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# The Crack Wants What It Wants

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# Abstract


- Changes in constrain, particularly at/near surfaces, are known to change the stress intensity and crack shape. This behavior is often referred to as surface "pinning". Observed differences between predicted and experimental behavior have resulted in various factors applied to the calculated stress intensity factor. Most notable is the crack closure factor developed by Newman that is included in many of the NASGRO stress intensity solutions and was recently added as an option in AFGROW. With the advent of multi-point fracture mechanics, which allows crack shapes to evolve based on many discrete points along the crack front, mismatches between predicted and experimental crack shapes still persist. This presentation will discuss an investigation that was undertaken to understand the primary factors driving the observed differences, define an initial approach to incorporate these differences, and compare to available experimental data.

# Agenda

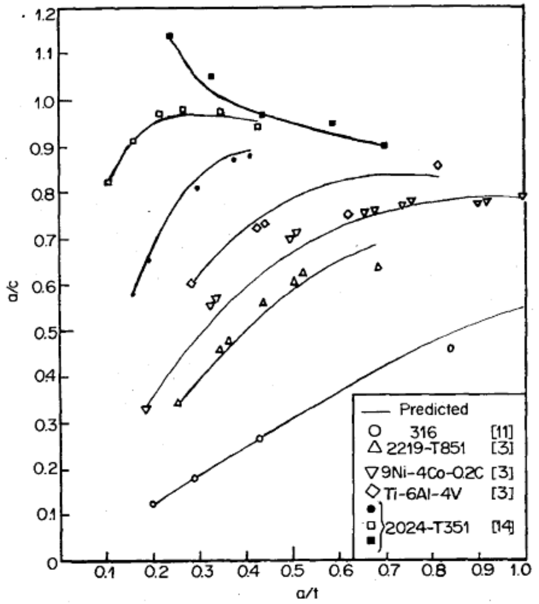
- ❑ Background
- ❑ Previous Studies
- ❑ BAMF Initial Implementation
- ❑ Comparisons to Observed Behavior
- ❑ Next Steps

# Background

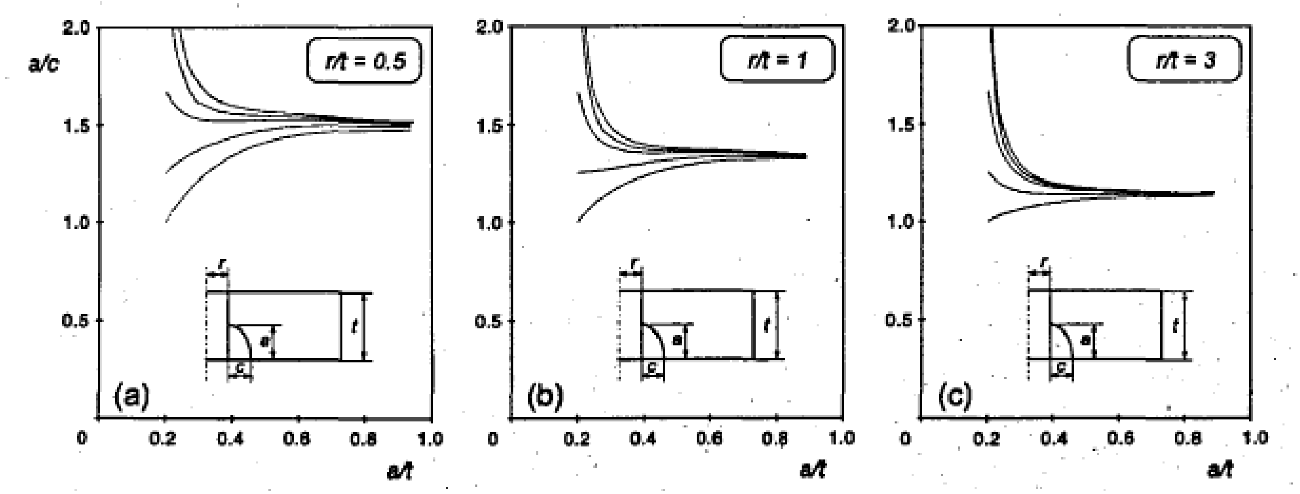
- For corner cracks at a hole, accurate characterization of crack shape and aspect ratio has been problematic for both AFGROW and BAMF
- Round Robin results (ERSI and AFGROW) have demonstrated the need to understand the underlying discrepancies and update the analysis approach
- Investigations into multi-direction material properties have resulted in mixed results
- Recently, SwRI researched the potential use of the crack closure factor for A-10 damage tolerance analyses
- One recommendation from this investigation was to perform a study utilizing a correction factor in BAMF to understand effects over the entire crack front
- As a result, Hill Engineering investigated discrepancies between naturally occurring crack profiles and analytical crack evolution

# Previous Studies – Equilibrium Crack Aspect Ratio (AFGROW 2011)

- **Cracks tend to grow to an equilibrium crack aspect ratio trend[1,2]**
  - Studies based on open hole tests, tension loading
  - Function of material (Paris exponent), and hole radius/thickness ratio




Crack aspect ratio variation for surface cracks, tension loading, various starting aspect ratios [Ref 1]




Example: Numerical prediction of crack aspect ratio variation for corner cracks at a hole, tension loading, various starting aspect ratios [Ref 2]

# Previous Studies – Equilibrium Crack Aspect Ratio (AFGROW 2011)

## Crack Aspect Ratio, Cont.

### Carlson/Pilarczyk Theses

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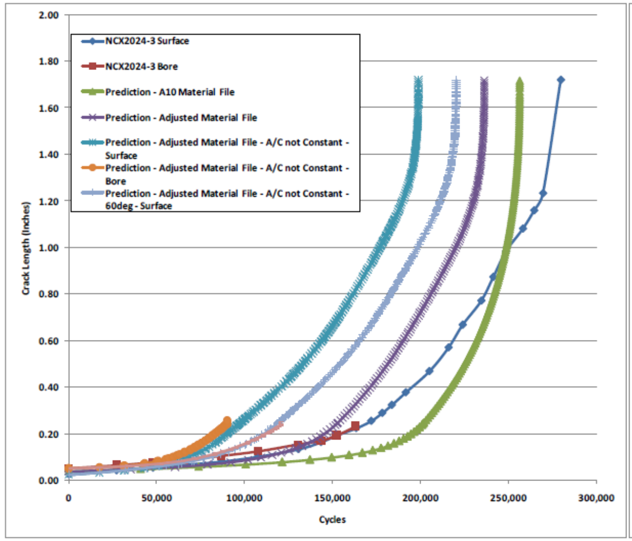
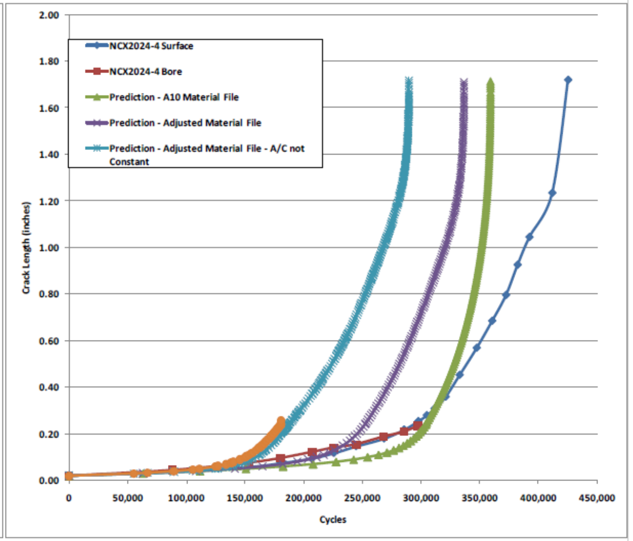
- A/C Constant, Avg. IFS Predicts 82% of Tested Life
- A/C ≠ Constant Predicts 70% of Tested Life

- Test Parameters
  - 2024-T351 Plate
  - W=4”, t=0.25”, B=2”, D=0.5”
  - CA, R=0.1, Max Stress = 10ksi

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## Crack Aspect Ratio, Cont.

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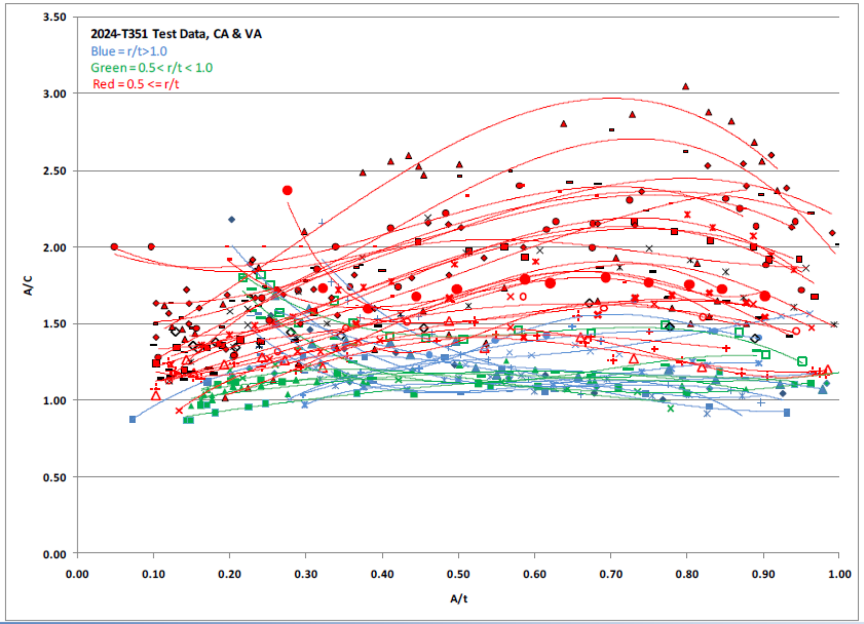
- Equilibrium Crack Aspect Ratio, Cont.

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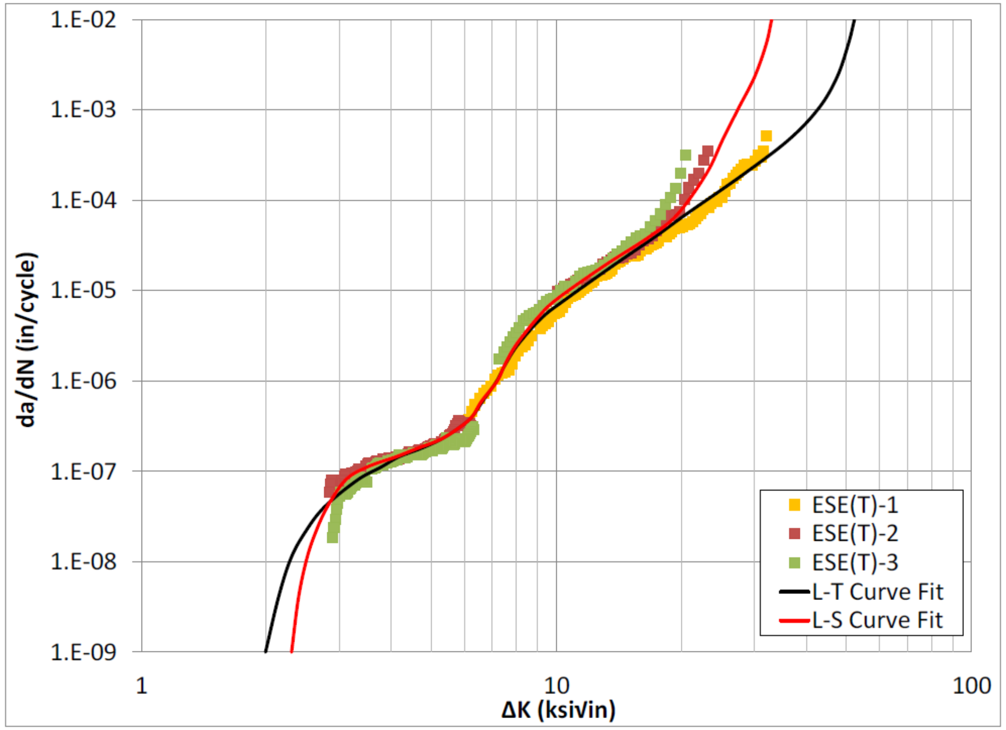
# Previous Studies – ‘a’ Crack Tip Material Properties (AFGROW 2015)

## Curve Fit of Test Data: 2024-T351 | R=0.1

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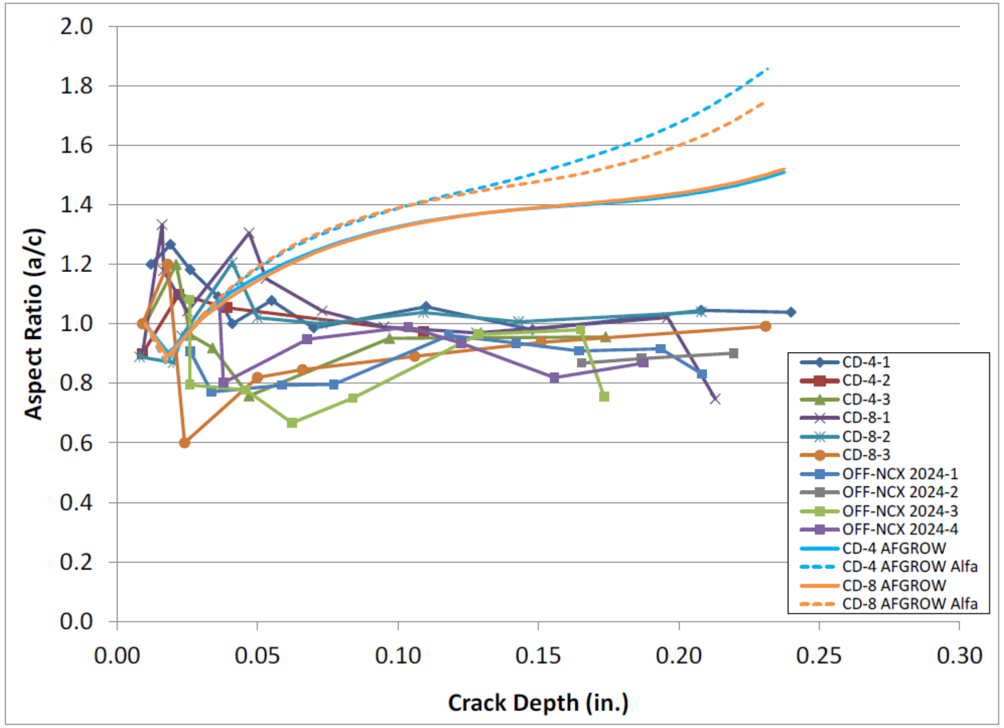
## Aspect Ratio Comparisons: 2024-T351, CA

