NDE Technology for Ceramic Composites

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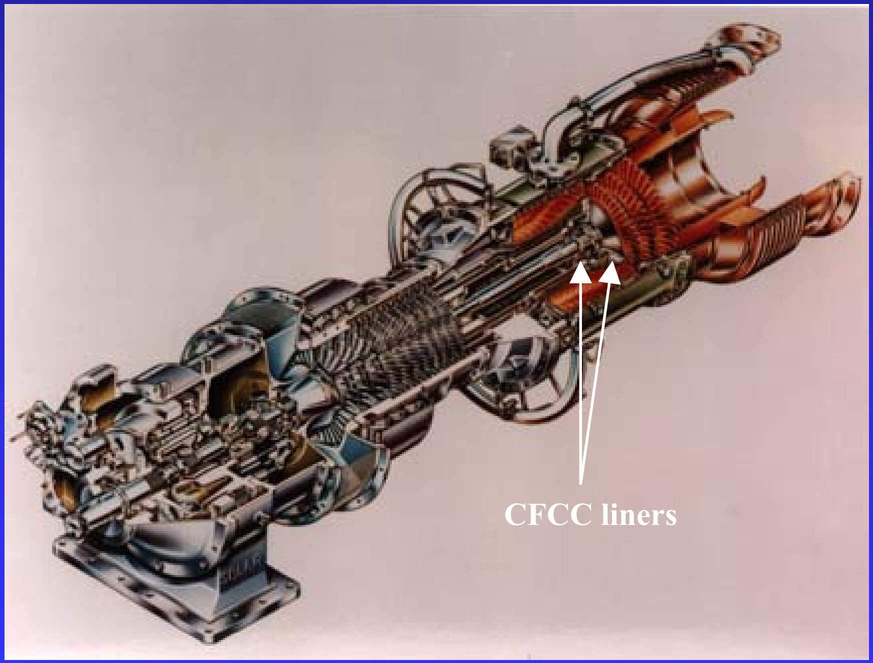
OUTLINE

- **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

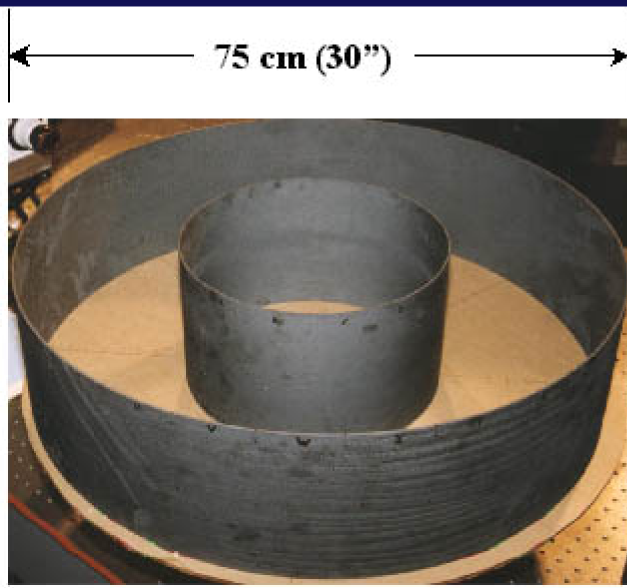
EBC coated continuous fiber ceramic composite components in field tests of stationary gas turbine engines

Outer Liner - 30" diameter **Inner Liner - 13" Diameter**



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

Uncoated



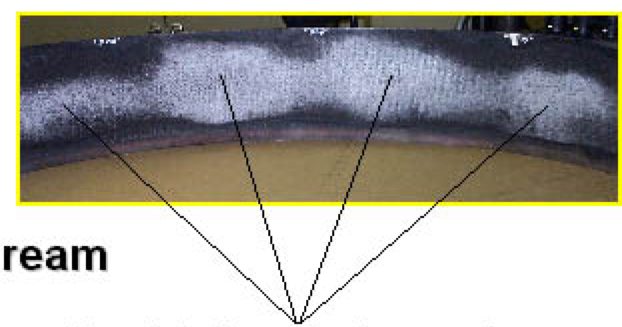
– Oxidation Damage (“white glass”)

