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# Crack Initiation and Growth in Rigid Polymeric Closed-Cell Foam Cryogenic Applications

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# Crack Initiation and Growth in Rigid Polymeric Closed-Cell Foam Cryogenic Applications

## Outline

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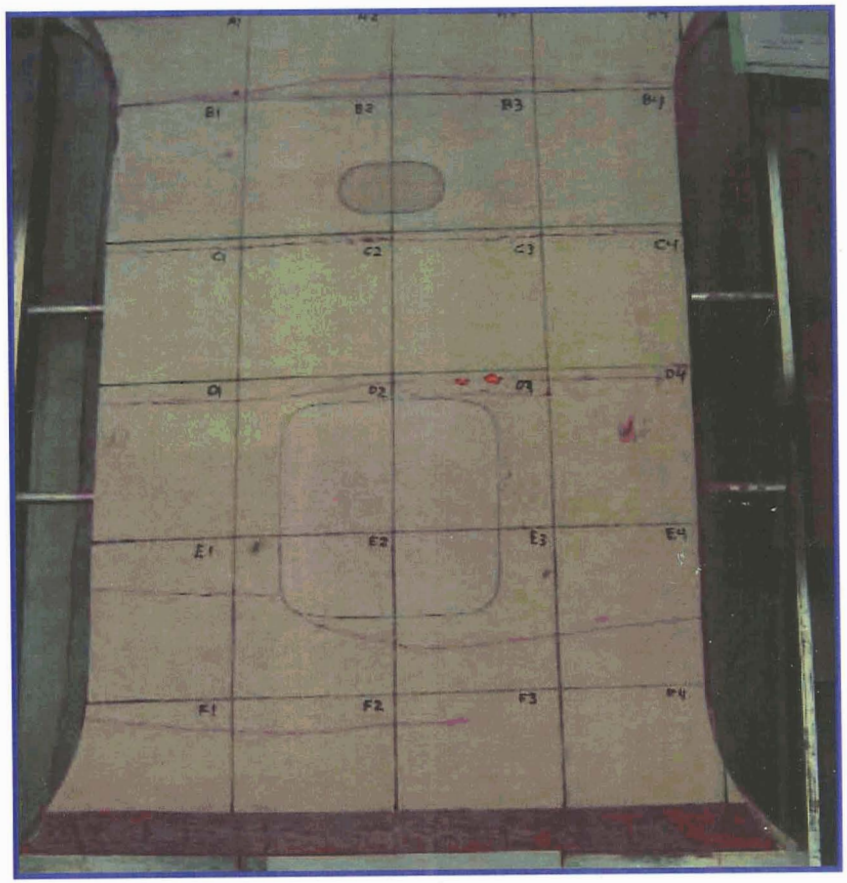
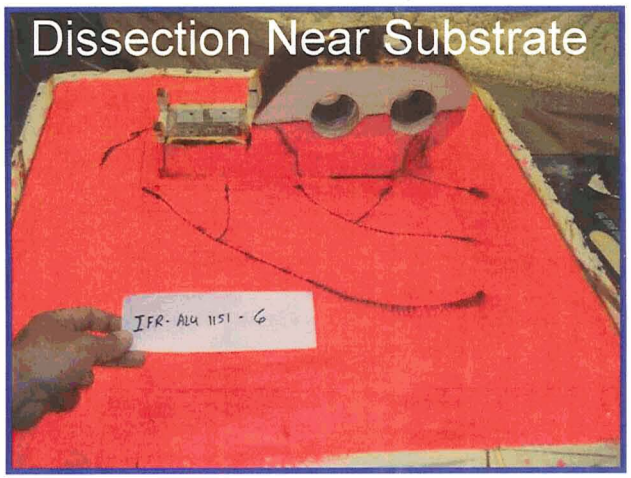
- Stress Profiles
- Crack Initiation
- Fracture Assumptions
- Flat Panel Crack Growth
- Orthogrid Panel Testing
- Delamination
- Conclusion



Cracking Seen in Cryogenic Tensile Test

# Introduction

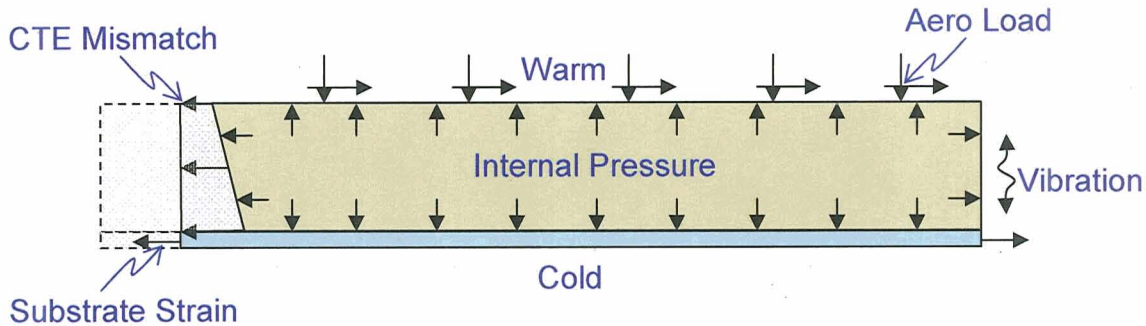
- Foam used to insulate cryogenic tanks experiences a significant amount of stress due to a CTE mismatch with the substrate and tank pressurization
- Additional stress risers can cause cracks to form
  - Additional local loading, geometric discontinuities, or regions of thick foam
- Cracks become potential sites for a substrate delamination to occur
- Cracks are also potential paths and volumes to ingest liquid air
- Understanding when and how cracks form can help to eliminate unnecessary cracking through careful design.



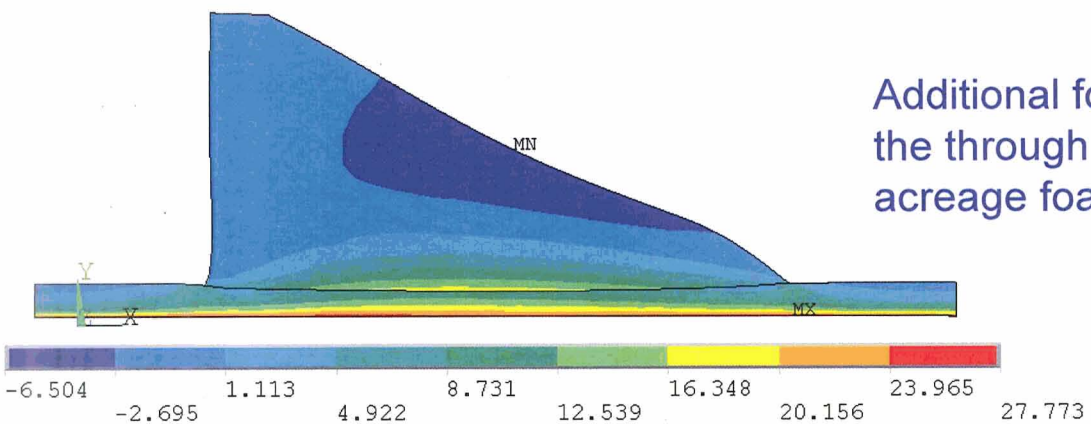

Ice-frost ramp testing
Cryogenic substrate, external vacuum and heating

# Introduction

- External Tank foam experiences multiple loads during pre-launch and ascent



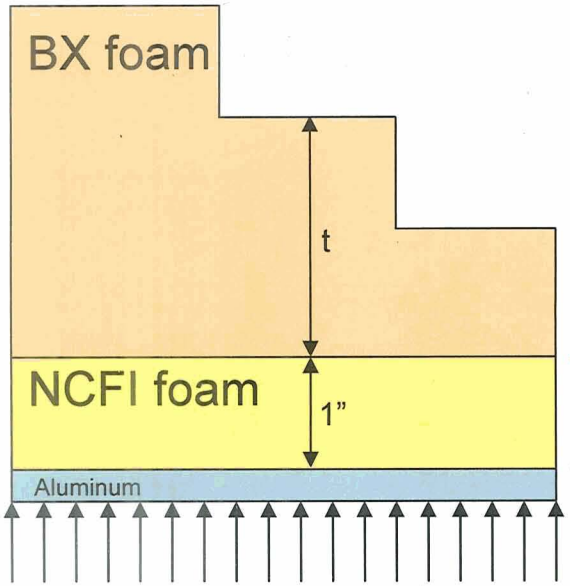

- The primary loads are the CTE mismatch with the aluminum, the tank substrate pressurization strain, and the internal pressure/external vacuum
- The peak stresses occur at the substrate