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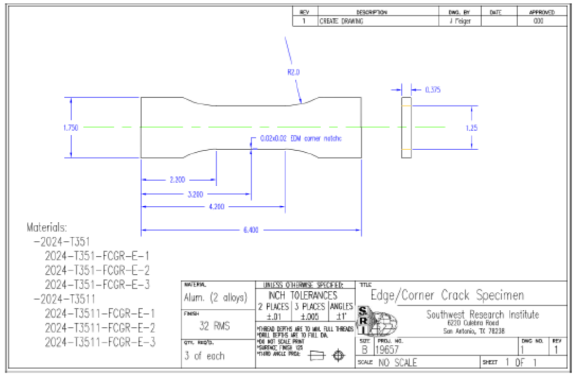
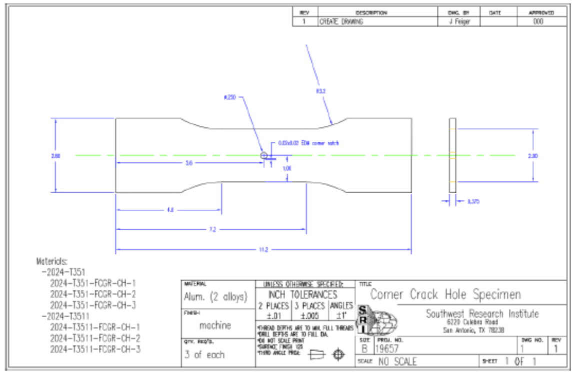
# Previous Studies – Corner Crack Rate Data Dev. (AFGROW 2017)

## Description of corner crack testing

- All procedures follow E647, with two non-standard specimens

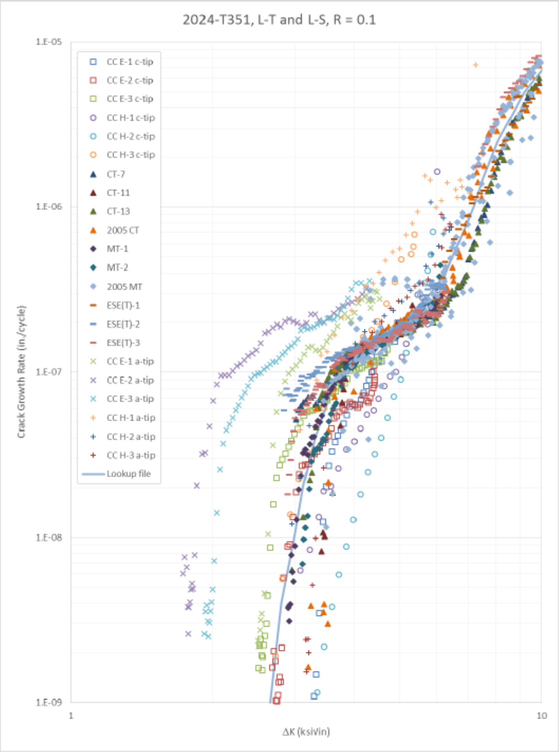


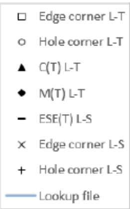

- R = 0.1 and -0.3
- Load shedding controlled by DCPD
  - C = -4 $in^{-1}$ $(0.035 < -C (K_{max,i} / \sigma_y)^2 < 0.097)$
  - Pre-test assumption of aspect ratios for a-tip K input
  - Post-test correction of applied K for da/dN-ΔK curves



## Test results: T351 L-T and L-S, R = 0.1



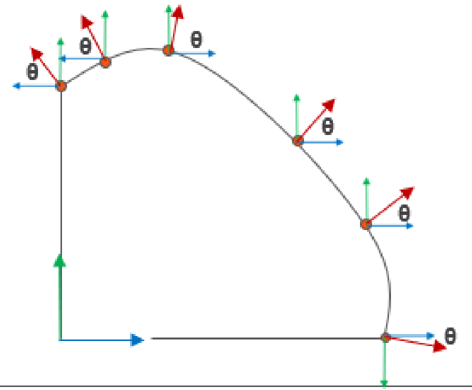

- L-S (a-tip and ESE(T)) data shows lower threshold than L-T (c-tip, C(T), and M(T)) data
- L-S data shows faster rates than the AFGROW lookup file
  - Potential for improved accuracy in corner crack aspect ratios

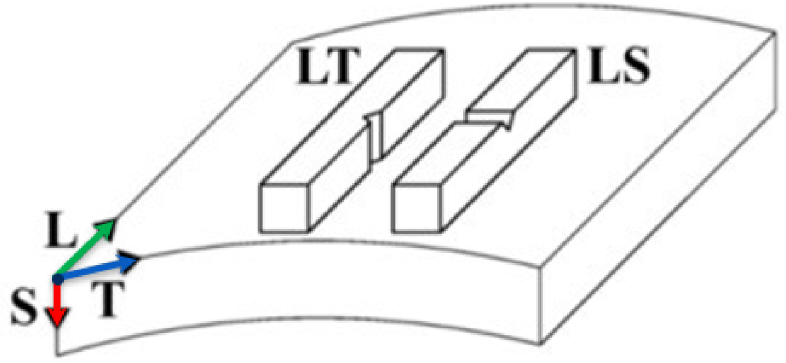


# Previous Studies – Multi-Directional Material Prop. (AFGROW 2019)

## BAMF Implementation

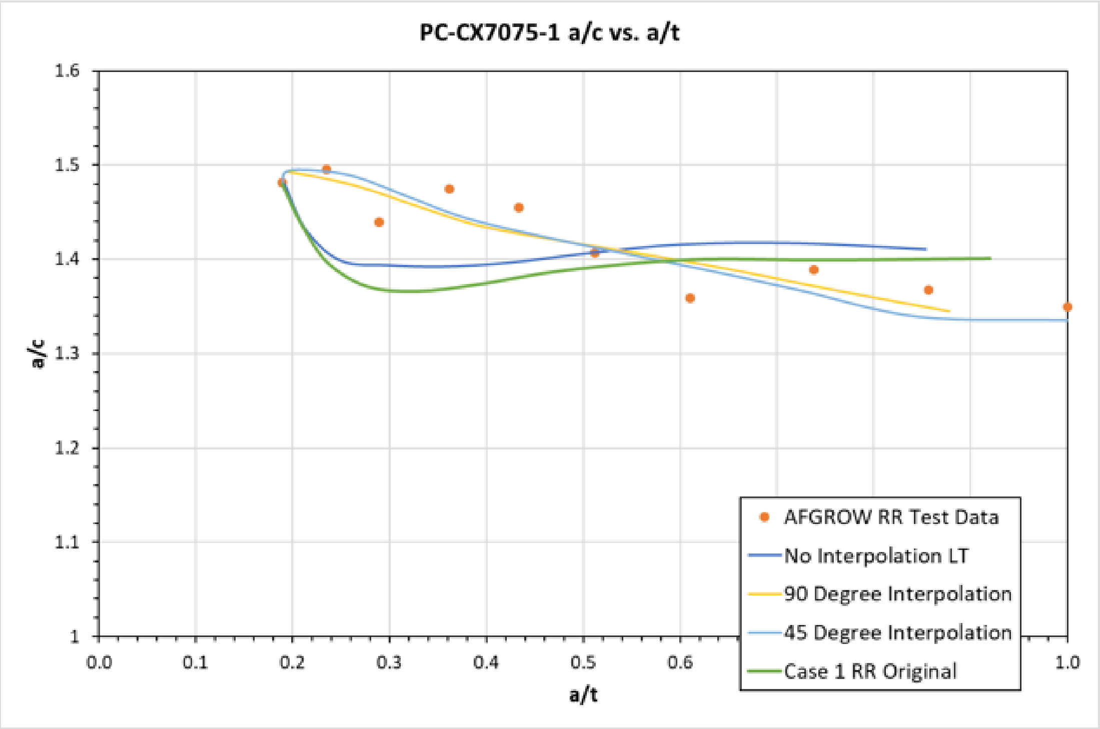
- **Approach**
  - Definition of material orientations on solid model
    - This is based on the local nucleation system of the crack
    - If the c-direction is the x-direction on the local nucleation system no value needs to be defined
  - Angle is based on angle used for growth direction
  - Functions for interaction (angles in degrees)
    - ISPredictManage.SetCrackDirectionParameter("Crack " & k, "P" & i, "angle", Mat_Dir_Angle(0, k, i))

