Smart Sensor Systems for High Temperature Intelligent Engine Applications

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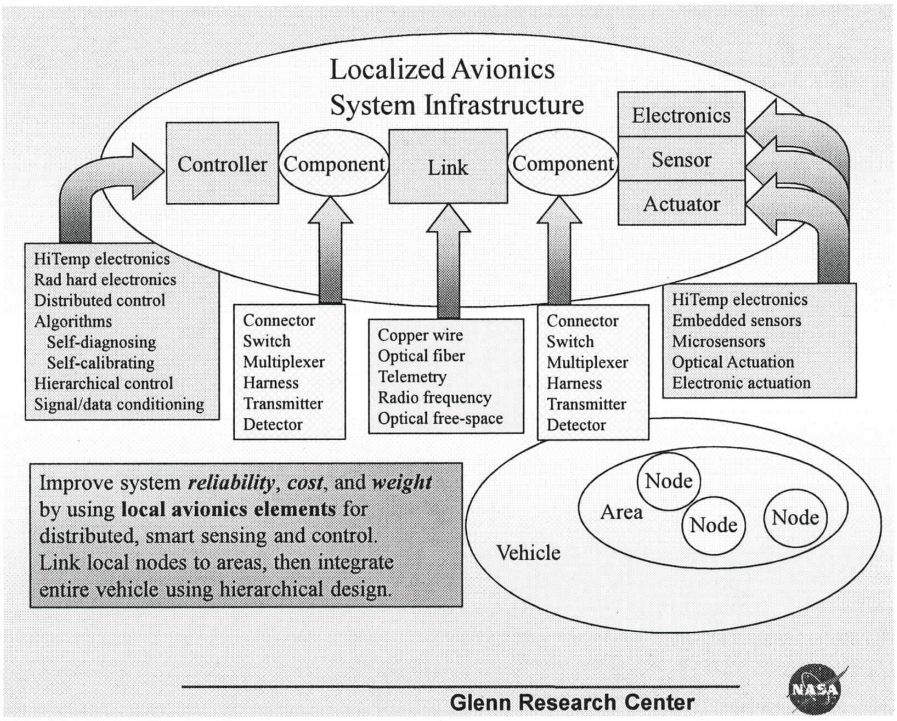
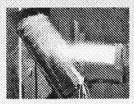
OUTLINE

- INTRODUCTION
- INTELLIGENT SYSTEMS FOR HARSH ENVIRONMENTS
- HIGH TEMPERATURE SENSORS FOR CERAMIC MATERIALS
- SIC SENSORS FOR EMISSIONS MONITORING (CERAMIC SENSOR)
- HIGH TEMPERATURE WIRELESS (CERAMIC SEMICONDUCTOR)
- NANOTECHNOLOGY (CERAMIC OXIDE NANOSTRUCTURES)
- SUMMARY

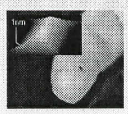


HARSH ENVIRONMENT ELECTRONICS AND SENSORS APPLICATIONS

- NEEDS:
  - ➢ OPERATION IN HARSH ENVIRONMENTS
  - ➢ RANGE OF PHYSICAL AND CHEMICAL MEASUREMENTS
  - ➢ INCREASE DURABILITY, DECREASE THERMAL SHIELDING, IMPROVE IN-SITU OPERATION

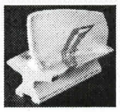


1998 R&D 100 Award



2004 R&D 100 Award

- RESPONSE: UNIQUE RANGE OF HARSH ENVIRONMENT TECHNOLOGY AND CAPABILITIES
  - ➢ STANDARD 500˚C OPERATION BY MULTIPLE SYSTEMS
  - ➢ TEMPERATURE, PRESSURE, CHEMICAL SPECIES, AND WIND AVAILABLE
  - ➢ HIGH TEMPERATURE ELECTRONICS TO MAKE SMART SYSTEMS

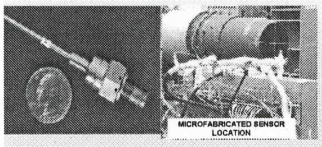


1995 R&D 100 Award

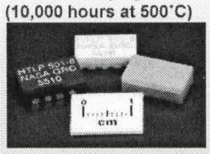
1991 R&D 100 Award

- ALL-IN-ONE SHOP FOR HARSH ENVIRONMENT SYSTEM APPLICATIONS
- ENABLE EXPANDED MISSION PARAMETERS/IN-SITU MEASUREMENTS

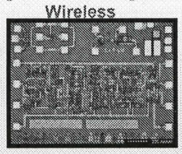
Range of Physical and Chemical Sensors for Harsh Environments



