Novel Thin Film Sensor Technology for Turbine Engine Hot Section Components

John D. Wrbanek and Gustave C. Fralick
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, OH 44135

Abstract

Degradation and damage that develops over time in hot section components can lead to catastrophic failure of the turbine section of aircraft engines. A range of thin film sensor technology has been demonstrated enabling on-component measurement of multiple parameters either individually or in sensor arrays including temperature, strain, heat flux, and flow. Conductive ceramics are beginning to be investigated as new materials for use as thin film sensors in the hot section, leveraging expertise in thin films and high temperature materials. The current challenges are to develop new sensor and insulation materials capable of withstanding the extreme hot section environment, and to develop techniques for applying sensors onto complex high temperature structures for aging studies of hot propulsion materials. The technology research and development ongoing at NASA Glenn Research Center for applications to future aircraft, launch vehicles, space vehicles, and ground systems is outlined.

Novel Thin Film Sensor Technology for Turbine Engine Hot Section Components

John D. Wrbanek and Gustave C. Fralick
NASA Glenn Research Center, Cleveland, Ohio

Presented at
18th AeroMat Conference & Exposition
June 26, 2007
Baltimore, Maryland

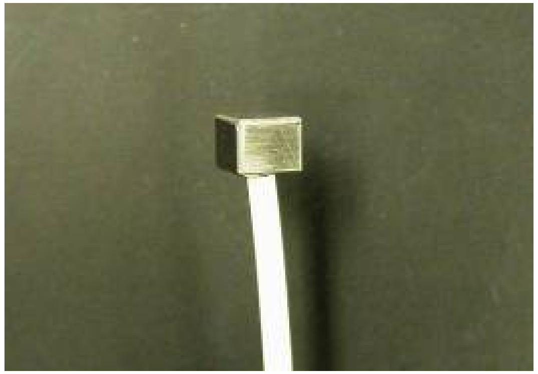
The Materials Information Society

Conference and Exposition

The Researchers

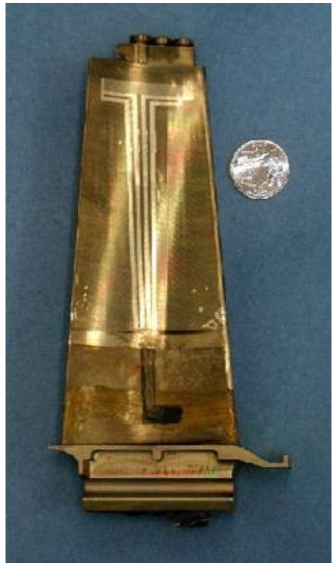
John Wrbanek & Gus Fralick

- Research Engineers / Physicists at NASA Glenn Research Center Sensors & Electronics Branch (GRC/RIS)
- Primarily Physical Sensors Instrumentation Research:
  - Thin Film Sensors
  - Temperature
  - Strain
  - Flow
- Also dabble in Radiation Detectors, and Research in Sonoluminescence & Other Revolutionary Concepts



Outline

- Introduction
- Thin Film Physical Sensors at GRC
- Ceramics as Thermocouples
  - $CrSi_2/TaC$ test
- Ceramics as Static Strain Gauges
  - AFRL/NASA Space Act Agreement (SAA)
- Aircraft Aging & Durability Project
  - Novel Thin Film Sensor Technology for Aging Component NDE

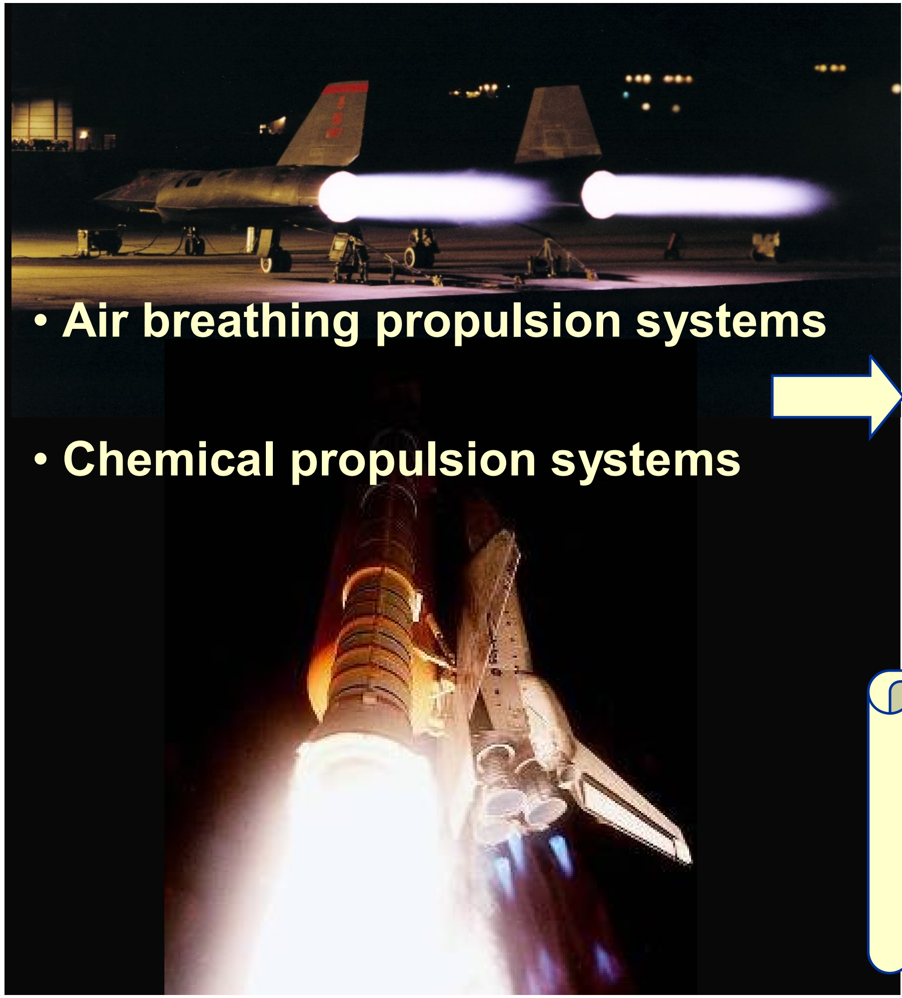


NASA's Mission: To pioneer the future in space exploration, scientific discovery, and aeronautics research

