Using Low Temperature Crack Growth Data in Crack Growth Analyses

11 September 2018

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Acknowledgements

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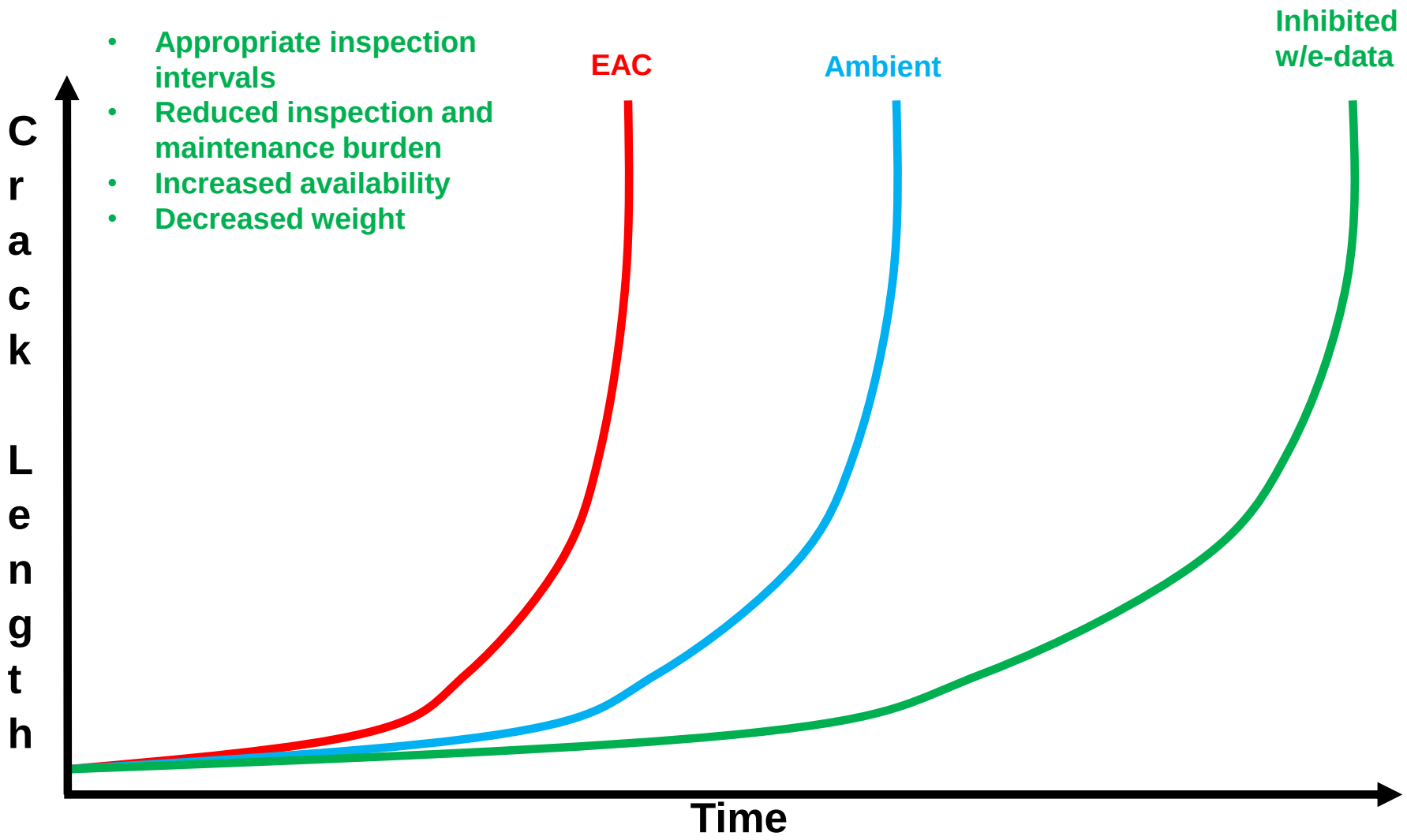
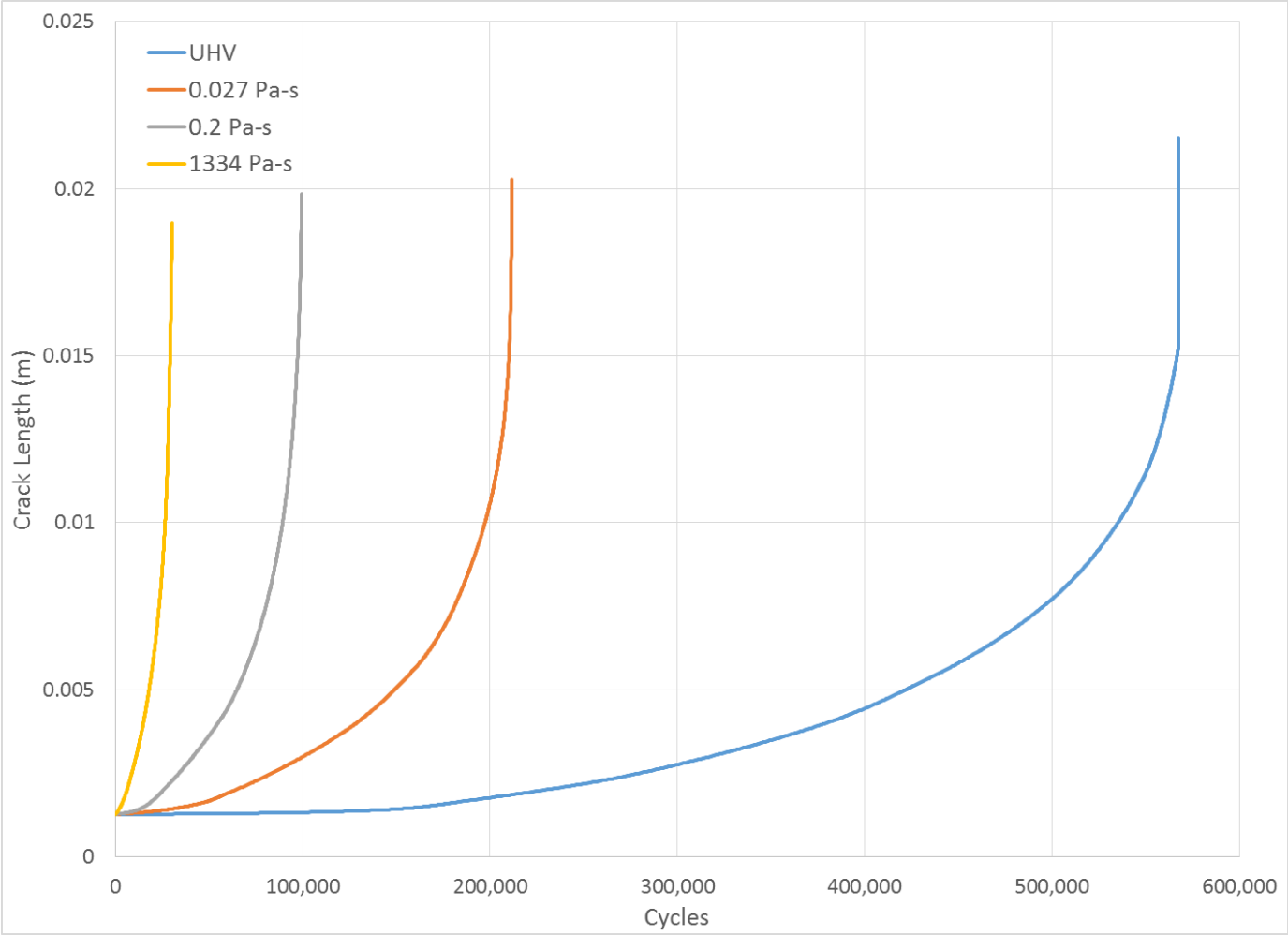
Motivation