1st Principal Stress Profile (psi)

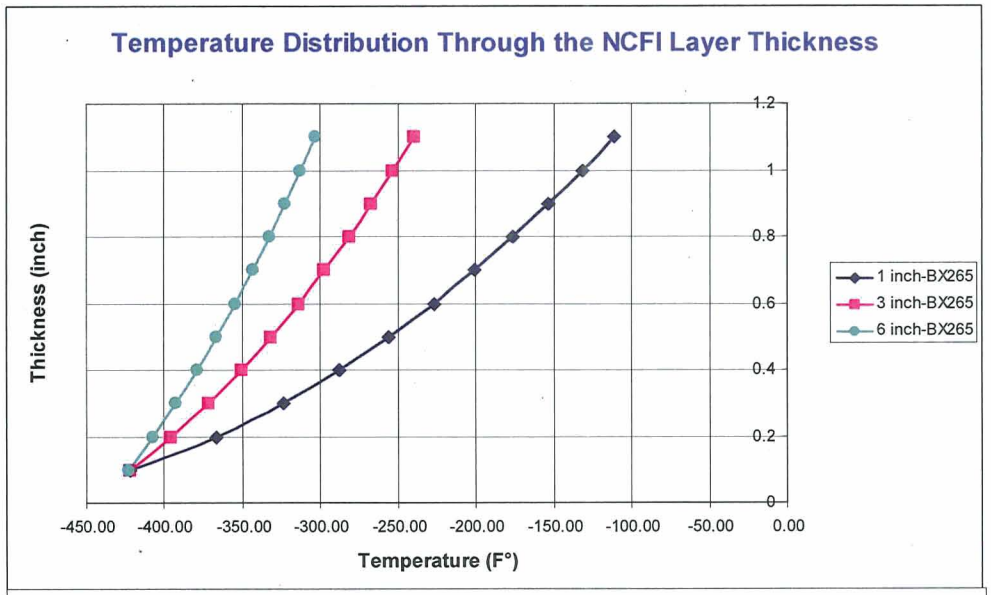
Additional foam-over-foam increases the through thickness stress in the acreage foam underneath

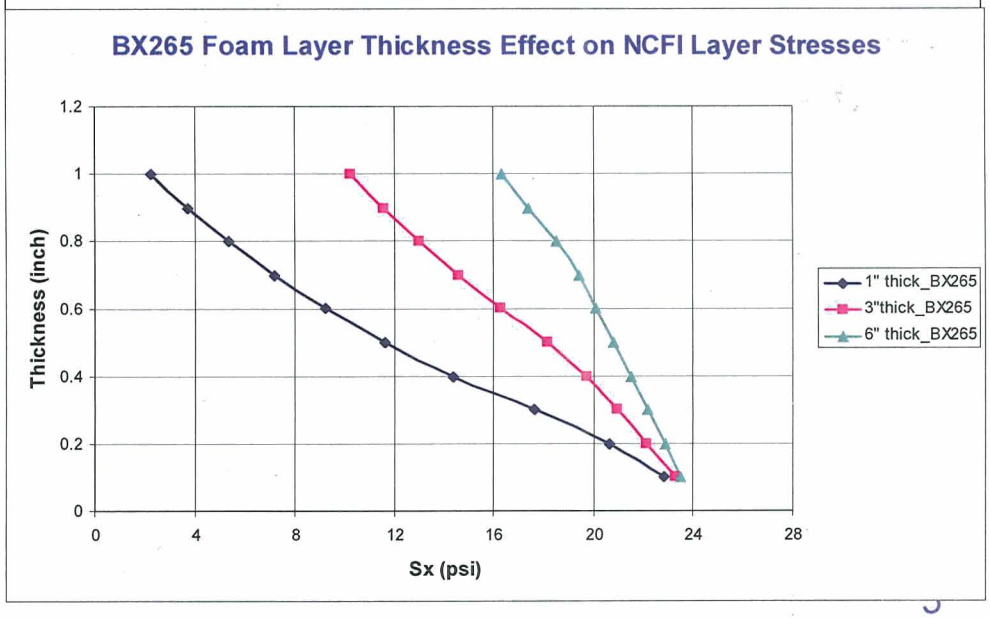
# Stress and Temperature Profiles




LH2 Cooling

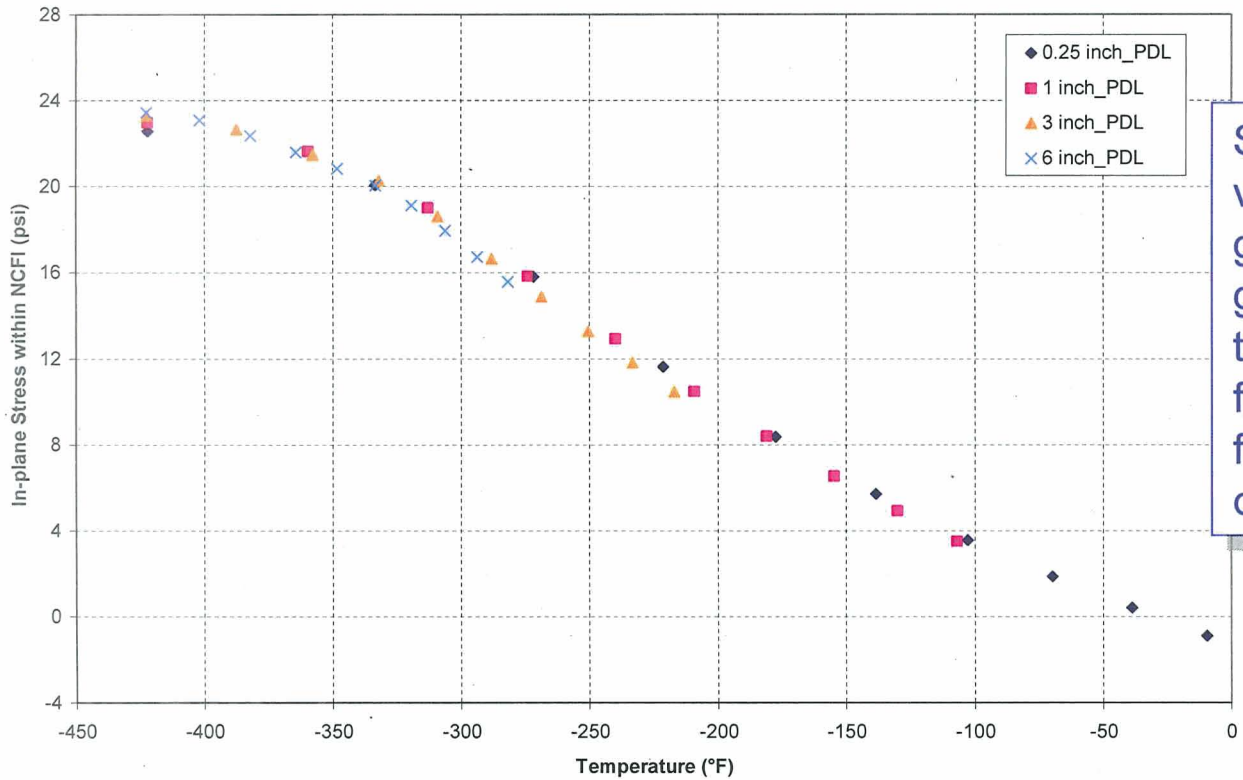
Height of BX or PDL foam over NCFI foam controls the temperature in the NCFI layer, which in turn controls the stress due to thermal mismatch between aluminum substrate and foam.