"Advance knowledge in the fundamental disciplines of aeronautics, and develop technologies for safer aircraft and higher capacity airspace systems."
– NASA 2006 Strategic Plan

"Develop the innovative technologies, knowledge, and infrastructures both to explore and support decisions about the destinations for human exploration"
– Vision for Space Exploration

Instrumentation Challenges for Propulsion System Environments



- **High gas temperatures**
- **High material temperatures (>1000°C)**
- **Rapid thermal transients**
- **High gas flows**
- **High combustion chamber pressures**

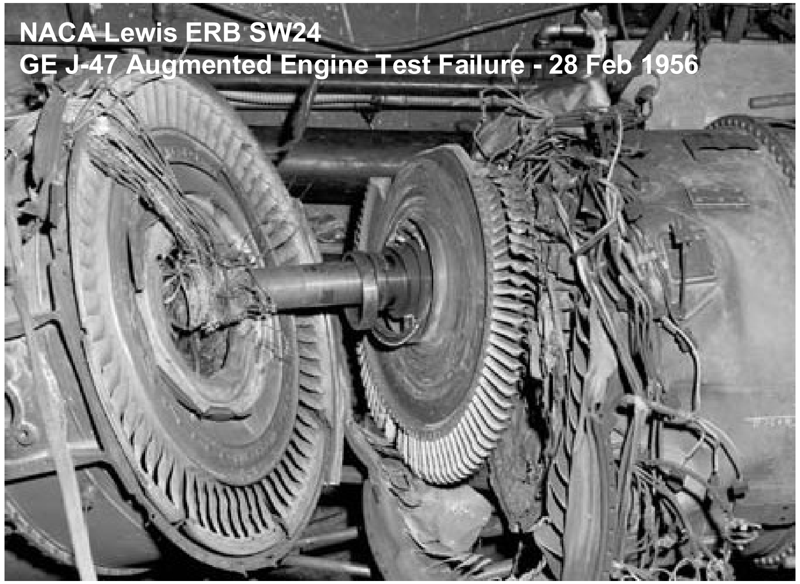
Wire-based sensors are bulky and disruptive to the true operating environment

Physical Issues for Life Prediction of Engine Hot Section

- Centrifugal Stress
- Thermal Stress
- Vibrational Stress from gas flow
- Contact Stresses from different materials (Thermal Expansions, Deformations)
- Blade Clearance (Creep)

Malaysia Airlines Boeing 777-2H6ER
RR Trent 892 Blade Delamination - 03 Nov 2006

Air New Zealand Boeing 767-219ER
GE CF6-80A In-Flight Failure - 08 Dec 2002

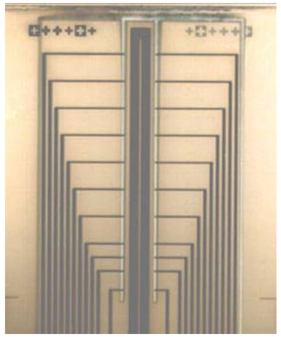


NACA Lewis ERB SW24
GE J-47 Augmented Engine Test Failure - 28 Feb 1956

Thin Film Physical Sensors for High Temperature Applications

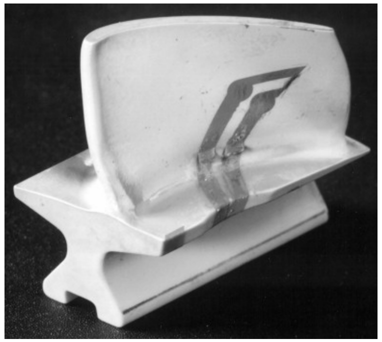
Advantages for temperature, strain, heat flux, flow & pressure measurements:

- Negligible mass & minimally intrusive (microns thick)
- Applicable to a variety of materials including ceramics
- Minimal structural disturbance (minimal machining)
- Intimate sensor to substrate contact & accurate placement
- High durability compared to exposed wire sensors
- Capable for operation to very high temperatures (>1000°C)

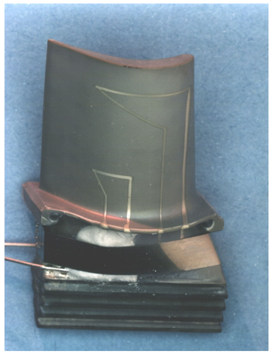


Flow sensor made of high temperature materials

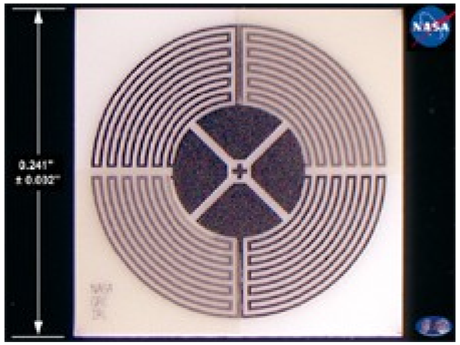
Multifunctional smart sensors being developed



