Overview of an Advanced Hypersonic Structural Concept Test Program

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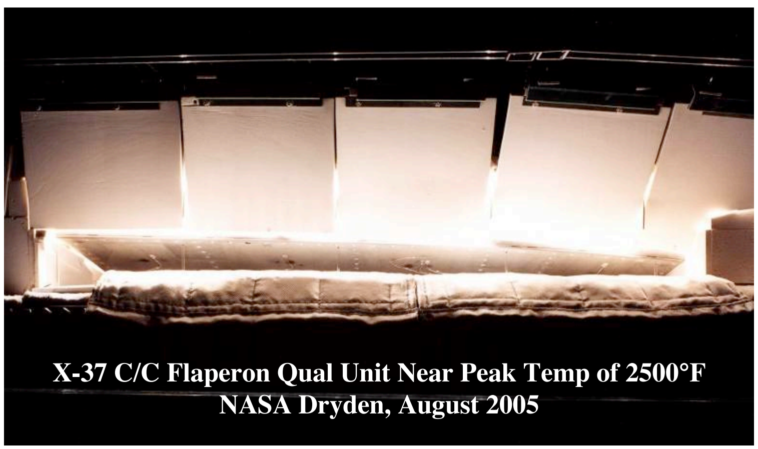
Outline

- **Hypersonics M&S Advanced Structural Concepts Development**
  - C/SiC Ruddervator Subcomponent Test Article (RSTA)
    - Background
    - Task Objectives
    - Test Plan
    - Current Status
- **Hypersonics M&S Experimental Methods**
  - Extreme Environment Sensors
    - Instrumentation Needs
    - Sensors of Interest
    - Examples of ongoing efforts
- **Conclusions**

C/SiC Ruddervator Subcomponent Test Article
Background

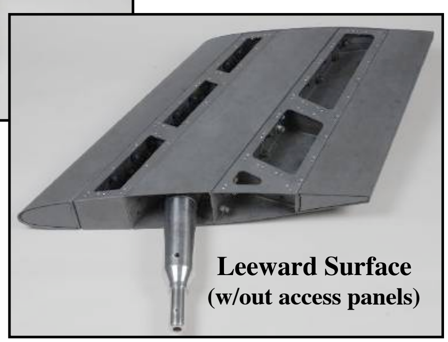


- **One of the key technology efforts during the X-37 program was the development and validation testing of hot-structure control surfaces**
  - Part of the risk mitigation effort was the parallel development of X-37 control surfaces using both carbon-carbon (C/C) and carbon-silicon carbide (C/SiC)

- **Two separate design and manufacturing teams developed <u>subcomponent</u> test articles**
  - C/C Flaperon subcomponent (built and tested)
  - C/C Ruddervator subcomponent (built and tested)
  - C/SiC Flaperon subcomponent (built and tested)
  - C/SiC Ruddervator subcomponent (built but not tested)

- **The X-37 program down selected to C/C and proceeded with the development and testing of both ruddervator and flaperon <u>qualification units</u>**
  - Flaperon thermally / mechanically tested at NASA Dryden
  - Ruddervator mechanically tested at Wright-Patterson, AFB

C/SiC Ruddervator Subcomponent Test Article
Background (Continued)



- **NASA proposed the C/SiC RSTA as a testbed to support ARMD research objectives and worked to formulate a multi-partner program**
  - Lockheed Martin (LM) is evaluating C/C and C/SiC control surface technology for hypersonic programs and expressed interest in collaborating

- **The X-37 C/SiC RSTA provides an opportunity to**
  - Apply both re-entry and trans-atmospheric derived thermal / structural loads to a hot-structure
  - Evaluate the thermal / structural performance of a C/SiC hot-structure control surface
  - Compare the thermal / structural performance of a C/SiC and C/C hot-structure control surface
  - Provide a testbed to evaluate the performance of advanced high-temperature instrumentation

C/SiC Ruddervator Subcomponent Test Article

Team Roles and Responsibilities

NASA Dryden

- Overall task management and test requirements definition
- Thermal, structural, and ground-vibration testing
- Non-destructive evaluation
- High-temperature instrumentation

NASA Langley

- Acoustic, vibration, and modal testing
- Thermal / acoustic testing

Materials Research & Design
Wayne, PA

- C/SiC RSTA designer
- Test requirements support (X-37 & LM loads)
- RSTA thermal / structural / dynamic analysis

GE Aviation
Ceramic Composite Products
Newark, DE

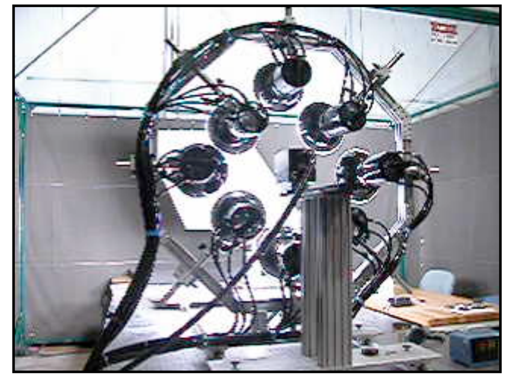
- C/SiC RSTA manufacturer
- RSTA modifications and assembly
- Non-destructive evaluation support

