6-2-2016

Examination and prediction of corrosion fatigue damage and inhibition

Sarah E Galyon Dorman
SAFE, Inc, sgd@saf-engineering.com

Justin W Rausch
SAFE, Inc

Saravanan Arunachalam
SAFE, Inc

Scott A Fawaz
SAFE, Inc

Recommended Citation

Sarah E Galyon Dorman, Justin W Rausch, Saravanan Arunachalam, and Scott A Fawaz, "Examination and prediction of corrosion fatigue damage and inhibition" in "International Workshop on the Environmental Damage in Structural Materials Under Static Load/Cyclic Loads at Ambient Temperatures", A.K. Vasudevan, Office of Naval Research (retired), USA Ronald Latanision, Exponent, Inc., USA Henry Holroyd, Luxfer, Inc. (retired) Neville Moody, Sandia National Laboratories, USA Eds, ECI Symposium Series, (2016). http://dc.engconfintl.org/edsm/27

Examination and Prediction of Corrosion Fatigue Damage and Inhibition

Sarah E.Galyon Dorman
Justin W. Rausch
Saravanan Arunachalam
Scott A. Fawaz
SAFE Inc.

Background

- Current environmentally assisted fatigue testing methodologies do not account for nucleation from corrosion damage
- The DoD is moving to ban the use of chromates as a protection system for DoD assets[1]
- The protection chromate provides to fatigue crack growth needs to be fully characterized so replacement coatings can be properly assessed and there is no unexpected loss of corrosion fatigue protection as chromate is phased out
- Current coating qualification methods do not account for mechanical damage

---

[1] *Undersecretary of Defense, John, J. Young, Jr., (2009) "Limiting the Use of Hexavalent Chromium," Memorandum for Secretaries of the Military Departments.*

Objective

- To address the issue of corrosion damage as it relates to crack nucleation and propagation of relevance to the DoD a large test development program has been undertaken to examine the effects of

1. Corrosion inhibitors on corrosion fatigue damage
2. Crack nucleation and propagation from a corrosion pit to a fatigue crack
3. Help influence methods for coating and inhibitor qualifications

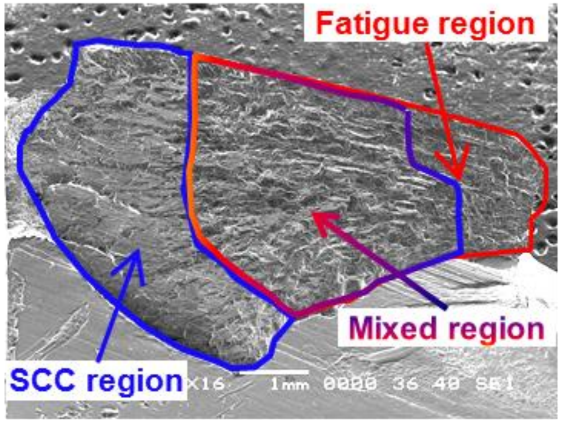
Test Design

- The United States Air Force Academy's (USAF) Center for Aircraft Structural Life Extension (CAStLE) has completed several aircraft structural teardowns
  - KC-135, C-130, C-5, T-37, T-38
- The findings from the teardowns were analyzed to breakdown the types and cause of damage on several aircraft[2]
- This analysis found that 78% of corrosion pits noted in the teardowns resulted in fatigue damage[2]
- It was also noted that many of the fatigue cracks had signs of corrosion oxides on the surface suggesting that environment is entering the cracks at some point during service[2]

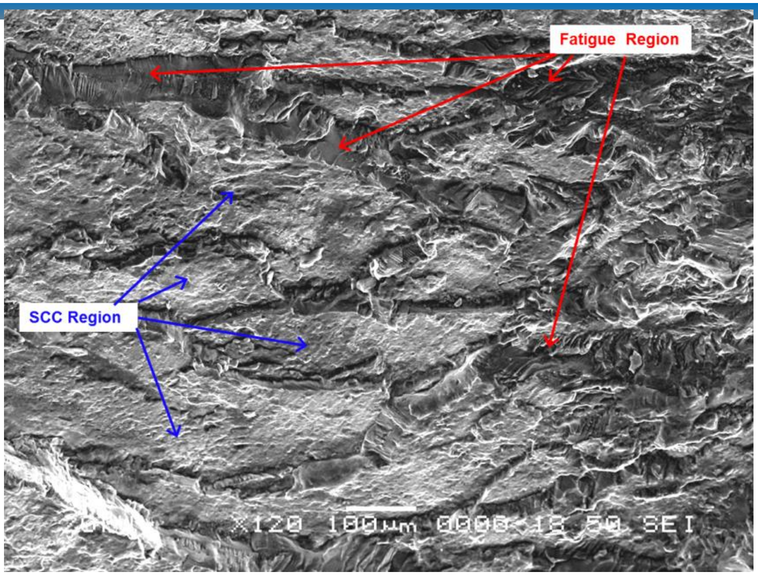
[2] *Shoales, G.A., Walters, M.R., Fawaz, S.A. (2009) "Compilation of Damage Findings from Multiple Recent Teardown Analysis Programs," Proceedings of the 2009 International Conference on Aeronautical Fatigue (ICAF) Symosium, Rotterdam, The Netherlands. pp.187-208*

Environmental and Mechanical Interactions

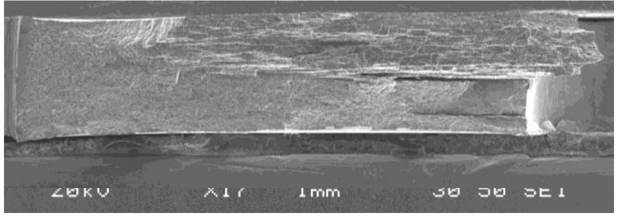
SCC and Fatigue combined on fracture surface



