Space Qualification of New Materials for Space Applications

I.A. Palusinski, D.B. Witkin, M.J. O'Brien

The Aerospace Corporation

Mirror Technology Days

16 Jun 2009

Outline

- **Motivation and process for material and mirror system space qualification**
  - ***Reasons for selecting SiC***
  - ***Space qualification of new materials***
  - ***Database***
  - ***Flight projects - MISSE***

- **SiC material properties characterization**
  - ***Materials testing***
  - ***Radiation testing***
  - ***Data analysis***

- **Defect tolerant design and proof load testing: necessary steps in SiC system development**
  - ***NDE***
  - ***Fatigue***
  - ***Proof load testing & FEA***

- **Lessons learned, Future work, Summary**

palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

Space Qualification Goals

- **Develop space qualification method for new optical materials**
  - ***Silicon carbide (SiC) is first material selected to validate method***
- **Emphasize material characterization as well as component and system evaluation**
- **Space qualify vendors for optical and structural applications**

palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

Why is SiC of Interest for Space Applications?

High specific stiffness for lightweighting and large aperture development, low cost, and short schedule

- **Glass**
  - ***Extensive space heritage***
  - ***Easily figured and polished***
  - ***Long lead times for large-diameter applications, single US supplier***
- **Be**
  - ***Space heritage, used for structures and mirrors***
  - ***Established material, proven long-term stability***
  - ***Single US supplier and challenges of toxicity***
- **SiC**
  - ***High bulk thermal conductivity, high specific stiffness, can be lightweighted***
  - ***Multiple US suppliers, relatively inexpensive substrates***
  - ***Good potential for space applications***
  - ***Limited space heritage and difficult to polish to an optical surface***

- **Challenge: Understand effects of lightweighting on SiC properties**
  - ***How does lightweighted structure differ in its performance relative to bulk material properties?***
  - ***Requires further testing, analysis, and/or modeling to establish these characteristics***
- **Resolution: Establish working group comprised of Gov and industry members to evaluate SiC performance**

palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

Future Space Application Challenges

- **SiC is not space-qualified: flight heritage does not necessarily mean space qualification is completed**
- **Currently, no standard test plan exists for space qualification**
  - ***Government and The Aerospace Corporation team are developing develop a method***
- **Multiple vendors and various processes to make SiC**
  - ***Confidence in one vendor's product does not translate to other vendors***
  - ***Understand vendor's process control and batch-to-batch variability***
- **To be successful, space qualification will require support from multiple programs and agencies**
- **SiC database will maintain knowledge continuity during funding fluctuations**
  - ***Developed initial prototype: contains test data, photographs, and documents***
  - ***Goal is a virtual laboratory to aid collaboration among Government agencies***

palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

Progress to Date

- **Defined comprehensive material testing approach and test plan matrix**
  - ***Basic material testing through systems integration***
  - ***Correlated to NASA TRL***
  - ***Applicable to any new optical material by judiciously choosing tests***
- **User can select tests for specific program needs to create unique space qualification plan and procedures**
- **Initial testing emphasized material properties and non-destructive evaluation (NDE) techniques**
- **Currently developing proof load testing to support transitioning from material characterization to component and sub-system evaluation**
- **Program benefits: vendors are independently evaluated and development programs are supported with sound scientific principles and methods**

palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

Space Qualification Method

- **Four evolutionary phases**

R&D

- **Material and Substrate Characterization**
  - Understand material strength and survivability
  - Includes mechanical tests, radiation exposure, NDE, and modeling
- **Component and Sub-system Characterization**
  - Includes thermal tests, additional mechanical tests, coating and polishing tests
  - Leads to space qualification of vendor's material

Acquisition

- **System Characterization**
  - Testing of telescope and assembly
    - Thermal vacuum, vibration tests, optical performance
  - Leads to space qualification of specific system
- **Post-Acquisition**
  - Post-storage system analysis, if applicable
  - Analysis of on-orbit performance throughout mission
  - End-of-life assessment of material performance
  - Provide feedback that is incorporated into R & D

palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

Space Qualification Approach: Overview

- **Optical systems produced from ceramic materials are not widely used in space**
  - ***Complete "recipe" for space qualification has not been developed***
- **Defect Tolerant Design (DTD) process is used to characterize ceramic materials and predict ceramic component performance**
  - ***Air Force implemented DTD in 1986 for F-100 engine used in F-15s and F-16s to extend component lifetimes.***
- **Government and The Aerospace Corporation team's approach is based on DTD process**
  - ***Includes augmentations that are specific to large aperture optical systems***

palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

Defect Tolerant Design (DTD): Overview

- **Build reliable components from brittle materials**
  - ***Based upon theory that engineering components are inherently flawed and contain cracks that can grow unstably during lifetime***

- **Develop reliable predictions of component lifetime using four unified steps**
  - ***Perform stress analysis to calculate spectrum of fracture and fatigue loads***
  - ***Measure ceramic's material properties (namely, resistance to fracture and fatigue)***
  - ***Using NDE, establish threshold for smallest flaw in ceramic that can be reliably identified***
  - ***Perform proof test to provide independent estimate of largest preexisting flaw***

- **Predict performance limits using safe growth of largest expected flaw under fatigue spectrum**
  - ***Structure's remaining strength after crack growth must be above acceptable limit***

palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

Principal Contributions

- **Performing radiation testing and mechanical testing pre- and post- exposure**
  - ***Complements other test programs***
    - ***Cryogenic testing at Marshall Space Flight Center (MSFC)***
    - ***System structural evaluation at AFRL***

- **Defining NDE techniques for future component and system testing, including optimizing current capabilities of existing technologies**
  - ***Complements other programs***
    - ***Developmental programs at AFRL/ML investigating new technologies***

- **Establishing protocols and framework for developing material database**

palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

Database Purpose and Philosophy

- **Provides centralized repository for organized SiC information with controlled access**

- **Will be government-accessible application for information sharing between agencies and The Aerospace Corporation**

- **Provides uniform platform to evaluate and compare SiC vendors**

- **Provides history of research on SiC**

- **Will be foundation for SiC space qualification**

palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

Database Key Features and Future Improvements

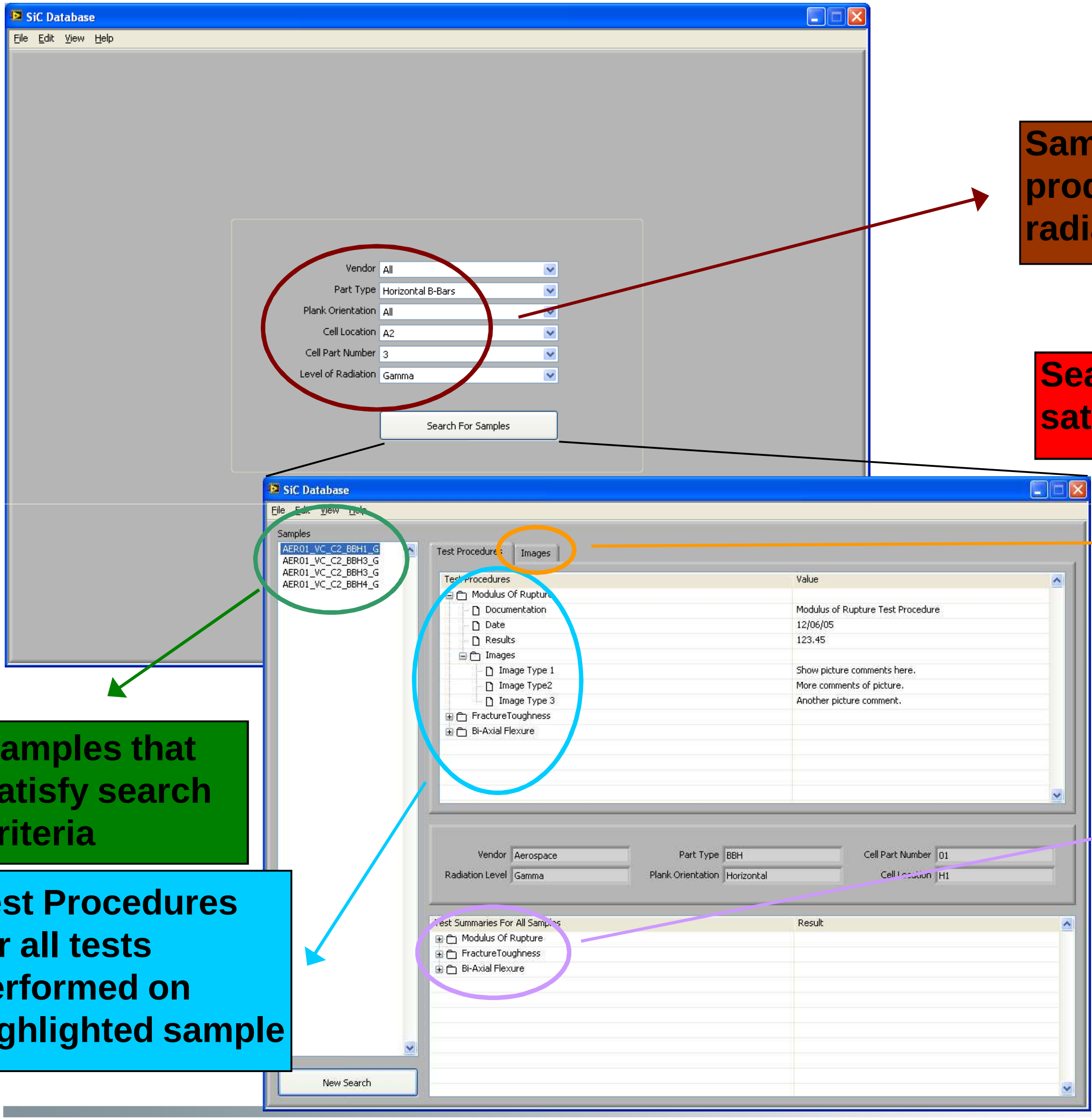
- **Establishes virtual laboratory**
  - ***In addition to data, view images of samples before and after testing***
- **Contains basic data analysis**
  - ***Quick-look graph feature to locate outliers***
- **Stores documents to support space qualification of SiC**
  - ***ASTM Standards***
  - ***Vendor information***
  - ***Test plans***
- **Export data for user-specific post-processing**

<u>Future improvements</u>

- **Develop server-client architecture with remote access via web browser or client app**
- **Address security issues and requirements for GWAN/ CWAN environment**
- **Include information about traditional optical materials to simplify performing design trades with SiC**

palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

Database Concept



Sample criteria such as vendor, production batch, sample type, and radiation level

Search for samples that satisfy search criterion

Sample photographs

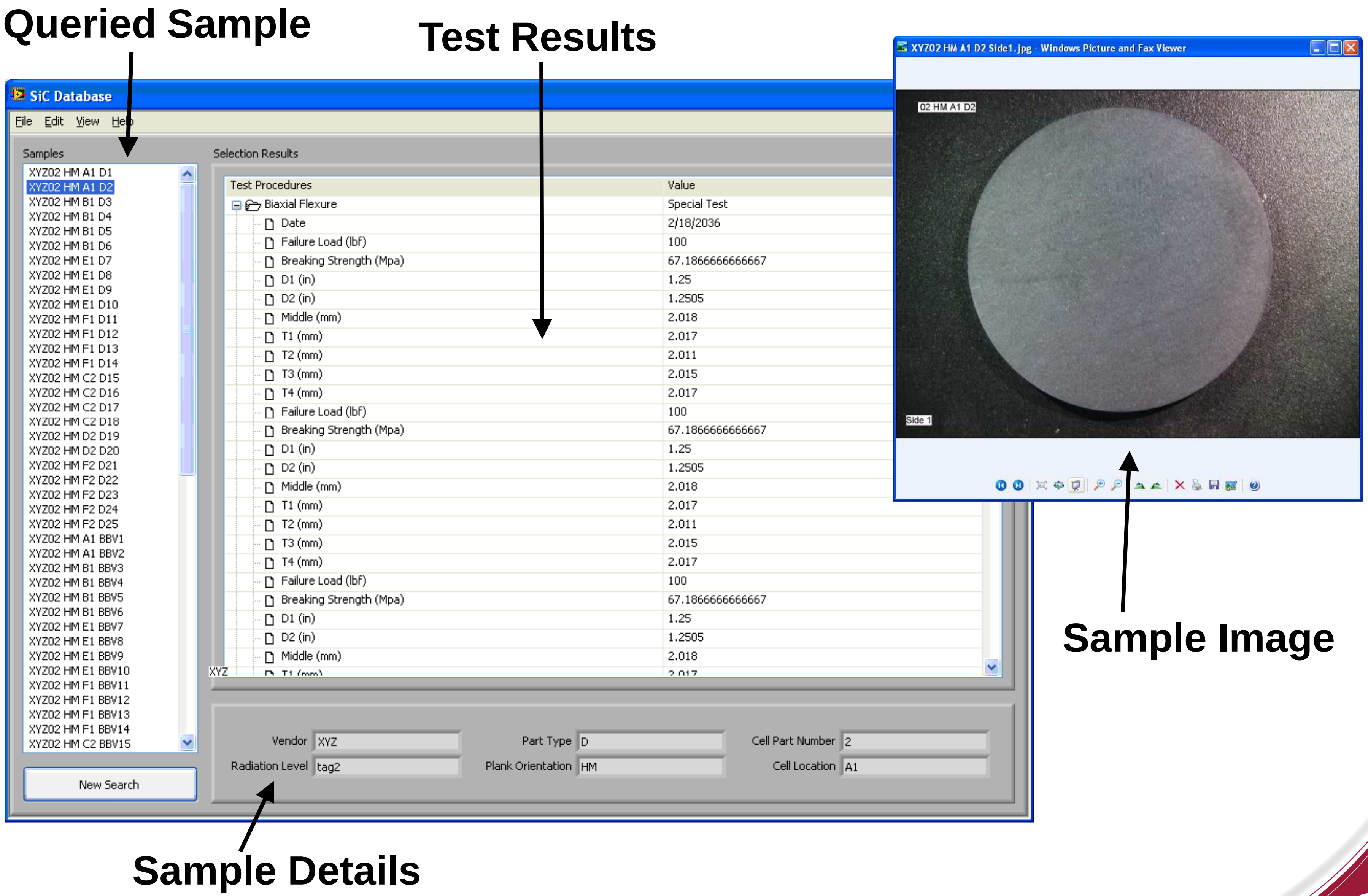
Samples that satisfy search criteria

Test Procedures for all tests performed on highlighted sample

Test summary for all samples returned by search, including histogram and statistical analyses

palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

Database Screenshot (One Sample)