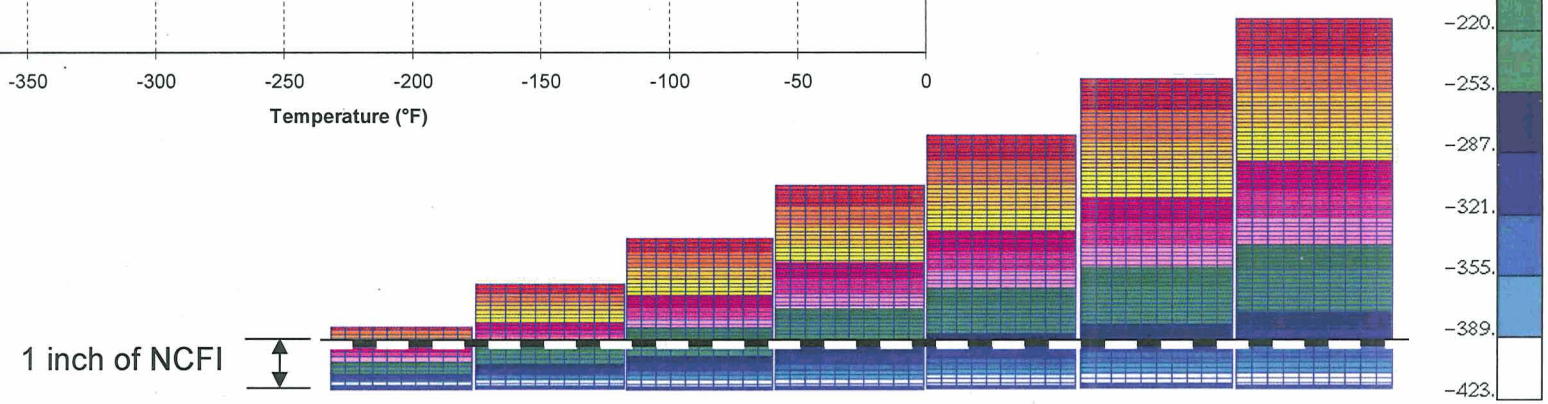



# Stress-Temperature Relationship

Temperature vs In-plane Stresses within NCFI with Covering PDL

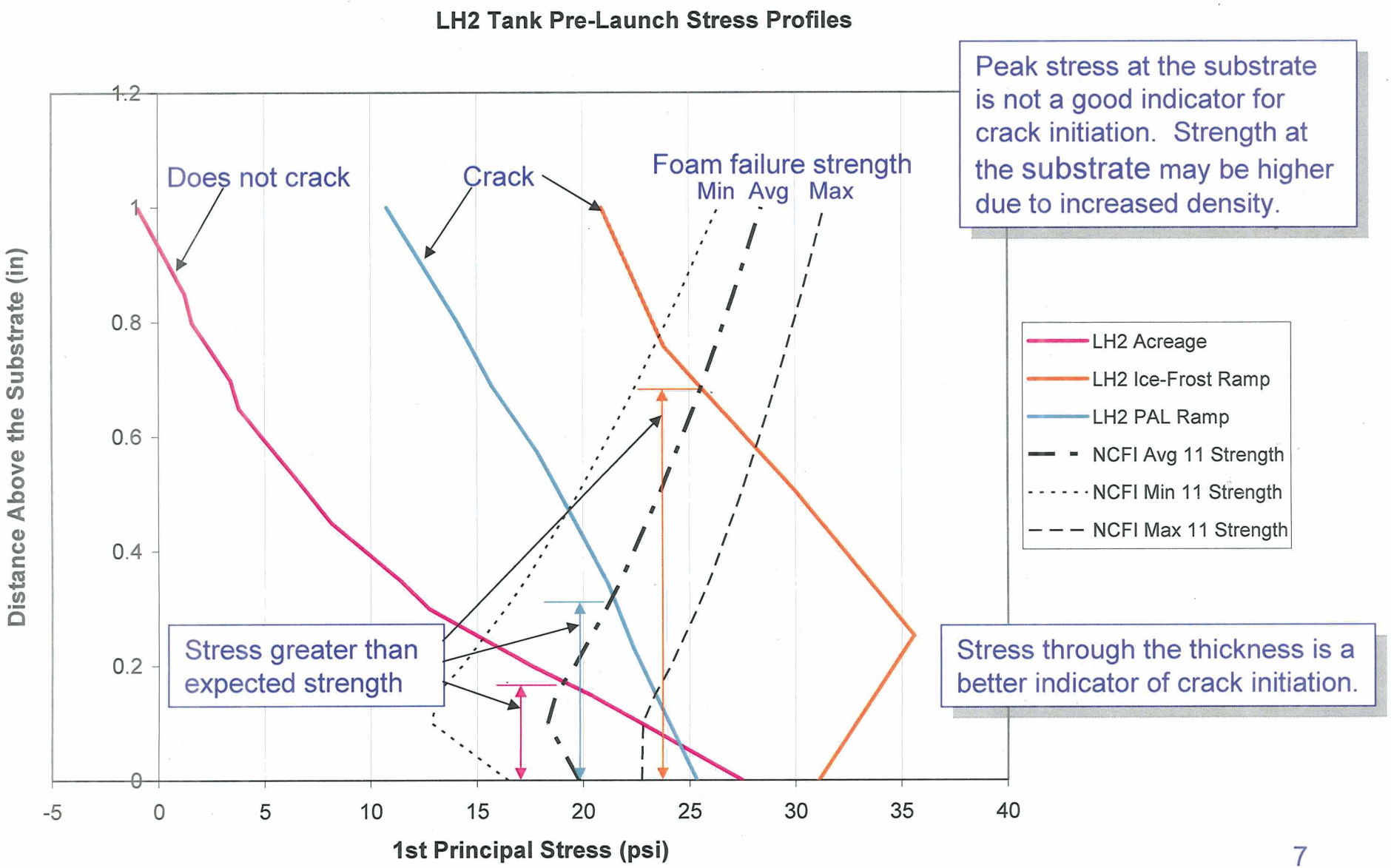



Stress profiles for various temperature gradients collapse to a general stress-temperature correlation for locations away from free edges or discontinuities.




***Thermal Analysis of BX265 Over NCFI Results ( Full Temperature Range @ t=6")***

# Crack Initiation




Peak stress at the substrate is not a good indicator for crack initiation. Strength at the substrate may be higher due to increased density.

Stress through the thickness is a better indicator of crack initiation.