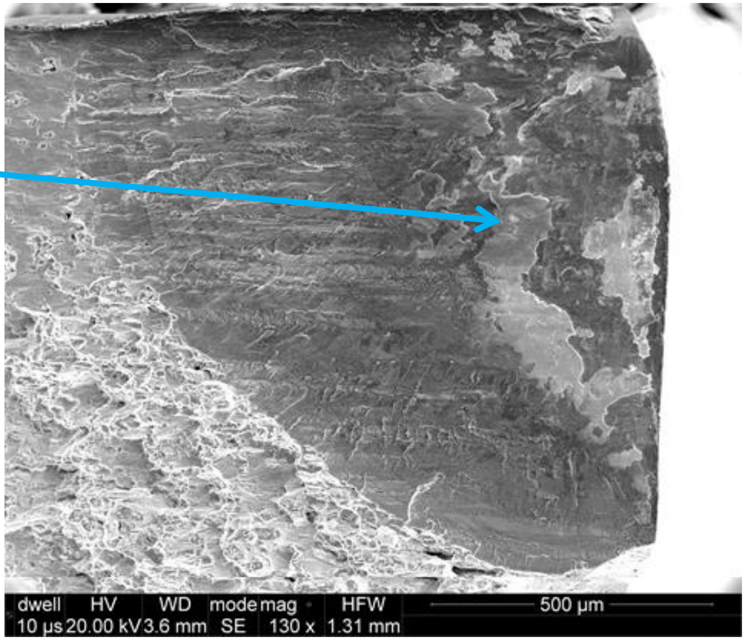
SEM micrograph shows three regions

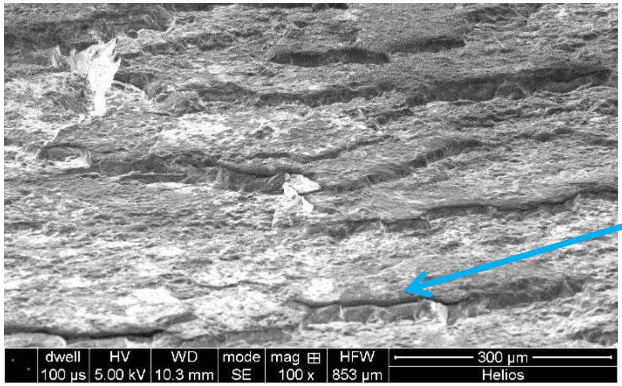


Fatigue fracture with intergranular corrosion



Fatigue crack with corrosion debris on surface

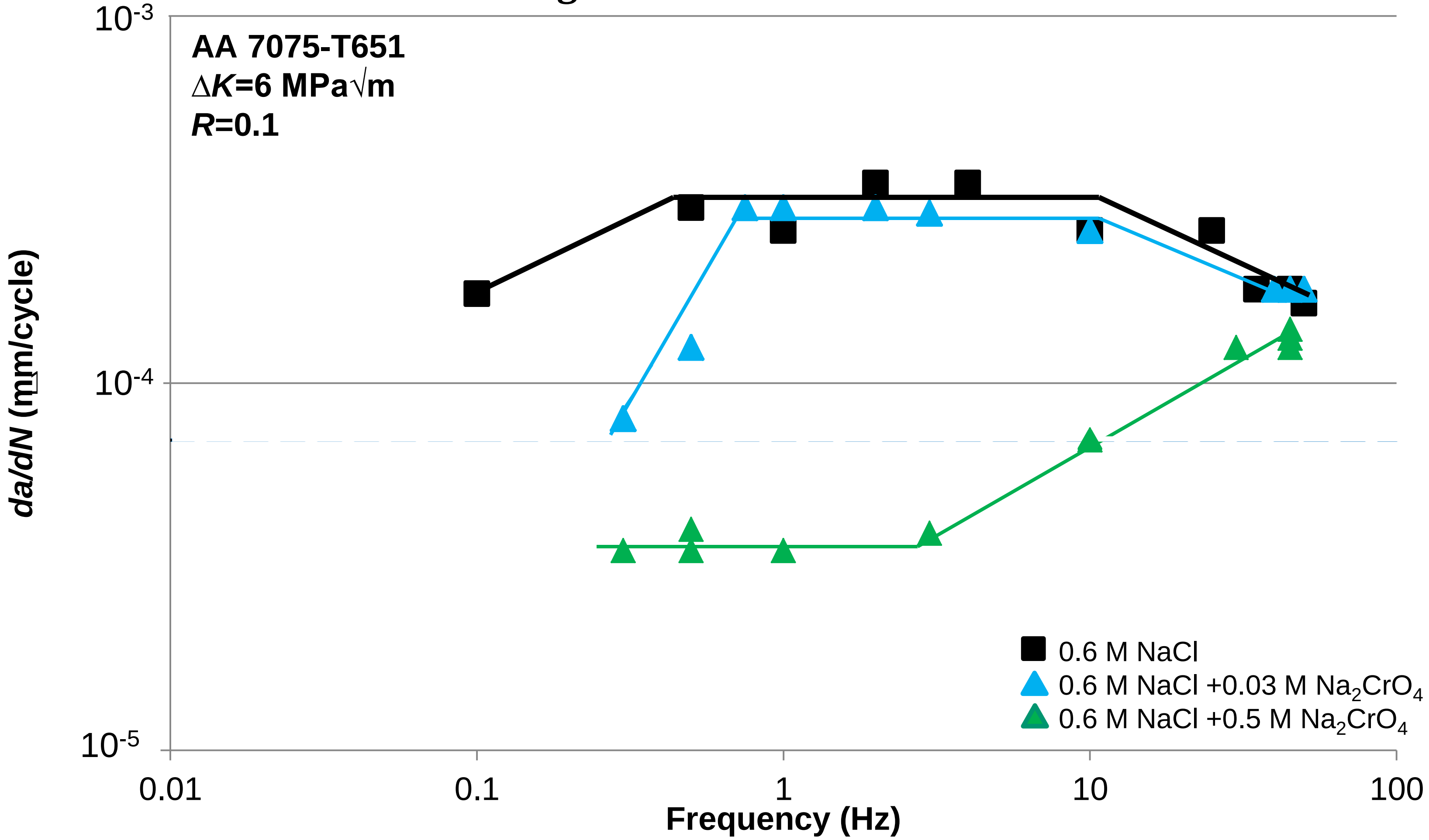




Intergranular corrosion noted on the shelf edges when sample tilted; main surface only shows fatigue

Corrosion Fatigue Inhibition by Chromate

ΔK=6 MPa√m Chromate in Bulk Solution Effect on AA7075-T651 Fatigue Crack Growth Rates[3]

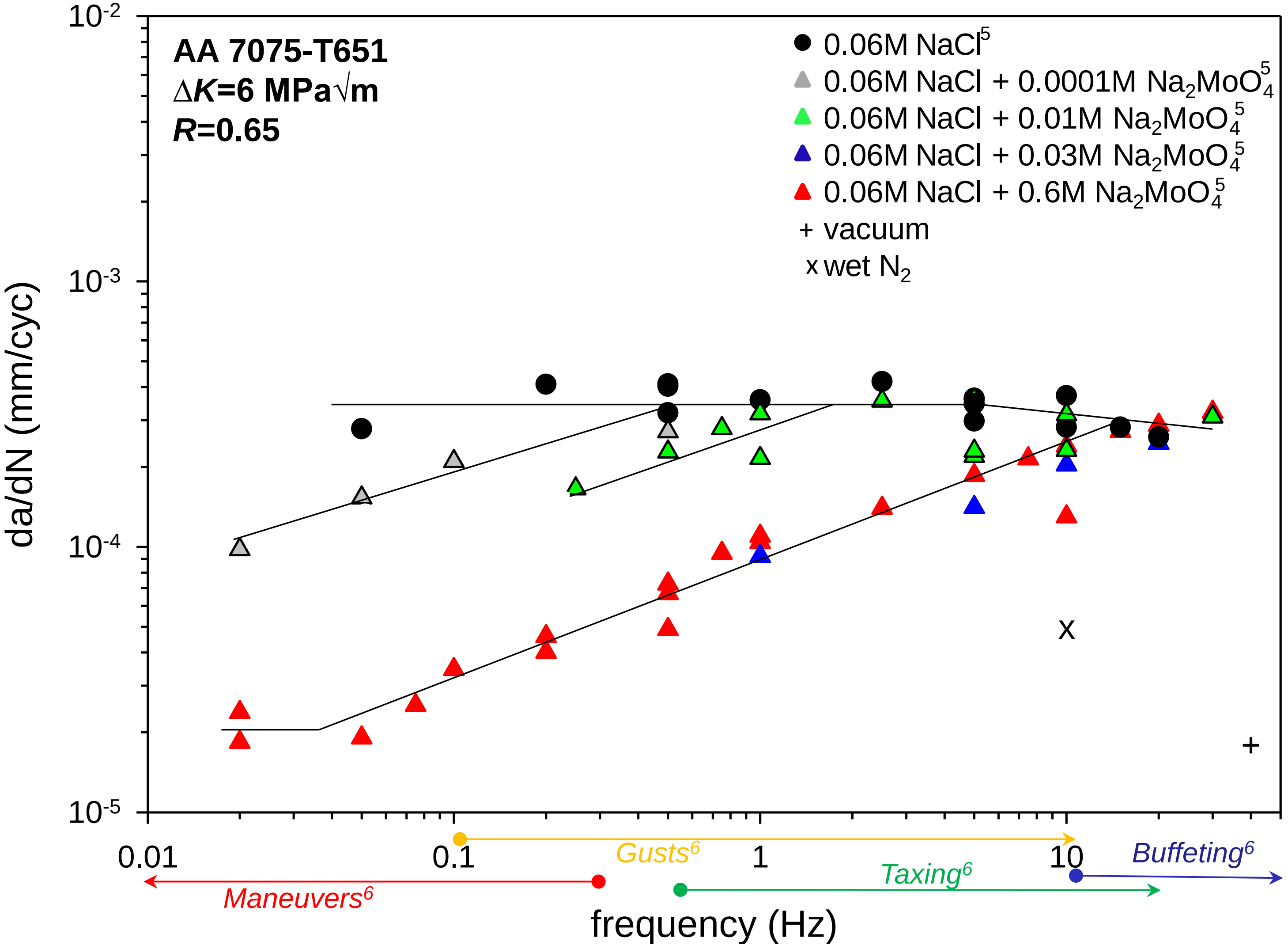


---

[3] Gasem, Z. and Gangloff, R.P., (2001) “Rate-Limiting Processes in Environmental Fatigue Crack Propagation in 7000-series Aluminum Alloys”, in *Chemisty and Electrochemistry of Corrosion and Stress Corrosion Cracking*, p. 501-521. R.H. Jones, Editor. TMS-AIME: Warrendale, PA.

Corrosion Fatigue Inhibition with Low Concentration Molybdate

Cabin Pressurization: 0.00003-0.0005 Hz [6]
Ground-Air-Ground: 0.00003-0.001 Hz [6]



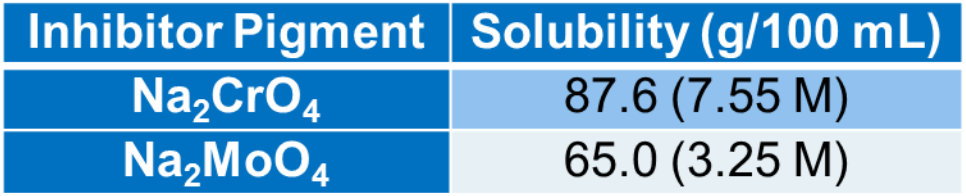
---

[5] Warner, J.S. (2010) *"The Inhibition of Environmental Fatigue Crack Propagation in Age-Hardenable Aluminum Alloys." PhD Dissertation, University of Virginia, Charlottesville, VA.*

[6] *Wanhill RJH (2001) Flight simulation fatigue crack growth guidelines, NRL-TP-2001-545. NRL, Amsterdam, The Netherlands.*

Inhibition Test Development

- **Can polymer coatings release enough inhibitor to protect against environmental damage?**
- **What amount of inhibitor is expected to leach from the coating?**
  - **All corrosion fatigue work to date used highly soluble inhibitor salts to minimize precipitate-phase crack closure**



Inhibitor Pigment	Solubility (g/100 mL)
Na_2CrO_4	87.6 (7.55 M)
Na_2MoO_4	65.0 (3.25 M)

  - **Coatings typically use low-solubility salts to prevent polymer matrix blistering**

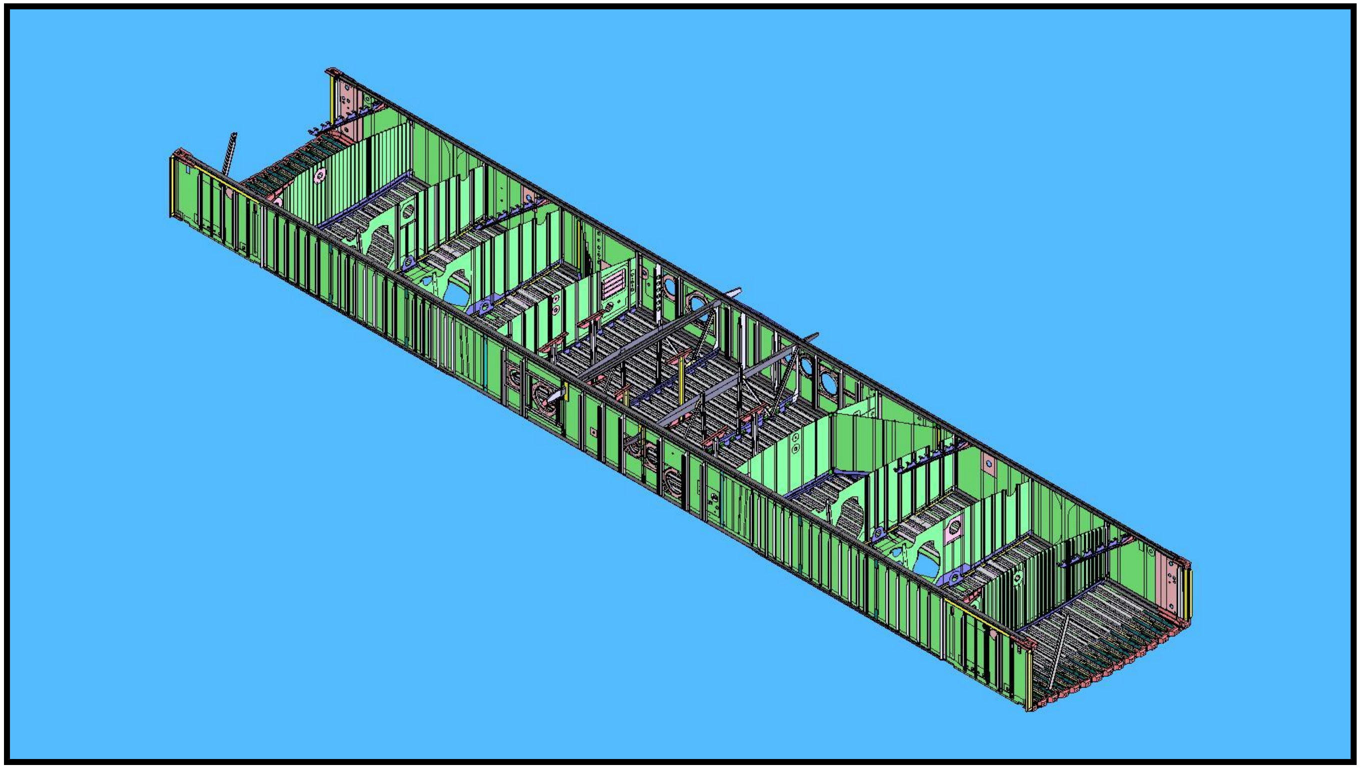
Inhibitor Pigment	Solubility (g/100 mL)	
$SrCrO_4$	0.096 (4.7 mM)	MIL-SPEC Class 1
$BaCrO_4$	0.00026 (0.01mM)	MIL-SPEC Class 2
$CaMoO_4$	0.0011 (0.05 mM)	MolyWhite 501