– Strength Loss

– Embrittlement

Upstream

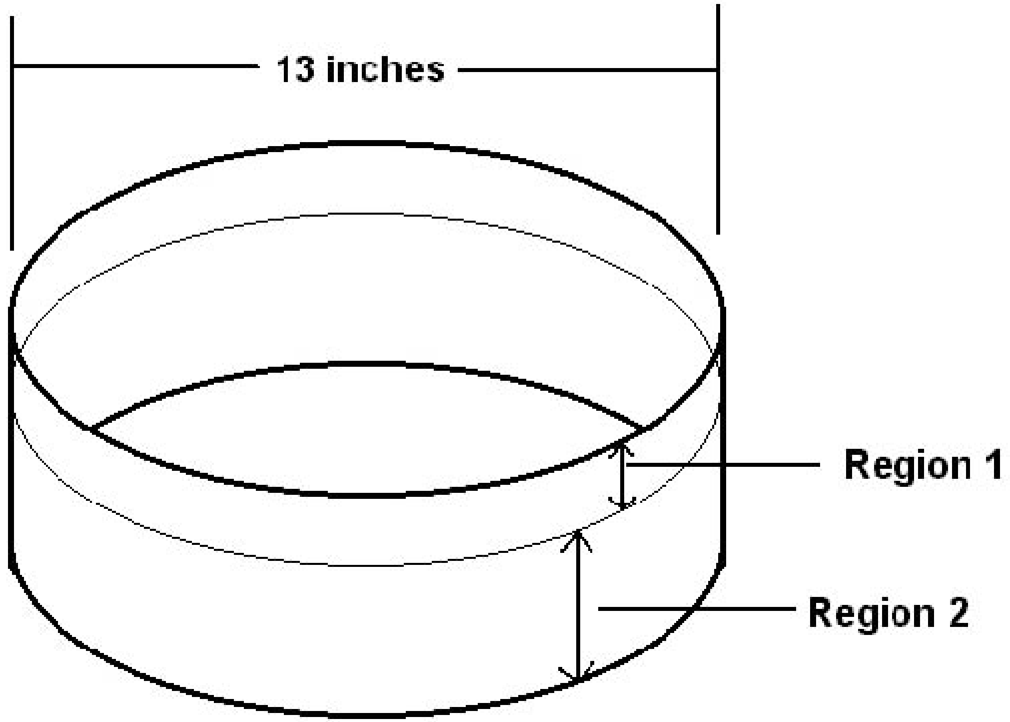
Coated



Downstream

Fuel Injector Locations

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

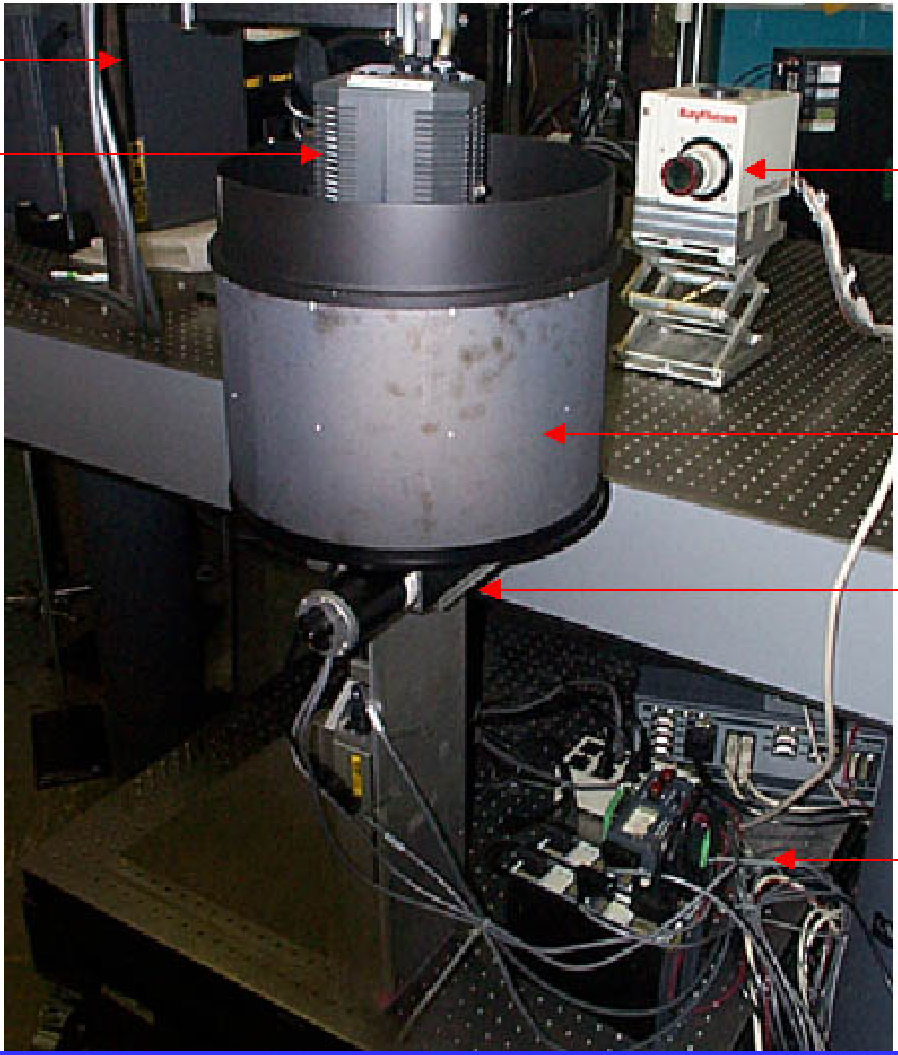


Before running in engine

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

Thermal Imaging Hardware

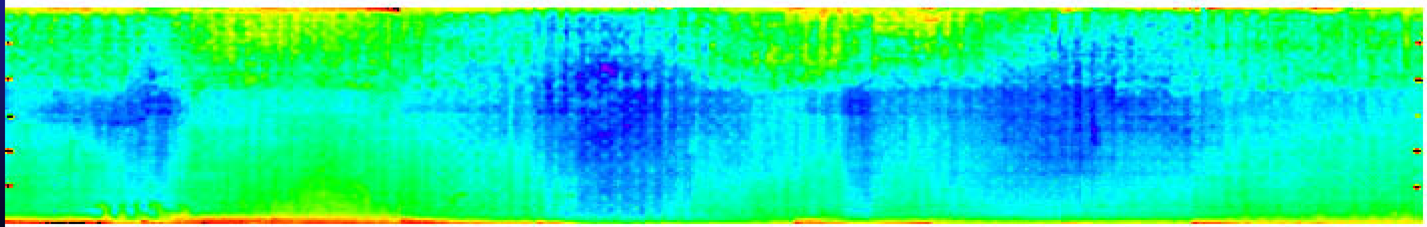
Automated Thermal Imaging Apparatus for Testing a 13” Liner



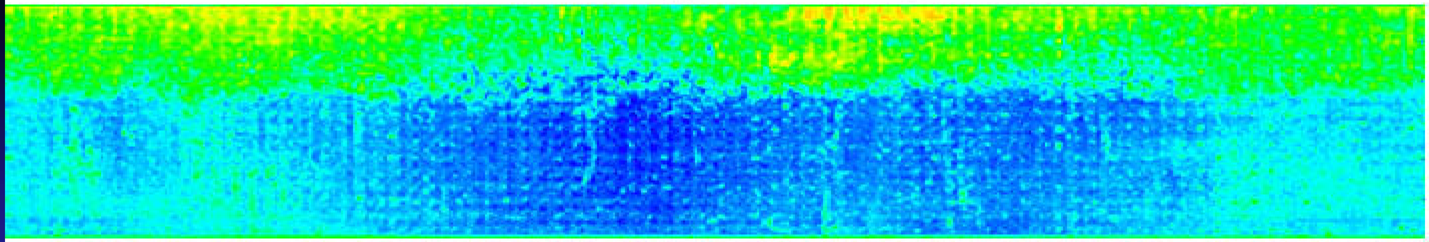
DETECTION OF POROSITY BY NDE METHODS::
Thermal imaging, water and air-coupled ultrasonics

- Correlation to NDE data to SEM data

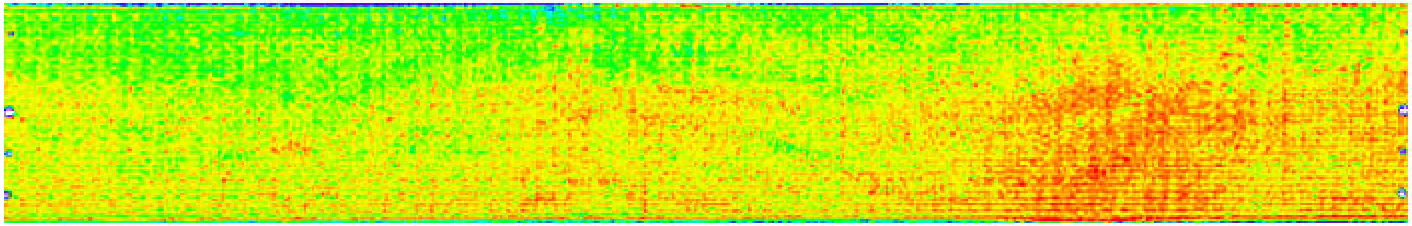
Thermal Diffusivity Image



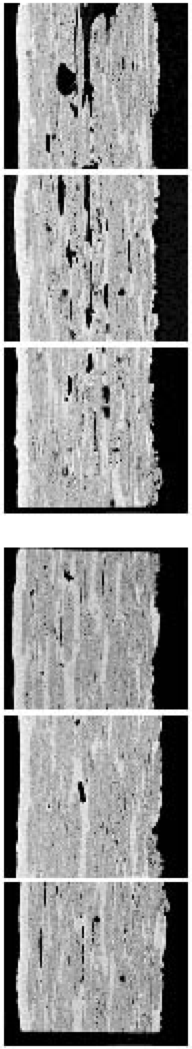
Water-Coupled UT Image



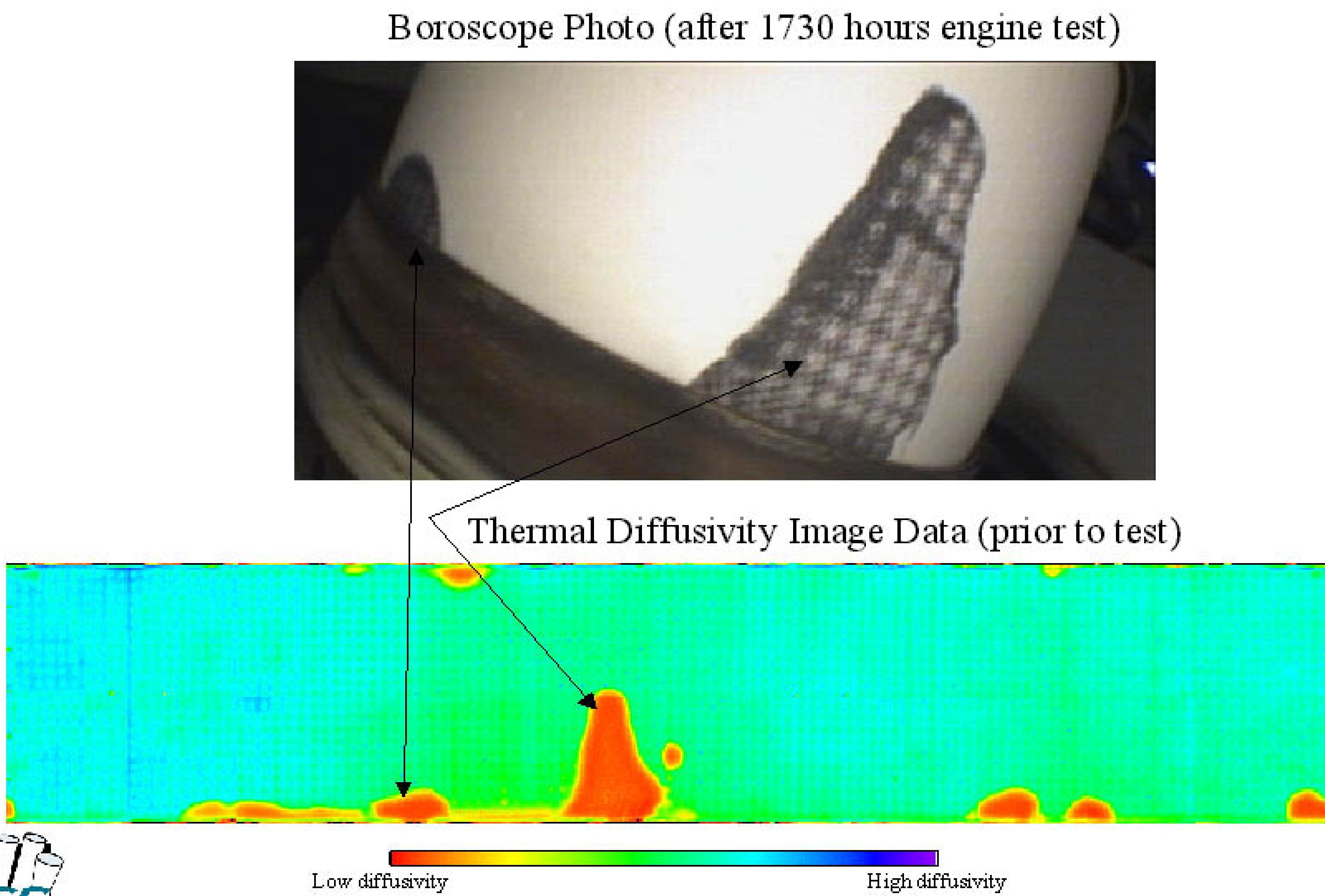
Air-Coupled UT Image



SEM Image (ORNL)



