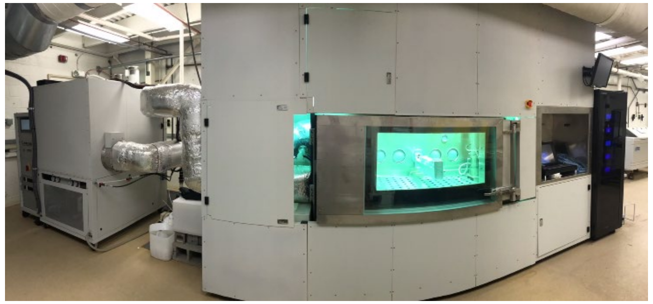
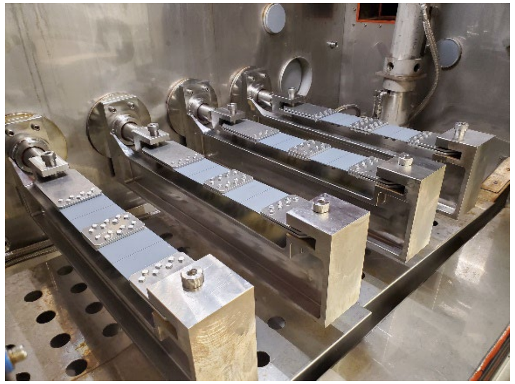
Development of Combined-Effects Testing at AFRL



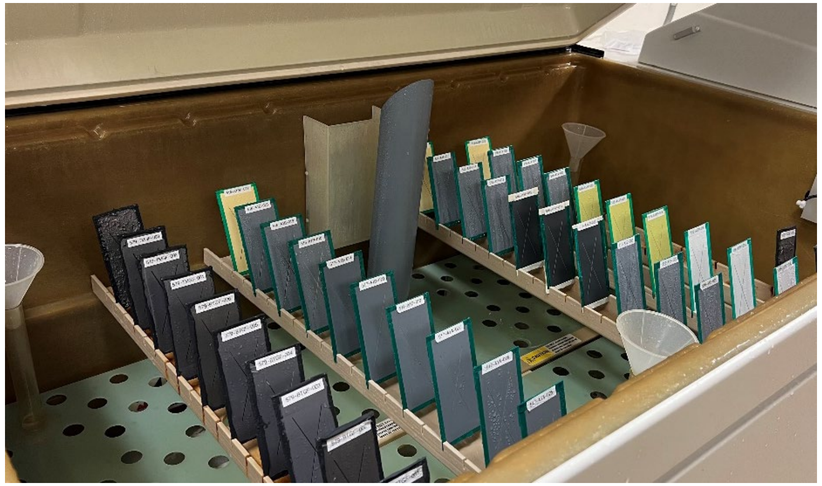


Dr. Chad Hunter, U.S. Air Force Research Laboratory (AFRL/RXNMD)

Co-authors: Mr. David J. Borth*, Dr. Douglas C. Hansen*, Dr. Matthew I. Hartshorne** Mr. Matthew J. Rothgeb*, Mr. Drew M. Sanders*, Dr. Nicholas S. Wilson**
*University of Dayton Research Institute, USA
**U.S. Air Force Research Laboratory

10 Oct 2023

Aircraft exterior coatings testing (historical)



Prior to 2014: ASTM B117 Salt Fog (2,000 – 3,000 hours)

After 2014: 18+ months of beach exposure

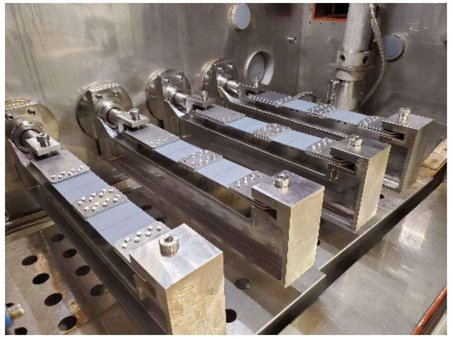
The Past - Shortcomings of pre 2014 and post-2014 Method:

- Too slow and/or doesn't reflect realistic damage modes
- Only assesses response to intentional damage, not ability to withstand typical service conditions
- Static design but added dissimilar metals areas of interest in sample after 2014

The Future - Newly Developed Capability:

- Accelerated Combined-Effects Simulation (ACES) Test Chamber

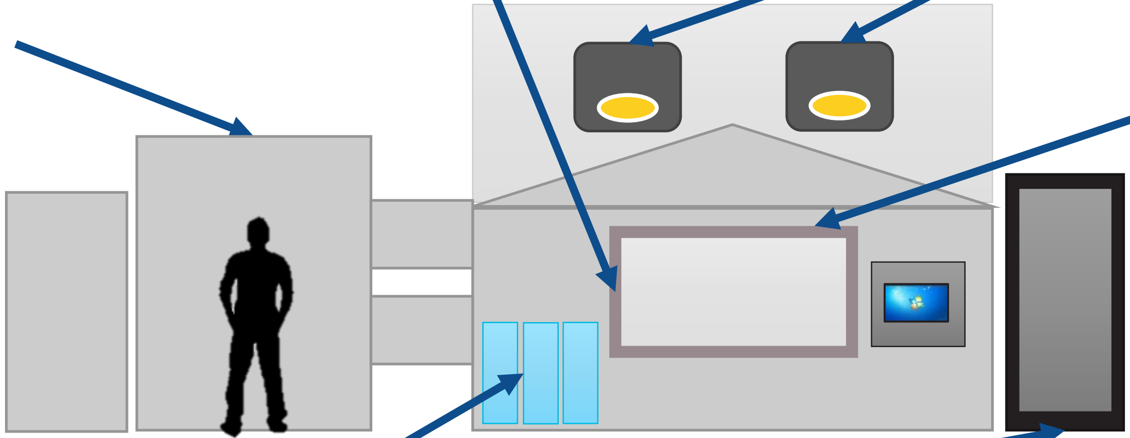
ACES Functionality

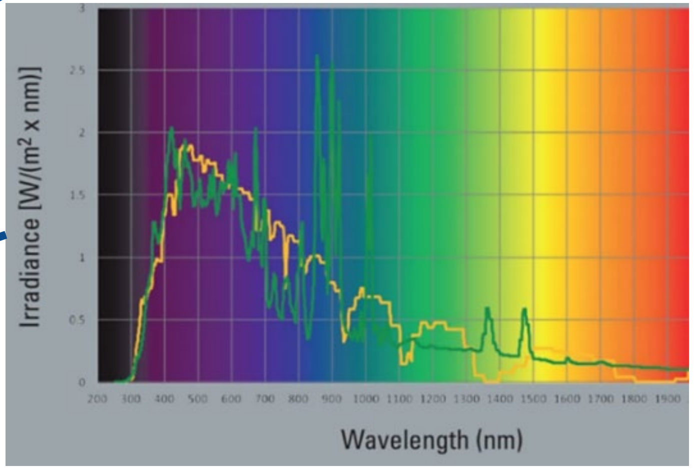


- **4 Electric Linear Actuators (Parker)**
  - ✓ Applies loads from 100 lbf to roughly 3000 lbf
  - ✓ Each actuator can hold 2 CASEE samples