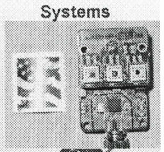
Harsh Environment Packaging (10,000 hours at 500˚C)



High Temperature Signal Processing and Wireless



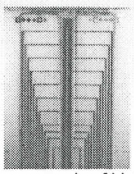
Long Term: High Temperature "Lick and Stick" Systems



Thin Film Physical Sensors for High Temperature Applications

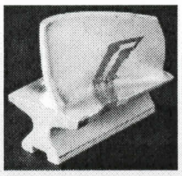
Advantages for temperature, strain, heat flux, flow & pressure measurement:

- 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)

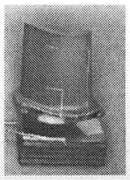


Flow sensor made of high temperature materials

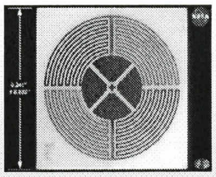
Multifunctional smart sensors being developed



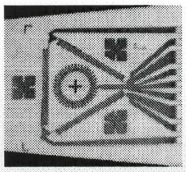
PdCr strain sensor to T=1000°C



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



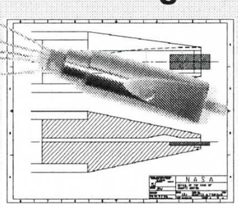
Heat Flux Sensor Array to T=1000°C



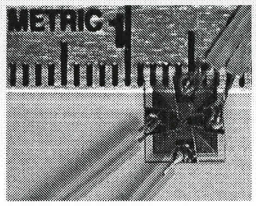
Multifunctional Sensor Array

GRC's Physical Sensor Instrumentation Research Progress

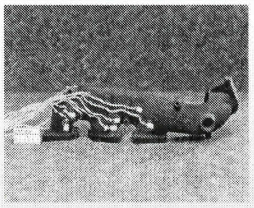
- R&D 100 Awards in 1991, 1995, and 1998
- NASA Group Achievement Award 2003
- NASA Tech Briefs *Create the Future Design Contest* Award 2008
- Partnerships in Sensor Development:



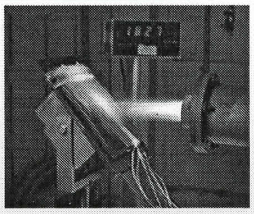
2003 NASA Group Achievement Award
SiC High Temperature Drag Force Transducer as part of the Integrated Instrumentation & Testing Systems project



2008 NASA Tech Briefs Create the Future Design Contest - Machinery & Equipment
Flexible Small Area Heat Flux Sensor developed for Goodyear Tire & Rubber Co.



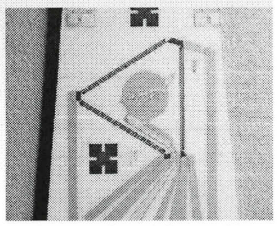
1991 R&D 100 Award
PdCr wire strain gauge applied on Ford Motor Co. exhaust manifold



1998 R&D 100 Award
Long-lived Convoluted Thermocouples For Ceramic Temperature Measurements

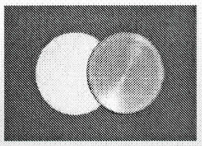
Novel Thin Film Sensor Technology Development

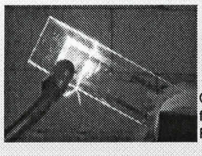
- Development of Thin Film Sensors with Ceramic, Laminate and Nanostructured Materials
  - Improve techniques for applying high temperature sensors onto complex structures
  - Develop thin film sensors to measure temperature, strain, and heat flux for hot section components
- Technology Challenge: Survivability in Extremely High Temperature Environments (>1500°C)
  - Build off of experience fabricating devices on more conventional components
  - Leverage partnerships with University of Rhode Island and NASA GRC Ceramics Branch for ceramic-based materials