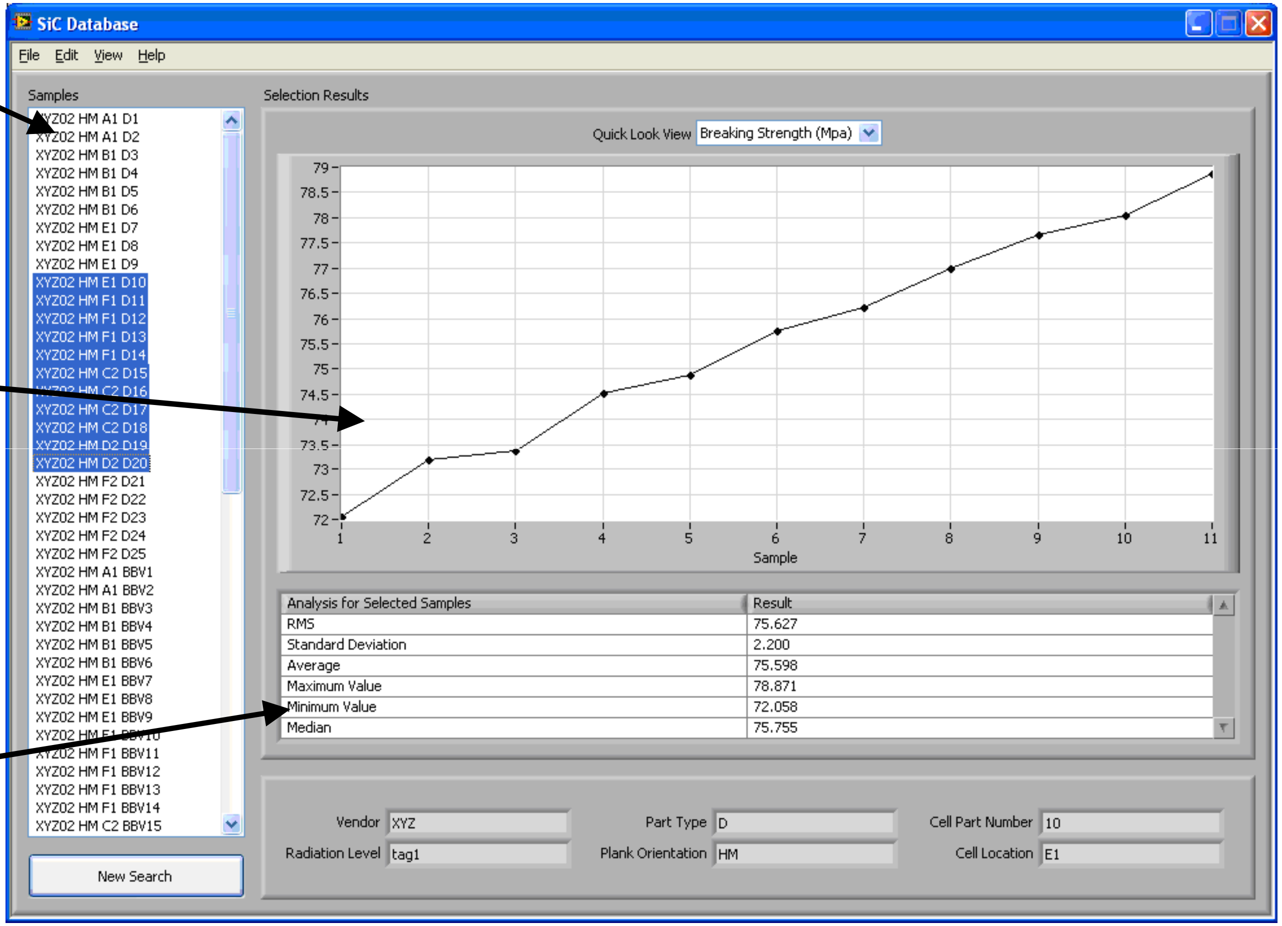
palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

Database Screenshot (Multiple Samples)

Queried Samples

Quick-look Graph of Selected Samples

Basic Numerical Analysis

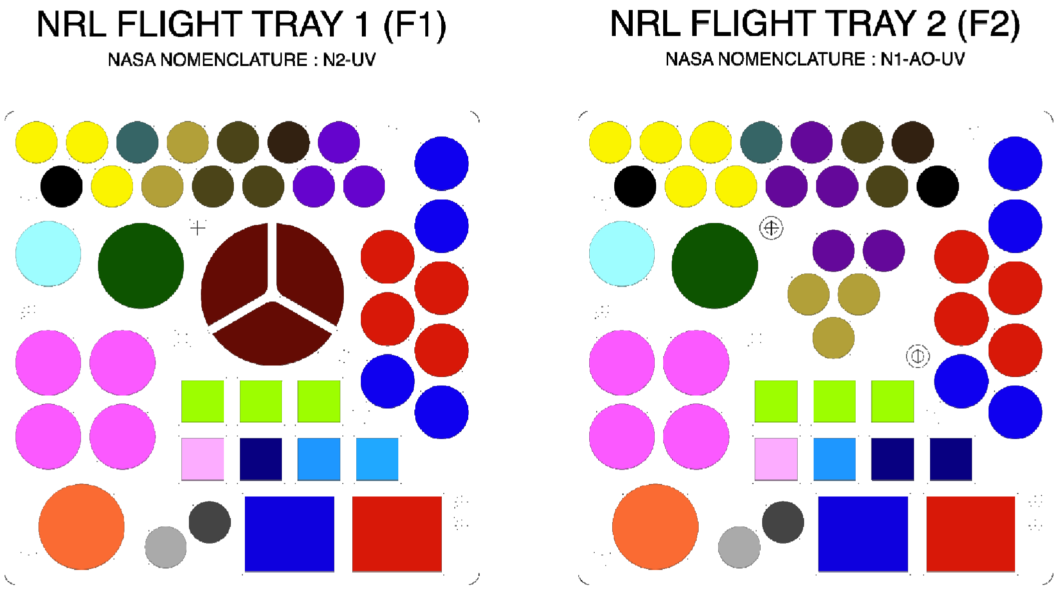


palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

Flight Programs Supporting Space Qualification

MISSE-6, -7, -8

- **NASA Langley program exposing material to low-Earth-orbit space environment**
- **Measure effects of space exposure on material and optical properties**
- **Temperature, atomic oxygen, and UV exposure measurements made on-orbit**
- **Passive experiment; all characterization will be done before and after flight**
  - ***Characterize optical material non-destructively pre- and post-flight***
  - ***Test mechanical properties destructively post-flight***
- **Ensure that selected samples have programmatic relevance**



NRL and The Aerospace Corporation have two 10x10 in^2 areas on MISSE-6

palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

SiC Material Property Characterization

D.B. Witkin
The Aerospace Corporation

Mirror Technology Days
16 Jun 2009

Outline

- **Motivation and process for material and mirror system space qualification**
  - ***Reasons for selecting SiC***
  - ***Space qualification of new materials***
  - ***Database***
  - ***Flight projects - MISSE***
- **SiC material properties characterization**
  - ***Materials testing***
  - ***Radiation testing***
  - ***Data analysis***
- **Defect tolerant design and proof load testing: necessary steps in SiC system development**
  - ***NDE***
  - ***Fatigue***
  - ***Proof load testing & FEA***
- **Lessons learned, Future work, Summary**

palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

Mechanical Testing: Purpose

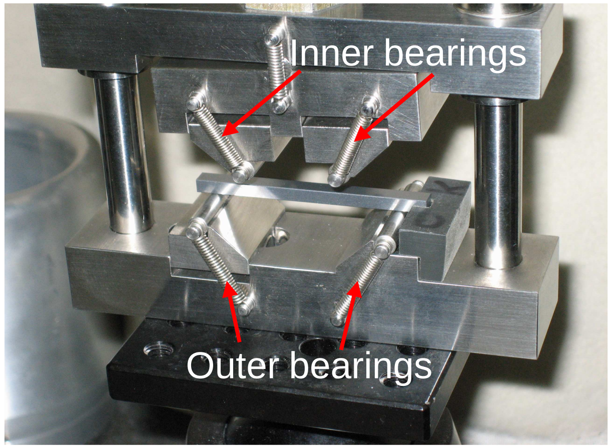
- Mechanical testing is necessary to characterize structural material
- Mechanical properties are essential for designing structures and components subjected to mechanical loads
- Strength of brittle materials must be assessed statistically: large number of tests must be performed
  - Strength of brittle materials scales inversely with size of sample under stress
  - Large data sets improve probabilistic modeling of strength and safety factors
- How does basic materials testing inform the space qualification process?

palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

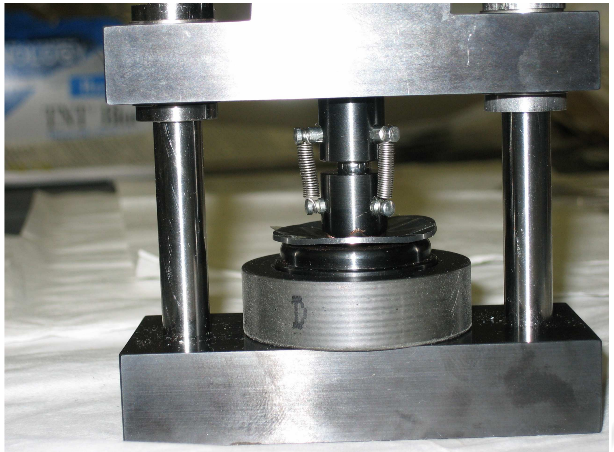
Mechanical Testing Overview

- **Three different tests performed in compliance with ASTM standards:**
  - ***Modulus of Rupture (ASTM C 1161-02c)***
  - ***Fracture Toughness (ASTM C 1421-01b)***
  - ***Equibiaxial Flexural Strength (ASTM C 1499-04)***
- **Test sequence includes:**
  - ***Measurement of specimen dimensions***
  - ***Verification that specimen fracture location and test outcome are valid within ASTM standard***
  - ***Photography and archiving of test specimens after testing***
- **Materials from four vendors have been tested to various degrees**
  - ***One vendor's material was tested before and after radiation exposure***

B Bars



Disk



palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

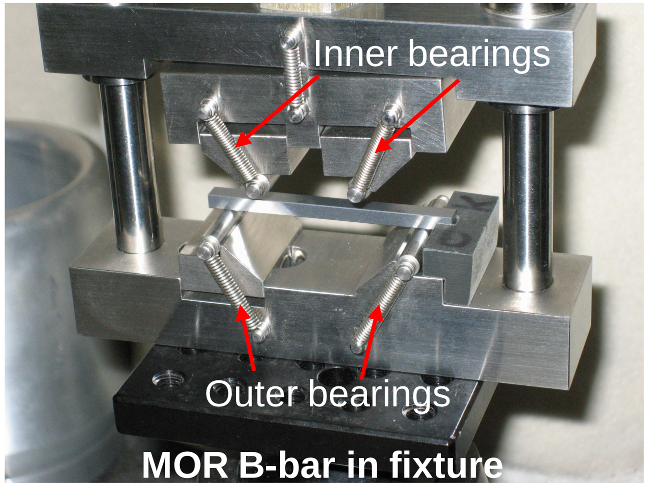
Modulus of Rupture (MOR)

Justification

Flexural strength test more reliable measure of uniaxial strength than tensile test

