

# **NDE Technology for Ceramic Composites**

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# OUTLINE

## ■ NDE TECHNOLOGIES FOR GAS TURBINE CMC COMBUSTOR LINERS

- ◆ Porosity detection
- ◆ Delamination detection
- ◆ Detection of adhesion of Environmental Barrier Coating (EBC)
- ◆ Impact damage assessment/Repair

## ■ NDE TECHNOLOGIES FOR ROTATING COMPONENTS

- ☞ Impact resonance

## ■ SUMMARY/CONCLUSIONS

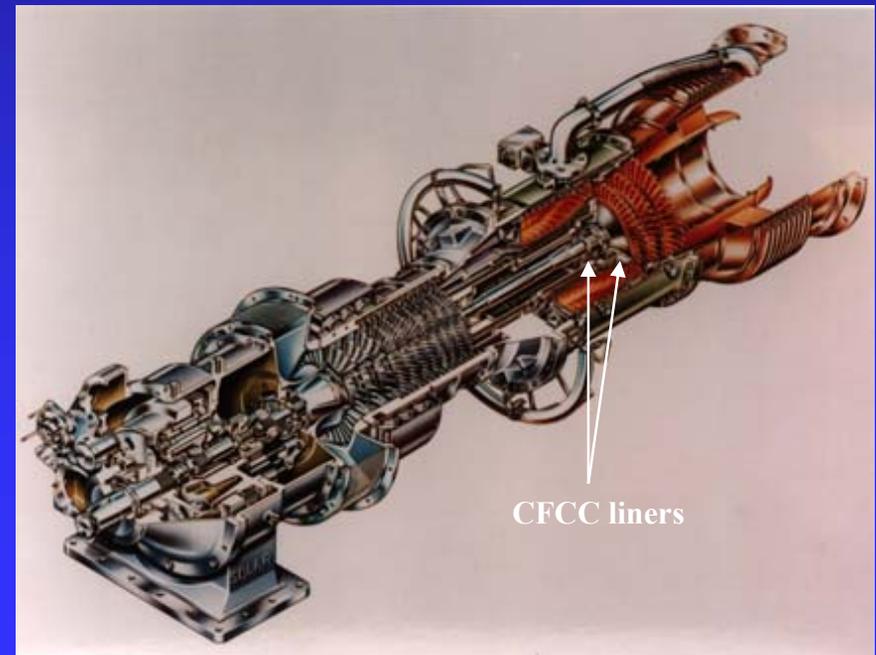
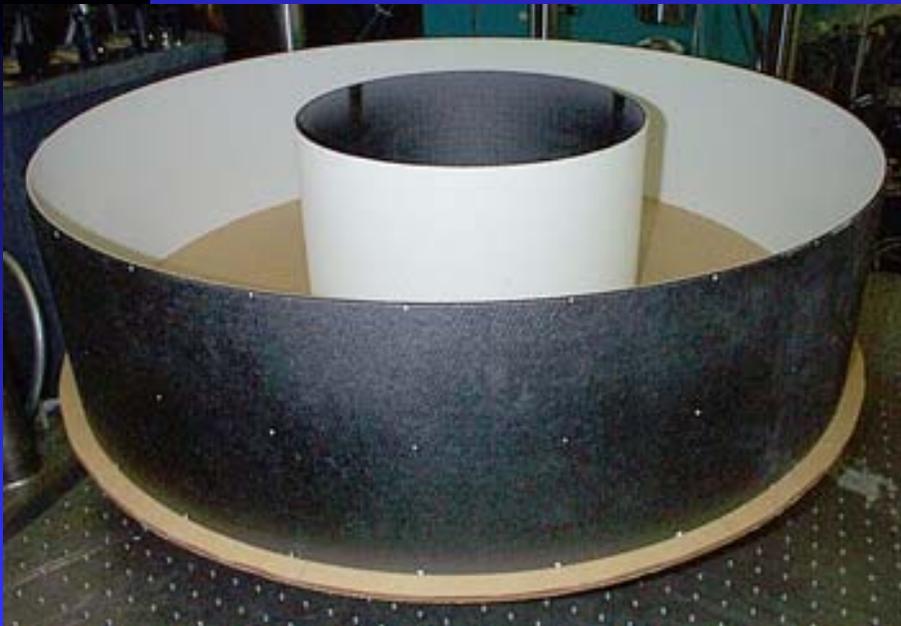


## Solar Turbines Combustor Liner

**EBC coated continuous fiber ceramic composite components in field tests of stationary gas turbine engines**

Outer Liner - 30" diameter

Inner Liner - 13" Diameter





# NDE Technology used for determining extent of oxidation of SiC/SiC gas turbine combustor liner

75 cm (30")

**Uncoated**

- Oxidation Damage ("white glass")
- Strength Loss
- Embrittlement

**Coated**

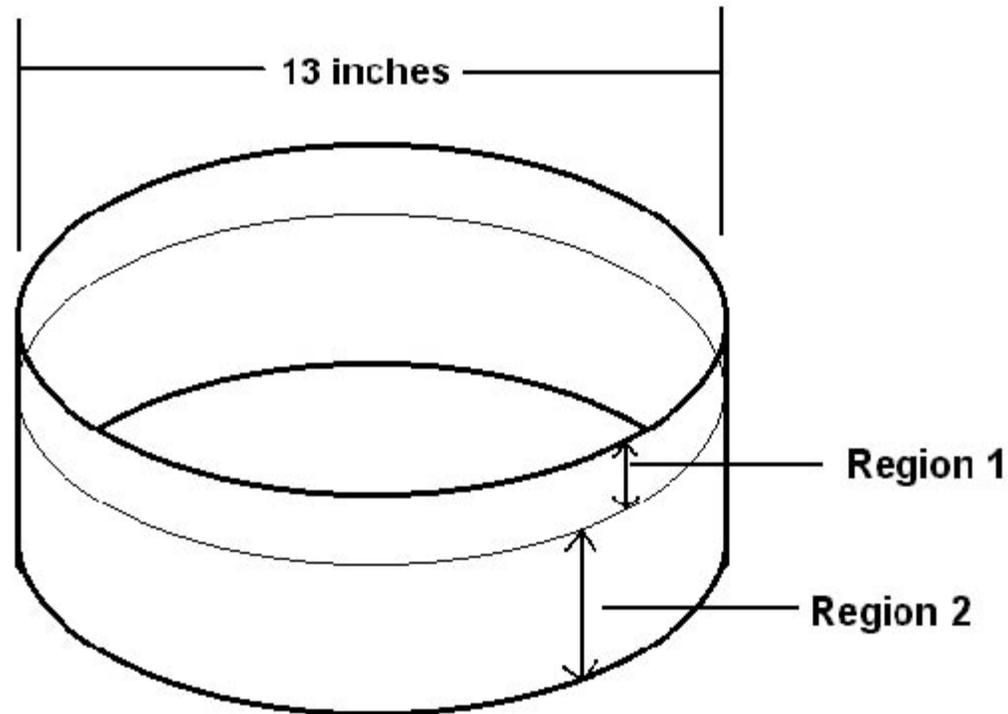
**Upstream**

**Downstream**

**Fuel Injector Locations**

The image contains several photographs and diagrams. On the left, two large circular combustor liners are shown side-by-side. The top one is labeled "Uncoated" and has a dark, textured surface. The bottom one is labeled "Coated" and has a smooth, light-colored surface. A dimension line above the uncoated liner indicates a diameter of 75 cm (30"). To the right of the uncoated liner, a list of effects is provided: "Oxidation Damage ('white glass')", "Strength Loss", and "Embrittlement". An arrow points from the "Oxidation Damage" text to a close-up photograph of a dark, crystalline surface. Below this, a diagram shows a cross-section of the combustor liner with a yellow rectangular area labeled "Upstream" and a white rectangular area labeled "Downstream". Three lines radiate from a point labeled "Fuel Injector Locations" at the bottom, pointing to the upstream and downstream areas.

## EXAMPLE OF USE OF NDE TECHNOLOGIES TO ASSESS MATERIALS PROCESSING ISSUES(Porosity)



Before running in engine

NDE data suggest difference in material density. Unknown at time. Region 2 > Region 1