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



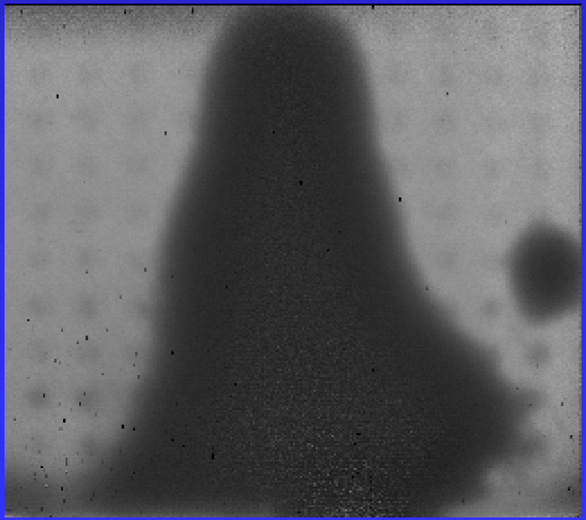
ANL

SPALLATION OF 13” diameter EBC COATING

4533 hours

7317 hours

14,000 hours

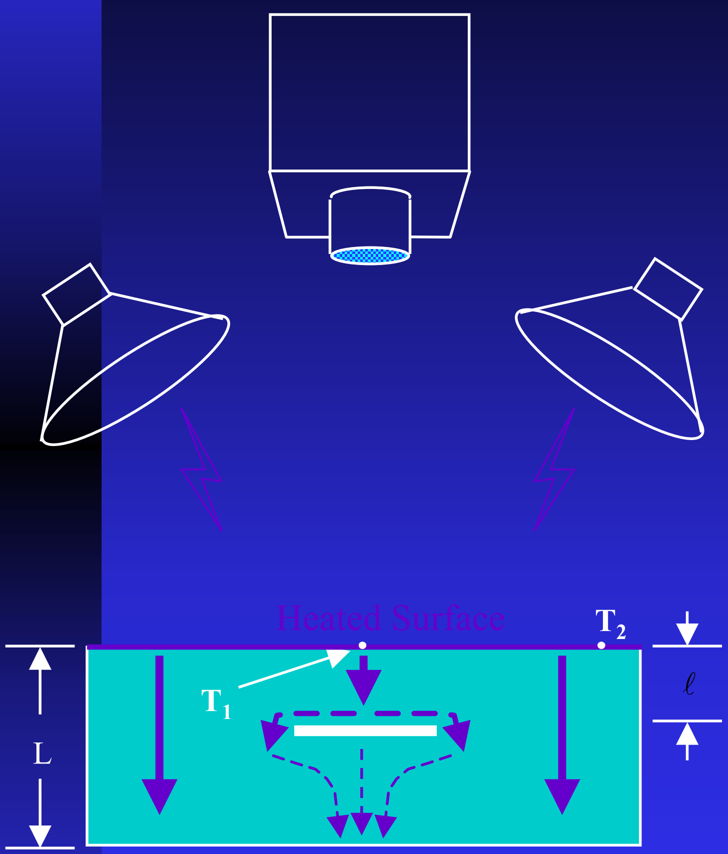


Thermal Diffusivity Map

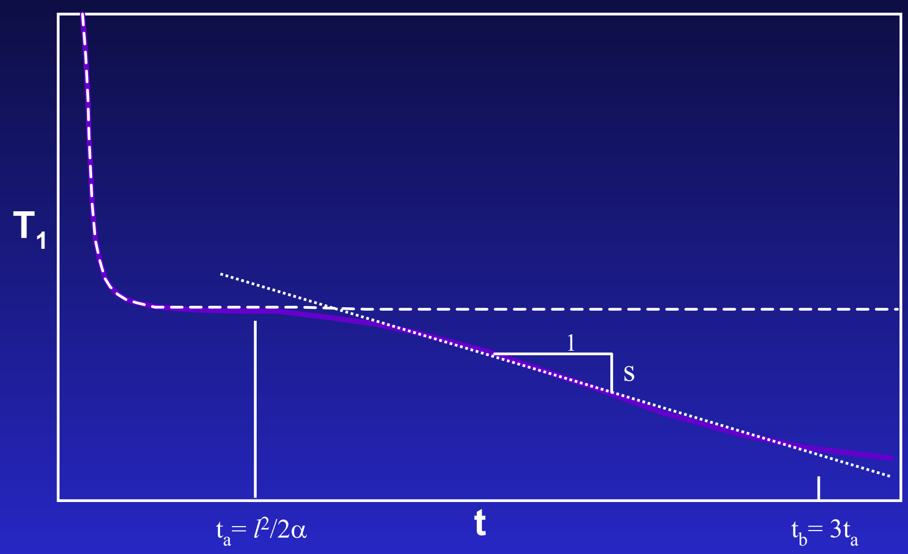
Boroscope Images Courtesy of Solar Turbines

Analytical method for calculation of defect depth

Thermal imaging system Setup



Typical Surface Temperature Variation



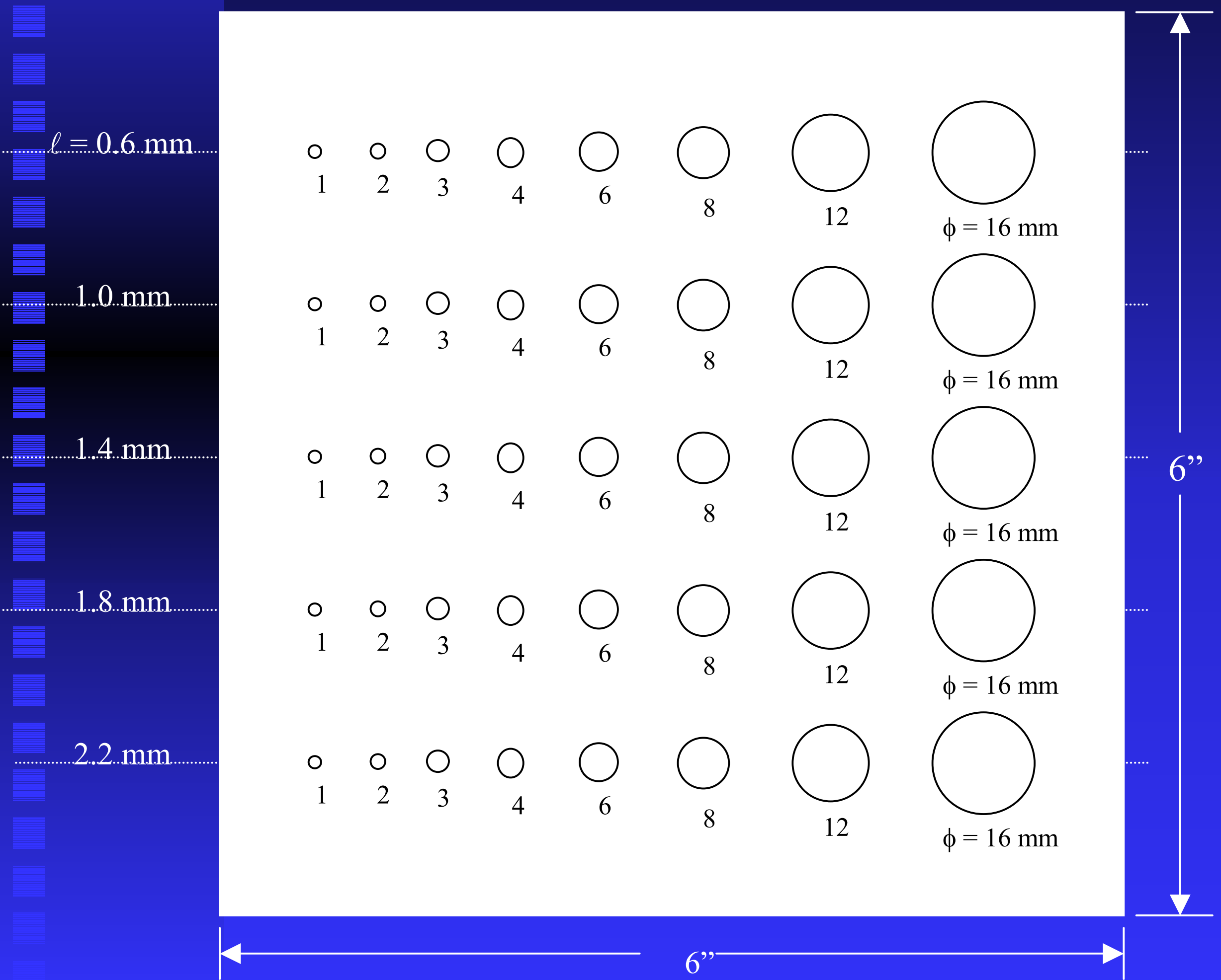
Theoretical model:

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

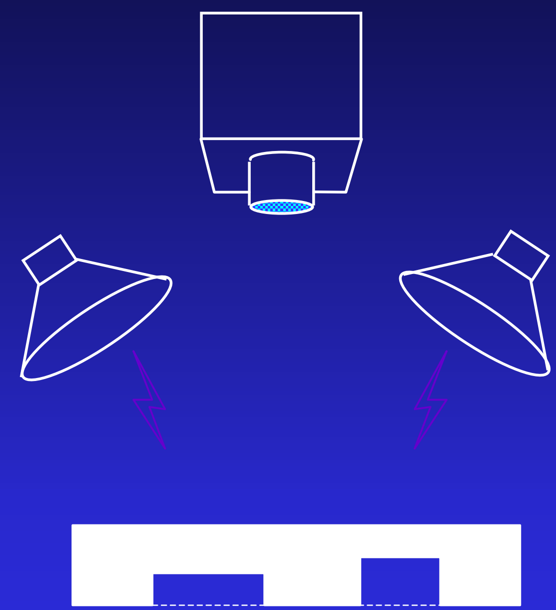
ARGONNE NDE

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

Machining diagram of CMC plate



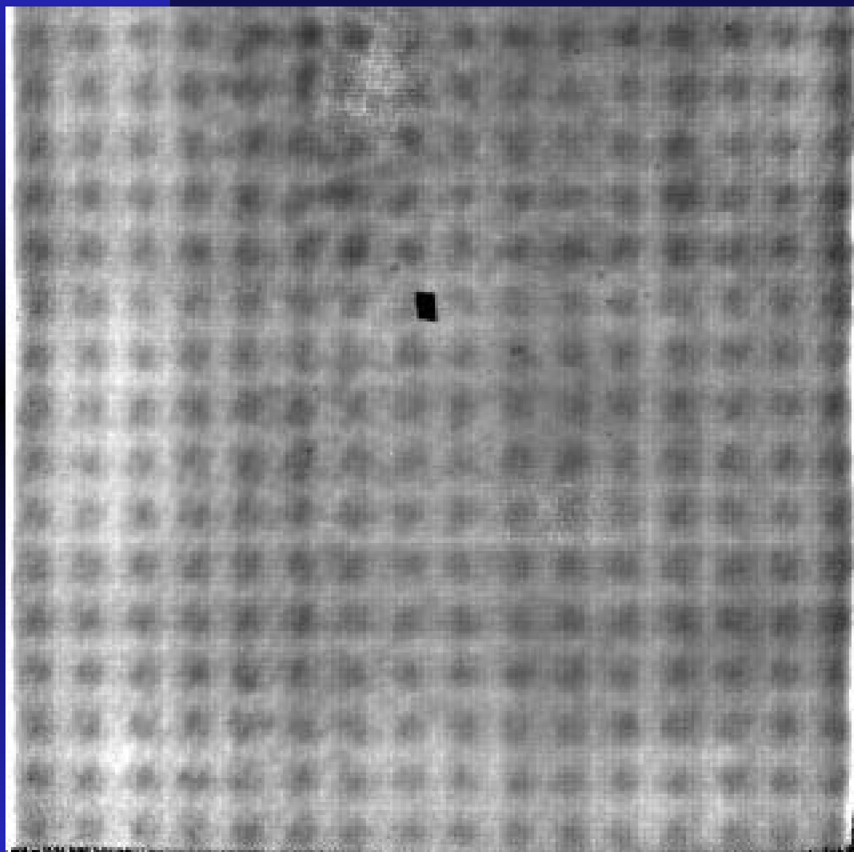
Test setup



Measure:
- diameter d
- depth *l*

Estimating defect depth with thermal imaging

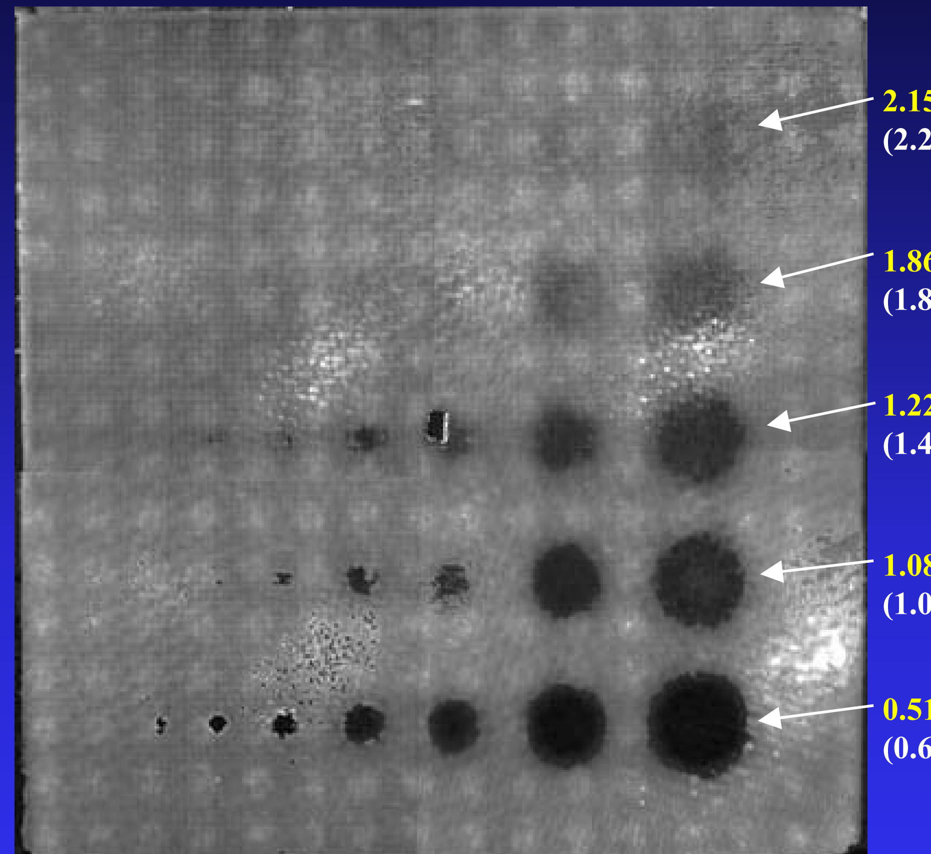
Thermal Diffusivity Image
- before machining of holes



5 mm²/s — 9 mm²/s

Predicted Depth Map
- after machining of holes

Predicted (measured) depth (mm)



0 mm — 5 mm

Mean diffusivity = 7.4±0.4 mm²/s

Mean thickness = 2.6 mm

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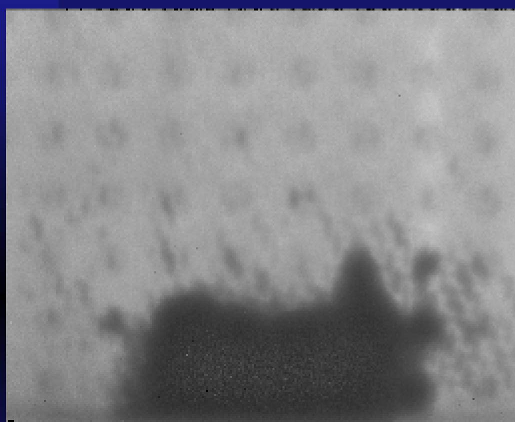
Effect of Coating Processing on Delam size

AICAC&C
Cocoa Beach
2001

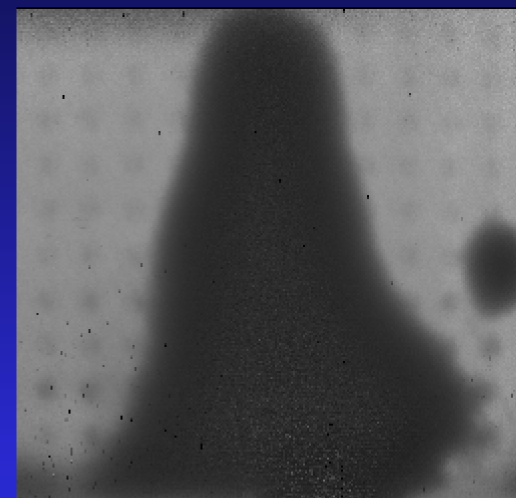
Lower Diffusivity — Higher Diffusivity

4”



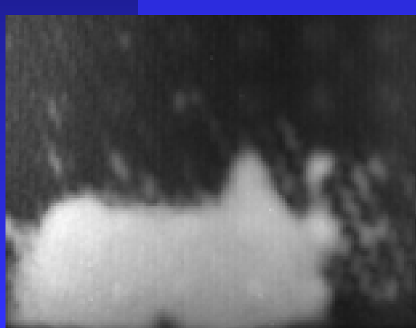
Delam size Before Coating

4”



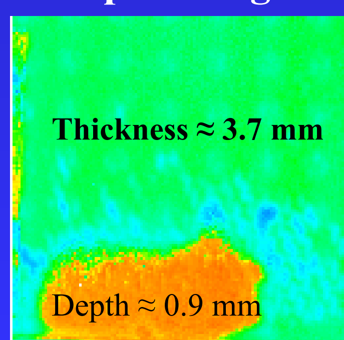
Delam size After Coating
--Note the delam has grown
In size