Multilayered Ceramic Sensor with Minimal Apparent Strain Sensitivity

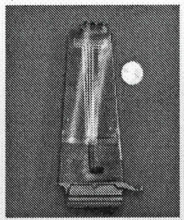
Ceramic TC Sputtering Targets fabricated by the NASA GRC Ceramics Branch



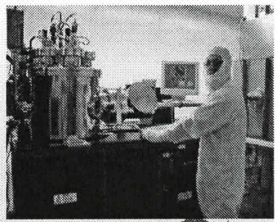


Ceramic Thermocouple fabricated at University of Rhode Island

RTD on Fan Blade

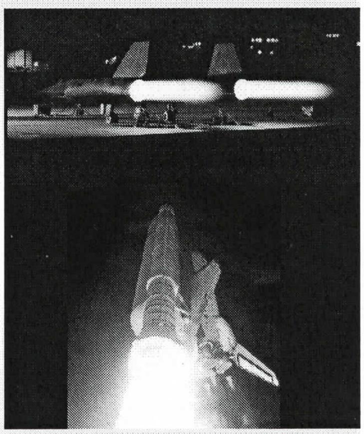


Sputtering System for Thin Film Sensor Fabrication



NASA Fundamental Aeronautics Program's Supersonics Project

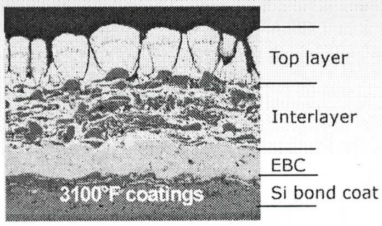
- Weight and temperature barriers for all supersonic vehicles
  - Space vehicles (launch/reentry) to military and commercial transport
  - Eliminate factors that limit efficiency and performance of supersonic vehicles
  - Application to hypersonic regimes as well
- Ceramic Matrix Composite (CMC) components
  - Allows high temperature operation at extended supersonic cruise times
  - Introduces significant weight reduction
  - Successful implementation of these ceramics requires reliable performance data and life prediction models

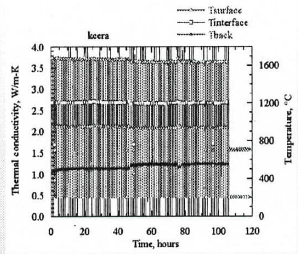


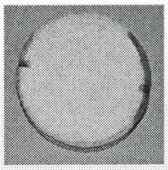
Propulsion system environments pose challenges for instrumentation

1700°C (3100°F) SiC/SiC CMC Turbine Vane Coating System

- **Multilayered coating system** successfully completed total 100, 1 hr cycle laser heat flux 1700°C test (3100°F, 60 min. hot, 3 min. cool)
- In situ measurements as part of the coating system during tests will better characterize the system
  - Currently, conditions on surface measured optically
  - Conditions at interfaces currently interpolated based on bulk thermo-conductivity values
- Technical Challenge: Embedded sensors cannot use flame-sprayed attachment or coatings without modifying characteristics
  - New technology needed
  - Ceramic Thin Film Sensors?



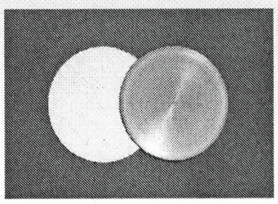




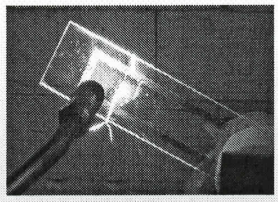
After testing

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 the University of Rhode Island (URI)
  - Nanocomposite films are being developed by URI that show potential as thermocouples



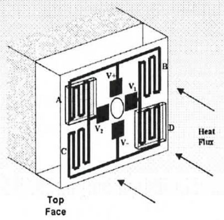
Ceramic TC Sputtering Targets fabricated by the NASA GRC Ceramics Branch



