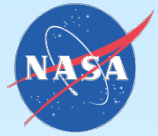
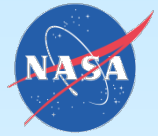


SUMMARY

- 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 MICROSYSTEMS
- DRIVE SYSTEM INTELLIGENCE TO THE LOCAL (SENSOR) LEVEL
  - DISTRIBUTED SMART SENSOR SYSTEMS
- FACILITIES FOR MICROFABRICATED SENSOR AND ELECTRONICS FABRICATION AND CHARACTERIZATION
- SENSOR AND SENSOR SYSTEM DEVELOPMENT EXAMPLES
  - THIN-FILM PHYSICAL SENSORS
  - HIGH TEMPERATURE ELECTRONICS AND WIRELESS
  - “LICK AND STICK” TECHNOLOGY
- NASA GRC IS A WORLD LEADER IN AEROSPACE SENSOR TECHNOLOGY WITH A BROAD RANGE OF DEVELOPMENT AND APPLICATION EXPERIENCE
- CORE MICROSYSTEMS TECHNOLOGY APPLICABLE TO A RANGE OF APPLICATION ENVIRONMENTS



A BRIEF OVERVIEW OF NASA GLENN RESEARCH CENTER SENSOR AND ELECTRONICS ACTIVITIES

Gary W. Hunter, Ph.D.
Intelligent Systems Hardware Lead
Sensors And Electronics Branch
NASA Glenn Research Center
Cleveland, OH

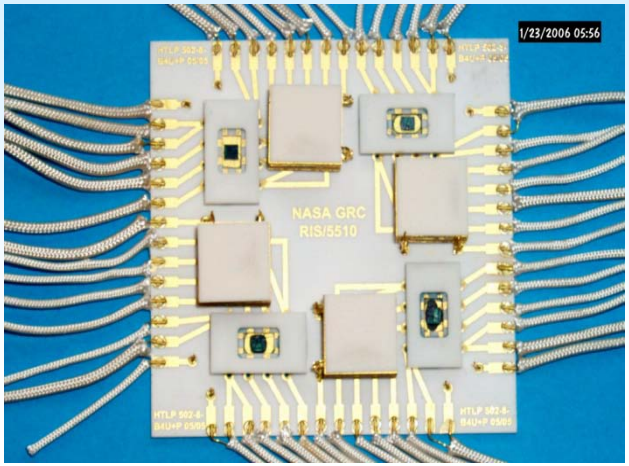
OUTLINE

- INTRODUCTION
- SMART MICROSENSOR TECHNOLOGY
- “LICK AND STICK” TECHNOLOGY
- PHYSICAL SENSORS
- HIGH TEMPERATURE WIRELESS
- SUMMARY

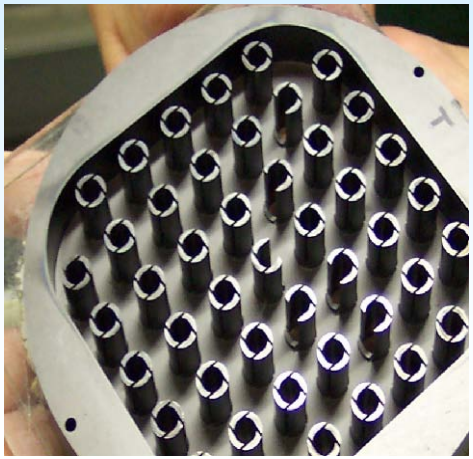
FUNDAMENTAL POINT:

A RANGE OF CORE CAPABILITIES EXIST WHICH CAN BE APPLIED TO A VARIETY OF APPLICATIONS

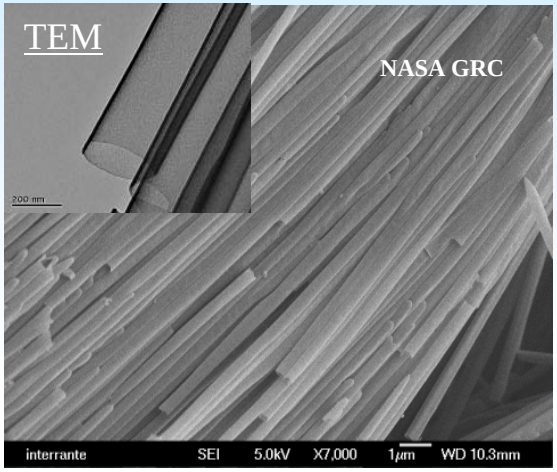
Sensors and Electronics Branch:
Scope of Work



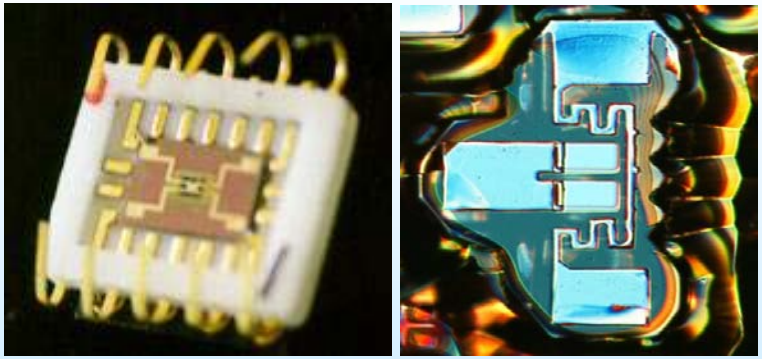
High Temperature SiC Electronics



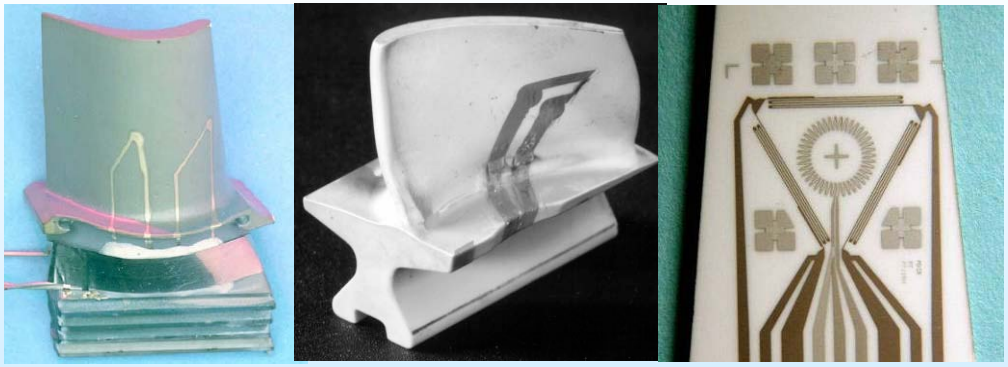
Micro-Electro-Mechanical Systems (MEMS)