A Front-Flash Thermal Image



t = 0.1 Sec

Predicted 2-D Depth Image



Distance of Delam Below surface

Depth determined from Xray CT = 0.5~1 mm

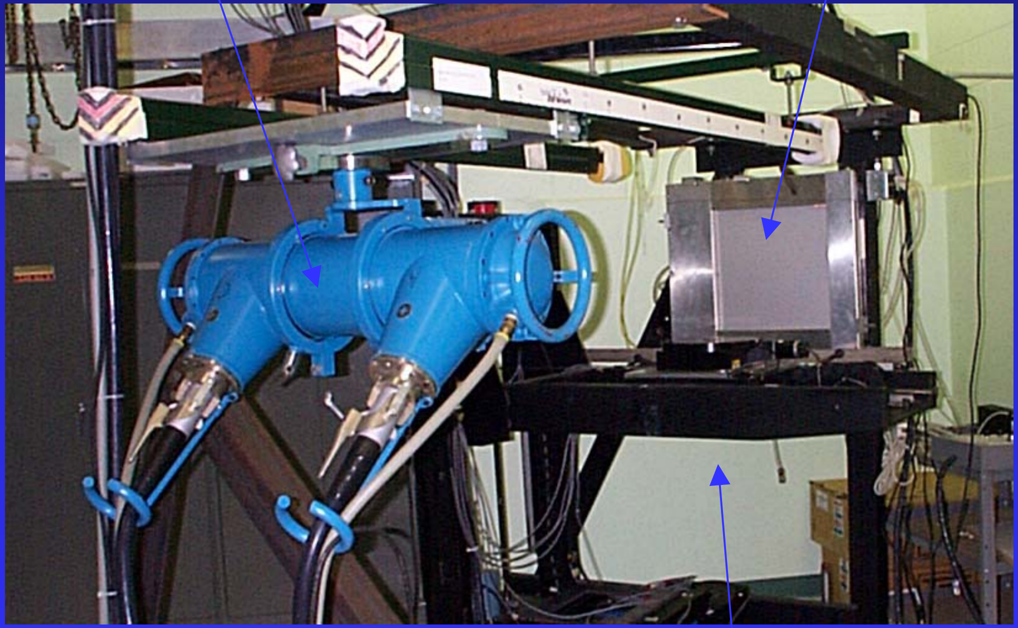
Depth determined from thermal imaging = 0.9 mm

3D X-RAY COMPUTED TOMOGRAPHY FACILITYUSED FOR ACQUIRING VERIFCATION 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

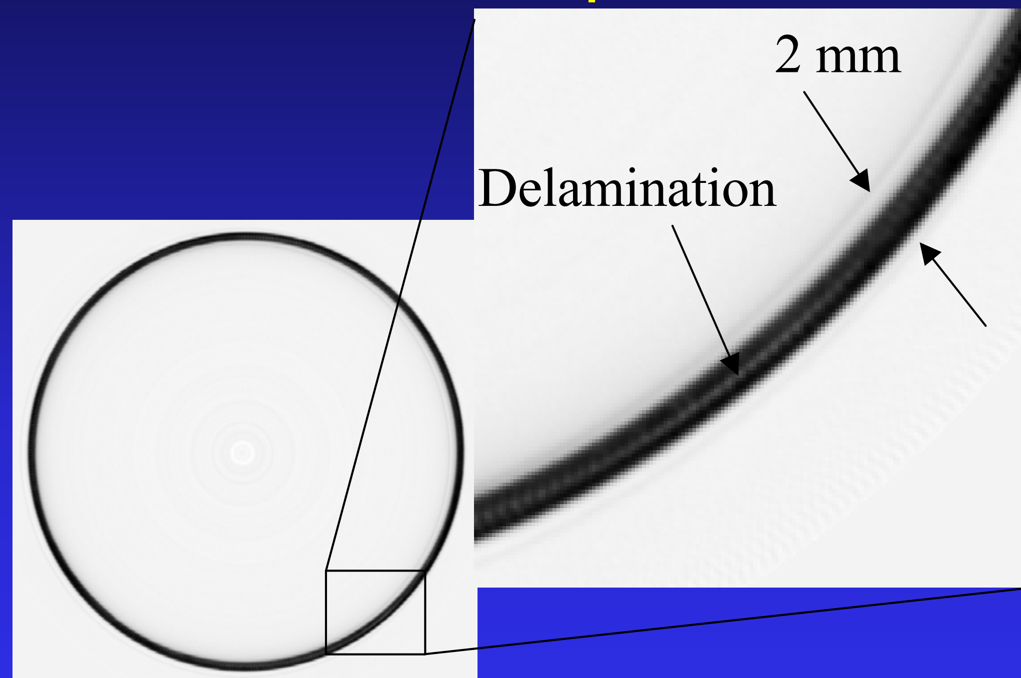
Flat-Panel 40-cm x 40-cm α-Si Detector



X,Y,Z,θ 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[tm]), 76 mm x 152mm
- Polymer Impregnation Process (PIP)
- 8 ply layup ~ 3 mm thick

