33rd Annual Conference on Composites, Materials, and Structures

High-Temperature Structural Instrumentation Developments for Hypersonic Airframe Applications

Anthony (Nino) Piazza, Craig Stephens, Larry Hudson
NASA Dryden Flight Research Center

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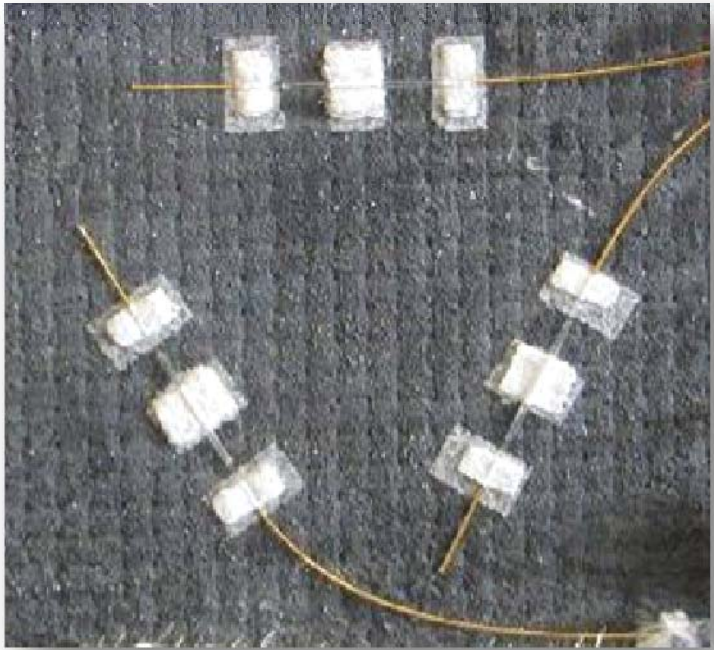
Outline



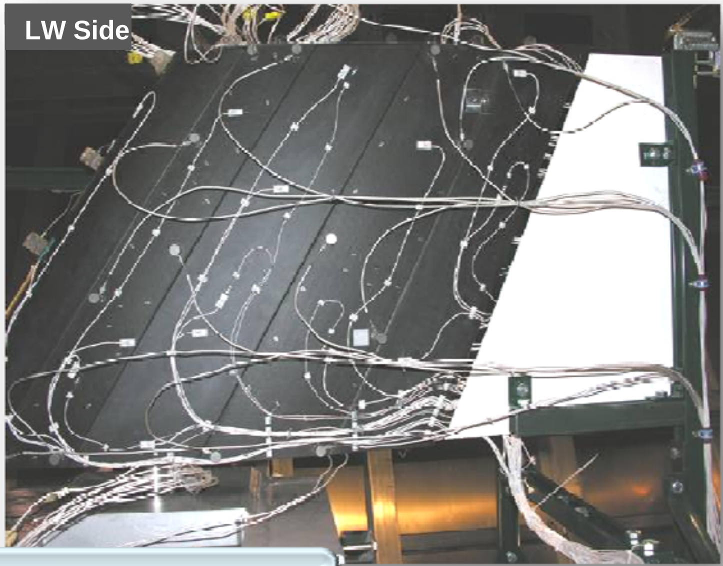
- Background
- Objective
- Sensors
- Attachment Techniques
- Laboratory Evaluation / Characterization

Background

Measurements Laboratory

Provide strain data for validating finite element models and thermal-structural analyses

- Develop sensor attachment techniques for relevant structural materials at the small test specimen level
  - Apply methods to large scale hot-structures test articles
- Perform laboratory tests to characterize sensor and generate corrections to apply to indicated strains

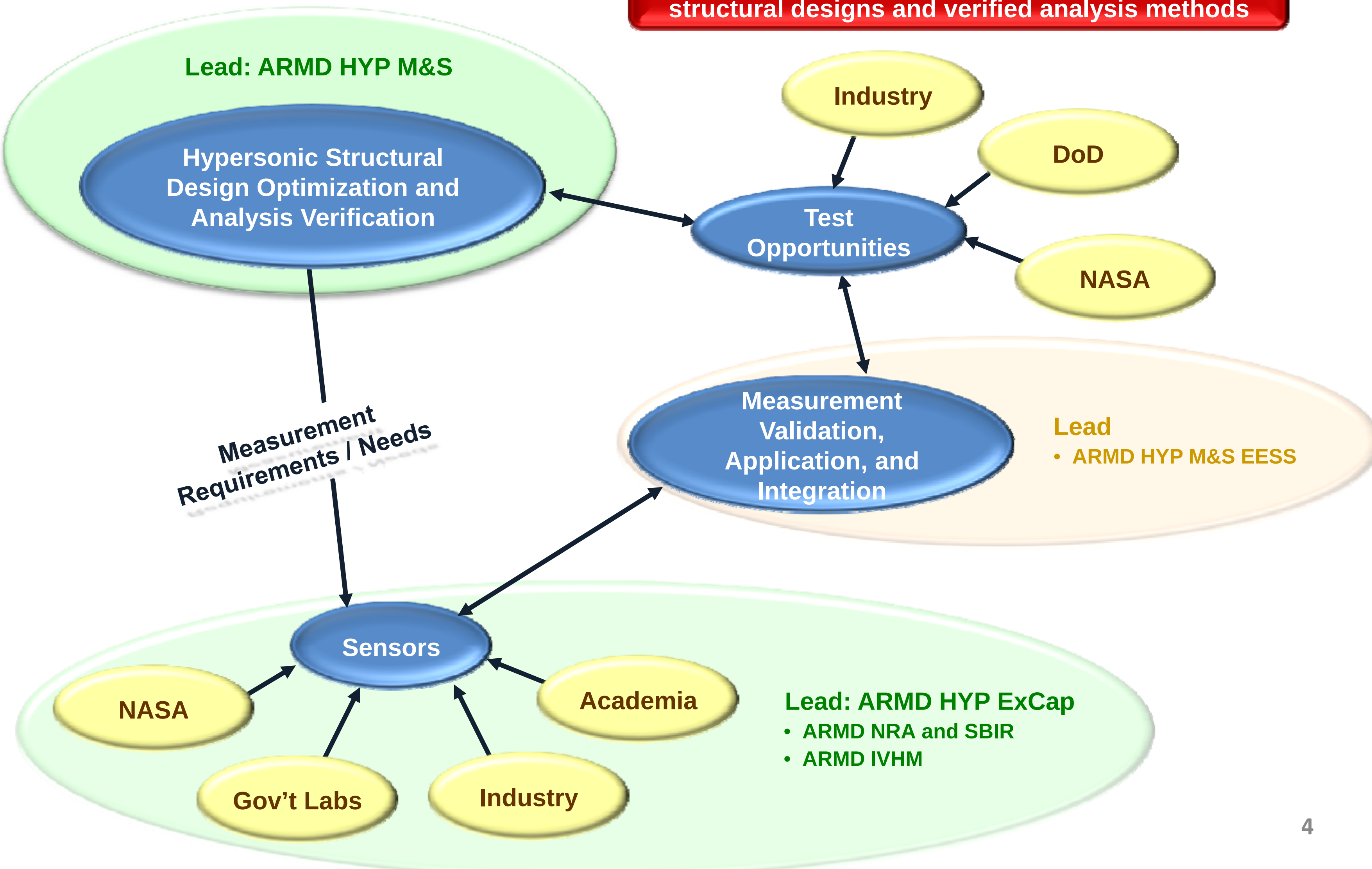


C/SiC X-37 Ruddervator tested under NASA's ARMD Program (M&S)

Background

Extreme Environment Structural Sensing (EESS)

Validated measurements enables optimized structural designs and verified analysis methods



Objective

Measurements Lab Under EESS

Structural Measurements of Interest
- Strain
- Temperature
- Heat Flux
- Acceleration
- Deformation

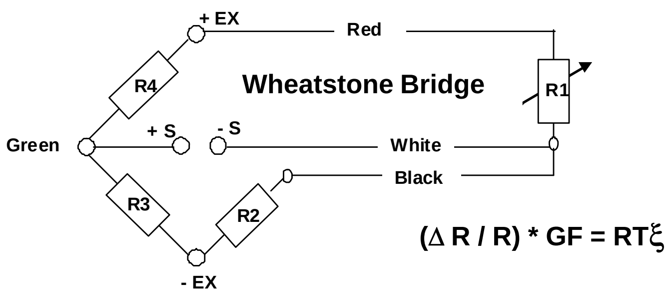
EESS Focus
- Attached sensors (single-point, distributed sensing, wireless)
- Non-contact optical techniques
- Embedded sensors
- Self-sensing material