LOCKHEED MARTIN
Palmdale, CA

- LM derived loads definition
- Oversight of LM related testing

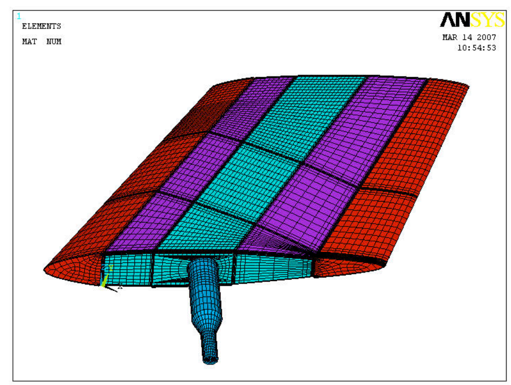
C/SiC Ruddervator Subcomponent Test Article
Test Objectives

- **Evaluate the thermal, structural, and dynamic performance of the C/SiC RSTA through the application of relevant hypersonic thermal, structural, acoustic and vibration loads**
  - Maintains and extends NASA's core knowledge in testing hypersonic structures
    - Obtain unique data through the development of test techniques
    - Application and evaluation of unique high-temperature instrumentation
    - Multi-mission simulation
  - Perform NDE throughout RSTA testing to identify defects and track potential damage propagation



IR Pulsed Thermography NDE

- **Pre- and post-test structural analysis to support test operations and development of test database**
  - Provides an extensive database for the evaluation of design and analysis methods for hypersonic structures
    - Provides data to validate advanced analysis techniques
      - **High-temperature vibration analysis**
      - **Using test data, non-linear material properties, and contact elements at fasteners to determine force levels at interfaces and fastener stresses (linear versus non-linear analysis comparison)**



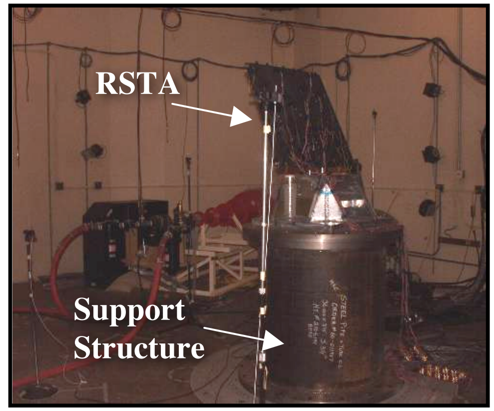
C/SiC Ruddervator Subcomponent Test Article
Test Plan

- **Evaluate RSTA performance under two different hypersonic flight conditions**
  - X-37: Re-entry conditions
    - Higher heating rates (i.e. higher surface temperatures) over shorter time periods
    - Mechanical loads over short time periods
    - Vibration / acoustic loads maximum at lift-off (i.e. low temperature conditions)
  - LM: Trans-atmospheric conditions
    - Lower heating rates (i.e. lower surface temperatures) over longer time periods
    - Mechanical loads over repeated cycles
    - Combined thermal / acoustic loads of interest

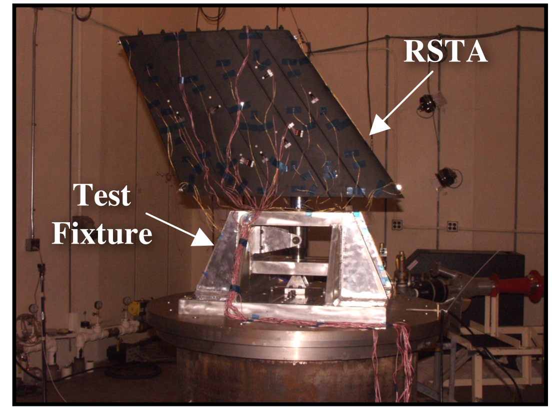
- **Developed a four-phase test program for the RSTA**
  - Phase 1: Acoustic and vibration loads to X-37 load conditions
  - Phase 2: Thermal and thermal / structural loading to X-37 and LM load conditions
  - Phase 3: Room-temperature mechanical loading to X-37 and LM load conditions
  - Phase 4: Vibration and thermal / acoustic testing to LM load conditions

