Sapphire Statistical Characterization and Risk Reduction (SSCARR) Program for Windows and Domes

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MIT Lincoln Laboratory
Lexington, MA

Outline

- Background
- SSCARR/THAAD Flexural Strength Testing Results
- SSCARR/Arrow Flexural Strength Testing Results
- SSCARR/Navy Flexural Strength Testing Results
- Laser Thermostructural Test Results
- NIST Advanced Diagnostics
- Summary

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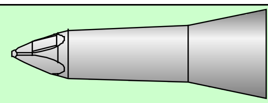
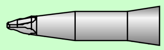
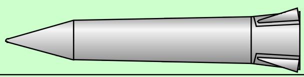
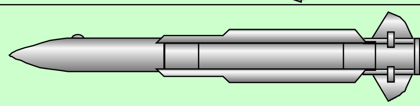
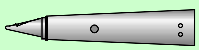
  - Teledyne Brown Engineering
  - National Institute of Standards and Technology
  - Naval Air Warfare Center
  - Arrow Project Office
  - THAAD Project Office

What is SSCARR?

- Sapphire Statistical Characterization And Risk Reduction Program
- Multi-service Program Primarily Sponsored by BMDO/AQS
- Program Deliverables Support Window/Dome Reliability Assessments for Three Theater Missile Defense Missiles:
  - THAAD, SM-2 Block IVA, and Arrow

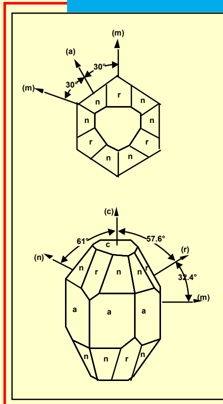
TMD Seeker Window/Dome Concepts

	**ARMY HEDI/KITE FULL KILL VEHICLE** • PRIOR TECHNOLOGY EXPERIMENT • N2 COOLED, SIDE-MOUNTED SAPPHIRE WINDOW (FLAT OCTAGON, 12.7mm THICK) • 1 FLIGHT WITH WINDOW
	**ARMY ADVANCED INTERCEPTOR TECHNOLOGY (AIT) KILL VEHICLE** • EXPLORING SEVERAL ADVANCED WINDOW MATERIALS
	**ISRAELI ARROW KILL VEHICLE** • COOLED, SIDE-MOUNTED SAPPHIRE WINDOW (FLAT OCTAGON, 5mm THICK) • 11 FLIGHTS WITH WINDOW
	**NAVY SM-2 BLOCK IVA MISSILE** • SIDE-MOUNTED SAPPHIRE DOME • LATERAL JET "AERO SPIKE" FOR SHOCK DEFLECTION • 1 FLIGHT WITH DOME
	**ARMY THAAD FULL KILL VEHICLE** • UNCOOLED, SIDE-MOUNTED SAPPHIRE WINDOW (FLAT OCTAGON, 5mm THICK) • 11 FLIGHTS WITH WINDOW

SINGLE-CRYSTAL SAPPHIRE IS MATERIAL OF CHOICE FOR MOST TMD SEEKER WINDOW/DOME CONCEPTS

Characteristics of Single-Crystal Sapphire

Crystalline Structure



Common Crystallographic Planes in Sapphire

Plane "Name"	Miller Index	d Spacing
a	$(11\bar{2}0)$	2.379 Å
m	$(10\bar{1}0)$	1.375 Å
c	(0001)	2.165 Å
r	$(1\bar{1}02)$	1.964 Å
n	$(11\bar{2}3)$	1.147 Å
s	$(10\bar{1}1)$	1.961 Å

Angle Between Common Planes

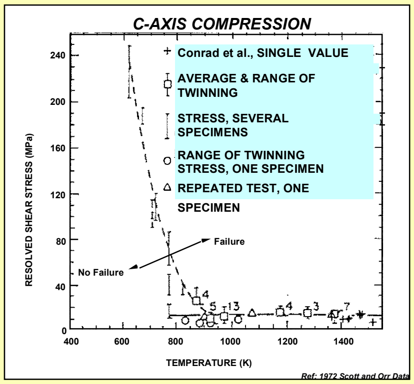
(0001) ^ $(\bar{1}102)$	57°35'
(0001) ^ $(11\bar{2}3)$	61°11'
(0001) ^ $(10\bar{1}1)$	72°23'
(0001) ^ $(11\bar{2}1)$	79°37'
(0001) ^ $(11\bar{2}0)$	90°00'
(0001) ^ $(10\bar{1}0)$	90°00'
$(11\bar{2}0)$ ^ $(10\bar{1}0)$	30°00'