# Foam Fracture

**Foam Failure**

- Rigid polyurethane foams fail in a brittle fashion under tensile loads, particularly at cold temperatures
- Fracture mechanics is used to predict the crack growth of pre-existing cracks
- LEFM successfully correlated with critical defect testing results
    - Adequately predicted when a circular or slotted flaw would fail under a external vacuum and aero-heating load as a function of flaw diameter and depth

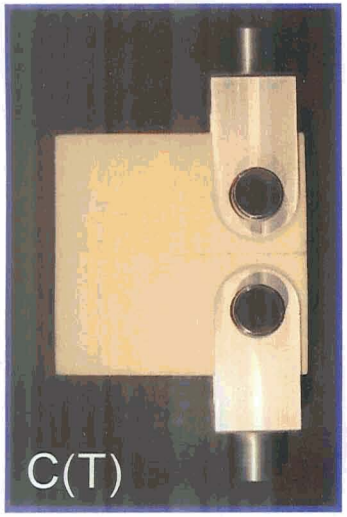
**Analytical Assumptions**

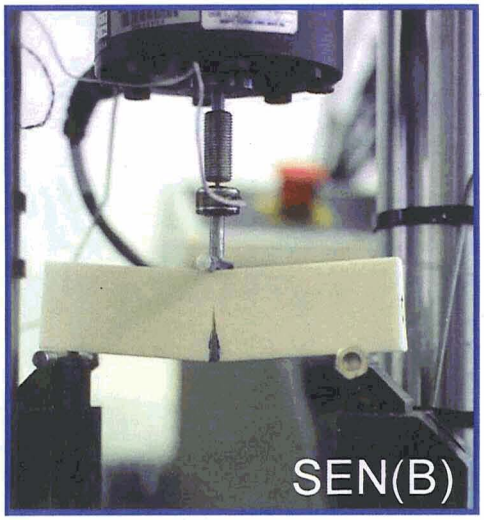
- Transversely isotropic properties used to model TPS
- Linear elastic fracture parameter $K_I$ used to predict onset of cracking
- Stress intensity calculated using crack face opening displacements assuming isotropic properties

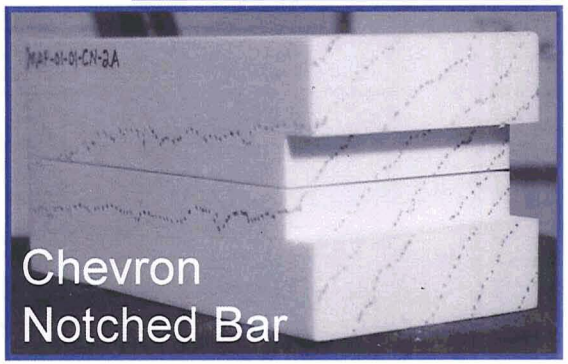
# Linear Elastic Fracture Mechanics

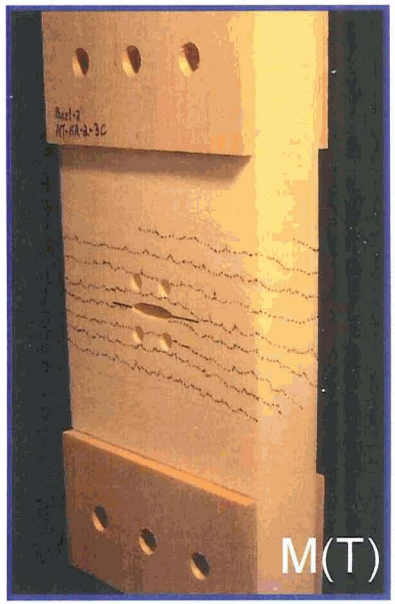
## Experimental Substantiation of LEFM as an Engineering Tool

- Correlation of failure
  - Stress intensity factor, K, predicts failure load accurately
- Consistent measure of toughness across geometries and loading conditions
  - Toughness found to be consistent, within expected material variability, for all cracked geometries tested. Provides substantiation for use of a single parameter fracture criterion (K).
- Linear load-displacement records during test
  - Linear elasticity prevails for all standard test geometries at temperatures <= 70F.