- **2 Halide Luminaries (Atlas)**
  - ✓ Mimics solar spectrum
  - ✓ 750-1600 W/m^2
  - ✓ Meets MIL-STD 810, ASTM E 892, and ISO 12097-2

- **Air Handling Unit (Russell)**
  - ✓ Temp range -55° C to 120° C (±1° C)
  - ✓ Humidity control (30-100% RH)

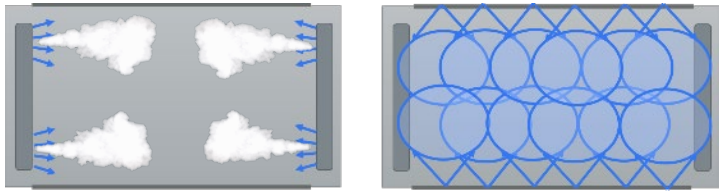




- **Solution Tanks**
  - ✓ Three distinct tanks (200L each)
  - ✓ Can be pumped to fog or spray
  - ✓ Salt water/ Rain

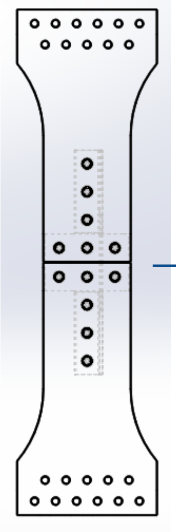
- **Gas Analyzers (American Ecotech)**
  - ✓ NO_2, SO_2, and O_3
  - ✓ 0.5ppb detection limit
  - ✓ Gas control available (bottle)

Top-down View of Exposure Area: Fog (left) and Spray Field (right)



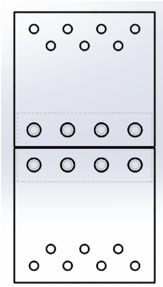
Slide 3

Corrosion Assessment Specimen for Environmental Evaluation (CASEE)



5 in. wide
18 in. long

Structural Component Corrosion Simulation (SCCS) specimen

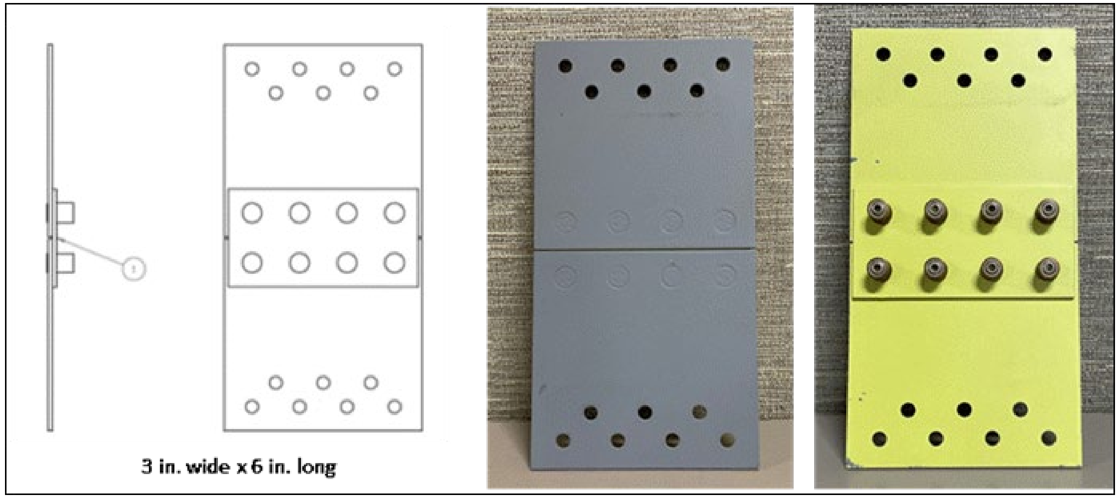


3 in. wide
6 in. long

Coatings Assessment Specimen for Environmental Evaluation (CASEE)

- SCCS:
- Multiple load paths complicates analysis
- Higher required applied load
- Higher cost
- Larger footprint
- Larger fixtures required

- CASEE:
- Reasons for Transition to CASEE
- Simplified load paths
- Lower cost to machine and assemble
- Smaller fixture required
- Greater sample throughput



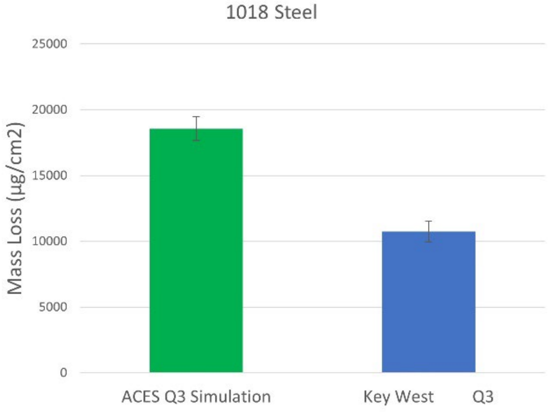
Simulation of Key West FL Environment in ACES

- Objective: demonstrate that corrosion damage in outdoor environments can be replicated (and eventually accelerated) in a lab environment
- Weather data from weather monitoring stations deployed in Key West collected between 20 Aug 2019 – 20 Nov 2020
- Temperature, relative humidity, solar irradiance, rainfall, and chloride deposition monitored; ACES chamber controlled to simulate conditions in the environment
- Data from the weather station was averaged into a representative 8- day program that was repeated 11 times to result in the same elapsed time as the outdoor exposure; artificial sea water was used to simulate deposition of sea spray aerosols (SSA) on the bare metal samples
- Validation via mass loss/pitting characteristics, LUNA Acuity CR sensors at both Key West and in ACES chamber

Translate weather conditions into ACES chamber controls

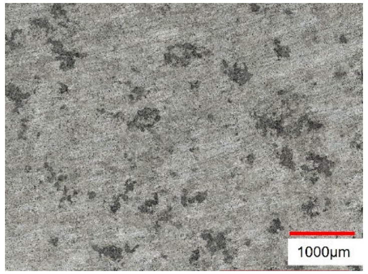
Results – 90-day Key West simulation in ACES