# Thermal Imaging Hardware

## Automated Thermal Imaging Apparatus for Testing a 13" Liner

Power supply

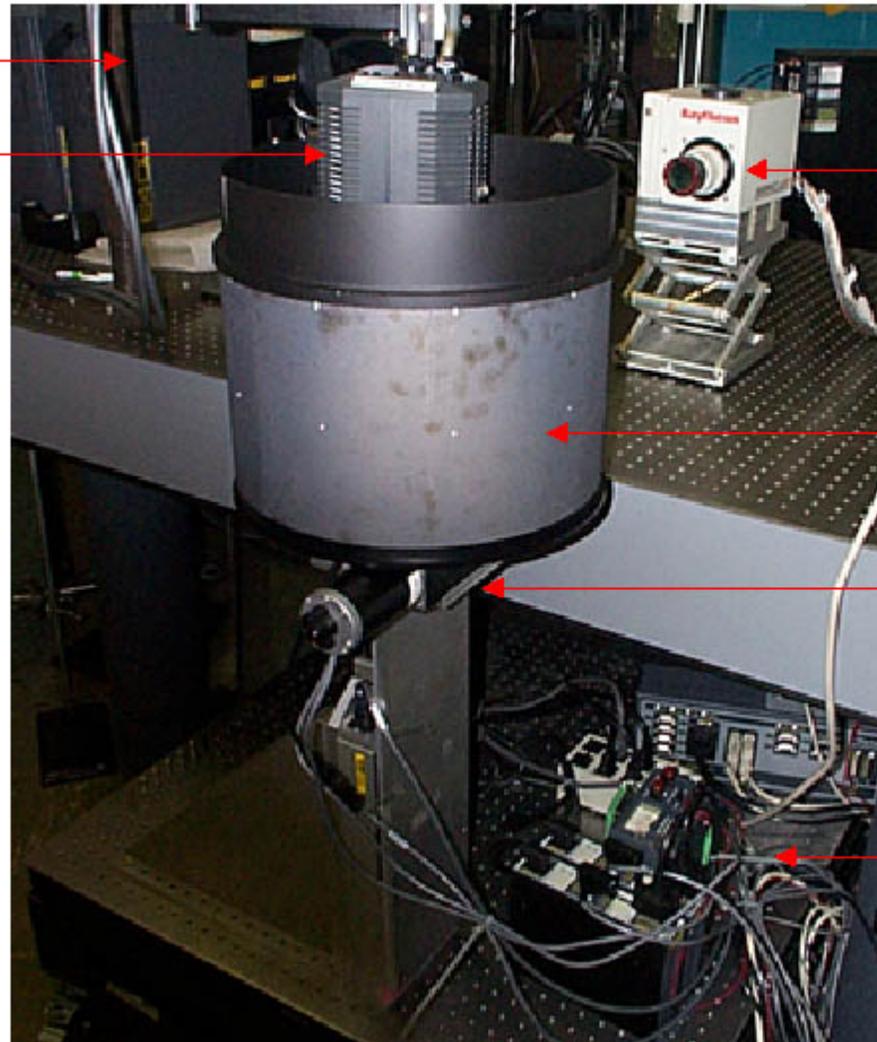
Flash lamp

Infrared camera

A 13-inch Liner

Rotation-translation stage unit

Motion control electronics



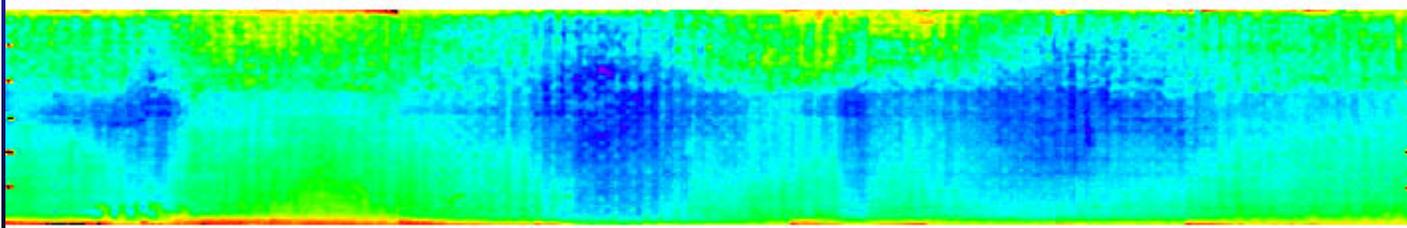


# DETECTION OF POROSITY BY NDE METHODS:: Thermal imaging, water and air-coupled ultrasonics

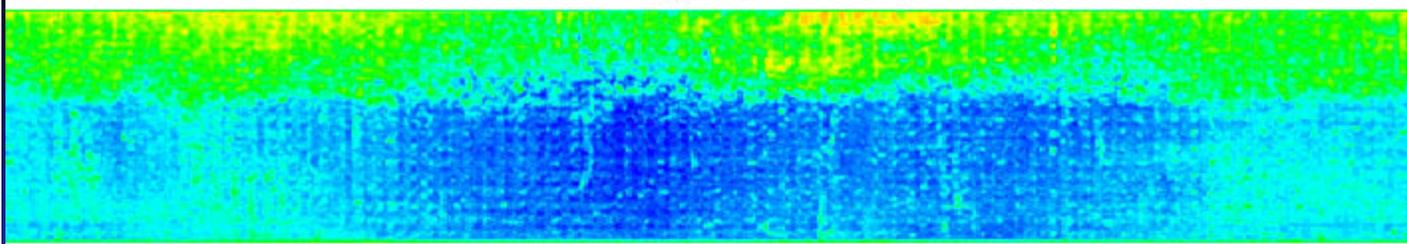
- Correlation to NDE data to SEM data

SEM Image  
(ORNL)

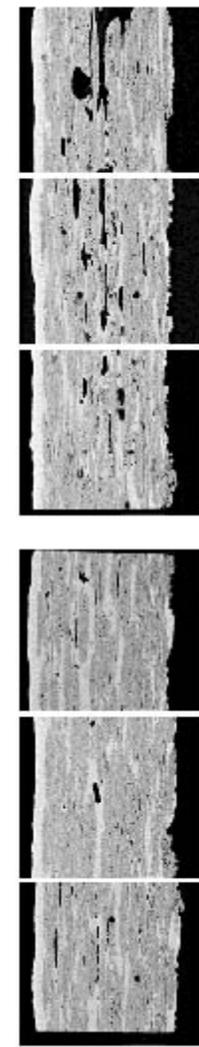
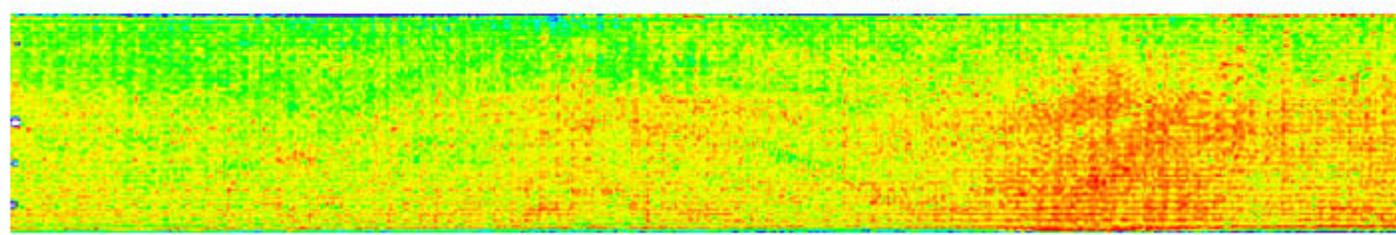
Thermal Diffusivity Image



Water-Coupled UT Image

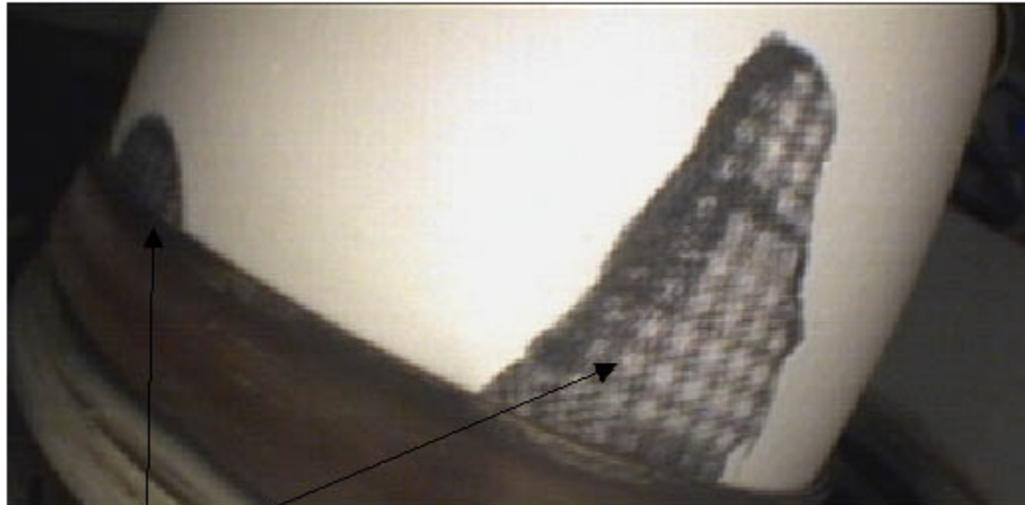


Air-Coupled UT Image

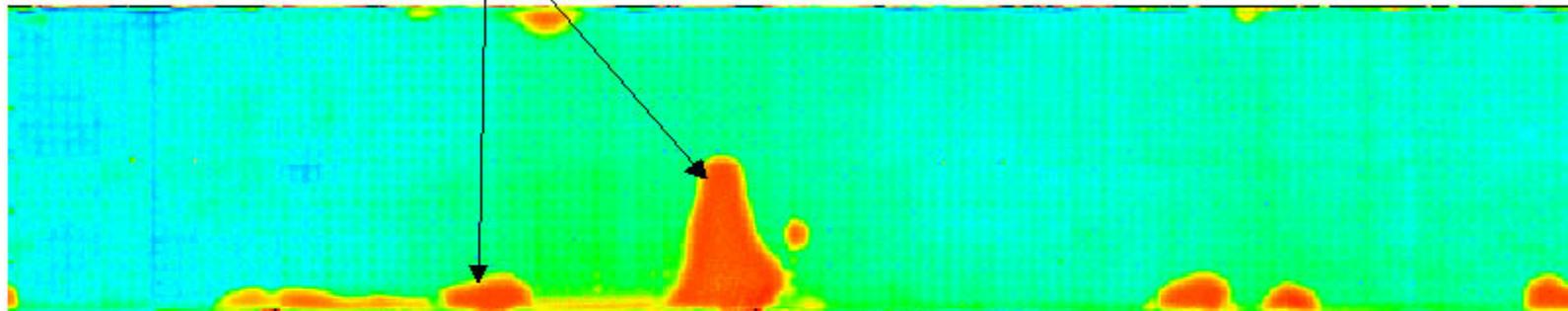


# Correlation of NDE Predicted Damage with Boroscope Observation for EBC Coated Inner Liner in Solar Turbine's Bakersfield Engine