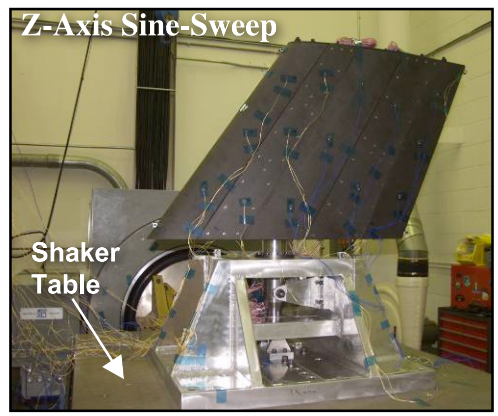
C/SiC Ruddervator Subcomponent Test Article
Phase 1 Tests (NASA Langley, Completed)

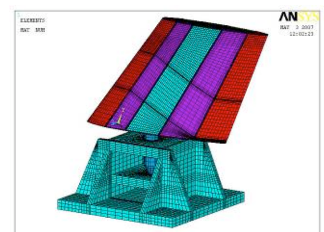
- **Objective:**
  - Evaluate RSTA dynamic performance under X-37 vibration and acoustic loads
- **Test Sequence:**
  - Modal survey
    - Free-free / fixed boundary condition
  - Pre-acoustic sine sweep
  - Acoustic testing
  - Vibration testing
    - Post-acoustic sine sweep
    - Random vibration testing
    - Post-random sine sweep
- **Data Acquired**
  - Accelerations
  - Strains
- **Database Elements**
  - Test requirements document and test plan
  - Instrumentation drawings and test data
  - Test correlation report

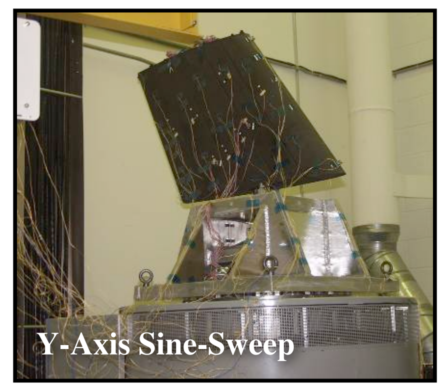


Acoustic Test Setup At LaRC Reverb Chamber





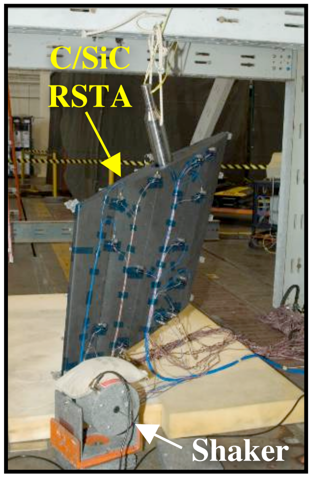




Vibration Test Setup At LaRC

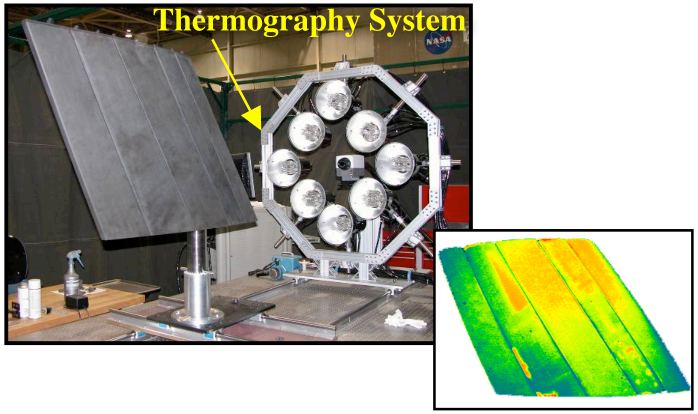
C/SiC Ruddervator Subcomponent Test Article
Phase 2 Tests (NASA Dryden, In Progress)

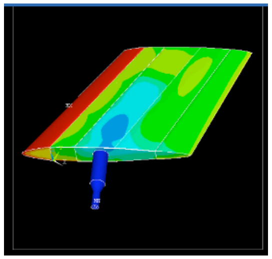
- **Objective:**
  – Evaluate RSTA performance under X-37 re-entry and LM thermal / mechanical load conditions
- **Test Sequence:**
  – Modal Survey (completed)
    - Free-free boundary condition
  – Room-temperature ground vibration test (GVT)
  – Elevated-temperature GVT
  – X-37 thermal loading (3 cycles)
  – X-37 thermal / mechanical loading (3 cycles)
  – LM thermal / mechanical loading (3 cycles)
  – Elevated-temperature GVT
- **Status:**
  – Pre-test predictions
    - LM thermal / mechanical test conditions (completed)
    - X-37 thermal / mechanical test conditions (in progress)
  – High-temperature sensor installations (in progress)
  – Thermal test hardware design (completed)
  – Thermal test hardware fabrication (in progress)