Mass Loss

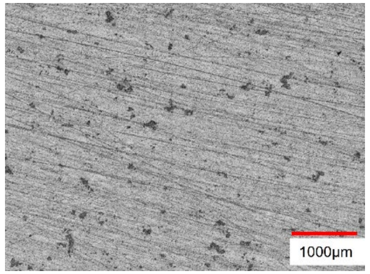


ACES simulation was more aggressive than the Key West environment

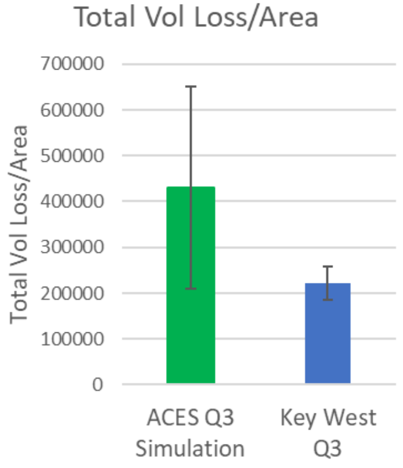
ACES Q3 simulation

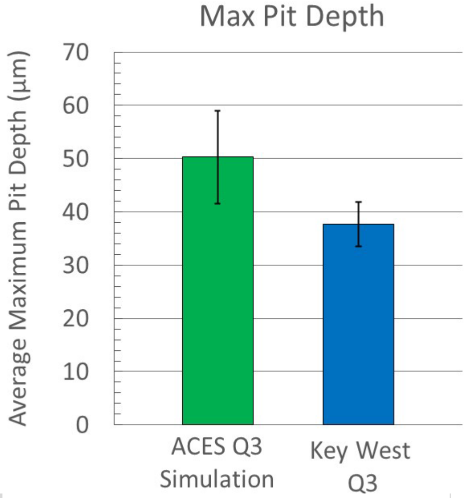


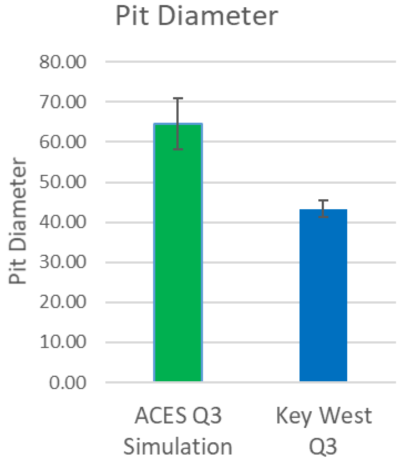
Key West Q3

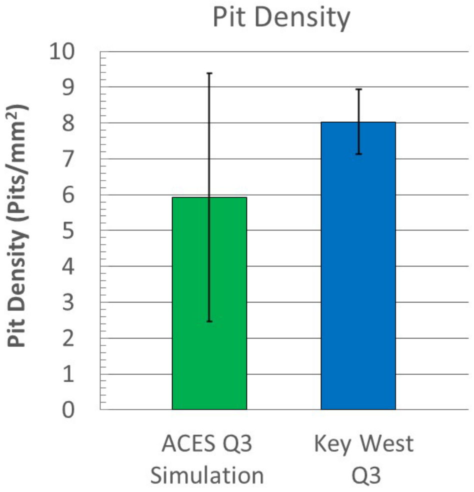


7075-T6 Pitting

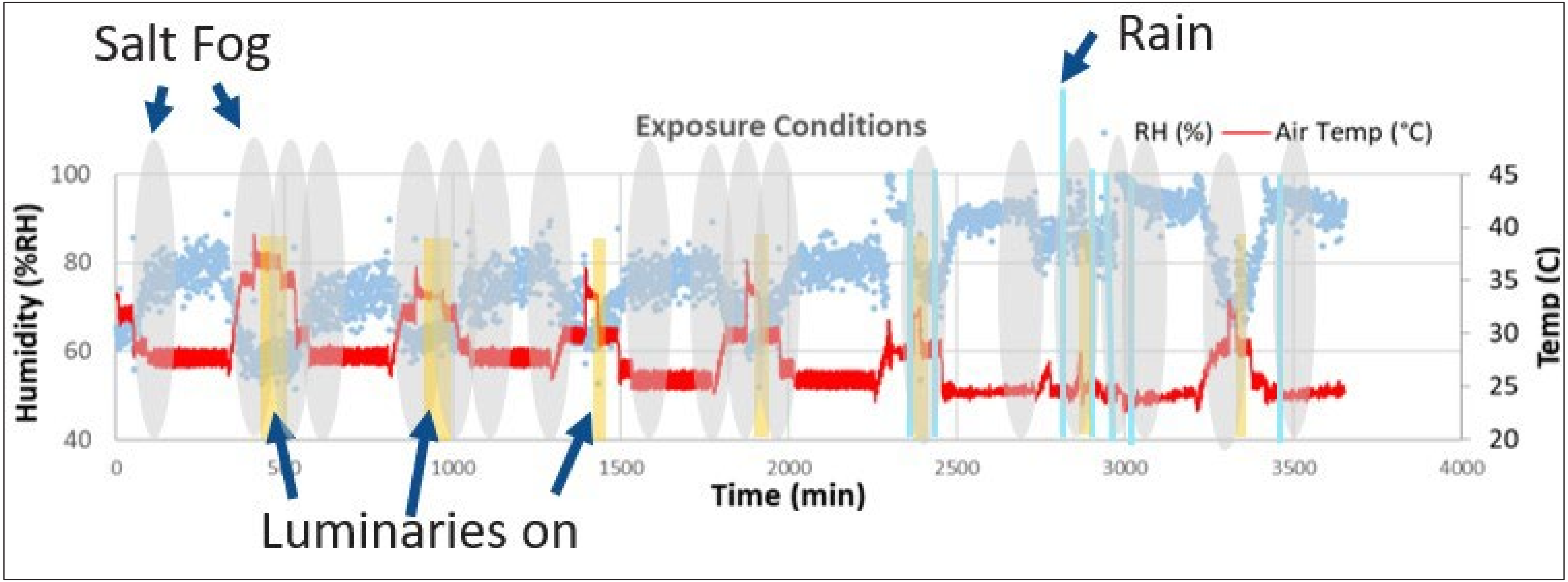




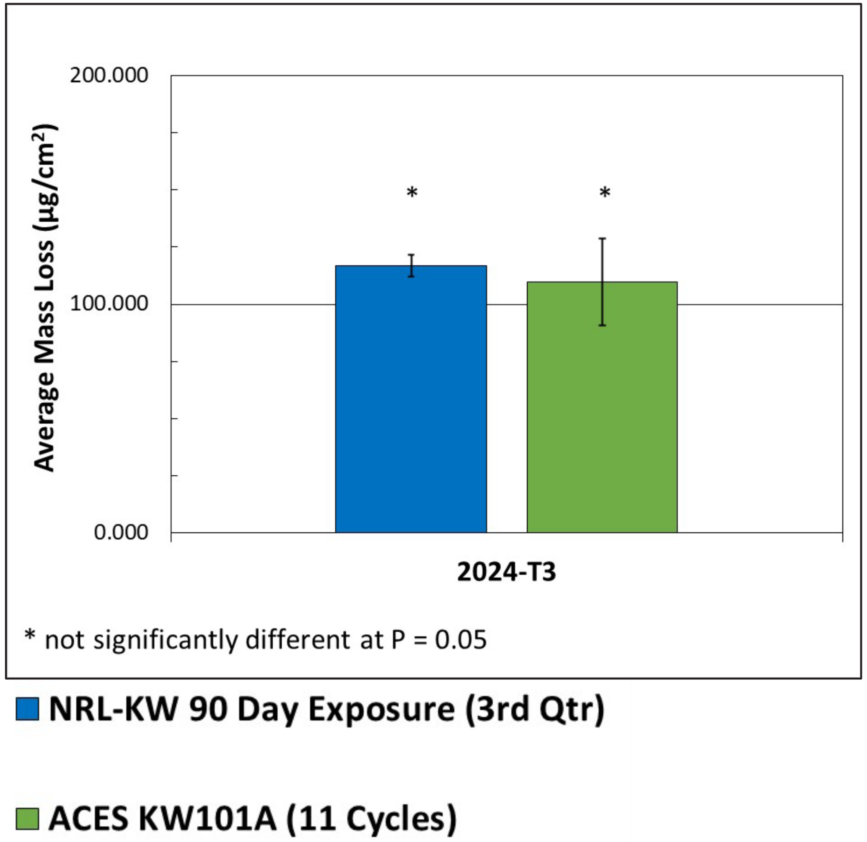


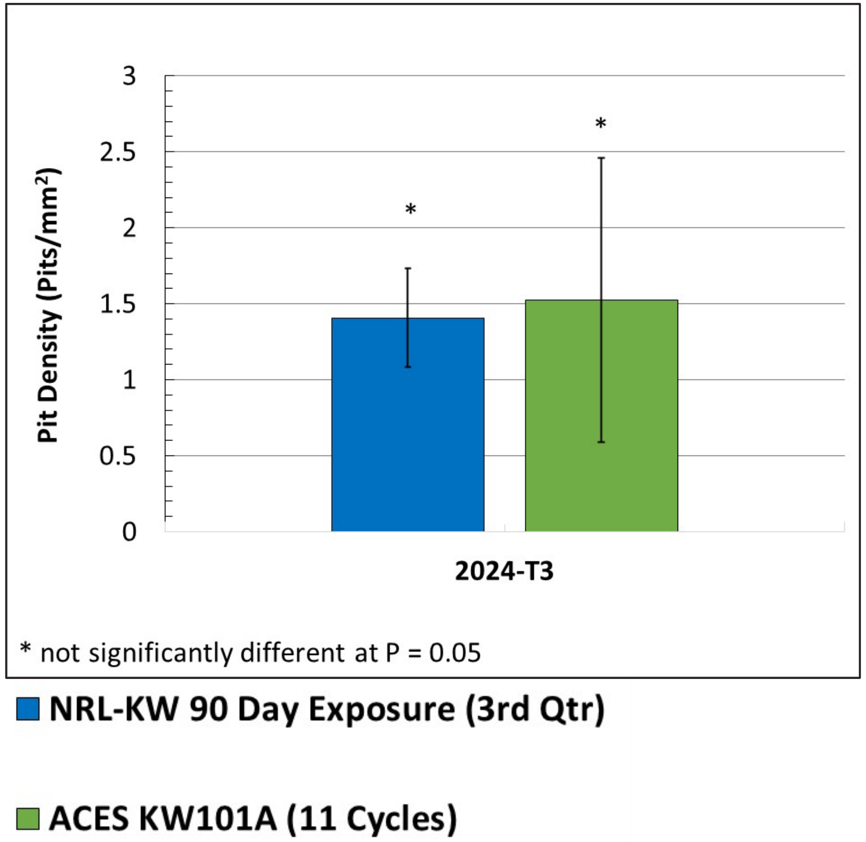


Experiment/Results – Key West acceleration (3.5 Day Cycle)



Results from Accelerated ACES KW Profile vs 90 Day Key West Exposure





Accelerated KW Profile in ACES (11 Cycles / 38 days) showed **no significant difference** at a 95% confidence interval for both mass loss and pit density on 2024-T3 vs 90-Day exposure at Key West