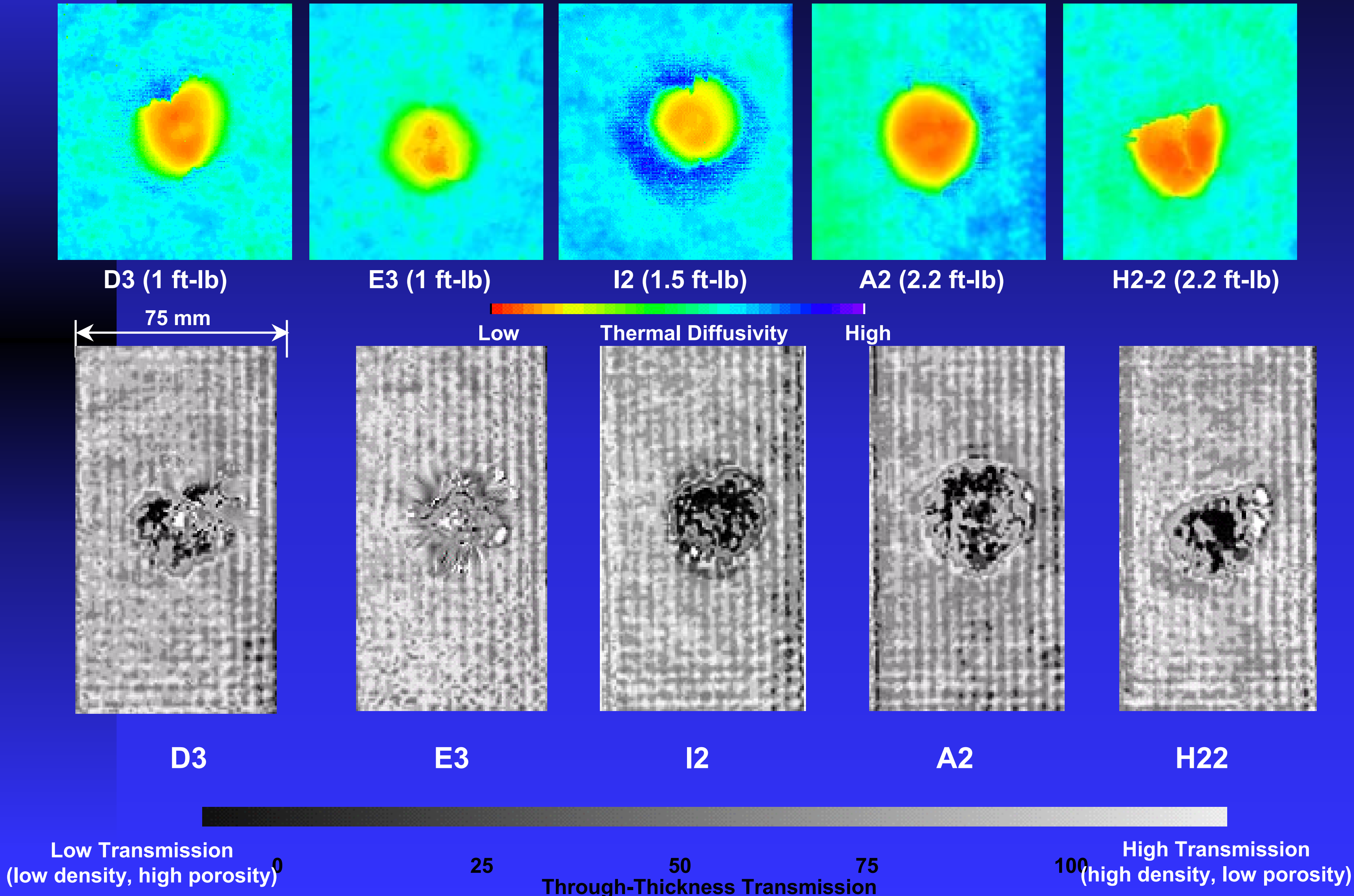
→ Pendulum impactor

→ 12 mm in diameter

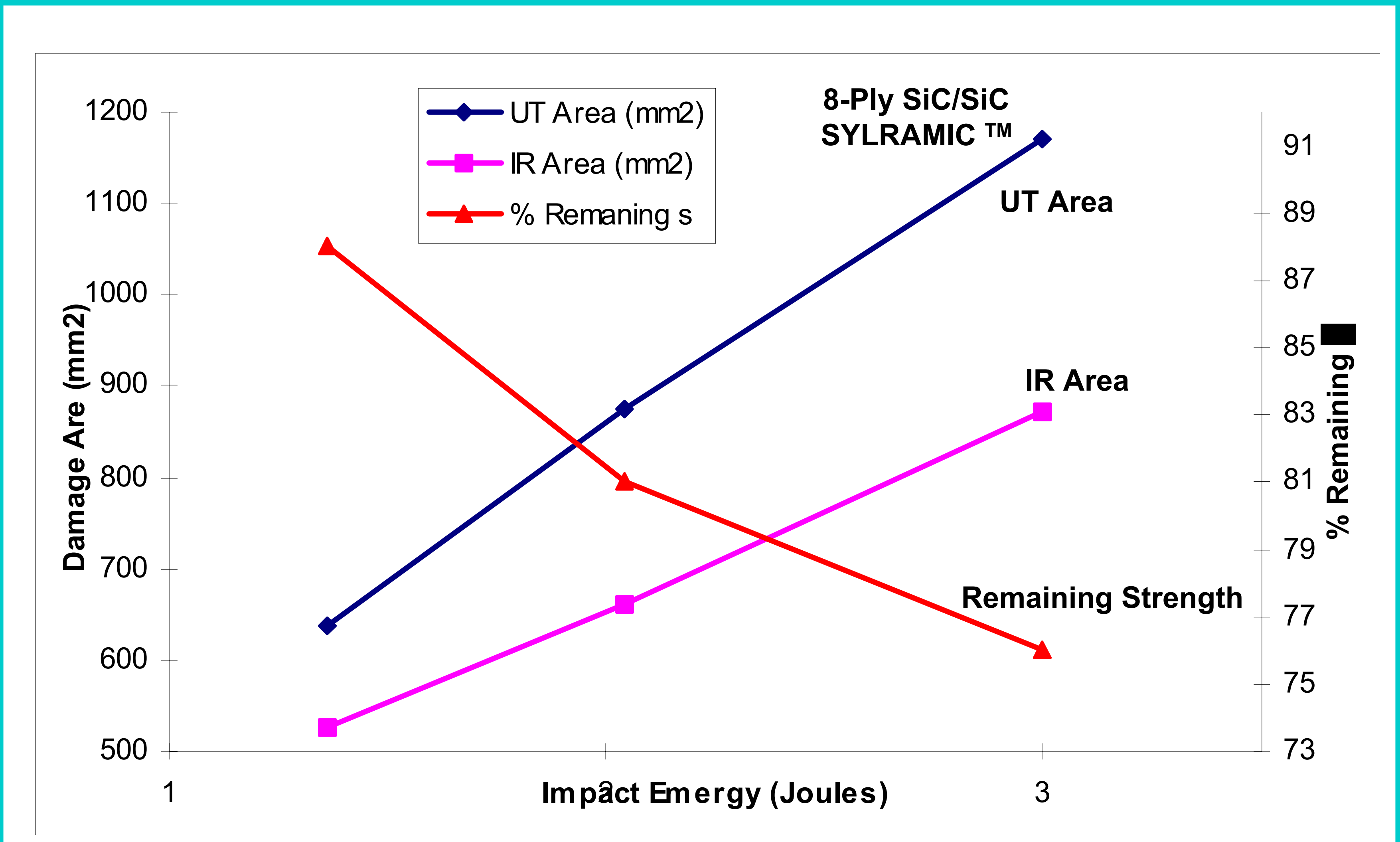
Impact Testing

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

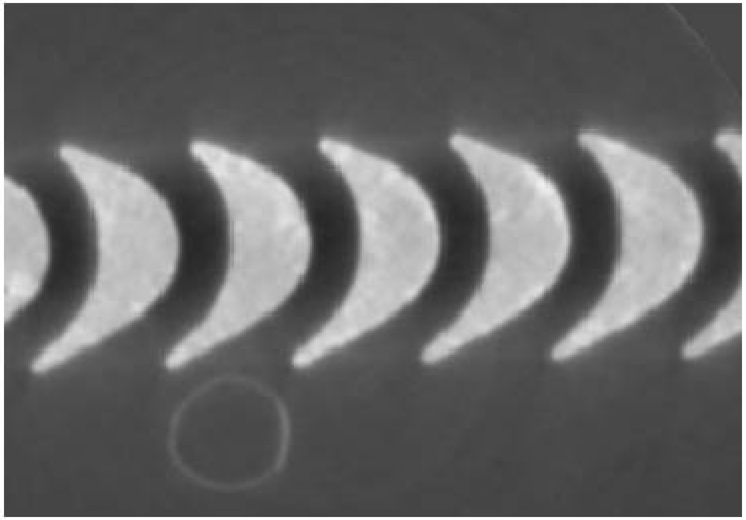


CORRELATION AMONG: DAMAGE AREA, REMAINING STRENGTH, AND IMPACT ENERGY



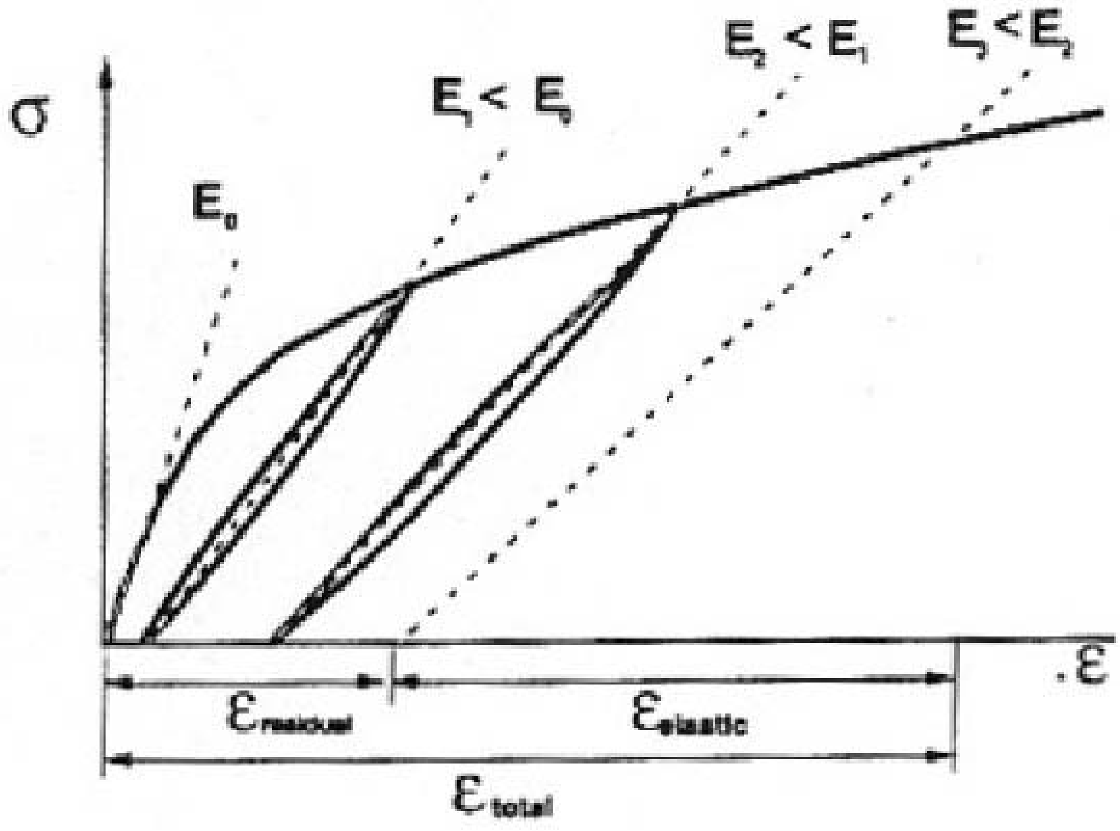
NDE TECHNOLOGY FOR ASSESSING CONDITION OF ROTATING COMPONENTS: C/SiC --Impact Acoustic resonance /Xray Tomography