Sapphire Fracture Strength Depends on Many Factors

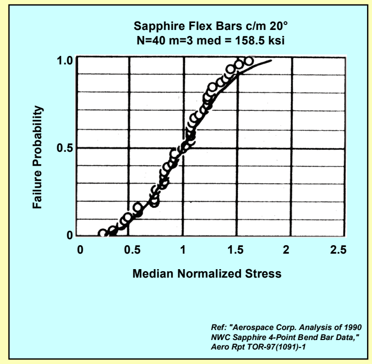
- **Crystalline Orientation**
- **Temperature**
- **Type and Quality of Surface Finish**
- **Material Growth and Fabrication Methods**
- **Material Purity and Defect Density**
- **Sample Size**
- **Test Methodology**

Characteristics of Single-Crystal Sapphire (Cont.)
– Technical Motivation for SSCARR in 1996 –

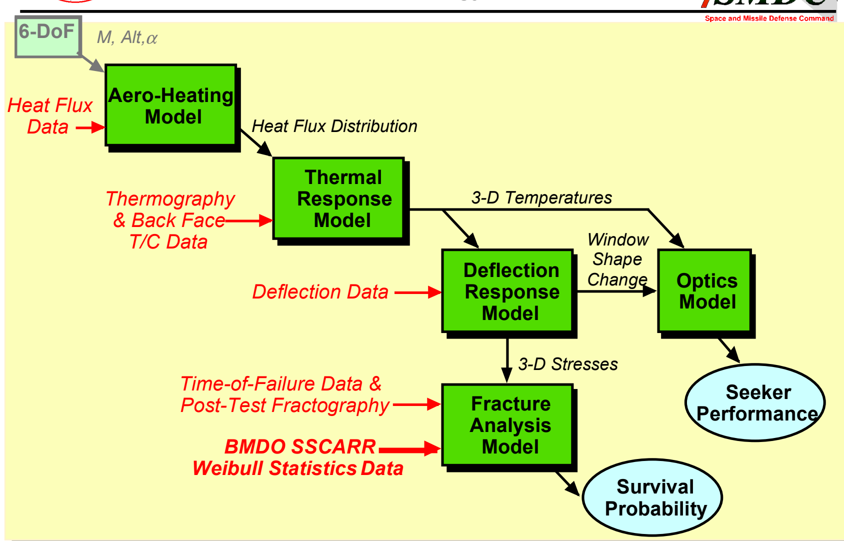
Failure due to Rhombohedreal Twinning



Representative Probabilistic Fracture Data



Window/Dome Thermostructural Analysis Methodology



SSCARR Program Objectives

Primary

- **Establish Applicable Statistical Fracture Data to Support Structural Reliability Predictions of Sapphire Windows/Domes Subjected to Missile In-Flight Heating**

Secondary

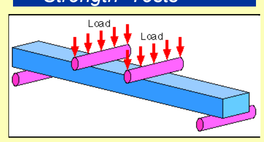
- **Provide Experimental Thermostructural Failure Baseline for Benchmarking Reliability Tools With Established Fracture Database**
- **Understand Observed Sapphire Fractures**
- **Improve Window/Dome Mechanical Strength**

SSCARR Program Highlights (U)

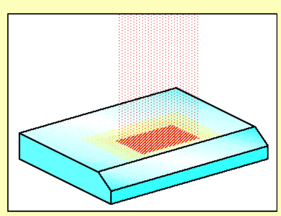
Key Components of SSCARR

- **Strength Tests** of ~1500 Sapphire Bars (UDRI)
  - — Variations in vendors, temp., crystal orientation
  - — Extensive statistical analysis (TBE)
- Extensive **Sapphire Diagnostics** (UDRI, CWRU, NIST)
- **Laser Thermostructural** Benchmark Test (TAC)
- Strength Enhancement Studies (NAWC)