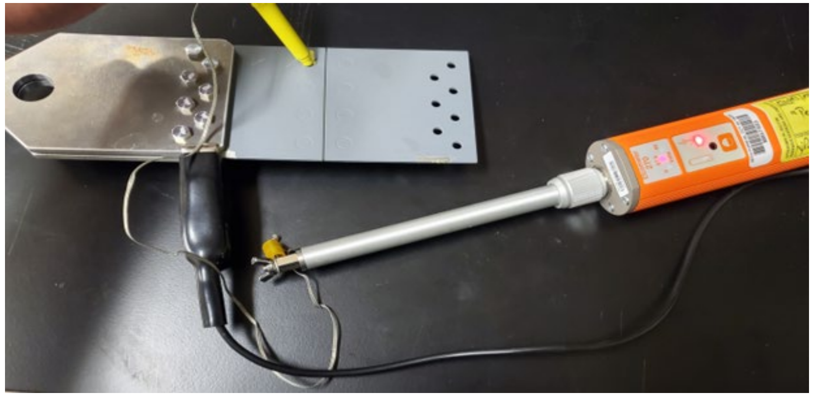
Coatings flexibility testing

Example of a standard flexibility testing for coatings:

- ASTM D6905 – Impact Flexibility of Organic Coatings
    - Tested pre and post artificial weathering
- MIL-PRF-32239 Class 2 (Highly Flexible Coating Systems must be ≥40% elongation for gloss and camo, both pre and post artificial weathering
- Failures are tested with Holiday Detector
- Provides an assessment of impact flexibility which is not a typical damage scenario in service conditions and looks at permanent deformation of coatings vs. dynamic loading, similar to in-service environments