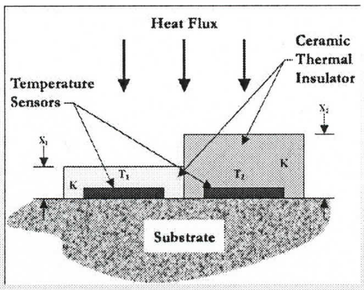
Ceramic TC fabricated at URI

Basic Heat Flux Sensor

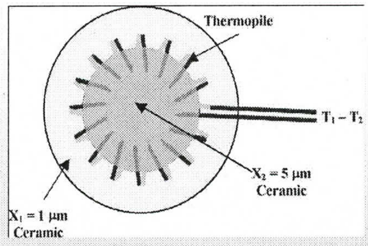
- Operates by measuring the temperature difference across a thermal resistance
- Thin film version compares temperature difference between two thicknesses of thermal insulating films
- Designs based on thin film thermopile, thermocouples and Wheatstone bridge developed at GRC
  - Example: 40-pair thermopile tested in arc-lamp up to 800°C with sensitivity of 1.2 μV/(W/cm²) and a dynamic frequency response of 3 kHz



Wheatstone Bridge Heat Flux Sensor Design



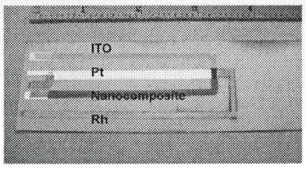
Heat Flux Sensor Operation



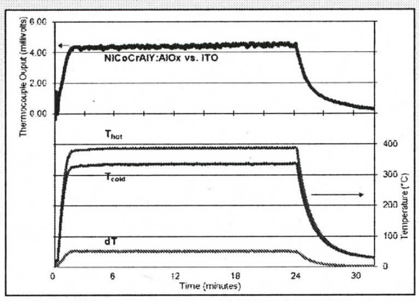
Thermopile Heat Flux Sensor Design

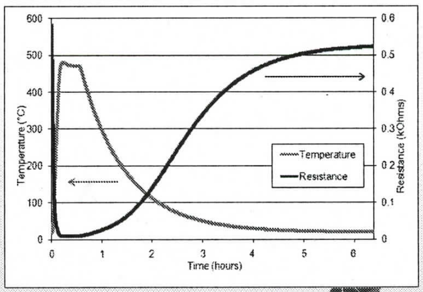
GRC Tests of Nanocomposite Sensors

- Nanocomposite of NiCoCrAlY:AlOx developed from AAD NRA w/ URI
- ITO/Nanocomposite test sample fabricated at GRC



- Tests show the 2 μm thick thermocouple stable in air with a 50 μV/°C sensitivity at 650°C
  - Compare Type R 12 μV/°C
- The nanocomposite resistance is well-behaved with an exponential temperature response
- Primary choice for High Temperature Heat Flux Sensor on CMC
  - Either Thermopile or RTD

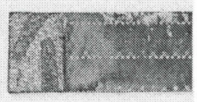




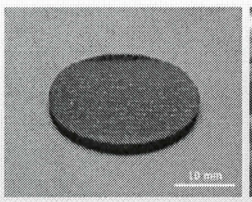
EBC-CMC Surface Challenges

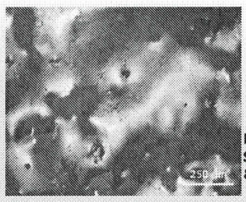
- Past Sensors on CMC <u>without</u> EBC
  - Wire Sensors flame-spray attachment >1000°C
  - Shadow masked Thermocouples >1000°C
  - Fine-line patterned sensors on AlOx flame-coated CMC >1000°C
- Test articles are <u>rough approximations</u> of final components (part of a long-term development program)
  - CMC is naturally rough (~ 100 μm)
  - EBC is naturally porous (~10%)
- Challenge is to pattern fine-lined sensors required for heat flux measurements using existing EBC-CMC materials <u>without</u> thick AlOx coatings
  - Smooth (~10 μm) α-SiC is typically used in EBC concept tests

Wire Sensors flame-spray attachment on CMC

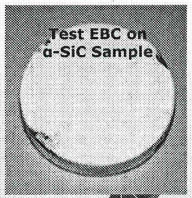


Fine-line sensors on AlOx-coated CMC





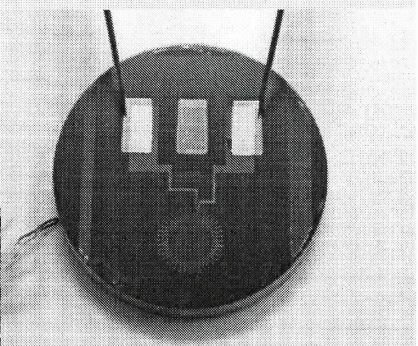
EBC-CMC: Sample (far left) & surface (left)