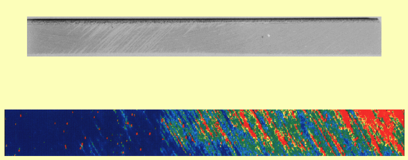
Strength Tests

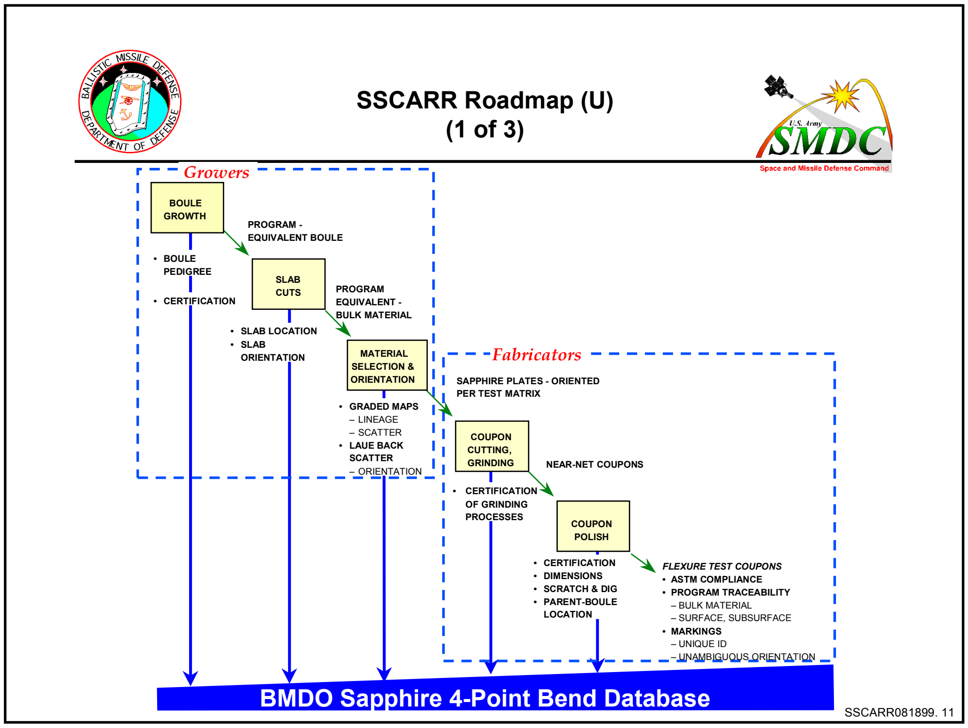


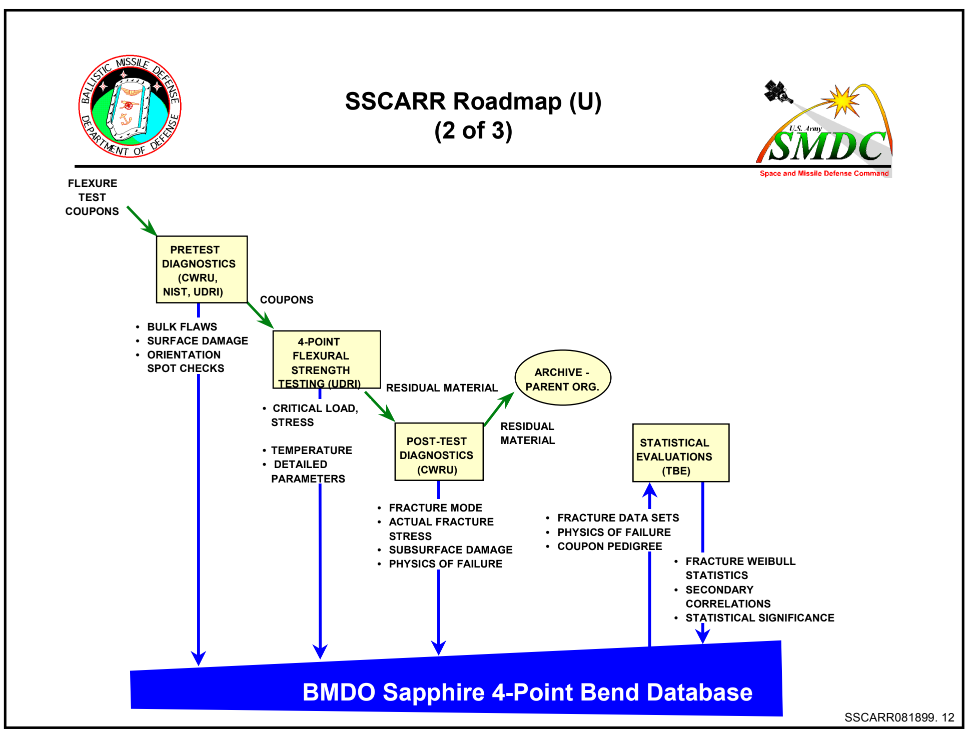
Laser Thermostructural



Sapphire Diagnostics




SSCARR Roadmap (U)
(1 of 3)
BALLISTIC MISSILE DEFENSE
DEPARTMENT OF DEFENSE
U.S. Army
SMDC
Space and Missile Defense Command
Growers
BOULE GROWTH
PROGRAM - EQUIVALENT BOULE
• BOULE PEDIGREE
• CERTIFICATION
SLAB CUTS
PROGRAM EQUIVALENT - BULK MATERIAL
• SLAB LOCATION
• SLAB ORIENTATION
MATERIAL SELECTION & ORIENTATION
• GRADED MAPS
– LINEAGE
– SCATTER
• LAUE BACK SCATTER
– ORIENTATION
Fabricators
SAPPHIRE PLATES - ORIENTED PER TEST MATRIX
COUPON CUTTING, GRINDING
NEAR-NET COUPONS
• CERTIFICATION OF GRINDING PROCESSES
COUPON POLISH
• CERTIFICATION
• DIMENSIONS
• SCRATCH & DIG
• PARENT-BOULE LOCATION
FLEXURE TEST COUPONS
• ASTM COMPLIANCE
• PROGRAM TRACEABILITY
– BULK MATERIAL
– SURFACE, SUBSURFACE
• MARKINGS
– UNIQUE ID
– UNAMBIGUOUS ORIENTATION
BMDO Sapphire 4-Point Bend Database
SSCARR081899. 11


SSCARR Roadmap (U)
(2 of 3)
BALLISTIC MISSILE DEFENSE
DEPARTMENT OF DEFENSE
U.S. Army
SMDC
Space and Missile Defense Command
FLEXURE TEST COUPONS