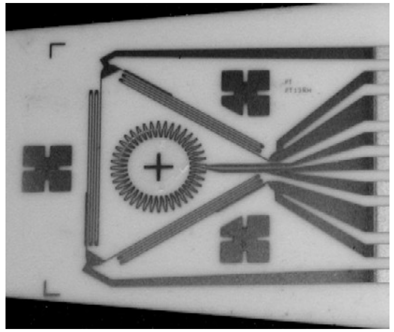
PdCr strain sensor to T=1000°C



Pt- Pt/Rh temperature sensor to T=1200°C



Heat Flux Sensor Array to T=1000°C



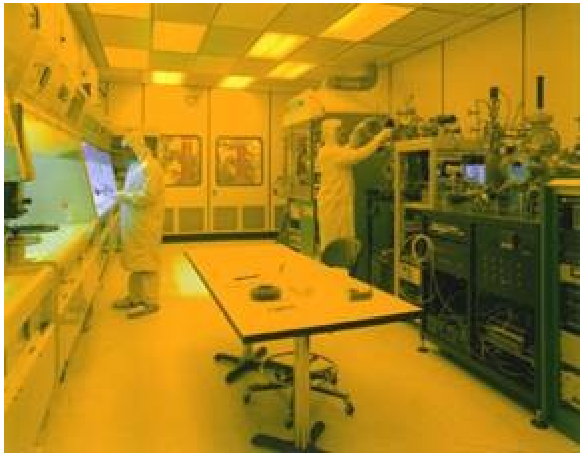
Multifunctional Sensor Array

Physical Sensors Facilities

Sputtering PVD Systems

Sensing Film layers are fabricated with physical vapor deposition methods (sputter deposition, e-beam vapor deposition)

Sensors are patterned by photolithography methods and/or stenciled masks



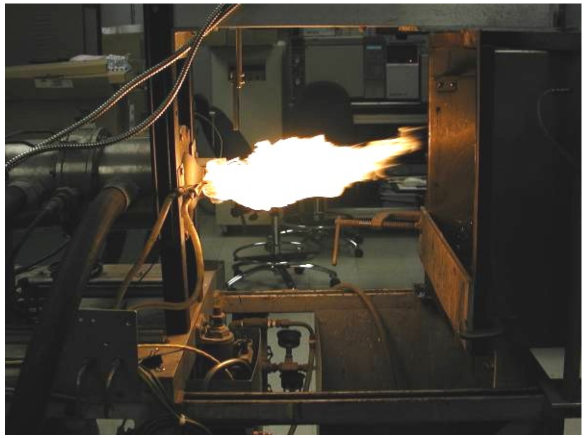
Microfabrication Clean Room

Evaluation of thin films with in-house Materials Characterization Facilities

Testing of films with in-house high-temperature furnaces & burn rigs

SEM/EDAX

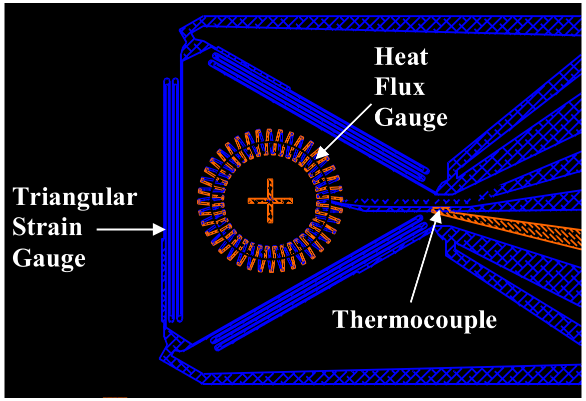
IRL Thin Film Lab



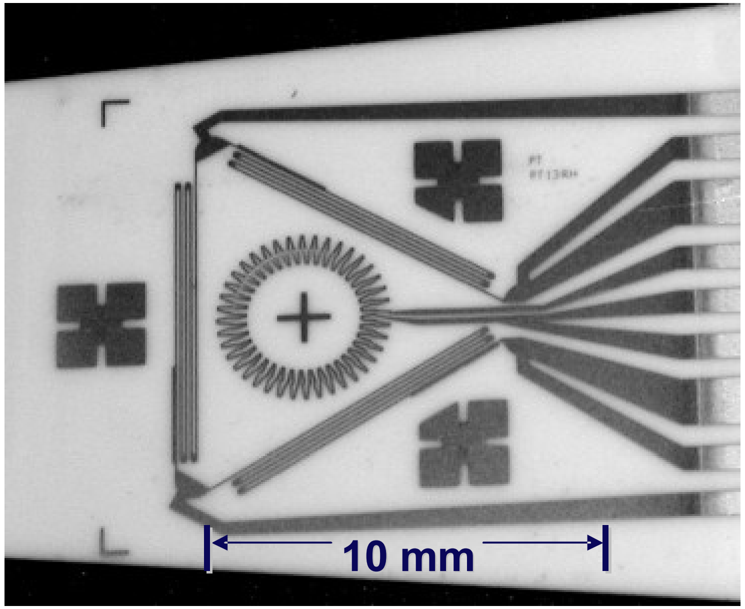
ERB Burn Rig

Multi-Functional Sensor System

- Multifunctional thin film sensor designed and built in-house (US Patent 5,979,243)
- Temperature, strain, and heat flux with flow all one the same microsensor
- Enables measurements on component surfaces, and reduces boundary layer trip on metals compared to wires or foils
- Weldable shim designed to simplify sensor mounting
- Dynamic measurements demonstrated in lab