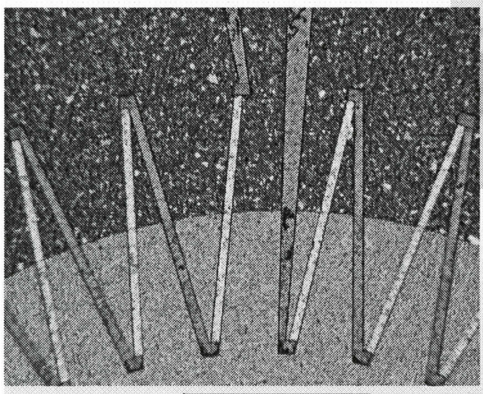
Test EBC on α-SiC Sample

ITO-Based Heat Flux Sensor #2

- Fine-lined 50-μm thermopile using Al:ZnO vs. ITO on 1" disk of α-SiC
  - ITO deposited at GRC
  - Al:ZnO deposited at URI
  - Mullite used as insulation



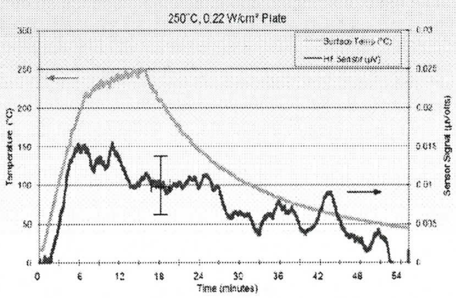
Thin Film Heat Flux Sensor on α-SiC (Films are transparent; detail left)

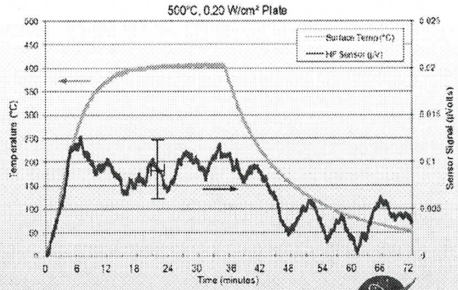


- Sensor survived fabrication
- Response tested on two heat sources with similar heat flux but different temperatures
  - 0.22 W/cm^2, 250°C maximum
  - 0.20 W/cm^2, 500°C maximum

Preliminary Results

- Sensor response was very small, but noticeable
- Signals were smoothed using a moving average over 170 seconds
  - Gives minimum variation of smooth signal with original data
- The result shows a sensitivity of 0.06 ± 0.02 μV/(W/cm²)
  - First thin film heat flux sensor pattern deposited and operated on such a surface.
  - Future sensors to increase sensor insulation to increase signal
- Future Work: Towards application on EBC-CMC
  - New, more novel materials?
  - Embedded in EBC?





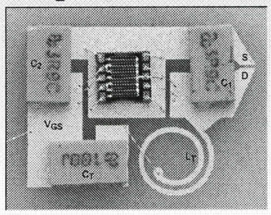
High Temperature Wireless Development

OBJECTIVES:
- **HIGH TEMPERATURE WIRELESS TELEMETRY, DISTRIBUTED ELECTRONICS OVER A BROAD OPERATING RANGE**

TECHNICAL CHALLENGES:
- **DEVELOPMENT OF RELIABLE HIGH TEMPERATURE TELEMETRY ELECTRONICS, POWER SOURCES, REMOTE COMMUNICATION ELECTRONICS, AND PACKAGING**

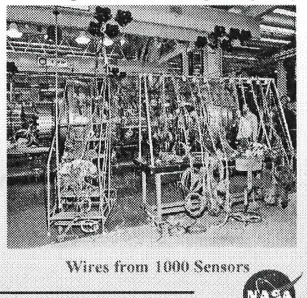
GOALS SUPPORTED:
- **ENHANCE PERFORMANCE**
- **SIGNIFICANTLY REDUCE COST**

PROVIDE DATA TRANSFER IN HARSH ENVIRONMENTS IMPROVING RELIABILITY AND ENABLING NEW CAPABILITIES



Prototype Oscillator Circuit

Example: Gas Turbine Engine Development Requires Extensive Instrumentation Yielding Extensive Wiring Complexity