Back Side

Front Side with failure at 60%

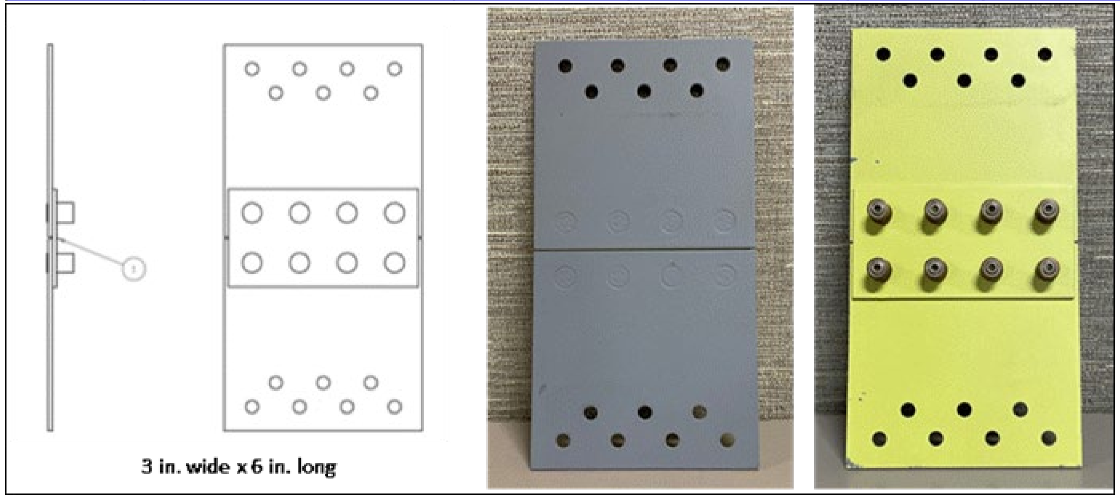


DC Holiday Detector

ASTM D2794 (GE Reverse Impact Test) Includes 0.5%, 1%, 2%, 5%, 10%, 20% 40% and 60% elongation

CASEE Sample Test Matrix

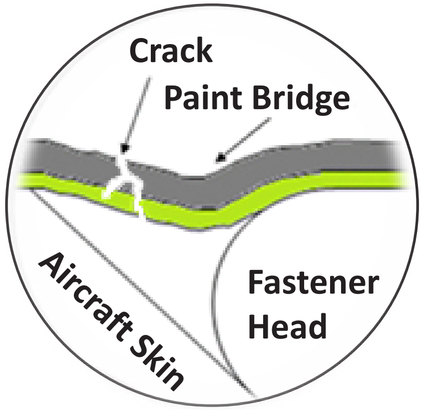
Applied coating systems										
System	Substrate	Pre Clean	Clean / Wash	De-Ox	Conversation Coat	Primer		Primer	Intermediate Primer	Topcoat
A	2024-T3 Bare 0.032" 2024-T3 Bare 0.032" 2024-T3 Bare 0.032"	MEK	Prekote			PPG PR1432GV	Assemble	PPG PR1432GV	NA	PPG CA9311/F36173
B	2024-T3 Bare 0.032" 2024-T3 Bare 0.032" 2024-T3 Bare 0.032"	MEK	Prekote			ANAC HS2118	Assemble	ANAC HS2118	NA	PPG CA9311/F36173
C	2024-T3 Bare 0.032" 2024-T3 Bare 0.032" 2024-T3 Bare 0.032"	MEK	Prekote			PPG CA7233	Assemble	PPG CA7233	NA	PPG CA9311/F36173
D	2024-T3 Bare 0.032" 2024-T3 Bare 0.032" 2024-T3 Bare 0.032"	MEK	Prekote			PPG PR1432GV	Assemble	PPG PR1432GV	PPG CA7233	PPG CA9311/F36173



Two Initial CASEE Tests Planned

1. Flex test (bending panels) in lab conditions
2. Tensile loading test (pulling panels) in ACES

- Both focus on **paint bridge** and **gap** failures



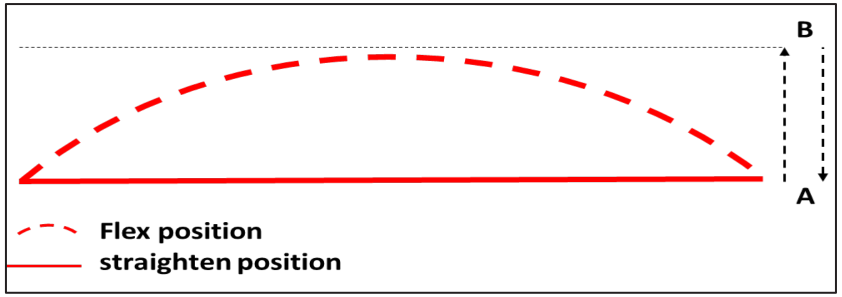
Experiment/Results – Custom Flex Test (Laboratory Ambient Conditions)

Cycle information:

- Block 1 – 7.5mm ↕ @25 sec flex/relax (22k cycles)
- Block 2 – 7.5mm ↕ @15 sec flex/relax (35k cycles)
- Block 3 – 7.5mm ↕ @1.5 sec flex/relax (153k cycles)
- Block 4 – 10mm ↕ @25 sec flex/relax (22k cycles)
- Block 5 – 10mm ↕ @15 sec flex/relax (34k cycles)
- Block 6 – 10mm ↕ @1.5 sec flex/relax (141k cycles)

Secondary Cycling (Sys C and B):

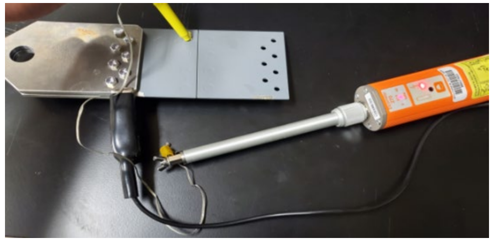
- Block 6 – 500k cycles or to failures



Displacements of 7.5mm and 10mm were performed, representing 5% and 7% shear strain, respectively.