Boroscope Photo (after 1730 hours engine test)



Thermal Diffusivity Image Data (prior to test)



Low diffusivity

High diffusivity





# SPALLATION OF 13" diameter EBC COATING

4533  
hours



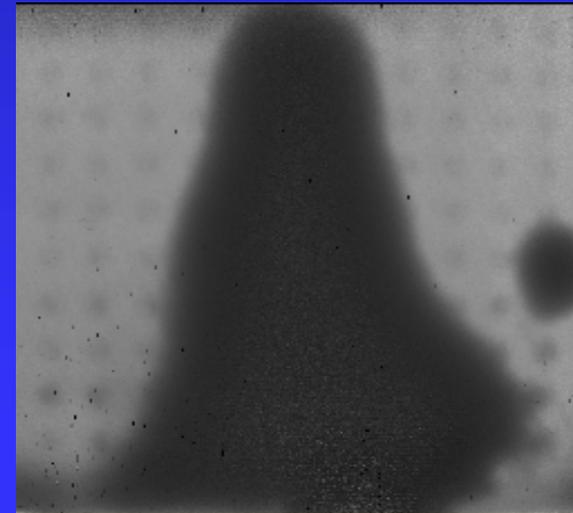
7317  
hours



14,000  
hours

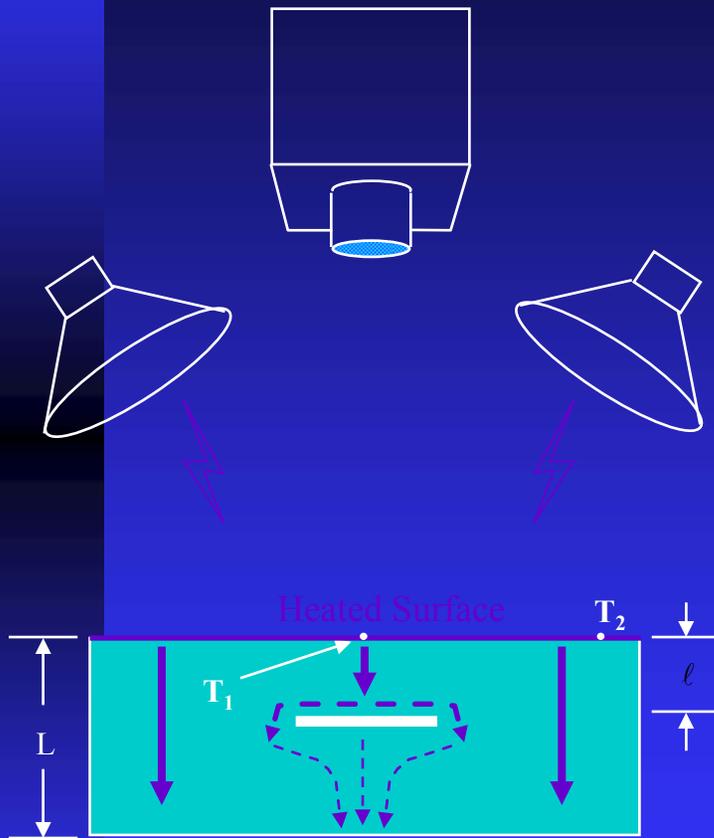


Thermal  
Diffusivity  
Map

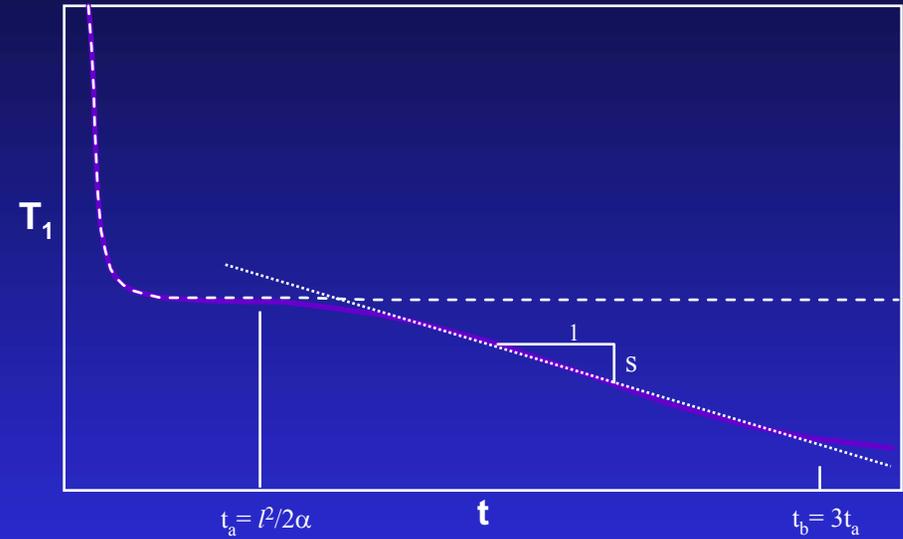


# Analytical method for calculation of defect depth

Thermal imaging system Setup



Typical Surface Temperature Variation

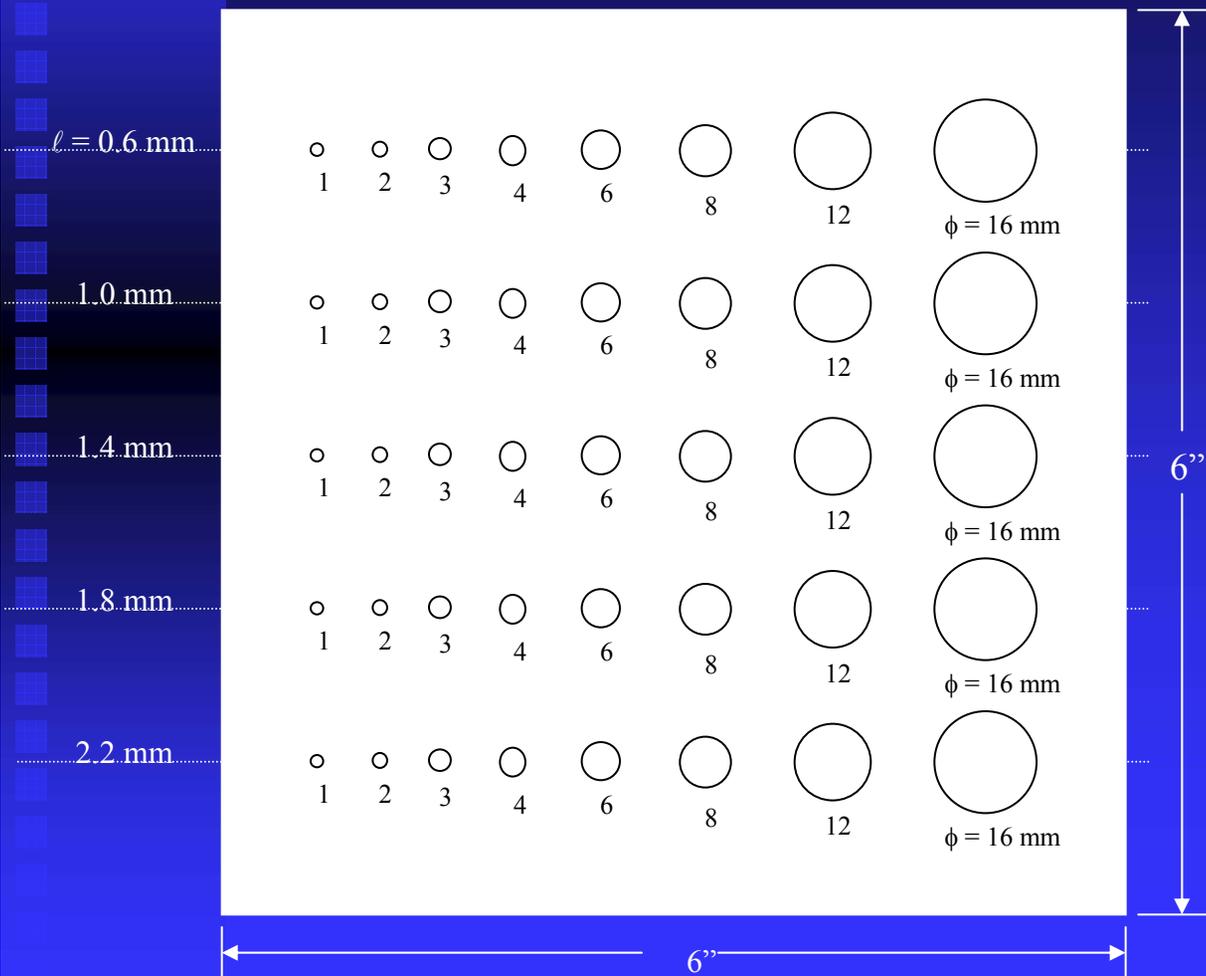


Theoretical model:

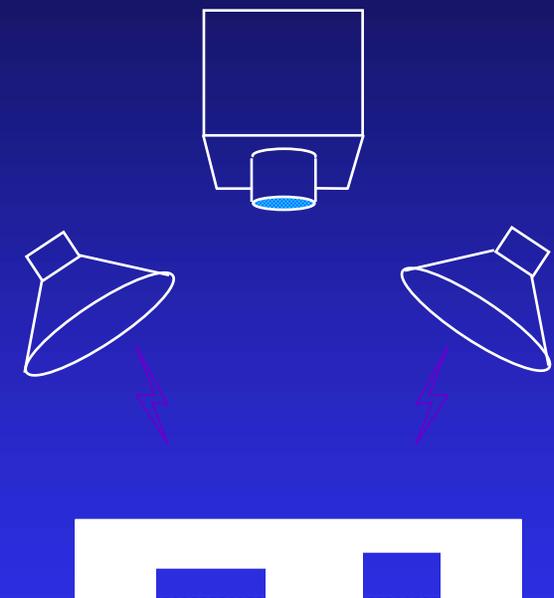
$$T(t) = \left[ 1 + 2 \sum_{n=1}^{\infty} \exp\left(-\frac{n^2 \pi^2}{l^2} \alpha t\right) \right] - st$$