[7] *Haynes, W.M. Ed, (2011) The Handbook of Chemistry and Physics, 92nd Ed.*

[8] *Sinko, J. (2001) Progress in Organic Coatings, vol.* ***42.*** *pp.267-282*

Inhibition Test Development

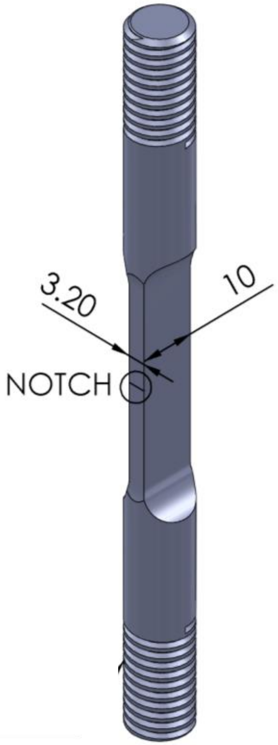
- **For the area in the wing known to collect liquid, analysis of the coated surface area-to-volume on fluid ratio was calculated using a 3D model of the aircraft**



---

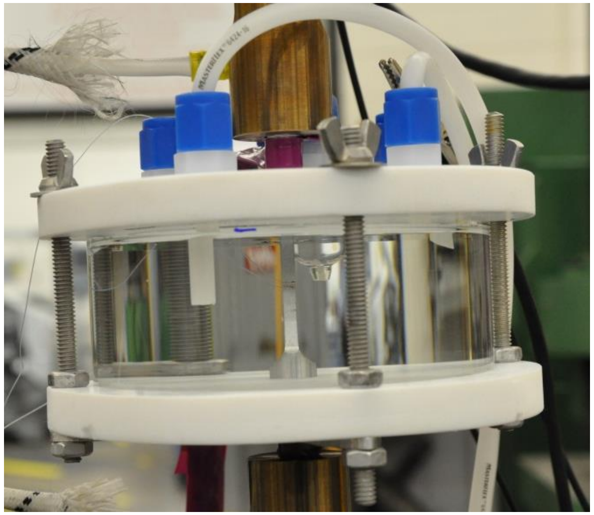
[9] *Hammond, Matthew, James Greer, Scott Fawaz, Börje Andersson, Robert Rainsberger, Monica Poelking (2010), "Detailed Three-Dimensional Modeling of the C-130 Center Wing Box for Damage Tolerance Analyses", Proceedings of the 2010 Aircraft Airworthiness & Sustainment Conference, Austin, TX*

Inhibition Test Development



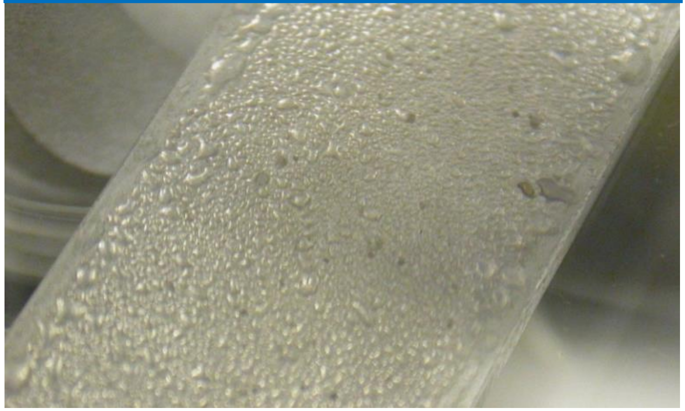
Single Edge Notch (SEN) Specimen

Bulk Solution

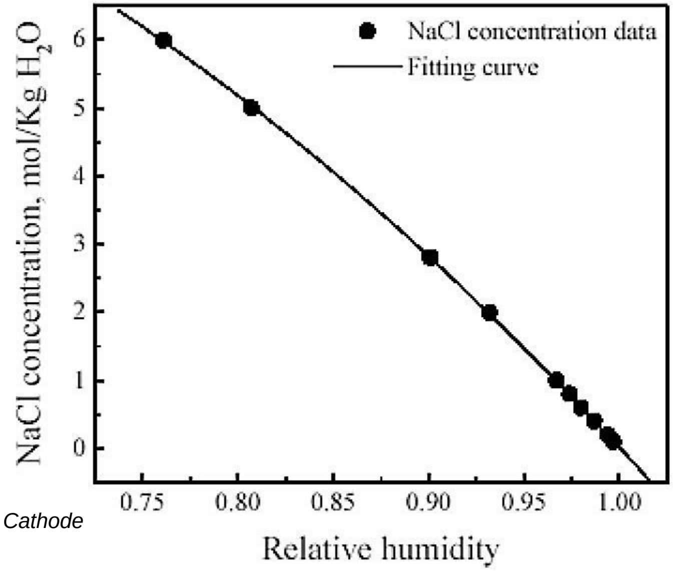


Atmospheric Thin Film

NaCl deposited by printing



NaCl Concentration vs. RH[10]



---

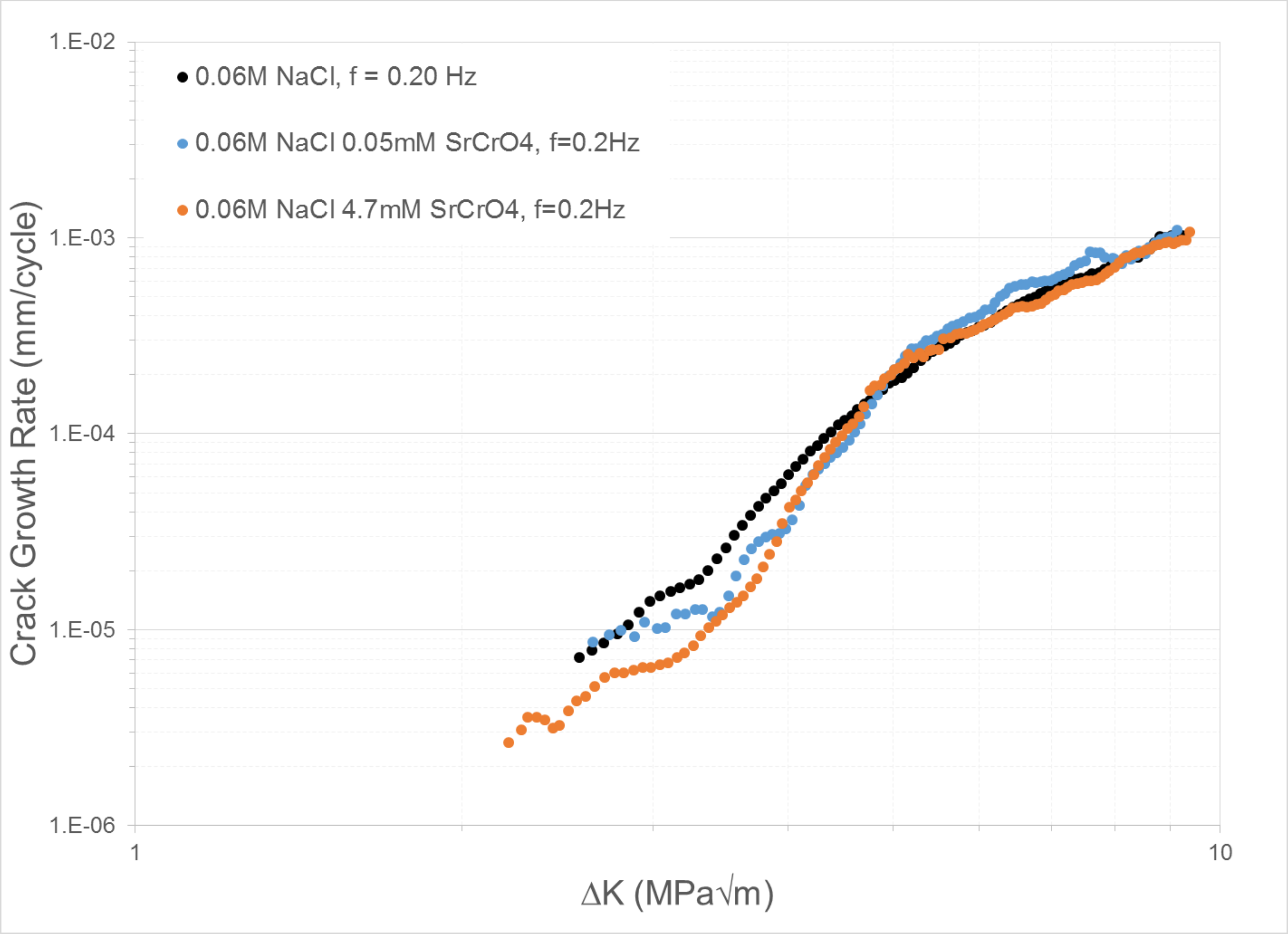
[10] *Chen, Z.Y., Cui, F. Kelly, R.G. (2007) "An Analytical Model for Calculating Current Delivery Capacity of Thin-film Cathode and the Stability of Localized Corrosion under Atmospheric Environments," ECS Proceedings 3(21) pp443-457.*