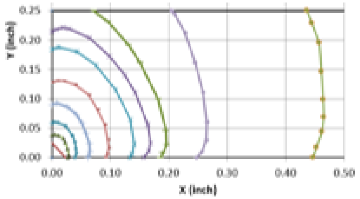


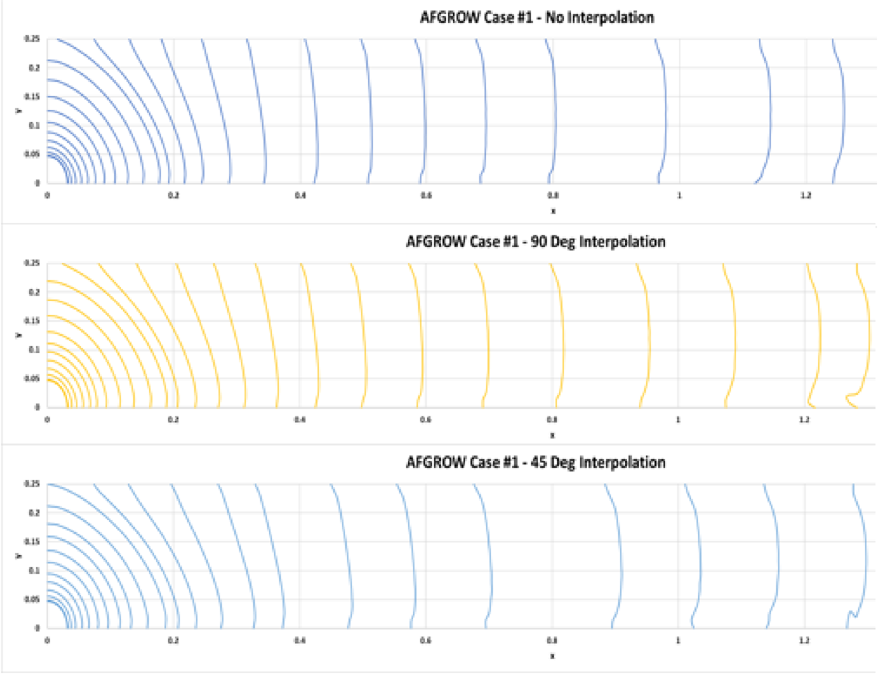



# Previous Studies – Multi-Directional Material Prop. (AFGROW 2019)

## AFGROW RR Case 1

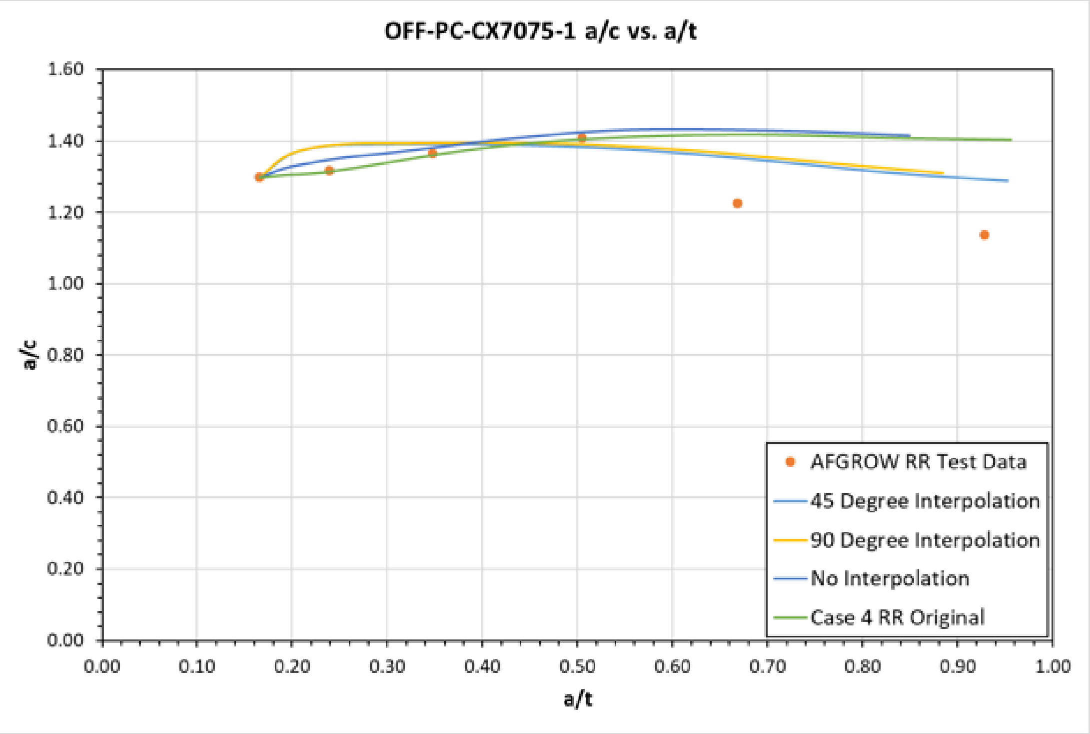


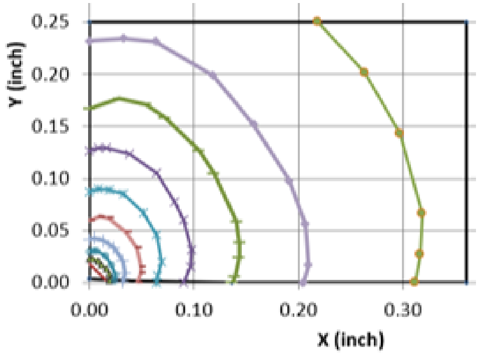



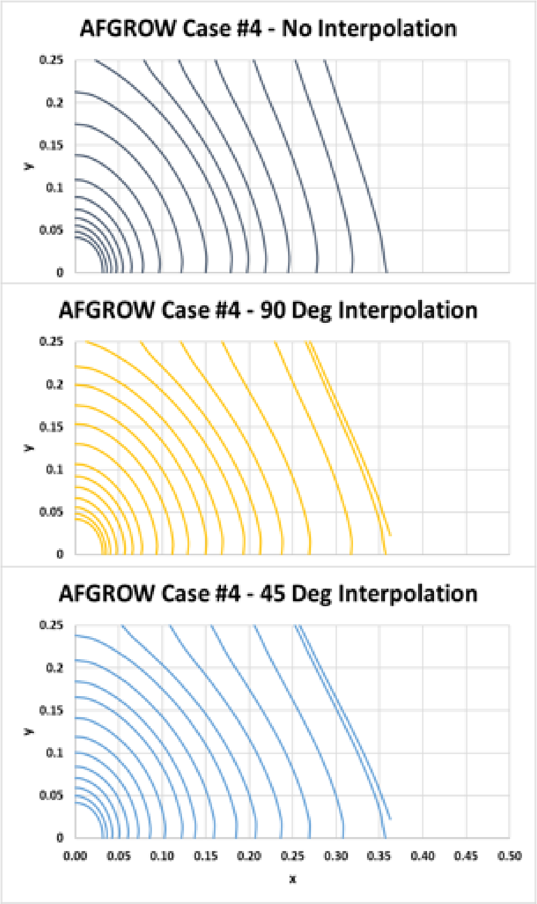



# Previous Studies – Multi-Directional Material Prop. (AFGROW 2019)

## AFGROW RR Case 4



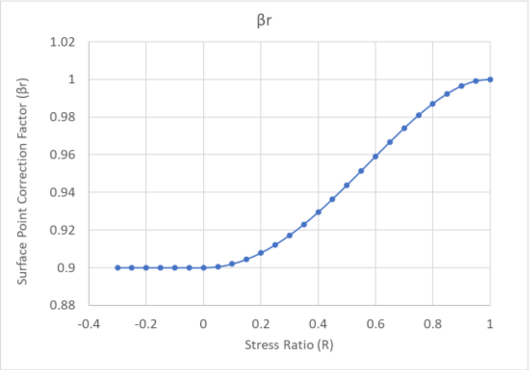
# Previous Studies - Summary

- **Crack aspect ratios**
  - General trends are observed as a function of r/t and material
  - Allowing a/c to vary in analyses does not result in predictions similar to observed behavior
- **Multi-directional material properties**
  - Mixed results indicate other factors are driving observed differences in predicted vs. experimental behavior
  - Many instances result in predicted a/c matching experiments; however, lives are overpredicted and crack shapes are still not correct
- **What are we missing?**

# Crack Closure

- **SwRI investigated the AFGROW implementation of crack closure and its impacts on typical A-10 control point analysis**
  - Surface crack growth showed moderate life improvements (2-6%) and decrease in a/c (2-5%)
  - Corner crack growth shows increased analytical predictions (2-37%) but very little change in aspect ratio
  - Crack closure factor not recommended for current A-10 Methods
    - Minimal difference from current method
    - Concerns of potential conservatism due to location of K extraction
    - Concerns of potential conservatism due to constraint variation with large and small load cycles
  - Methods utilizing multi-point analysis should consider investigating effects of closure factor
    - Recommend performance of analytical study to compare multi-point growth with and without beta corrections at the free surfaces of the crack face

$$\beta_R = 0.9 + 2\,R^2 - 0.1R^4 \; for\; R > 0$$
$$\beta_R = 0.9 \; for\; R \leq 0$$



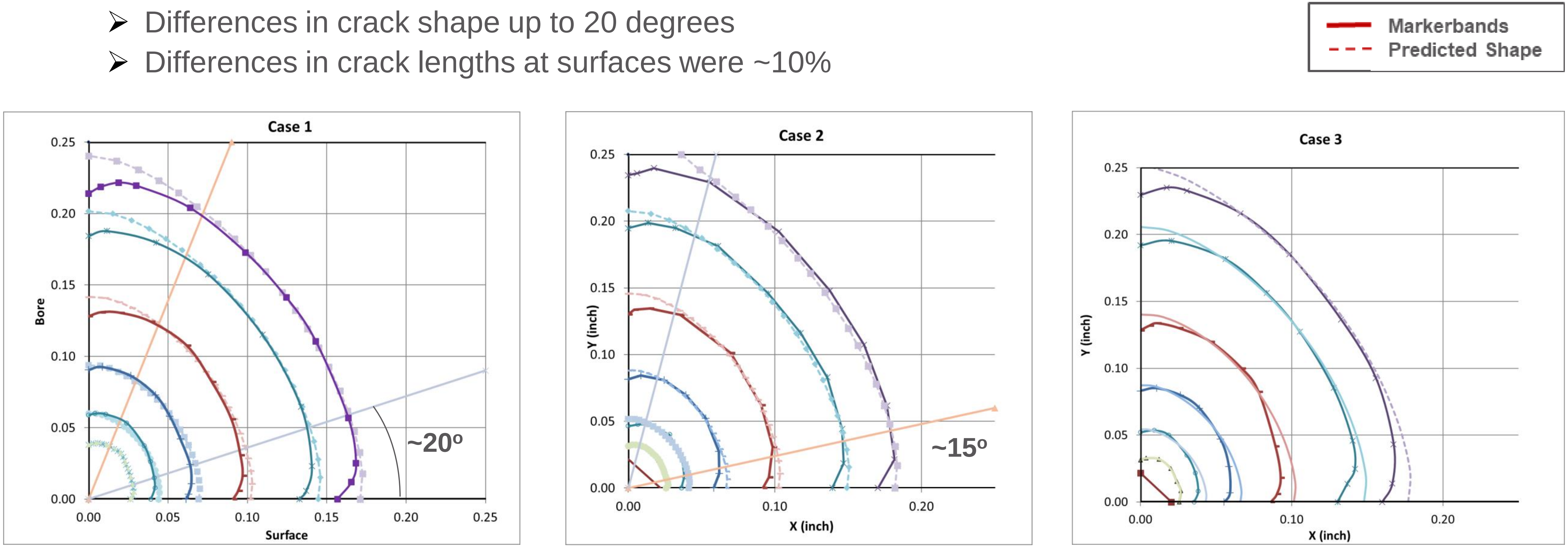

**Note: this implementation still forces an assumed elliptical crack shape**

# Approach

- **Investigate differences in crack shape evolution from predicted shape**
- **Investigate effects modifying surface points have on crack shape**
- **Incorporate updates into BAMF**
- **Complete predictions for defined conditions**
  - AFGROW round robin
  - Other available data with good markerband and test correlation

# AFGROW Round Robin – BAMF Comparisons

- **Using BAMF to make comparisons to markerbands**
  - Similar to the midpoint elliptical assumptions
  - End points evolve naturally and are not perpendicular to the surface
  - Differences in crack shape up to 20 degrees
  - Differences in crack lengths at surfaces were ~10%





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# BAMF Initial Implementation

- **Initial approach**
  - Implement function to modify $K_{app}$ with a correction factor and an angle for both the surface and the bore
    - Implement capability to adjust angle utilizing BAMF parameter features
  - Utilize an equation based on differences in crack growth profiles to determine correction factor and angle
    - Linearly interpolate correction factor from surface to defined angle
  - Utilize new functionality to determine effects the correction factor and angle have on life and crack shape

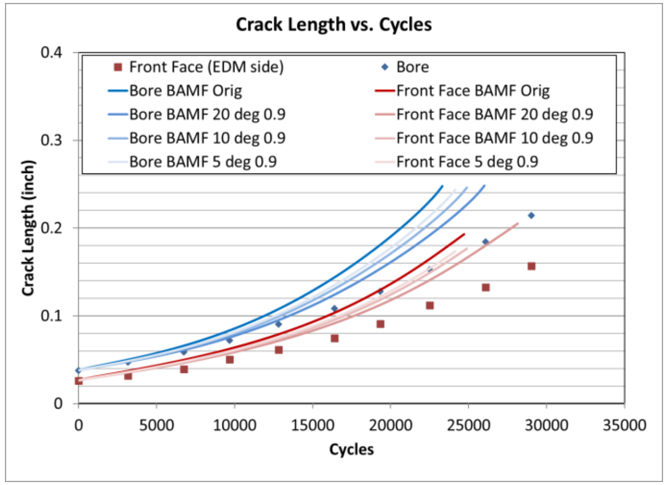
```
2 references
Public Function SPCFEquation(ByVal PointAngle As Double, ByVal MaxAngle As Double) As Double

    Return 0 * PointAngle ^ 2 + (0.2 / MaxAngle) * PointAngle + 0.8

End Function
```

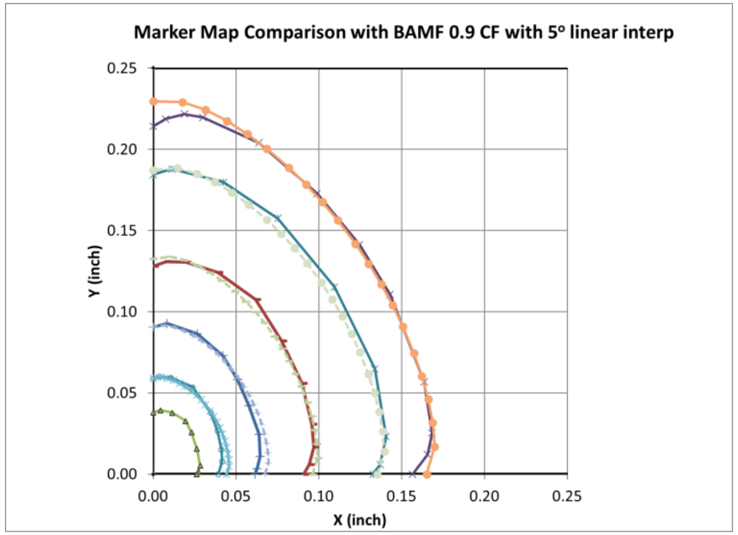
$$\beta_{surface\ correction} = \frac{(1 - CF)}{Max_{angle}}\phi + CF$$

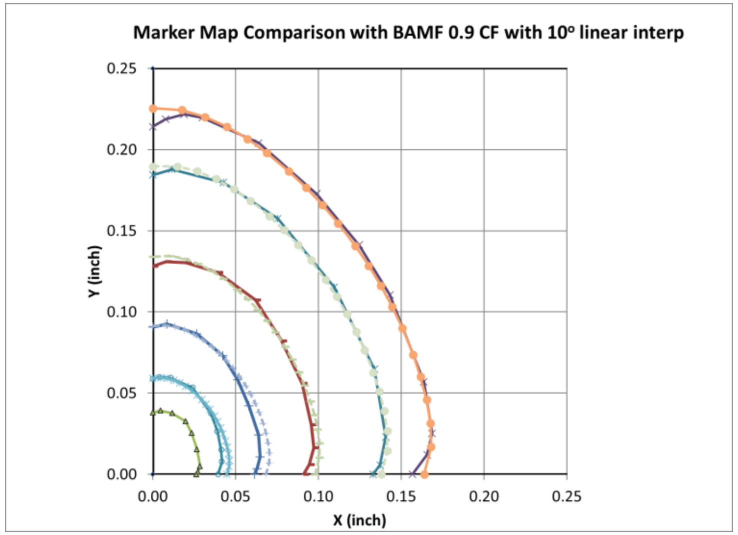
**CF= Correction factor**
**Max Angle= Maximum angle the correction factor acts over**
**Φ=Angle from surface**