# Measurement of flat-bottom holes in ceramic-matrix-composite (CMC) plates

Machining diagram of CMC plate



Test setup

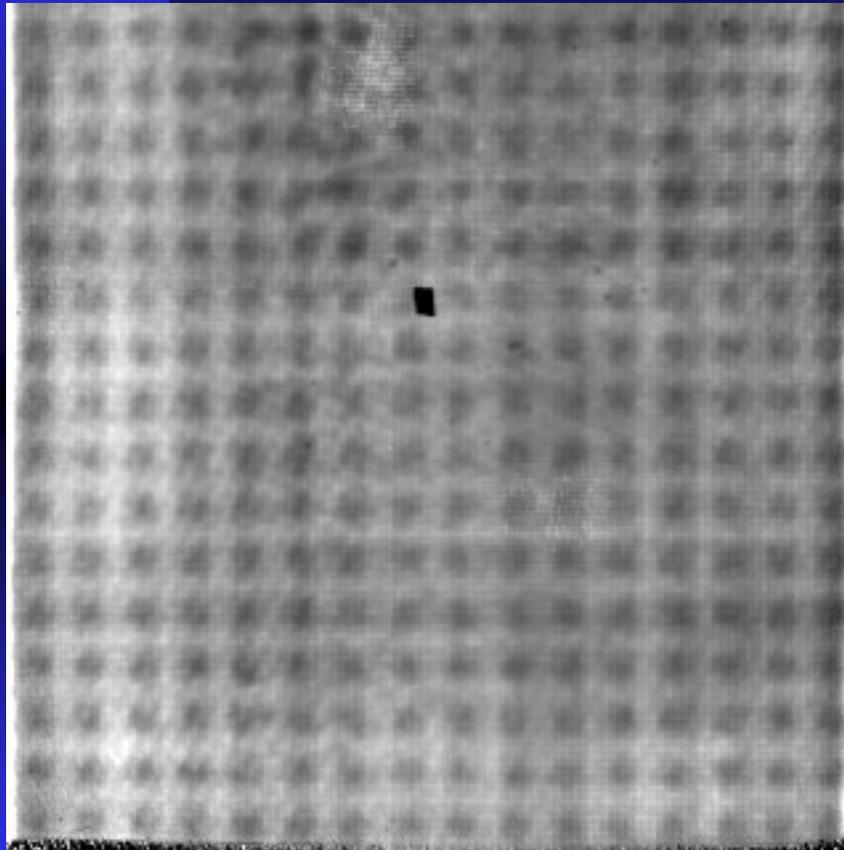


Measure:

- diameter  $d$
- depth  $l$

# Estimating defect depth with thermal imaging

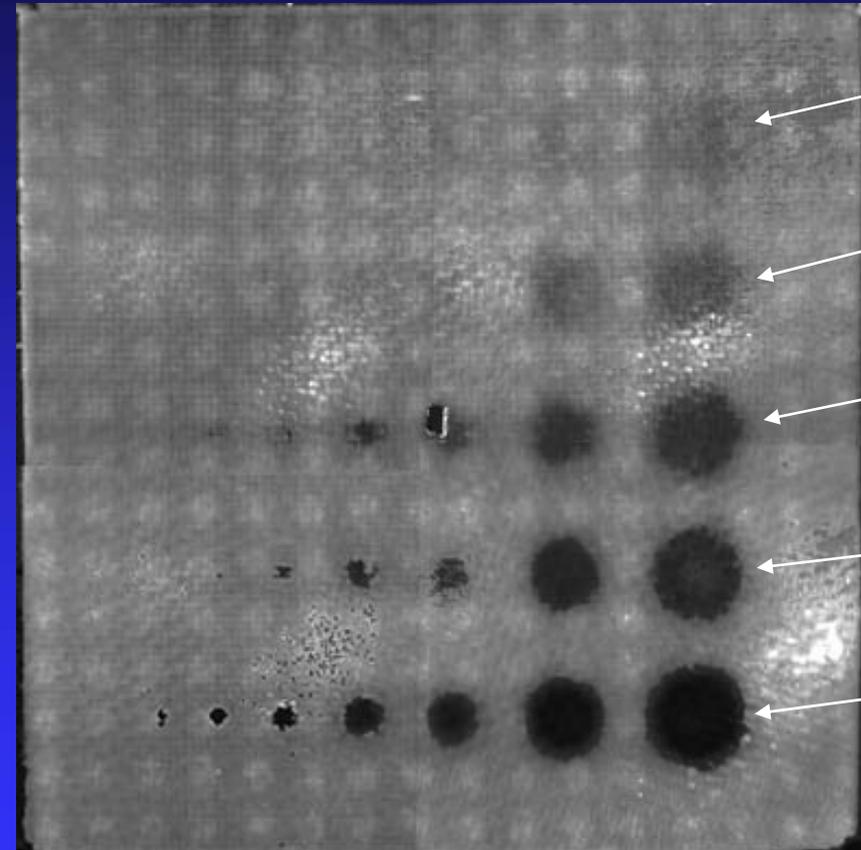
Thermal Diffusivity Image  
- before machining of holes



5 mm<sup>2</sup>/s  9 mm<sup>2</sup>/s

Mean diffusivity =  $7.4 \pm 0.4$  mm<sup>2</sup>/s

Predicted Depth Map  
- after machining of holes



Predicted  
(measured)  
depth (mm)

2.15  
(2.2)

1.86  
(1.8)

1.22  
(1.4)

1.08  
(1.0)

0.51  
(0.6)

0 mm  5 mm

Mean thickness = 2.6 mm

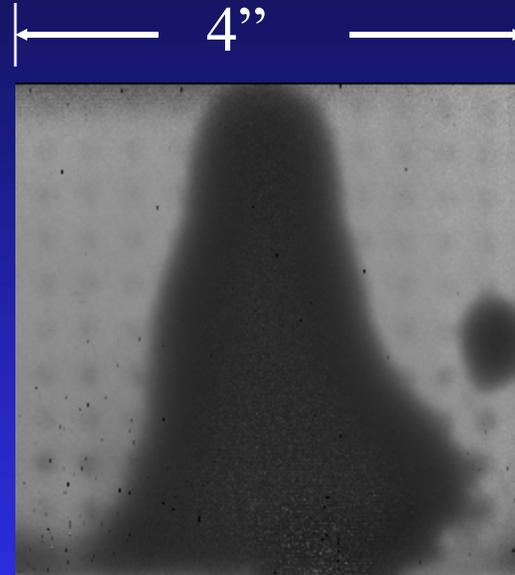
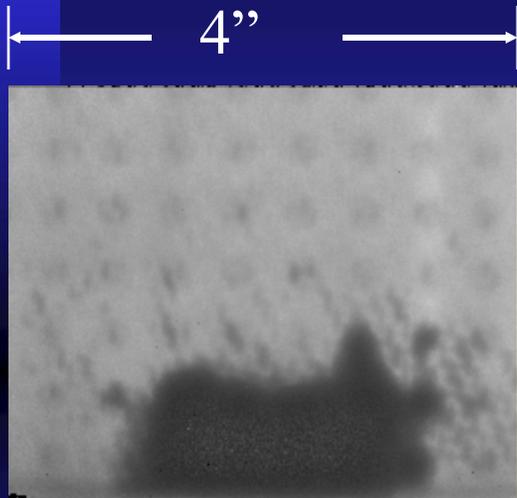


# Effect of Coating Processing on Delam size

AICAC&C  
Cocoa Beach  
2001

Lower Diffusivity

Higher Diffusivity

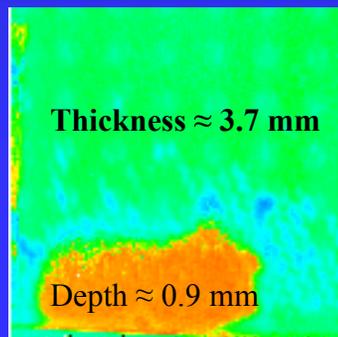
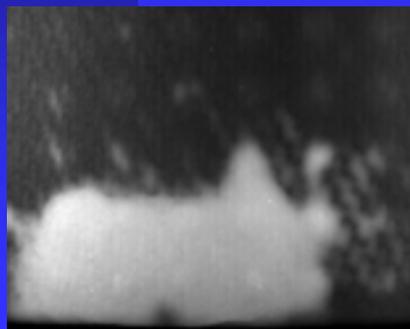