Inhibition Test Development

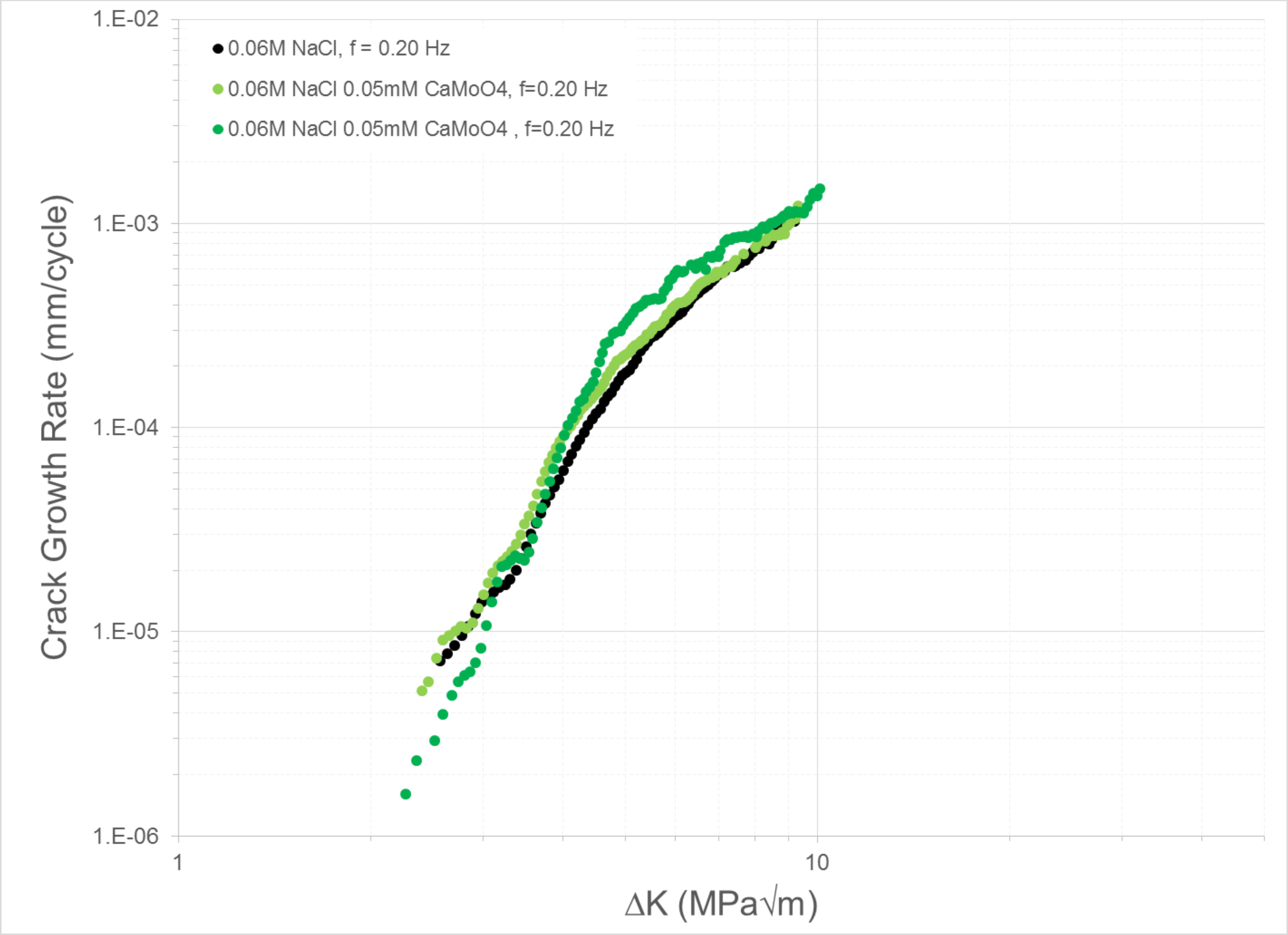
- The maximum concentration of inhibitor expected in solution is limited by solubility:
    - 4.7 mM $CrO_4^{=}$ from $SrCrO_4$ coating
    - 0.05 mM $MoO_4^{=}$ from $CaMoO_4$ coating

- Bulk solution (500 mL) fatigue testing of a COATED SPECIMEN produces low inhibitor concentration
    - Concentrations < 0.05mM $CrO_4^{=}$ from $SrCrO_4$
    - Concentrations < 0.002mM $MoO_4^{=}$ from $CaMoO_4$

Effect of Chromate

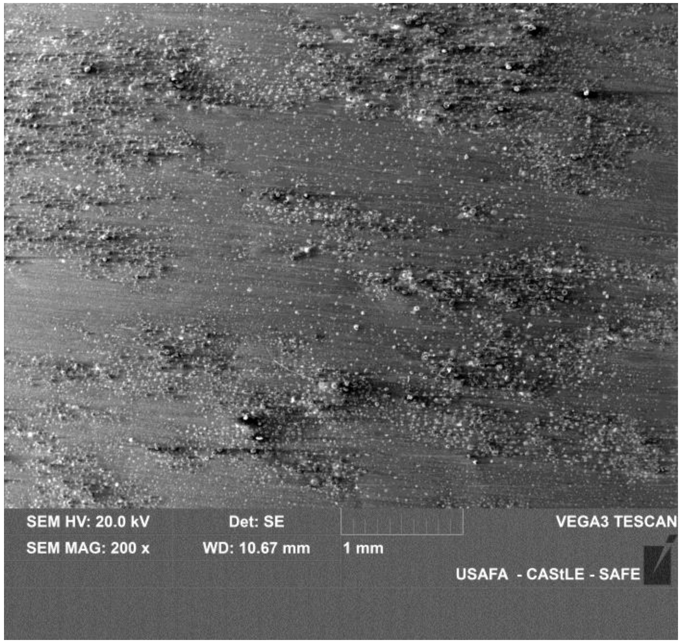


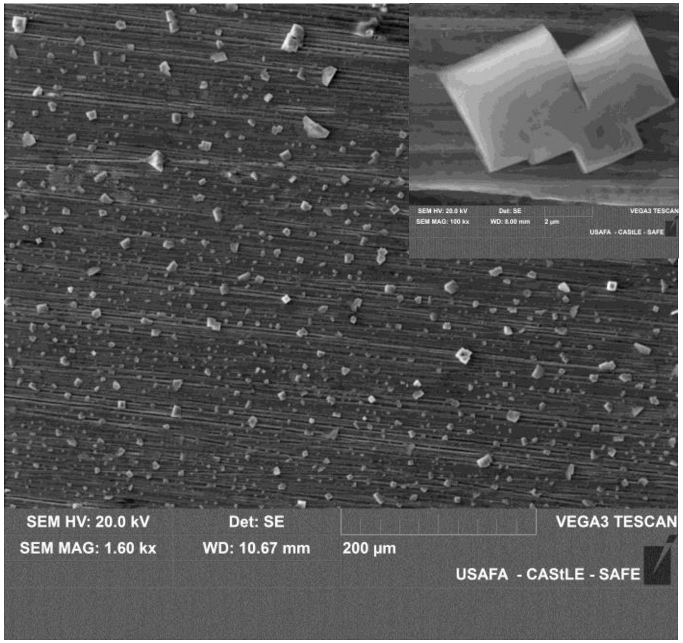
Effect of Molybdate



Atmospheric Testing

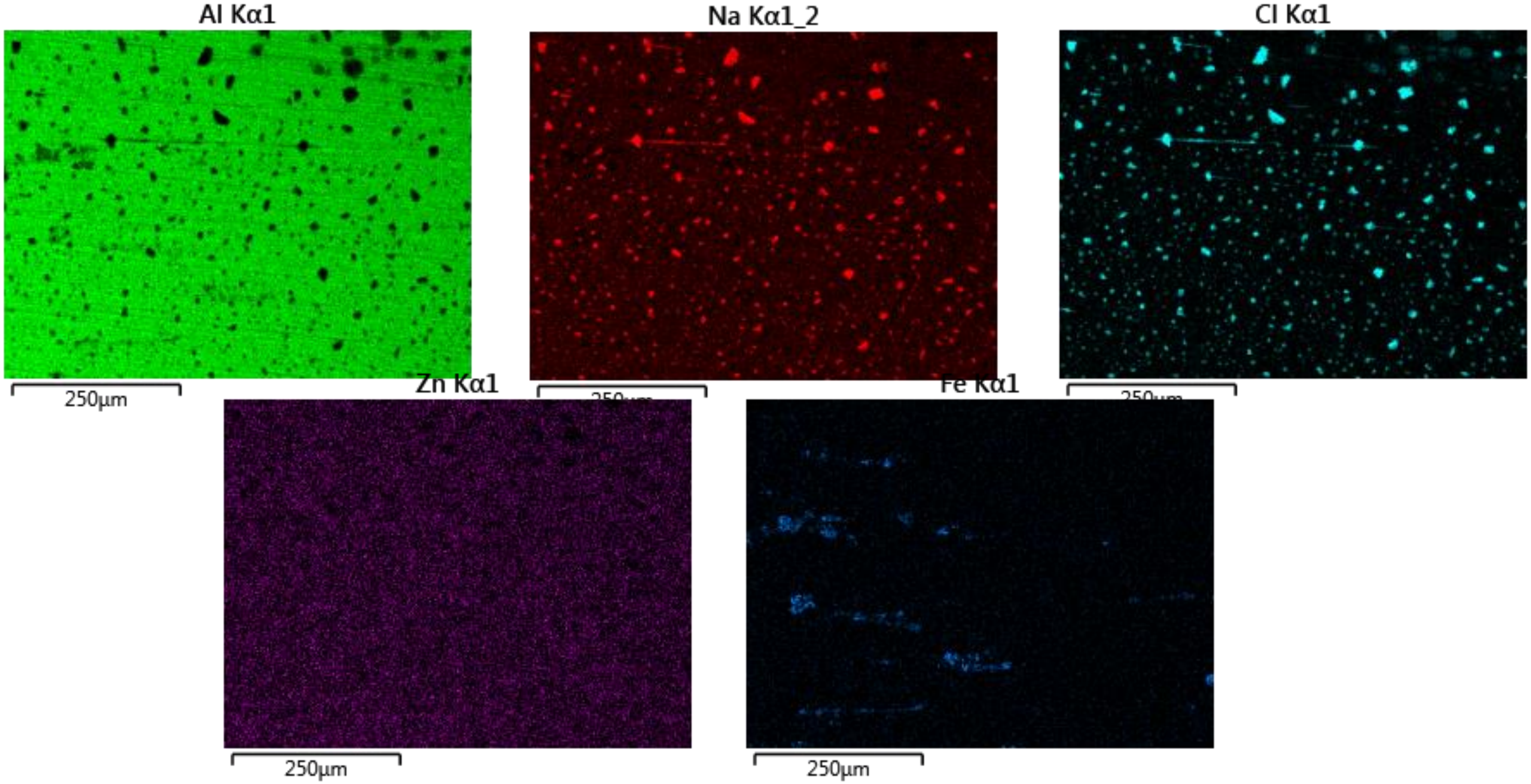
- **A salt layer added to mimic representative corrosion conditions-loading was 400µg/cm^2**
- **Using glycerin solutions to hold steady RH (80%)**