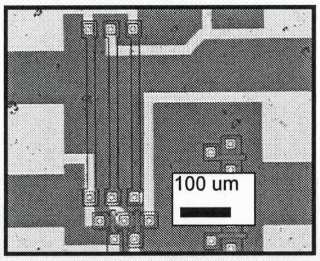
Wires from 1000 Sensors

NASA Glenn Silicon Carbide Differential Amplifier

World's First Semiconductor IC to Surpass
4000 Hours of Electrical Operation at 500 °C

Demonstrates CRITICAL ability to <u>interconnect transistors</u> and other components (resistors) in a small area on a single SiC chip to form useful integrated circuits that are durable at 500 °C.

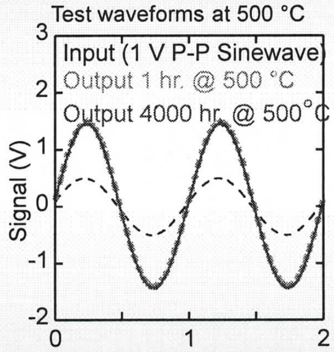
Optical micrograph of demonstration amplifier circuit before packaging



2 transistors and 3 resistors integrated into less than half a square millimeter.

Single-metal level interconnect.

Test waveforms at 500 °C



Less than 5% change in operating characteristics during 4000 hours of 500 °C operation.

INTERMEDIATE MILESTONE

- **BREADBOARD DEMONSTRATION OF POWER SCAVENGING AT 300°C WITH 3V VOLTAGE, PRESSURE SENSOR AT 300°C, AND A WIRELESS CIRCUIT WITH RF COMMUNICATION AT 300°C OVER 1M DISTANCE. (FY09Q4)**
- **PREPARE FOR 500°C BY MAKING A SYSTEM WORK AT 300°C. THIS MILESTONE IS A TRIAL AND PROVING GROUND FOR:**
  - **SYSTEM APPROACHES AND INTEGRATION NEEDED FOR 500° C OPERATION**
  - **CHARACTERIZATION AND BENCHMARKING OF OPERATIONAL SENSOR SYSTEMS OPERABLE AT 300°C**
  - **IDENTIFY TECHNOLOGY CONCENTRATION AREAS WHICH WILL BE NEEDED FOR 500°C OPERATION**
- **OVERALL APPROACH IS TO USE EXISTING TECHNOLOGIES AT 300°C IF VIABLE**
  - **DEVELOP WHAT IS NEEDED FOR THE MILESTONE/LEVERAGE THE REST**
- **MILESTONE BRINGS TOGETHER MULTIPLE FIELDS OF EXPERTISE IN HIGH TEMPERATURE TECHNOLOGY**
- **NECESSARY COMPONENTS FOR MILESTONE DEMONSTRATION**
  - **PRESSURE SENSOR (COMMERCIAL SILICON BASED SENSOR)**
  - **POWER SUPPLY (COMMERCIAL POWER SCAVENGING MODULE)**
  - **SIC CIRCUITY (COMMERCIAL MESFET CIRCUIT)**
  - **WIRELESS CIRCUIT**
  - **SYSTEM INTEGRATION**
  - **TESTING SYSTEM**