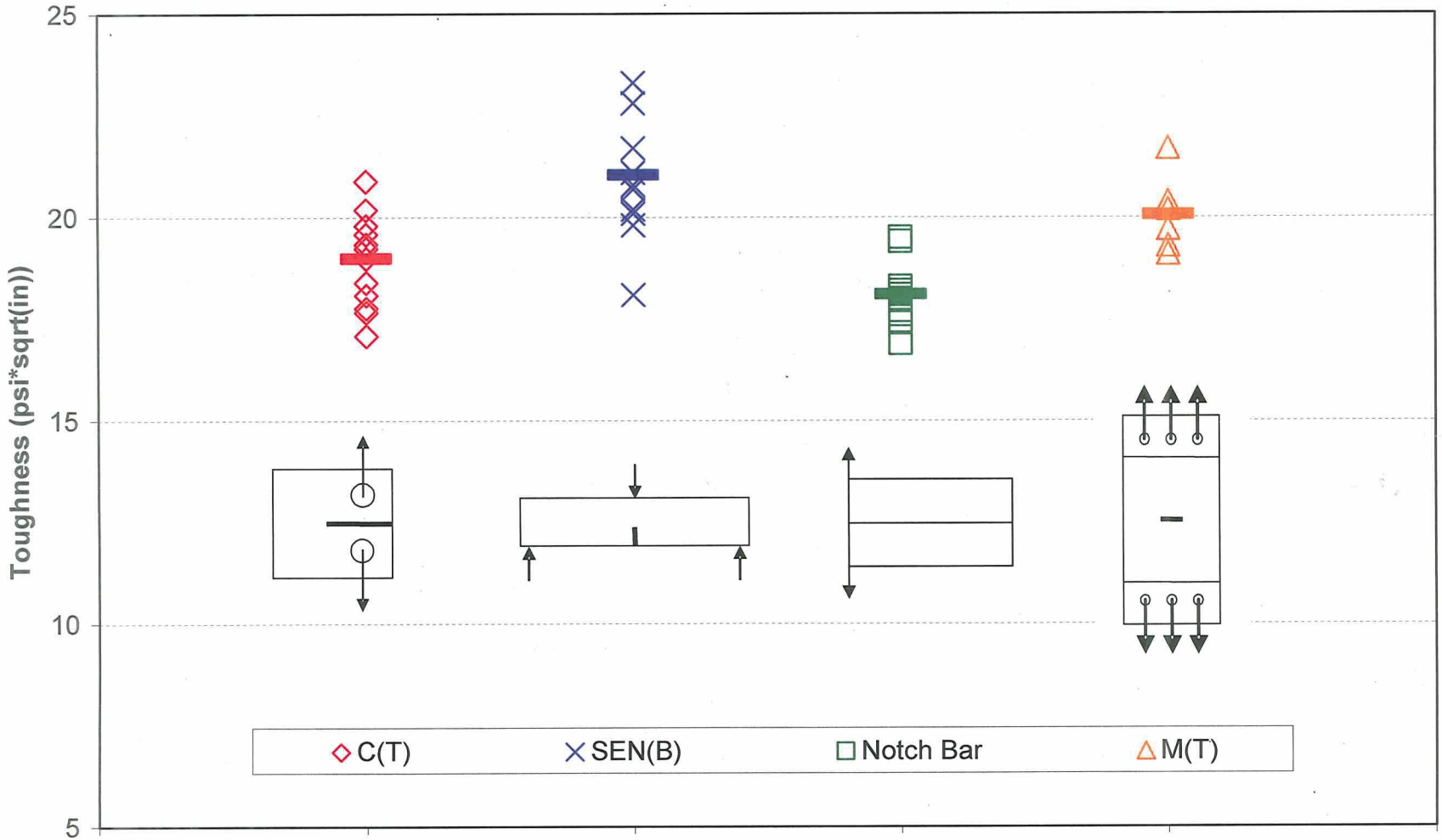





# Linear Elastic Fracture Mechanics

## LEFM Consistency Across Geometries



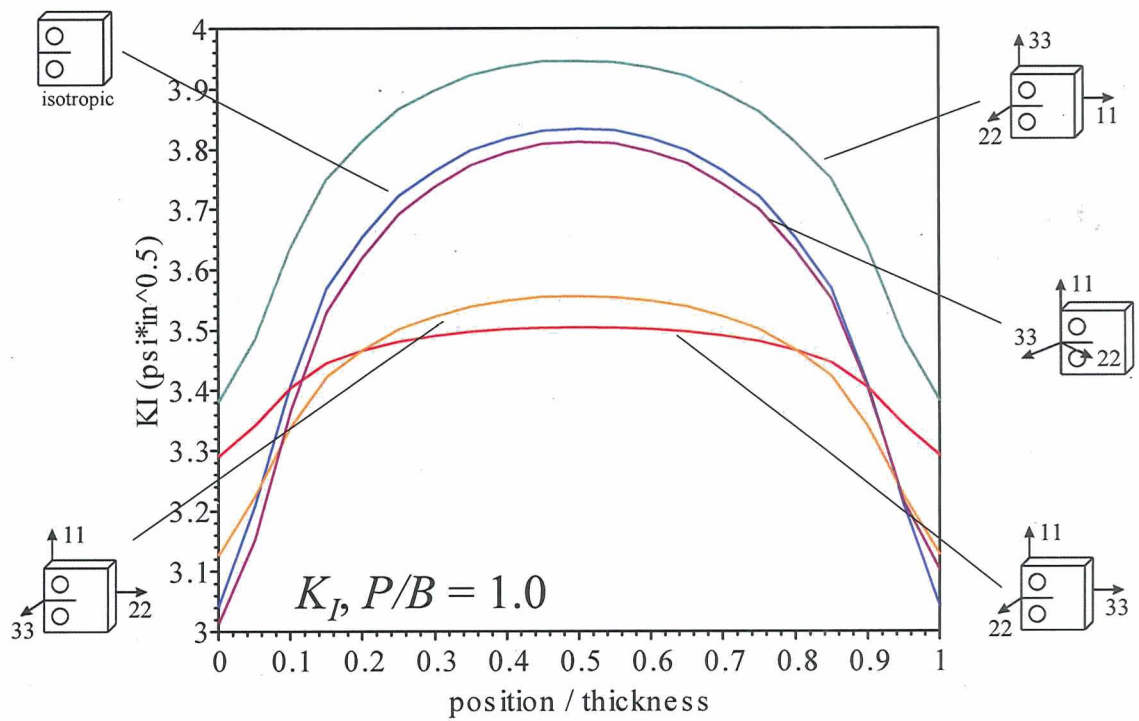
# Anisotropic Effects

- Experimental substantiation tests indicate that application of the stress intensity factor using isotropic homogenous assumptions is a valid engineering approach as long as all length scales for the cracked body (crack length, ligament, thickness, etc.) are very large compared to the cellular microstructure.

- The effects of anisotropic material behavior on the K-field and mixed-mode contributions have been modestly investigated and found to introduce error on the order of 10%.

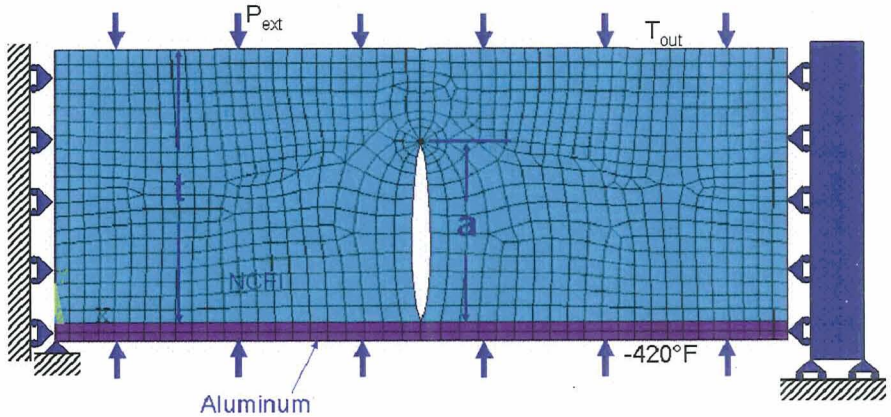
Assessment performed by
Dr. Paul A. Wawrzynek and
Dr. Bruce J. Carter

Fracture Analysis Consultants, Inc.



# Flat Panel Crack Growth Resistance

## Subsurface Normal Crack Resistance Curves

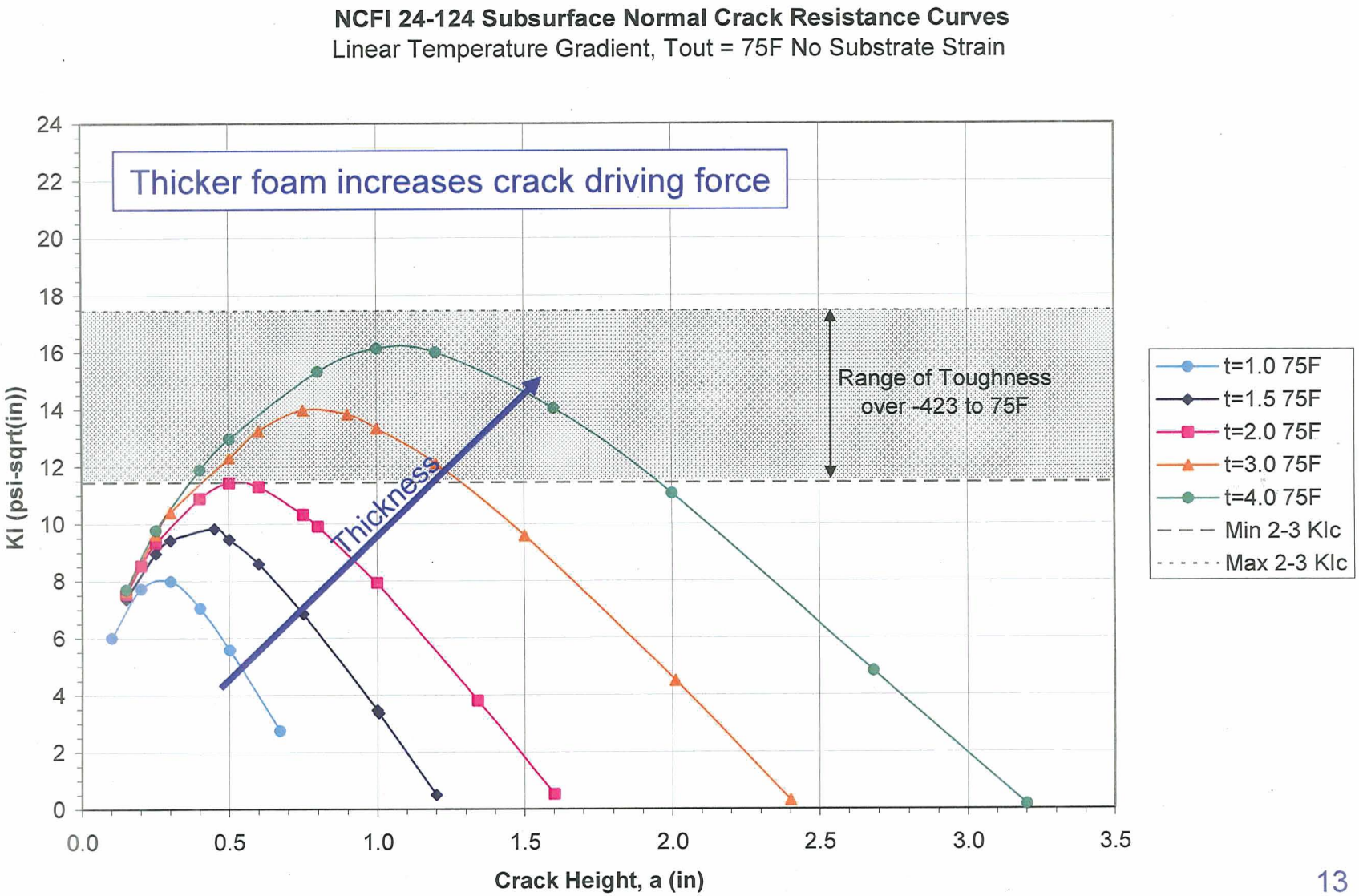



- Determined using simple 3D FE model
  - Foam on a flat 0.25" substrate
  - Through crack normal to the substrate
  - Symmetry boundary conditions simulating an infinite acreage
- Linear thermal gradient
  - -420°F at the substrate
  - 75 or 0°F at the outer surface
- Substrate uniaxial stress (60ksi) applied in some cases
- Orthotropic material properties (rise direction normal to substrate)
  - Crack in 1-3 orientation
- NCFI alone and NCFI under PDL or BX-265