**Delam size Before Coating**

**Delam size After Coating**  
--Note the delam has grown  
In size

**A Front-Flash  
Thermal Image**

**Predicted 2-D  
Depth Image**



Distance of Delam Below surface  
Depth determined from Xray CT = 0.5~1 mm  
Depth determined from thermal imaging = 0.9 mm

t = 0.1 Sec

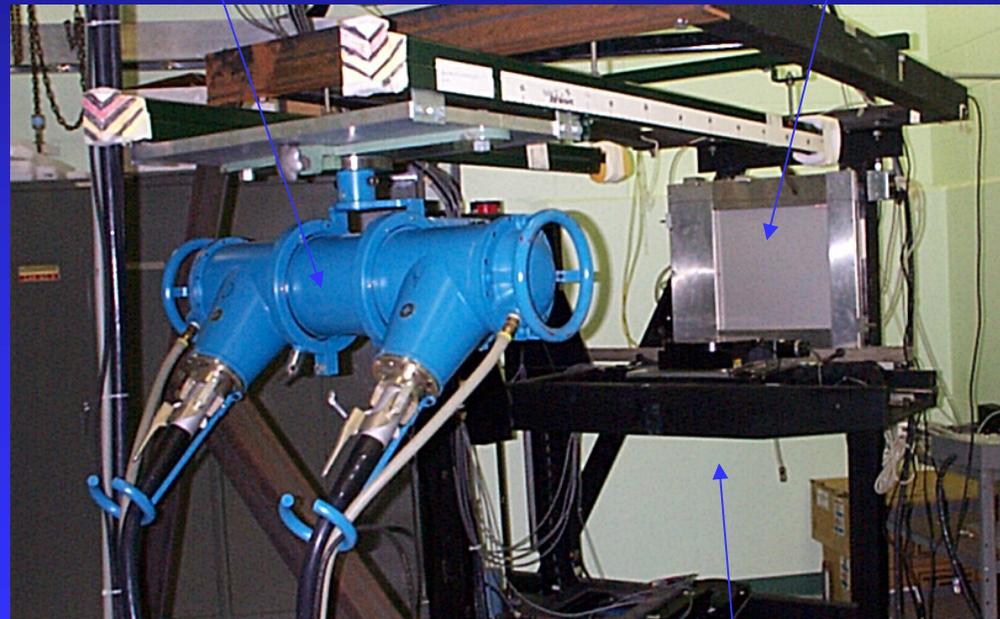


# 3D X-RAY COMPUTED TOMOGRAPHY FACILITY USED FOR ACQUIRING VERIFICATION DATA

TFI 320 kVp X-ray Source

- Max 10 mA
- Spot sizes:
  - 4.0 mm x 4.0 mm
  - 0.8 mm x 0.8 mm

Flat-Panel 40-cm x  
40-cm  $\alpha$ -Si Detector



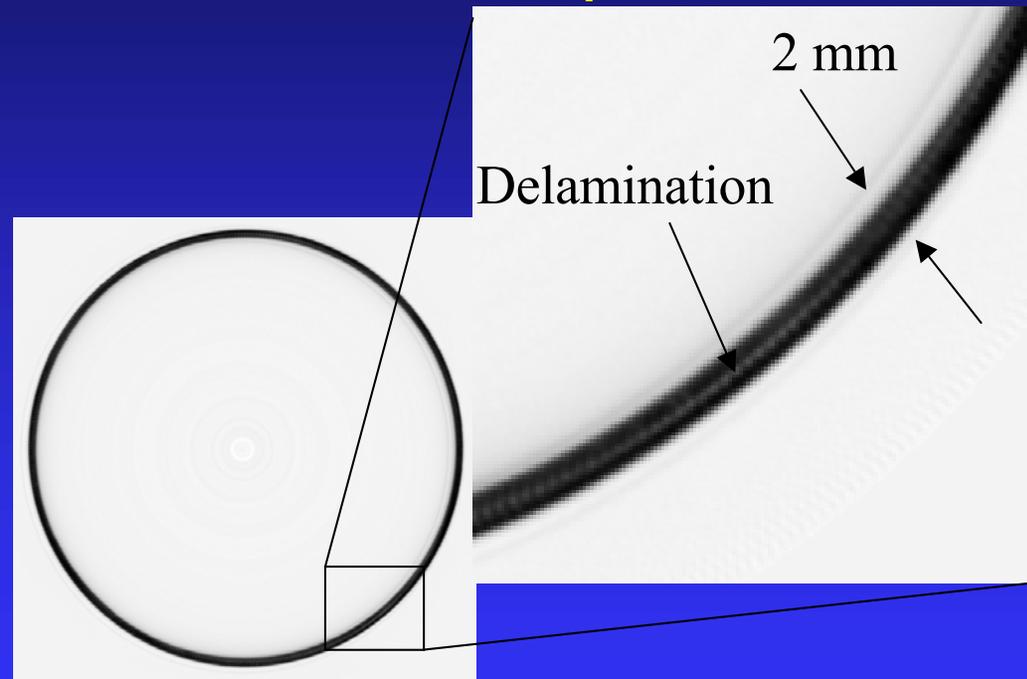
X,Y,Z, $\theta$   
Motion Stages

# EXAMPLE OF X-RAY COMPUTED TOMOGRAPHY FOR DELAM DETECTION

Can handle up to 36 in-diameter



MI SiC/SiC  
Non-Coated





# NDE FOR IMPACT DAMAGE ASSESSMENT

- Cooperative effort with Dow-Corning Corporation

- SiC/SiC (Sylramic<sup>tm</sup>), 76 mm x 152mm
- Polymer Impregnation Process (PIP)
- 8 ply layup ~ 3 mm thick

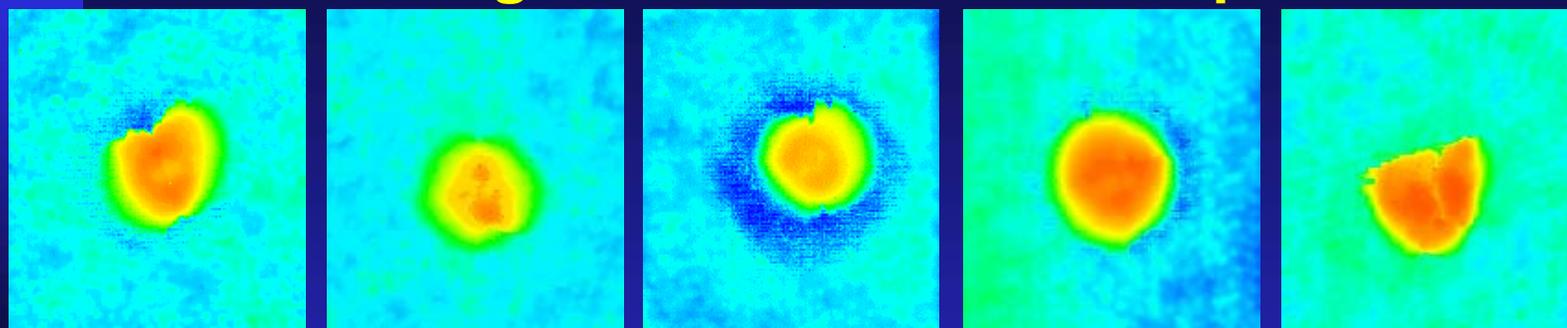
→ Pendulum impactor

→ 12 mm in diameter

## Impact Testing

Specimen	Impact Energy
1	1.36 Joules (1 ft-lb)
2	1.36 Joules (1 ft-lb)
3	2.04 Joules (1.5 ft-lb)
4	3 Joules (2.2 ft-lb)
5	3 Joules (2.2 ft-lb)

# Noncontact Thermal Diffusivity Imaging and Air-Coupled Ultrasound for Assessing Impact Damage Level :: SiC/SiC Composites



D3 (1 ft-lb)

E3 (1 ft-lb)

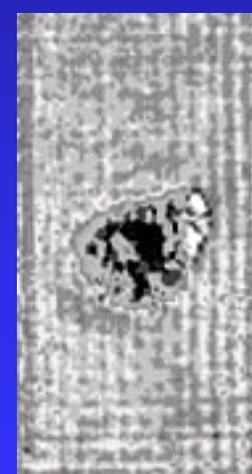
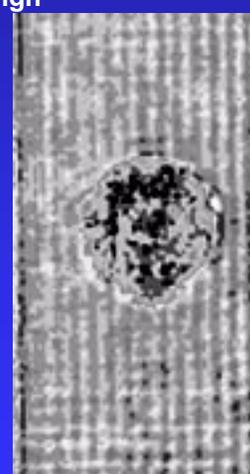
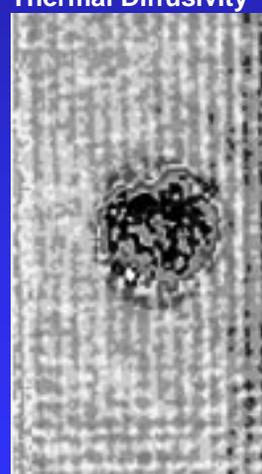
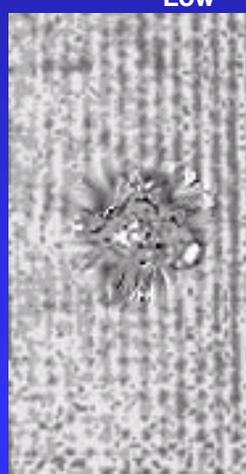
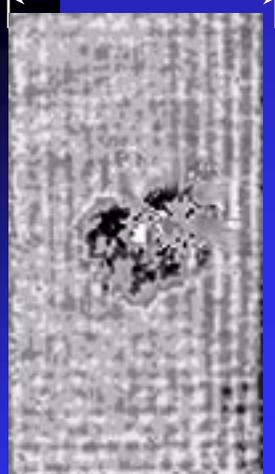
I2 (1.5 ft-lb)

A2 (2.2 ft-lb)

H2-2 (2.2 ft-lb)