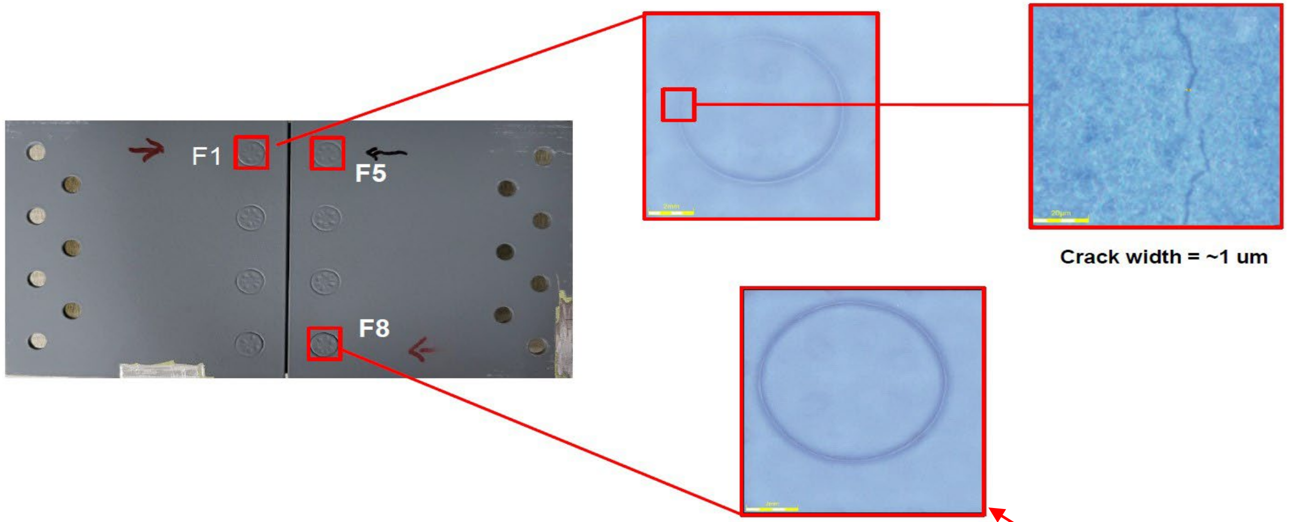
Holiday Testing of Fasteners (pinhole detection)

- Testing each fastener for holidays daily both in flex and relaxed positions



Experiment/Results – Custom Flex Test

Fastener location



F8 Crack not visible under magnification

Results – Custom Flex Test

SYS	Sample #	Displacement	Cycles	Holidays	Cycle to Fail	
System A	Sample 001	7.5mm displace	209,806	None	N/A	
		10mm displace	196,383	None	N/A	
	Sample 002	7.5mm displace	209,806	None	N/A	
		10mm displace	196,383	None	N/A	
	Sample 005	7.5mm displace	209,806	None	N/A	
		10mm displace	196,383	None	N/A	
	Sample 006	7.5mm displace	209,806	None	N/A	
		10mm displace	196,383	Yes, F1	100,465	
System B	Sample 001	7.5mm displace	209,806	None	N/A	
		10mm displace	556,057	Substrate Fail	556,057	*
	Sample 002	7.5mm displace	209,806	None	N/A	
		10mm displace	556,057	Substrate Fail	556,057	*
	Sample 005	7.5mm displace	209,806	None	N/A	
		10mm displace	196,383	None	N/A	
	Sample 006	7.5mm displace	209,806	None	N/A	
		10mm displace	196,383	Yes, F1	166,243	

* Substrate Failed

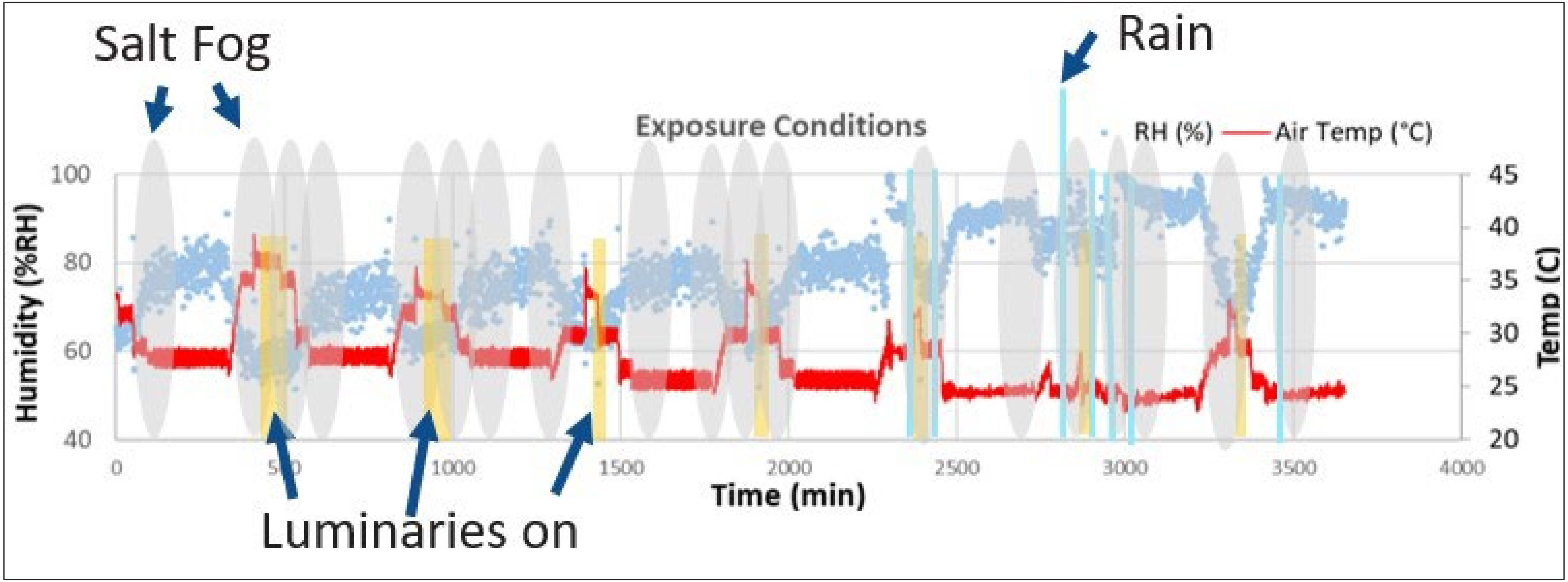
SYS	Sample #	Displacement	Cycles	Holidays	Cycle to Fail	
System c	Sample 001	7.5mm displace	209,806	None	N/A	
		10mm displace	407,359	Yes, F2, F3, F4,	377,180	**
	Sample 002	7.5mm displace	209,806	None	N/A	
		10mm displace	407,359	Yes, F4	397,313	
	Sample 005	7.5mm displace	209,806	None	N/A	
		10mm displace	196,383	Yes, F1, F8	146,150	
	Sample 006	7.5mm displace	209,806	None	N/A	
		10mm displace	196,383	Yes, F1	166,243	
System D	Sample 005	7.5mm displace	209,806	None	N/A	
		10mm displace	196,383	None	N/A	
	Sample 006	7.5mm displace	209,806	None	N/A	
		10mm displace	196,383	None	N/A	