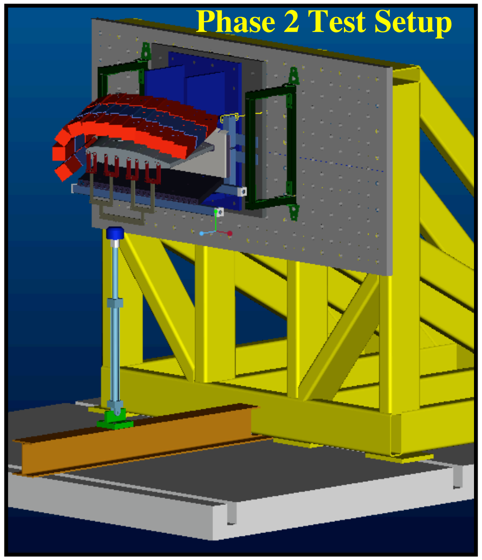


Free-Free Modal Survey

IR Thermography NDE of the RSTA



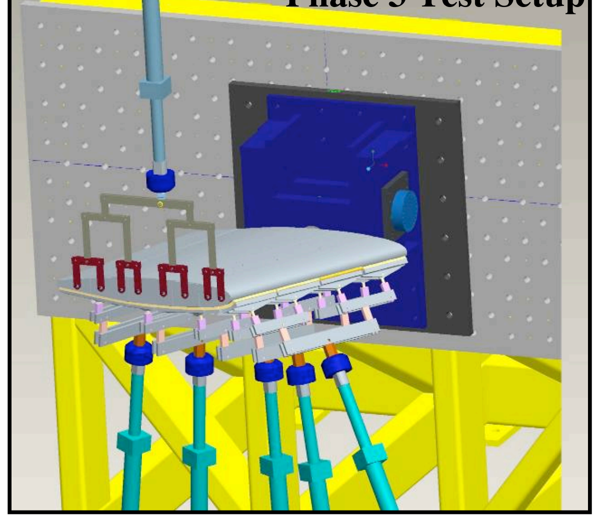

Transient RSTA Leeward Temps from Pre-Test Analysis of LM Trajectory



C/SiC Ruddervator Subcomponent Test Article
Phase 3 & 4 Tests

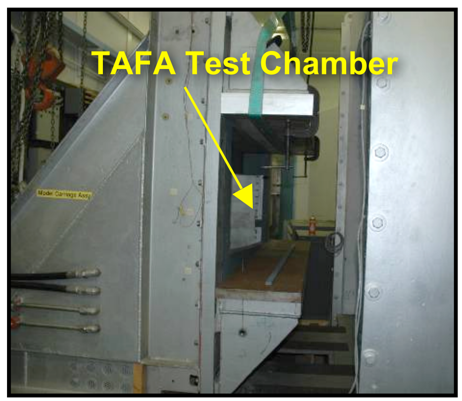
- **Phase 3 Objective: (NASA Dryden)**
  - Evaluate RSTA performance under X-37 derived 100% DLL loads
- **Test Sequence:**
  - Multi-cycle loading to 100% DLL condition
    - Reverse loading
- **Data To Be Acquired**
  - Deflections (control surface and freeplay)
  - Strains
  - Input and reaction loads