- Stress intensity calculated using ANSYS *kcalc* fit to crack face opening displacement
  - Uses isotropic in-plane properties to calculate KI

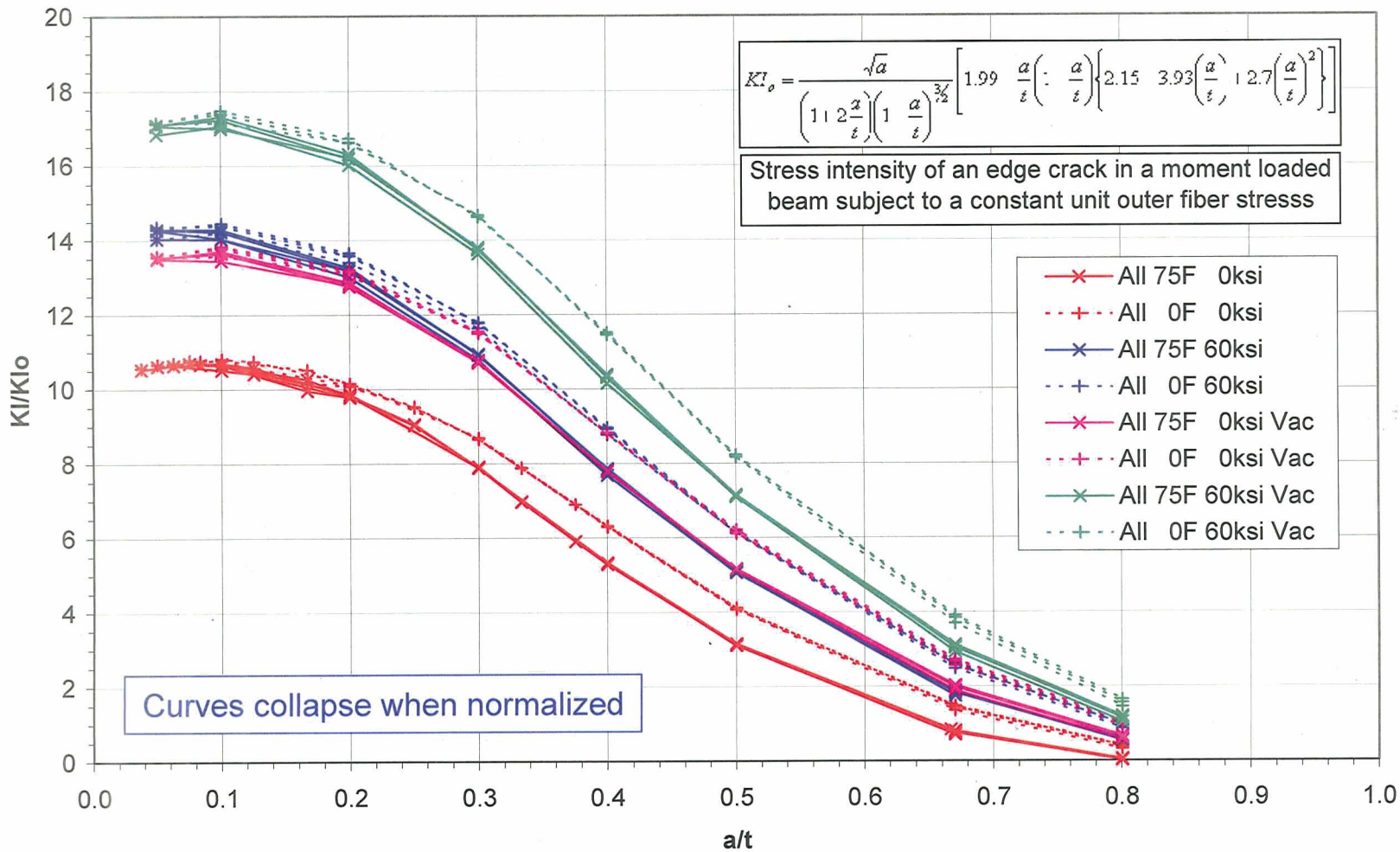
- Stress intensity compared to range of KIc in the 2-3 direction

# NCFI Flat Panel R-Curves



# NCFI Flat Panel R-Curves

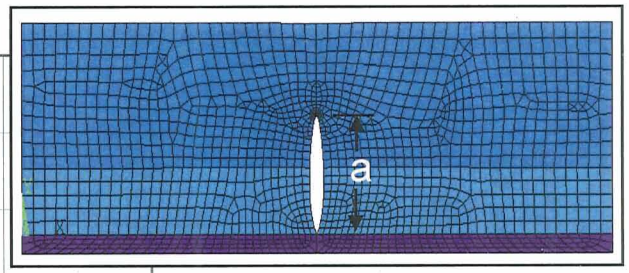
- Substrate stress and vacuum significantly increase stress intensity
- Colder outside surface temperature affects results near the surface

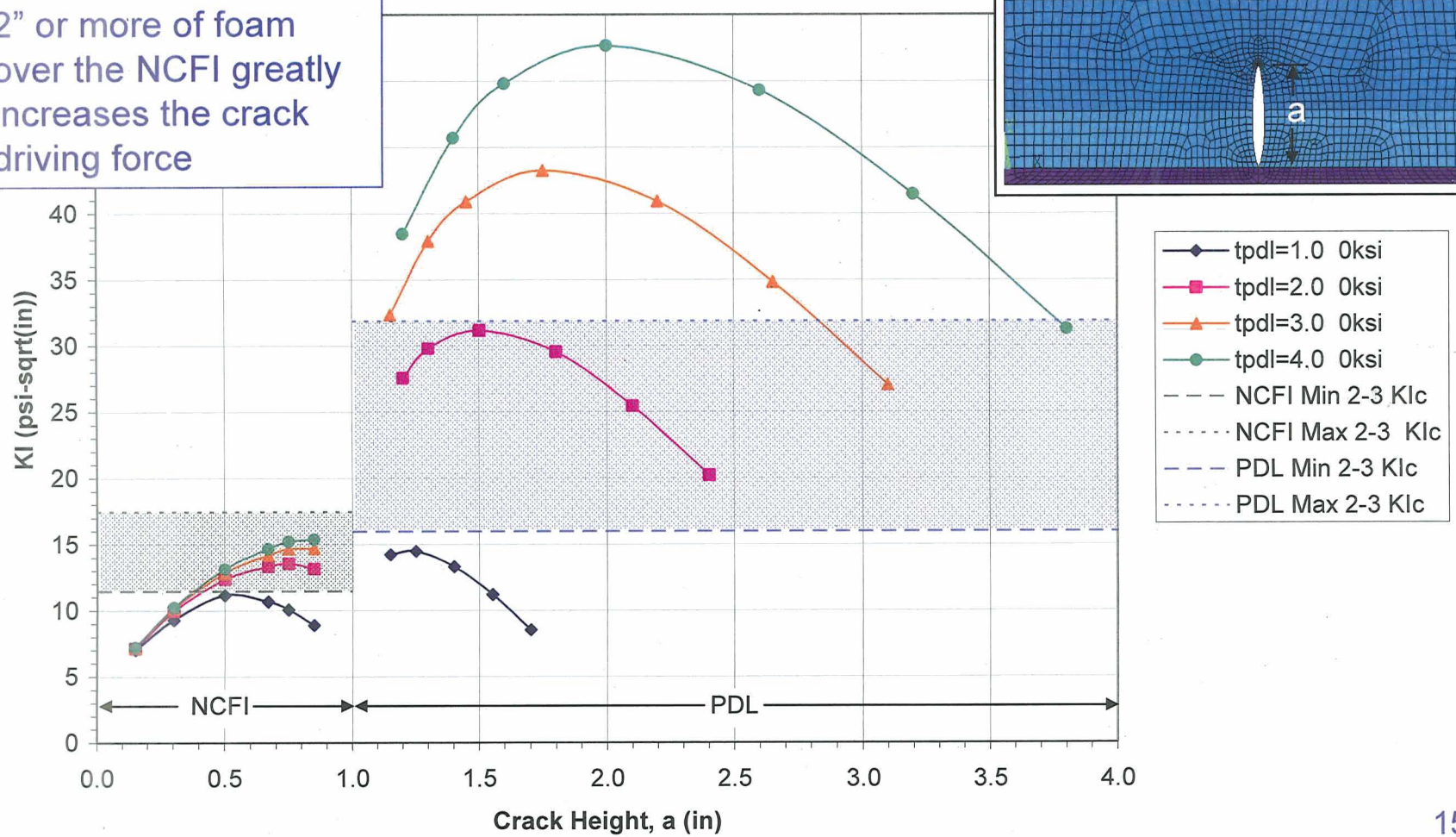


# NCFI Under PDL R-Curve

**PDL 1034 over NCFI 24-124 Subsurface Normal Crack Resistance Curves**
Linear Temperature Gradient, Tout = 75F, NCFI Thickness = 1.0in