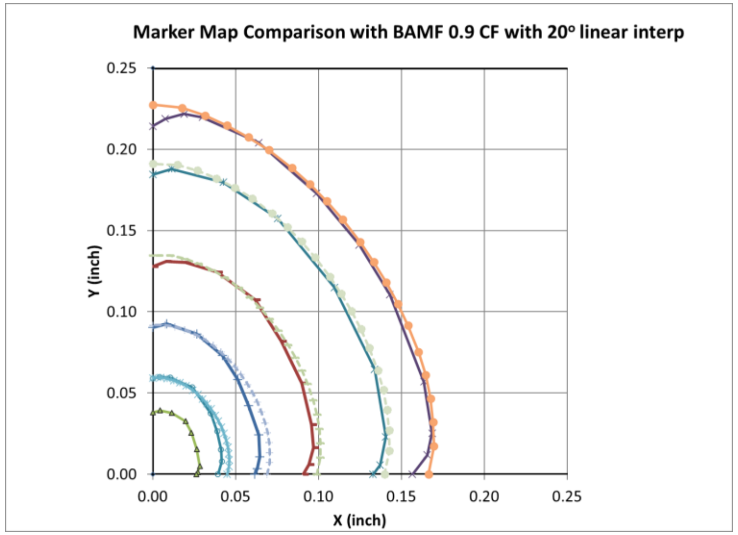
# BAMF Predictions – AFGROW Round Robin Coupons

- Utilized different maximum angles with a 0.9 correction factor
- Differences in shape were largely independent of the maximum angle
- Maximum angle influences life differences
  - 20º~12% increase; 10º~5% increase; 5º~4% increase



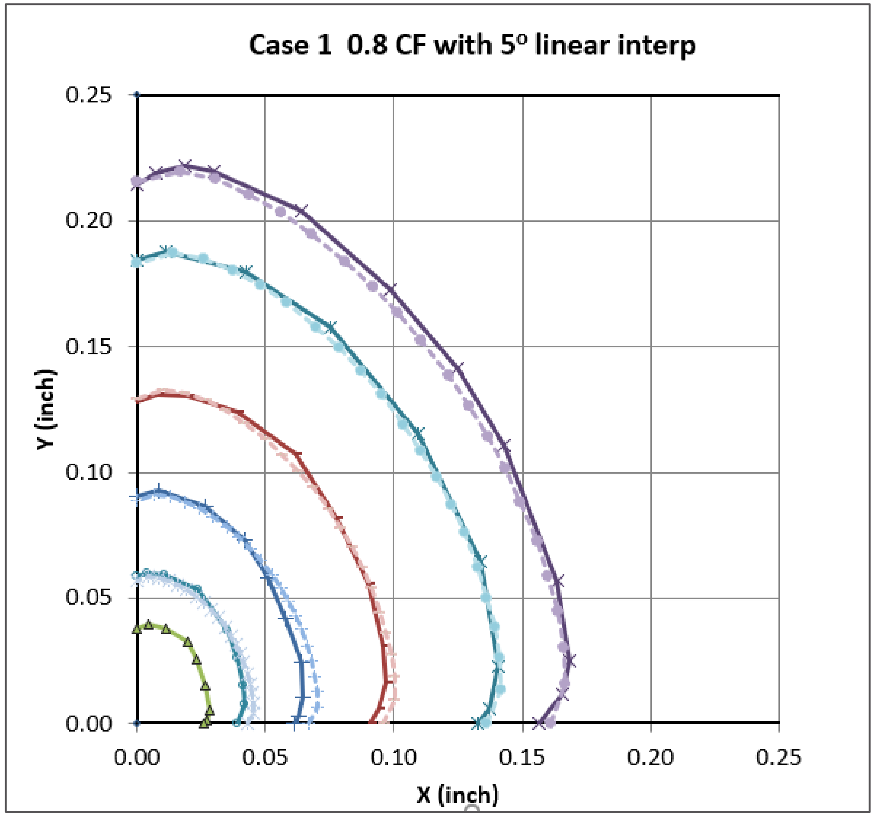



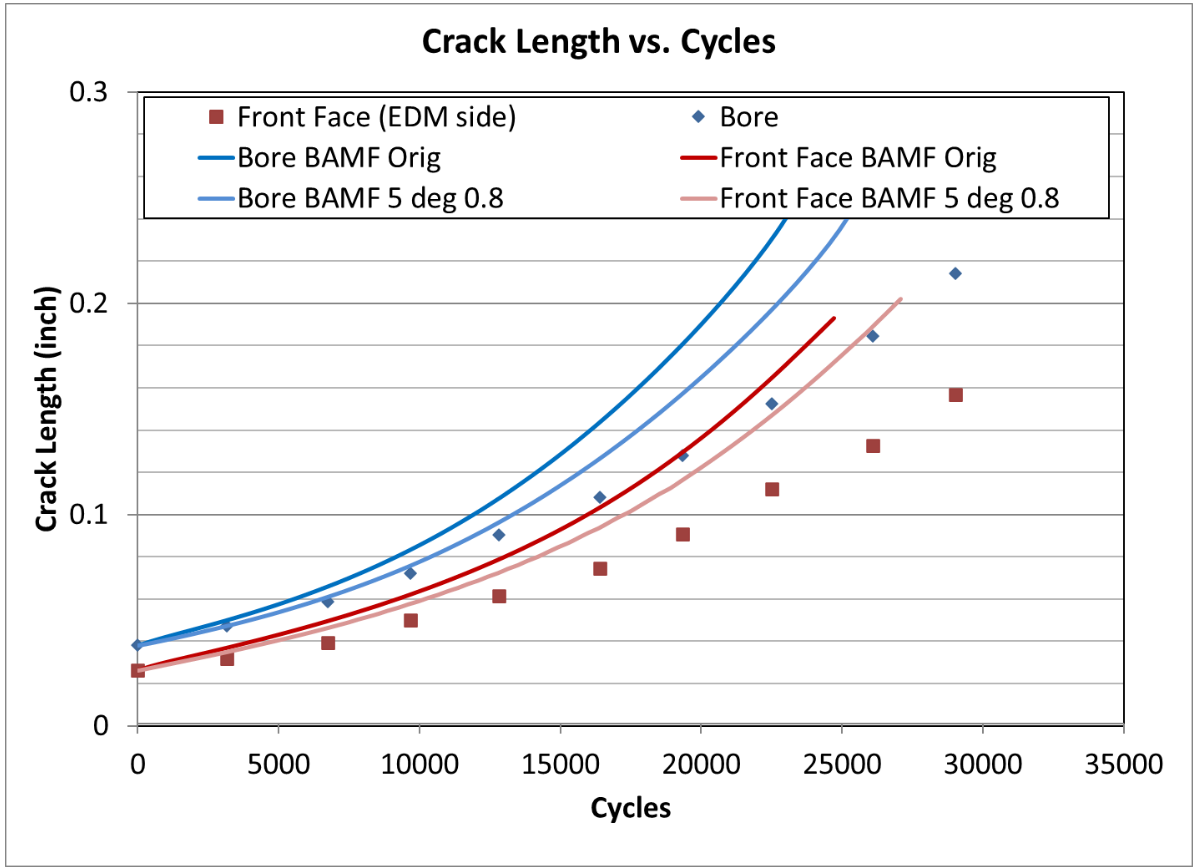

Markerbands
Predicted Shape

# BAMF Predictions – AFGROW Round Robin Coupons

- **AFGROW RR Case 1**
  - Max angle = 5º
  - Correction factor = 0.8

Markerbands
Predicted Shape

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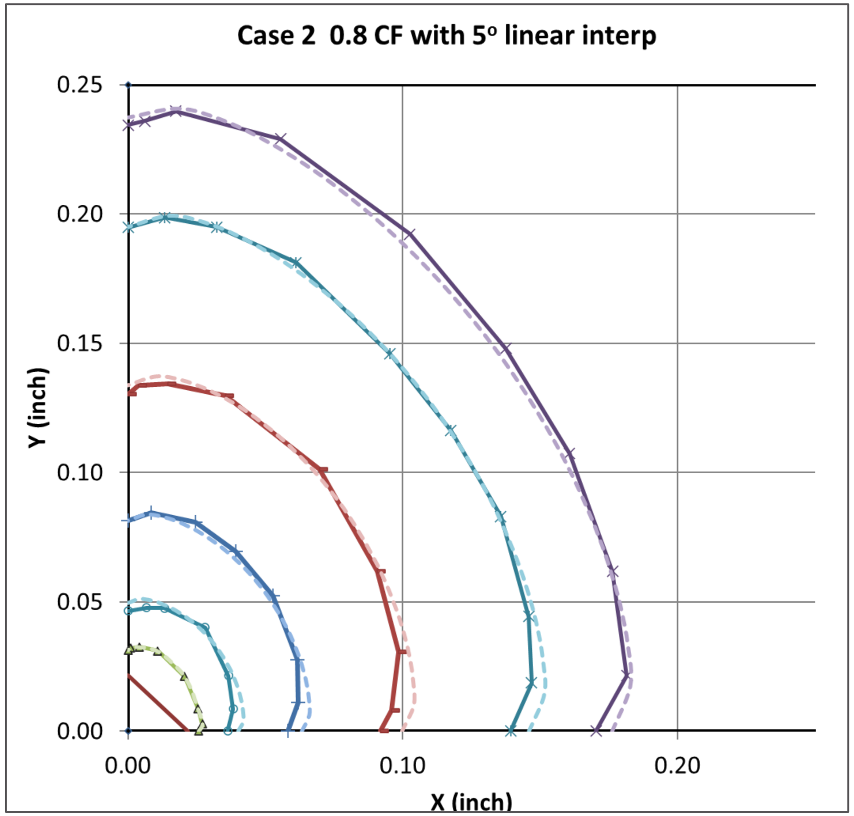
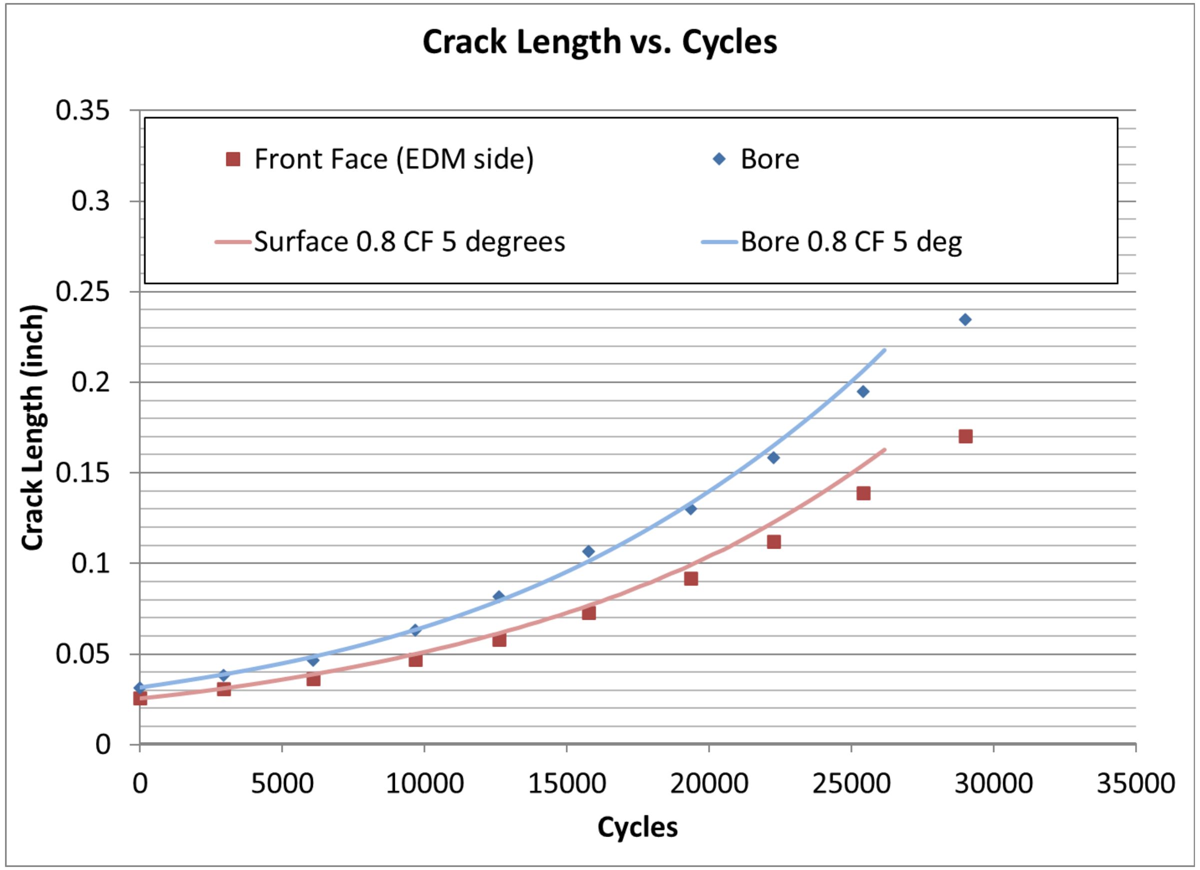
# BAMF Predictions – AFGROW Round Robin Coupons