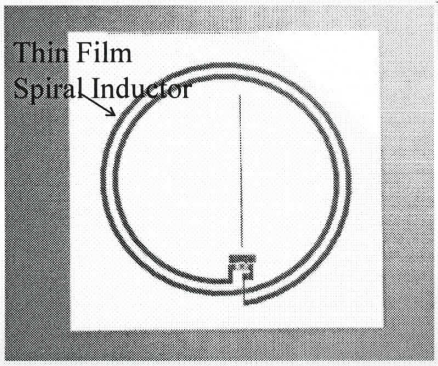
WIRELESS CIRCUIT

- PREVIOUS WORK AND CIRCUIT DESIGNS ARE INSUFFICIENT TO MEET THIS MILESTONE/TARGETED SYSTEM DEVELOPMENT NECESSARY
- SIGNIFICANT ADVANCEMENTS MADE
  - DEVELOPED AND CHARACTERIZED THIN FILM COMPONENTS (MIM CAPACITORS AND THIN FILM SPIRAL INDUCTORS) TO 400°C
  - DEVELOPED AND CHARACTERIZED PLANAR ANTENNAS TO 400°C
  - **DEVELOPED AND CHARACTERIZED OSCILLATORS OPERATING AT 30, 100, 800, AND 1000 MHZ**
    - **OPERATED 800 AND 1000 MHZ OSCILLATORS TO 270°C**
    - OPERATED 30 AND 100 MHZ OSCILLATORS TO 470°C
  - DEVELOPED AND CHARACTERIZED TRANSMISSION LINES ON BOTH SAPPHIRE AND ALUMINA SUBSTRATES TO 400°C
  - DESIGNED MINIATURE ANTENNAS UTILIZING CAPACITIVE LOADING TECHNIQUES ON FOLDED SLOT ANTENNAS TO REDUCE OVERALL SIZE OF THE WIRELESS PRESSURE SENSOR.
  - DEVELOPED THIN FILM PECVD SIC PACKAGING TECHNOLOGY FOR HIGH TEMPERATURE ELECTRONICS AND HARSH ENVIRONMENTS

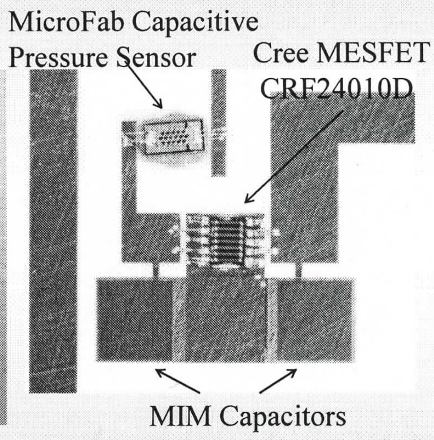
IT SHOULD BE NOTED THAT EACH OF THESE ARE CONSIDERED WORLD FIRSTS. NOTABLE SYSTEM INTEGRATION USING THIN FILM APPROACHES

ACTIVITIES IN RED CONSIDERED PARTICULARLY SIGNIFICANT AND FOUNDATIONAL FOR 500° C OPERATION

WIRELESS CIRCUIT



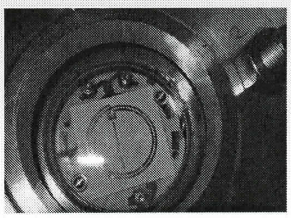
100 MHz Wireless Pressure Sensor System



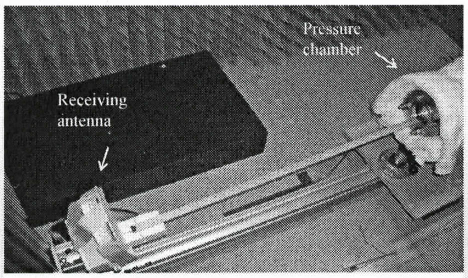
Close up of MESFET, capacitive pressure sensor, and MIM capacitors from adjacent photo.

SYSTEM INTEGRATION AND TESTING

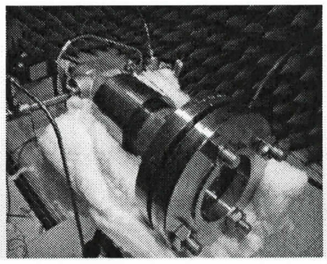
- DESIGNED HIGH TEMPERATURE PRESSURE VESSEL WHICH ALLOWED WIRELESS SENSOR TO TRANSMIT OVER A 1 METER DISTANCE TO RECEIVING ANTENNA WHILE UNDER VARIOUS PRESSURES AND TEMPERATURE RANGES FROM 25°C TO 300°C.