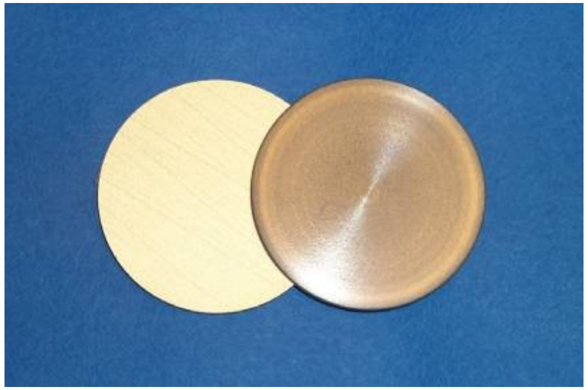
Schematic of Multifunctional Sensor



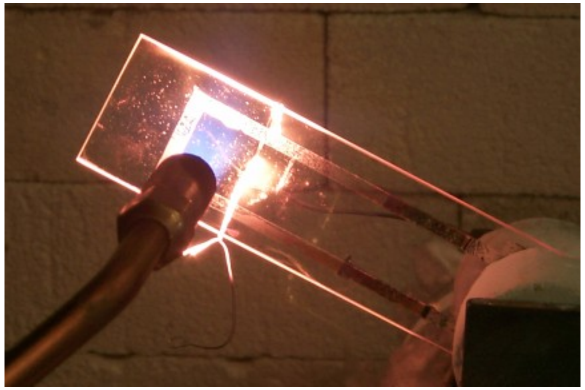
Multifunctional Sensor Prototype

Application of Ceramics as Thin Film Sensors

- The limits of noble metal thin film sensors of 1100°C (2000°F) may not be adequate for the increasingly harsh conditions of advanced aircraft and launch technology (>1650°C/3000°F)
- NASA GRC investigating ceramics as thin film sensors for extremely high temperature applications
- Advantages of the stability and robustness of ceramics and the non-intrusiveness of thin films
- Advances have been made in ceramic thin film sensors through collaborations with Case Western Reserve University (CWRU) and University of Rhode Island (URI)



Ceramic TC Sputtering Targets fabricated by the CWRU & NASA GRC Ceramics Branch

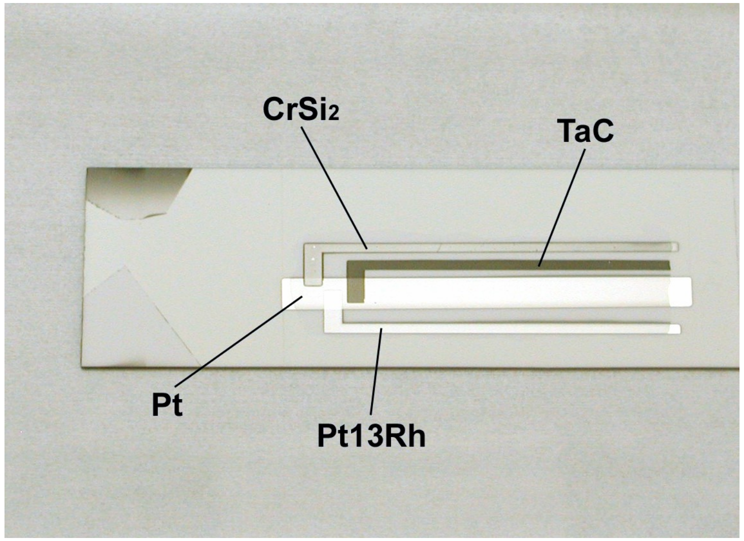


Ceramic TC fabricated at URI

Considerations for Ceramic Thermocouples

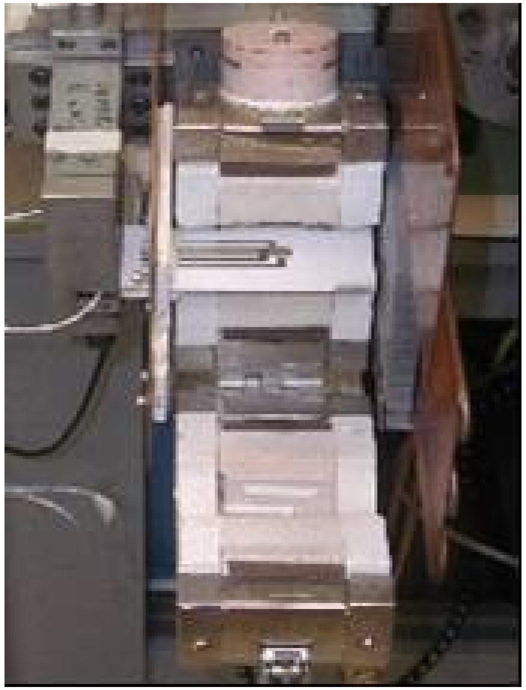
- Silicides and Carbides have highest thermoelectric output of non-metallic thermocouple (TC) elements as bulk materials
- Carbides have a very high use temperature in inert and reducing atmospheres (>>3000°C)
- Most Robust Carbides: TaC, HfC, and ZrC
- Silicides form a natural passivation layer in oxygen
- High Performance Silicides: $CrSi_2$ and $TaSi_2$