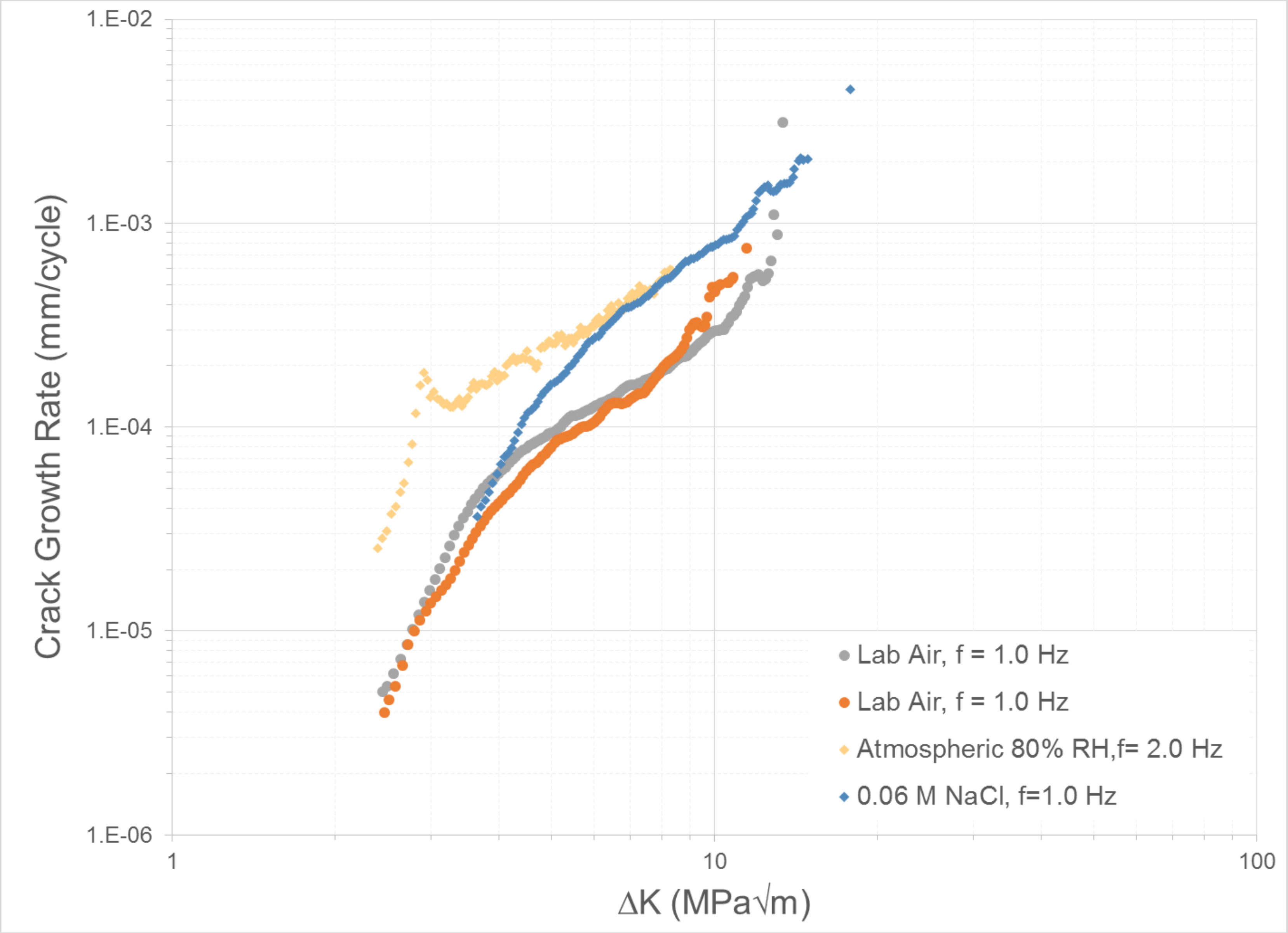


Atmospheric Testing

- A salt layer added to mimic representative corrosion conditions-loading was 400μg/cm^2
- Using glycerin solutions to hold steady RH (80%)



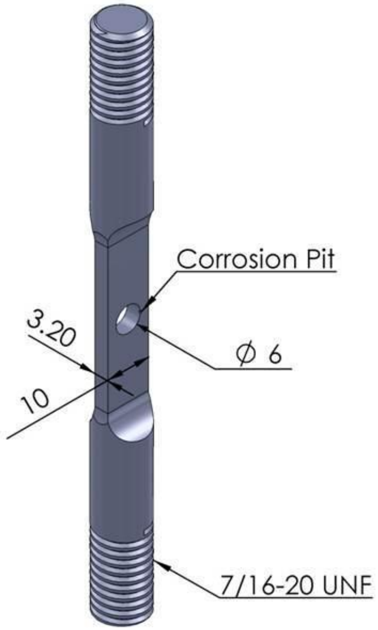
Atmospheric Corrosion Fatigue

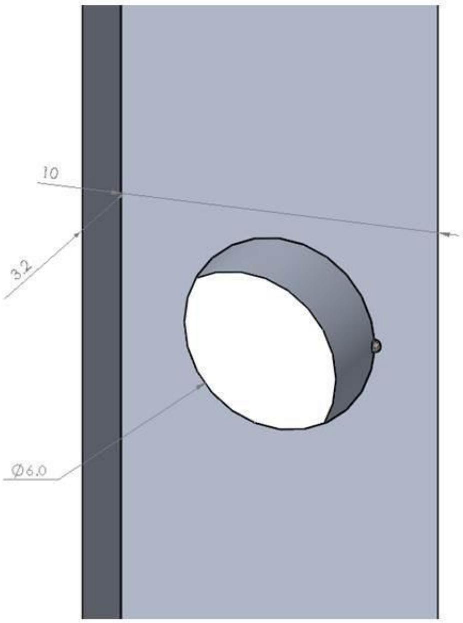


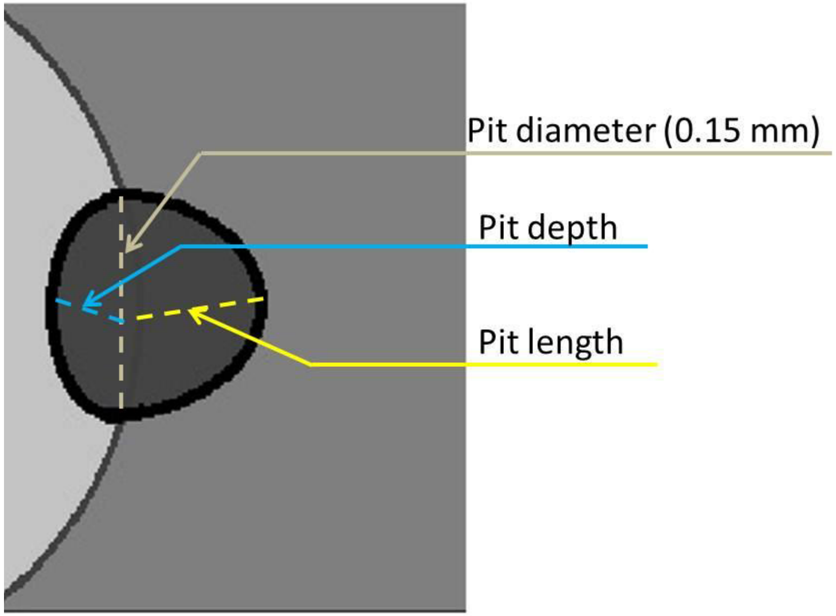
Corrosion Damage to Fatigue Test Development

- Width: 10 mm
- Thickness: 3.2 mm
- Central hole: 6 mm
- Corrosion pit: 0.15 mm diameter