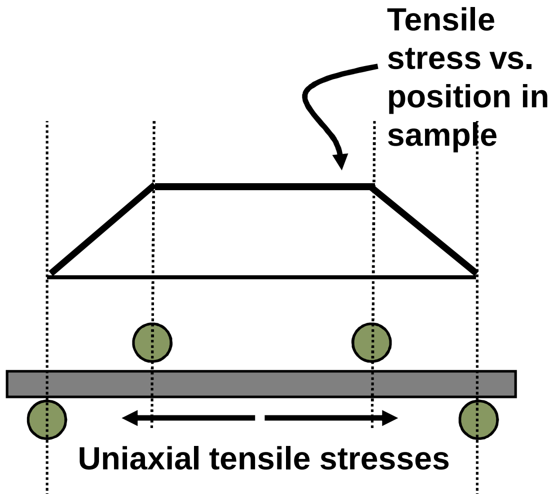
Four point bend testing for MOR gives uniform tensile stress in load span

B Bars

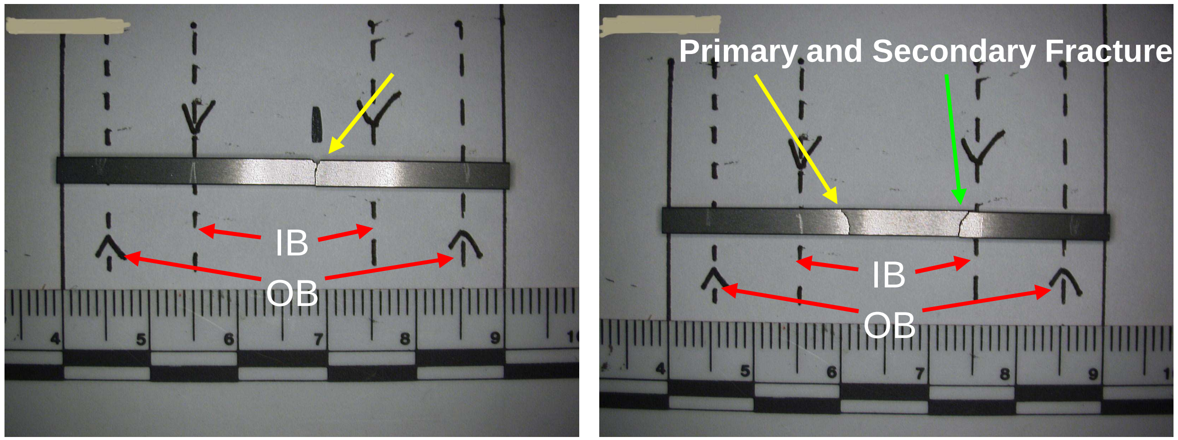


Testing Sequence

1. **Perform mechanical test; inspect fracture locations for test validity**
2. **Measure dimensions of broken B-Bar**
3. **Photograph broken sample**
4. **Intermittent surface and chamfer inspection**



Crack locations for two MOR samples



palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

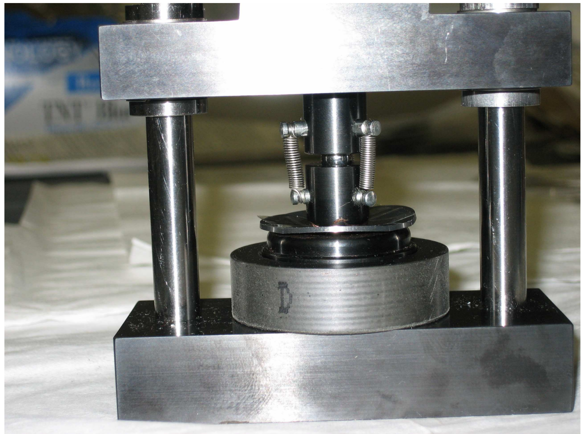
Equibiaxial Flexural Strength (EFS)

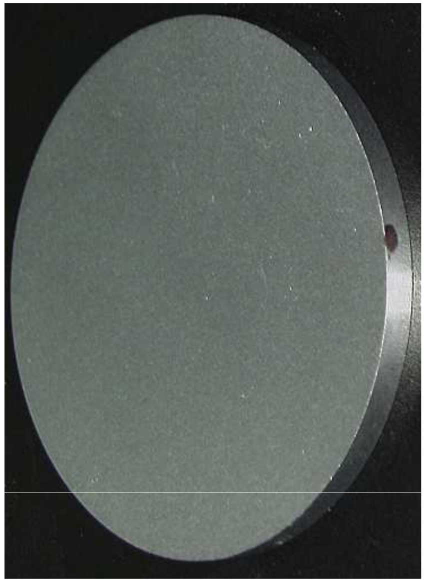
Justification

Equibiaxial flexural strength provides lowest flexural strength of a material

Data free of edge effects. Sample edge is at lower stress than area under load ring

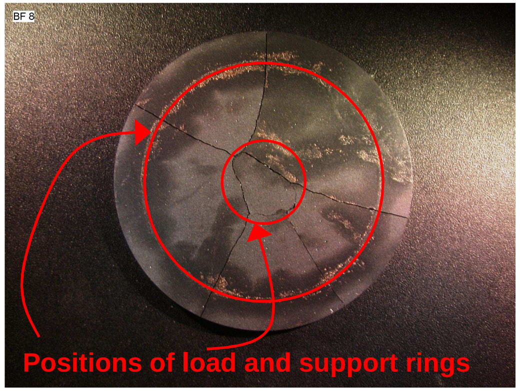
Effect of surface polishing on strength of mirror can be evaluated

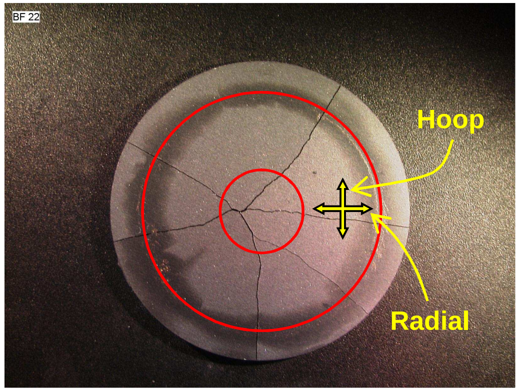


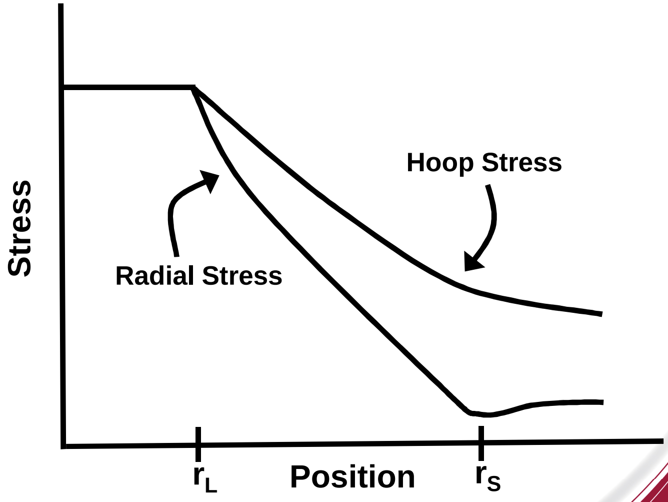


Testing Sequence

1. **Measure sample dimensions (disk diameter and thickness)**
2. **Perform test; evaluate fracture pattern for test validity**
3. **Photograph broken sample**







palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

Fracture Toughness (FT)

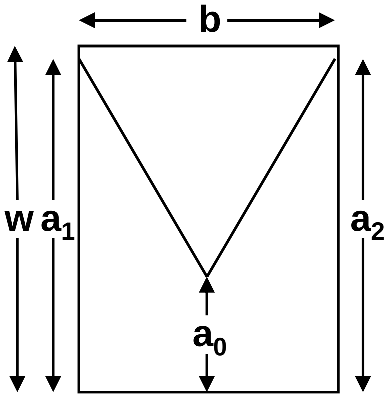
Justification

Fracture toughness is a material property that describes resistance to crack propagation: unlike strength, it is not dependent on specimen size

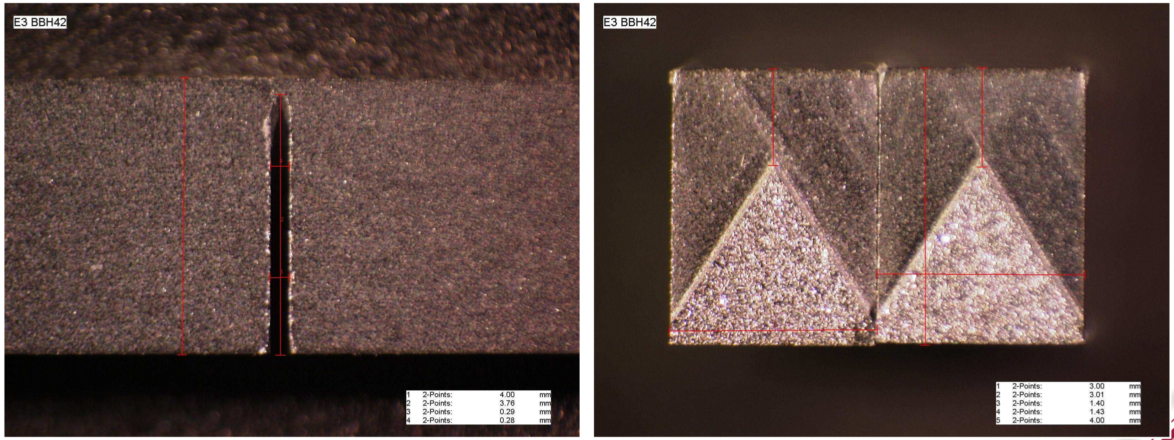
Used to predict strength of material from fracture mechanics perspective (minimum flaw size necessary to cause fracture under given loading condition)

Testing Sequence

1. **Perform mechanical test**
2. **Measure dimensions of broken sample, including width and height and chevron dimensions**
3. **Examine load-displacement curve for test validity and estimate of K_{Ic}**



Measurements for Fracture Toughness Samples



palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

Advantages of Chevron-Notched Beam Technique

- **ASTM C 1421 allows three different specimens for fracture toughness testing. All are based on a rectangular bar, but there are some differences in test specimens :**
  - ***Precracked Beam (K_{Ipb}): A notch is cut in the sample by a blade, or by a series of connecting Vickers indents. The formation of the pre-crack requires a separate compression fixture***
  - ***Surface Crack in Flexure (K_{Isc}): A series of Knoop indents are used to form a crack below the surface, with the indented surface lapped and polished to reduce it to a uniform depth***
  - ***Chevron Notched Beam (K_{Ivb}): Two cuts form the chevron cross section***
- **In addition, the chevron notched beam provides a singular point for crack initiation and propagation**

Fracture Toughness of sintered α-SiC (all values MPa·√m)

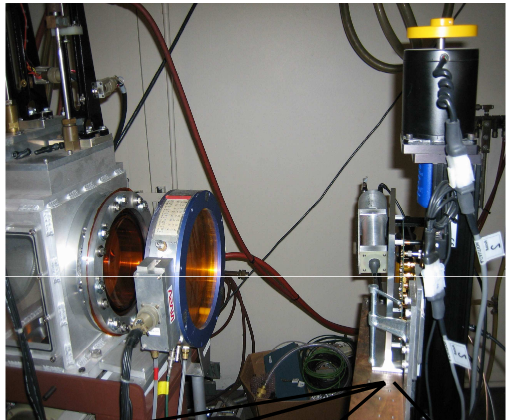
K_{Ipb}	K_{Isc}	K_{Ivb}
2.58±0.08	2.76±0.08	2.61±0.05