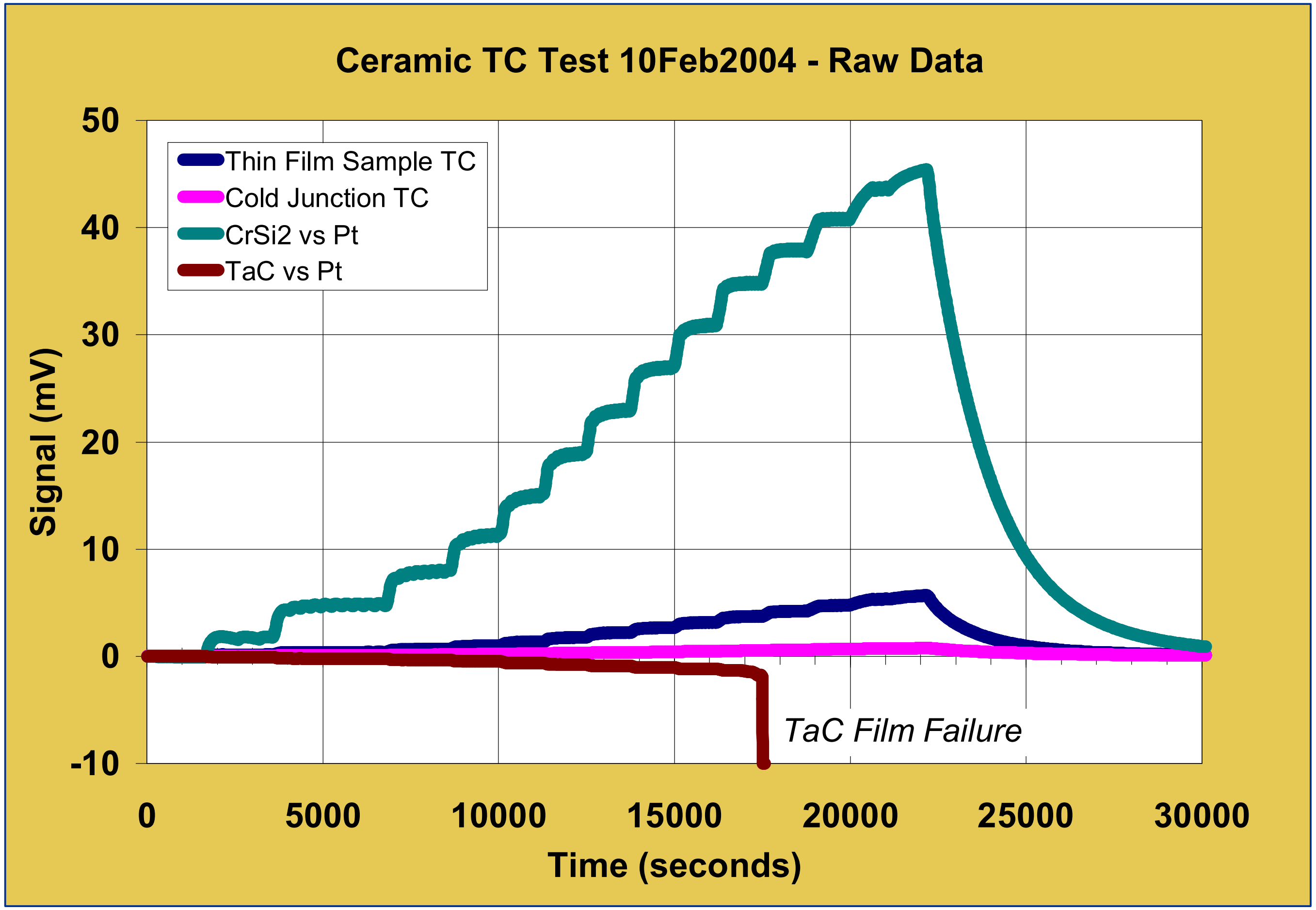
- **Ceramic TC Sample fabricated on-site in Microsystems Fabrication Clean Room Facility using magnetron sputtering and shadow-masks**



Ref.: "Development of Thin Film Ceramic Thermocouples for High Temperature Environments," J.D. Wrbanek, et al., 40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Ft. Lauderdale, FL, July 11-14, 2004. NASA TM-2004-213211.