SIPS AA7075–T651

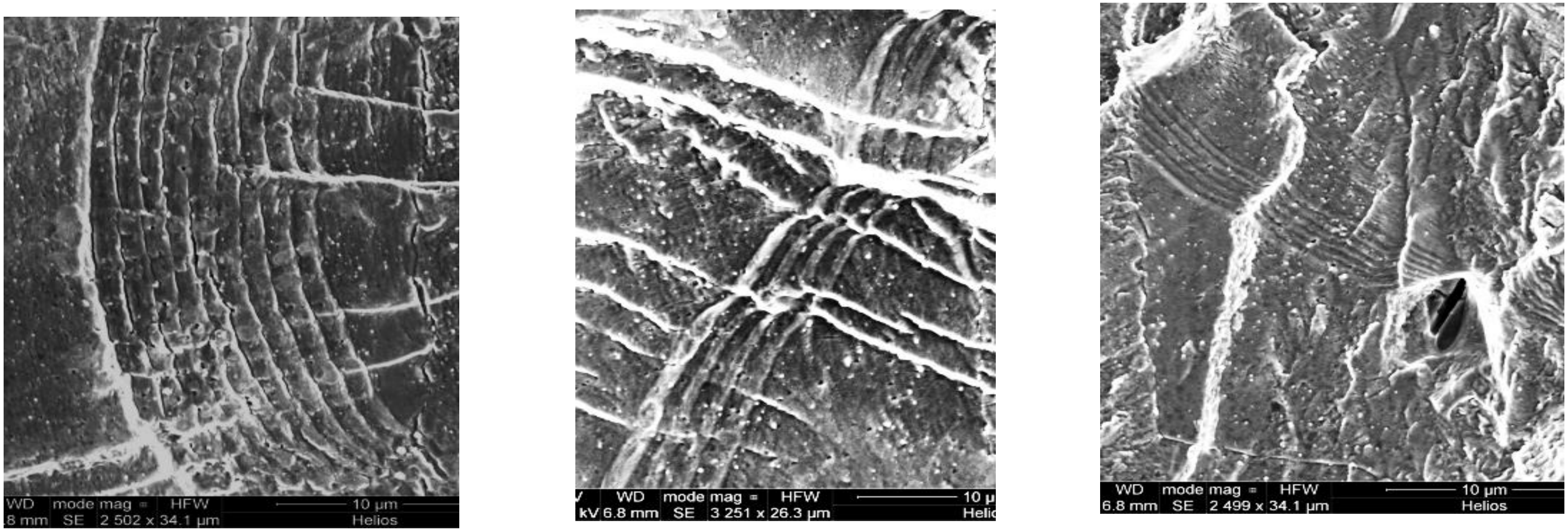






Corrosion Damage to Fatigue Test Development

- **Crack growth monitored by dcPD method and unique marker loading spectrum**
  - **Marker loading spectra: 10-4-6, Baseline loading at stress ratio (*R*) = 0.65**



Corrosion Damage to Fatigue Test Development

- Obtained the crack growth data from marker bands and identified crack nucleating features using a scanning electron microscope
- Calculated the crack growth rates and life to crack nucleation and periphery crack formation
- Determined the normalized voltage signal limits to detect crack nucleation and periphery crack formation irrespective of pit dimensions, stress conditions

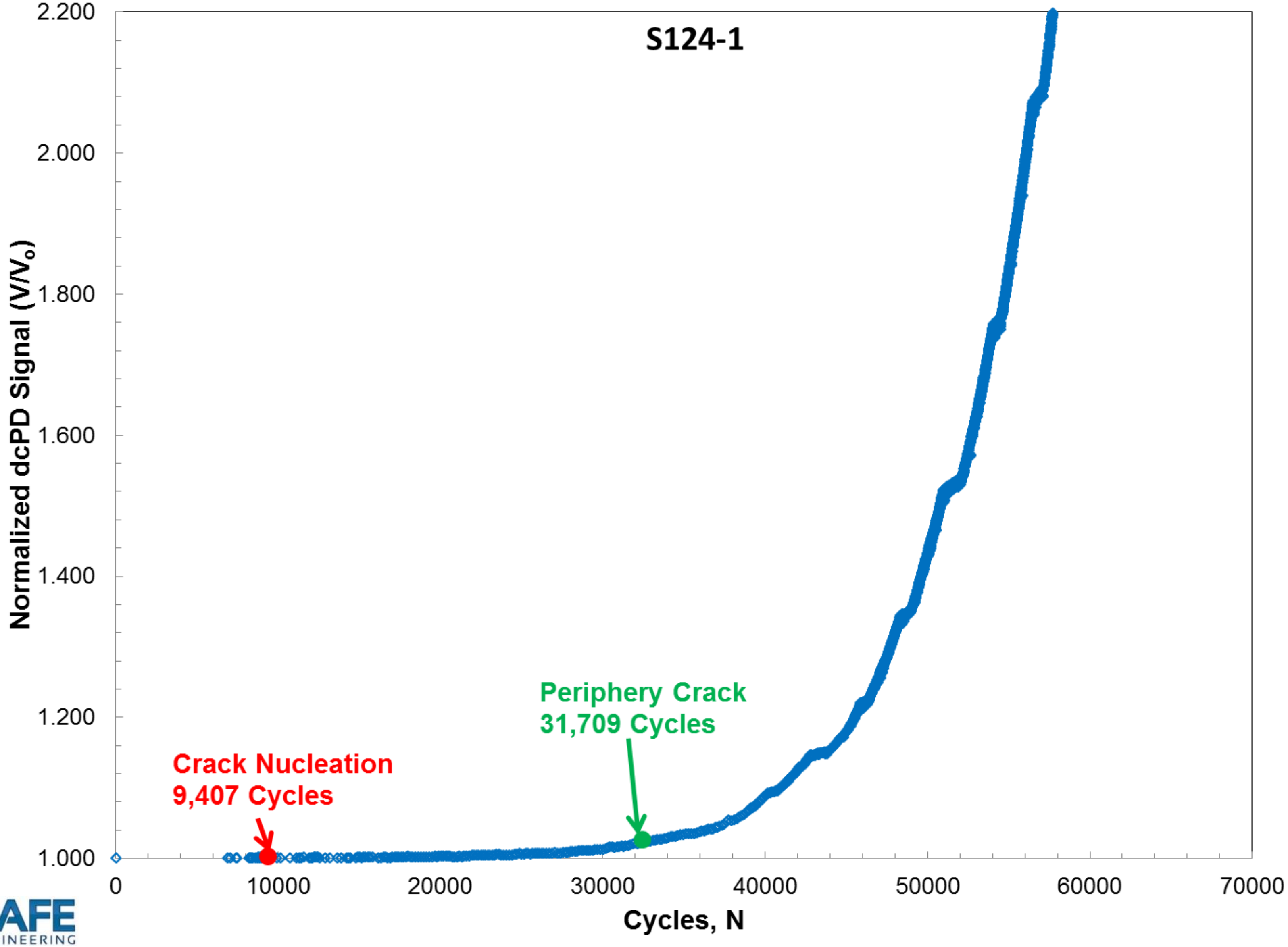
Stress, σ_{max}, MPa	Specimen ID	Pit Dimensions		a/c
		a, mm	c, mm	
70	S70-1	0.0984	0.100	0.987
	S70-2	0.084	0.117	0.718
	S70-3	0.121	0.091	1.330
124	S124-1	0.116	0.096	1.208
	S124-2	0.111	0.112	0.991
	S124-3	0.207	0.136	1.552
180	S180-1	0.113	0.134	0.843
	S180-2	0.084	0.109	0.771
	S180-3	0.113	0.123	0.919

Corrosion Damage to Fatigue Test Development-Results

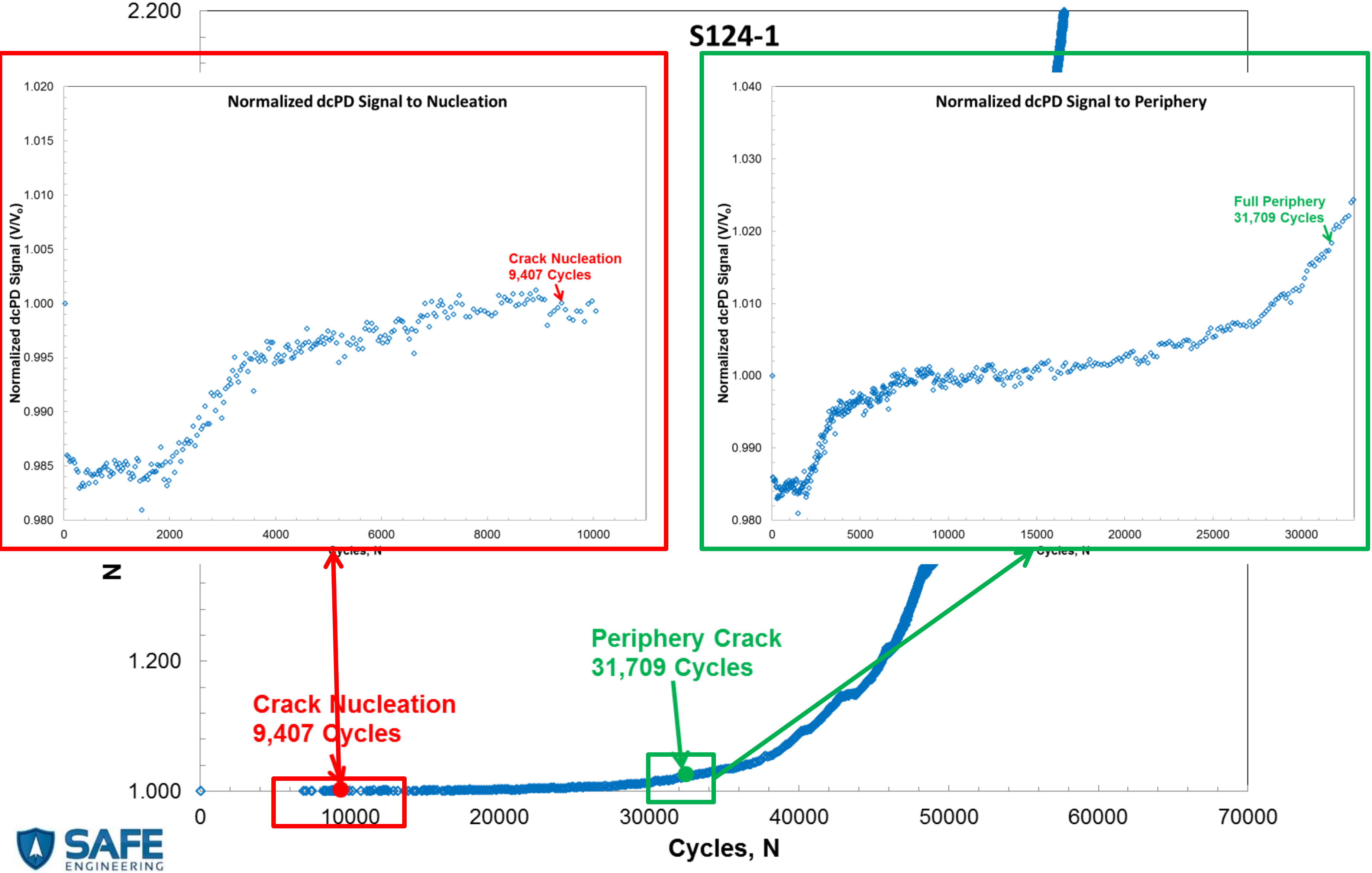
Specimen ID	Norm dcPD at Nucleation	Cycles to Nucleation	Periphery Crack Dimension		Norm dcPD at Periphery Crack	Cycles to Periphery Crack	Total Cycles	%Life for Nucleation	%Life for Periphery
			a, mm	c, mm					
S70-1	1.00036	728,658	0.107	0.161	1.00366	782,480	906,080	80	86
S70-2	1.00025	634,921	0.245	0.134	1.02480	810,072	930,582	68	87
S70-3	1.00009	1,881,617	0.126	0.196	1.00413	1,943,417	2,097,917	90	93
S124-1	1.00004	9,406	0.259	0.213	1.01832	31,709	60,399	15	52
S124-2	1.00002	8,608	0.249	0.119	1.00190	25,413	50,523	17	50
S124-3	1.00023	14,521	0.445	0.276	1.01850	27,539	48,348	30	56
S180-1	1.00018	225	0.369	0.279	1.00610	7,725	13,101	1.7	58
S180-2	1.00013	370	0.253	0.121	1.00520	7,210	16,012	2.3	45
S180-3	1.00034	138	0.473	0.638	1.01520	10,815	18,216	0.8	59