Phase 3 Test Setup

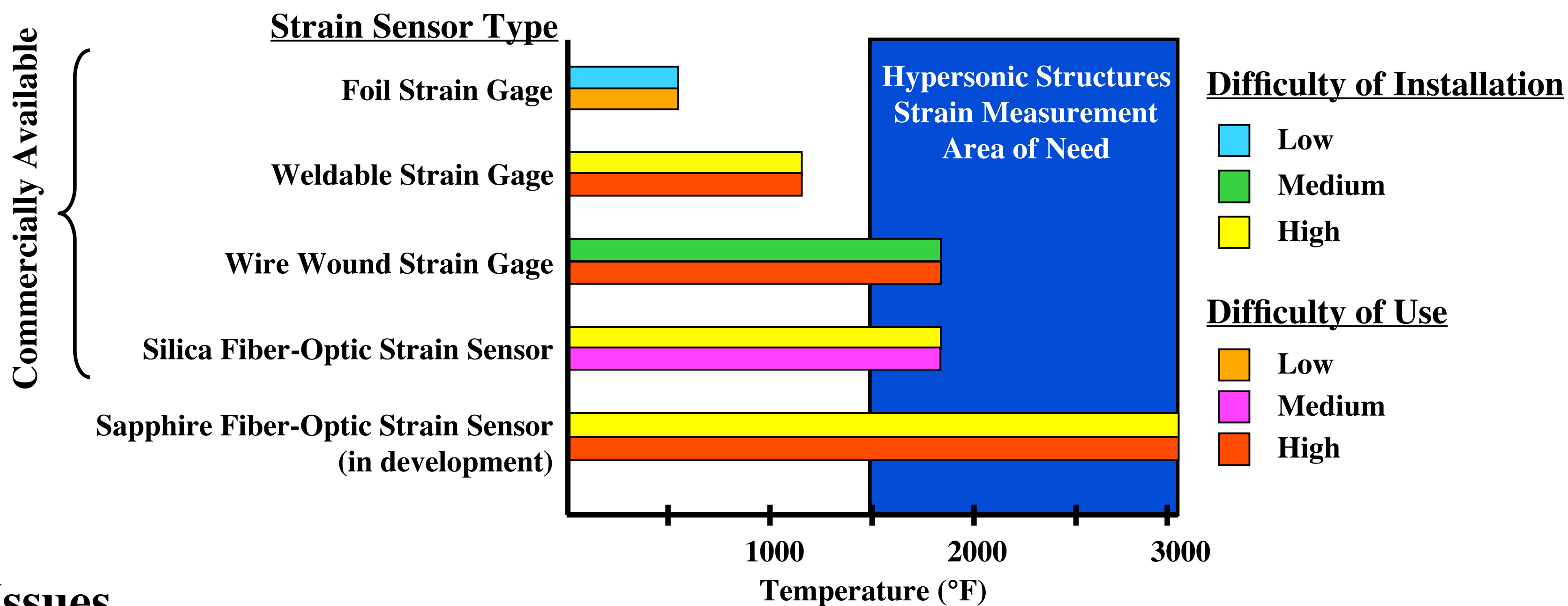


- **Phase 4 Objective: (NASA Langley, TBD)**
  - Evaluate RSTA performance under LM derived vibration and thermal / acoustic loads
- **Test Sequence:**
  - Modal survey (free-free boundary condition)
  - Pre-acoustic sine sweep
  - Thermal / Acoustic testing
  - Vibration testing
    - Post-acoustic sine sweep
    - Random vibration testing
    - Post-random sine sweep
- **Data To Be Acquired**
  - Temperatures
  - Accelerations
  - Strains

Phase 4 Test Facility



Extreme Environment Structural Sensors
High-Temperature Instrumentation Needs

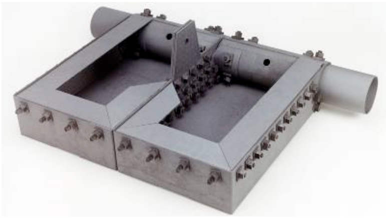


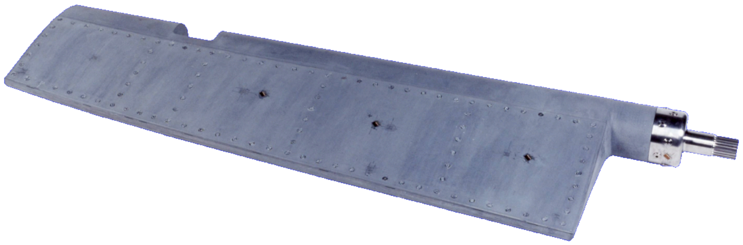
- **Issues**
  - Hypersonic structures are utilizing advanced materials that operate at temperatures that exceed current ability to measure structural performance
  - Robust structural sensors that operate accurately and reliably in hypersonic environments do not exist
- **Implications**
  - Hinders ability to validate analysis and modeling techniques
  - Hinders ability to optimize structural designs

Extreme Environment Structural Sensors
Instrumentation Attachment Needs

- **Hypersonic structural test or flight articles are usually one-of-a-kind, expensive, and time consuming to manufacture**
  - Metallics
  - Metal matrix composites
  - Superalloys
  - High-temperature composites (i.e. C/C, C/SiC, SiC/SiC)

- **Issues**
  - Integrating structural sensors that do not compromise structural integrity
    - Drilling holes, mechanical fastening, etc. are typically not allowed
  - Developing sensor attachment methods that provide valid measurements for all environmental loading conditions without adversely affecting the substrate
    - Thermal conditions
    - Mechanical loading
    - Vibration and acoustic loads
    - Exposure to chemically reacting flows





Extreme Environment Structural Sensors

High-Temperature Structural Measurements of Interest

- **Strain**
  - Sapphire fiber-optic sensors
  - High-temperature Bragg Gratings
- **Temperature**
- **Heat Flux**
  - Calibration methods
- **Acceleration**
- **Deformation**

Sensors and Sensory Materials

Bonding / attachment method development throughout structural component operating range

Current Efforts:

- SOA structural sensor assessment to coordinate NASA, NRA and SBIR opportunities
- Evaluate sensor / systems under laboratory, ground test, and flight test opportunities

Extreme Environment Structural Sensors

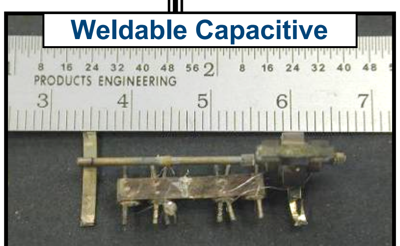
Example of Strain Sensing Technology Progression