- **AFGROW RR Case 2**
  - Max angle = 5º
  - Correction factor = 0.8

Markerbands
Predicted Shape

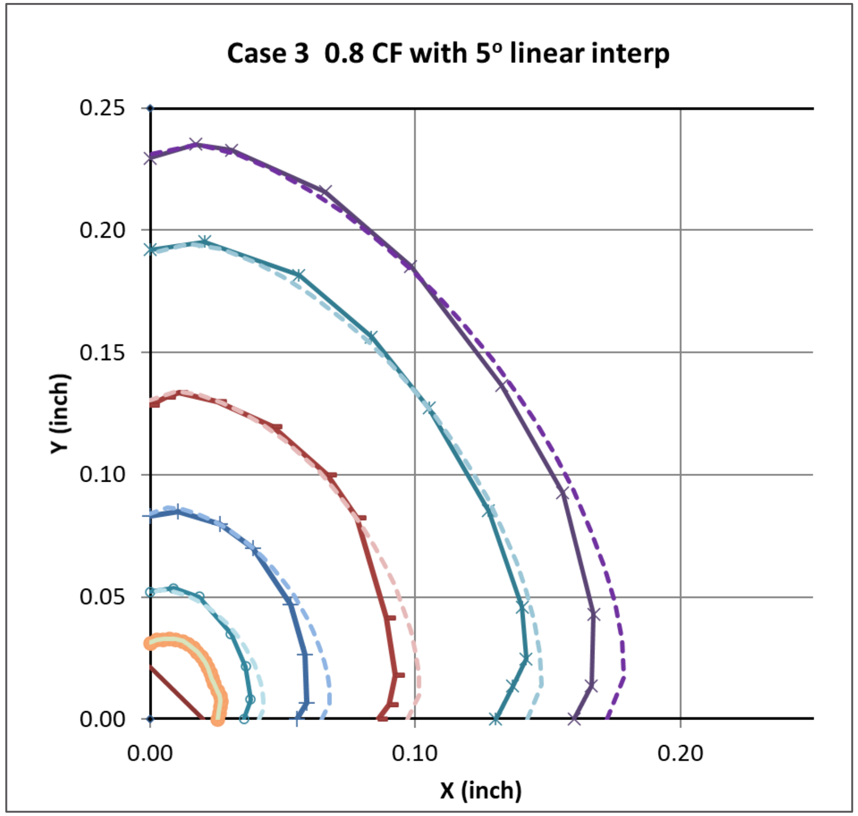


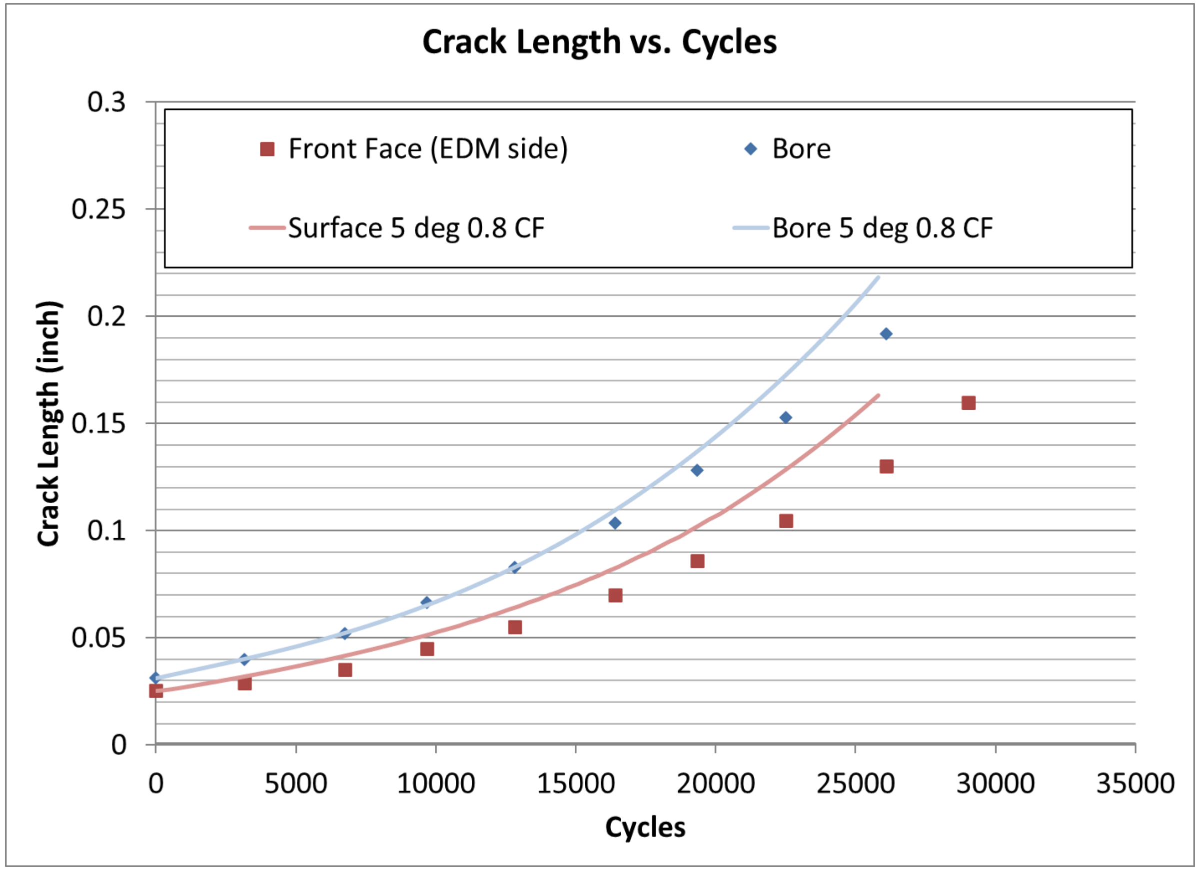



# BAMF Predictions – AFGROW Round Robin Coupons

- AFGROW RR Case 3
  - Max angle = 5º
  - Correction factor = 0.8

Markerbands
Predicted Shape

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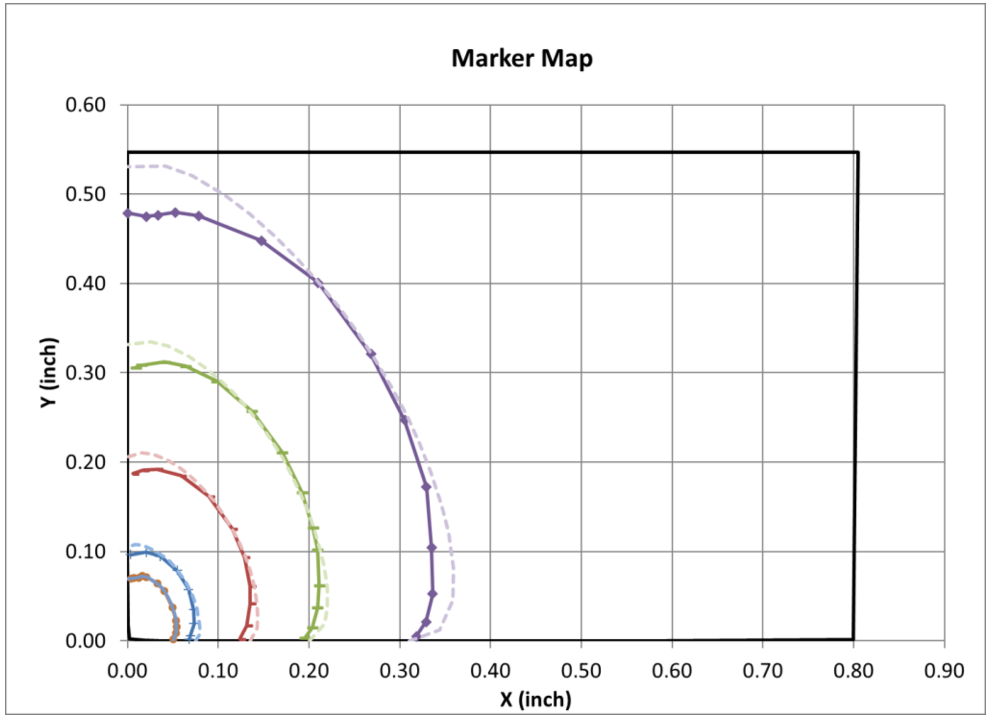
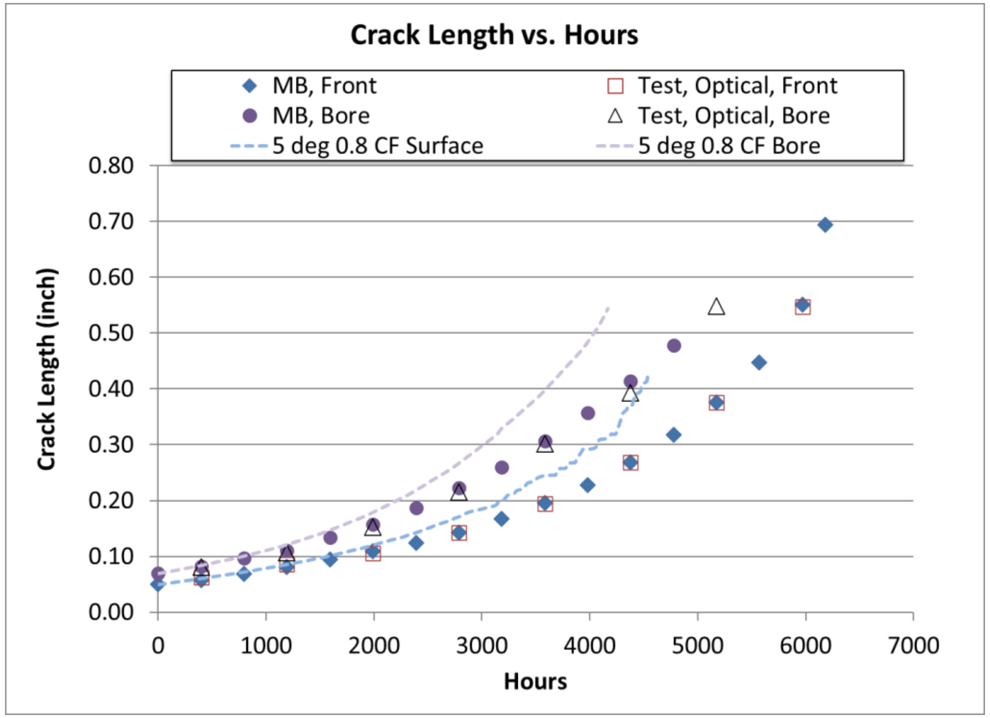
# BAMF Predictions – Other Test Data

- **Utilized approach from AFGROW RR to blind predict VA test**
  - D=0.622, t=0.55 in, t/D=0.9; Max Stress 19.89 ksi
  - 0.8 CF and 5º max angle
  - Resulted in poor shape comparisons and short life