- Appropriate inspection intervals
- Reduced inspection and maintenance burden
- Increased availability
- Decreased weight



Crack Growth as a Function of Exposure

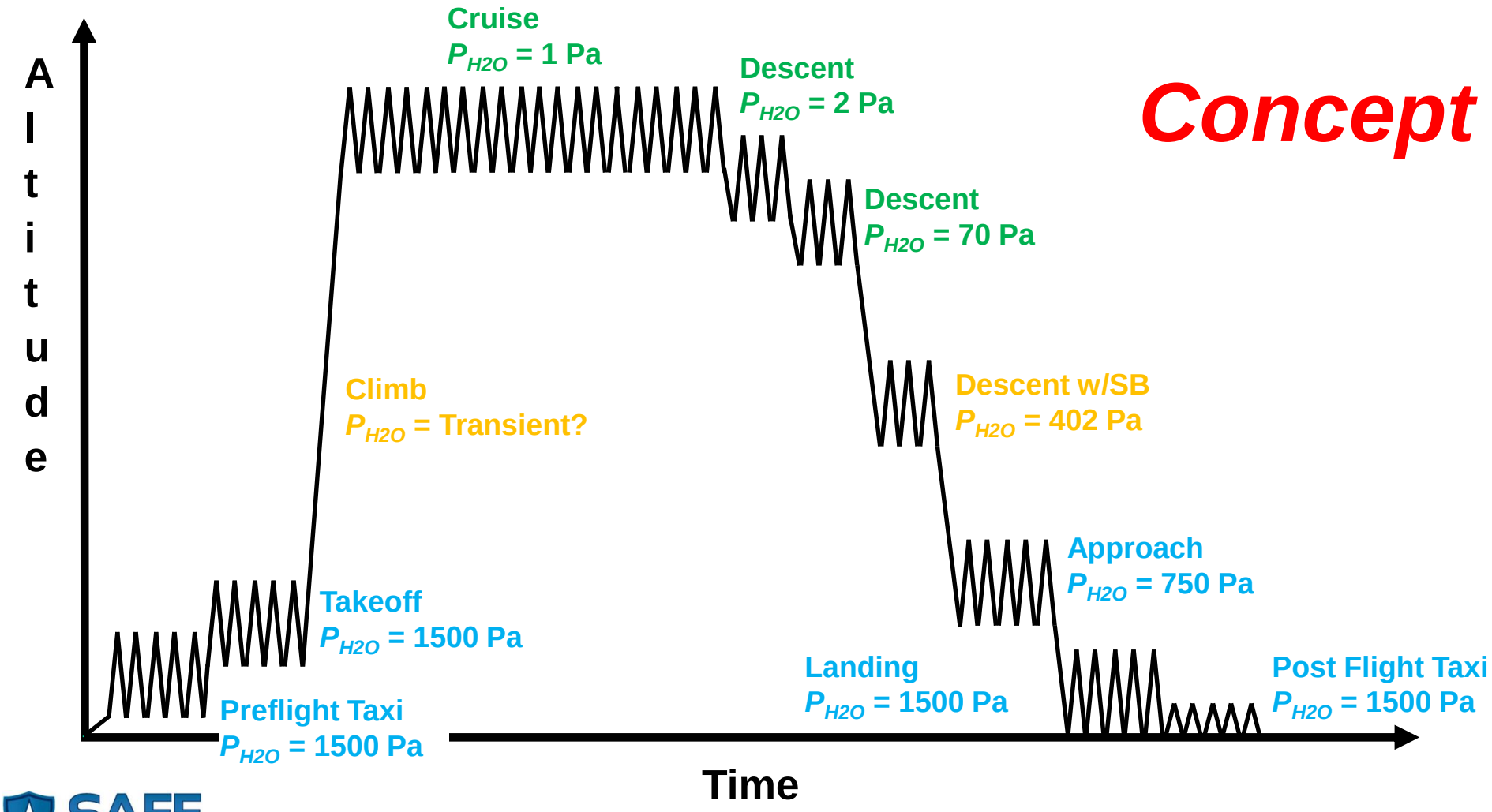
USAF Academy Center for Aircraft Structural Life Extension (CAStLE)