Source: Jenkins et al., ASTM STP 1409, 2002

palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

Radiation Testing

- **Completed 5 radiation experiments using 88” cyclotron at Lawrence Berkeley Laboratory (LBL)**
  - ***Each sample is exposed to protons and heavy ions***
    - ***Low***
      - ***$3*10^{12}$ Protons / cm2***
      - ***$1*10^{8}$ Oxygen atoms / cm2***
      - ***$1*10^{8}$ Xenon atoms / cm2***
    - ***High***
      - ***$9*10^{12}$ Protons / cm2***
      - ***$4*10^{8}$ Oxygen atoms / cm2***
      - ***$4*10^{8}$ Xenon atoms / cm2***



palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

LBL and Orbital Exposure Equivalents

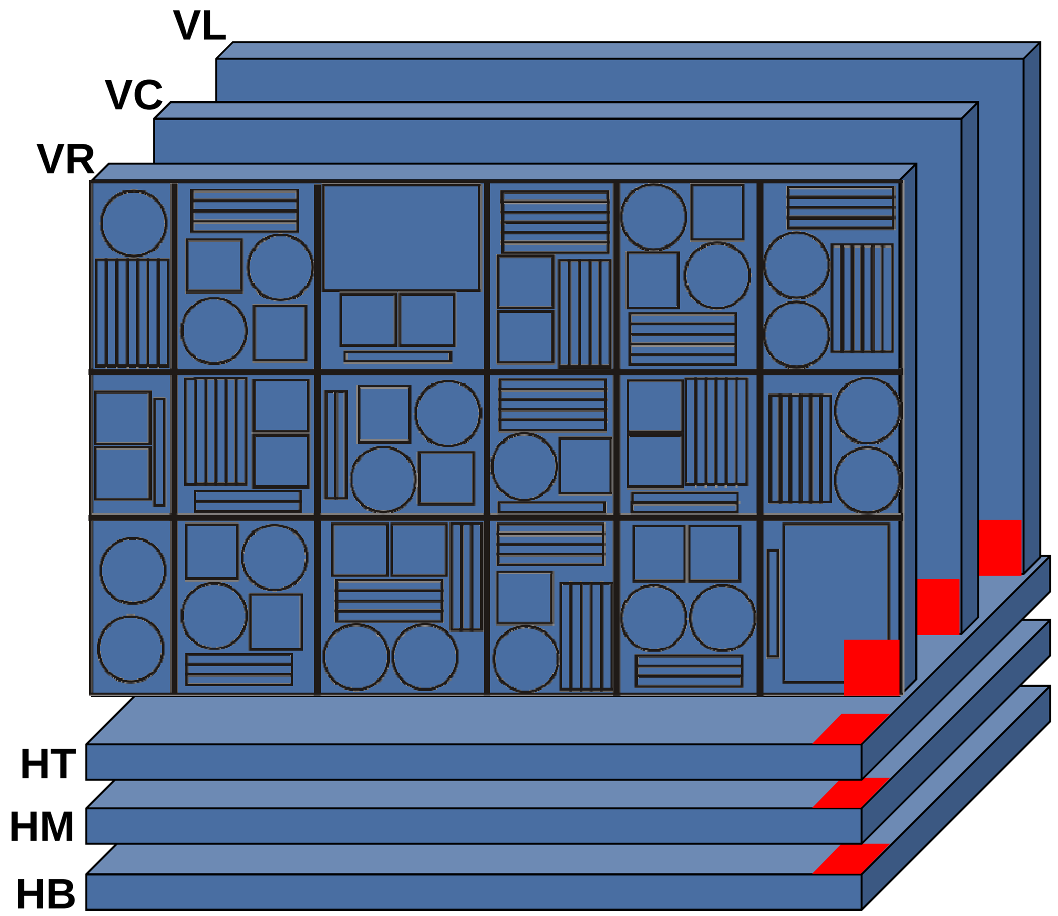
- **Radiation model developed at The Aerospace Corporation**
  - ***Two sources of radiation are considered***
    - ***Trapped protons***
    - ***Ions generated from galactic cosmic rays (GCR)***
  - ***Model assumes solar minimum so trapped proton levels are overestimated***
- **Radiation exposures at low levels correspond to:**
  - ***150 years of orbit in LEO***
  - ***75 years of orbit in HEO***
  - ***Greater than 200 years orbit in GEO***
  - ***7.5 years of orbit in GPS***
  - ***4 weeks in MEO***
- **Radiation exposures at high levels correspond to:**
  - ***450 years of orbit in LEO***
  - ***225 years of orbit in HEO***
  - ***Greater than 200 years orbit in GEO***
  - ***22.5 years of orbit in GPS***
  - ***3 months in MEO***
- **Payloads rarely flown in MEO orbits due to radiation levels**

No change in material properties has been observed thus far due to radiation exposure

palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

Materials Processing Setup

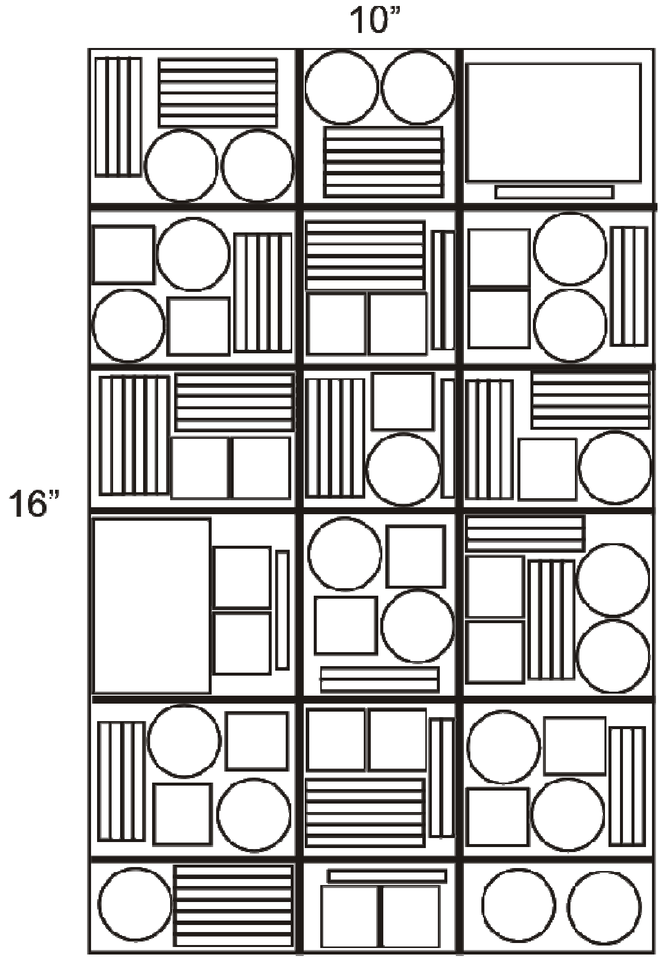
- **Goal of experiment**
  - *Determine if material properties vary with*
    - *Plate location in furnace*
    - *Plate orientation (vertical and horizontal)*
    - *Sample location within planks*
- **Motivation for setup**
  - *Test maximum capacity of furnace*
  - *Plate orientations during firing are representative of different applications*
- **Nomenclature**
  - *Horizontal planks: “B” for bottom, “M” for middle, or “T” for top*
  - *Vertical planks: “L” for left, “C” for center, or “R” for right*
  - *Marking on lower right corner tracks orientations*



palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

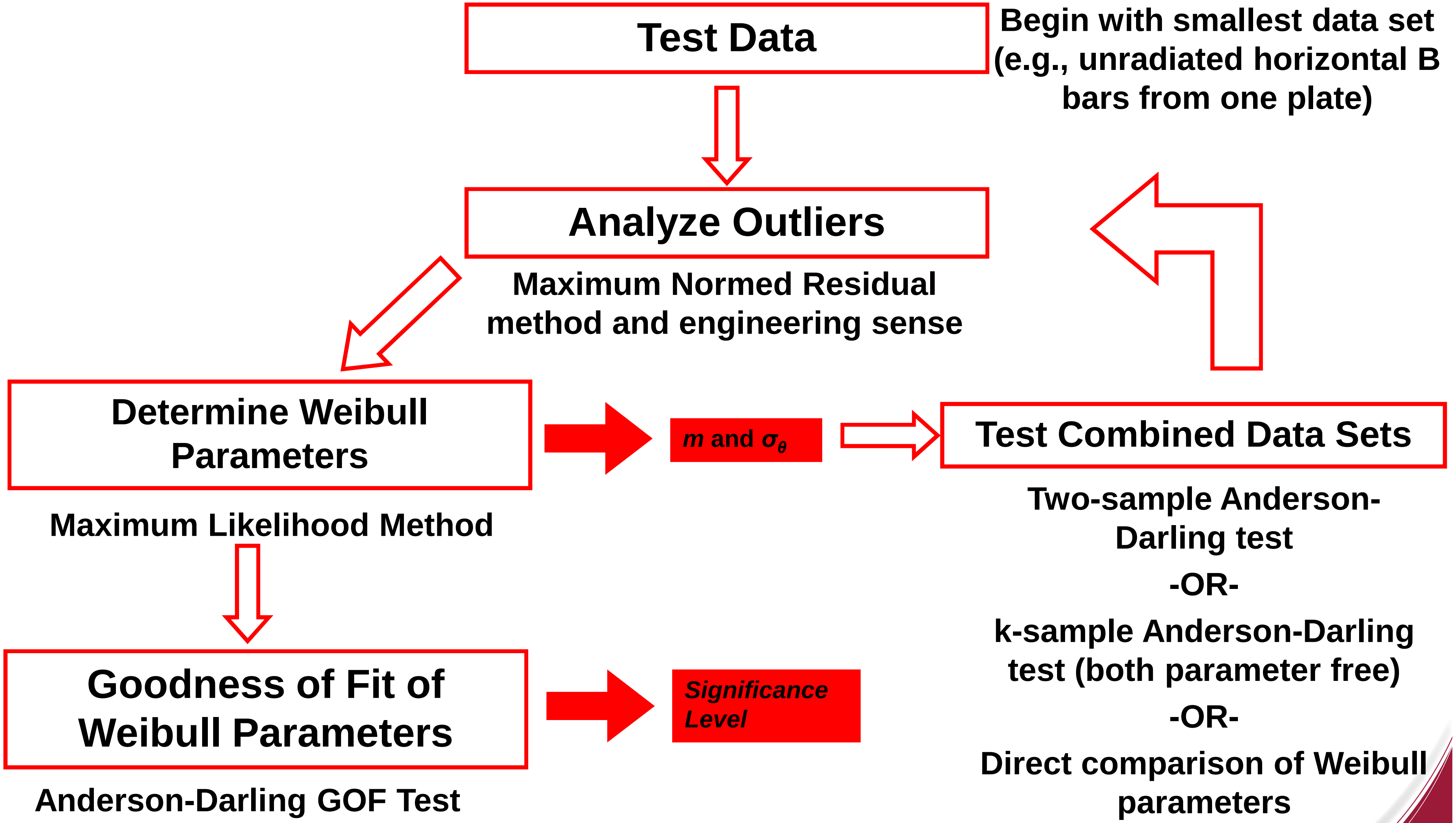
Samples and Bulk SiC Map

- **Two vendors supplied materials at this scale**
- **Each plate contains 24 Tiles, 42 disks, 2 rectangles, and 92 b-bars (fracture toughness and modulus of rupture)**
- **B-bars oriented both horizontally and vertically to evaluate texture in material**
- **Number of test samples were chosen to be statistically meaningful**
- **Selected experienced machining vendor**
  - ***Critical to limit subsurface damage caused by machining***
  - ***Subsurface damage causes lower material performance***



palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

Analytical Approach



palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

References for Analytical Approach

- **There is no single source for analyzing test data according to this scheme, but here are a few places to start:**
  - *ASTM C 1239-00:* ***Standard Practice for Reporting Uniaxial Strength Data and Estimating Weibull Distribution Parameters for Advanced Ceramics*** *(accepted practice is Maximum Likelihood Estimate,* NOT *linear regression!)*
  - *Pai, S.S. and J.P. Gyekenyesi,* ***Calculation of Weibull Strength Parameters and Batdorf Flow Density Constants for Volume- and Surface-Flaw-Induced Fracture in Ceramics,*** *NASA Technical Memorandum 100890, 1988 (Good for analyzing individual data sets)*
  - *Neal, D., M. Vangel, and F. Todt,* ***Statistical Analysis of Mechanical Properties****, in Engineered Materials Handbook, Vol. 1: Composites. 1987*
  - *MIL-HDBK 5 and MIL-HDBK 17*
- **There is no substitute for good engineering sense!**

palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

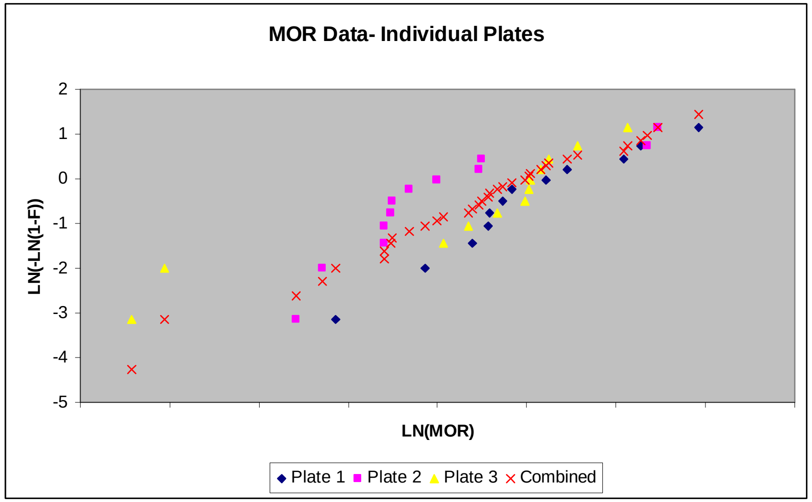
Notes on Presentation of SiC Test Data

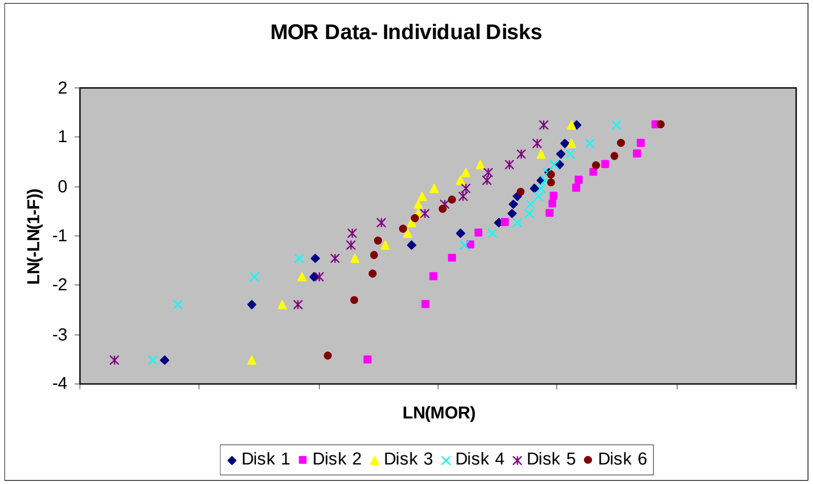
- **The Aerospace Corporation is treating all vendors' test data as proprietary**