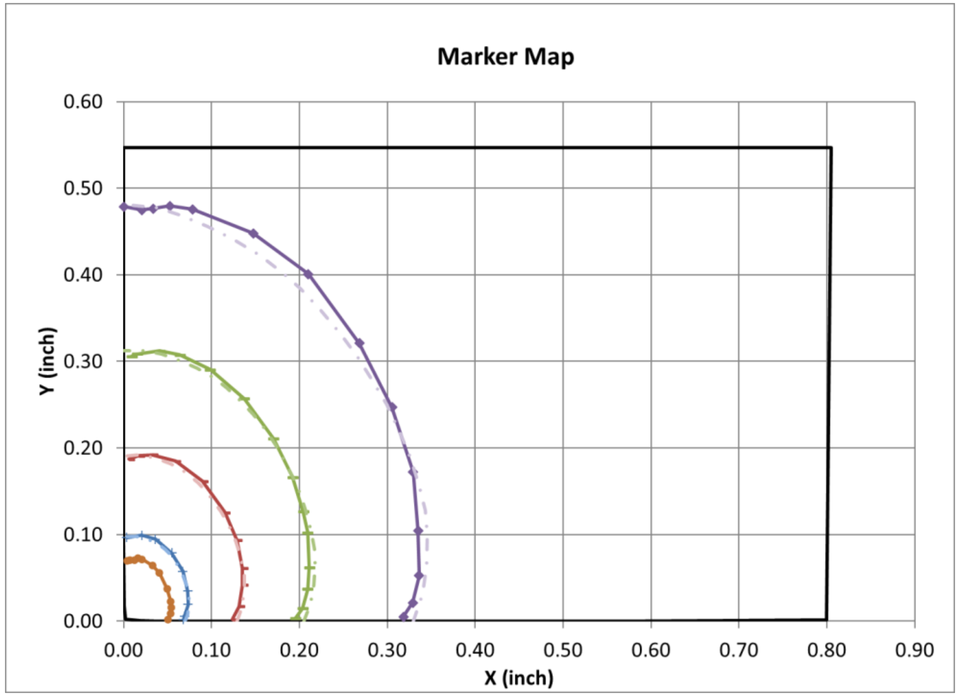
Markerbands
Predicted Shape

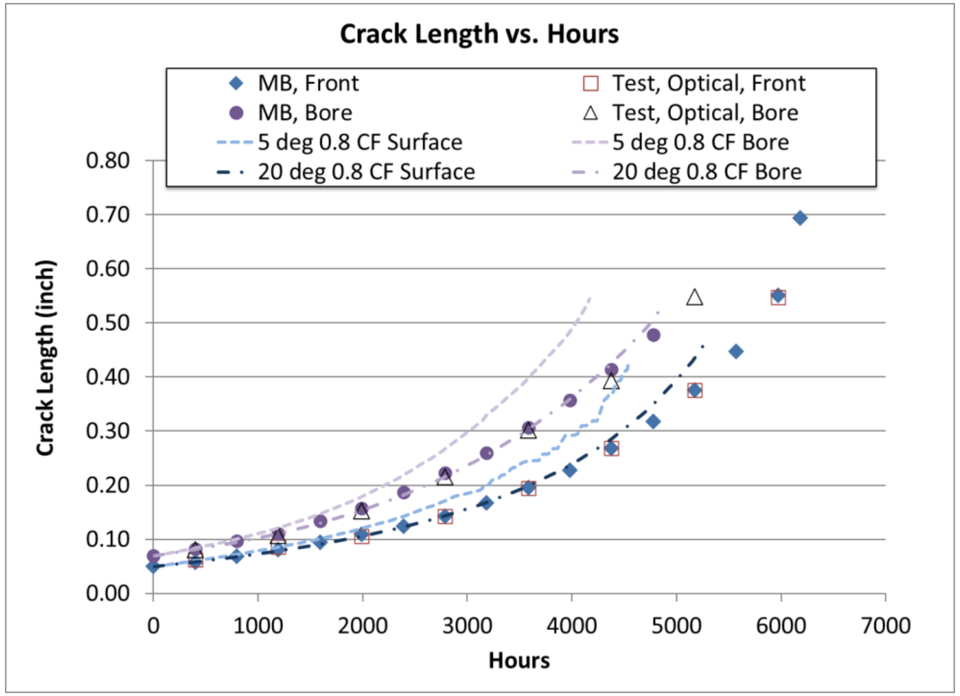


# BAMF Predictions – Other Test Data

- Due to the differences in crack shape, a post-diction was completed with 0.8 CF and 20º max angle
- Shapes and lives are very comparable to test data
- Are we on to something or just a self-licking ice cream cone?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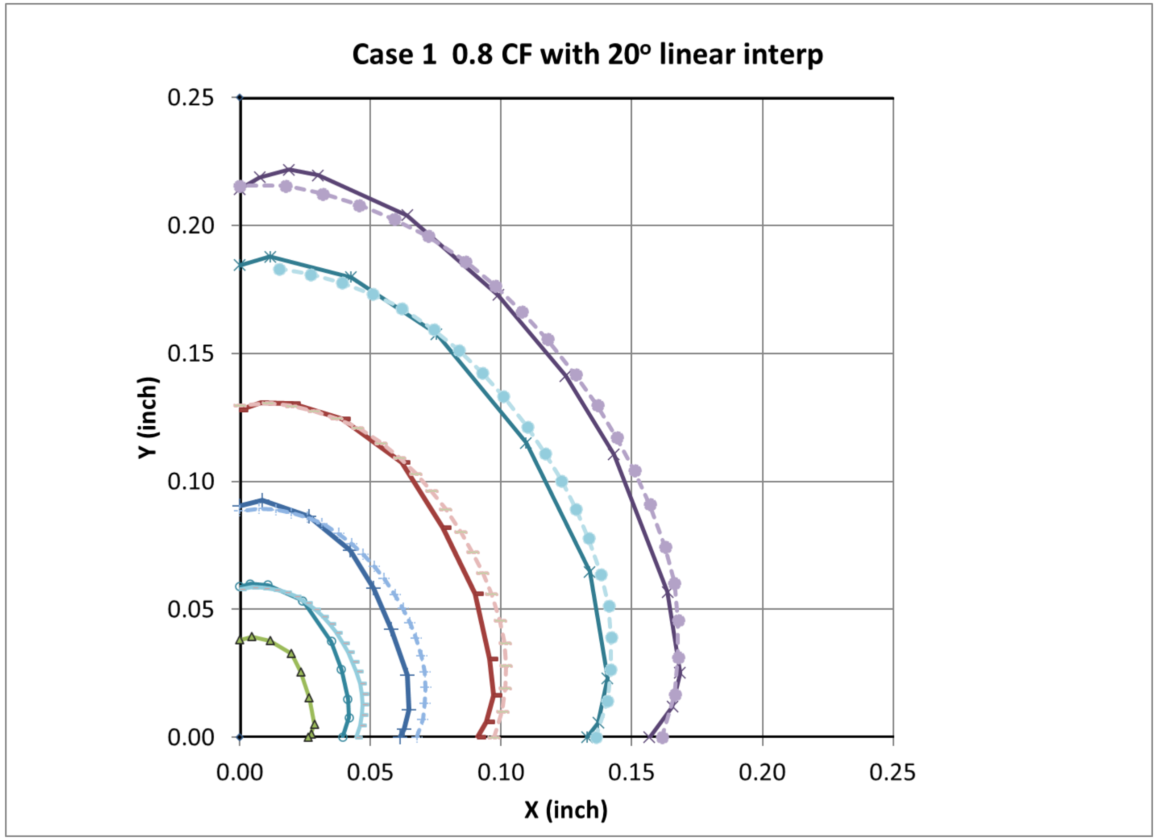
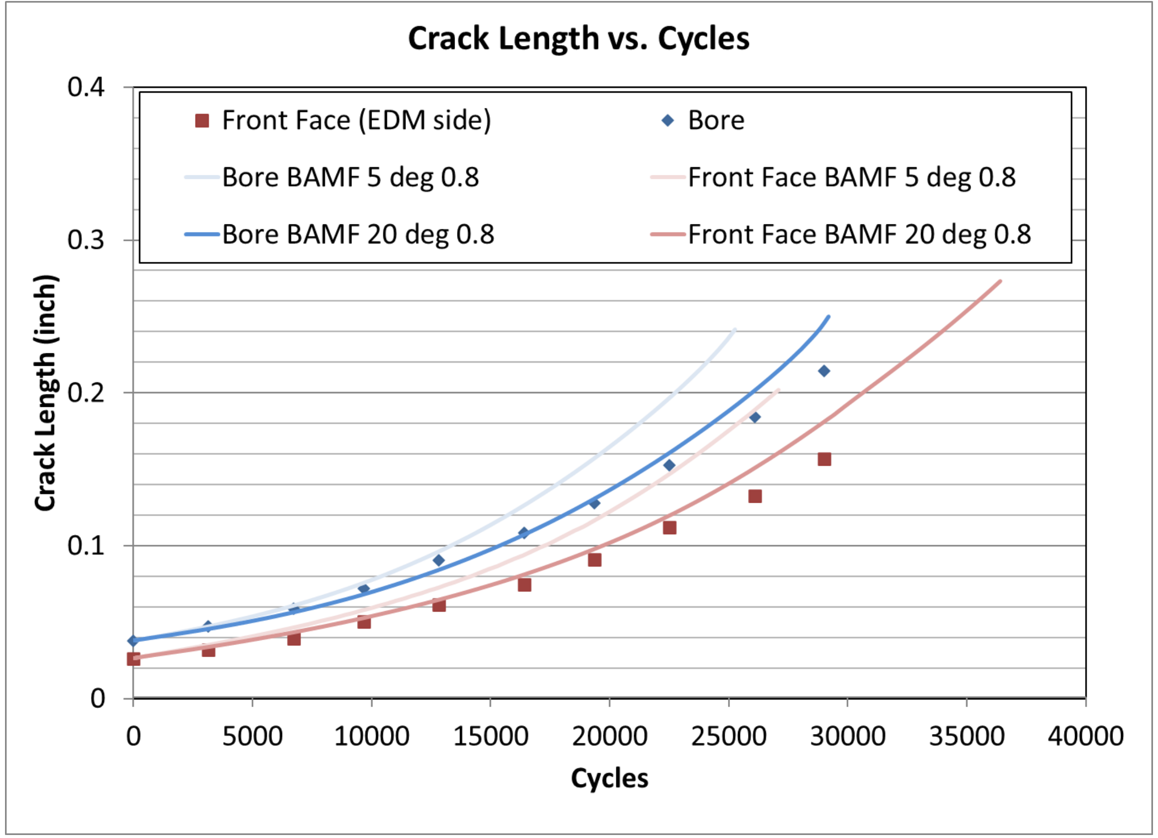
# BAMF Predictions - AFGROW Round Robin with Updated Angle

- **AFGROW RR Case 1**
  - Updated AFGROW RR results with 0.8 CF and 20º max angle
  - Shape and life predictions are very consistent with test data

Markerbands
Predicted Shape

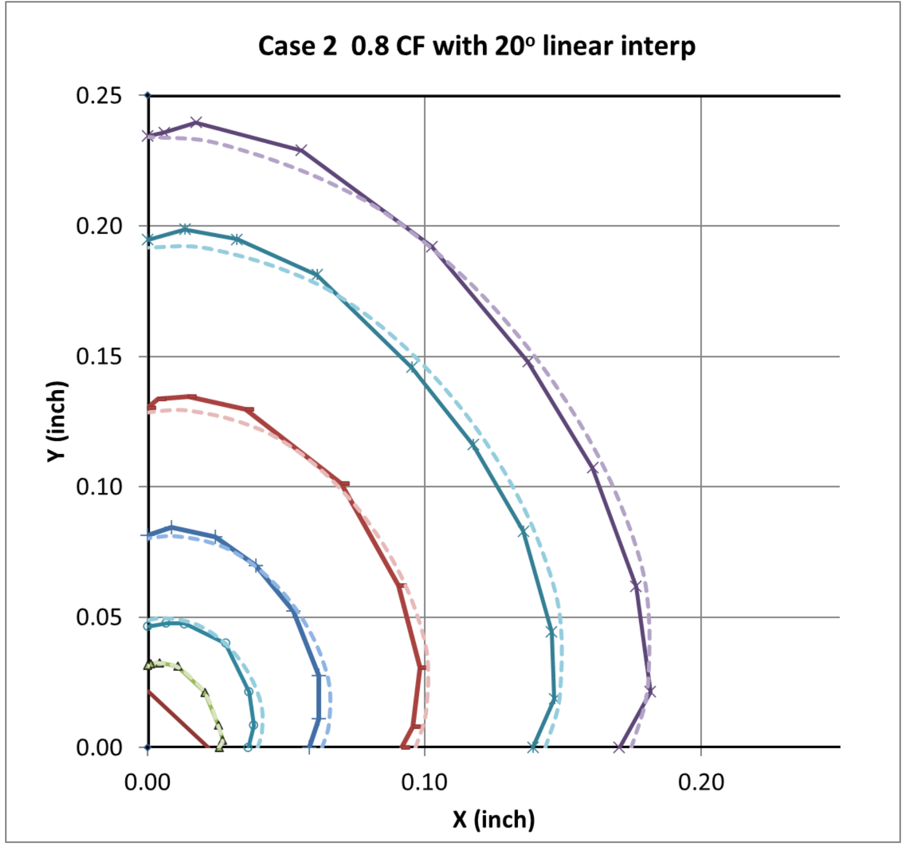


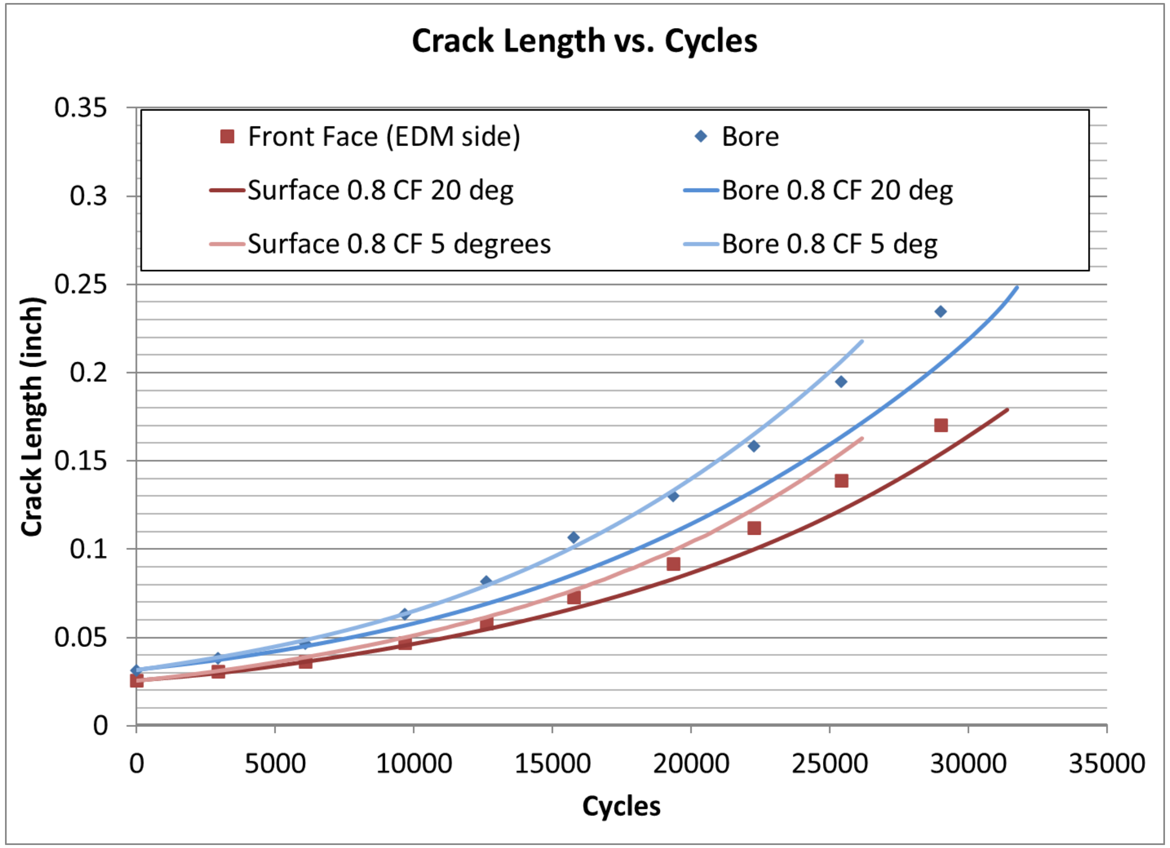



# BAMF Predictions - AFGROW Round Robin with Updated Angle

- **AFGROW RR Case 2**
  - Updated AFGROW RR results with 0.8 CF and 20º max angle
  - Life is slightly long (5% slower in prediction)