Nanotechnology SiC Nanotubes



Chemical Sensors

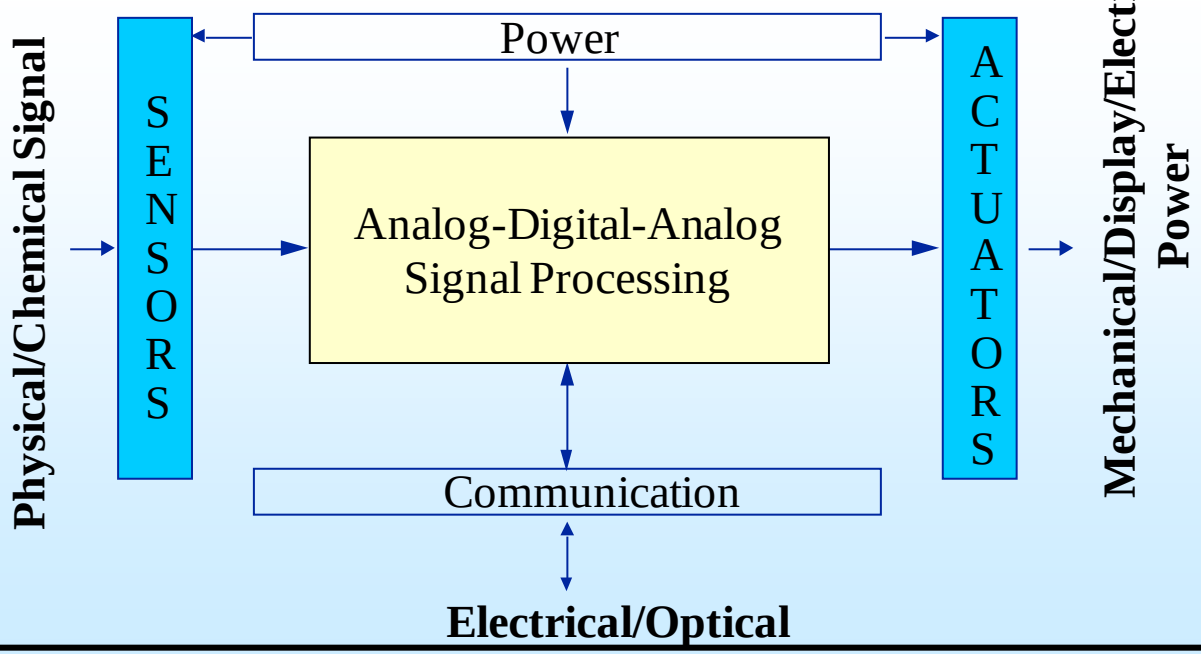


Thin Film Sensors

MICROSYSTEMS TECHNOLOGY

- A RANGE OF SENSOR SYSTEMS ARE UNDER DEVELOPMENT BASED ON MICROFABRICATION TECHNIQUES AND SMART SENSOR TECHNOLOGY
- MICROSYSTEMS APPROACH: STAND-ALONE, COMPLETE SYSTEMS INCLUDING SENSORS, POWER, COMMUNICATION, SIGNAL PROCESSING, AND ACTUATION
- ENABLE SYSTEM LEVEL INTELLIGENCE BY DRIVING CAPABILITIES TO THE LOCAL LEVEL USING DISTRIBUTED SMART SYSTEMS
- BROAD RANGE OF APPLICATIONS
- MICROSYSTEMS TECHNOLOGY MOVING TOWARDS A RANGE OF APPLICATIONS

Microsystem Block Diagram



BASE PLATFORM CHEMICAL SENSOR TECHNOLOGY

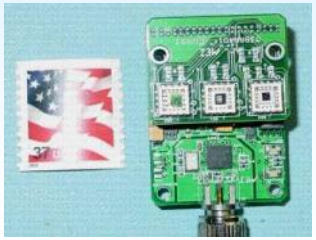
Integration of Micro Sensor Combinations into Small, Rugged Sensor Suites

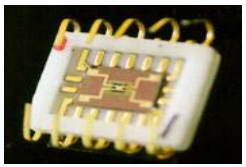
Example Applications: AEROSPACE VEHICLE FIRE, FUEL LEAKS, EMISSIONS, ENVIRONMENTAL MONITORING CREW HEALTH, SECURITY

Multi Species Fire Sensors for Aircraft Cargo Bays and Space Applications

Environmental Monitoring

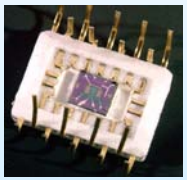
"Lick and Stick" Space Launch Vehicle Leak Sensors with Power and Telemetry