1960-1970

Flame-Sprayed Resistive

Weldable Resistive

Weldable Capacitive



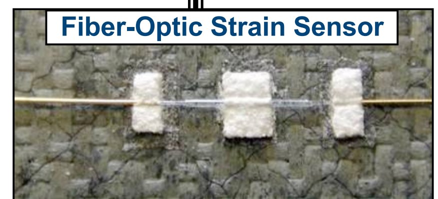
Large thermal outputs and measurement uncertainties

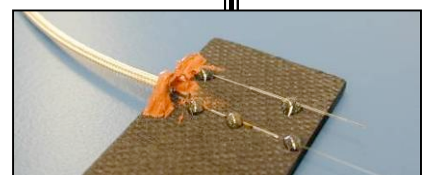
1980-1990

Improved temperature-compensation using flame-sprayed resistive gages

>2000

Fiber-Optic Strain Sensor

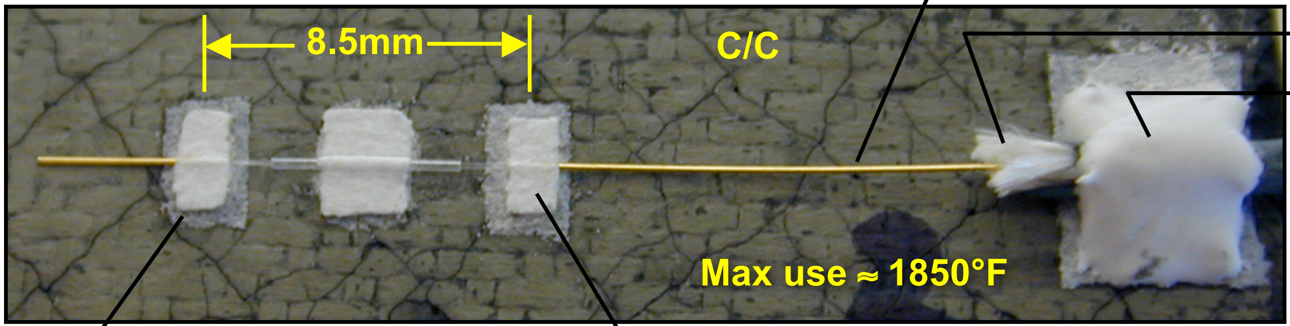




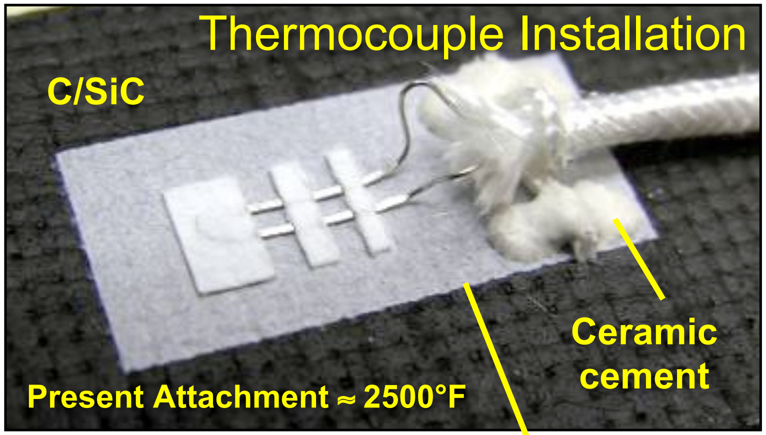
Improved measurement accuracy applying silica and sapphire fiber-optic technology

Extreme Environment Structural Sensors
Examples of Strain and Temperature Sensors

Fiber-Optic Strain Sensor Installation



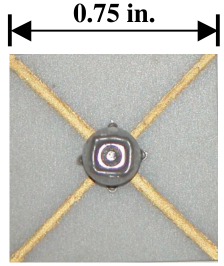
- **Challenge**
  - Advance strain sensing technology beyond 2000°F
  - Develop durable high-temperature fiber-optic sensors
  - Advance temperature sensing methods
  - Develop sensor attachment techniques suitable for hypersonic environments (ground and flight testing)