2" or more of foam over the NCFI greatly increases the crack driving force



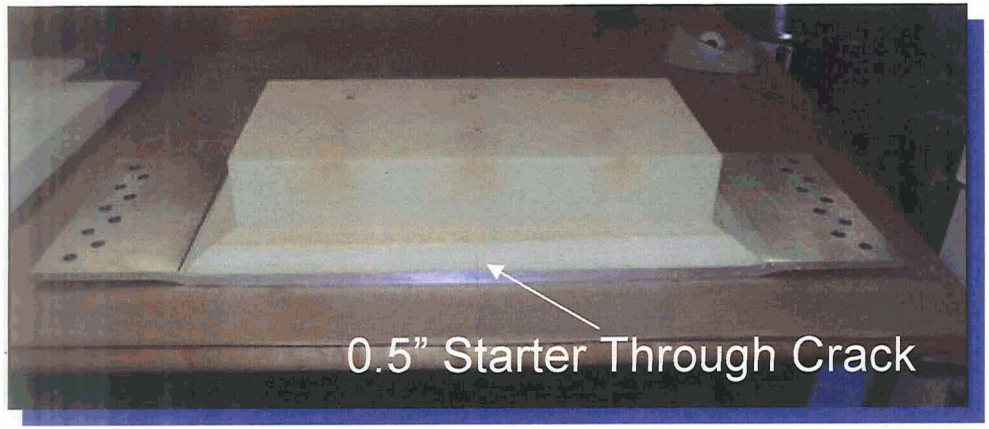



# Orthogrid Tensile Test Panel

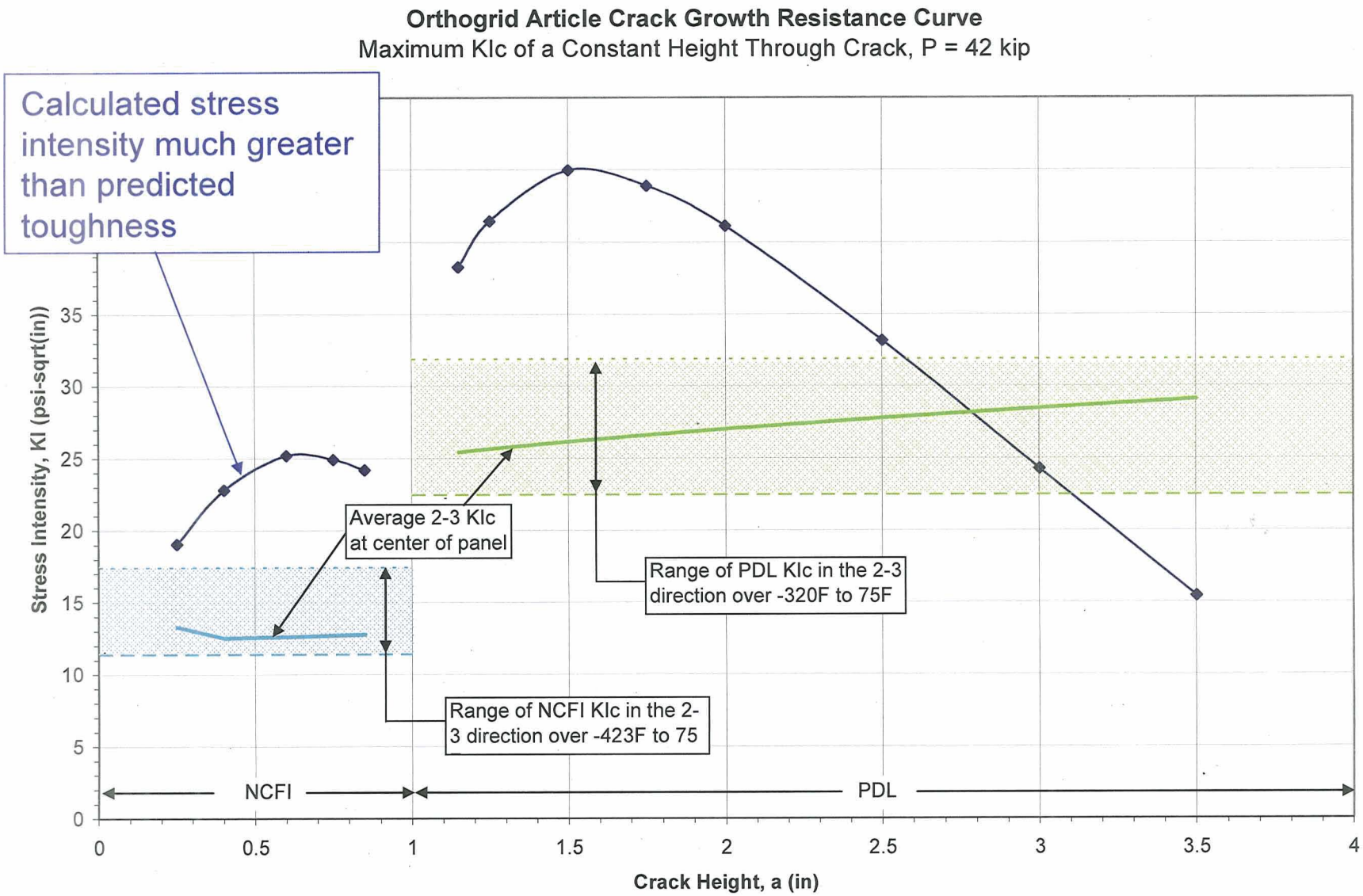
## Panel Description

- 12" wide uniaxial tensile panel
- Aluminum substrate
- 1" thick NCFI under 3.3" of PDL
- Orthogrid stiffener pattern in gage section
- Includes ½" starter through crack
- Substrate is chilled with liquid helium
- Maximum load is 75,000 lb

- Two panels tested so far
  - Panel 1: Starter crack extended at 42 kip
  - Panel 2: No noticeable crack growth