- Develop SOA of structural sensor technology for hypersonic applications
  - Issue
    - Identify / evaluate maturity of structural sensor technology for hypersonic applications
  - Goal
    - Provide NASA the framework to focus effort on high-payoff sensing methods
    - Develop SOA to coordinate current and future HYP M&S development efforts (NRA and SBIR)
  - Method
    - 2007 HYP M&S NRA – University of Massachusetts
      - Developing a review / assessment on the state of the art in high-temperature structural sensing technology
      - Develop report (both public and ITAR versions)
    - Solicit input from NASA instrumentation experts as required
  - Work to Date
    - 1-year NRA effort was initiated in January 2008

Sensors

Dynamic Strain Measurements (Max Op 1850°F)

High-Temp Quarter-Bridge Strain Gage

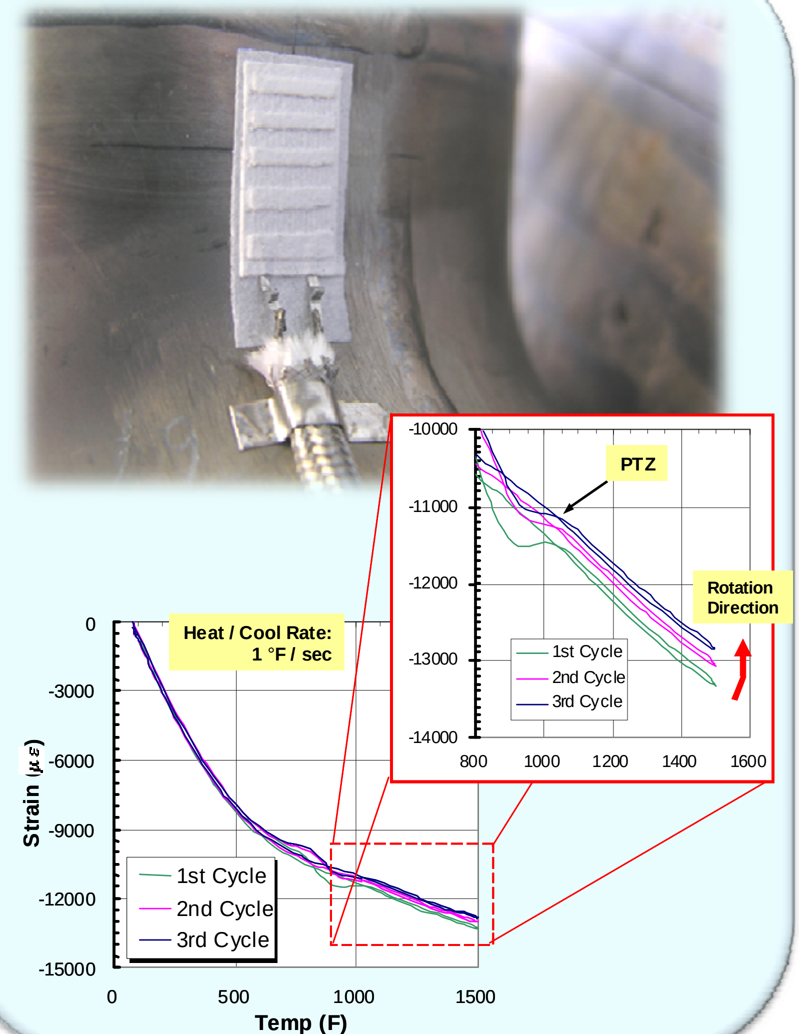


Pro's

- Sturdy / rugged thermal sprayed installation and spot-welded leadwire stakedown
- Available high sample rate DAS, usually AC coupled to negate large ξapp

Con's

- Large magnitude ξapp primarily due to wire TCR, slope rotates cycle-to-cycle
- Sensitivity (GF): Function of temperature



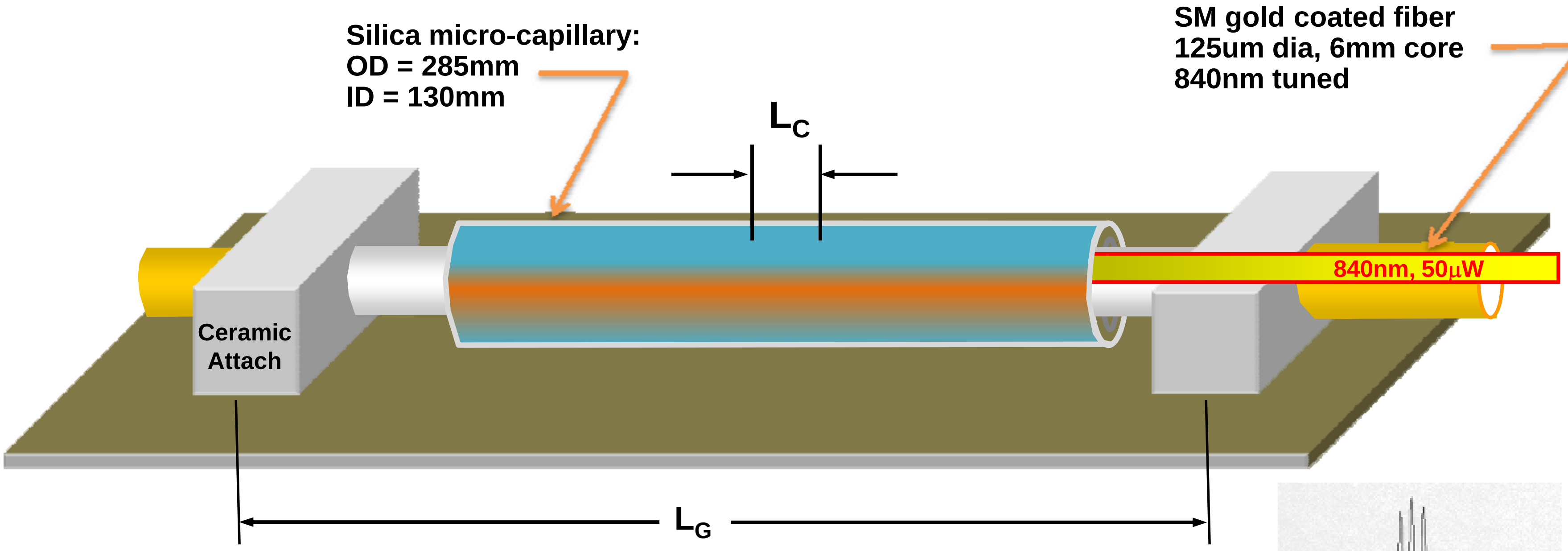
Apparent Strain = [TCR_{gage} / GF_{set} + (α_{sub} - α_{gage})] * (ΔT)

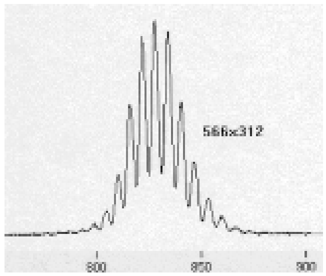
Sensors

Static Strain Measurements (Max Op 1850°F, Short-Term)

Single-Mode Gold Coated
Extrinsic Fabry-Perot Interferometer (EFPI)

Commercially Available





Strain = $\delta L_C \;/ L_{G\,(initial)}$, where sensitivity = L_G

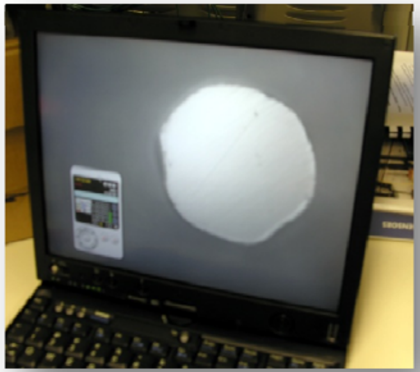
Apparent Strain (ξapp) = $(\alpha_{sub} - \alpha_{fiber}) * \Delta T$

