature range and b) decrease of corrosion with temperature in the high temperature range.

Why?

"The increasing part (a) can be related to increased time of wetness. The decreasing part (b) is attributed to faster evaporation of moisture layers*…"

*J. Tidblad, V. Kucera, A. Mikhailov, J. Henricksen, K. Kreislova, T. Yates, B. Stockle and M. Schreiner, "UN ECE ICP Materials: Dose-Response Functions on Dry and Wet Acid Deposition Effects after Eight Years of Exposure," *Water, Air, and Soil Pollution,* vol. 130, pp. 1457-1462, 2001.



- **The CCDM was not constructed to fit Figure 1, rather an inverse approach was used to optimize the model's fit to its calibration data**
- **The fact that the model results match Figure 1 so well (shape and temperature at the maximum corrosion rate) provides evidence of the efficacy of the CCDM methodology!**

Comparison of CCDM to Published "Dose-Response" Functions

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- The overwhelming majority of regression and power-law corrosion models dating back 50 years do not account for temperature effects. Two 'traditional' modeling papers found in the literature considered temperature but only as an annual average
- Two relatively recent efforts have attempted to address this omission
  - "*UN ECE ICP Materials*… (**2001**)" this paper (referred to in previous slide) developed models for numerous metallic (and two nonmetallic) materials used to construct historical and cultural monuments
    - Each material has two models… most have one for ≤10°C and the other for >10°C (a couple were for ≤11°C and >11°C)
  - ISO 9223:**2012** "*Corrosion of metals and alloys — Corrosivity of atmospheres — Classification, determination and estimation*"… current ISO standard on corrosion
    - Presented models for structural materials including carbon steel, zinc, copper, and aluminum. Two models are presented for each material, one for ≤10°C and the other for >10°C
  - Both efforts had to use two separate models to consider temperature effects
- The CCDM approach uses a single model to calculate corrosion rates over a wide range of temperatures with a maximum rate predicted at the same temperature range as the "UN ECE ICP Materials" and "ISO 9223" efforts!

Expansion of Test Sites for CCDM Extension

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More data are needed to extend the model so that it can consider a broader range of environmental conditions. Current extension is based upon the employment of new data reflecting hot and arid conditions so the model can evolve to consider "deliquescence"

Calibration Sites for Proof-of-Concept

- Fort Drum, NY* ("cold" climate zone)
- Rock Island Arsenal, IL* ("cold")
- Kennedy Space Center, FL** ("hot-humid")

Validation Sites for Phase II

- Kirtland AFB, NM* ("mixed-dry")
- Lackland AFB, TX*** ("hot-humid")
- Mansfield ANG Base, OH ("cold")
- McGhee Tyson ANG Base, TN ("mixed-humid")
- Stewart ANG Base, NY ("cold")
- Tyndall AFB, FL* ("hot-humid")
- Wright Patterson AFB, OH* ("cold")
- Fort Campbell, KY* ("mixed humid")
- Fort Eustis, VA ("mixed humid")
- Hunter AAF, GA ("hot-humid")
- Fort Polk, LA ("hot-humid")
- Fort Rucker, AL* ("hot-humid")
- USCG Base Manistee, MI*** ("cold")
- USCG Base Seattle, WA ("marine")
- NAS Brunswick, ME ("cold")
- NAS Jacksonville, FL ("hot-humid")
- NAS Lemoore, CA*** ("hot-dry")
- West Jefferson, OH* ("cold")

Calibration Sites for Phase II

- Fort Drum, NY* ("cold" climate zone)
- Rock Island Arsenal, IL* ("cold")
- Kennedy Space Center, FL** ("hot-humid")
- Fort Hood, TX* ("hot humid")
- USCG Base Sacramento, CA ("hot-dry")
- Westover ARB, MA ("cold")