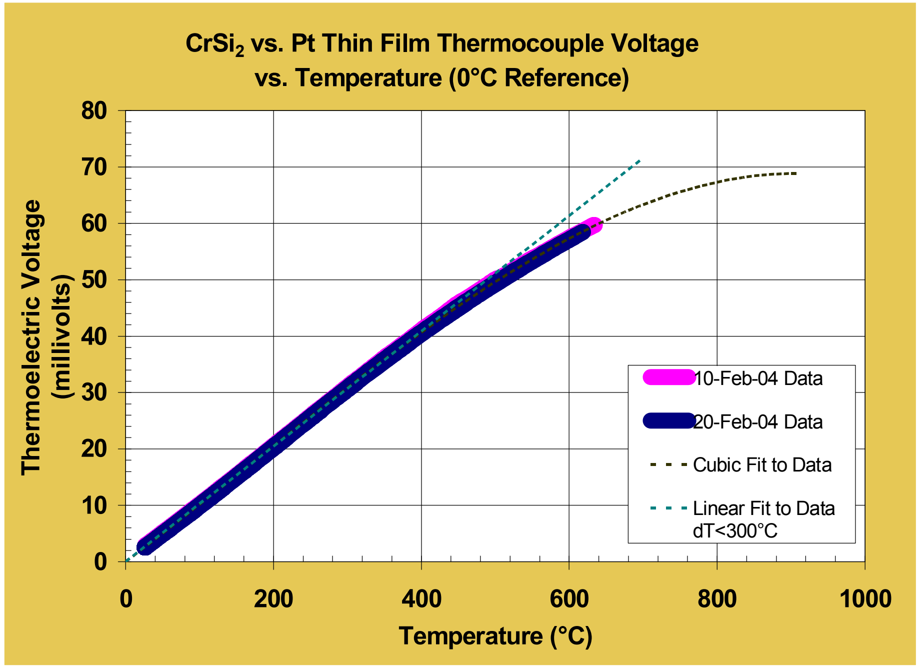
$CrSi_2$/TaC vs. Pt Test Run

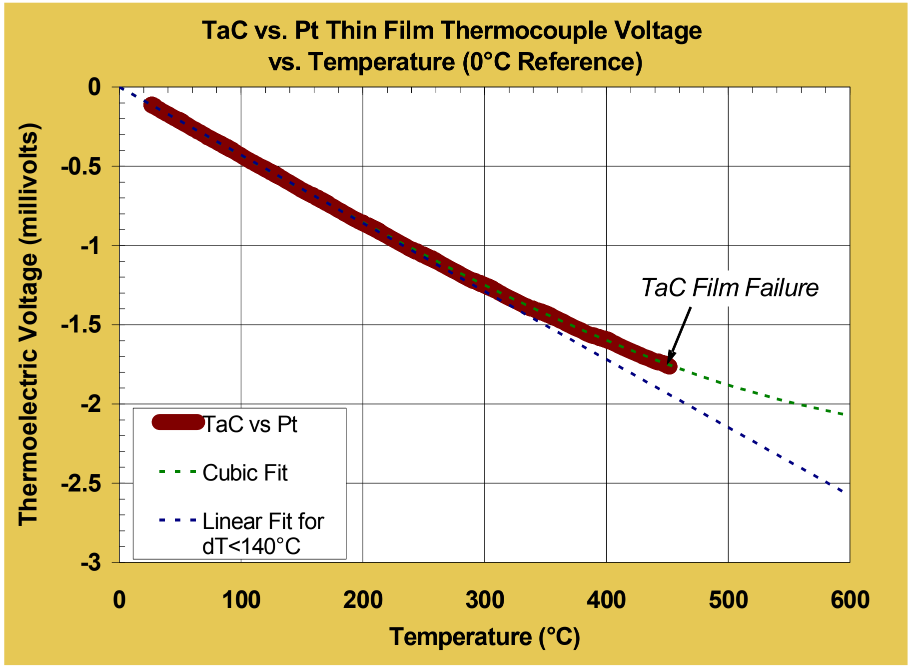




- Initial Testing in air to assess the high temperature response and capabilities

$CrSi_2$ & TaC vs. Pt Thermoelectric Voltage





Linear Fit

- $CrSi_2$ vs. Pt

$V(T°C)_{T1=0}$ = 0.1022075 * *T [mVolts]*

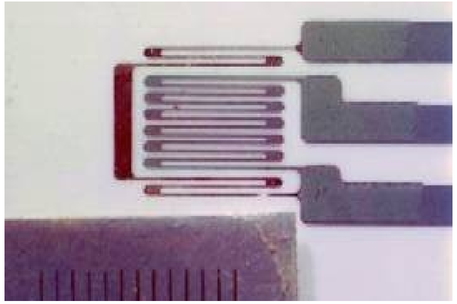
- TaC vs. Pt

$V(T°C)_{T1=0}$ =-0.004296 * *T [mVolts]*

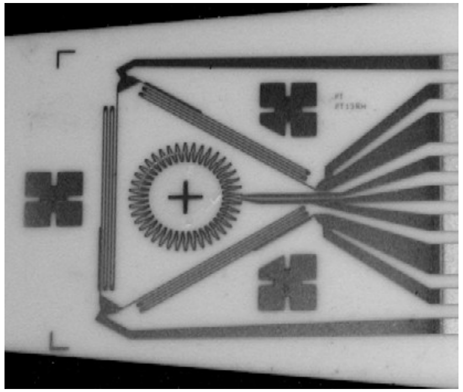
- Oxidation will cause a shift in carrier concentration, which is suspected to be causing the cubic response.
- Linear fit may be more indicative of response in inert environments.

Considerations for Static Strain Gauges

- Required accuracy: ±200 με (±10% full scale)
  - Currently accomplished with a temperature compensating bridge circuit with PdCr
- Multifunctional Sensor design does not lend itself to compensating bridges
  - Multiple strain gauges in a rosette pattern does not allow compensation to be included in design
  - Design eliminates temperature effects if apparent strain is low enough
- High Temperature Static Strain measurements with Multifunctional Sensor requires a more passive method of reducing or eliminating apparent strain
- Temperature Sensitivity Goal for Multifunctional Sensor algorithm: <±20 με/°C



PdCr Strain Gauge in Compensation Bridge



Multifunctional Sensor Design

Apparent Strain

- Gauge factor (γ) of the strain gauge relates the sensitivity of the gauge to Strain (ε):

$$\frac{\delta R}{R} = \gamma \frac{\delta l}{l} = \gamma\varepsilon$$

- Apparent Strain (ε_a) can be falsely interpreted as actual strain due to the gauge's Temperature Coefficient of Resistance (TCR) and Coefficient of Thermal Expansion (CTE):

$$\frac{\varepsilon_a}{\Delta T} = \frac{TCR}{\gamma} + \Delta CTE$$

- Goal: To minimize apparent strain by minimizing TCR and maximizing gauge factor