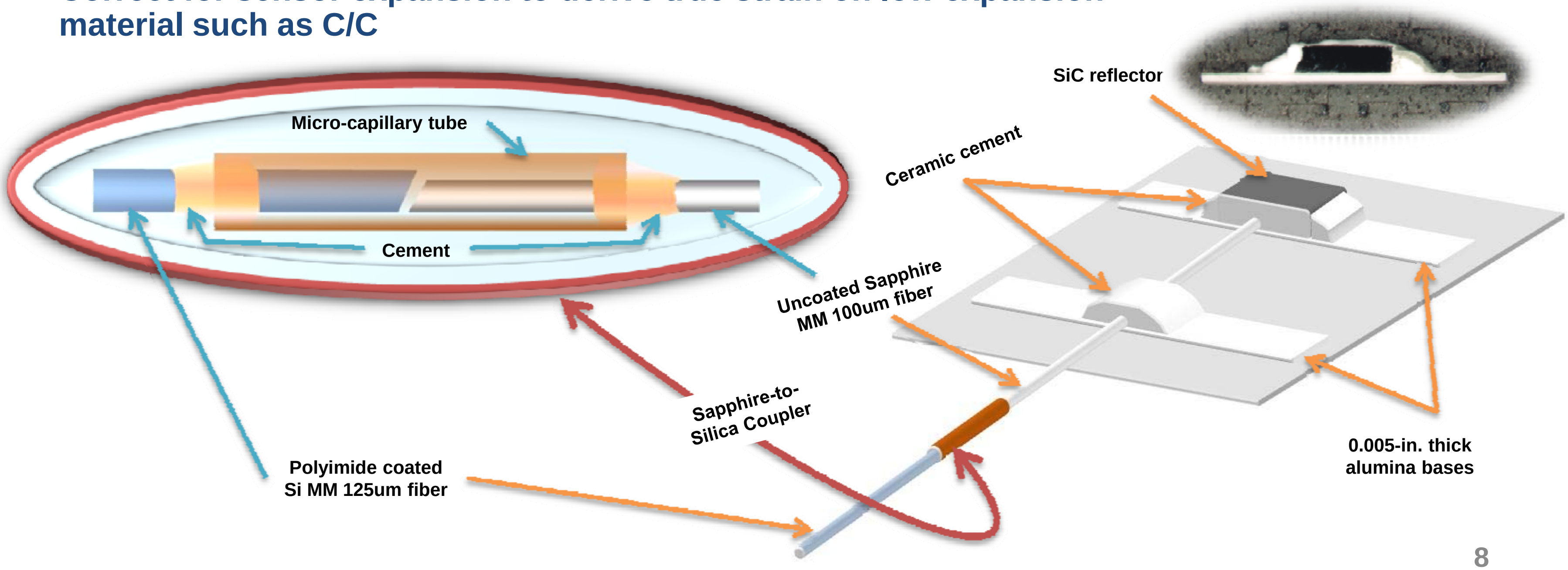
Sensors
Static Strain Measurements (Possible Max Op 3000°F)

Multi-Mode Sapphire EFPI

Challenges:

- Quality fringes at 100um gap
  - Achieve highly polished Sapphire fiber and SiC reflector faces
  - Minimize higher order modes at Sapphire / Si splice
- Fabricate and transfer to substrate w/o degradation to fridges
- Attach w/o effecting fridges
- Install into test fixture w/o breaking (Sapphire fragile with no coating)
- Correct for sensor expansion to derive true strain on low expansion material such as C/C

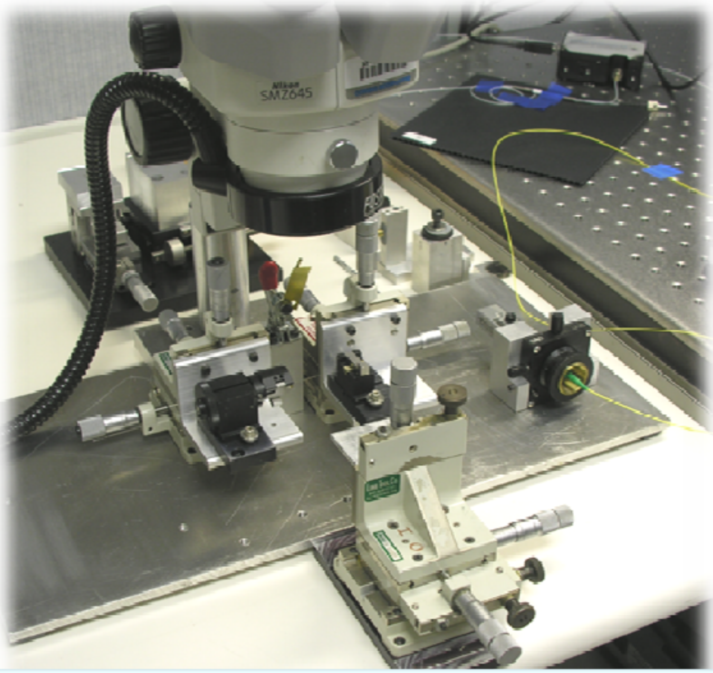


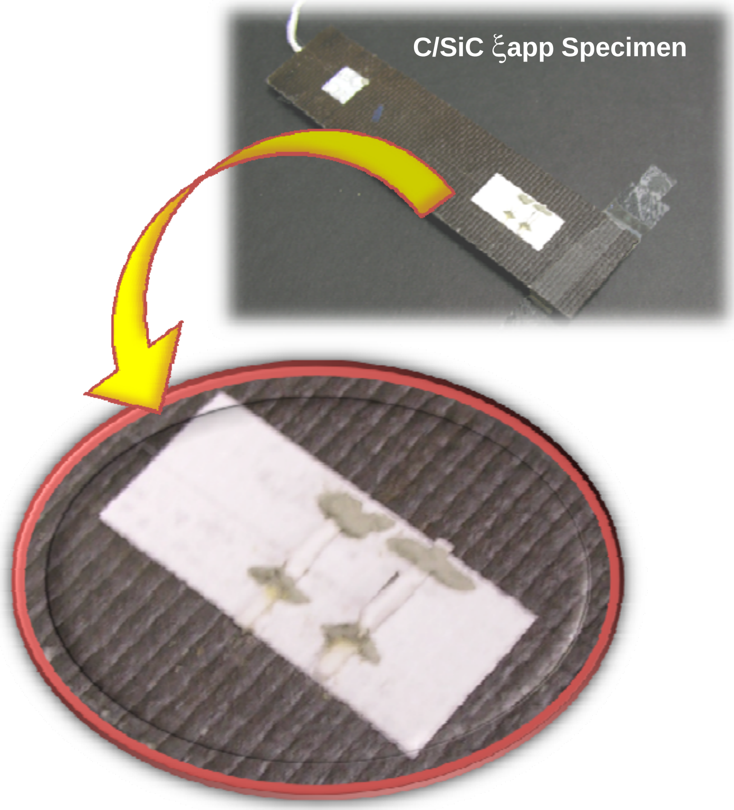


Sensors

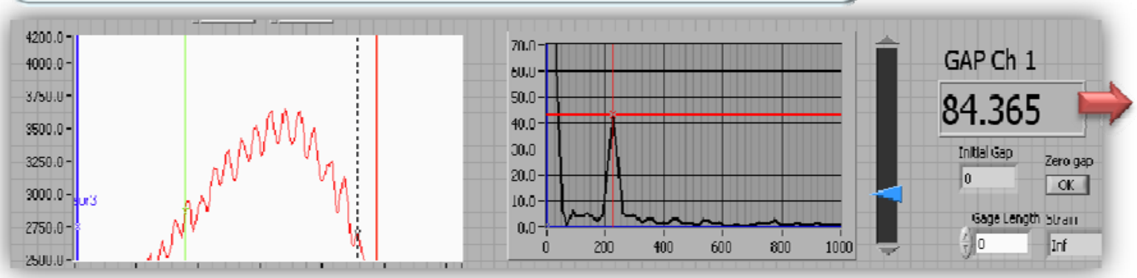
Static Strain Measurements (Possible Max Op 3000°F)

Multi-Mode Sapphire EFPI





Work has been performed through a PHII SBIR with Lambda Instruments, Inc., POC Jonathon Greene