Circuit installed inside chamber

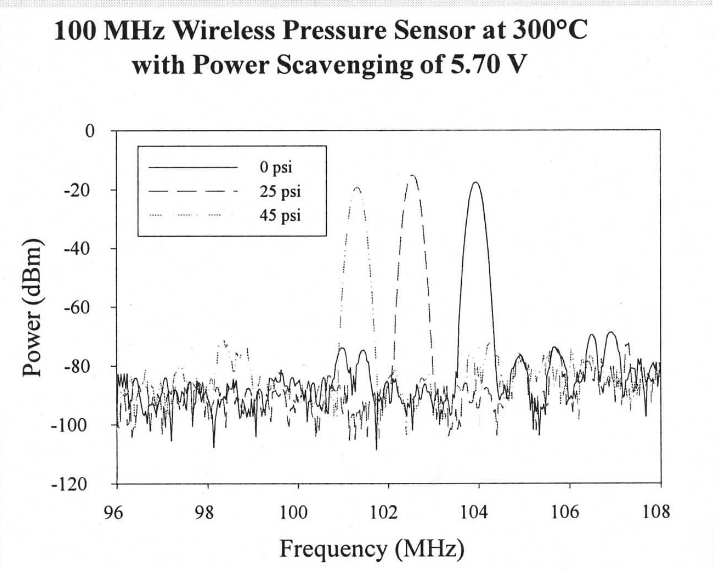


High temperature/pressure measurement system.



High temperature/pressure test vessel

TESTING RESULTS



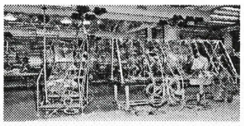
OBJECTIVE : TO MOVE TOWARD HIGHER DEGREES OF COMPLEXITY ALLOWING WIRELESS TRANSMISSION AND HARSH ENVIRONMENT SMART SENSOR SYSTEMS

Overall Approach:
Smart Systems in High Temperature Environments

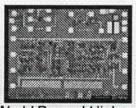
Milestone: **Demonstrate High Temperature Sensing, Wireless Communication, and Power Scavenging for Propulsion Health Management 8/30/2011**

Metric: **Demonstrate integrated self powered wireless sensor system at 500°C with data transmission with operational life of at least 1 hr**

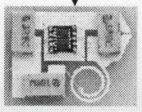
Significant wiring exists with present sensor systems



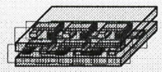
Allow Sensor Implementation by Eliminating Wires



World Record High Temperature Electronics Device Operation



High Temperature RF Components



Energy Harvesting Thin Film Thermoelectrics

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SUMMARY

- AEROSPACE APPLICATIONS REQUIRE A RANGE OF SENSING TECHNOLOGIES
- A RANGE OF SENSOR AND SENSOR SYSTEM TECHNOLOGIES BEING DEVELOPED USING MICROFABRICATION AND MICROMACHINING TECHNOLOGY TO FORM SMART SENSOR SYSTEMS AND INTELLIGENT CHEMICAL MICROSYSTEMS
- DRIVE SYSTEM INTELLIGENCE TO THE LOCAL (SENSOR) LEVEL
  - ➢DISTRIBUTED SMART SENSOR SYSTEMS
- SENSOR AND SENSOR SYSTEM DEVELOPMENT RELATED TO CERAMICS
  - ➢HIGH TEMPERATURE SENSORS FOR CERAMIC MATERIALS
    - THE 1700°C EBC-CMC SYSTEMS UNDER DEVELOPMENT REQUIRE INTEGRATED SENSORS TO ALLOW A MORE COMPLETE CHARACTERIZATION
    - HEAT FLUX SENSORS WERE FABRICATED WITH NANOCOMPOSITES
    - BEST RESULTS FROM PRELIMINARY DATA WAS A RESPONSE OF 0.06 ± 0.02 $\mu V/(W/CM^2)$ WAS MEASURED
  - ➢ SIC SENSORS FOR EMISSIONS MONITORING (CERAMIC SENSOR)
    - HIGH SENSITIVITY GAS SENSORS BASED ON SiC SCHOTTKY DIODES
    - INTERACE CONTROL FUNDAMENTAL TO OPERATION
    - HIGH TEMPERATURE ELECTRONIC NOSE APPROACH BEING TESTED
  - ➢ HIGH TEMPERATURE WIRELESS (CERAMIC SEMICONDUCTOR)
    - WORLD LEADING WORK IN HIGH TEMPERATURE ELECTRONICS
    - INTEGRATION INTO A HIGH TEMPERATURE WIRELESS SYSTEM
    - WIRELESS TRANSMISSION AT 300˚C DEMONSTRATED
  - ➢ NANOTECHNOLOGY (CERAMIC OXIDE NANOSTRUCTURES)
    - SIGNIFICANT PROMISE BUT TECHNOLOGY BARRIERS EXIST
    - EMPHASIS ON CREATING OPERATIONAL MICROSENSORS

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