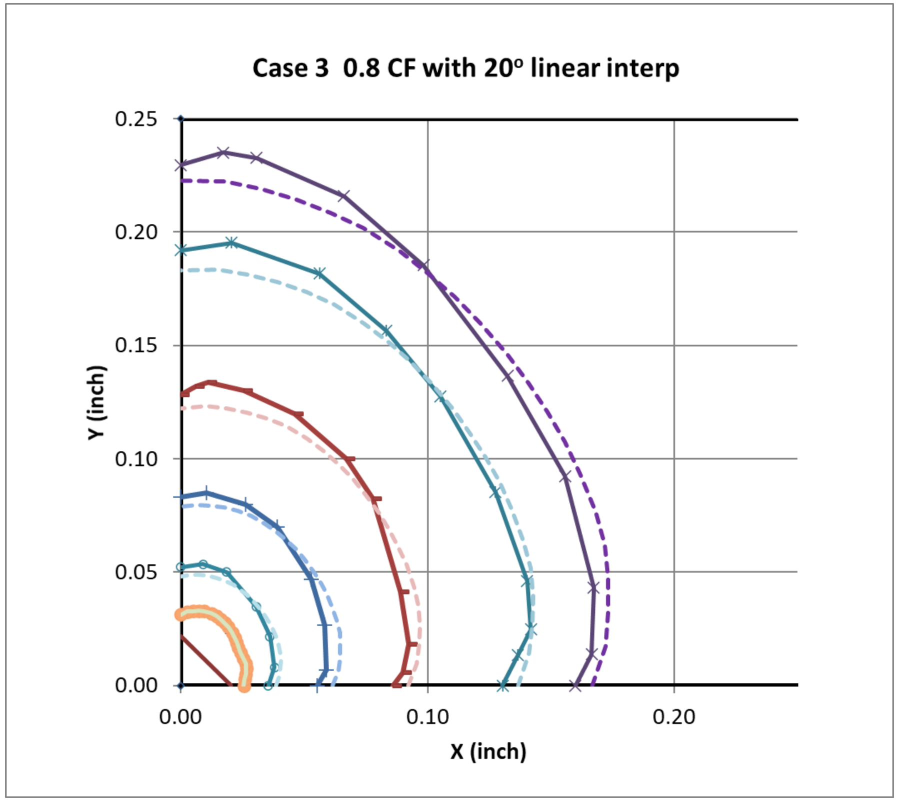
Markerbands
Predicted Shape

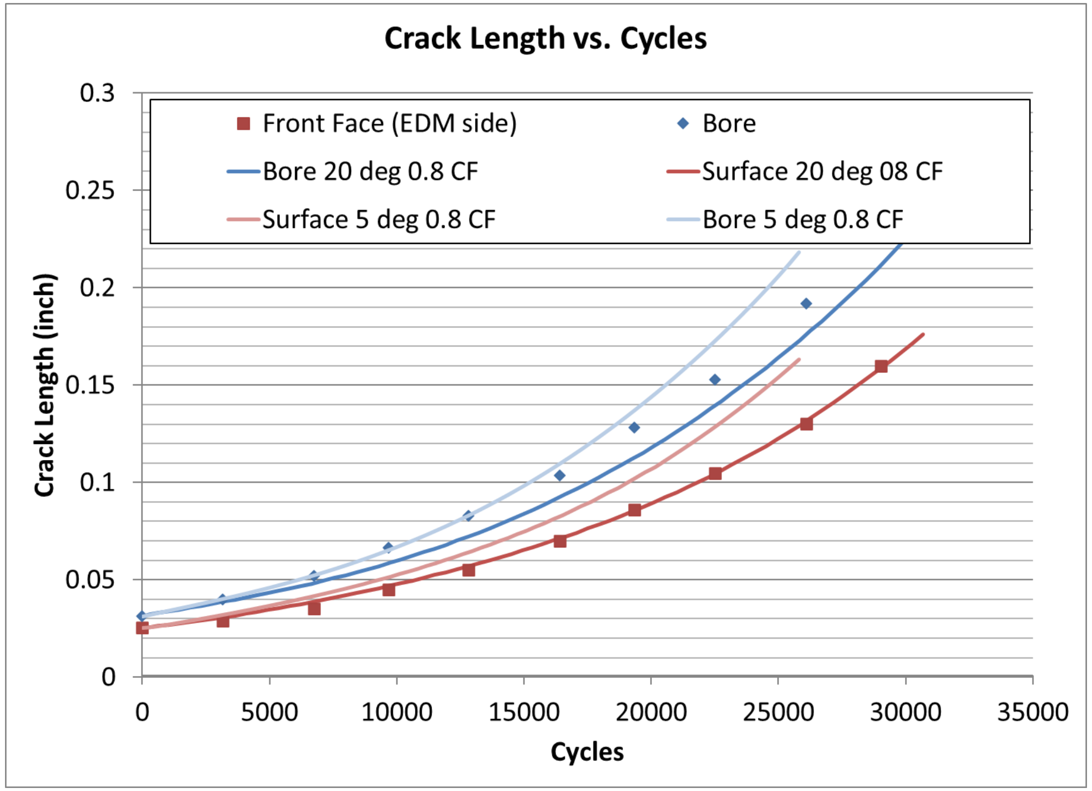


# BAMF Predictions - AFGROW Round Robin with Updated Angle

- **AFGROW RR Case 3**
  - Updated AFGROW RR results with 0.8 CF and 20º max angle
  - Life looks pretty good! Crack shape isn't bad (bore grows faster in test)

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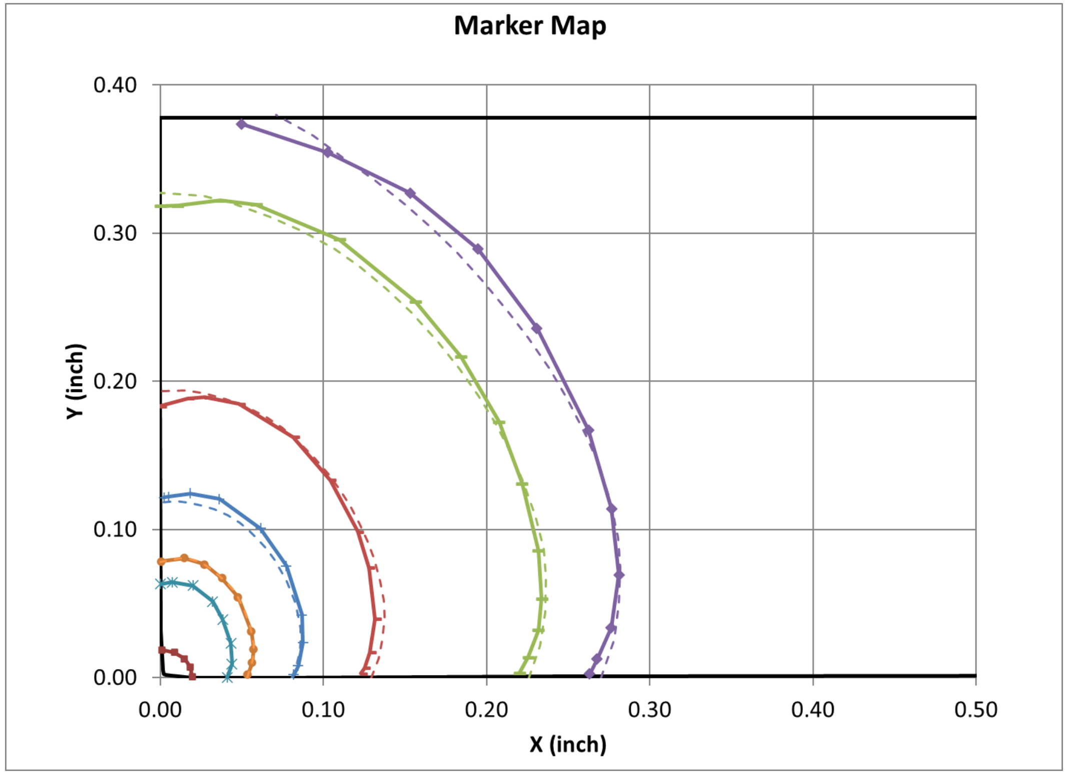
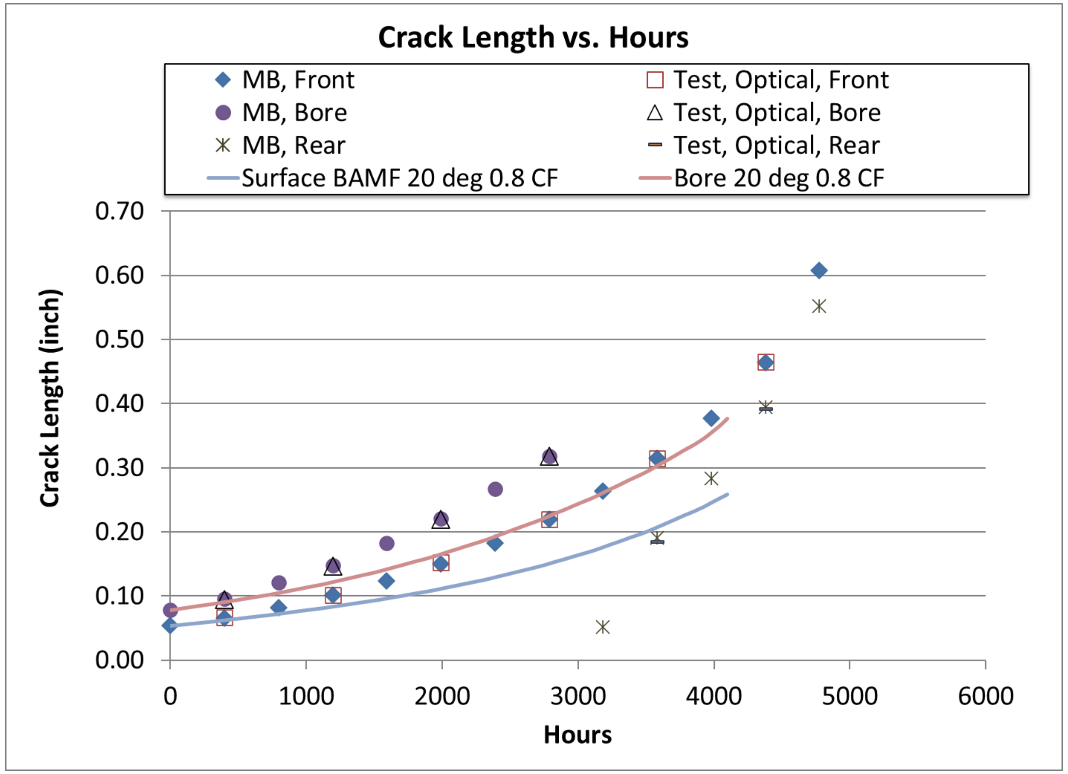
# BAMF Predictions - Other Test Data

- **Other Test Data – Condition #2**
  - D=0.472 in, t=0.38 in, t/D=0.8; Max Stress 20.05 ksi
  - 0.8 CF and 20º max angle
  - Longer lives then test (32%) (all NDWS analyses utilized the same SOLR)