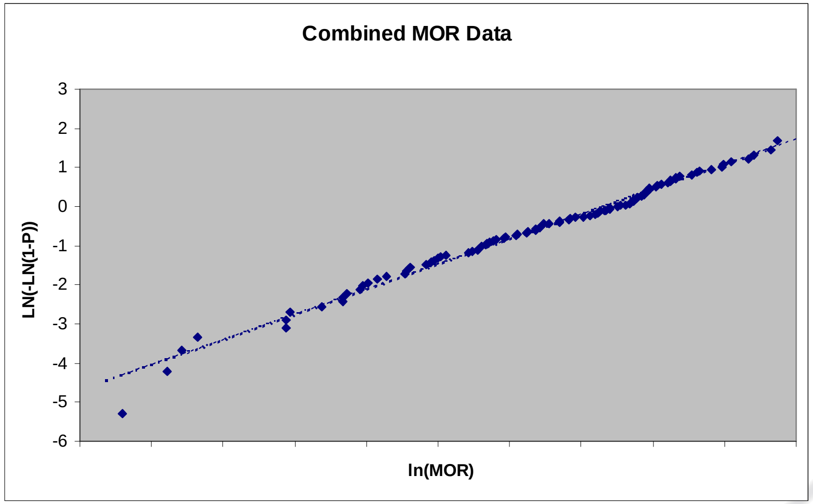
- **Examples of test data on the following several slides are all real data sets, HOWEVER…**
  - ***No association between vendor and test data will be made in this presentation***
  - ***No references to type of SiC will be given***
  - ***No actual strength values or KIc values will be given***

palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

Aggregation of Test Data: Two Different Vendors





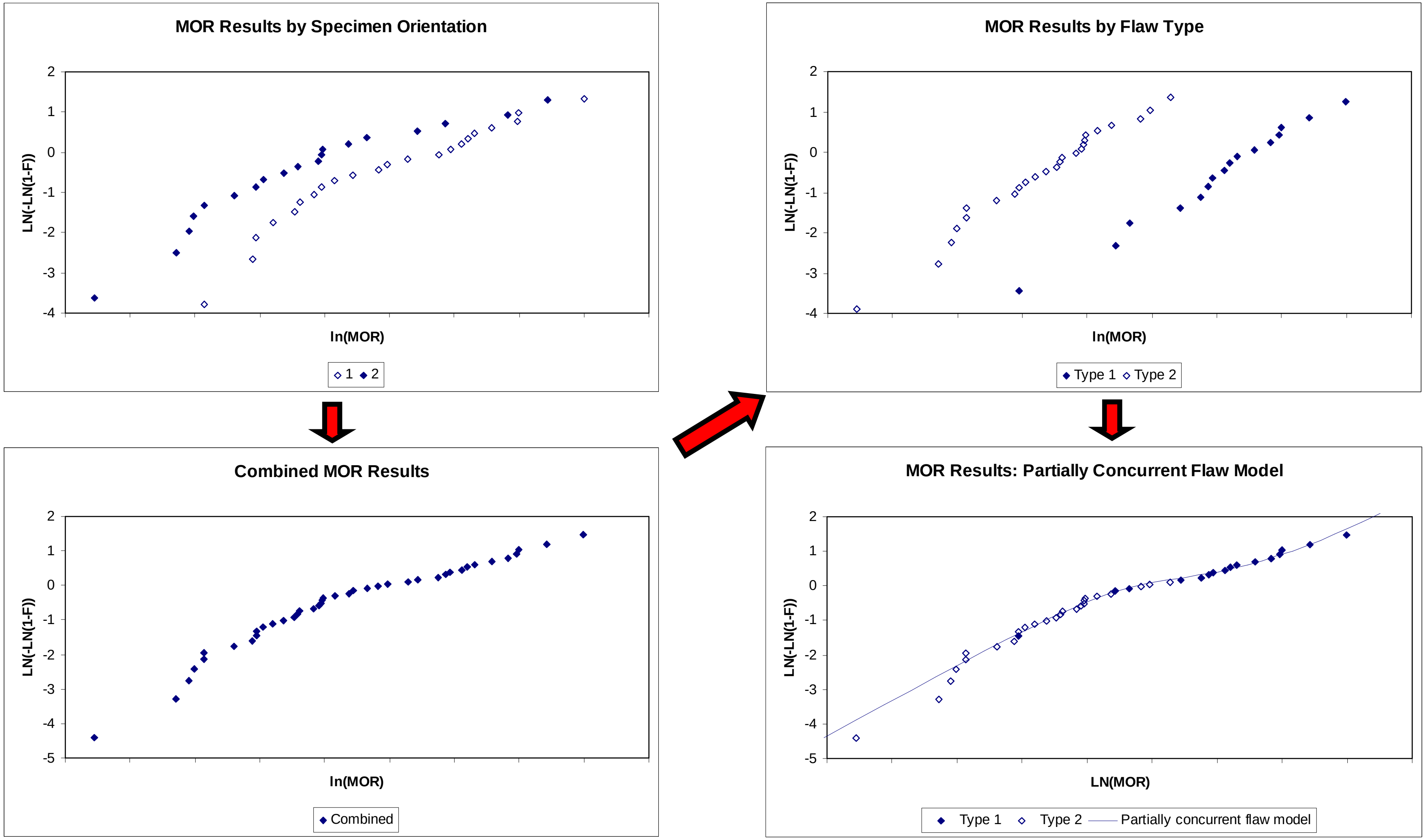


Individual plate data are for MOR bars with same orientation within plates with same furnace orientation (n = 12 for each data set). Combining into a single data set (n = 36) shows good fit to a single Weibull distribution.

Data from six individual disks (n = 17) appear to show differences in Weibull distributions, but combine to give a single Weibull distribution with good fit.

palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

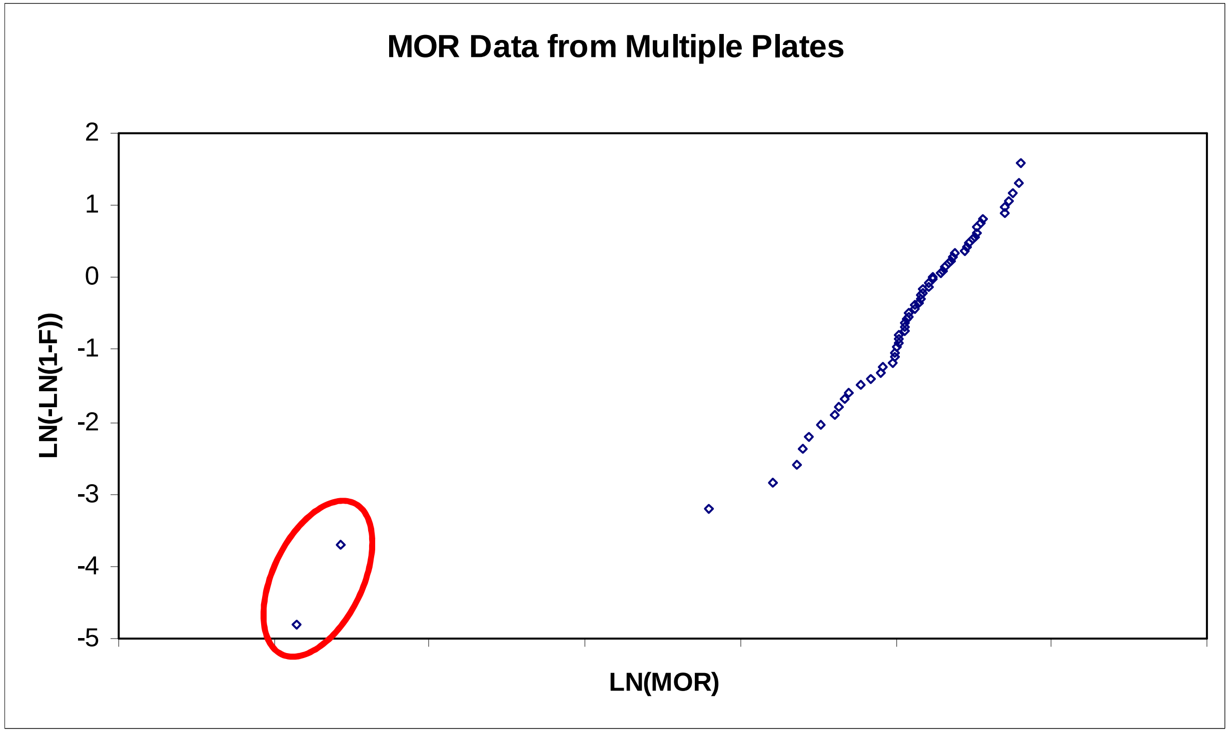
Dis- and Re-aggregation of Test Data



MOR data plotted by: specimen orientation within single plate (upper left); combined data (lower left); separated by flaw type (upper right); combined partially concurrent two-flaw Weibull distributions (lower right)

palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

Dealing with Outlying Test Data: Example



- **Fractography revealed a processing defect in one of the specimens with low MOR value, but in general specimens could not be categorized by flaw type.**
- **Goodness of Fit after removing two outliers shows good agreement to single Weibull distribution**
- **B basis from this Weibull distribution was ~5% higher than B basis calculated for entire data set using non-parametric estimator**
- **Defect was easily detected (albeit after the fact) using NDE (acoustic microscopy, x-ray)**

palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

Purpose of Material Testing Revisited

- **Benefits of sufficient number of test samples:**
  - ***Dispersion of strength results, and therefore flaw sizes, is well characterized***
  - ***Mechanical tests are perceptive of manufacturing flaws***

- **Uses of mechanical test results**
  - ***Design trades***
  - ***Probabilistic modeling of service loads***
  - ***Fracture mechanics-based design of structures***

- **Limitations of mechanical testing**
  - ***Materials for test samples are representative of actual optical structure fabrication***
  - ***For more complex, light-weighted optics, mechanical testing of coupons derived from replicates of flight designs may be necessary***

palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

Defect Tolerant Design and Proof Load Testing: Necessary Steps in SiC System Development

M.J. O'Brien
The Aerospace Corporation

Mirror Technology Days
16 Jun 2009

Outline

- **Motivation and process for material and mirror system space qualification**
  - ***Reasons for selecting SiC***
  - ***Space qualification of new materials***
  - ***Database***
  - ***Flight projects - MISSE***

- **SiC material properties characterization**
  - ***Materials testing***
  - ***Radiation testing***
  - ***Data analysis***

- **Defect tolerant design and proof load testing: necessary steps in SiC system development**
  - ***NDE***
  - ***Fatigue***
  - ***Proof load testing & FEA***

- **Lessons learned, Future work, Summary**

palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

Non-Destructive Evaluation

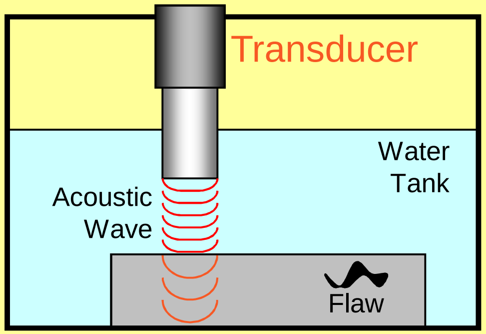
- **Selected NDE techniques**
  - ***Acoustic imaging***
    - **Uses transmitted and reflected acoustic energy to locate cracks, voids, and other anomalies within a slice of material**
    - **Water is the medium used to transmit acoustic waves**
  - ***Eddy current***
    - **Sensitive to conductivity of test samples**
  - ***X-Ray imaging***
    - **Relative transmitted X-ray energy is used to determine location of less dense areas within a volume of material**
- **Computed tomography imaging**
  - ***Allows for full reconstruction of sample in three dimensions***
- **Use NDE for qualification of an optical assembly (mirror and structure)**
  - ***X-ray images can be used to quickly locate large anomalies***
  - ***Acoustic imaging can be used for finer investigation of anomalies found in X-ray***
- **NDE contributes to**
  - ***DTD by establishing threshold for smallest flaw that can be reliably identified***
  - ***Quality assurance by evaluating substrate throughout production***

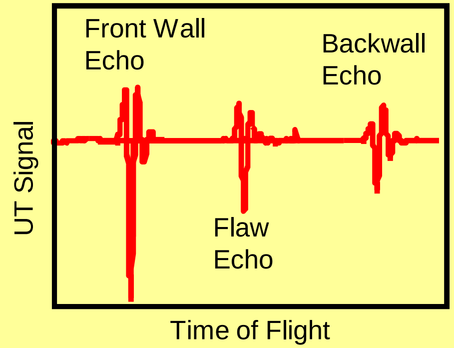
palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

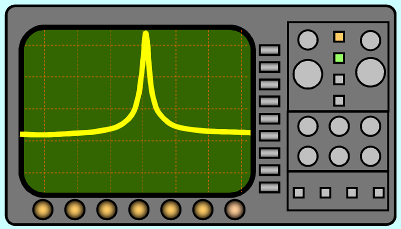
NDE Techniques Used

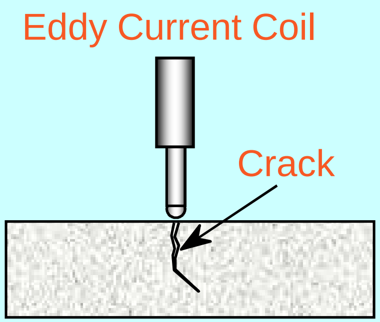
Ultrasound:

Propagating acoustic waves in the plate interact with the physical and mechanical properties of the part.