75 mm

Low Thermal Diffusivity High



D3

E3

I2

A2

H22

Low Transmission  
(low density, high porosity) 0

25

50  
Through-Thickness Transmission

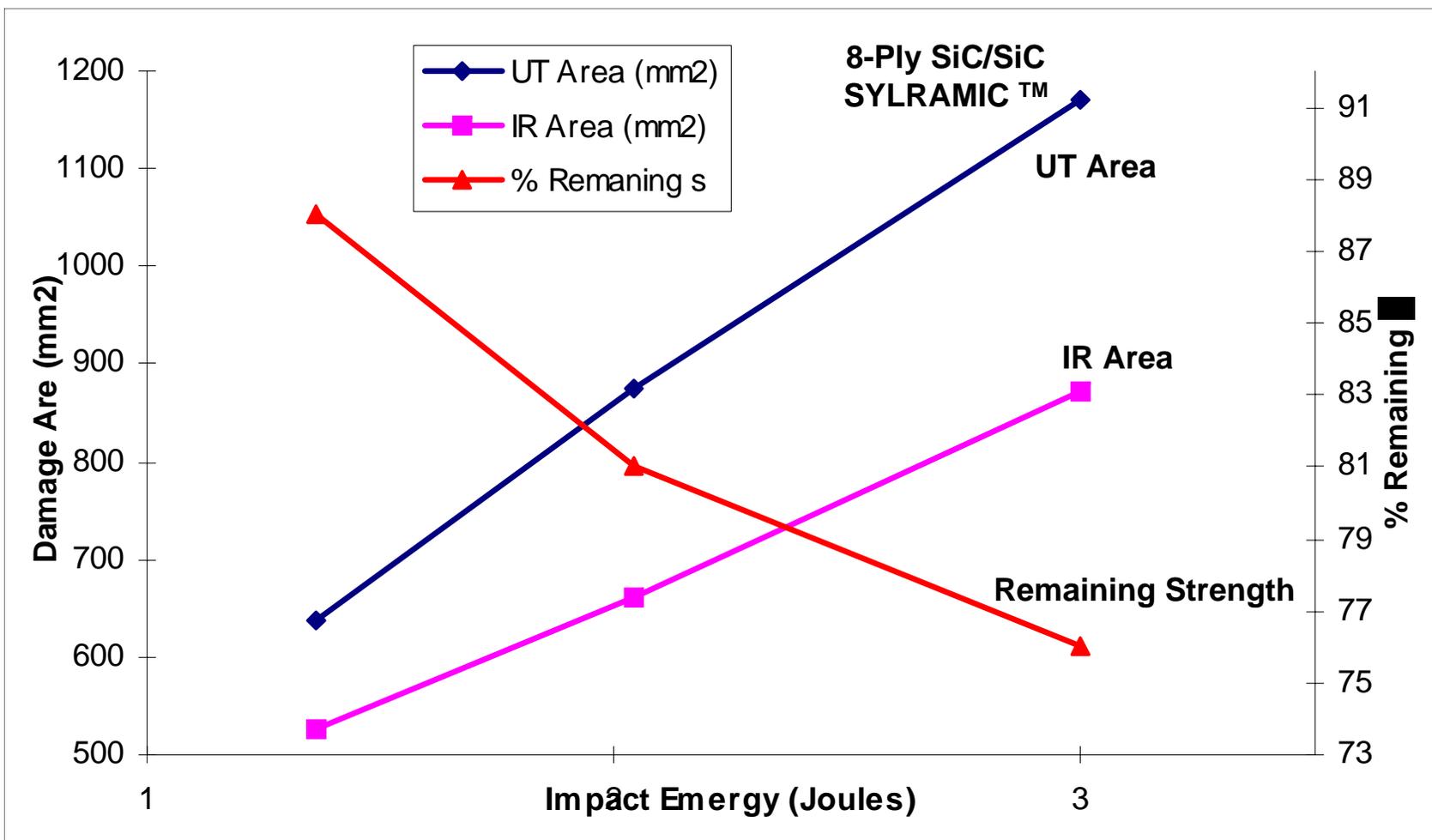
75

100

High Transmission  
(high density, low porosity)



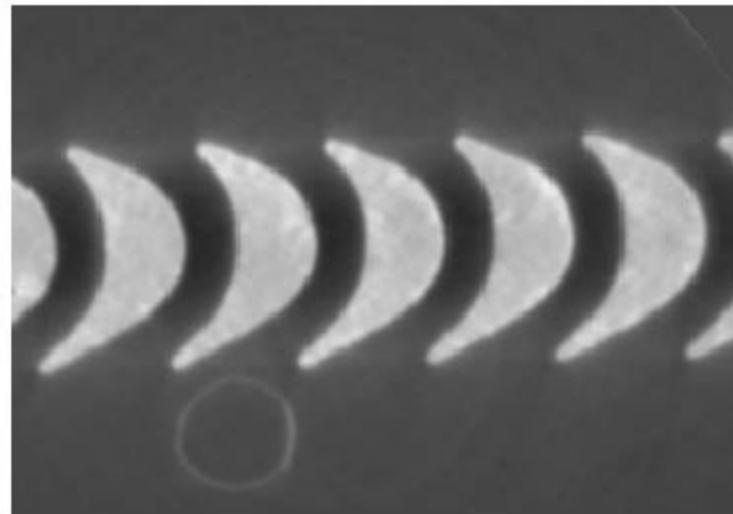
# CORRELATION AMONG: DAMAGE AREA, REMAINING STRENGTH, AND IMPACT ENERGY



# NDE TECHNOLOGY FOR ASSESSING CONDITION OF ROTATING COMPONENTS: C/SiC --Impact Acoustic resonance /Xray Tomography

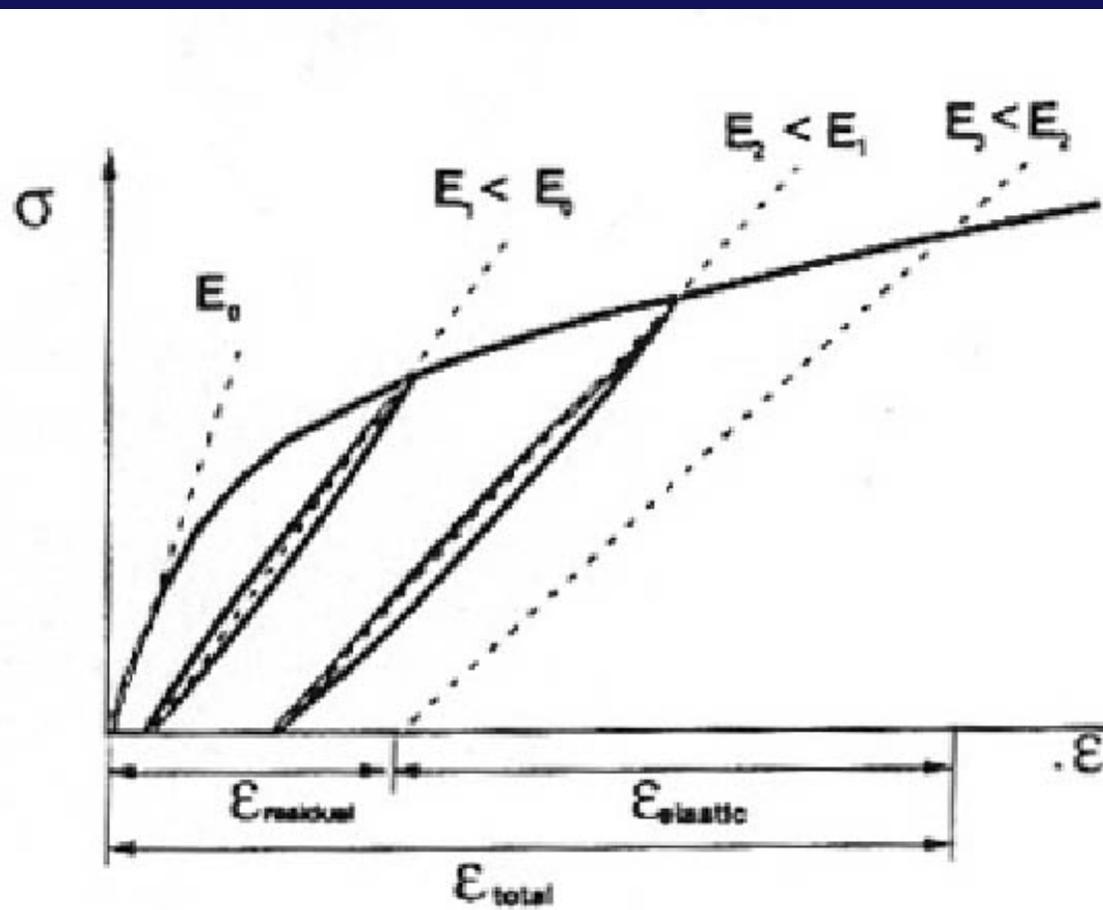


5 blade sections were imaged in 3D X-Ray CT. Each data set 48 .25mm thick X-Ray CT sections per blade. 95  $\mu$ m pixels.