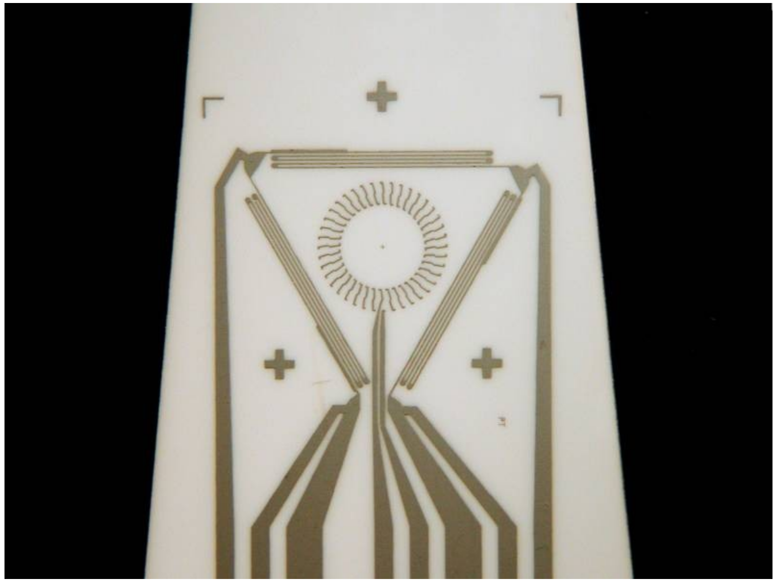
Tantalum Nitride Sensor Fabrication

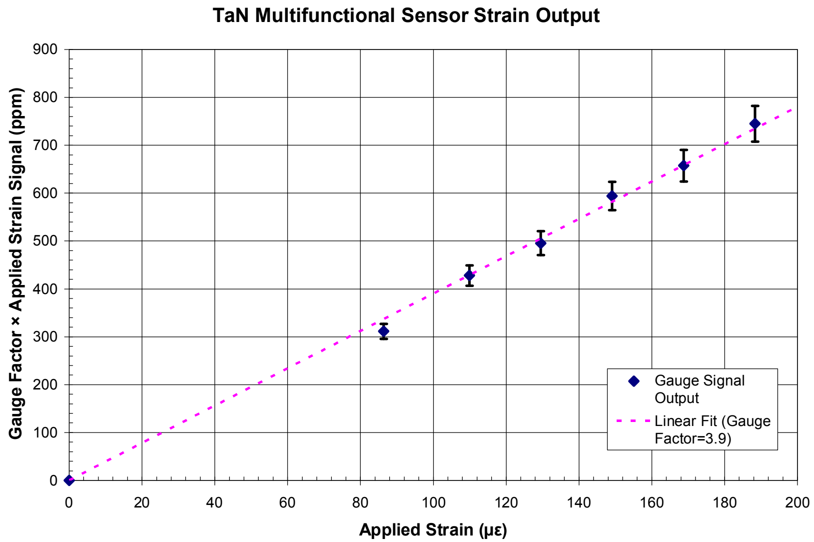
TaN Test Films (2004)

- Reactively-sputtered
- Patterned using shadow masks

TaN Multifunctional Rosette (2005)

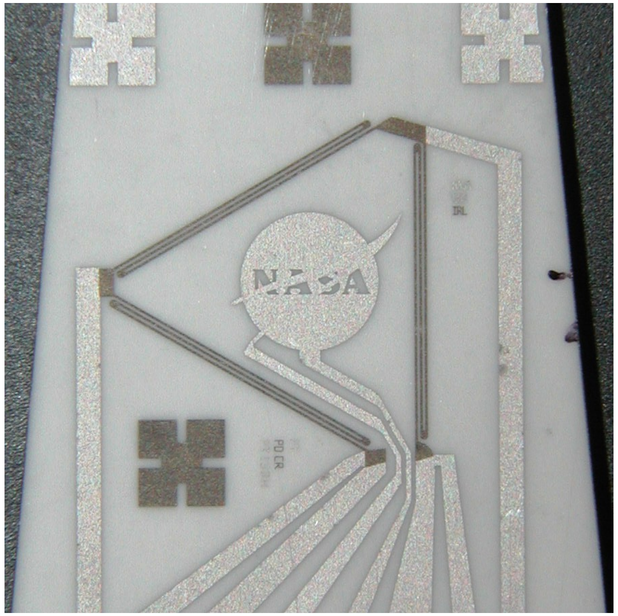
- Patterned using lift-off
- Gauge Factor: 3.9
- Resistivity: 259 μΩ-cm @20°C
- TCR: -93 ppm/°C
- $\varepsilon_a/\Delta T$: -24 με/°C (>20με/°C)





Multilayered Multifunctional Sensor

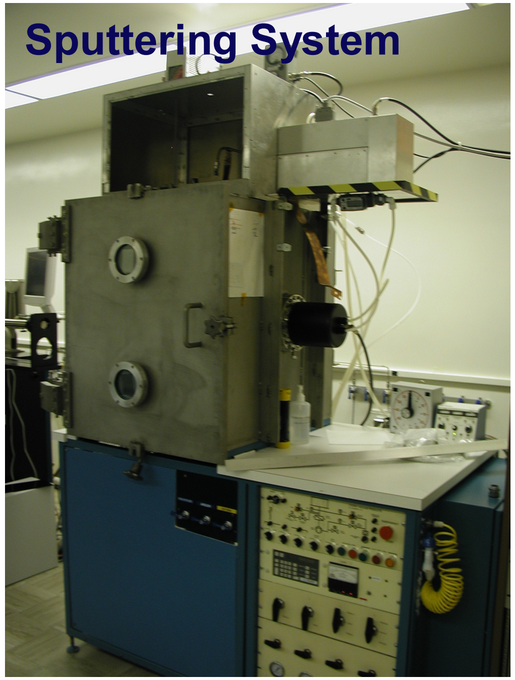
- TaN layered to PdCr strain gauge for the passive elimination of apparent strain sensitivity
- Initial test to 150°C (2006)
  - Gauge Factor: 1.2
  - Resistivity: 146 μΩ-cm
  - TCR: +15 ppm/°C
  - $\varepsilon_a/\Delta T$: +12 με/°C (<20με/°C)
- Follow-up test to 600°C (2007)
  - Output unstable: $\varepsilon_a/\Delta T$: +71 με/°C (>20με/°C)
- Potential Issues
  - Multilayer Delamination / Diffusion
  - Compatible with sacrificial lift-off patterning process (Reactivity)
  - High Temperature Expansion Issues (CTE)
- Other Materials? (AFRL NDE)



Ref.: *"Developing Multilayer Thin Film Strain Sensors With High Thermal Stability," J. D. Wrbanek, et al., 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Sacramento, CA, July 10, 2006. NASA TM-2006-214389.*

AFRL/NASA SAA3-307-A30

- Reactivity restrictions allow:
  - Ta, Cr, Al, Au
  - TiO, ITO, CrSiO, TiB_2
  - TaN, TiN, ZrN
- CTE Issues?
  - TiO, ITO, CrSiO, TiB_2, TiN, ZrN
- Procurements (2006)
  - Targets & Substrates
  - Equipment & Clean Room Support
- Test to Increasing Temperatures
  - 200°C, 700°C, 1300°C +
- TCR, $\varepsilon_a/\Delta T$, Drift Rate
- Other Formulations?