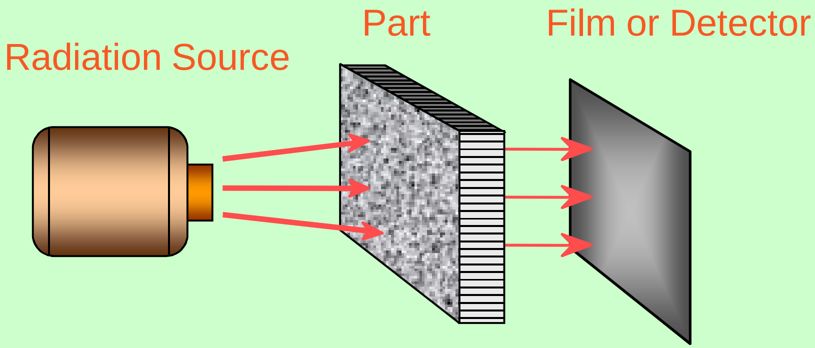


Eddy Current:

Induced electrical field measures the absolute electrical conductivity of the part.

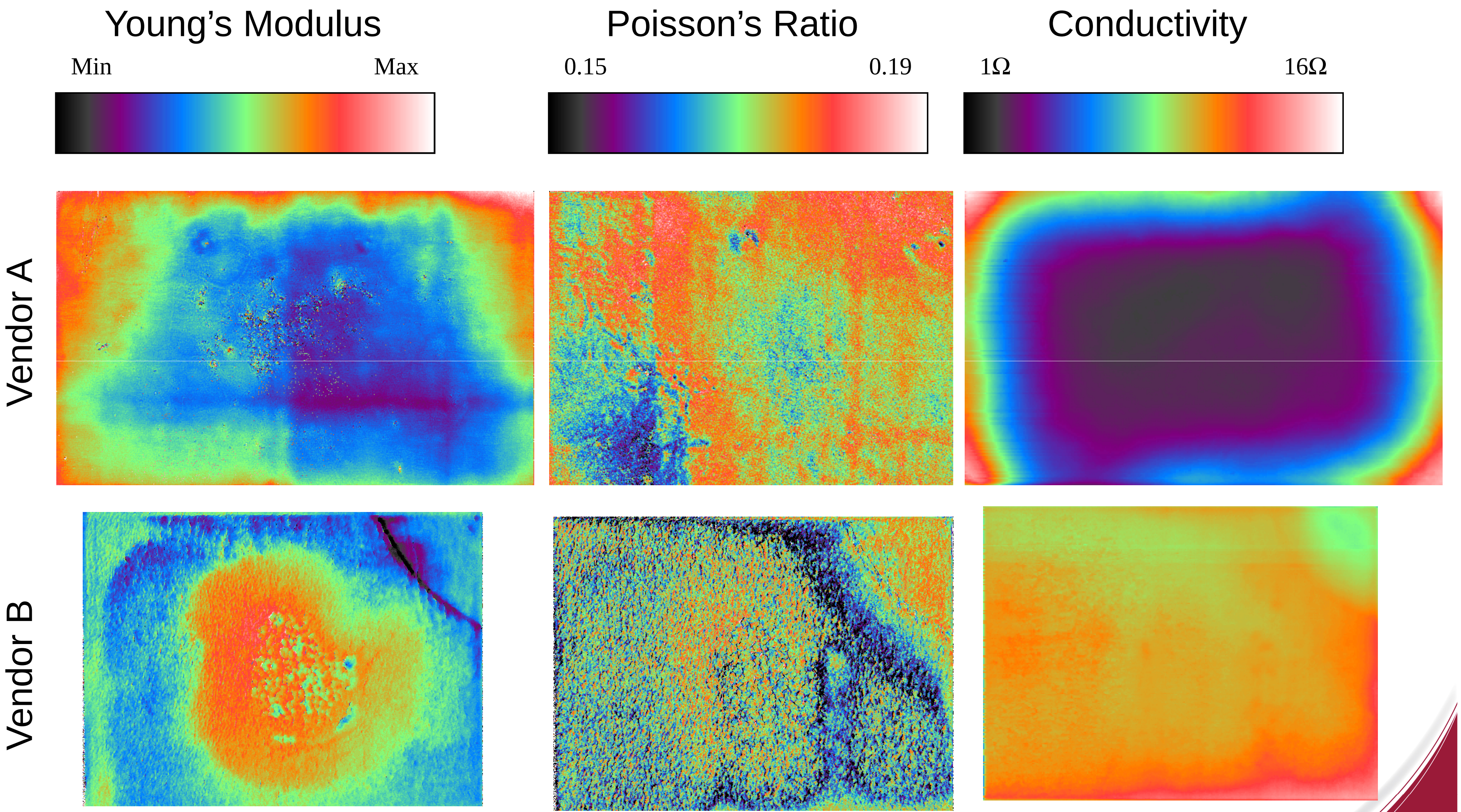
X-Ray:

Radiation penetrating the part is absorbed depending on atomic number, density, and thickness of the part.



palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

Materials Properties Measurements



palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

Summary of NDE Findings

- **Plate thickness variations greatly affect acoustic velocity measurements**
  - ***Young's modulus measurements are also affected***
- **Poisson's ratio measurements are independent of plate thickness**
  - ***Thickness cancels out in ratio of velocities***
  - ***Measurement is still susceptible to scatter effects of acoustic wave due to non-uniform surface roughness***

Comparison of plates from two vendors

- **Manufacturing process effects and patterns are evident in mapping Young's Modulus profile of both types of plates**
- **Poisson's ratio is relatively uniform throughout both plates**
- **Conductivity profile of one plate type has extremely wide range suggesting some kind of a non-uniform diffusion process**
- **Conductivity profile of other plate type has a narrow and uniform range**

palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

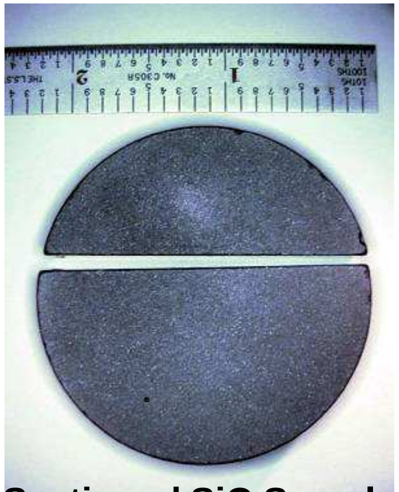
Capabilities and Use of NDE Techniques

Ultrasound Capabilities: Can measure: - Elastic Constants - Physical & Mechanical Properties - Dimensions - Voids & Porosity	**Ultrasound Use:** These measurements are obtained by scanning part in immersion tank. Flat and stand-alone parts are ideal for this method. This method of ultrasound is not portable.
Eddy Current Capabilities : Measures Conductivity and Capacitance to infer: - Type of Material or Alloy - Presence of cracks voids or inclusions	**Eddy Current Use:** Portable – can be used on systems and installations. Requires contact or near contact
X-Ray Capabilities : Optical density of exposure depends on: - Material atomic number & density - Thickness of the part	**X-Ray Use:** Portable – can be used on systems and installations. Not sensitive to mechanical and physical properties.

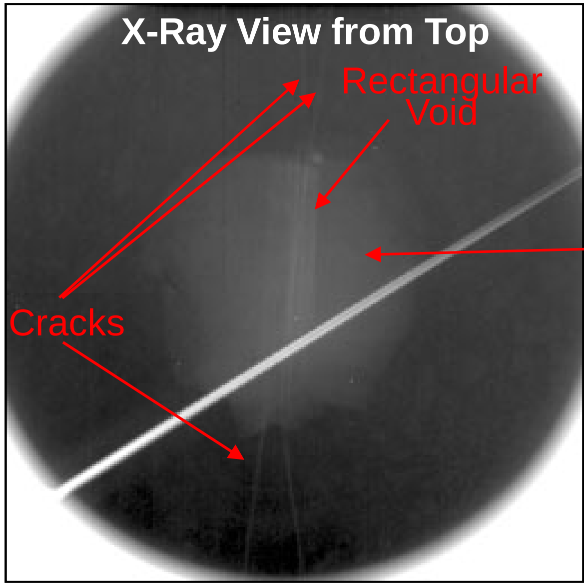
palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

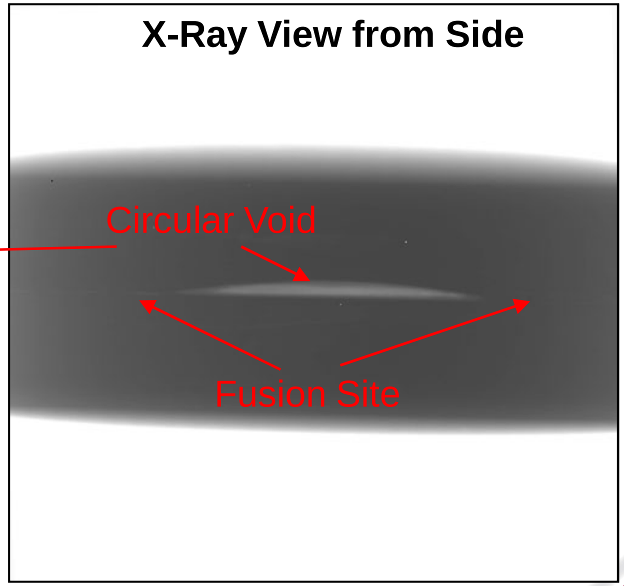
Example of NDE - X-Ray

- **X-Ray capabilities**
  - ***Penetration depths greater than 2"***
  - ***Detail detectability: 2 µm***
- **Intentionally defective sample below is 2" diameter disk**
  - ***Two ¼" disks were fused together resulting in a ½" th ick disk***
  - ***Intentionally flawed with several voids and cracks to assess NDE capabilities***



Sectioned SiC Sample

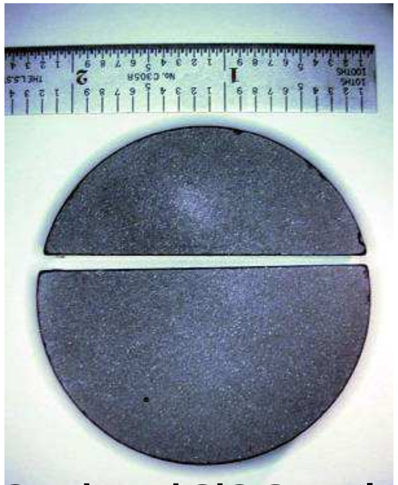




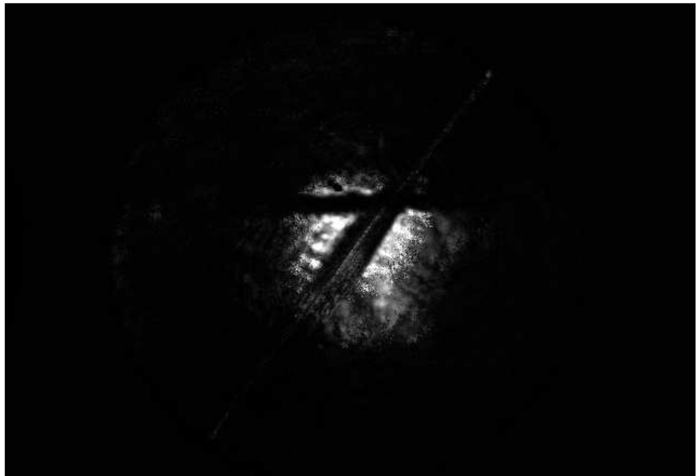
palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