PRETEST DIAGNOSTICS (CWRU, NIST, UDRI)
COUPONS
• BULK FLAWS
• SURFACE DAMAGE
• ORIENTATION SPOT CHECKS
4-POINT FLEXURAL STRENGTH TESTING (UDRI)
RESIDUAL MATERIAL
ARCHIVE - PARENT ORG.
• CRITICAL LOAD, STRESS
• TEMPERATURE
• DETAILED PARAMETERS
POST-TEST DIAGNOSTICS (CWRU)
RESIDUAL MATERIAL
• FRACTURE MODE
• ACTUAL FRACTURE STRESS
• SUBSURFACE DAMAGE
• PHYSICS OF FAILURE
STATISTICAL EVALUATIONS (TBE)
• FRACTURE DATA SETS
• PHYSICS OF FAILURE
• COUPON PEDIGREE
• FRACTURE WEIBULL STATISTICS
• SECONDARY CORRELATIONS
• STATISTICAL SIGNIFICANCE
BMDO Sapphire 4-Point Bend Database
SSCARR081899. 12

SSCARR Roadmap (U)
(3 of 3)

- *Fracture Database*
- *Laser Thermostructural Testing (Aerospace)*
- *Strength Enhancement Study (NAWC)*
- *Diagnostics Evaluations (NIST)*

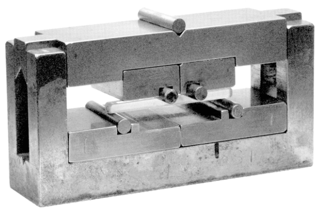
SSCARR Products

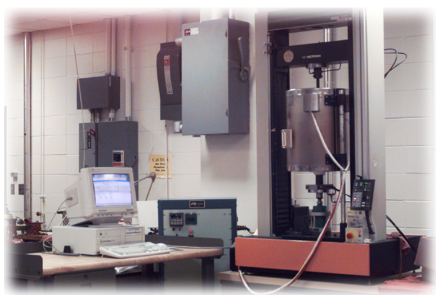
- TMD-TRACEABLE FRACTURE DATABASE
- THERMOSTRUCTURAL FAILURE BENCHMARK DATA SET
- POTENTIAL STRENGTH ENHANCEMENT TECHNIQUES
  - ACTIVE MODIFICATION
    - COMPRESSIVE COATING
  - "LESSONS-LEARNED" FOR IMPROVED DESIGN, FABRICATION, AND CHARACTERIZATION & SCREENING