- **Crack nucleation typically at *a*-tip of the pit from a jut-in or micro pit**
- **For the σ_{max} =70 MPa case 90% of the life is spent on growth of a mechanically small crack**
- **For the σ_{max} =180 MPa crack nucleation occurs at less than 3% of the total life for all cases**
- **Crack nucleation occurs before the normalized dcPD signal (V/V_o) is 1.00036**
- **The full periphery crack is formed by the time V/V_o is greater than 1.02**

Corrosion Damage to Fatigue Test Development-Results

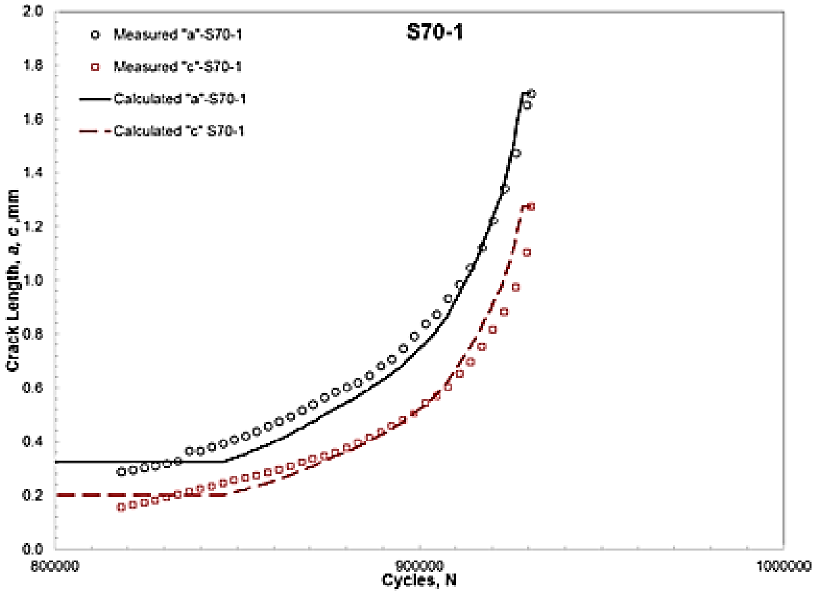


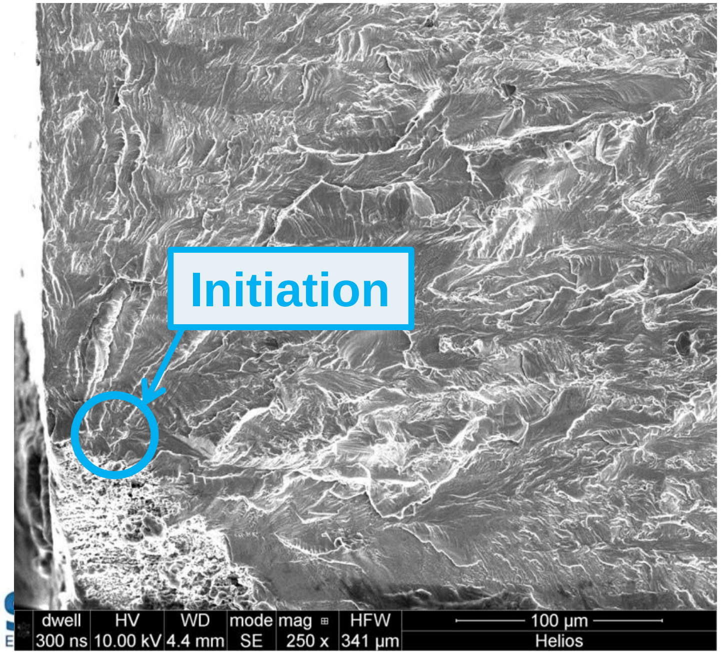
Corrosion Damage to Fatigue Test Development-Results

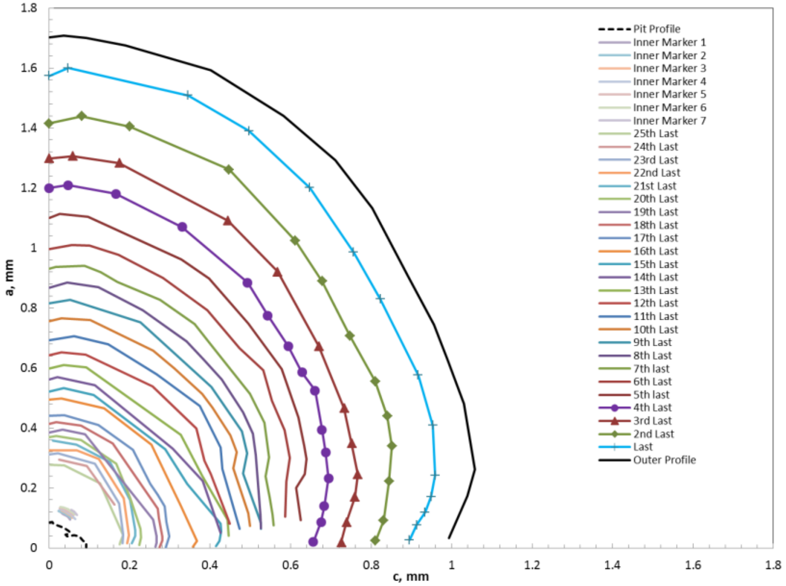


Corrosion Damage to Fatigue Test Development-Results

- **The measured and calculated crack lengths were compared using the marker bands from the fracture surface**
- **The fatigue crack initiation site was also determine and the corrosion pit roughness observed**







Corrosion Damage to Fatigue Test Development-Stress Ratio

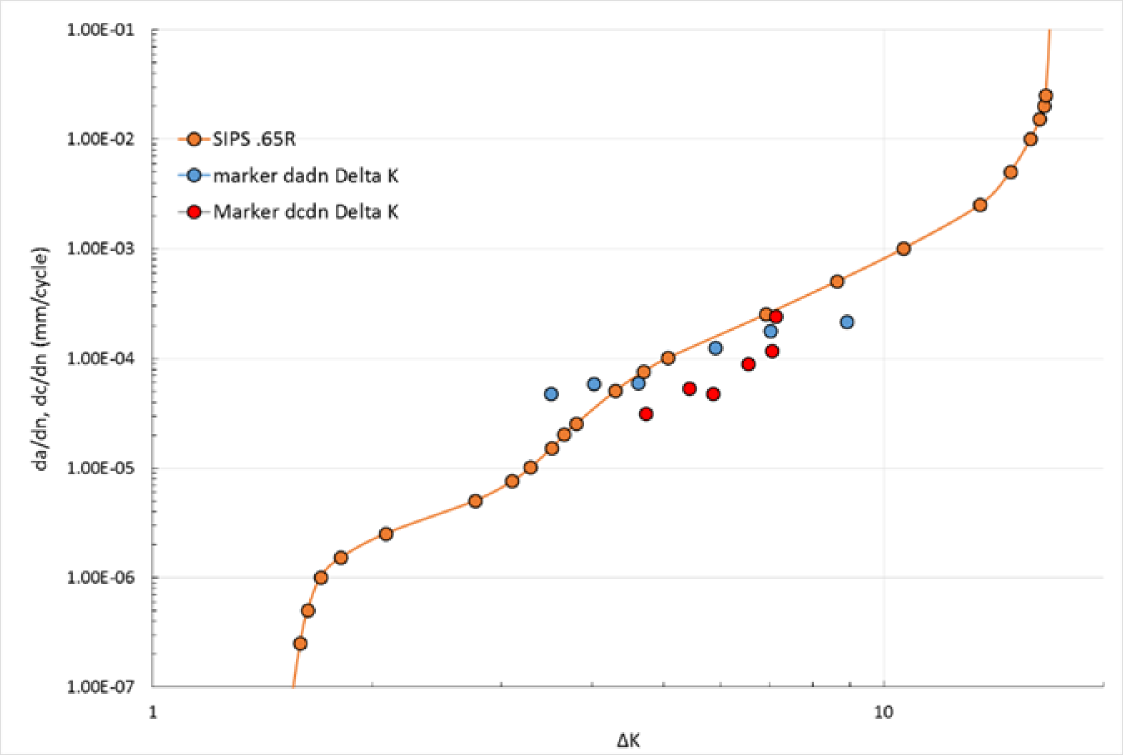
		Pit Dimensions		Periphery Crack Dimensions				
Max Remote Stress (σ)	**Stress Ratio (R)**	**a (mm)**	**c (mm)**	**a (mm)**	**c (mm)**	**Cycles to Periphery Crack**	**Total Cycles (1.5mm)**	**Nucleating Feature**
123.7	0.65	0.080	0.087	0.290	0.218	21,475	60,399	Micro-pit
124.2	0.65	0.113	0.122	0.284	0.181	27,600	50,523	Micro-pit
124.2	0.65	0.207	0.136	0.333	0.212	13,475	36,833	Micro-pit
127.5	0.10	0.117	0.108	0.230	0.181	2,545	9,504	Micro-pit
128.4	0.10	0.118	0.108	1.018	0.824	8,180	12,447	Micro-pit