Example of NDE – Acoustic Imaging

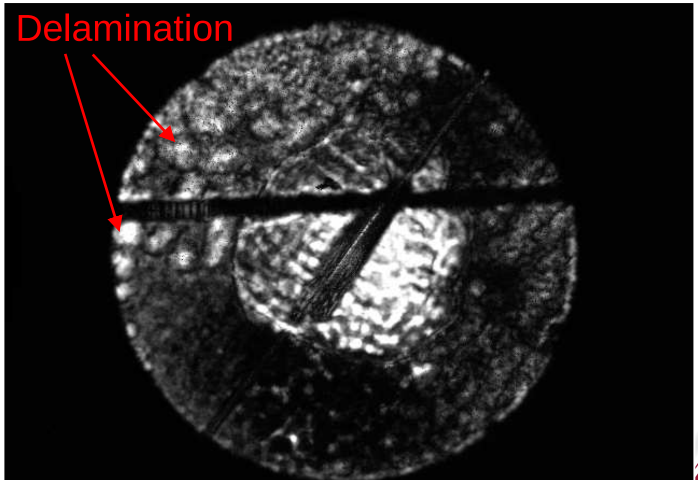
- **Acoustic imaging capabilities**
  - ***Range of penetration depths: 6 – 75mm***
  - ***Axial resolution: 0.001 – 17mm***
  - ***Spatial resolution: 0.010 – 0.250mm***
  - ***Acoustic signal penetration depth, axial resolution, and spatial resolution depend on transducer frequency and focal length.***
- **Features in voids and delaminations at fusion site are more detailed in acoustic image than x-ray image**



Sectioned SiC Sample



Top of circular void at fusion site

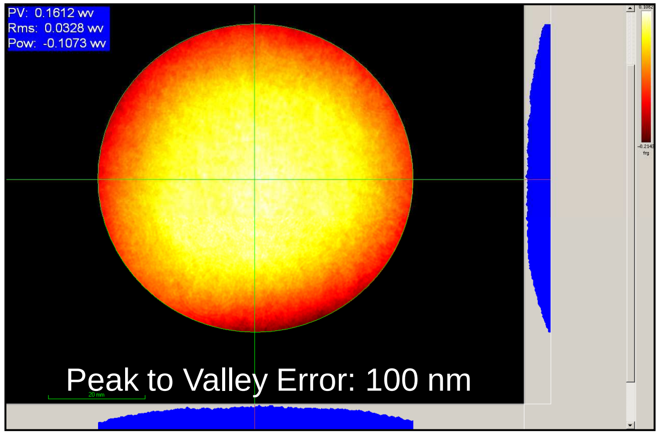


Void and delaminations at fusion site

palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

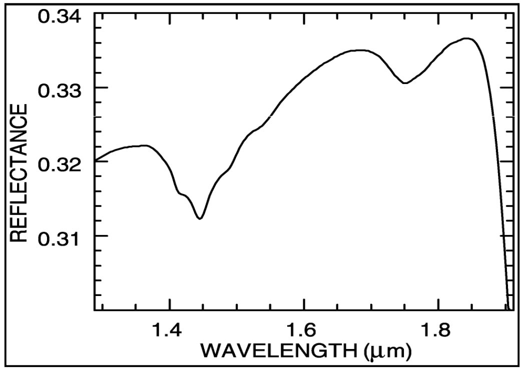
Examples of Optical Analyses

- **Interferometry**
  - ***Phase Shifting Interferometry***
    - ***Determine surface profile of reflective and transmissive optical components with resolution on the order of 20nm***



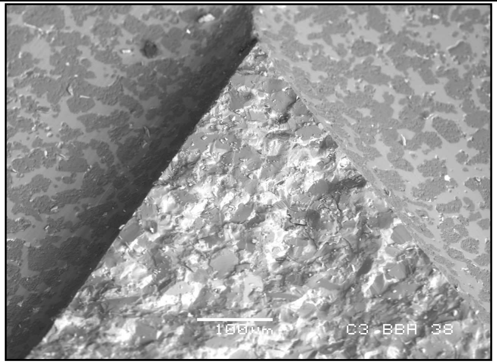
Surface profile of 1" SiC mirror

- **Spectroscopy**
  - ***Fourier Transform Spectroscopy***
    - ***Determine spectral reflectance of coating or substrate surface***



Reflectance spectrum of multilayer coating

- **Microscopy**
  - ***Scanning Electron Microscopy***
    - ***Produce highly magnified image of surface***



SEM image of SiC sample at site of fracture

palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

Defect Tolerant Design (DTD)

- **DTD is most modern and successful theory for fracture control**

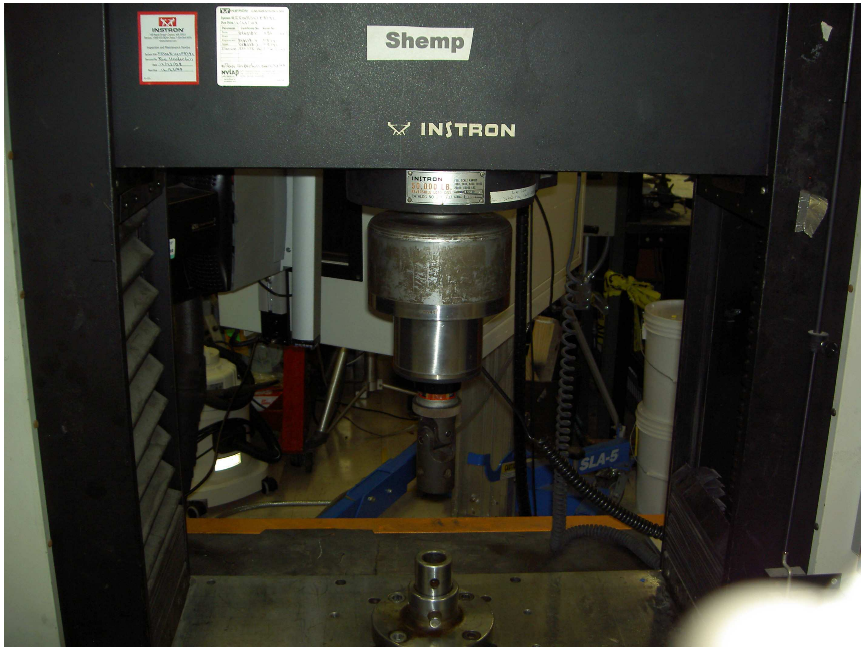
- **DTD is based upon principle that engineering components have inherent cracks that can grow unstably during component lifetime**

- **Goals of DTD**
  - ***Build reliable components from brittle materials***
  - ***Develop reliable predictions of component lifetime***
  - ***Predict performance limits through data analysis and modeling***

- **Successful implementation of the DTD process requires effort in several areas**
  - ***Mechanical testing to determine material strength***
  - ***Proof load testing to set threshold for largest possible flaw in structure***
  - ***NDE to determine flaw locations and size distributions***
  - ***Stress analysis to calculate lifetime under spectrum of service loads***

palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

Proof Test Designed for Mirrors



- **Goal: develop proof test to identify manufacturing flaws in mirror**
  - ***Lightweighted ceramic mirrors have thin webs likely to have flaws***
  - ***Use early in manufacturing to limit further "investment" in flawed part***
- **Proof test must apply tensile stress to mirror**
- **Proof test uses quasi static loading on Instron test machine**
- **Purchased five surplus small scale (25 cm) substrates**
- **Contacted two additional vendors for quotes on test substrates for subsequent vendor evaluations**

palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

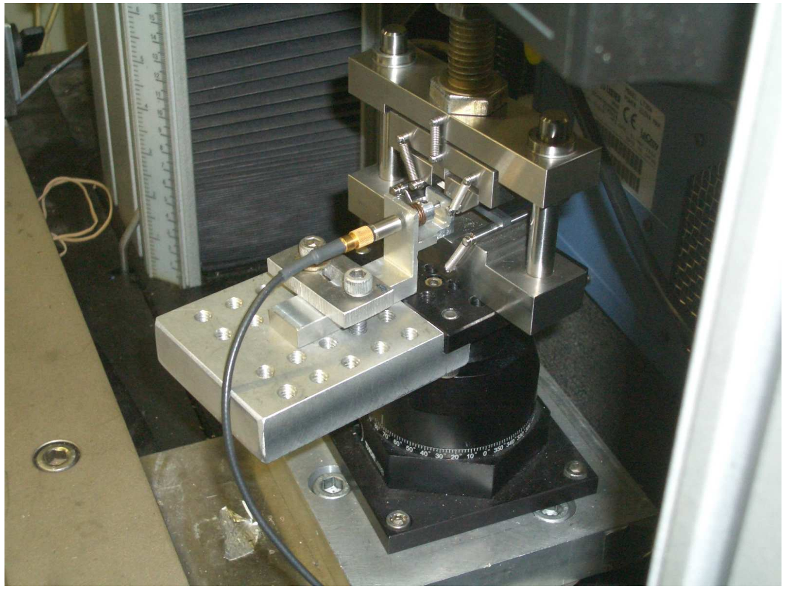
Proof Testing Provides Three Advantages

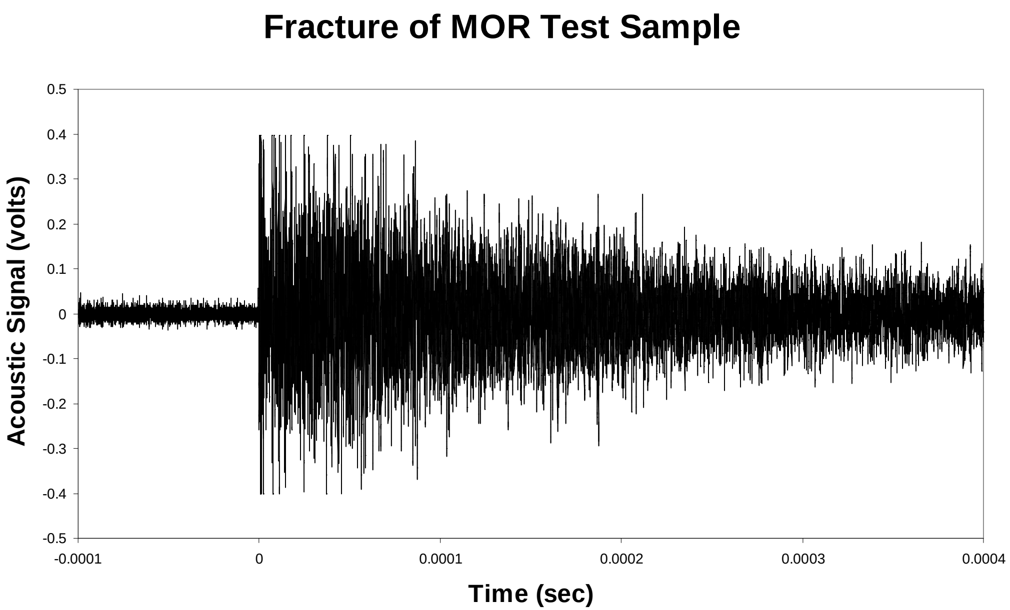
- **Proof testing a prototype or spare mirror to failure validates design and eliminates uncertainty in factor of safety**
  - ***Potential payoff to improve lightweighting if mirror is "overdesigned"***
- **Proof testing a production mirror at less than the failure loads eliminates possibility of flaws in high-risk locations**
  - ***Testing before polishing prevents further investment in a flawed mirror***
  - ***Testing after polishing ensures that polishing does not introduce fresh flaws***
- **If service loads are lower (by suitable margin) than design's failure loads, then critical flaw size might be below NDE's limit of resolution and proof testing of flight components might not be needed**

palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

Preparation for Proof Load Testing

- **Acoustic monitoring of MOR test**
  - ***Provides baseline acoustic crack signature of SiC material which may be useful in performing proof tests***
  - ***Evaluated preliminary test set up which yields good results***
  - ***Improve set up by plotting load and acoustic signal together***