Strain (micro-in/in)

$\mu\xi = \Delta s / GL$

where:

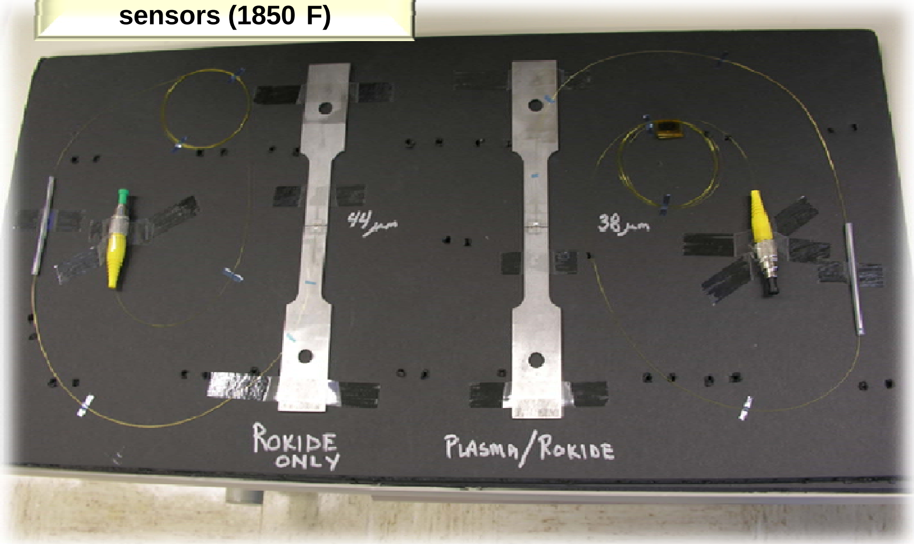
s = cavity gap in microns

GL = gage length in millimeters

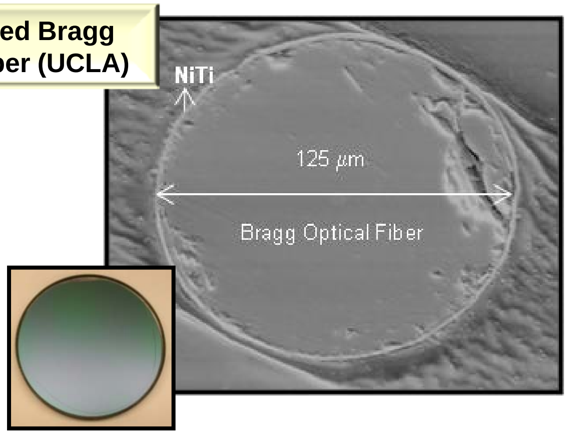
Sensors

High-Temp Strain Measurements

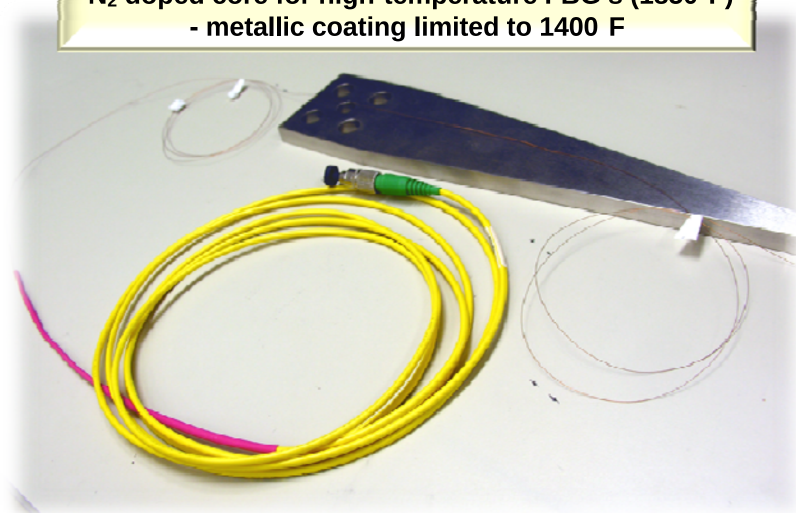
Weldable Si EFPI strain sensors (1850 F)

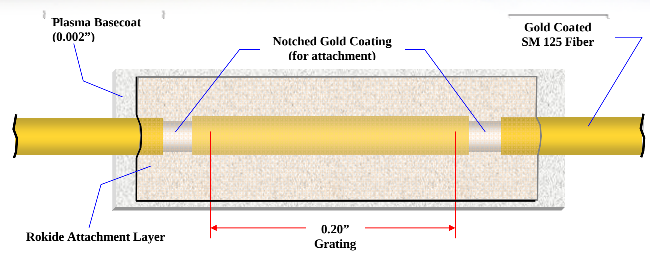


NiTi Coated Bragg Optical Fiber (UCLA)



N_2 doped core for high-temperature FBG's (1850 F) - metallic coating limited to 1400 F

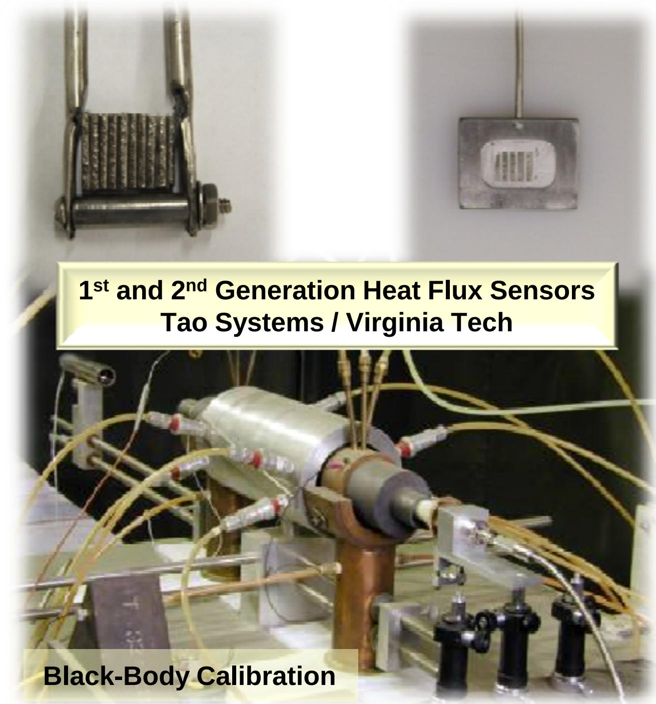




Sensors
High-Temp Accel's, Heat Flux, & TC's

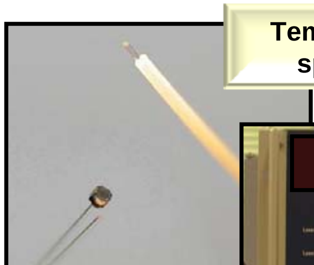
Commercial Accelerometers
(900°F to 1200°F)

1st and 2nd Generation Heat Flux Sensors
Tao Systems / Virginia Tech

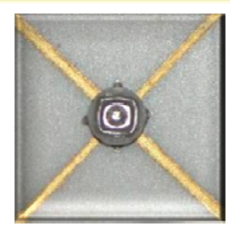


Black-Body Calibration

Temperature measurements using high speed fiber optic systems (1850 F)



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

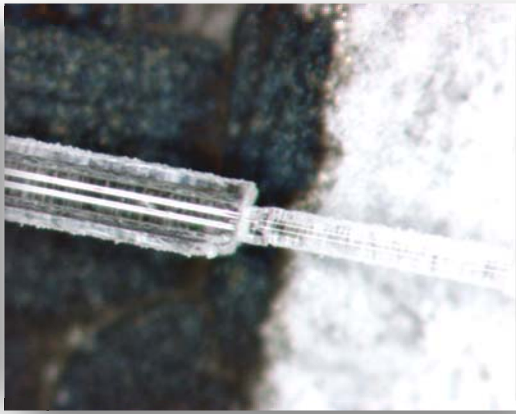


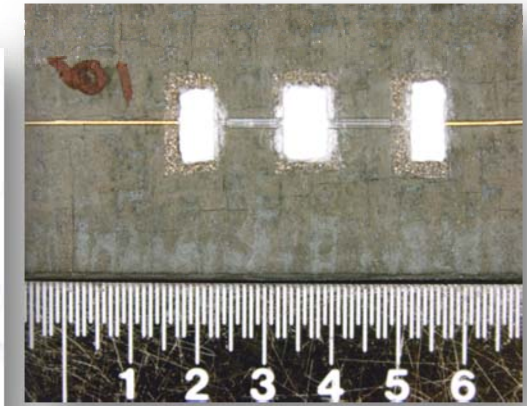
Attachment Techniques

Applications Above 600°F

Develop sensor attachment techniques for relevant structural materials

- Derive surface prep and optimal plasma spray parameters for applicable substrate
  - i.e., powder media / type, power level, traverse rate, feed rate, and spraying distance
- Or, optimize / select cement that best fits application
- Improve methods of handling and protecting fragile sensor during harsh installation processes