- ***R*= 0.1 developed fully formed fatigue crack and grew to 1.5 mm faster than the *R*=0.65 tests**
- **The fatigue crack nucleating feature did not change based on stress ratio**

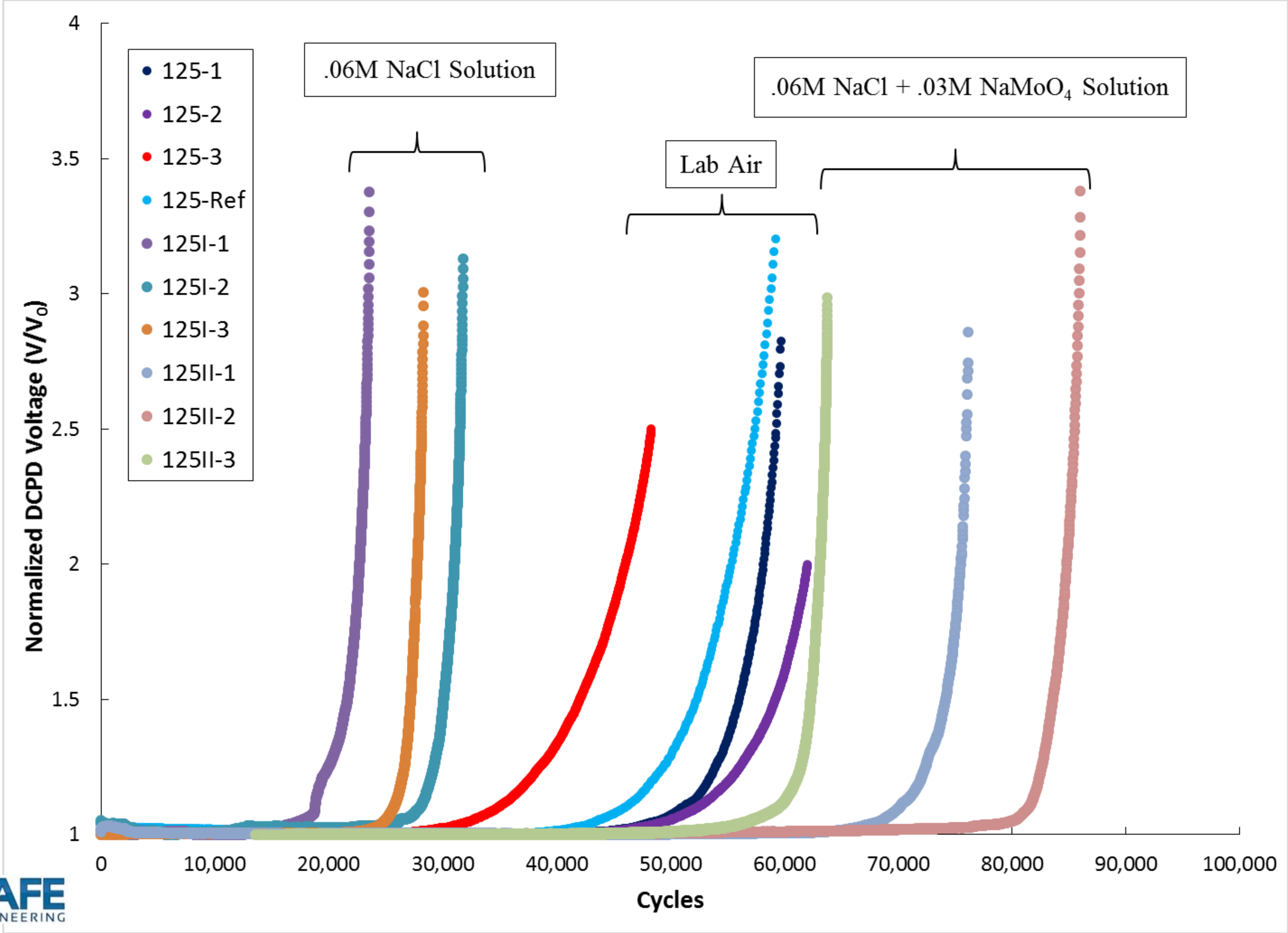
SAFE ENGINEERING

Corrosion Damage to Fatigue Test Development-Results

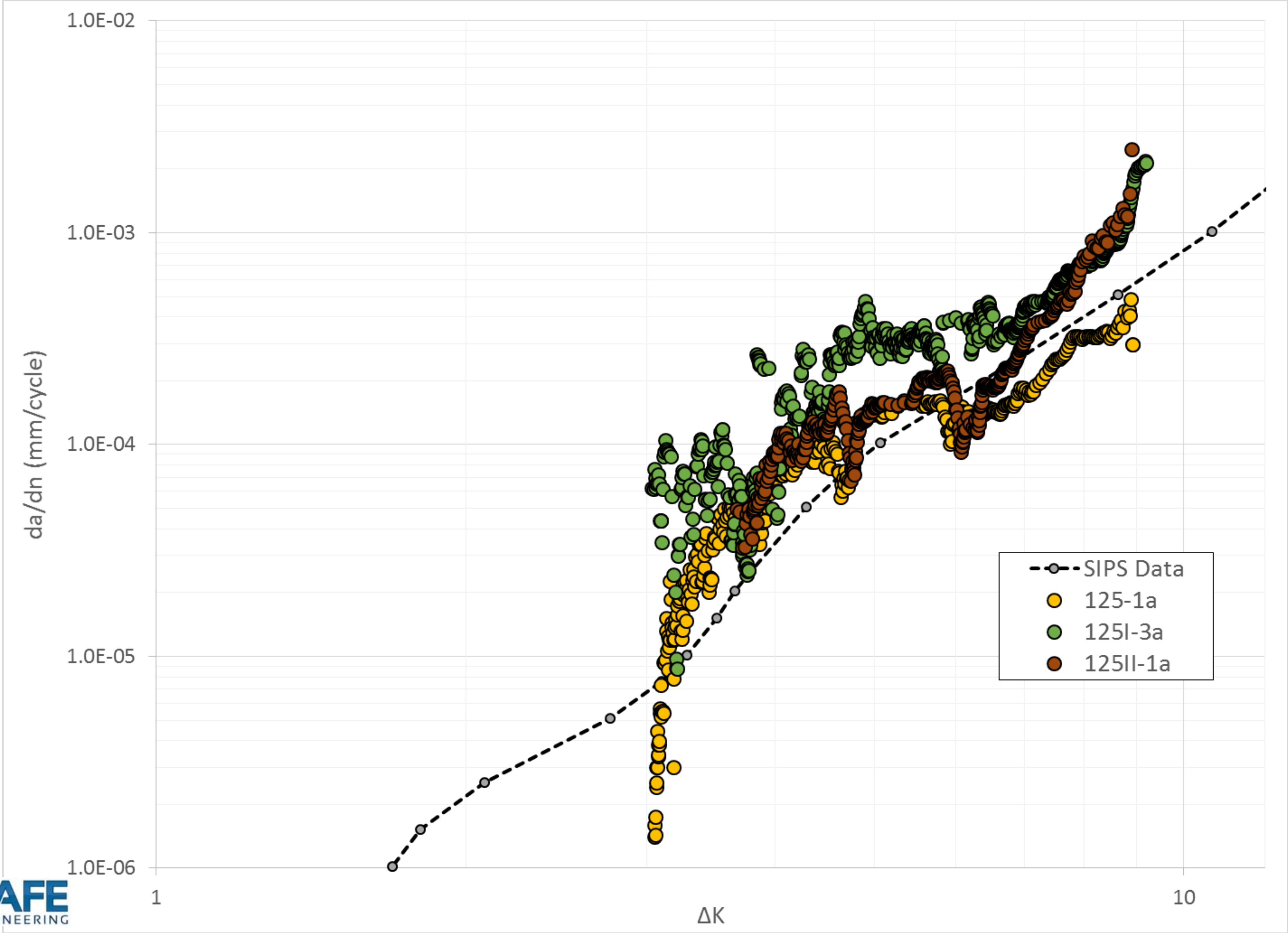
- **Crack growth rates were calculated from the measured crack dimensions using the incremental polynomial method using the Fawaz/Andersson solutions in AFGROW**
- **The *ΔK* values in the *a* and *c*-directions range from 1.2 to 12 MPa√m for all conditions tested**
- **The da/dN and dc/dN results were comparable with the published SIPS data for this AA7075-T651 plate being used for the study**



Corrosion Damage to Fatigue Test Development-Environmental Effects



Corrosion Damage to Fatigue Test Development-Environmental Effects



Summary

- Low solubility inhibitors (chromate & molybdate) have been shown to slow fatigue crack growth rates, but only below a ΔK=5 MPa√m at frequencies of 0.2 Hz
- New test methodologies for examining inhibitor effects have been designed using aircraft geometries and an understanding of atmospheric corrosion processes
- A standardized test method for studying the corrosion pit to fatigue crack transition using dcPD has been developed and validated
- The combination of these two test methods is moving forward to continue to expand the understanding of fatigue crack inhibition
- Current coating qualification methods fail to consider mechanical loading; test methodology to address this limitation has been designed and validated

Future Work

- Use the pit to crack transition fatigue methodology with coated samples under more complex environments
- Add other environmental factors including UV-light, ozone and temperature effects
- Integrate the crack growth rate data inhibitor and environment into AFGROW for better modeling and prediction capability
- Publish updated testing protocols related to the pit to crack transition sample

Acknowledgements

This research is funded by
OSD Corrosion Policy and Oversight Office (FA7000-11-2-0011)
ONR Science and Technology (N0001413C0113)

Research work is completed at the USAF Center for Aircraft Structural Life Extension

The U.S. Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon

This briefing, presentation, or document is for information only. No U.S. Government commitment to sell, loan, lease, co-develop or co-produce defense articles or provide defense services is implied or intended