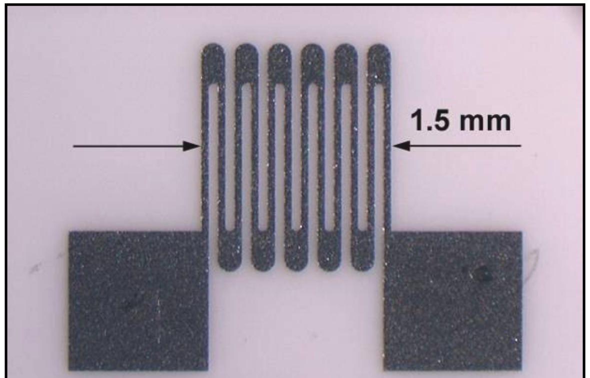


Ref.: *"Thin Film Ceramic Strain Sensor Development for Harsh Environments,"* *J.D. Wrbanek, et al., (December 2006).* *NASA TM-2006-214466*.

Low Temperature Testing

Film	Ar/N/O flow mix	Deposition Time	Thickness	Resistivity	TCR	ΔR_o for 200°C Cycle
Ti	40/0/0	369 min.	2.0 μm	133 μΩ-cm	1360 ppm/°C	4.45%
TiN	38/2/0	1200 min.	2.8 μm	1490 μΩ-cm	624 ppm/°C	114%
TiON	18/1/0.5	360 min.	0.6 μm	62 μΩ-cm	1400 ppm/°C	0.83%
Zr	40/0/0	198 min.	2.0 μm	140 μΩ-cm	1090 ppm/°C	2.73%
ZrN	38/2/0	750 min.	2.4 μm	1090 μΩ-cm	146 ppm/°C	4.26%
ZrON	18/1/0.5	360 min.	1.7 μm	82 μΩ-cm	695 ppm/°C	-1.3%

- All films fabricated using a 3” unbalanced magnetron source at 125W RF
- All films patterned & vacuum annealed at 600°C
- TCR tested using a 4-wire method to 200°C
- N-doping lowered TCR (not enough)
- ON films more stable in air
- Examining Al incorporation, multilayered films



Sample Pattern (detail)

Aircraft Aging & Durability: Novel Thin Film Sensor Technology

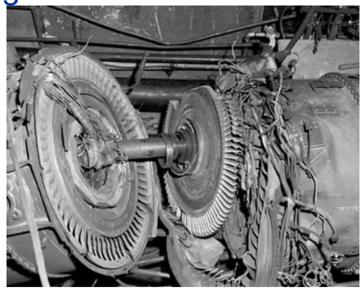
Problem:
- Degradation and damage that develops over time in hot section components can lead to catastrophic failure.
- Poor characterization of degradation processes in harsh environment conditions hinders development of durable hot section components

Demonstrated Need:
- Very difficult to model turbine blade temperatures, strains, heat fluxes; measurements are needed
- The turbine section has been consistently responsible for >$40M/yr in losses to the Air Force

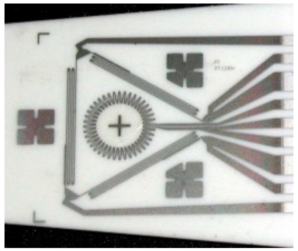
Project Content:
- Develop new sensor and insulation materials capable of withstanding the hot section environment
- Develop techniques for applying sensors onto complex high temperature structures
- Develop thin film sensors to measure temperature, strain, and heat flux during aging studies for hot propulsion materials.

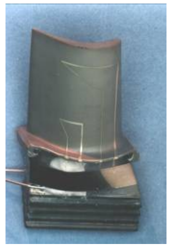
Current SOA:
- Wire thermocouples, strain gauges-disrupt flow, change thermal & mechanical behavior of substrate
- Metal thin films, NiCoCrALY insulation

Catastrophic Turbine Engine Failures



Value Added, Contribution of Research:
- New bulk and nano-structured sensor materials with tailored properties
- Novel thin film harsh environment sensors for high temperature characterizations





On-Component Thin Film Sensors for Harsh Environments

Summary of Ceramics of Interest and Application

Ceramic	Thermocouple	RTD	Strain Gauge	Flow Sensor
TiC	X			
ZrC	X		X	
TaC	X			
$CrSi_2$	X			
$MoSi_2$		X		X
$TaSi_2$	X			
CrN	X			
ZrN		X	X	X
TaN			X	
CrB_2		X		X
ZrB_2			X	
TiB_2			X	

- Film Fabrication and Testing a challenge; Purity large concern

Summary

- For the advanced engines in the future, knowledge of the physical parameters of the engine and components is necessary on the test stand and in flight
- NASA GRC is leveraging expertise in thin films and high temperature materials, investigations for the applications of thin film ceramic sensors
- High output ceramic thermocouples have been demonstrated
- Attempts to improve thermal stability with Tantalum Nitride with an interlayered Palladium-Chromium strain gauge was met with positive results initially, but proved unstable
- Under AFRL/NASA SSA, began examination of other nitrides as possible candidates for ultra-high temperature strain gauges
- Currently examining sputtered films of candidate materials as sensors through NASA's Aircraft Aging & Durability Project

Acknowledgements

- Craig Neslen of the AFRL Nondestructive Evaluation (NDE) Branch for support and discussions related to this work
- Dr. Gary Hunter of the NASA GRC Sensors and Electronics Branch for his participation in discussions and advocacy of this work
- Kimala Laster of Sierra Lobo, Inc. for the ceramic film depositions currently on-going as part of the NASA GRC Test Facilities Operation, Maintenance, and Engineering (TFOME) organization
- NASA GRC Ceramics Branch, CWRU & URI for collaborative support.

Researchers

Gustave C. Fralick

John D. Wrbanek

Physical Sensor Instrumentation Research

Sensors and Electronics Branch

NASA Glenn Research Center

Cleveland, Ohio

Gustave.C.Fralick@nasa.gov

John.D.Wrbanek@nasa.gov

http://www.grc.nasa.gov/WWW/sensors/PhySen/