Typical X-Ray CT image through 5 blades

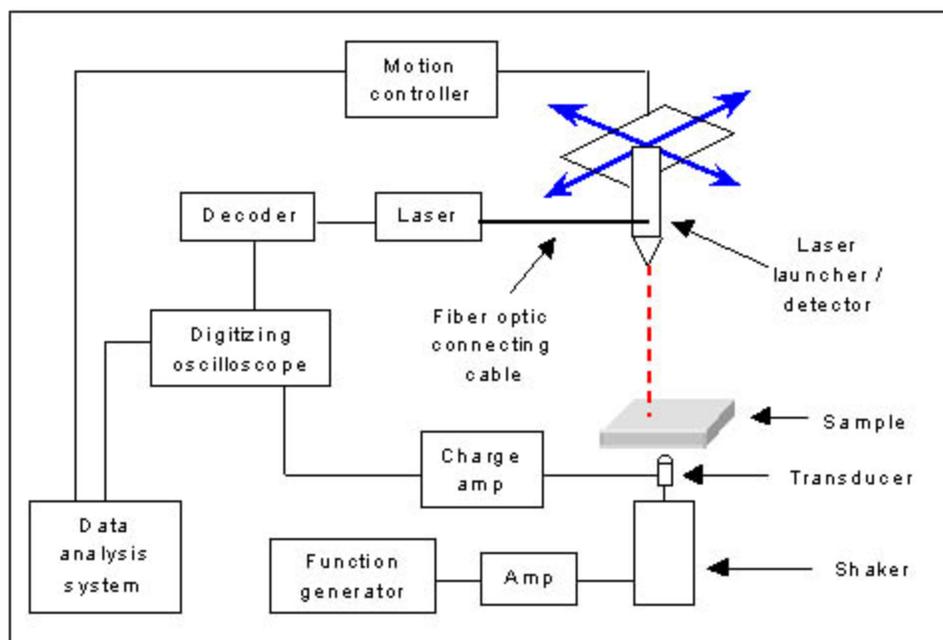
# Effect of load-cycling on elastic modulus For C/SiC



Typical Tensile/Relation Test

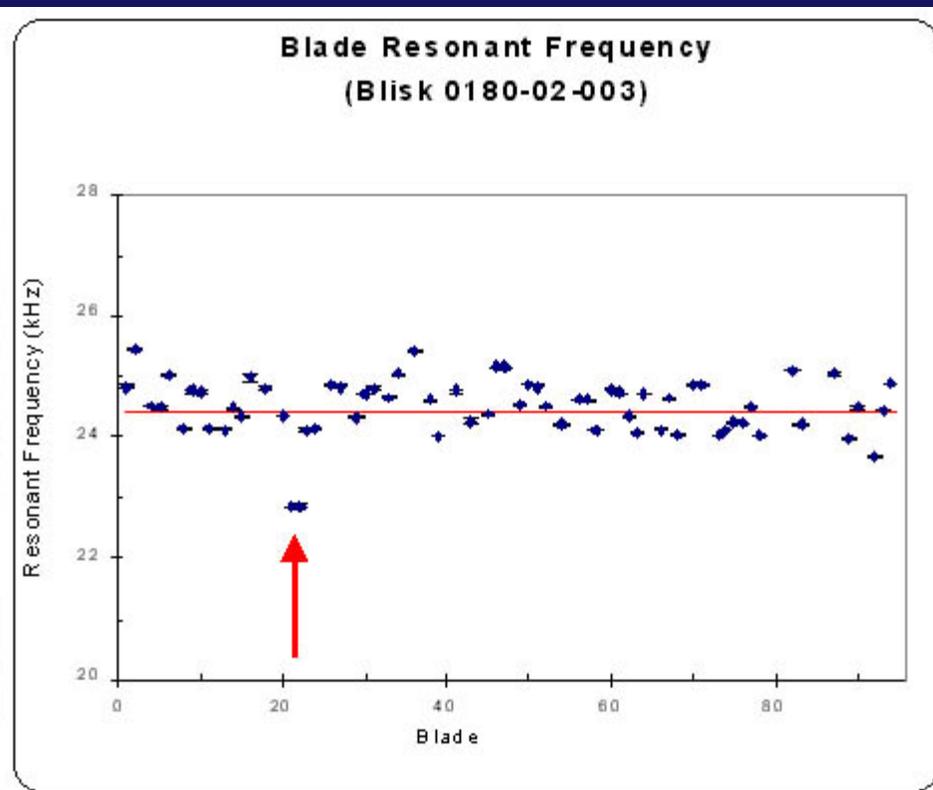
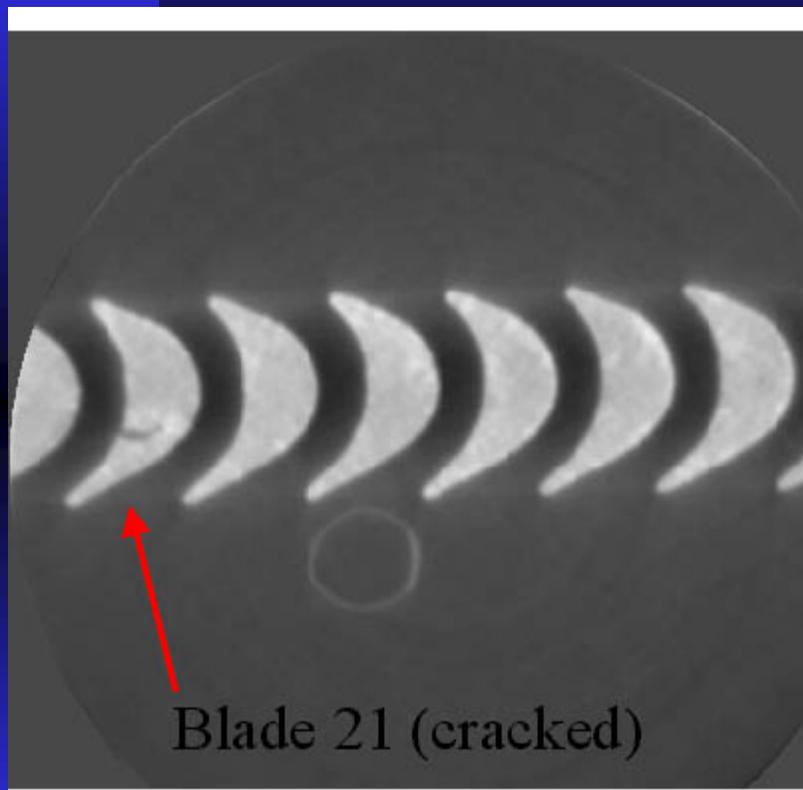
# IMPACT ACOUSTIC RESONANCE SYSTEM WITH LASER VIBROMETER: SOFTWARE PACKAGE USED FOR DETERMINATION OF MODE SHAPE

Use of scanning laser vibrometer for confirmation of mode shapes



AS OPPOSED TO FIXED LOCATION ACCELEROMETER, SCANNING LASER ALLOWS FREE MOVEMENT OF DETECTOR

## Correlation of Resonant Frequency of Cracked Blade and x-Ray CT image data



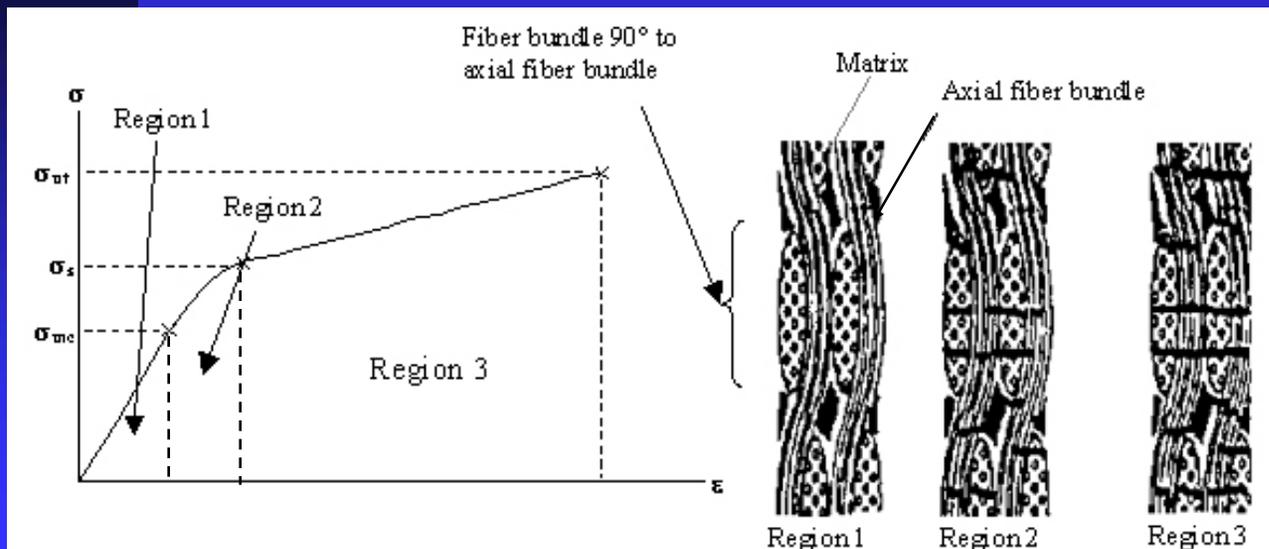
Xray Tomographic image data

Note the cracked blade. Same one with lower resonant frequency

Resonant frequency

# PREDICTING REMAINING USEFUL LIFE

- When a component should be removed is not well defined.
  - ◆ especially for on-engine conditions where dynamic loading occurs
- Material degradation from environmental attack is dependent on the amount of matrix cracking.
- Number of cracks in the matrix can be associated with stress level from monotonic testing.
  - ◆ Failure of the material assumed to occur in non-linear region of stress-strain relationship (Region 2).
- Accumulation of cracking is estimated from the decay of the elastic modulus using shear lag model.
- Decay of elastic modulus can be monitored using nondestructive ultrasonic guided plate waves.