Revised Calibration Sites for Phase II

- Rock Island Arsenal, IL* ("cold")
- Westover ARB, MA ("cold")
- Fort Campbell, KY* ("mixed humid")
- Kennedy Space Center, FL** ("hot-humid")
- Kirtland AFB, NM* ("mixed-dry")
- USCG Base Sacramento, CA ("hot-dry")

Data Locations

- POC
- Expanded

*Proof-of-concept (POC) site, **POC site located five miles inland from coastal surf,
***Full data proxy not available…. sites used for CMAQ analysis only

AFRL Concept: Use Ground Based Sensors and CCDM "Smart Rack"

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For Environmentally (Climate + Pollutants) driven corrosion, the CCDM framework (or one similar) opens the possibility of developing correlations to specific platforms and/or subsystems, based on Environmental Sensors located on the ground (base and/or flightline/hangar…).

- **Eliminates Need for many A/C Based Sensors**
- **One set of Sensors serves fleet, GSE, facilities**
- **Implementable (utilize operational, weather++…)**
- **Extensible/Tailorable Based on Operations (locations) and Environment**

TRANSITION SUCCESS: EZP embraced this approach in Summer 2015

AFRL: Still much S&T to be done!

Smart Rack

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Problem: Corrosion rate and environmental characterization data must be measured together in order to create the most accurate corrosion model.

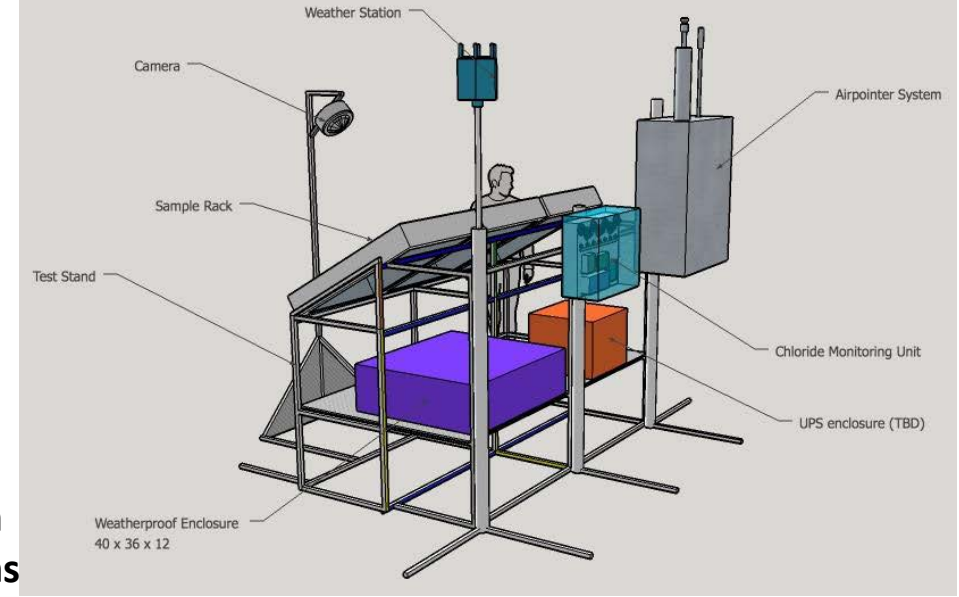
Customer: AFLCMC/EZP, Weapon systems, ASIP

The Smart Rack will enable the most accurate calibration data possible

Work Accomplished, Ongoing, and Future:

- Identified the parameters to measure and the measuring systems
- Currently procuring equipment for two racks:
  - WPAFB
    - Humid, warm summers, cool winters, higher air pollution (e.g., SO2) levels, low chlorides
  - AFRL Information Directorate, Rome, NY
    - Humid, cool summers, severe winter conditions, low air pollution and chlorides
- Hardware design, software development, integration, and system test to be completed in FY17

Rack will upload data daily to a central server



Impact

- Characterization of the highly variable atmospheric environment at the site of corrosion
- Enables improved corrosion engineering decisions in acquisition and sustainment via CCDM