Jimmy Burns (UVa) crack growth rate data, 2012

Significant effect on fatigue life and inspection intervals

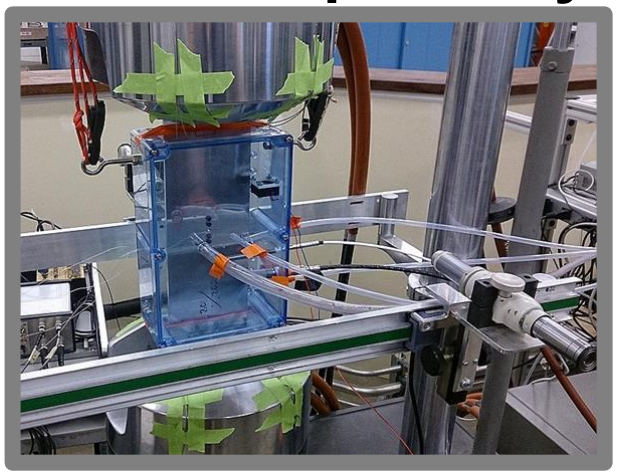
Crack Growth Rate Data by Mission Segment

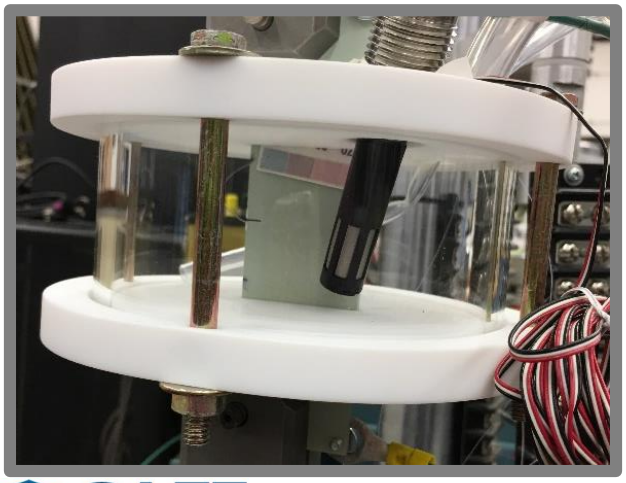


Concept

Environmental Chamber

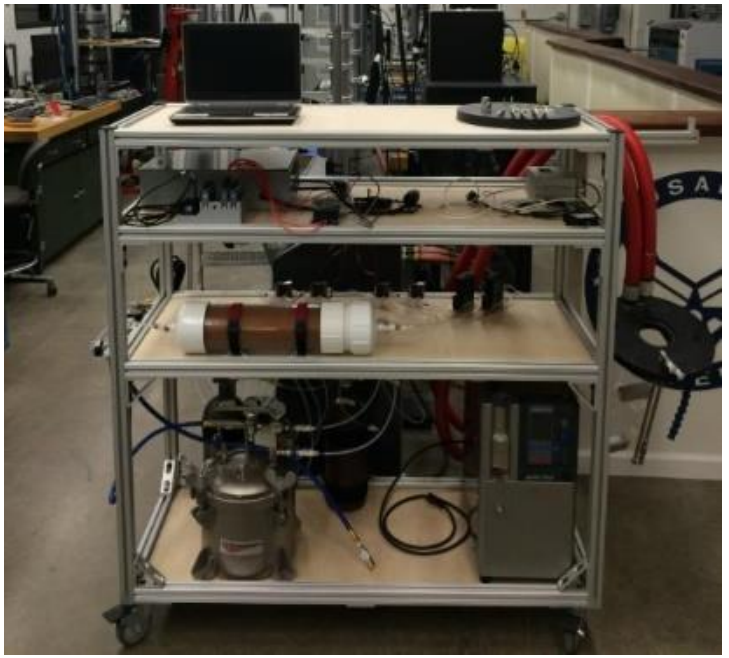
- **Environmental systems are modular**
  - **Adapt to any "chamber" (container for environment)**





Environmental Chamber

- **Cart contains systems for generating, monitoring, and controlling environment**
- **Environmental variables include:**
  - **Temperature**
    - **-60 to 150°C (-76 to 302°F)**
  - **Relative Humidity**
    - **0-100%: ± 1%**
  - **Ozone**
    - **30 ppb- 30 ppm**
  - **UV-light**
    - **UVA/UVC**
  - **Background gas/spray**



Crack Growth at Low Temperature

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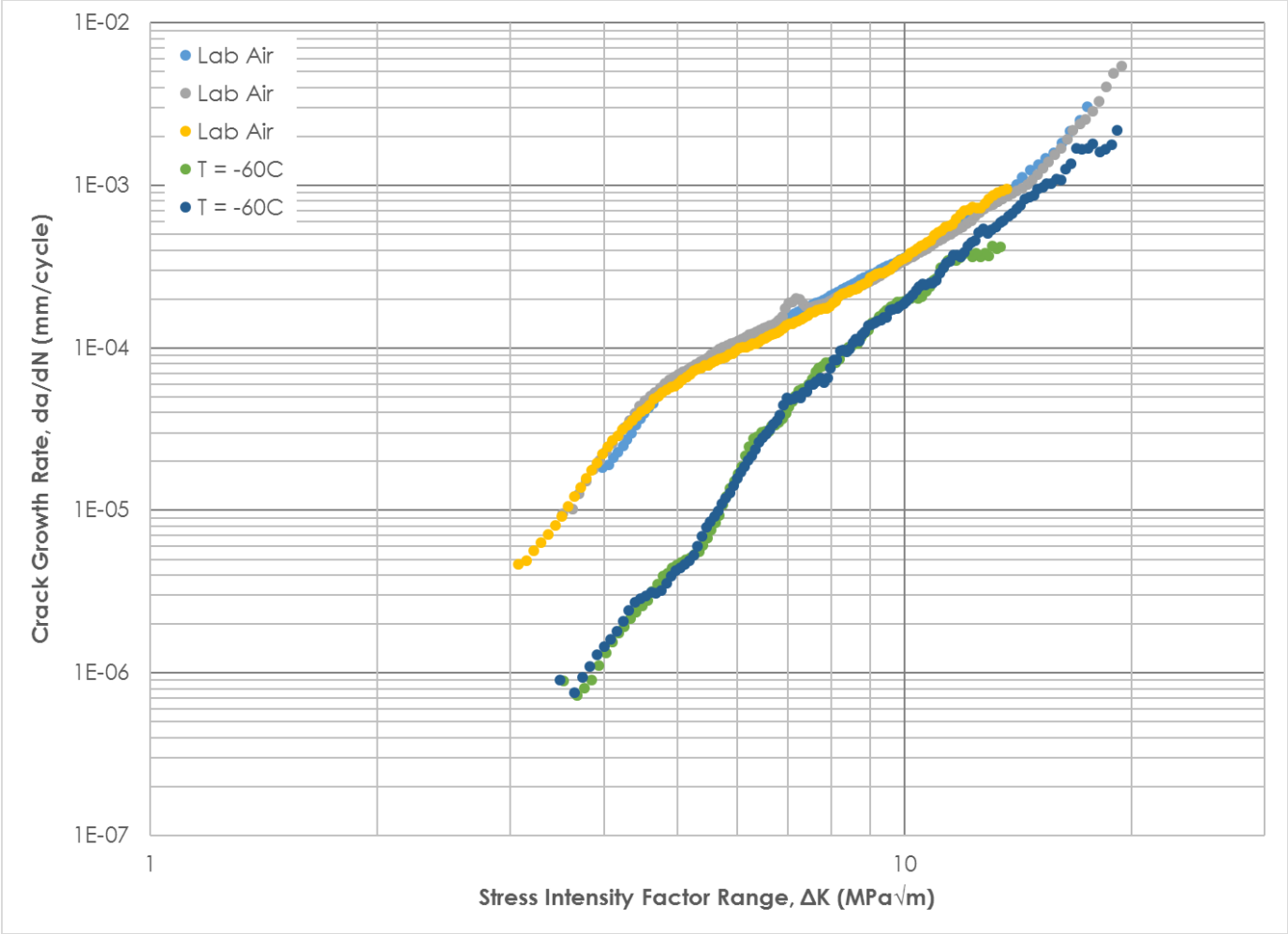