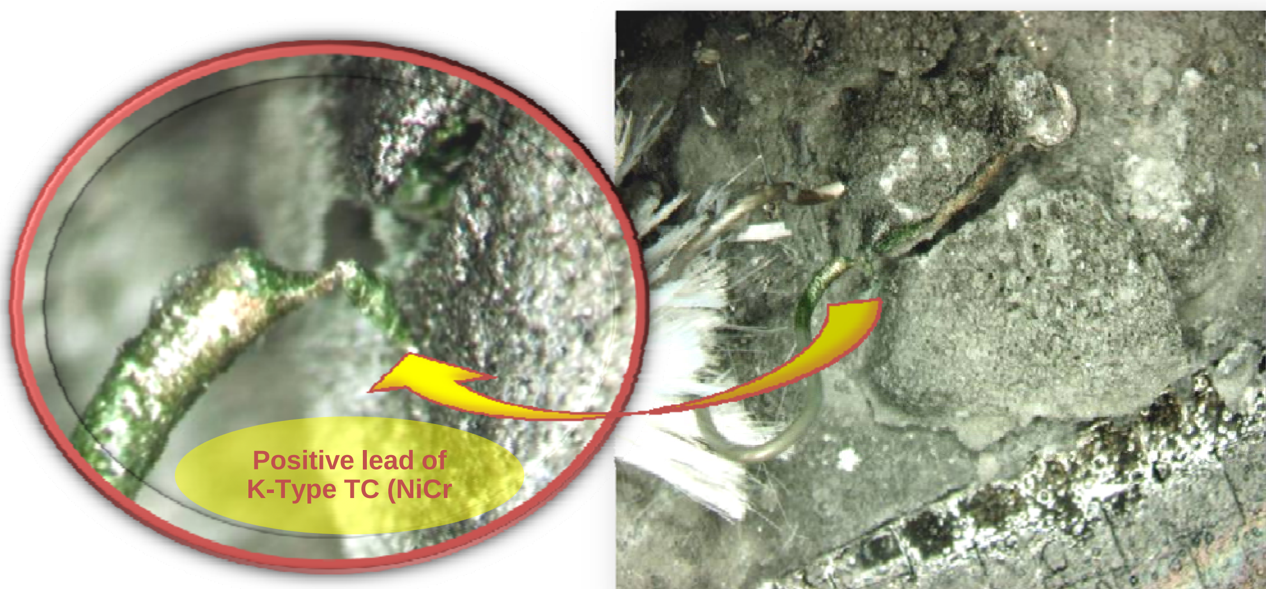


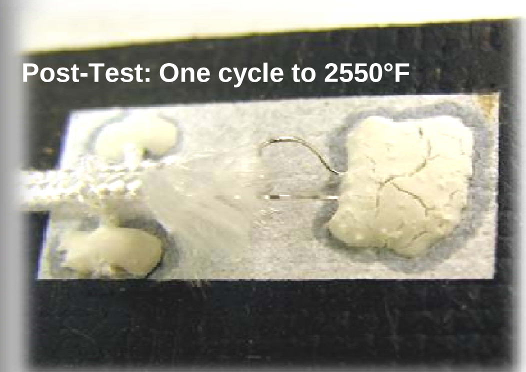


Attachment Techniques
Thermal Spray vs. Cement

Thermal sprayed attachments are preferred even though cements are simpler to apply

- Cements are often corrosive to TC or strain gage alloys
  - Si / Pt, NaF / Fe-Cr-Al alloys, alkali silicate / Cr
- Cements are more prone to bond failure due to shrinkage and cracking caused when binders dissipate
- *Tests indicate increased EFPI gage-to-gage scatter on first cycle*





Attachment Techniques
Thermal Spray Equipment

Thermal Spray Room

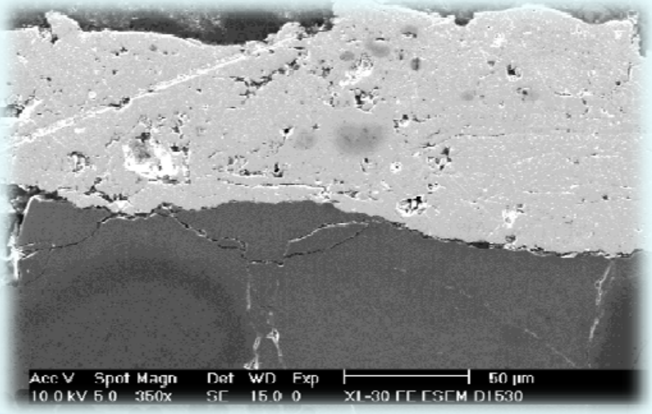
- 80KW Plasma System
- Rokide Flame-Spray System
- Powder Spray System
- Grit-Blast Cabinet
- Micro-Blast System
- Water Curtain Spray Booth

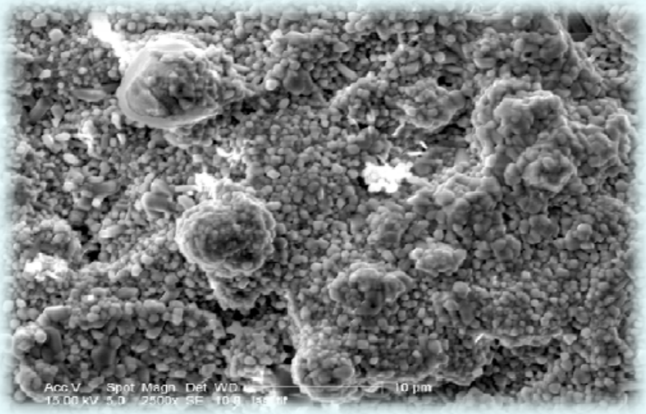
Attachment Techniques
Thermal Spray Technology

Arc-plasma sprayed base coat

- Metallic Substrates: Used to transition high expansion substrate metal with low expansion sensor attachment material (Al_2O_3)
- CMC Substrates (inert testing): High melting-point ductile transitional metals (i.e. Ta, TiO_2, & Mo) more conducive for attachment to smooth surfaces like SiC

Collaborative work done through grants with Dr. Richard Knight, Drexel University

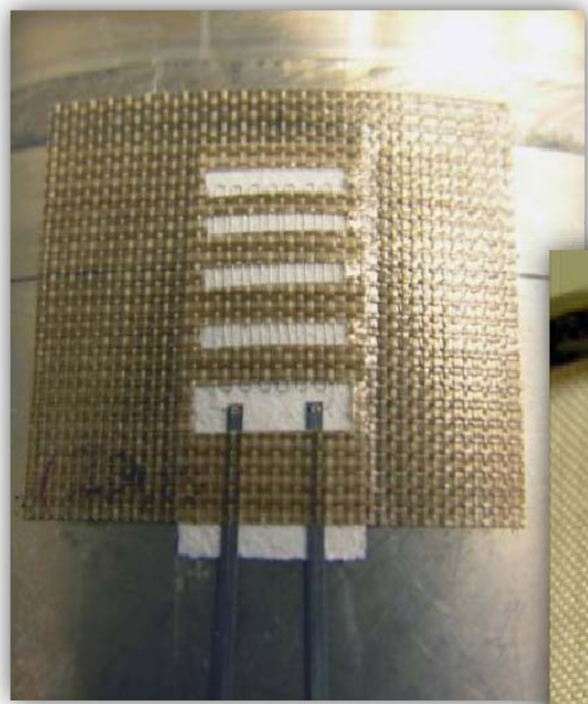




Rokide flame-sprayed sensor attachment

- Applies a less dense form of alumina than plasma spraying
- Electrically insulates (encapsulate) wire resistive strain gages