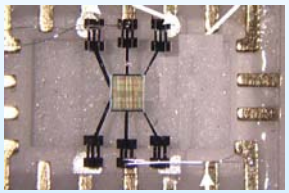


Oxygen Sensor

SiC Hydrocarbon Sensor

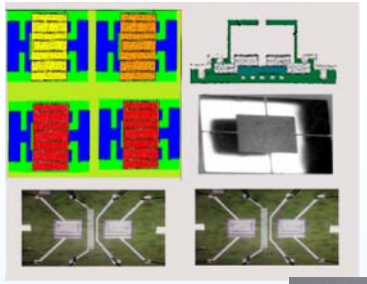


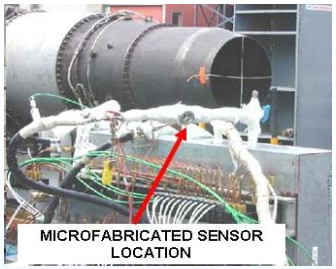
H2 Sensor



Nanocrystalline Tin Oxide NOx and CO Sensor

Aircraft Propulsion Exhaust High Temperature Electronic Nose



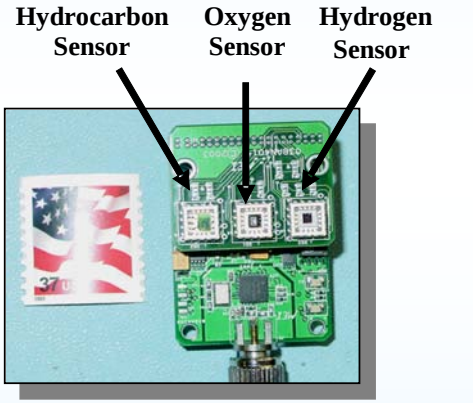


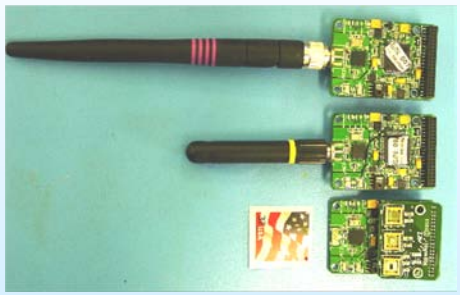
Breath Sensor System for Human Health Applications

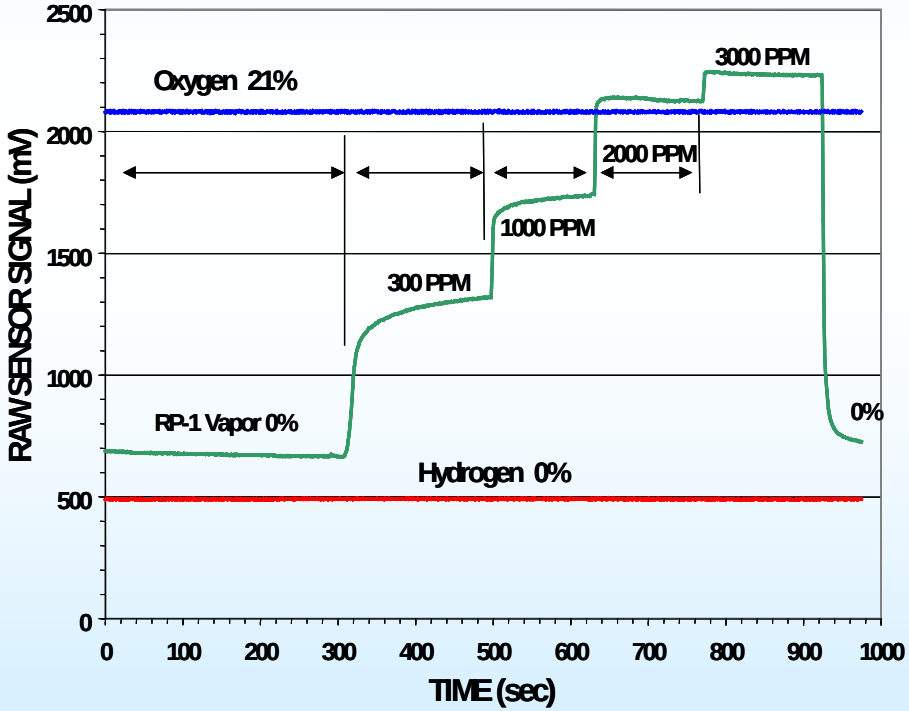
Hydrazine EVA Sensors (ppb Level Detection)