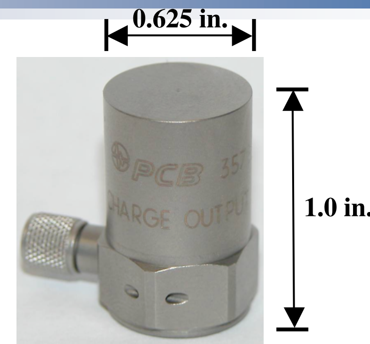
Extreme Environmental Sensors

Examples of Acceleration, Heat Flux, Network Sensors

- **Accelerometers**
  - COTS sensors
  - NASA GRC

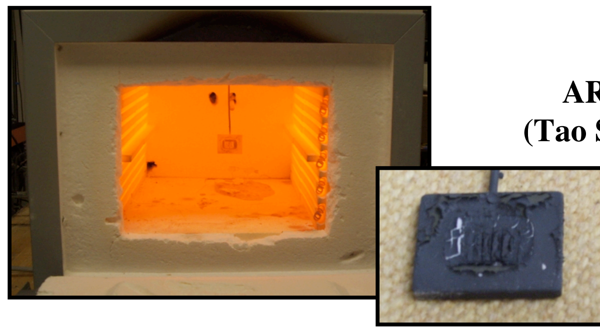


NASA GRC
High-Temperature SiC High-g sensor
(1000°F)



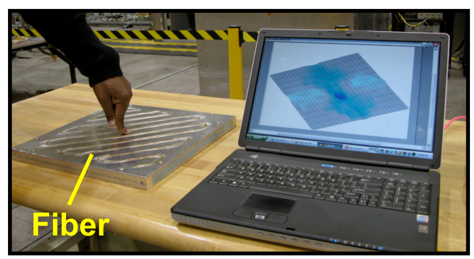
COTS
High-Temperature Accelerometer
(900°F)

- **Heat Flux Sensors**
  - Low profile
  - Rapid response

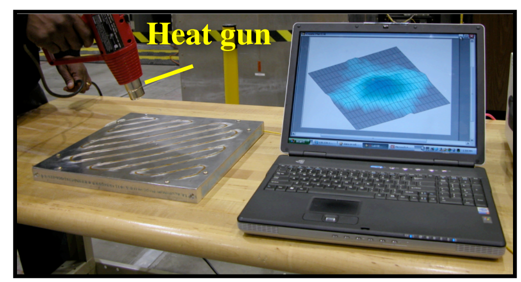


Heat Flux Array
ARMD ExCap NRA Effort
(Tao Systems and Virginia Tech)

- **Distributed Bragg Grating System**
  - Simultaneous measurements of strain, temperature, and deformation
  - Increase operating temperature