Future Work

- **Generate Environmental test data**
  - **Temperature**
  - **Relative Humidity**
  - **Ozone**
  - **UV**
  - **Mechanical/environmental spectrum effects**

Stress intensity factors of various size single edge-cracked tension specimens

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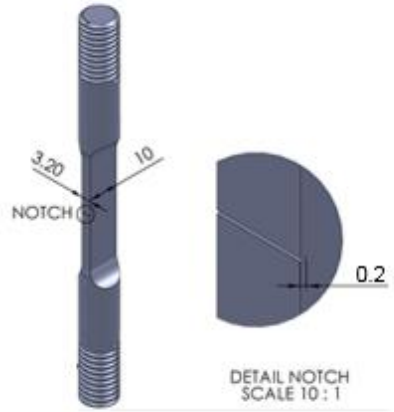
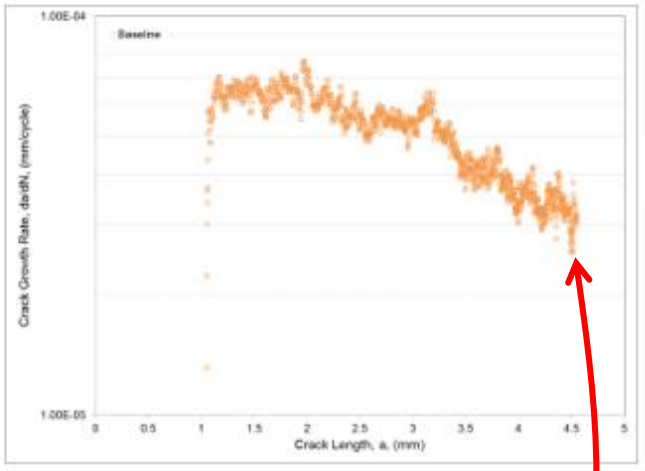
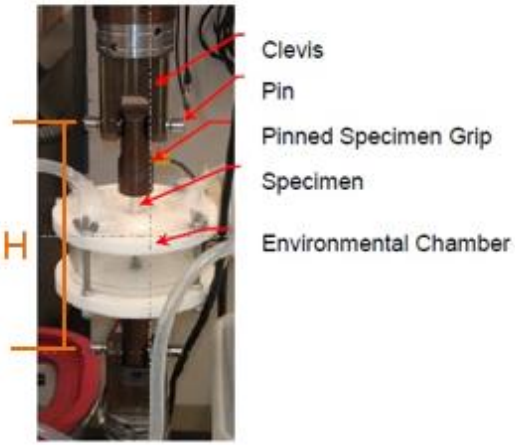
Motivation

- **Corrosion Fatigue Experiments**
- **Single Edge Notch Tension (*aka* SEN(T) or SE(T))**
  - **Pin/Pin BC**
- **Constant ΔK**
  - **K control test using FTA dcPD system**
    - **Tada K solution**
- **Large aspect ratio, H/W, to accommodate environmental chamber**







Crack growth rate is not constant as it should be

Investigating Decreasing FCGR with Increasing Crack Length

- SEN(T) design has been used for 15+ years for FCGR and SCC testing.
- With such extensive use, we did not expect any issues with the K solution.
- Hypothesized some or all of the below could be the cause
  - Notch geometry
  - Grip kinematics
  - Clevis pin size
  - Specimen manufacturing facilities
  - Machining techniques
  - Plate location
  - Spot-weld procedures
  - Electrical isolation with respect to dcPD system
  - Test laboratory and personnel
- After extensive testing, none of the above were the cause of the decreasing FCGR with increasing crack length.
  - SAFE-RPT-15-008 “Constant Stress Intensity Factor Tests using the FTA dcPD System,” 26 February 2015.

Investigating Decreasing FCGR with Increasing Crack Length (cont.)