"LICK AND STICK" SENSOR SYSTEM

- SENSORS, POWER, AND TELEMETRY SELF-CONTAINED IN A SYSTEM NEAR THE SURFACE AREA OF A POSTAGE STAMP
- MICROPROCESSOR INCLUDED/SMART SENSOR SYSTEM
- ADAPTABLE CORE SYSTEM WHICH CAN BE USED IN A RANGE OF APPLICATIONS
- BUILT-IN SELF CHECK, INTERNAL DATA TABLES
- MULTIPLE CONFIGURATIONS AVAILABLE
- HYDROGEN, OXYGEN, AND HYDROCARBON DETECTION AVAILABLE

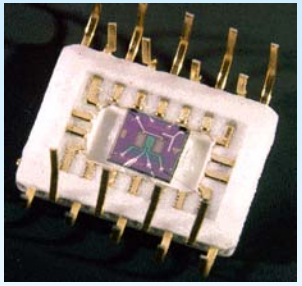






BASIC APPROACH: MEET THE NEEDS OF MULTIPLE APPLICATIONS BUILDING FROM A CORE SET OF SMART MICROSENSOR TECHNOLOGY

HYDROGEN LEAK SENSOR TECHNOLOGY



MEMS-Based Hydrogen Sensor

- MEMS-BASED WIDE RANGE HYDROGEN SENSOR CO-DEVELOPED BY NASA GRC
- COMMERCIALIZED AS PART OF AN STTR PROGRAM WITH A RANGE OF APPLICATIONS
- STATUS: OPERATIONAL SYSTEM ON ISS/AVAILABLE FOR CREW LAUNCH VEHICLE IMPLEMENTATION

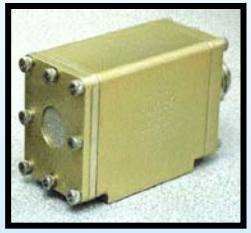
Automated Hydrogen Leak Detection On Natural Gas Powered Crown Victoria Assembly Line

1995 R&D 100 AWARD WINNER

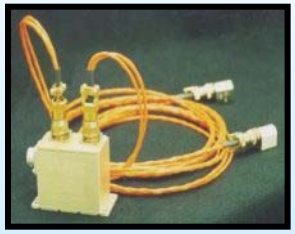
NASA 2003 TURNING GOALS INTO REALITY SAFETY AWARD

Shuttle X33 X43 Helios ISS

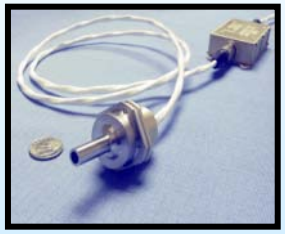
Aft Compartment Hydrogen Monitoring



Hydrogen Safety Monitoring



Hydrogen Safety Monitoring



Fuel Cell Safety and Process Monitoring

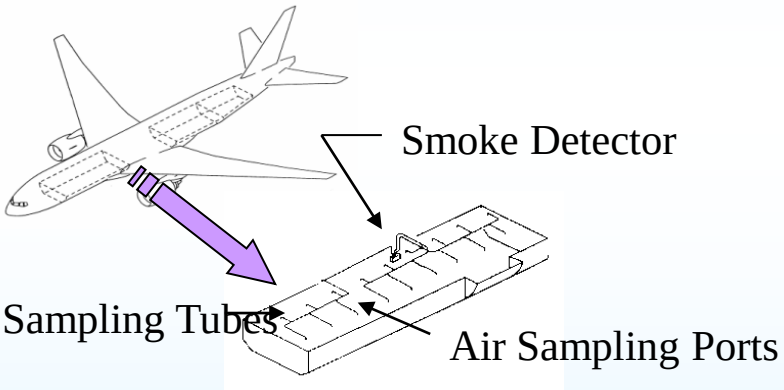
Life Support Process and Safety Monitoring