UDRI Flexural Strength Testing

- **Pretest Characterization**
  - Polariscopic inspection documented no gross flaws
  - Nomarski inspection documented many types of flaws
  - PBS documented variations in subsurface damage
- **Flexural Strength Testing**
  - Flexural strength of ~1475 specimens determined
- **Fractography**
  - Documented surface, edge, side, volume, and undetermined failures

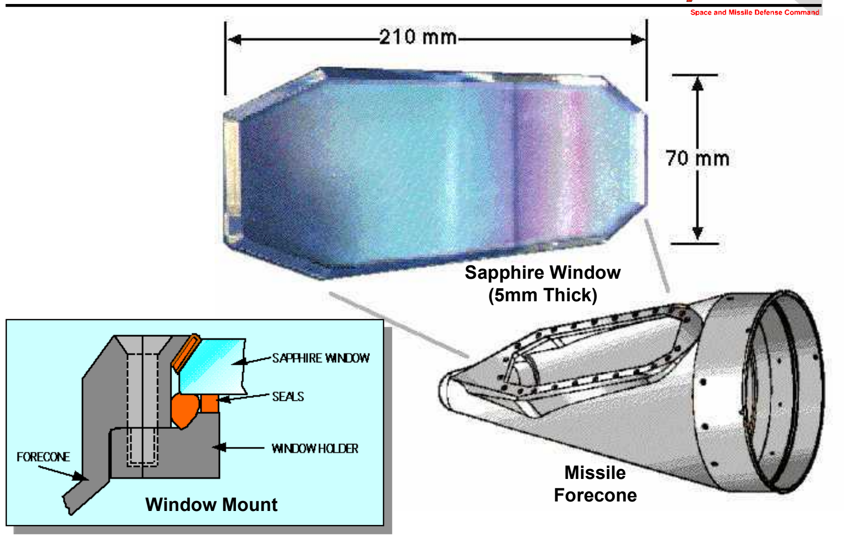
UDRI Flexure Testing Equipment





SSCARR081899. 15

THAAD Seeker Window

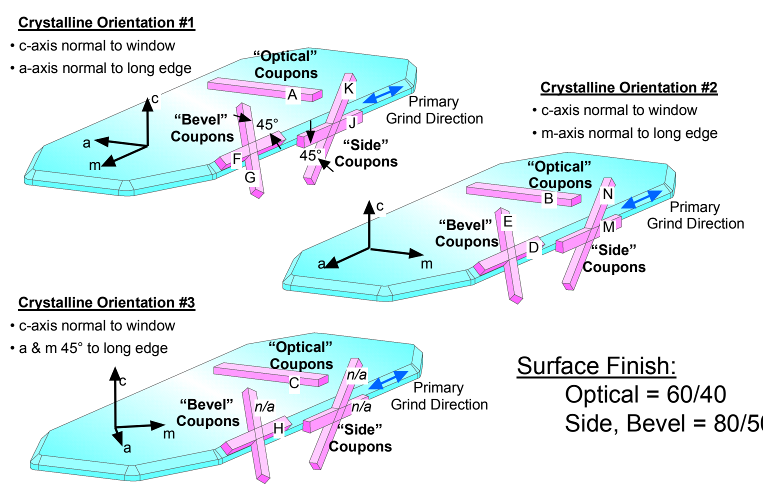


SSCARR081899. 16

SSCARR/THAAD
Flexural Strength Testing Overview

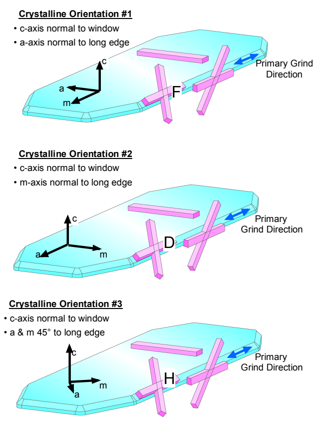
Objective	Technical Approach
• Build fracture data base for THAAD window flight reliability analysis.	• 4-point flexure tests for directionality. • THAAD sapphire & surface prep. traceability. • Statistical validity: 25 coupons per point. • Temperatures & orientations traceable to flight. • Apply Weibull results by window surface type. • Fit results by orientation, tensile direction, temp.
• Develop understanding of parameters affecting reliability of THAAD window.	• Maintain cradle-to-grave coupon records. • Perform extensive diagnostics. • Correlate coupon pedigrees, measured. strengths, and fractography results. • Apply lessons-learned from correlations.