Traditional Rack

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Traditional racks typically do not include any instrumentation

The Smart Rack will

- Be based upon traditional designs but will have environmental monitoring equipment directly attached
- Will enable the most accurate calibration (environmental and corrosion test) data possible
- Once accurate models have been developed, predictions can be made for other locations using the same type of environmental data

Smart Rack – Conceptual Design

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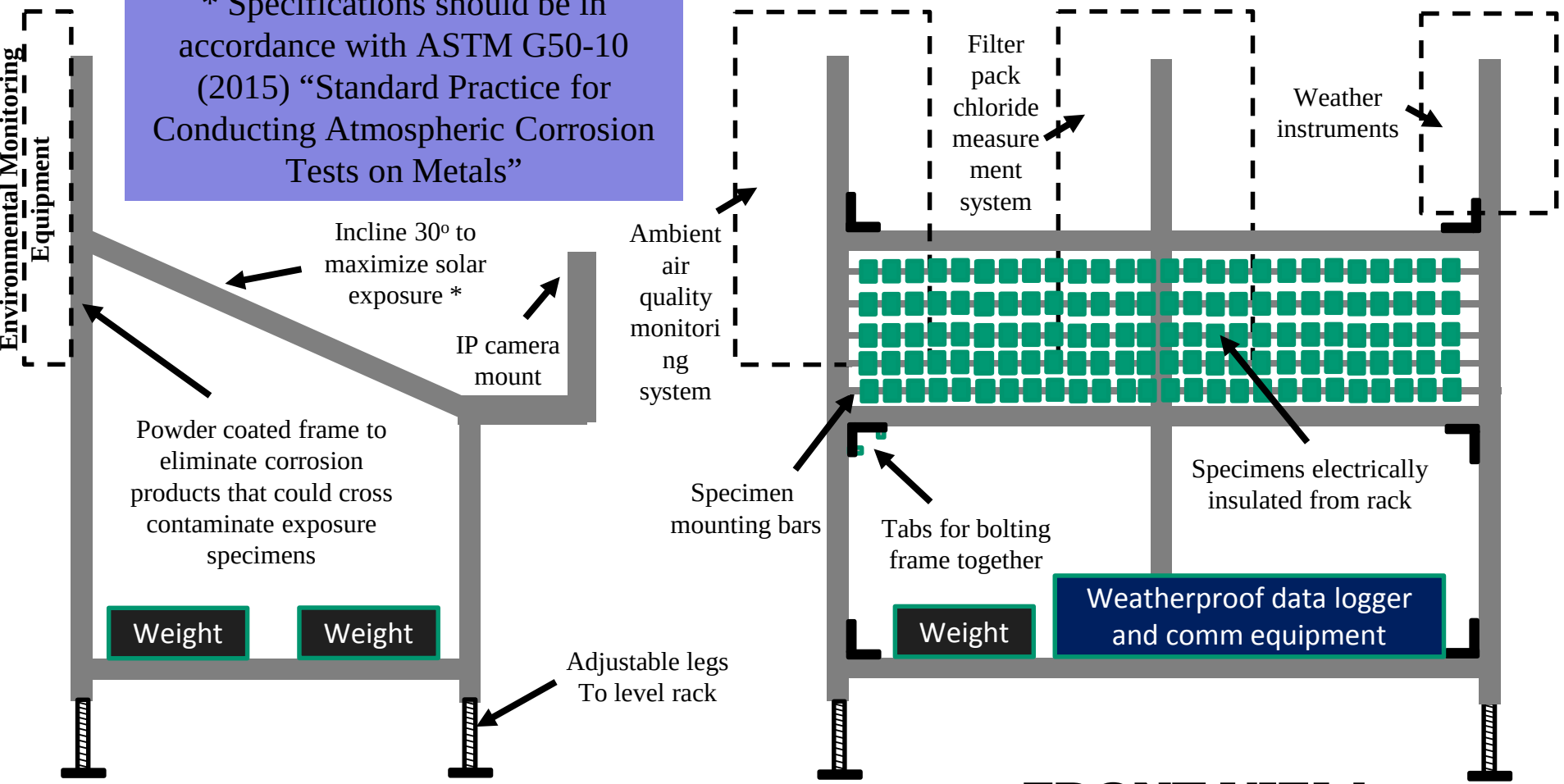
* Specifications should be in accordance with ASTM G50-10 (2015) "Standard Practice for Conducting Atmospheric Corrosion Tests on Metals"