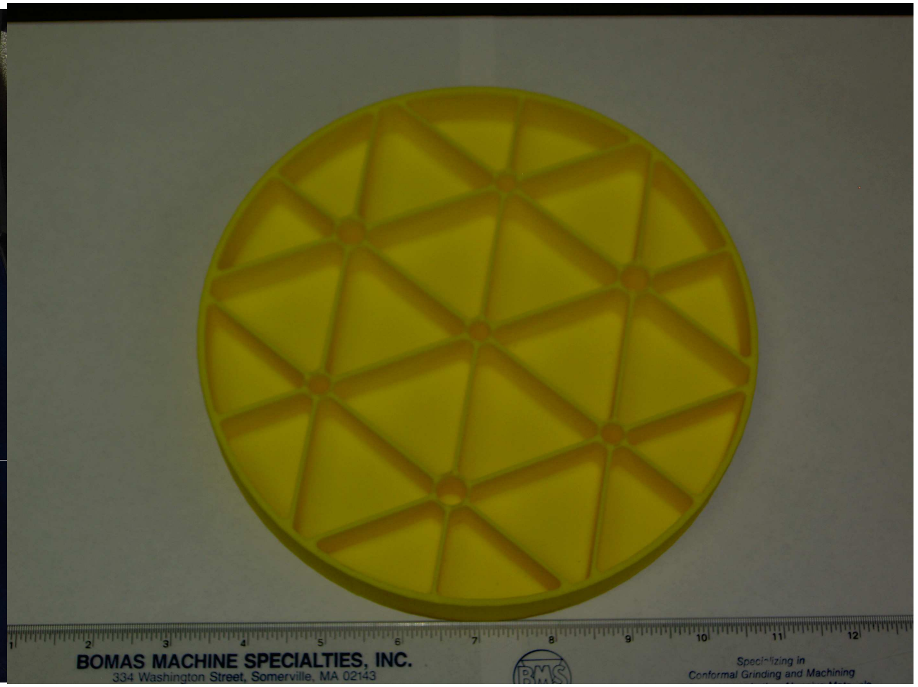




Acoustic set up and signature

palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

Prototype Test Sample for Proof Load Test



Prototype Mirror Substrate
0.25 m Flat

Stereolithography Demonstrator
0.75 scale of mirror

Stereolithographic demonstrator will be used for proof load test development and validation

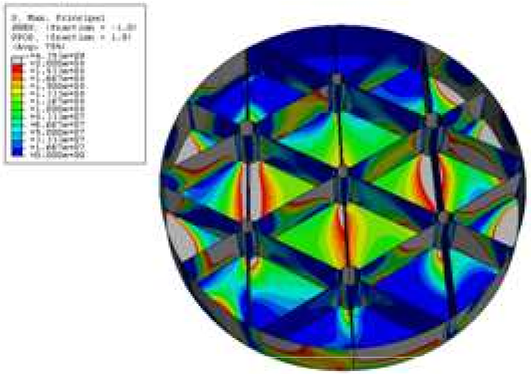
palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

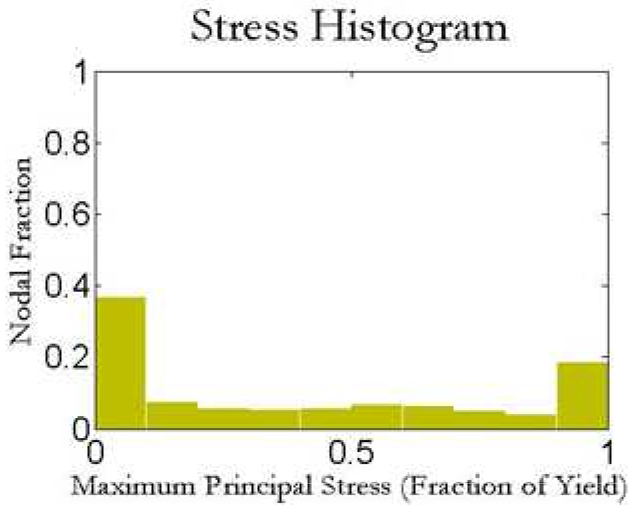
FEA Modeling to Design Proof of Concept for Proof Test

- **Goal of proof test: to place as large a fraction of the mirror under a uniform tensile stress as possible**
- **Metric for each concept: histogram of maximum principal stress for constituent elements in FEA mesh**
- **Preliminary FEA has been performed to evaluate different concepts for proof load test**
- **Concepts evaluated: bending, internal pressurization, compression, torsion and combined compression/torsion**

palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

FEA Modeling of Proof Test: Selected Candidate





- **Combined compression/torsion outperforms bending, pure compression or pure torsion**
- **Physical effects:**
  - ***Compression across a diameter at poles produces useful "tensile" bulging at equator***
  - ***Torsion produces a useful shear with associated tensile stress***
- **Strong tension in face sheet and ribs**
- **Next step: design and implement test fixture for experiments**

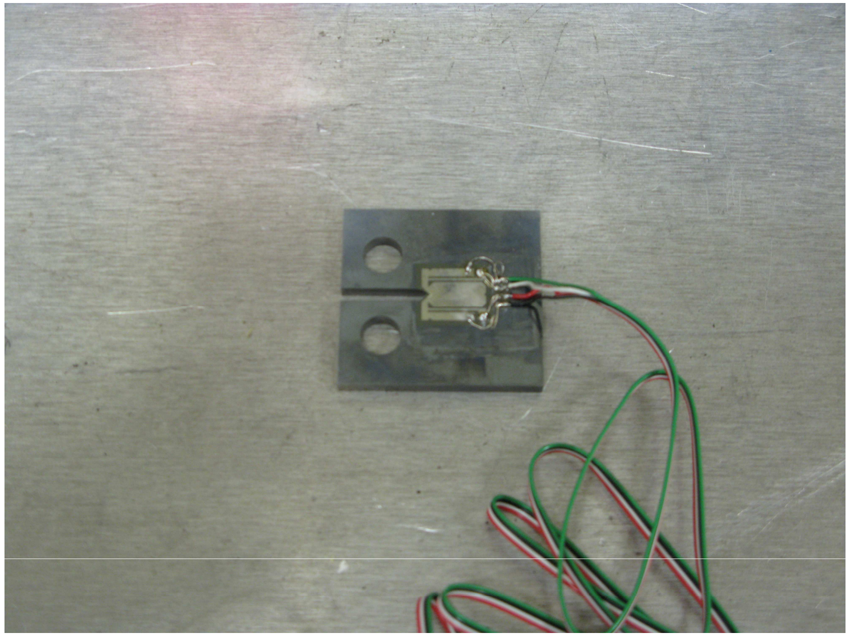
palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

Fatigue Testing

- **Variety of ceramics display fatigue growth of cracks under applied cyclic tension**
  - ***Fatigue occurs in ceramics with a fracture toughness that increases with crack length (known as R-curve effect)***
  - ***Under cyclic loading, toughness is progressively degraded***
- **Fatigue measured in compliance with ASTM standards**
  - ***Test protocol in ASTM E 647***
  - ***Chevron notch specimen from ASTM E 399***
- **Fatigue testing provides the lifetime estimate needed as part of defect tolerant design**
- **What is result of fatigue?**
  - ***Parts fail at lower loads than expected or designed***
  - ***Incorrect to use peak fracture toughness values in presence of fatigue***
    - ***<u>Knock down/safety margin factors required for designs</u>***

palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

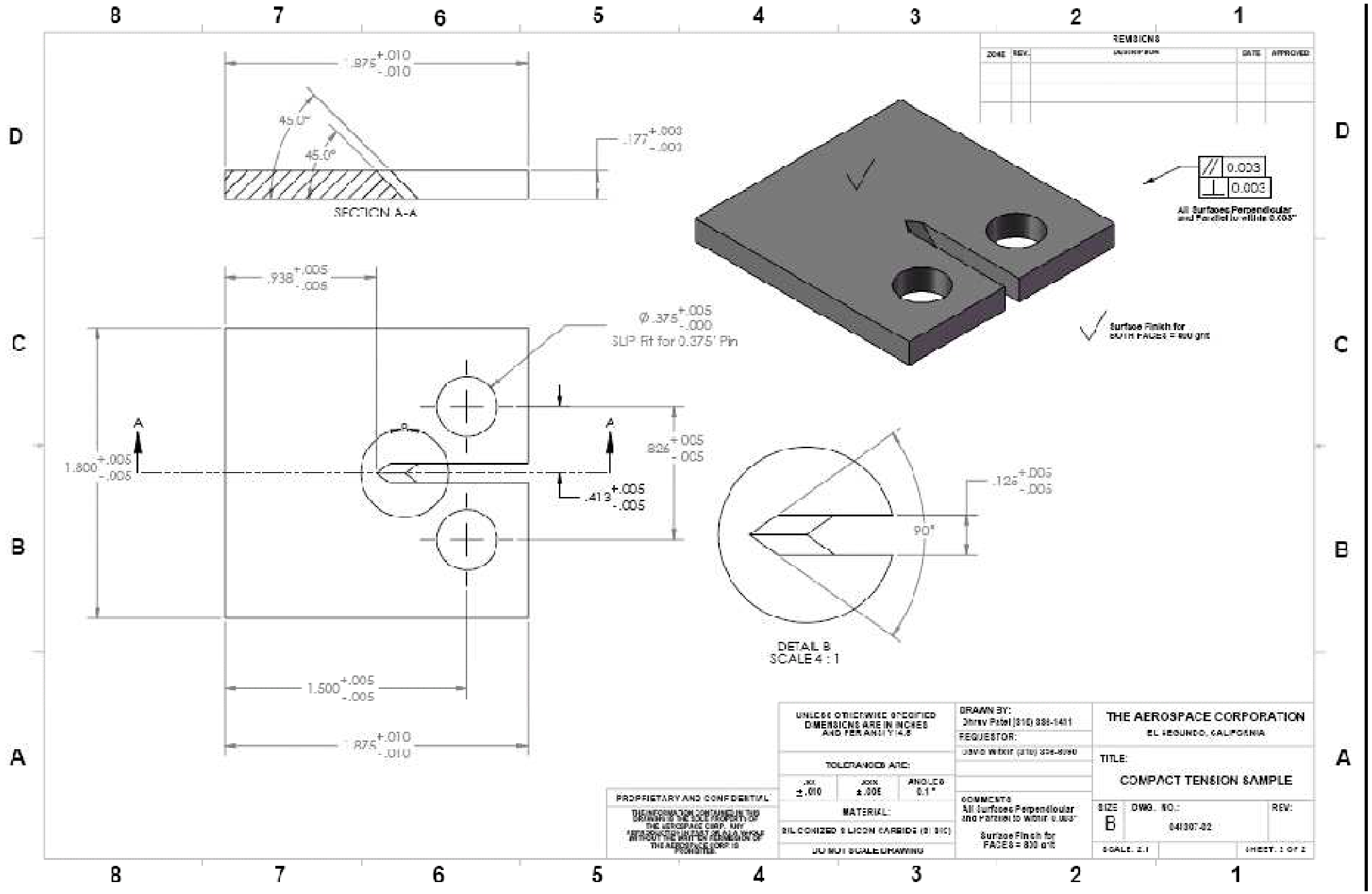
Status of Fatigue Testing



- **Fatigue measurement requires a technique to measure growth in crack length in-situ while applied load is recorded**
- **"Resistance drop" gage has been selected and test samples have been instrumented**
- **Fatigue testing has now commenced**

palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

Fatigue Test Sample



Chevron notch is stress riser from which precursor crack is grown

palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

Outline

- **Motivation and process for material and mirror system space qualification**
  - ***Reasons for selecting SiC***
  - ***Space qualification of new materials***
  - ***Database***
  - ***Flight projects - MISSE***

- **SiC material properties characterization**
  - ***Materials testing***
  - ***Radiation testing***
  - ***Data analysis***

- **Defect tolerant design and proof load testing: necessary steps in SiC system development**
  - ***NDE***
  - ***Fatigue***
  - ***Proof load testing & FEA***

- **Lessons learned, Future work, Summary**

palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

Applying Lessons Learned to Space Qualification Process

Relating SiC material testing knowledge to general SiC optical systems

- **Space qualification is SiC-type dependent**
  - ***To fully validate mechanical testing results, must understand manufacturing process***
  - ***Selection of NDE techniques varies with material composition***
- **Evaluate material strength using a sufficient number of tests for statistically valid characterization of mechanical properties**
- **"Test what you fly"- processing conditions and equipment will affect flaw and defect populations which control material strength, proper size correlation**
- **Use defect tolerant design for fracture control**

palusinski@aero.org, david.b.witkin@aero.org, michael.j.obrien@aero.org

Future Work

- **Continue developing proof load testing techniques**
- **Continue researching NDE techniques for SiC with other collaborators such as AFRL/ML, ARL, and universities**
- **Continue updating SiC database**
- **Expand materials testing of SiC and new optical materials as appropriate**
  - ***Provide government with independently evaluated data***
  - ***Certify multiple sources for future projects***
- **Continue supporting multiple agencies**
  - ***Increase communication between agencies***
  - ***Apply lessons learned from one organization to another, increase speed of development***
  - ***Combine funds for common goals, reduce duplication and cost of research***

palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

Summary

- **Developed space qualification method from basic material characterization through component and sub-system evaluation**
- **Identified new tests to increase robustness of SiC design**
  - ***Defect tolerant design, flaw identification and characterization, fatigue testing, NDE***
- **Developed preliminary SiC database to store and view test data**
  - ***Includes images and documentation***
  - ***Currently for internal use only***
- **Developing proof load test for SiC substrates**
  - ***Links material testing to mirror properties and NDE***
  - ***Increases level of maturity of space qualification process to second evolutionary phase***
- **Participating in MISSE-6, -7, and -8 flight experiments**

palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org

Concluding Remark

- All trademarks, service marks, and trade names are the property of their respective owners

palusinski@aero.org, david.b.witkin@aero.org,
michael.j.obrien@aero.org