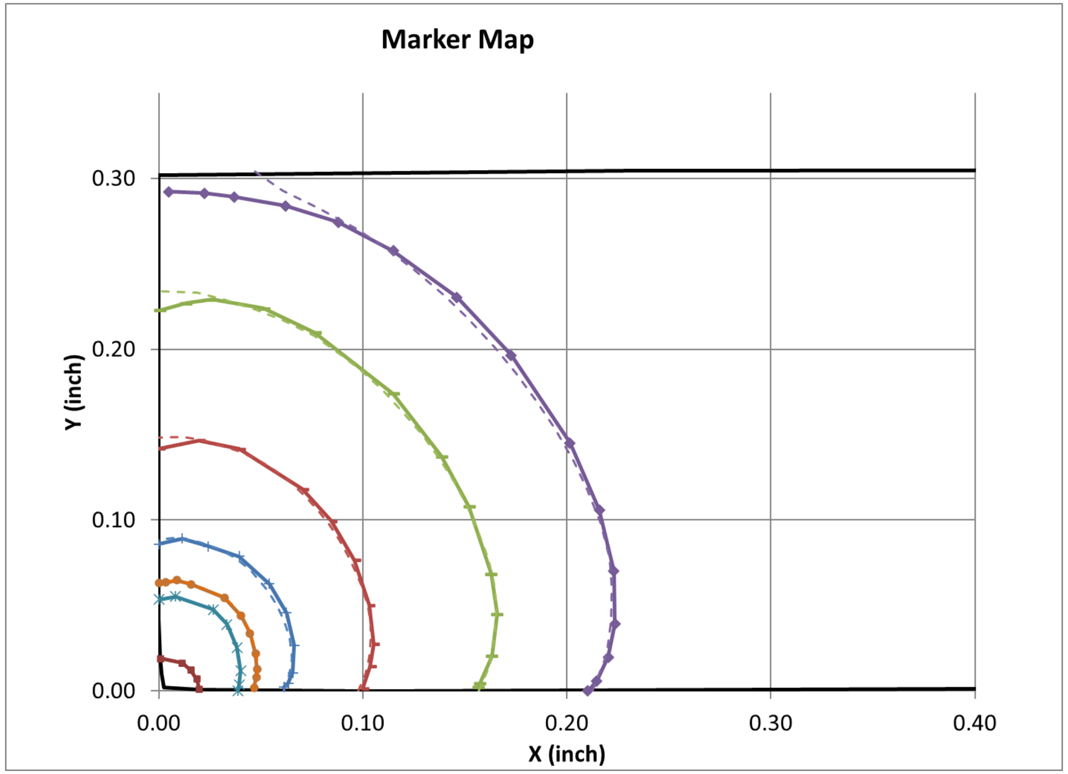


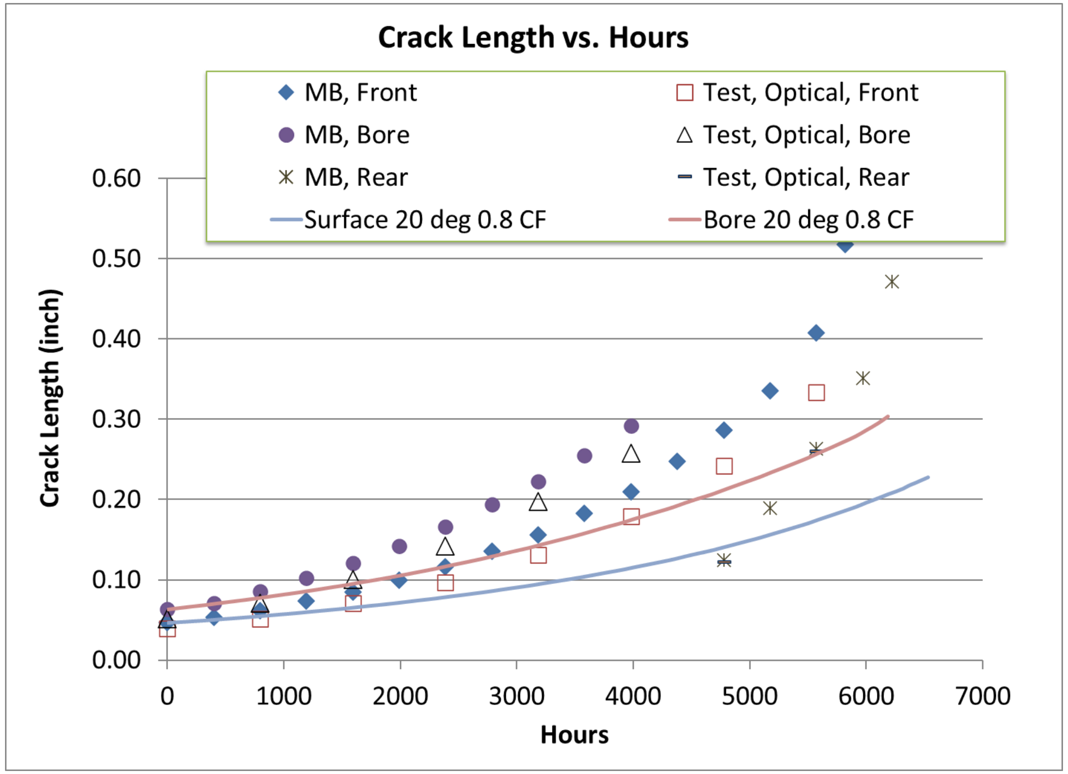



# BAMF Predictions - Other Test Data

- Other Test Data – Condition #3
  - D=0.34 in, t=0.306 in, t/D=0.9; Max Stress 19.68 ksi
  - 0.8 CF and 20º max angle
  - Longer lives then test (50%) (all analyses utilized the same SOLR).

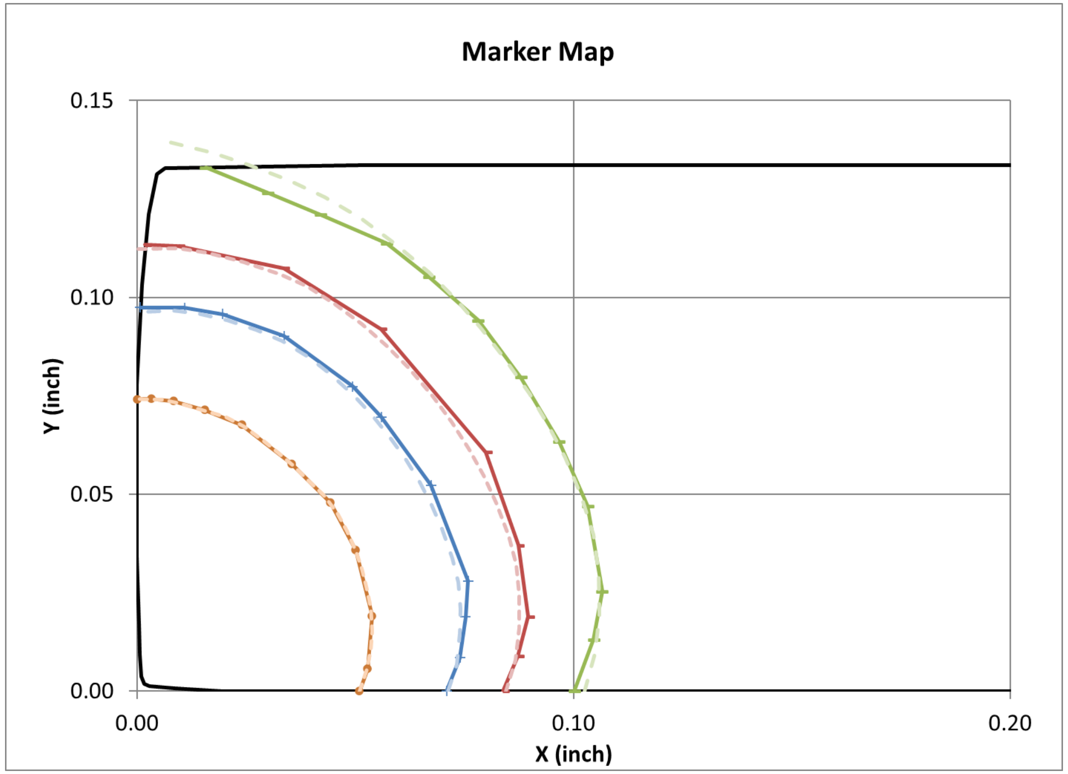
Markerbands
Predicted Shape

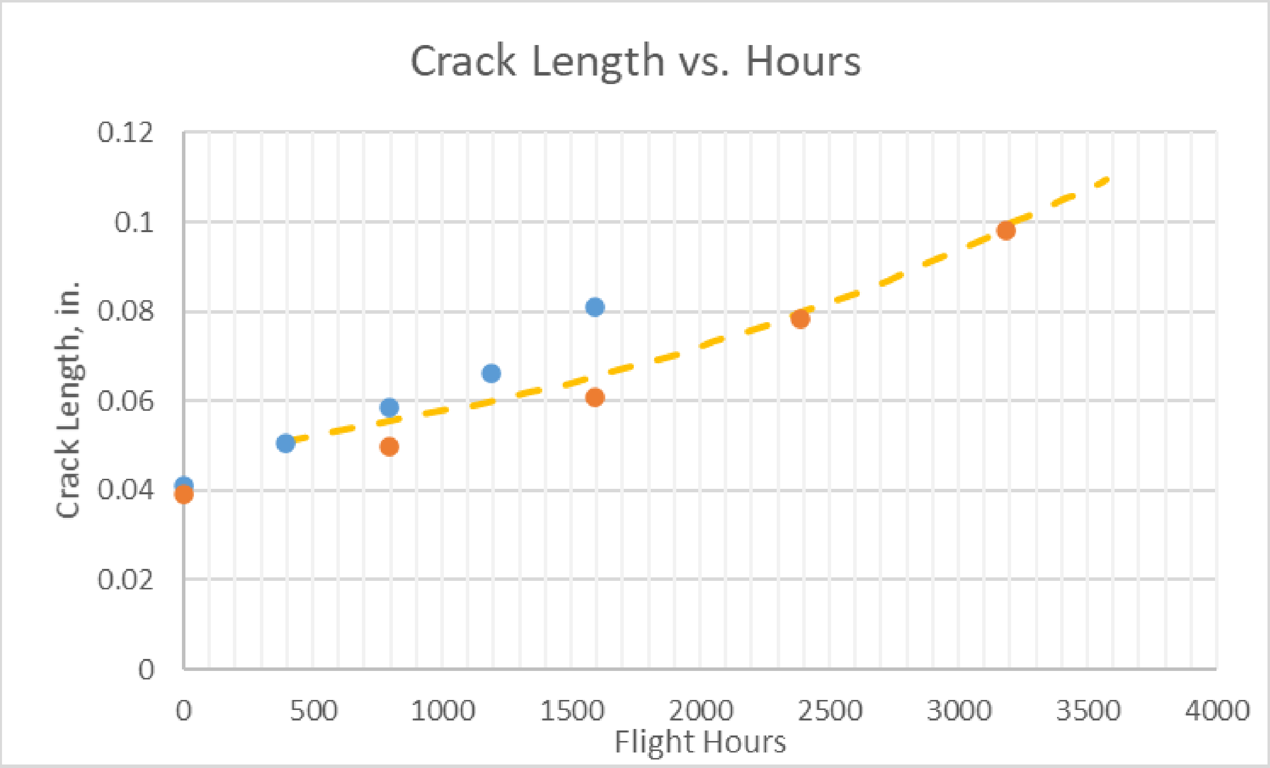


# BAMF Predictions - Other Test Data

- **Other Test Data – Condition #4**
  - D=0.388 in; t=0.14 in; 26 ksi; Ti 6Al-4V
  - 0.8 CF and 20º max angle
  - Good life and aspect ratio agreement

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# Conclusions

- **Method developed to implement surface corrections into BAMF using a max angle and CF**
  - Initial predictions indicate a correction factor of 0.8 and a max angle of 20 degrees correlates best to test data
  - Corrections appear to work for crack shapes in both CA and VA testing
  - Corrections resulted in good life correction for CA tests, however, VA tests showed life that was longer than test
- **So far, this is just experimentation to understand if we can consistently match observed test behavior**
  - How do we move forward from here to understand the physics of the behavior and ensure the implementation isn't just a tuning knob (no self-licking ice cream cones)?
  - What is the correct implementation approach?
  - What data can we utilize to guide the approach?

# Discussion Points

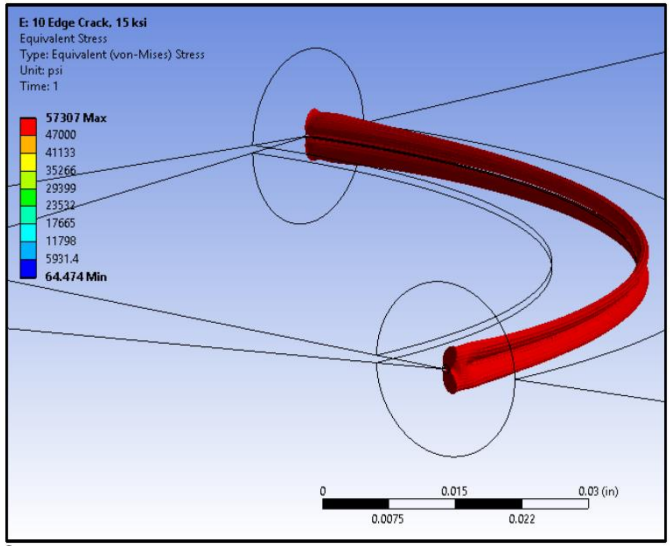
- Observed behavior is not a new topic for discussion
  - Elber (1970) [1,2] – Cracks remain closed at positive stress in cyclic loading
  - Forman, Kavanaugh, Stuckey (1972) [3] – Changes in stress state along crack front leads to different growth rates
    - Scaled rates along surface to match test
  - Newman, Raju (1979, 1981) [4,5,6] – Cracks stayed semicircular even though the SIF at the surface is approximately 10% higher
  - Many others

**Newman and Raju postulated differences may be attributed to the changing relationship between the stress intensity factor and the crack growth rate as the stress state changes from plane stress on the surface to plane strain at the maximum-depth point**

**Is this a DRIVING FORCE or MATERIAL RESISTANCE discrepancy?**

# Next Steps

- **Key focus areas**
  - Plastic zone size
    - Investigate plastic zone sizes/depths and shapes along crack front
      - Parametric study of critical factors
  - Elastic-plastic analysis
    - Characterize differences in stress intensity
  - Existing crack closure models
    - Investigate adaptions to multi-point analyses
  - Material FCGR data
    - Investigate plane stress relevant data




Smith and Domyancic [8]

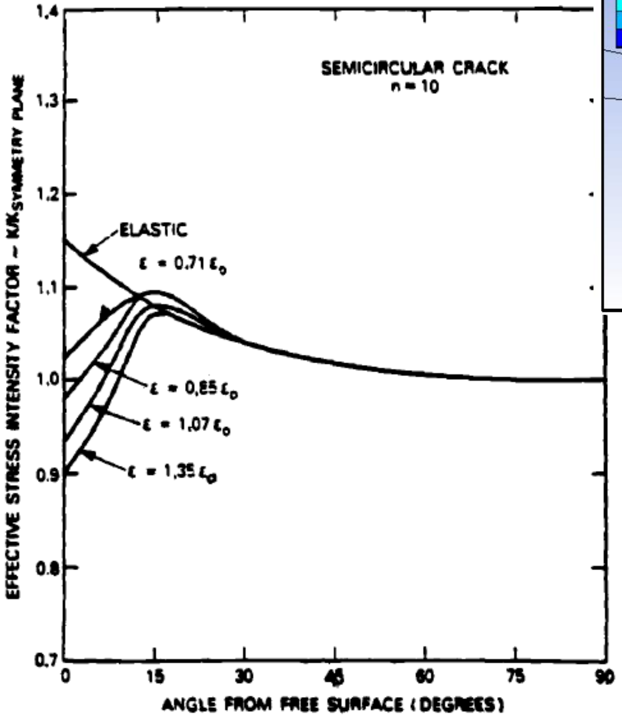



FIG. 3—*Continued: (b) showing the variation of K at the surface normalized relative to K at the symmetry plane.*

Stone, Gilbert, Gooden, Laflen [7]

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