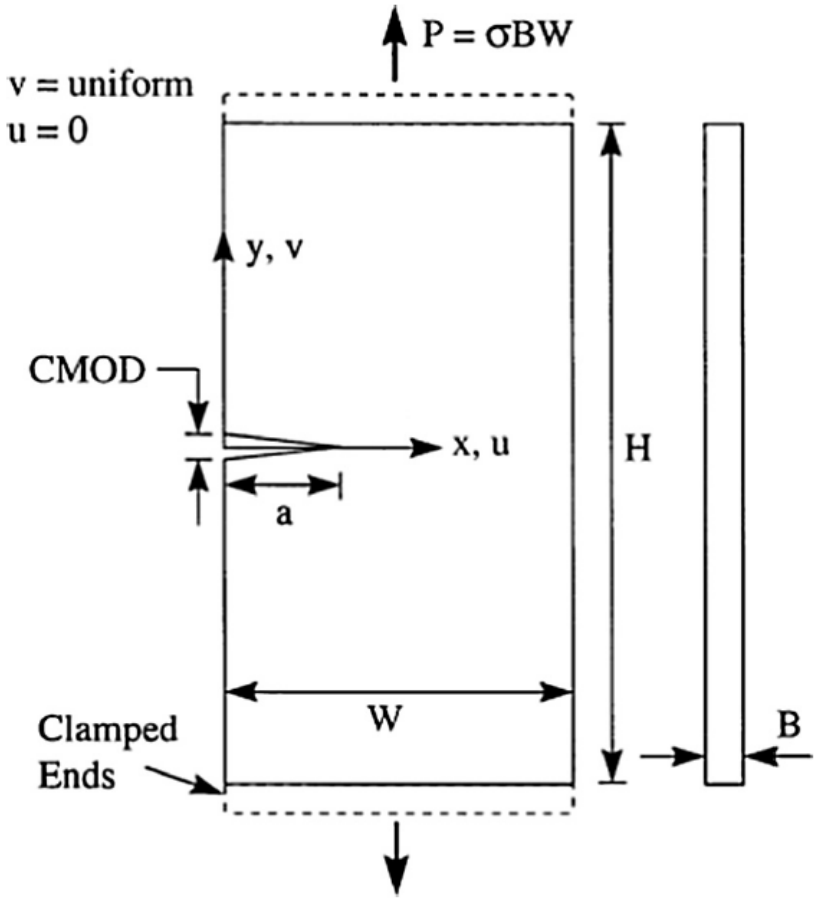
- After discussions with Dr. Borje Andersson, we hypothesized the large aspect ratio could result in a non-linear relationship between the applied load and K.
- Using the geometry and boundary conditions of our test setup, Dr. Andersson calculated K using the non-linear solution capability in STRIPE.
- Non-linear K's for a/W = 0.5 were 30% lower than the linear K solution.
- Conclusion:
  - FTA system using the Tada K solution is over-estimating K
  - Applied K is lower than target K because the K is incorrect
- Solution:
  - Easy to calculate all the non-linear K's needed
  - Difficult to implement non-linear K's in FTA system

Way Forward for Corrosion Fatigue Testing

- Use current specimen design, but do not use K control testing
  - Using load control does require a K calculation to control the test; thus issues with non-linear K's is not relevant.
- Change specimen geometry or boundary conditions
  - Extended Single Edge Notch Tension, ESE(T)
  - SEN(T) clamped/clamped
    - After experience with SEN(T) pinned/pinned, we evaluated K for geometries relevant to corrosion fatigue testing which require large H/W due to the environmental chamber

Background

- **Current stress intensity factor solutions (*K*) for the Modified Single Edge Tension, MSE(T), specimen do not account for finite height effects**
  - **Clamped ends**
    - **No rotation or lateral contraction**
  - **No compression in uncracked ligament**
  - **Non-uniform stress distribution for**
    - **small aspect ratio (H/W) plates**
    - **large crack lengths**



Analysis

- **StressCheck®**
  - **2D, plane stress, linear elastic constitutive model, Poisson's ratio, $\nu = 0.33$**
  - **Automatic K extraction using contour integral method**
  - **Degrees of freedom ranged from 78 - 274K**
    - **Tetrahedral elements, $p = 8$**
- **Analysis Space**
  - **$0.01 \leq a/W \leq 0.975$**
  - **$0.8 \leq H/W \leq 10.0$**

Benchmarking

- **Compare Tada pinned/pinned solution to current FEA results**

$$\beta(a/W) = \sqrt{\frac{2W}{\pi a}\tan\left(\frac{\pi a}{2W}\right)} * \frac{0.752 + 2.02(a/W) + 0.37\left(1 - \sin\left(\frac{\pi a}{2W}\right)\right)^3}{\cos\left(\frac{\pi a}{2W}\right)}$$

  - **Tada H, Paris PC, Irwin GR. The stress analysis of cracks handbook. Hellertown, Pa., USA: Del Research Corporation; 1973.**
  - **Reported accuracy is 0.5% for any a/W**
  - **H/W ≥ 2.0**
- **StressCheck®**
  - **H/W = 20.0**
  - **Degrees of freedom ranged from 104 - 177K**