Attachment Techniques
Thermal Sprayed Free-Filament Wire SG



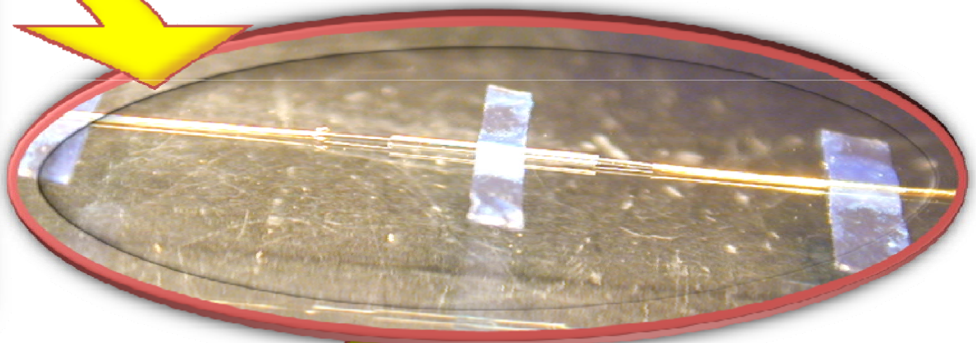
Place SG on thermal sprayed basecoats via carrier tape

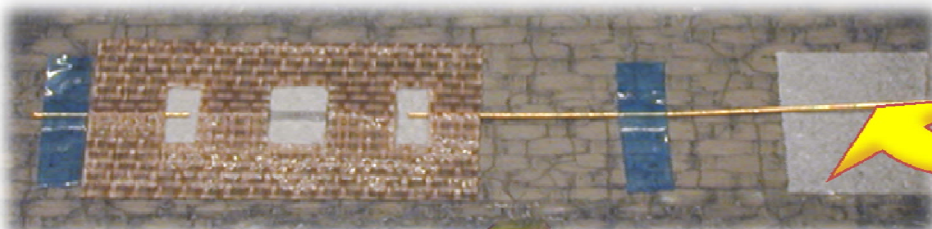
Apply flame-sprayed tack and cover coats

Spot weld three-conductor leadwire

Attachment Techniques
Thermal Sprayed Gold-Coated Si EFPI

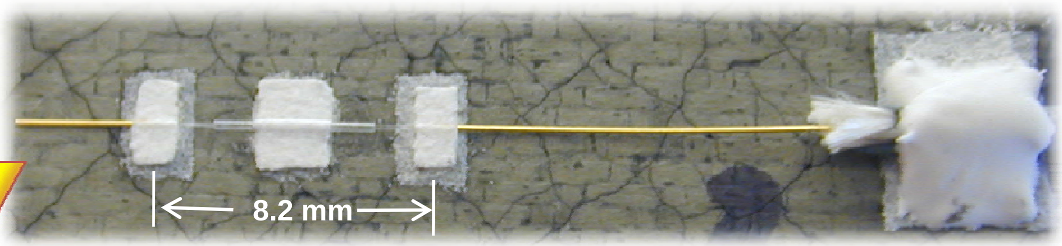
Fabricate sensor under microscope





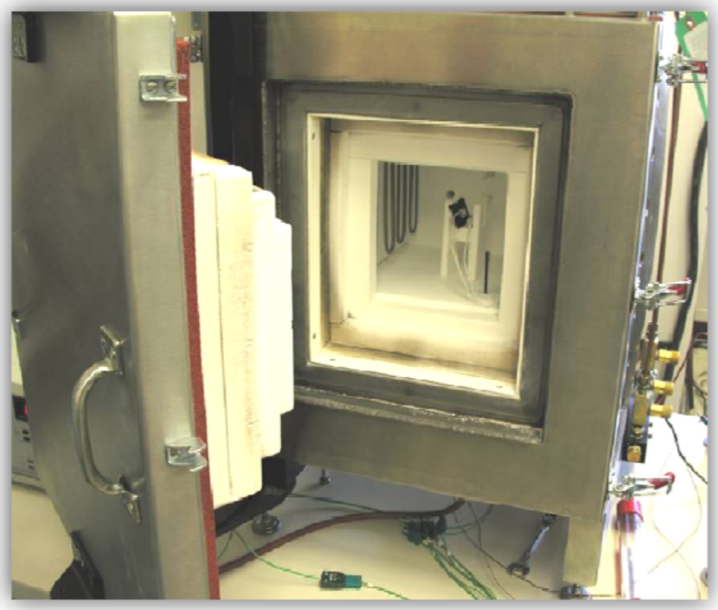
Transfer to thermal sprayed base coat using carrier tape

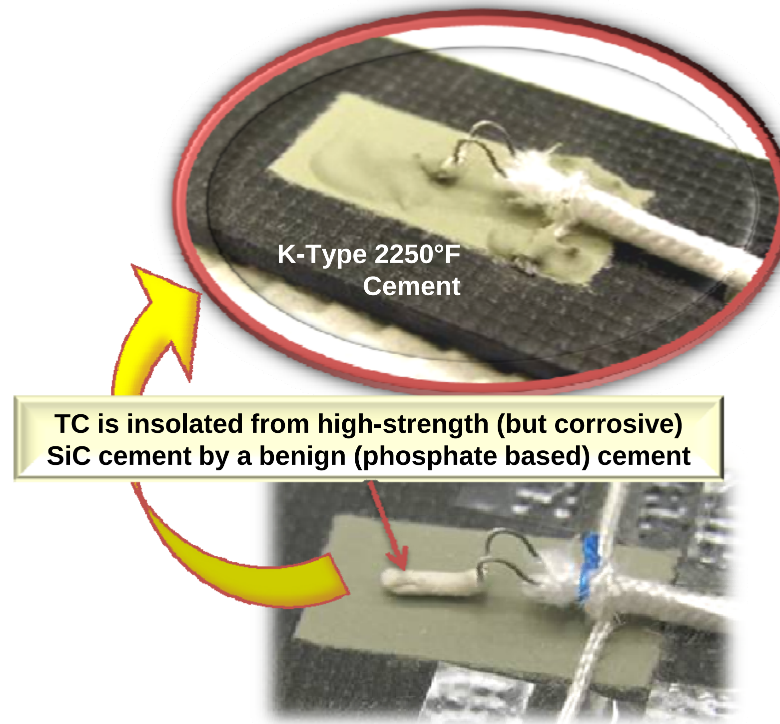
Flame-spray sensor attachment

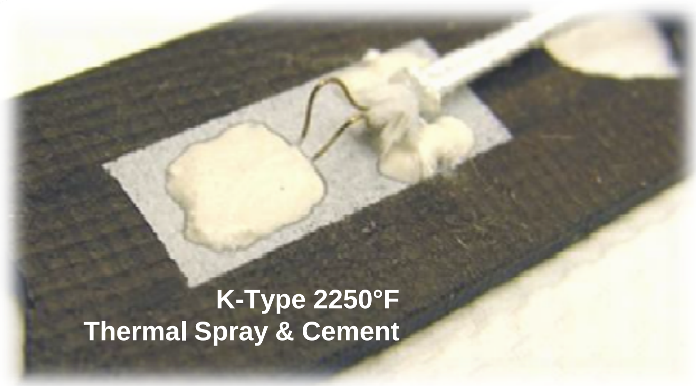


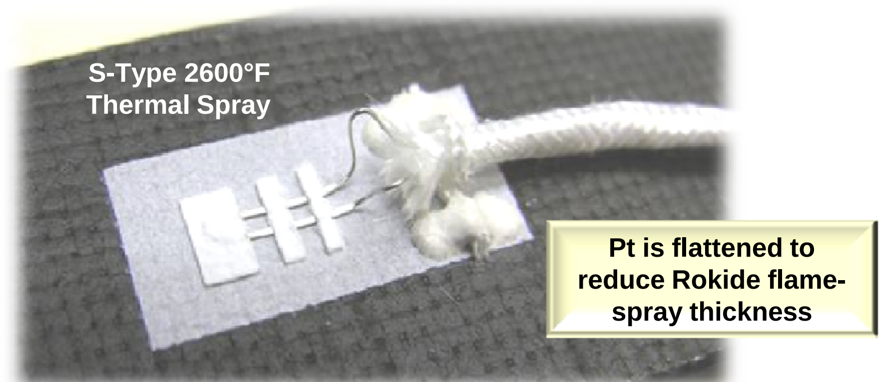
Attachment Techniques
Thermal Spray / Cemented Thermocouples