SSCARR/THAAD Bend Bar Orientations

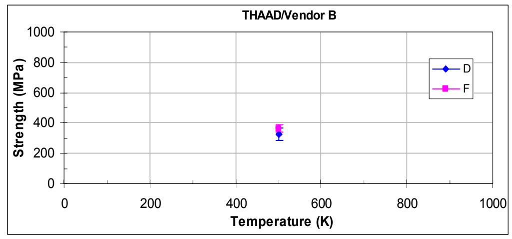


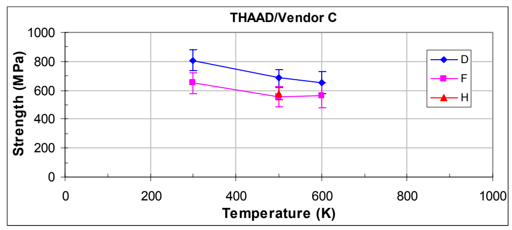
Surface Finish:
Optical = 60/40
Side, Bevel = 80/50

Subset of SSCARR/THAAD Data: On-Axis Bevel Coupons



Surface Finish:
Side, Bevel = 80/50

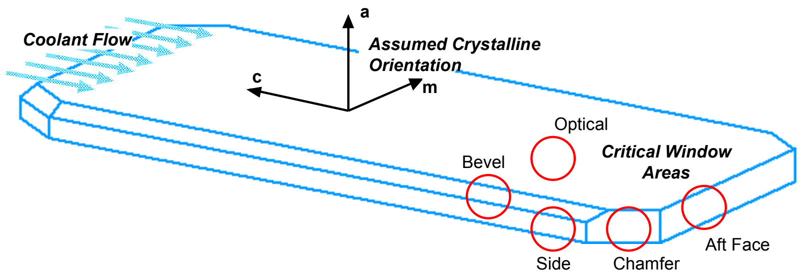




Summary of SSCARR/THAAD Strength Data

- Edge and Side Wall Preparation is Critical
  - Can be difficult
- Bend Bars Satisfied THAAD Window Specifications, but To-Date, Delivered Windows are Superior to Bars
- Strength Differences Detected Between Fabricators Using Identical Sapphire Stock
- Increasing Temperature Tends to Reduce Strength
- Some Effects of Crystalline Orientation Detected

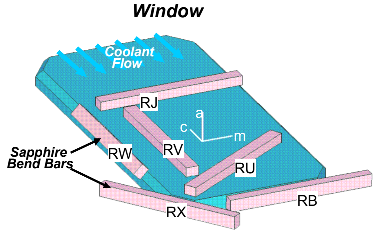
SSCARR/Arrow Test Matrix Drivers and Assumptions

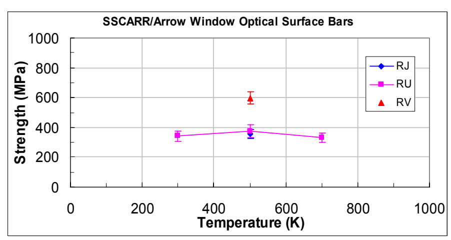


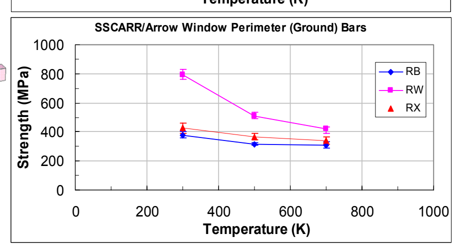
- Stresses at front of window (cooled) are assumed to be negligible.
- Tensions on bevels and sides are approximately parallel to c-axis.
- Tensions on optical surface, chamfers, and aft face are assumed to be multi-directional.
- Optical surfaces are polished (80-50). Perimeter surfaces are ground (220 grit).
- Temperature is a strength driver.