LOW FALSE ALARM FIRE DETECTION SYSTEM

2005 R&D 100 AWARD WINNER

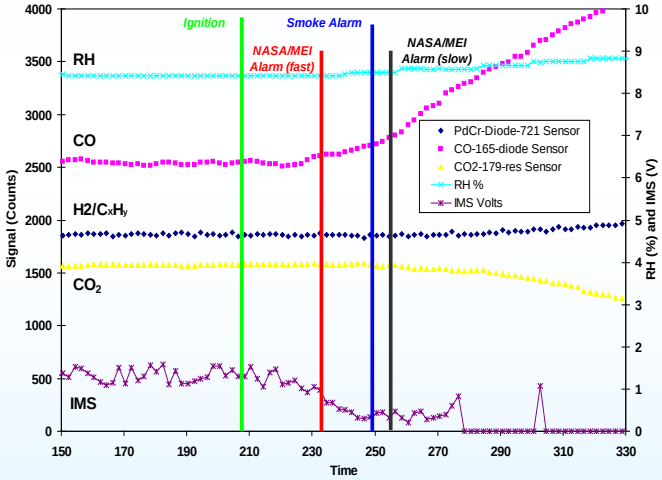
NASA 2005 TURNING GOALS INTO REALITY AA's CHOICE AWARD

- **OBJECTIVE: DECREASE FALSE ALARM RATE IN AIRCRAFT CARGO BAYS (AS HIGH AS 200:1)**
- **CHEMICAL GAS SENSORS PROVIDE GASEOUS PRODUCT-OF-COMBUSTION INFORMATION TO COMPLEMENT EXISTING FIRE DETECTION SYSTEMS**
- **FAA TESTING: CONSISTENT DETECTION OF FIRES/NO FALSE ALARMS**
- **FUNDAMENTALLY CHANGE APPROACH TO FIRE DETECTION: TRANSITIONING TOWARD SPACE APPLICATIONS**



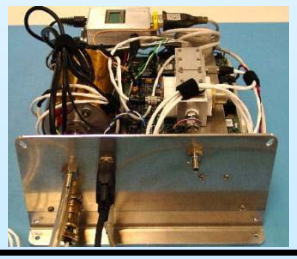
Current B757 Cargo Compartment Smoke Detection: High False Alarm Rate

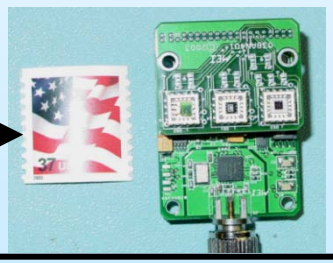
FAA Cargo Bay Fire Simulation Aircraft



FAA Cargo Bay Fire Test Data: No False Alarms

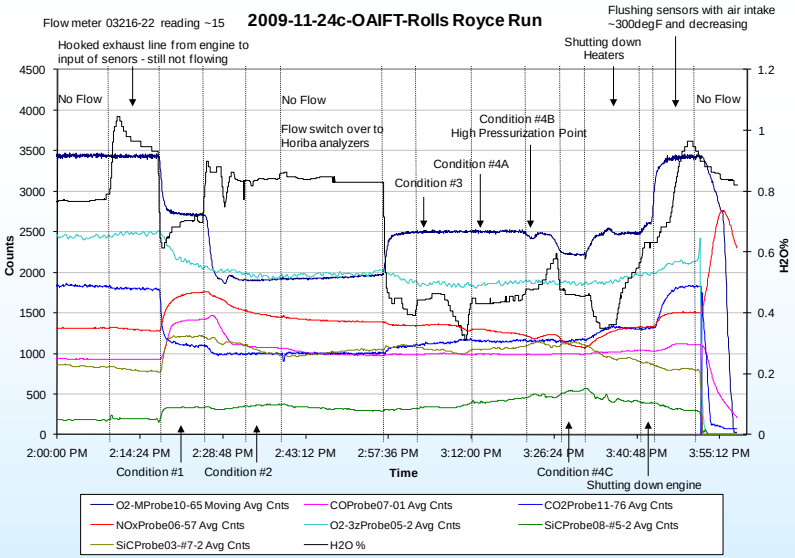
Transition Aeronautics Hardware Into Core "Lick And Stick" Spaceflight Hardware Platform