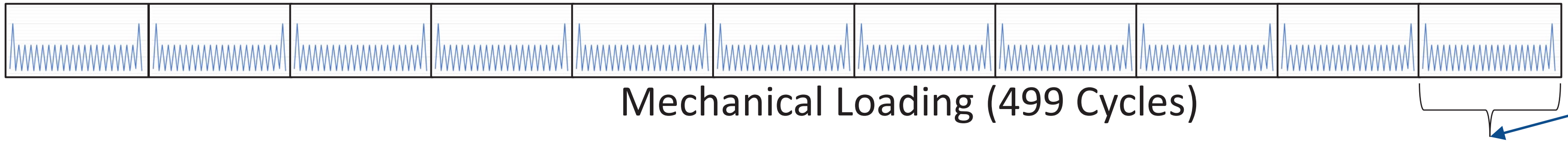
** First Fail (F2) Detected at 196,383

Test performed in ambient lab conditions using a custom two-point flex tester

- Summary of Results:
  - **System C** was worst performer, as expected due to less flexible system layup.
  - **System B** had (one paint bridge) failure
  - **System A** and **D** had none (most flexible systems)

Experiment/Results – Key West acceleration (3.5 Day Cycle)



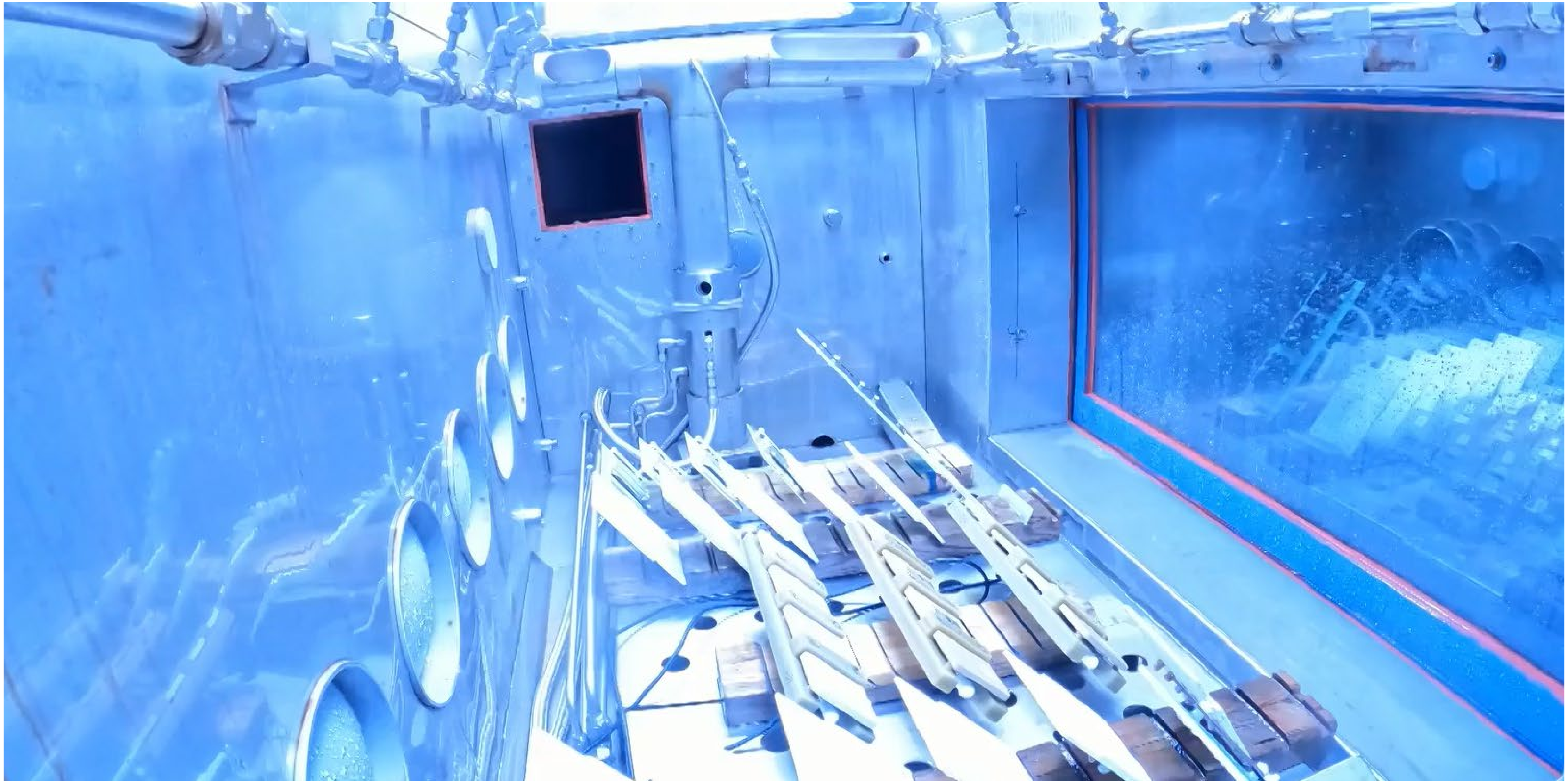


ACES Chamber in Cycle Testing – Temp/Humidity Period

ACES Chamber in Cycle Testing – Fog Period

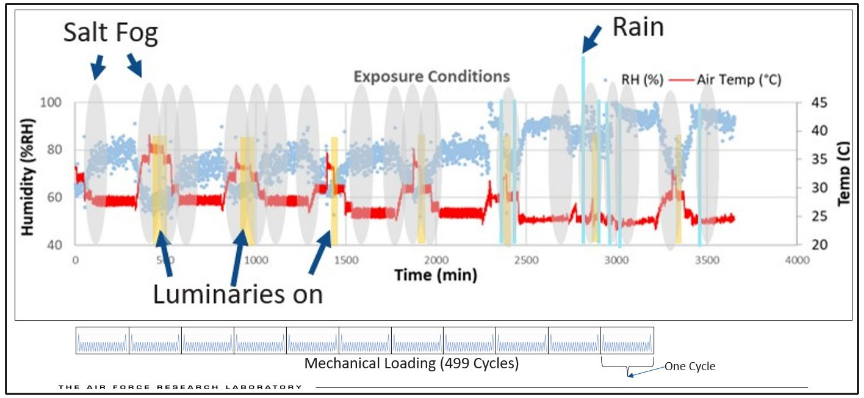
ACES Chamber in Cycle Testing – Rain Period