Benchmarking - Results

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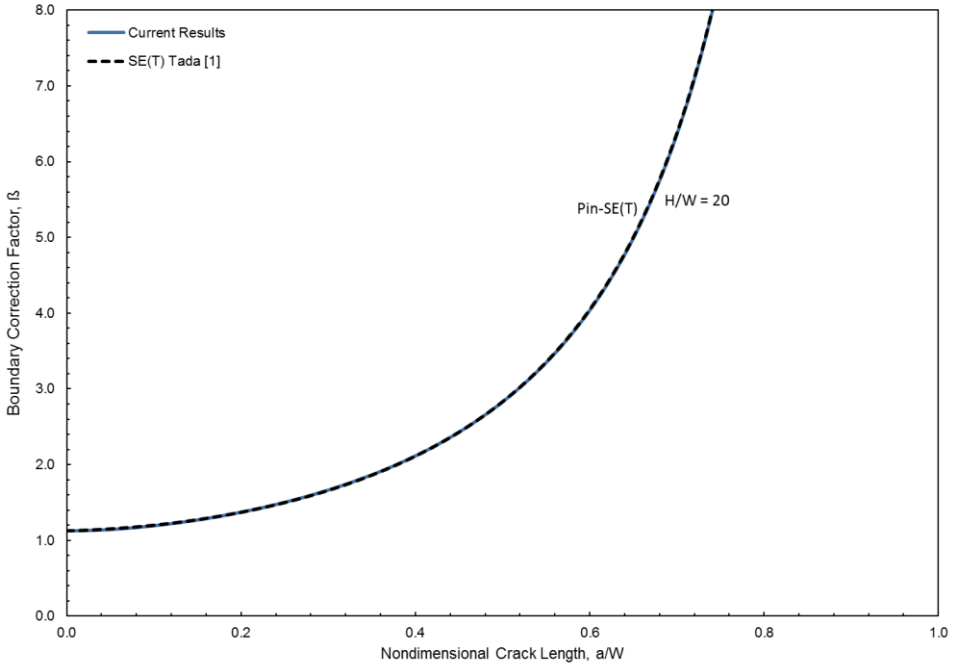