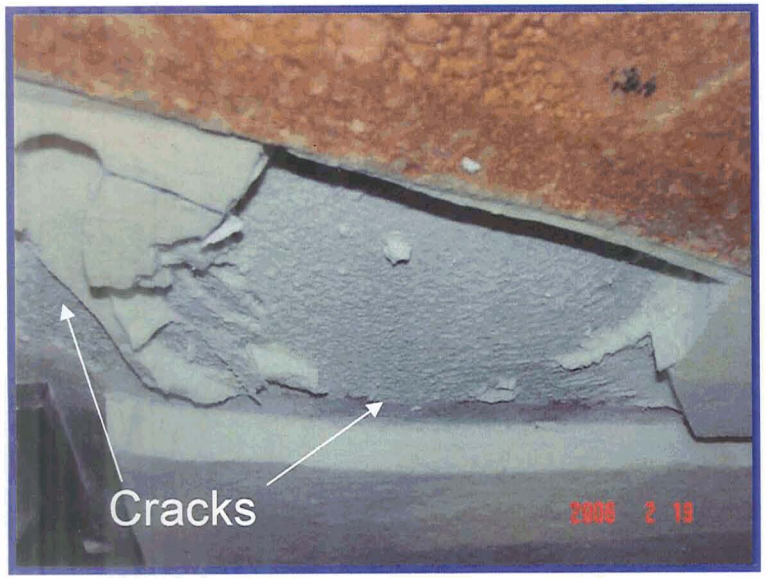


# Orthogrid Tensile Test Panel R-Curve



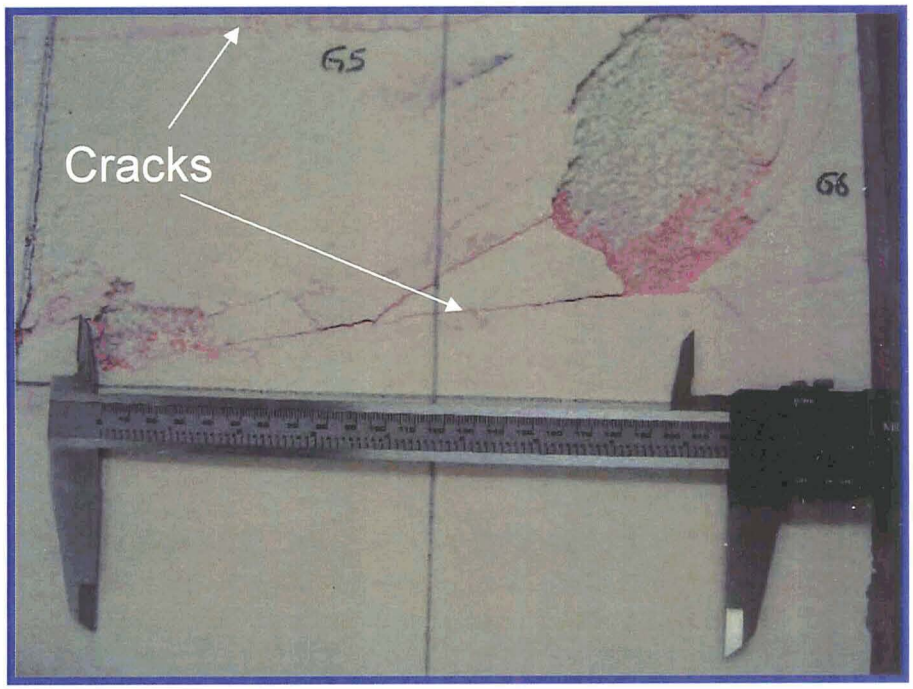
# Delaminations

- At sufficient load cracks will form which may initiate a delamination near the substrate
- Cracks introduce a peel and shear stress concentration
- Delaminations often occur just above the substrate near the first knitline

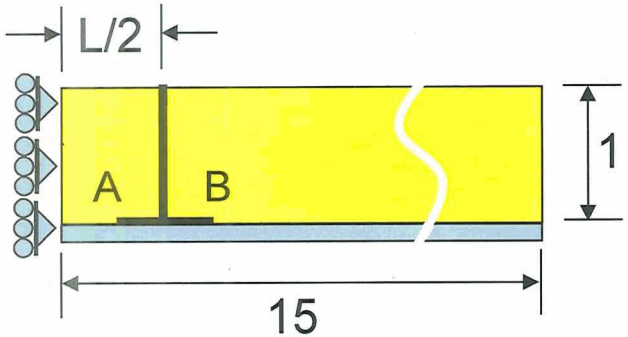



LH2 Ice-Frost Ramp

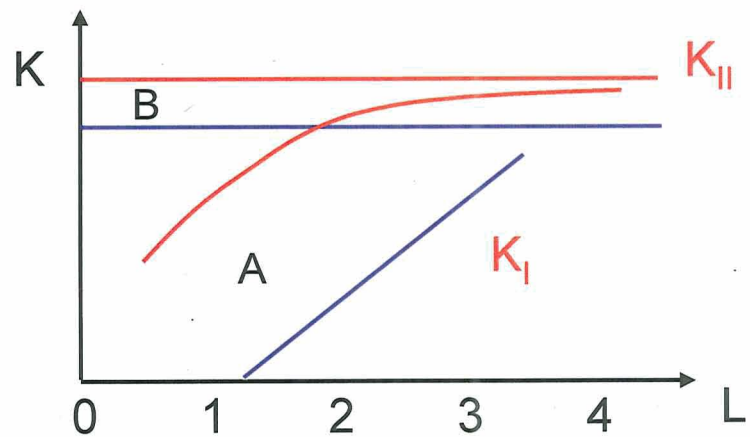
Wide Panel Test



# Thermal Crack and Delamination Interaction

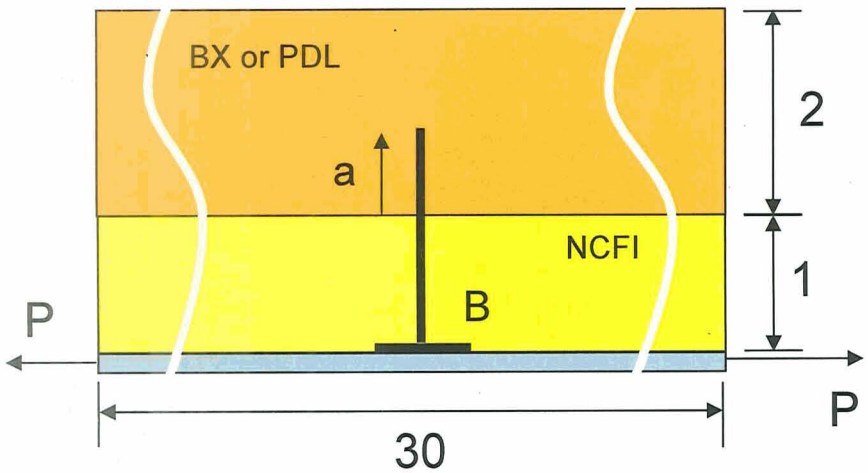



- Delamination interface cracks at A and B are 0.25 long
- Loading by uniform $\Delta T$ = -493F




- ABAQUS 2D plane strain model, domain integral for K evaluation
- Parametric assessment performed, small subset shown
- Observations on thermal crack and delamination interaction effects:
  - Delamination is most commonly observed between thermal cracks
  - $K_I$ and $K_{II}$ driving forces are reduced if thermal cracks are within 4 to 5 inches of each other
  - Additional contributors to the mode I and II driving forces between the thermal cracks are likely required to create and propagate delamination

# Delamination Crack Driving Forces




Loading: Thermal equilibrium gradient (-423F to 70F) and substrate strain

| P → | 0 | 60ksi | 0 | 60ksi |
|---|---|---|---|---|
| a ↓ | $K_I$ | $K_I$ | $K_{II}$ | $K_{II}$ |
| 1 | 5 | 30 | 14 | 22 |
| Thru | | | 14 | 24 |

Vertical Delamination

- ABAQUS 2D plane strain model
- Domain integral for K evaluation
- Large parametric assessment performed, small subset shown
- Observation on substrate strain effects:
  - Generally adds approximately 15-20% to thermal stresses
  - Influence on crack driving forces is more significant
  - Vertical (thermal) crack $K_I$ can be strongly affected, 6x in this example
  - Interface (delamination) crack $K_{II}$ reflects 2x factor in this example

# Conclusion

- Linear elastic fracture mechanics is a good tool to describe fracture in rigid polyurethane foams
- Currently do not have a good indicator to predict crack initiation in foam on a cryogenic substrate
  - Related to peak stress and stress gradient through the thickness
- Thick foam and foam-over-foam applications have a greater crack driving force to propagate cracks toward the surface
- Orthogrid panel results show less propensity to grow a crack than predicted analytically
- Substrate strain significantly increases the delamination driving force