Corrosion Indication and Prediction

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AFLCMC/ EZP Effort
Corrosion Indicators

Phase I

- Define Corrosion Indicators
- Test and down-select monitoring systems

Phase II

- Deploy Corrosion Monitoring Systems
- Multi-Environmental Severity Index
- Crawl-Walk-Run Approach

Phase III

- Implementing corrosion indicators through CBM+ Pilot Programs, changing maintenance schedule
  - maintenance inspections
  - wash intervals

Duration: 1-2 Years

AFRL Effort
Corrosion Prediction Modeling

Cumulative Corrosion Damage Model:
… based on the variance of the rate of a chemical reaction with temperature

- A piecewise function is used to implement the temperature and RH boundary conditions

$$K_i = \begin{cases} f(T, RH, Cl, SO_2, O_3), & RH > RH_{TH} \text{ and } T > T_f \\ 0, & RH \le RH_{TH} \text{ or } T \le T_f \end{cases}$$

Material Reactivity (kinetics) | Chloride Reaction | Sulfur Dioxide Reaction

$$K_i = \exp\left(\frac{\Delta H}{kT}\right)\left[A_{CL}T^{\alpha CL} f_{Cl}(T,RH) f(T,Cl) + A_{SO2}T^{\alpha SO2} f_{SO2}(T,RH) f(T,SO_2) + A_{O3}T^{\alpha O3} f_{O3}(T,RH) f(T,O_3)\right]$$

Ozone Reaction

Contains Relevant
- **Chemistry**
- **Environment**
- **Time (by hour)**

ASIP Dec 2014 Texas

Duration: 5-10 Years

Parallel and Cross-Linking Data to Validate Both Approaches

AFRL Corrosion IPT: Summary

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Projected Problem:

Will Cost

- Hex-chrome laws
- Loss of corrosion expertise

Corrosion IPT Goals:

- Deliver Corrosion Prevention & Control Capabilities
  - Prevent, Predict, Detect and Manage
- Establish and Sustain S&T Foundation
  - R&D, Collaboration, Education/Training, Systems Support

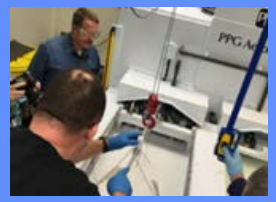
Anticipated Result

Should Cost

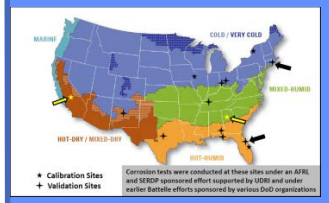
- Non-chrome tech
- Robust corrosion competency

Prevent

- Corrosion Protection Schemes
- Design Tools



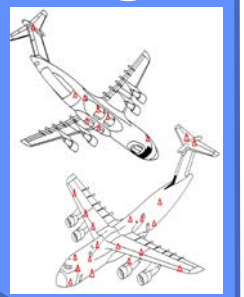
Predict



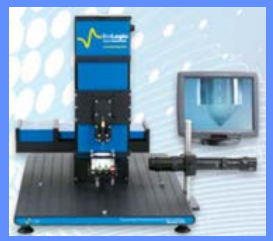
- Models: Electrochemical, Cumulative, Probabilistic
- Environmental Factors
- Advanced Test Methods

Manage

- Corrosion Management Tools
- MX Practices/Tools
- Standards/Specs



Detect



- NDI
- Corrosion Characterization