Evaluate High-Temp Attachments
(Rapid Furnace, Inert 2600F)









Laboratory Evaluation / Characterization

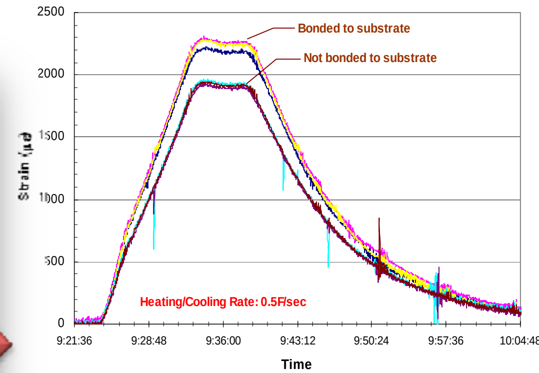
Validate and characterize strain measurement

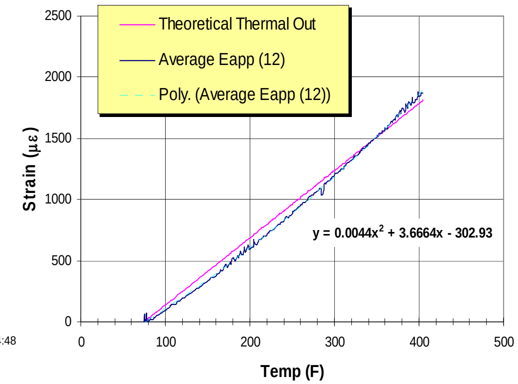
- *Base-line / characterize high-temperature strain sensors on monolithic Inconel specimens*
  - known material spec's isolate substrate from inherent sensor traits prior to testing on more complex composites
- Evaluate / characterize sensitivity (GF) of strain sensors on ceramic composite substrates using laboratory combined thermal / mechanical load fixture
- Generate apparent strain curves for corrections of indicated strains on relevant ceramic composite hot-structures

Laboratory Evaluation / Characterization

FBG Apparent Strain (< 600°F)

Optical Frequency Domain Reflectometry





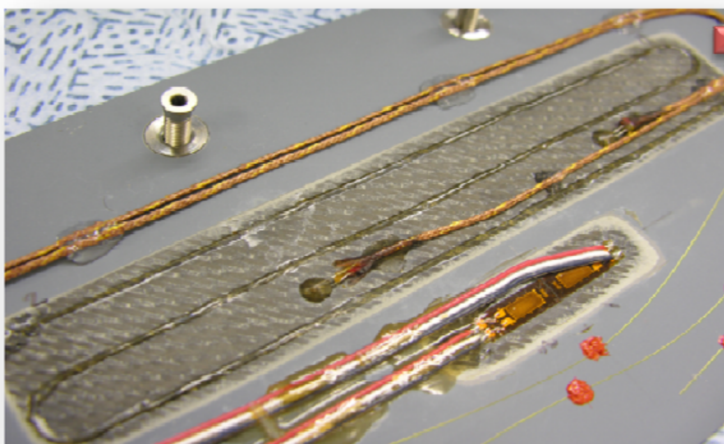
Thermal Out (unbonded) = (α_{fiber} + x / Pe) * ΔT

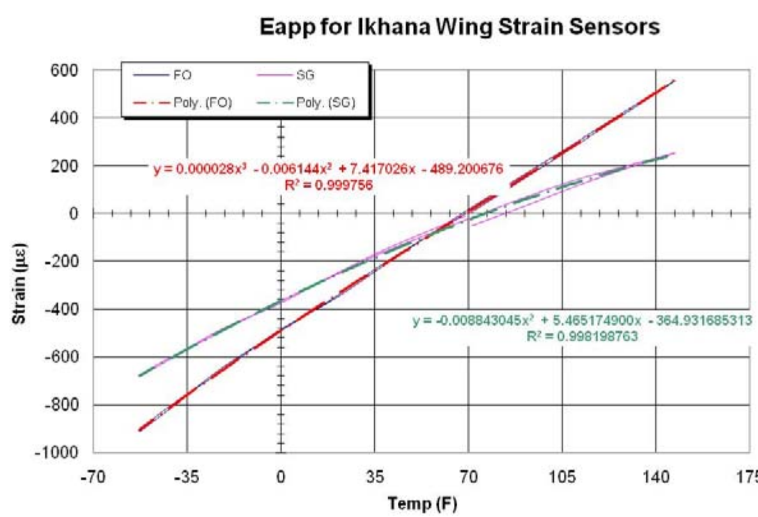
where:

Thermal Optic Effect (x) = 3.78 με/F

Strain Optic Constant (Pe) = 0.725

FBG on Graphite / Epoxy Composites

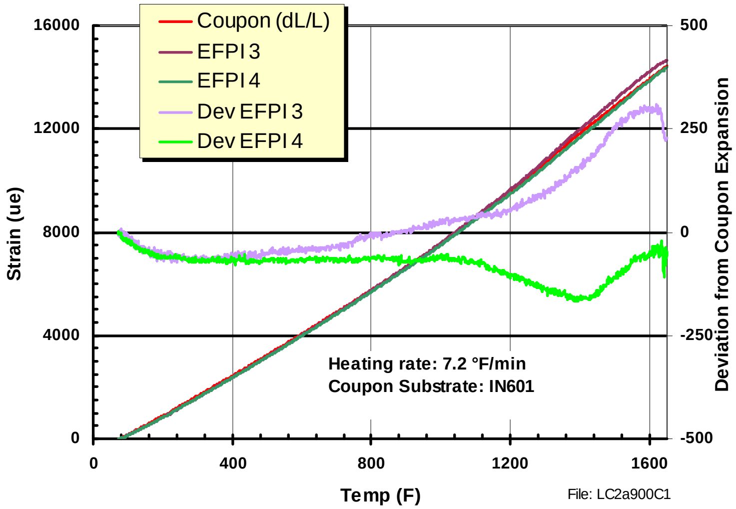




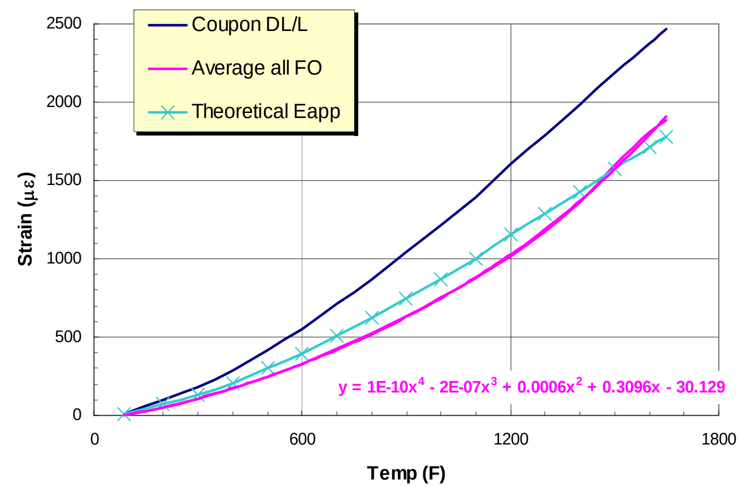
Laboratory Evaluation / Characterization

Gold Coated Si EFPI Apparent Strain

Inconel Substrate



CMC Substrate



ξ_{app} Correction: Removal of inherent sensor traits and substrate expansion from indicated strain to acquire true strains or thermal stresses

$$\xi_{true} = \xi_{indicated} - \xi_{app}, \text{ where } \xi_{app} = (\alpha_{sub} - \alpha_{fiber}) * \Delta T$$