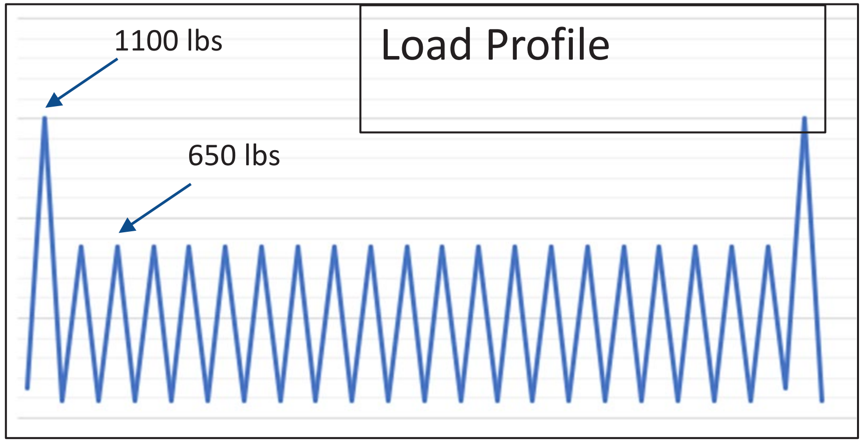
ACES Chamber in Cycle Testing – Luminary Period



ACES Chamber in Cycle Testing – With Actuators and CASEE Samples

Experiment – ACES test



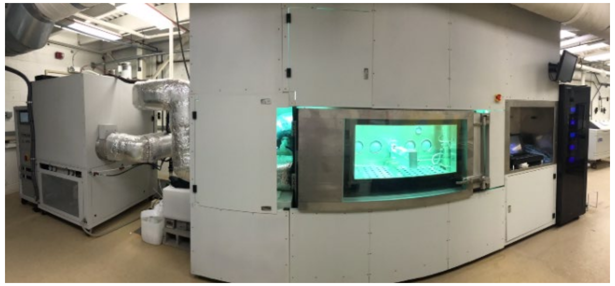


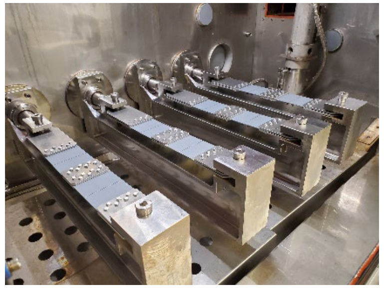
Initial 90-day Simulation Testing Procedure:

- Each cycle consists of an environmental cycle and a strain cycle
- The environmental cycle is a 3.5 day test to mimic a week in Key West
- The strain cycle is a load profile of 2 high load pulls (beginning and end) and 20 moderate load pulls
- For this test 11 cycles are being ran.
- Holidays are being checked at the end of each cycle.
- Holidays are check on the samples when the samples are relaxed and when the samples are pulled to the high load.

Current Status:

- The test has completed **3992** strain cycles out of **5490**
- The test has completed 8 out of 11 environmental cycles (72.7%)

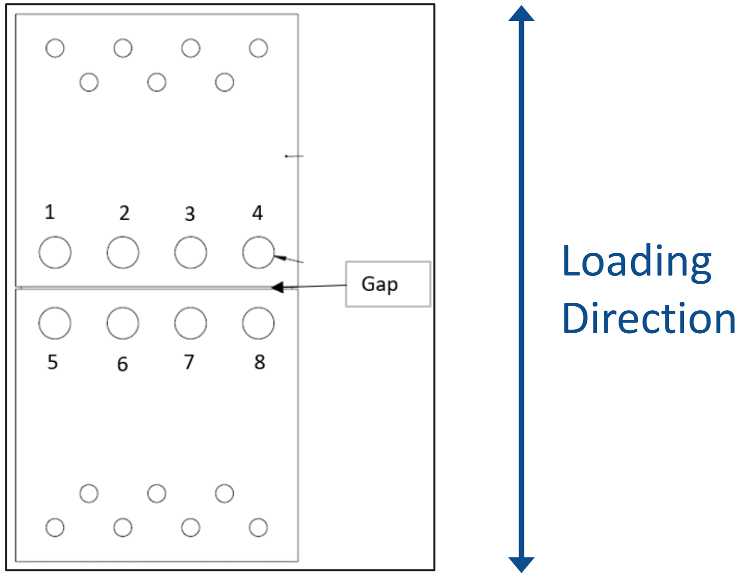




Results – ACES test

Samples Relaxed									
Samples	Rivet 1	Rivet 2	Rivet 3	Rivet 4	Rivet 5	Rivet 6	Rivet 7	Rivet 8	Gap
558-A1A-013	No	No	No	No	Yes	No	No	No	No
558-A1D-013	No	No	No	No	No	No	No	No	Yes
558-A1B-013	No	No	No	No	No	No	No	No	Yes
558-A1C-013	No	No	No	No	No	No	No	No	Yes
558-A1C-014	Yes	No	No	No	No	No	No	No	Yes
558-A1B-014	No	No	No	No	No	No	No	No	Yes
558-A1D-014	No	No	No	No	No	No	No	No	No
558-A1A-014	No	No	No	No	No	No	No	No	Yes

Samples Under Tension									
Samples	Rivet 1	Rivet 2	Rivet 3	Rivet 4	Rivet 5	Rivet 6	Rivet 7	Rivet 8	Gap
558-A1A-013	No	No	No	No	Yes	No	No	No	No
558-A1D-013	No	No	No	No	No	No	No	No	Yes
558-A1B-013	No	No	No	No	No	No	No	No	Yes
558-A1C-013	No	No	No	No	No	No	No	No	Yes
558-A1C-014	Yes	No	No	No	No	No	No	No	Yes
558-A1B-014	No	No	No	No	No	No	No	No	Yes
558-A1D-014	No	No	No	No	No	No	No	No	Yes
558-A1A-014	No	No	No	No	No	No	No	No	Yes



Summary to Date:

- Holidays Detected with System A and C
- Will continue testing to determine how coating system performance/durability **differentiate** over time in test
- After initial run - loading force and frequency may be increased to induce coating failure showing performance differences between coatings

Conclusions

- Faster, more discerning tests are needed for military aerospace coatings
- AFRL developed a laboratory test capability that can simulate and accelerate in-service conditions including weathering and cycling mechanical loading
- New test specimens were designed to mimic simple aircraft structure with representative materials and processes
  - Objective is to demonstrate the ability of coatings to maintain integrity under test conditions
- Promising results to date; combined-effects testing of coating systems with a wide range of coating flexibility will continue in order to provide a ranking of overall durability

Questions?