SSCARR/Arrow Strength Data

Arrow II EOS Window



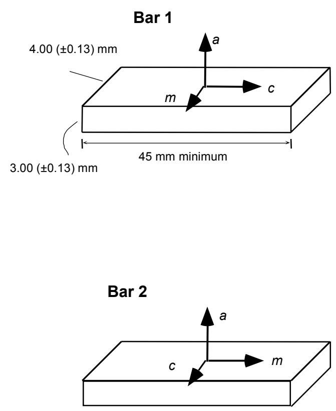


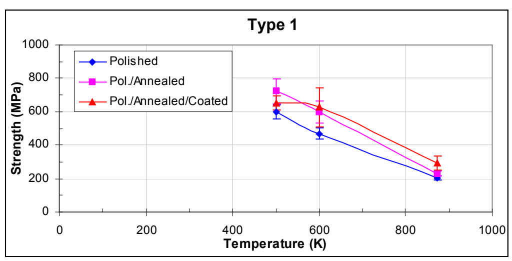


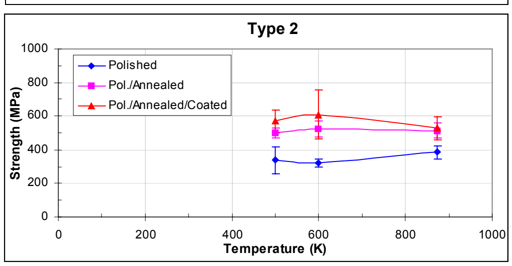
Summary of SSCARR/Arrow Basic Strength Data

- Bars in c-axis Tension Strongest
  - No other significant orientation effects detected
- Temperature Effect Most Pronounced for Type RW
- Ground Samples Have Strength Comparable to Polished Bars