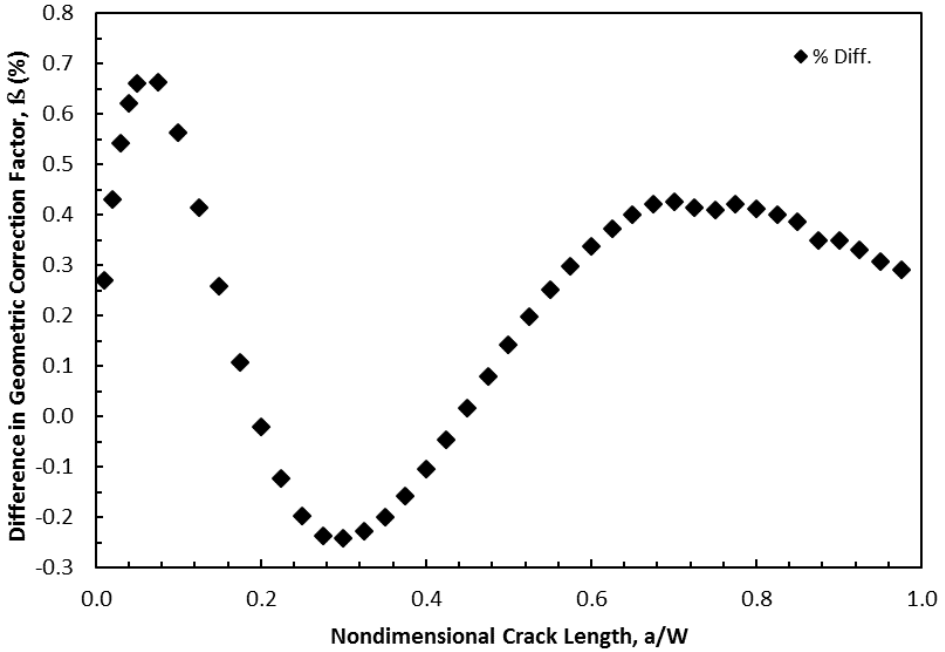
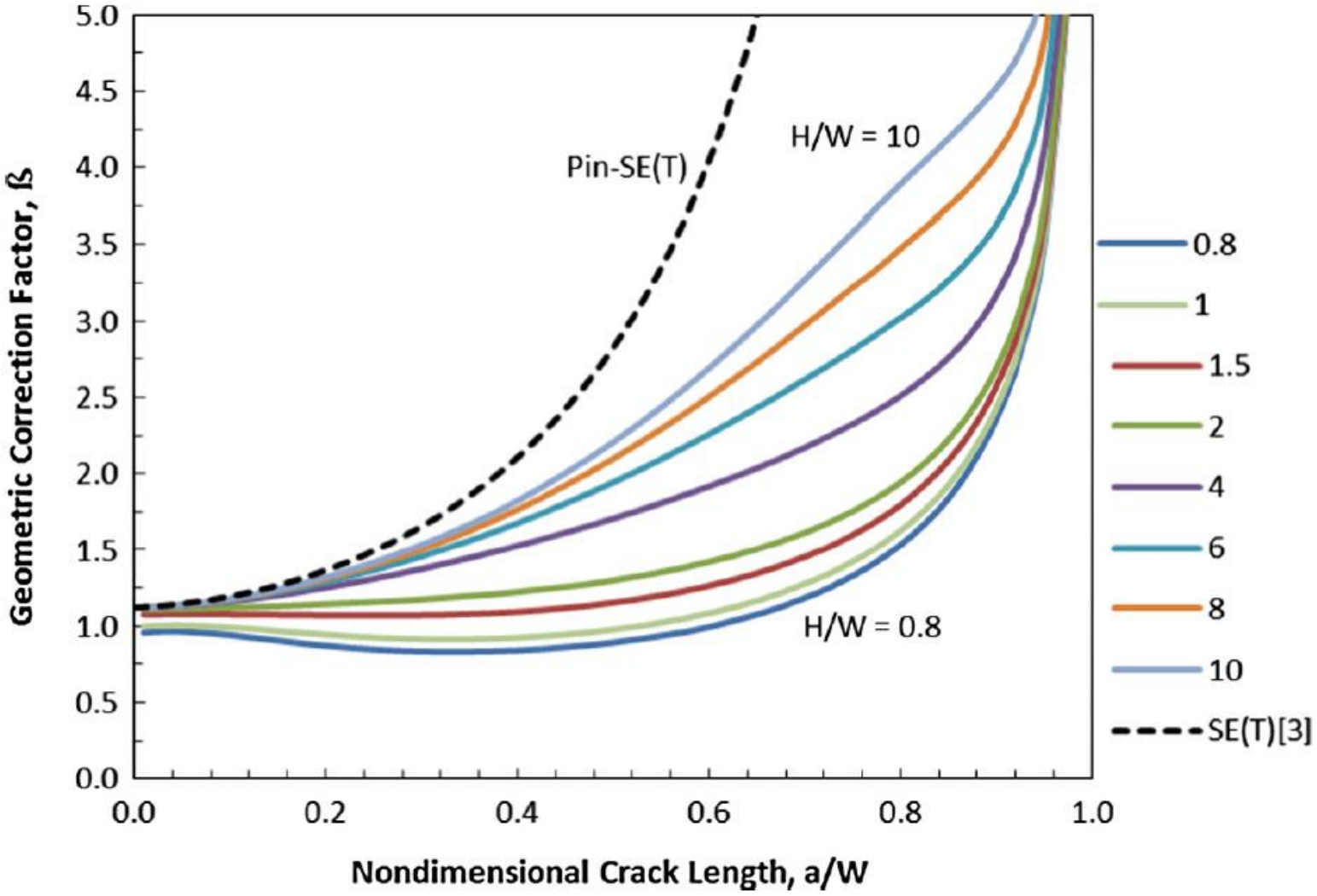
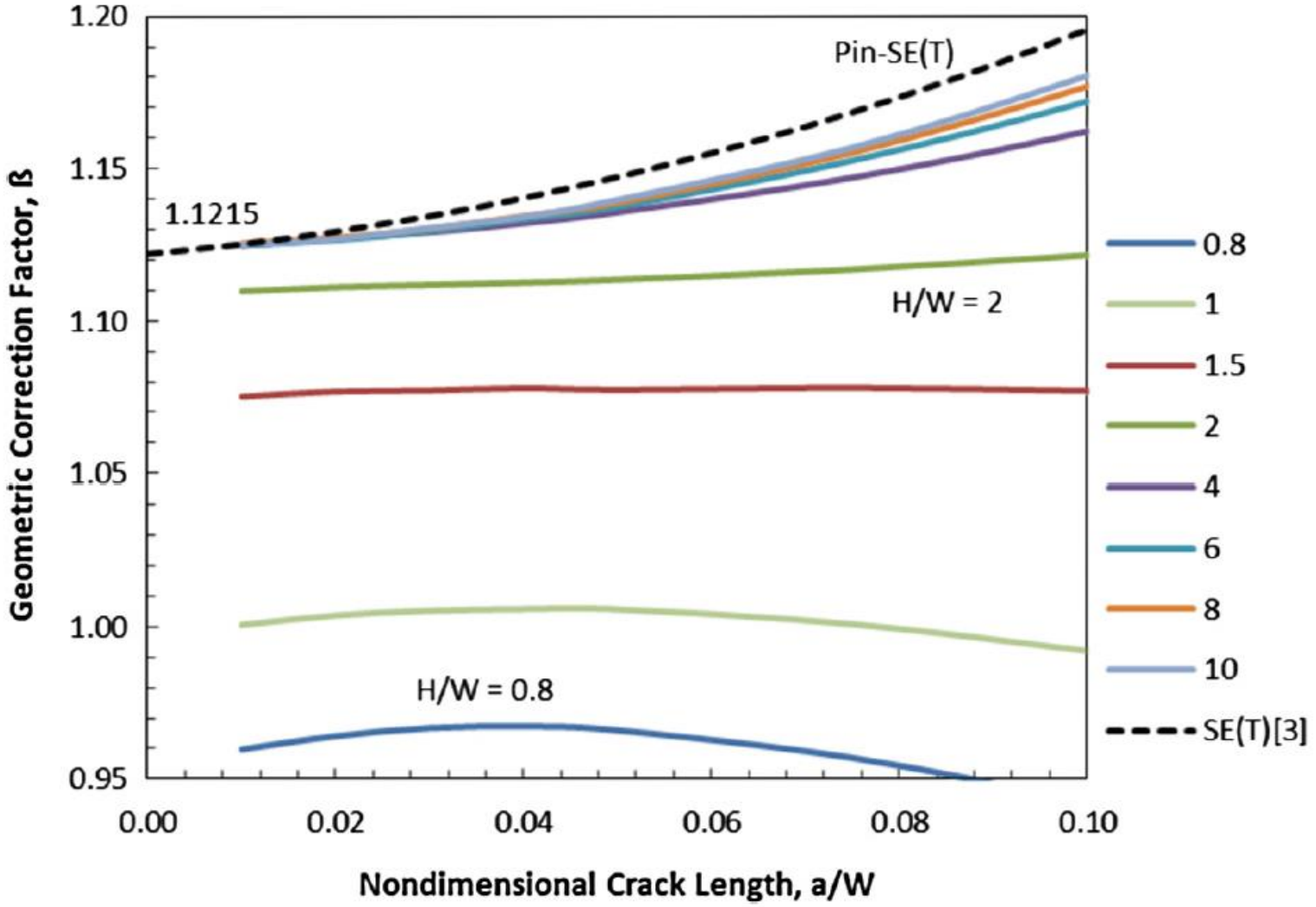