Pressure Loading

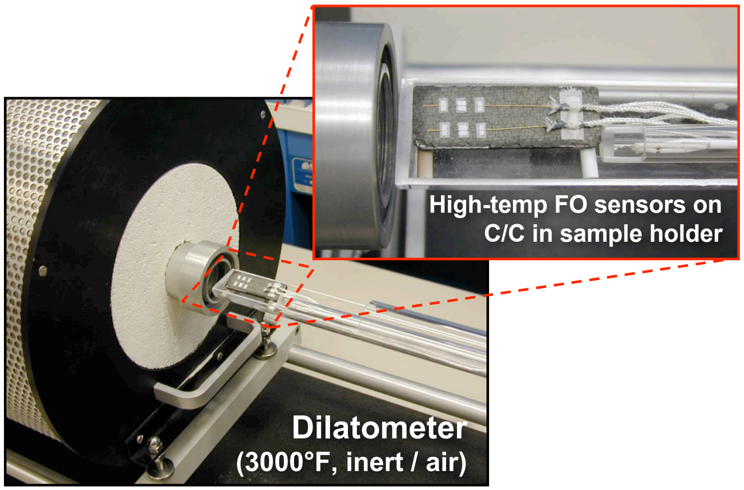


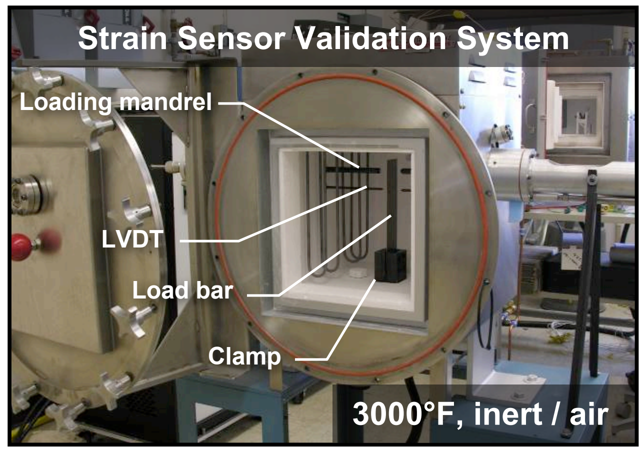
Thermal Loading

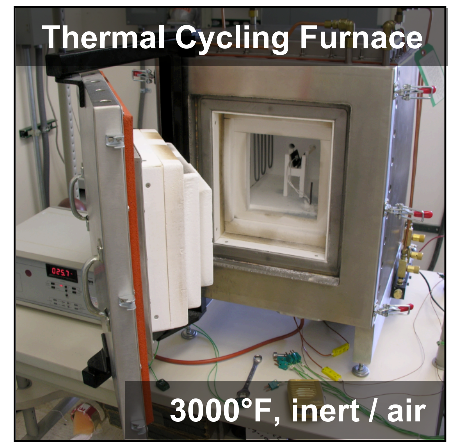
Extreme Environmental Sensors

Validation of Sensor Outputs and Attachment Methods

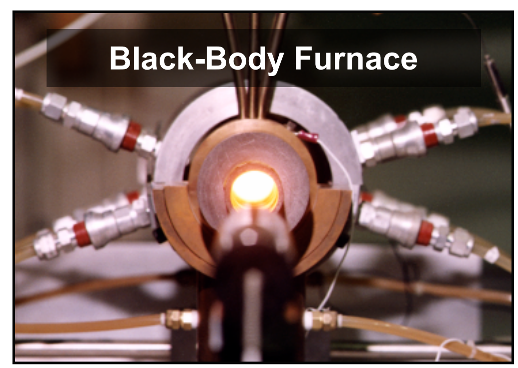
- **Goal: Provide valid sensor data to structural analysts**
  - Validate sensor output through characterization testing
    - Compare sensor outputs to available standards
  - Validate and assess attachment techniques





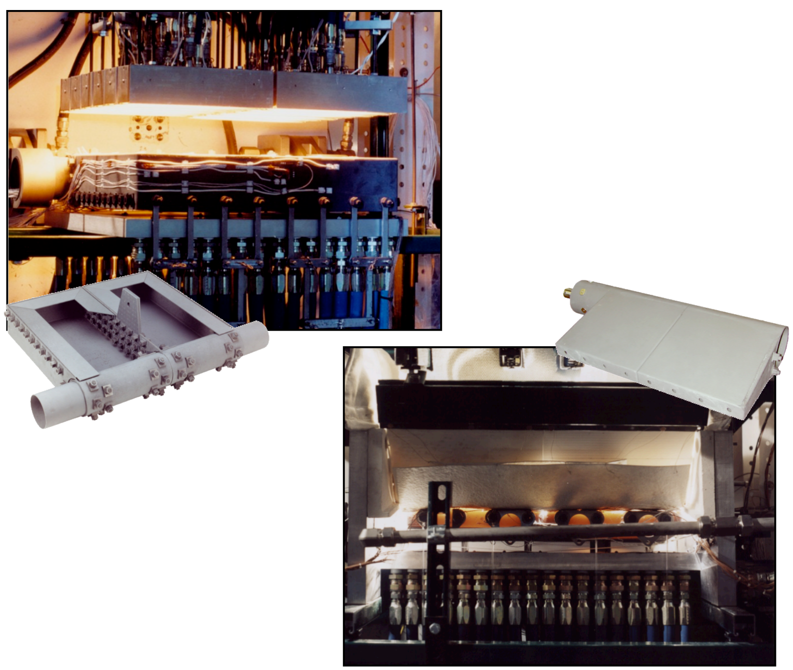


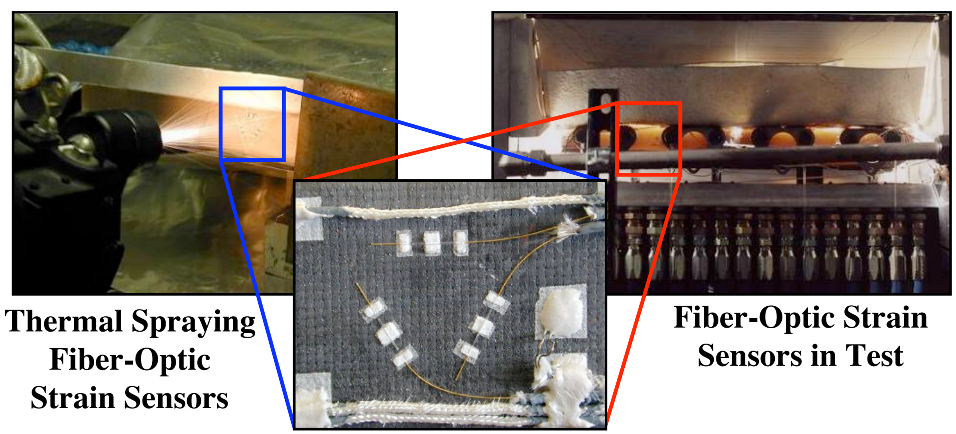
Typical Systems for Sensor Validation Testing



Conclusions

- **Hypersonics M&S is developing**
  - Advanced structural concepts for hypersonic vehicle applications
  - Ground test techniques to obtain data that validates structural performance and analysis techniques for design optimization
  - Sensor technology to acquire structural data subjected to hypersonic conditions for analysis validation and design optimization
  - A knowledge base for the technical community





Thermal Spraying Fiber-Optic Strain Sensors

Fiber-Optic Strain Sensors in Test