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



Typical X-Ray CT image through 5 blades

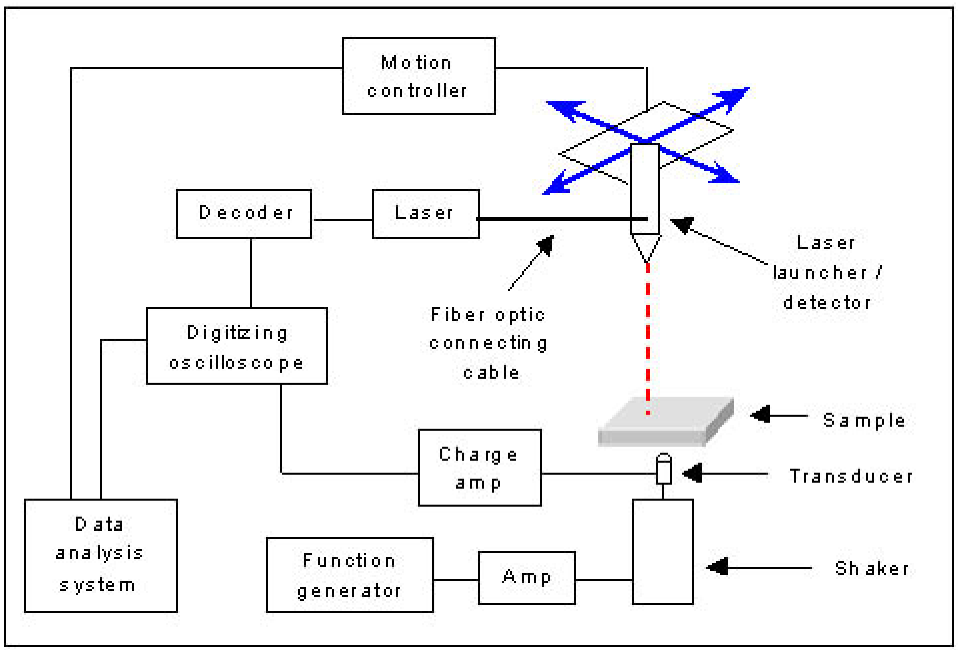
Effect of load-cycling on elastic modulus For C/SiC



Typical Tensile/Relation Test

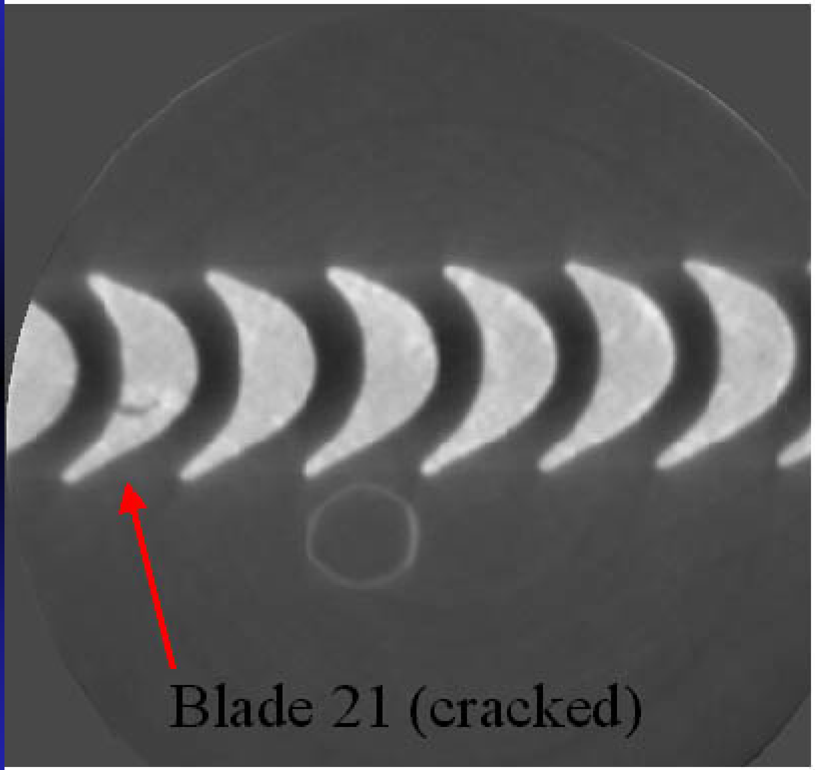
IMPACT ACOUSTIC RESONANCE SYSTEM WITH LASER VIBROMETER: SOFTWARE PACKAGE USED FOR DETERMINATION OF MODE SHAPE

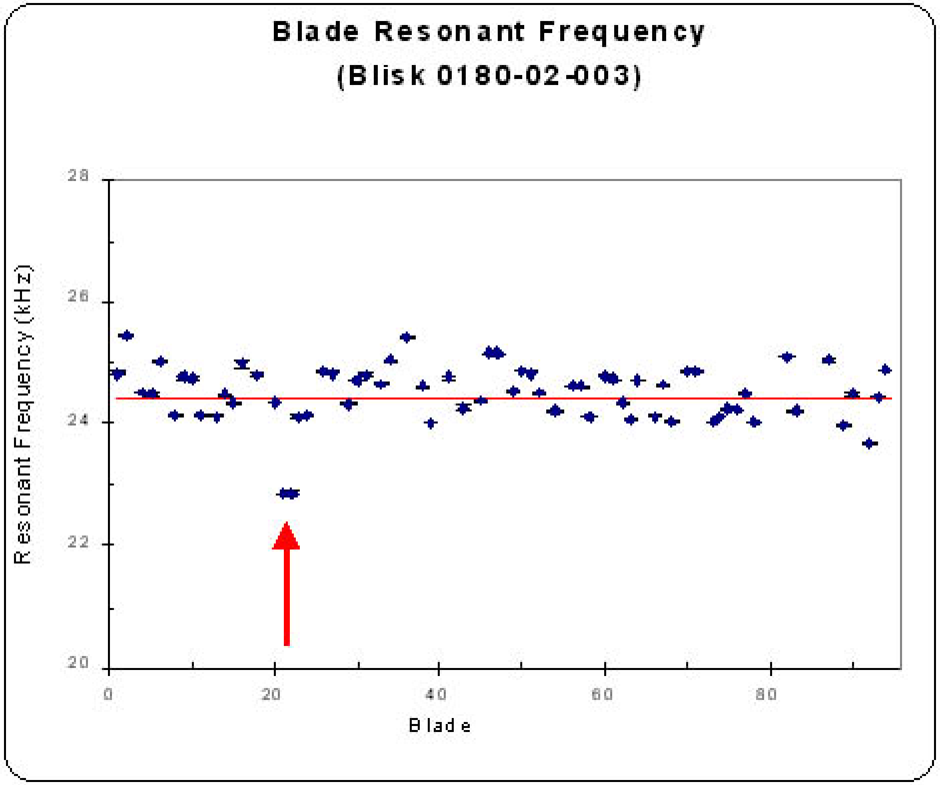
Use of scanning laser vibrometer for confirmation of mode shapes



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





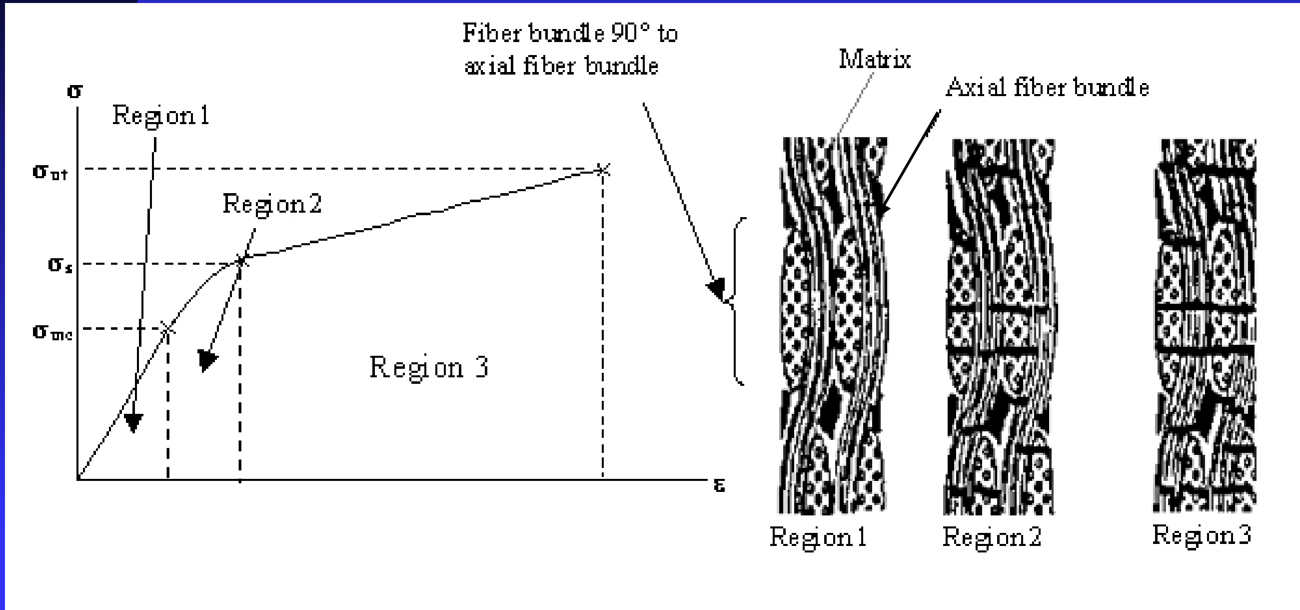
Xray Tomographic image data

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.