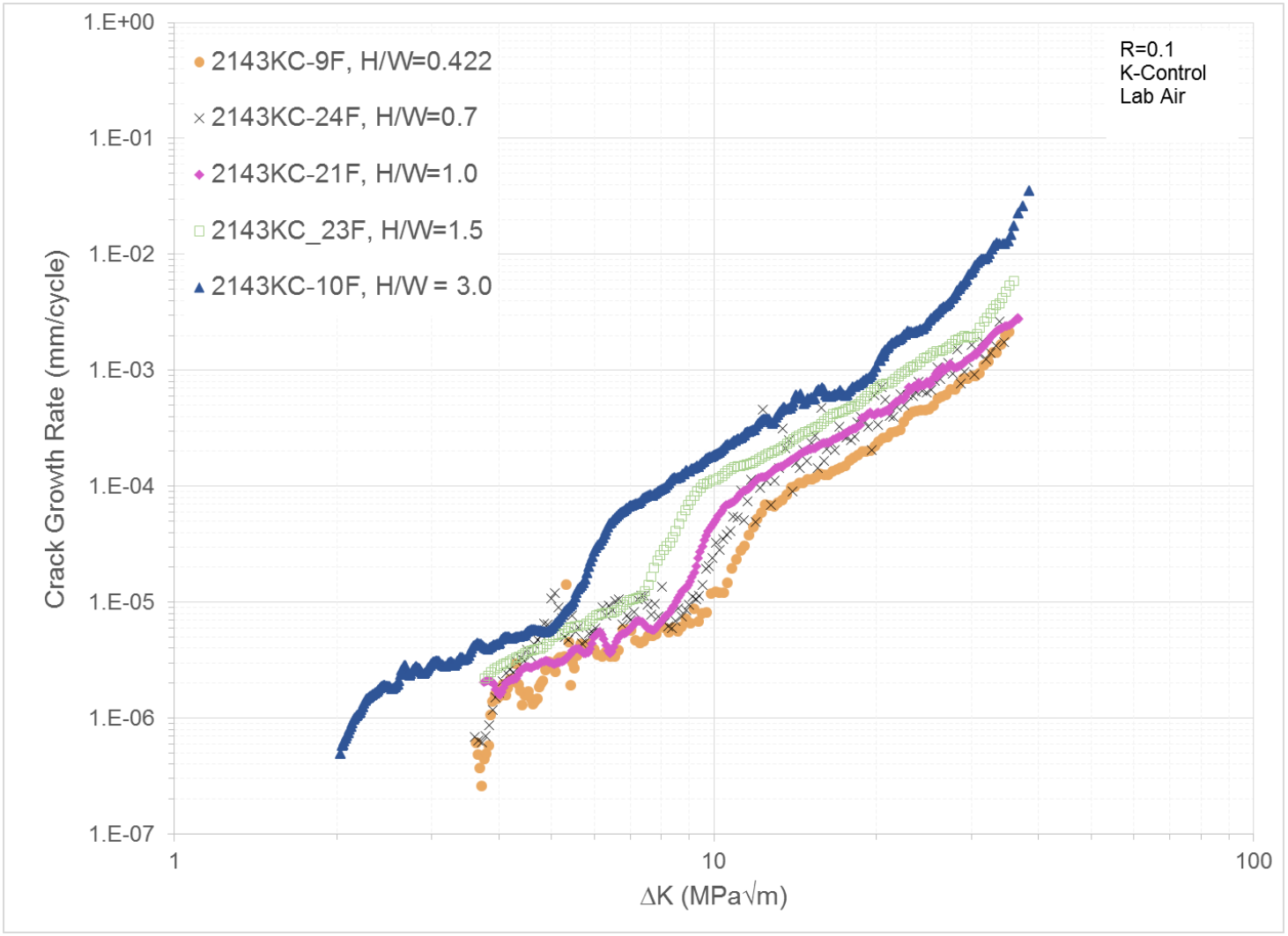
New FEA Results – Effect of H/W



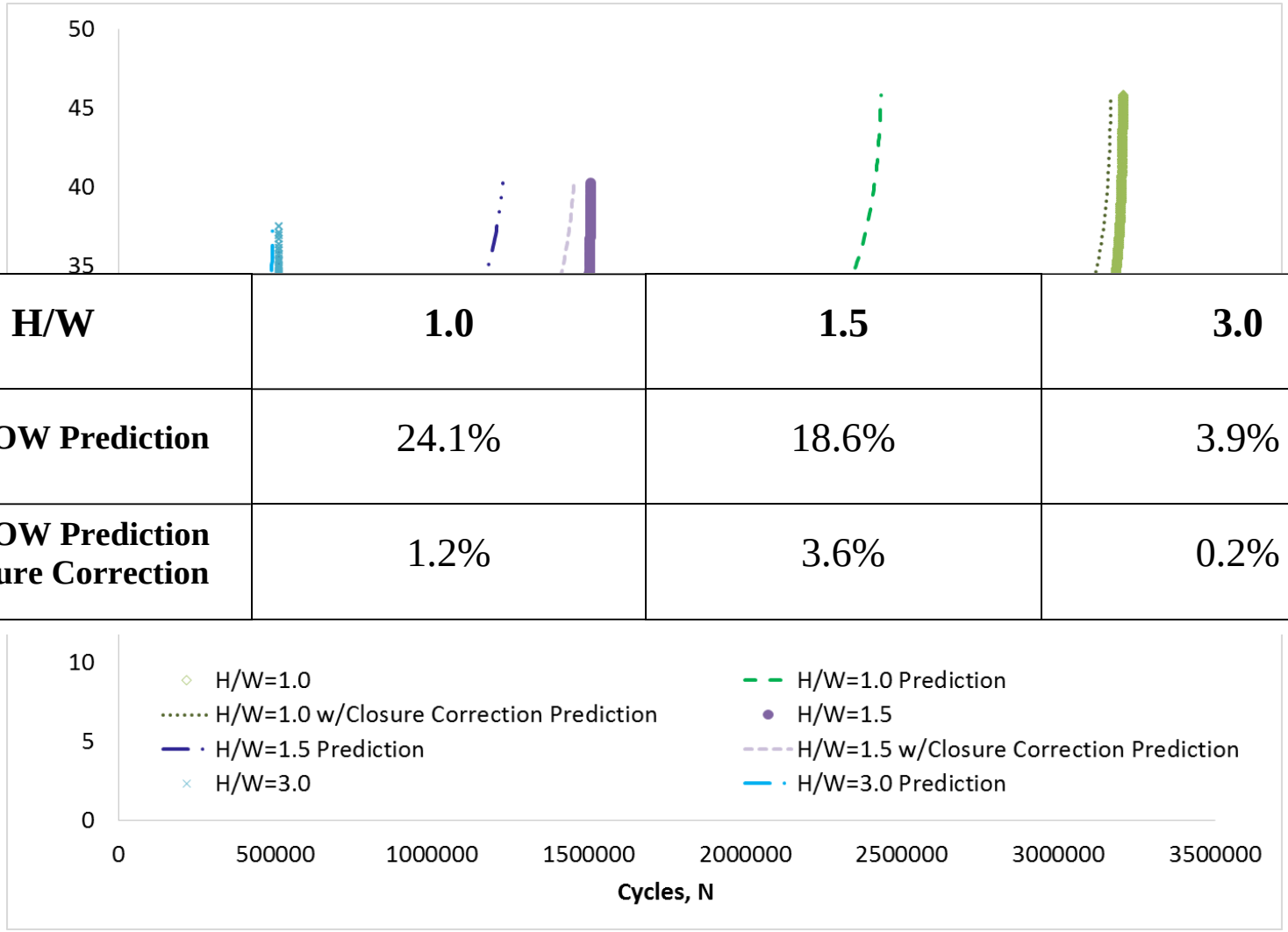
New FEA Results – Small H/W



Test Results – Effect of H/W



Predictions



H/W	1.0	1.5	3.0
AFGROW Prediction	24.1%	18.6%	3.9%
AFGROW Prediction w/Closure Correction	1.2%	3.6%	0.2%

Conclusions

- **Identified K solution inaccuracy for SEN(T) specimens with pinned/pinned boundary conditions and large H/W.**
- **Developed new K solutions for MSE(T) clamped/clamped specimens**
- **Alex implemented new solutions in AFGROW**
- **Validated new K solutions for several H/W**
  - **New K solutions over-estimate K → *conservative***
  - **Using closure correction, β_R, correlation to test is within 4%**
  - **Used NASGRO database for 7075-T651 L-T**
    - **Perhaps rate data for this lot/batch of material would produce different correlation results?**

Hammond, Matthew, J. and Scott Fawaz. (2016). "Stress intensity factors of various size single edge-cracked tension specimens: A review and new solutions." Engineering Fracture Mechanics 153; pp. 25-34.