SSCARR/Navy Strength Data



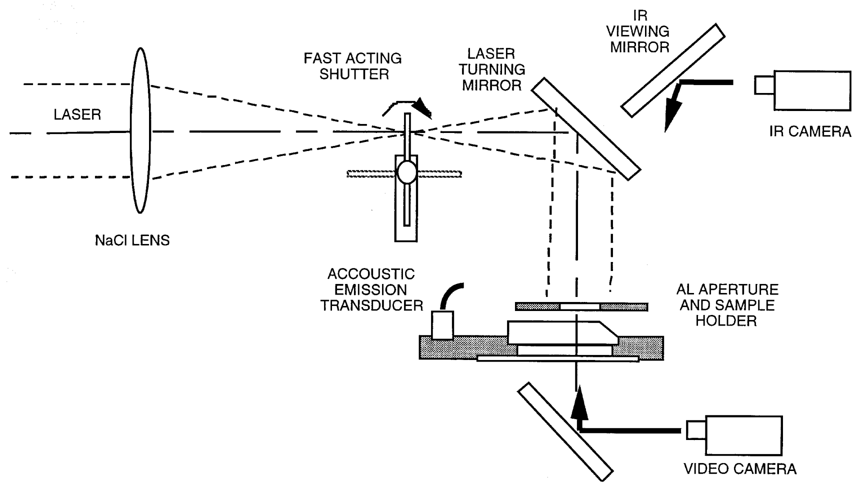




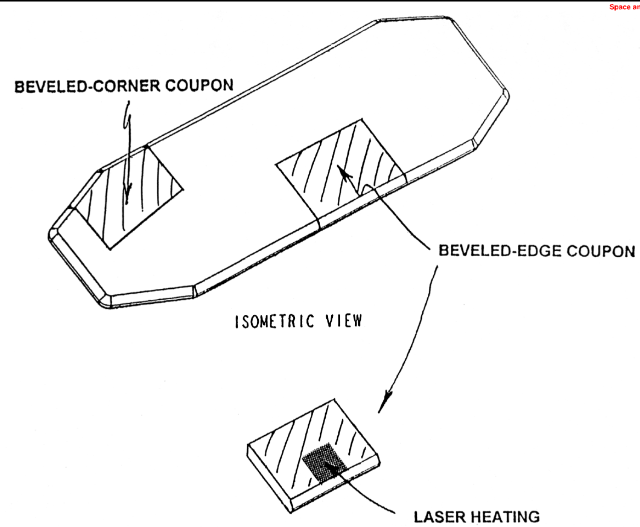
Summary of SSCARR/Navy Strength Data

- Bend bar (flat) fabrication techniques differ from dome (round) techniques
  - Data not directly applicable to dome reliability assessments
- C-axis tension (Type 1) stronger than m-axis tension (Type 2) at low to moderate temperatures, but high temperatures rapidly degrade c-axis strength
  - previously explained as rhombohedral twinning due to c-axis compression
- Annealing provides some increase in mean strength
- Coating provides little benefit

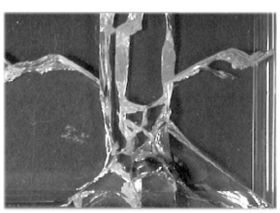
Principle Elements and Beam Path for Laser Thermostructural Test



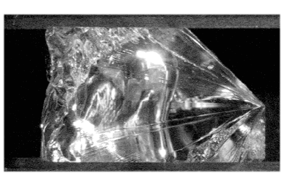
THAAD Window Coupon Schematic



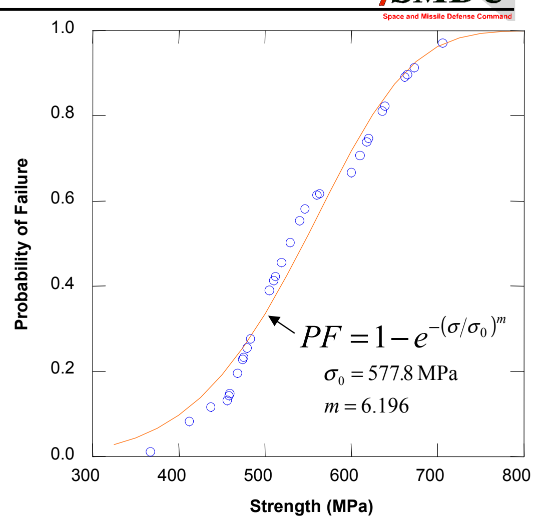
Laser Thermostructural Test Results



Typical Fracture: Top View



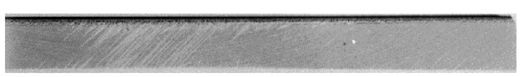
Typical Fracture: Cross Section



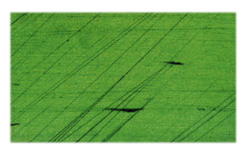
Laser Thermostructural Test Results

- CO_2 laser heating is an effective means of characterizing sapphire thermal fracture strength for seeker window performance assessment
- Sapphire strength is highly dependent on the fabrication process
- A first-order failure prediction analysis of thermally fractured window coupons gives conservative results when based on flexural strength test data

NIST Advanced Diagnostic Results



Typical X-Ray Topograph



Typical Polariscopic Micrograph

- As expected, x-ray topography proved to be an effective *but qualitative* method for identifying subsurface damage in polished sapphire
  - Could identify groups of strong & weak bars, but could not readily identify individual critical flaws
  - Not amenable to production screening
- Polariscopic microscopy is useful in locating *surface* defects
  - Critical flaws are often subsurface
  - Affordable
- Proof testing is required to screen production window/domes for critical flaws

SSCARR Program Summary

- Technical Findings
  - Methodology established to statistically characterize thermostructural fracture of TMD windows
  - Program-specific strengths measured
    - Using same stock sapphire, strength differences observed between fabricators
    - Temperature effects are strong, orientation effects generally moderate
    - Ground sapphire not significantly weaker than corresponding polished sapphire
    - Annealing is beneficial, coating showed little to no effect
  - Thermostructural performance baseline established
    - Reliability prediction based-on flexure test data was conservative
  - Sapphire diagnostic tools implemented and ranked
    - Proof test required to detect fatal flaws in production sapphire windows/domes
  - Lessons-learned applicable to future material characterization efforts
- Programmatics
  - SSCARR has been a successful model for multi-agency programs
  - A comprehensive report and database will be cleared for public release and made widely available in September