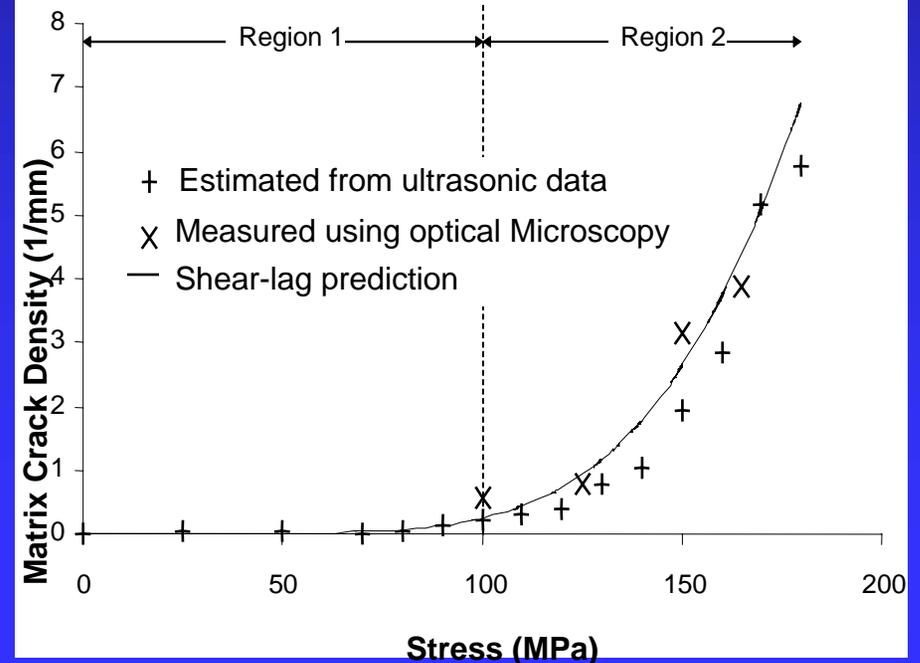
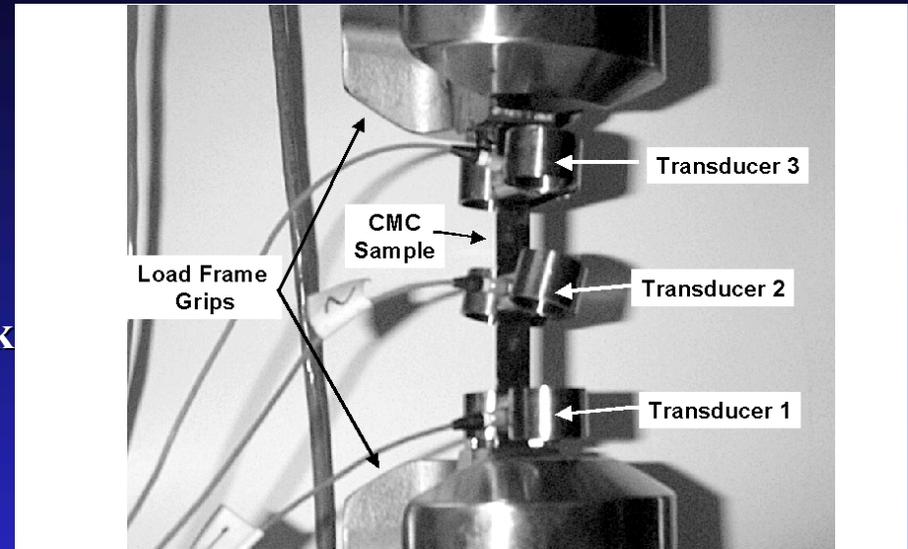
# Approach for RUL Estimation

## Determine current damage

- Velocities of ultrasonic guided plate wave:
  - ◆ Measured using contact ultrasonic transducers,
  - ◆ Directly related to elastic modulus.
- Evaluate “current” transverse matrix crack density using shear-lag model
  - ◆ Monotonic tensile loading and
  - ◆ Tension-tension cyclic fatigue.

## Predict future damage

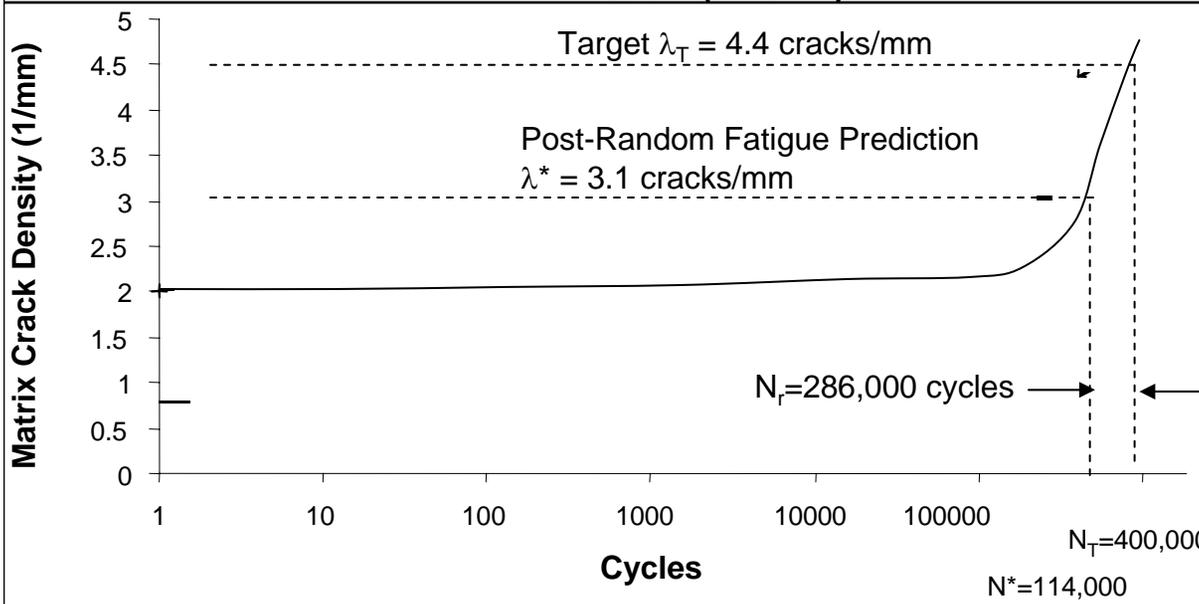
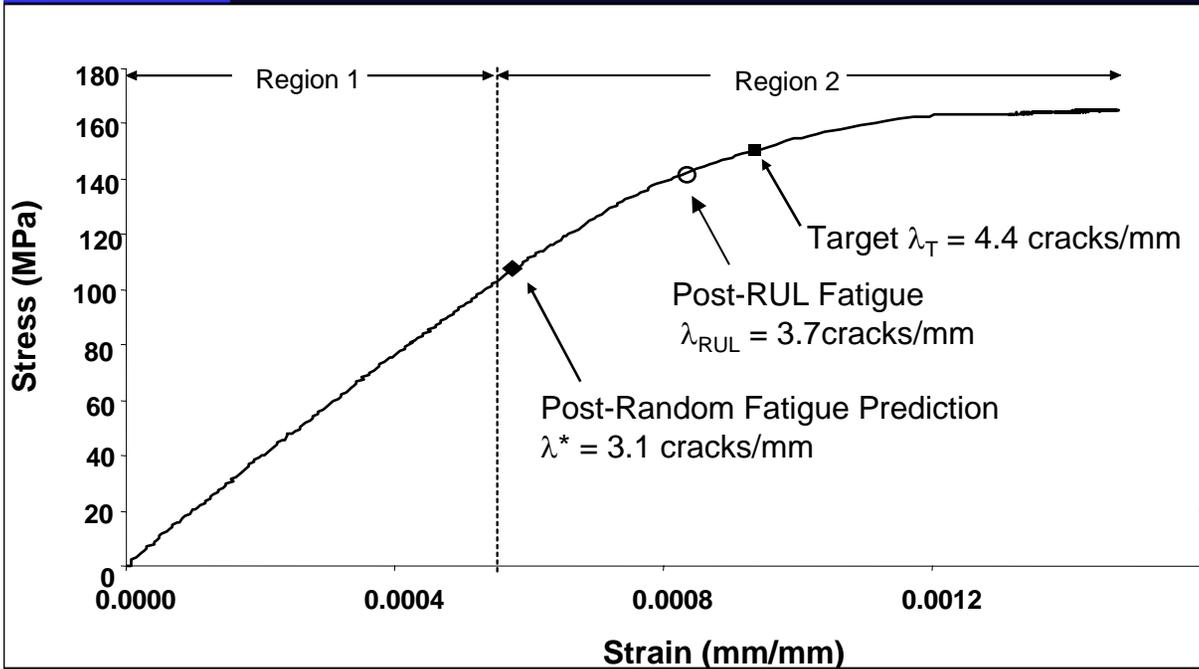
- Assume future loading conditions
- Using shear-lag model:
  - ◆ Compute number of tension-tension cyclic fatigue cycles required to reach current damage state,  $N^*$
  - ◆ Compute number of tension-tension cyclic fatigue cycles required to reach failure damage state,  $N_T$
  - ◆ Take difference to find RUL,  $N_R$





MI SiC/SiC

# Current and Failure Matrix Crack Density



- Determine failure matrix crack density
- Unknown matrix cracking extent induced by random tension-tension cyclic fatigue
- Estimate matrix crack density using ultrasonic data
- Compute number of cycles required to induce current matrix crack density,  $N^*$ :
- Compute number of cycles required to induce failure matrix crack density,  $N_T$ .
- Estimate RUL,  $N_r = N_T - N^*$ :
- Samples cycled at assumed future loading condition for  $N_r$  cycles
- Post-RUL fatigue damage was compared to target matrix crack density – 17% below target

# SUMMARY



- **NDE Technology has been developed and demonstrated for defect detection for ceramic composite combustor liners. This helps to reduce risks when using these components in an engine**
  - ◆ Thermal imaging is a useful method for delam and porosity detection
  - ◆ Air-Coupled ultrasound is useful and negates use of water coupling for ultrasound
  - ◆ Detected defects and delaminations can be verified by use of advanced x-ray tomography systems
  
- **Estimation of remaining residual life has been demonstrated**
  - ◆ Use of shear-lag model along with guided plate waves has been shown to predict RUL for certain materials