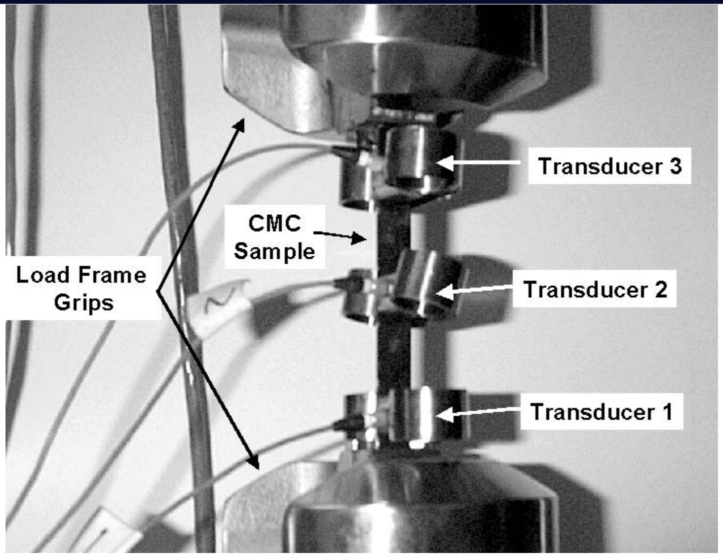
Approach for RUL Estimation

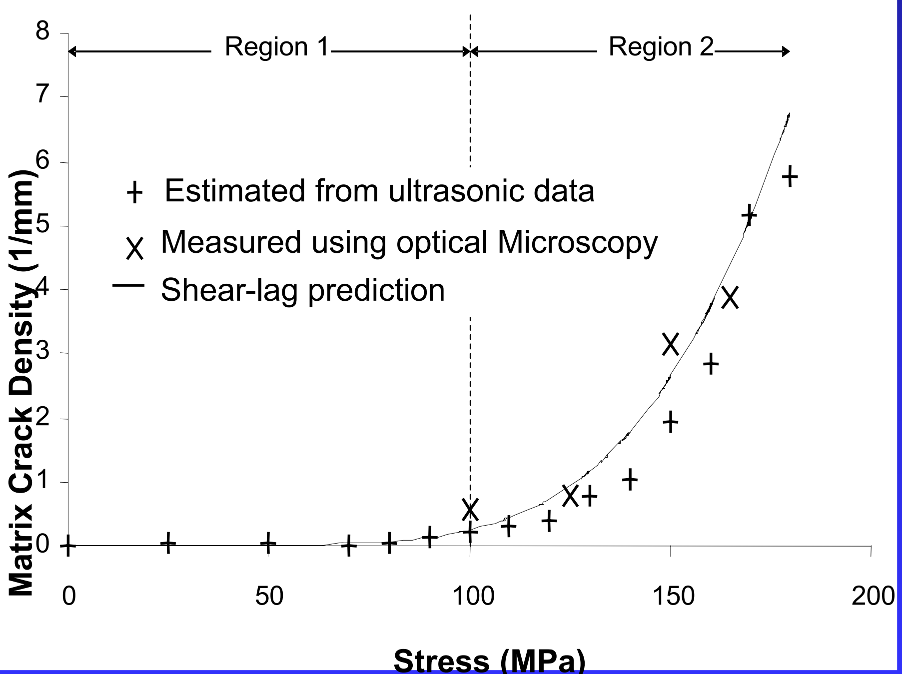
Determine current damage

- 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

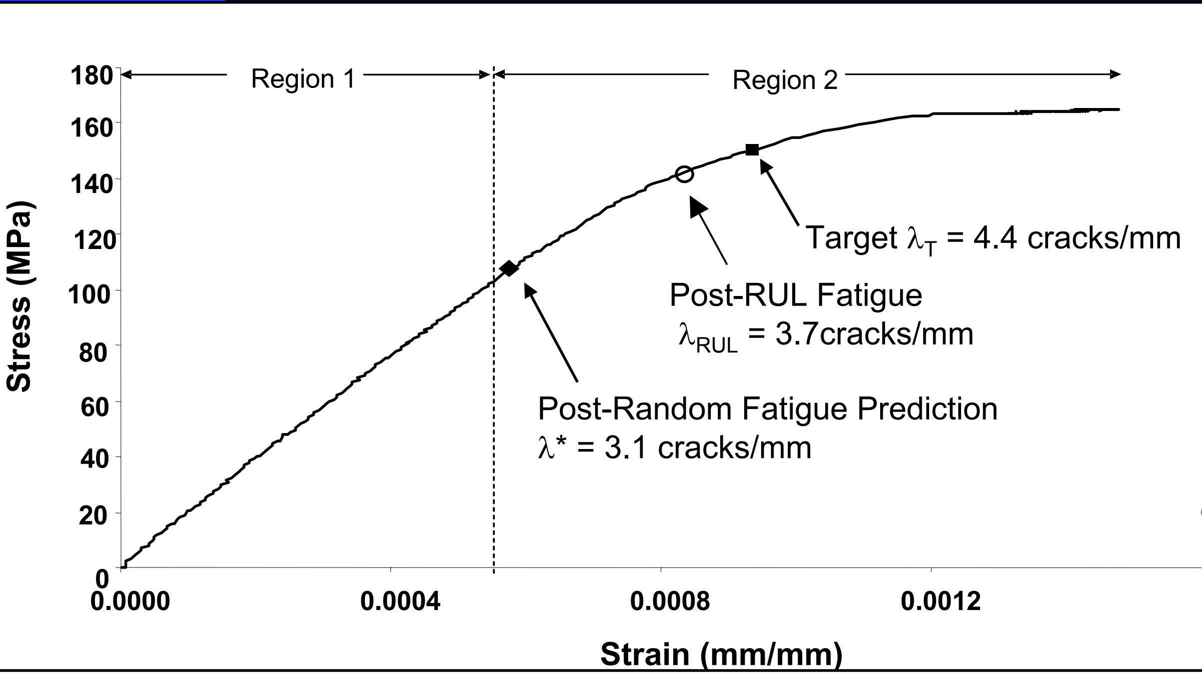
- Assume future loading conditions
- Using shear-lag model:
  - Compute number of tension-tension cyclic fatigue cycles required to reach current damage state, N*
  - Compute number of tension-tension cyclic fatigue cycles required to reach failure damage state, N_T
  - Take difference to find RUL, N_R

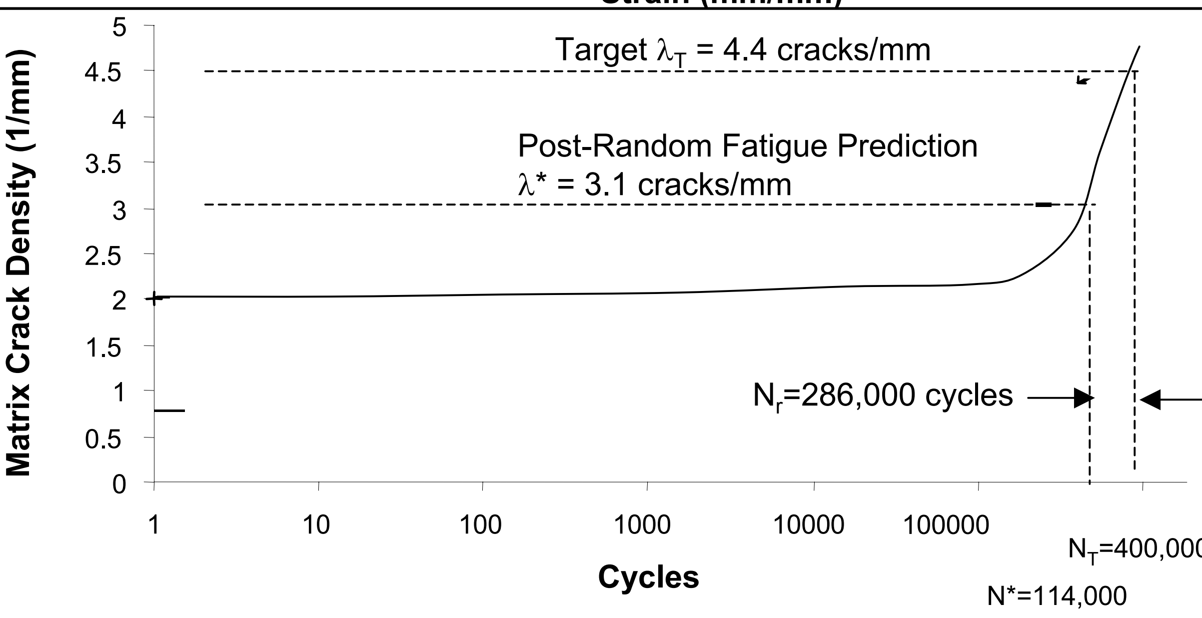




Current and Failure Matrix Crack Density

MI SiC/SiC





- 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**