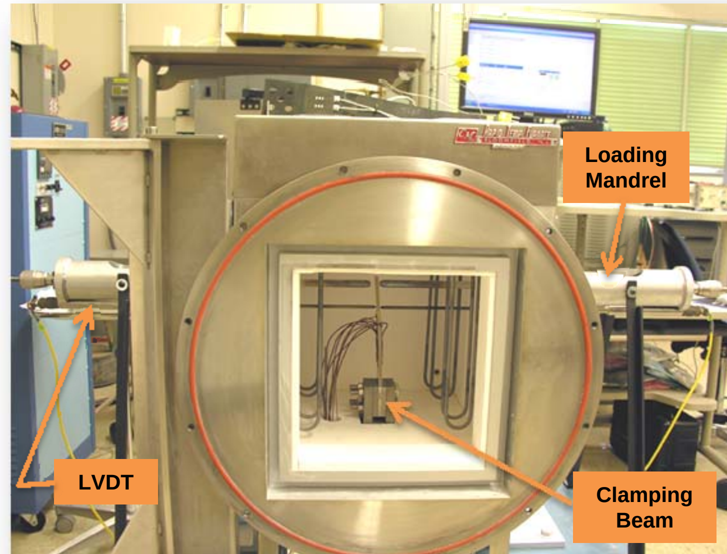
- Inconel (LH chart): Large expansion differential between IN601 and Si
  - output primarily substrate expansion, CTE * ΔT
- CMC (RH chart): Small expansion ratio between C-SiC and Si
  - requires correction for fiber expansion (lessening cavity gap)
- *Graphs demonstrate how well actual ξapp curves followed theoretical*

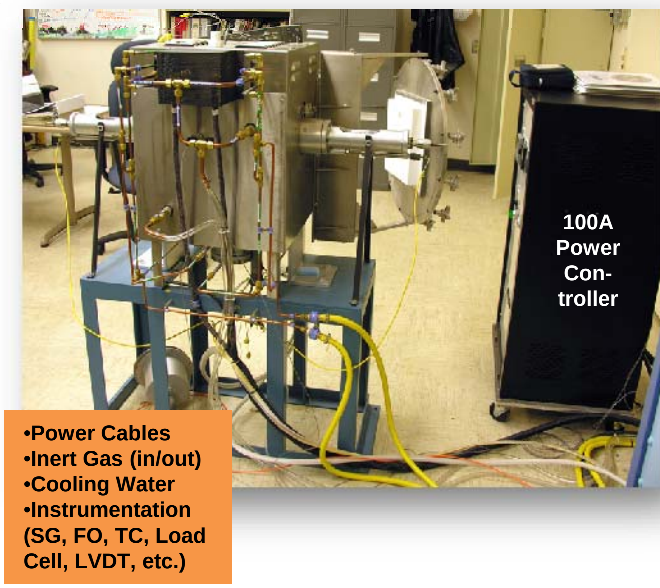
Laboratory Evaluation / Characterization

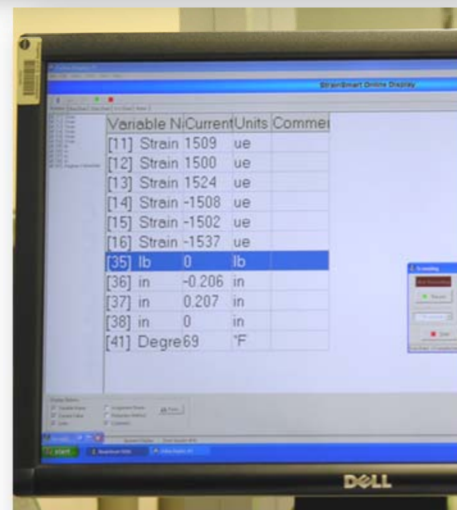
Combined Thermal / Mechanical Loading

Furnace / cantilever beam loading system for sensitivity testing

- *Air or inert (3000°F max)*
- 12-in^3 inner furnace with Molydisilicide elements
- Micrometer / mandrel side loading
- LVDT displacement measurements
- POCO Graphite hardware for inert environment testing of ceramic composites
- IN625 hardware for metallic testing in air
- Sapphire viewing windows





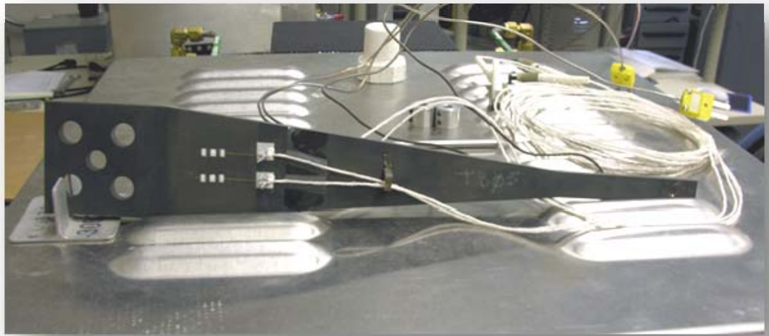


Laboratory Evaluation / Characterization

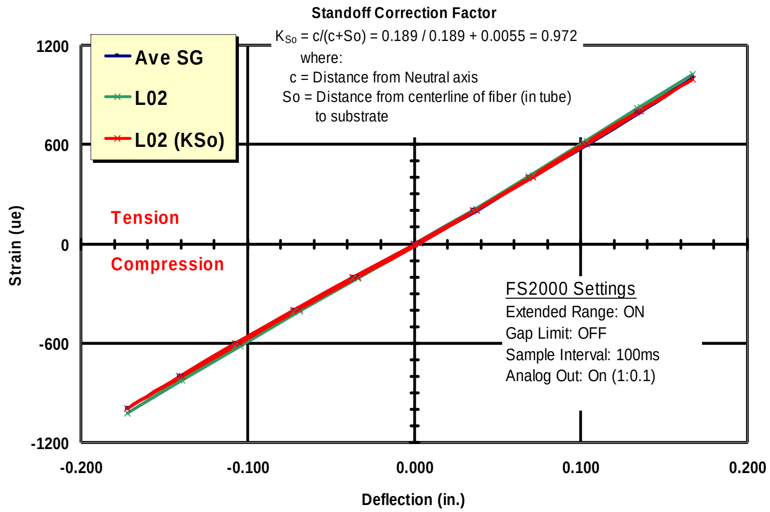
Combined Thermal / Mechanical Loading

Testing

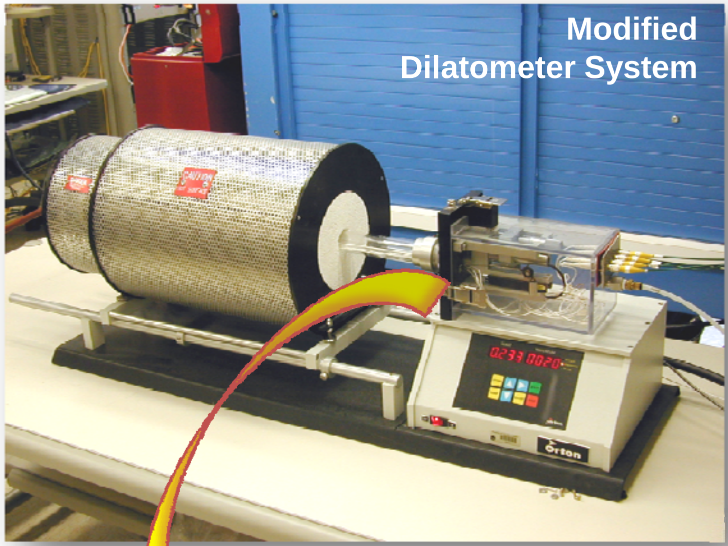
- Completed
  - Baselined Si EFPI on IN625 to 1650ºF, ±1000$\mu\varepsilon$ (lower RH chart)
  - Contracted machining of C-SiC tapered load bars for testing of Si EFPI
- Near-Future
  - Rebaseline Si EFPI using new load system
  - Complete Si EFPI testing on C-SiC to 1800ºF, ±1000$\mu\varepsilon$, inert atmosphere (<400ppm)
  - Attempt testing of Sapphire EFPI to 2500ºF
  - Determine next promising sensor from University of Massachusetts NRA report



EFPI Combined Loading on IN625



Laboratory Evaluation / Characterization
Dilatometer Thermal Expansion Testing



Sensor Characterization
Air or inert (3000°F max)

- Evaluate bond integrity
- Generate ξapp correction curves
- Evaluate sensitivity and accuracy
- Evaluate sensor-to-sensor scatter, repeatability, hysteresis, and drift