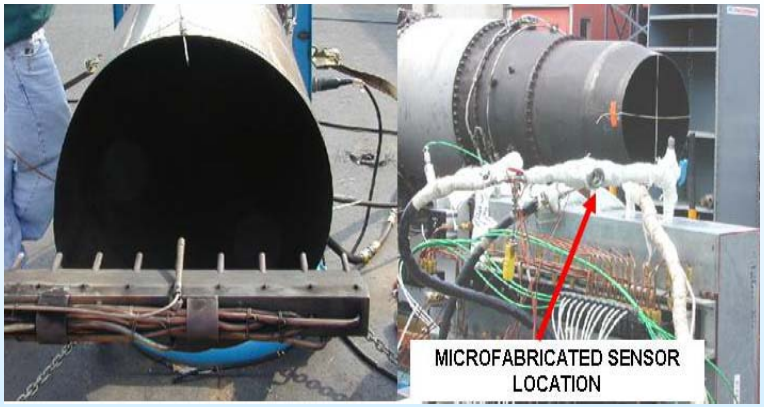
HIGH TEMPERATURE GAS SENSOR ARRAY
HIGH TEMPERATURE ELECTRONIC NOSE

- **PLACEMENT OF SENSORS SIGNIFICANTLY CLOSER TO THE ENGINE OUTLET THAN TRADITIONAL EQUIPMENT ALLOW REPLACEMENT OF INSTRUMENT RACKS**
- **NAVY FUNDED PROJECT WITH INDUSTRY:**
  - **SENSOR ARRAY DEVELOPED FOR THIS APPLICATION: CO, CO2, OXYGEN, HYDROGEN, HYDROCARBONS, AND NOx**
  - **NEW PRODUCT LINE AVAILBLE FOR CO, CO2 AND O2 FOR TESTSTAND MEASUREMENTS WITH QUANTATIVE MEASUREMENTS**
- **INCLUCES PATENTED SIC GAS SENSOR WHICH WAS NOMINATED FOR 2009 INVENTION OF THE YEAR**



Sensor Array Engine Data At Rolls-Royce

Packaged Sensor



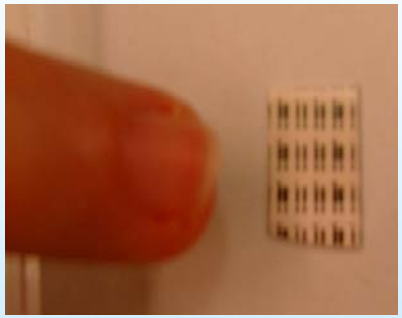
Rake Sampling System At The Outlet Of The JT-12 Jet Engine.

Smart Sensor Systems For Human Health Breath Monitoring Applications

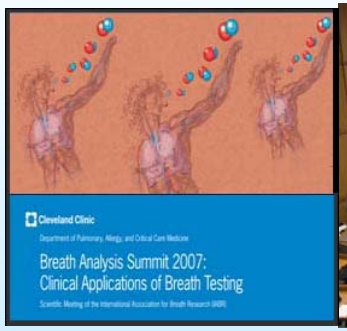
Approach: Use Array of Micro Sensors Combine with Smart Hardware to Monitor Breath For Exercise And Health

- **Biomarkers For The Diagnosis Of Disease Are Present In The Breath**
  - **Correlation Between Chemical Species in Breath and Range of Health Conditions**
- **Medical, Academia, Industry and Government Team Developing Smart Sensor Systems to Diagnose Human Health by Monitoring Breath**
  - **NASA and Collaborators: World Leaders in Chemical MicroSensor Technology**
  - **Cleveland Clinic Foundation: World Leader In Exercise/Breath Monitoring Research**
- **State Of Ohio Third Frontier Program: Produce Commercial Breath Monitoring Product For Asthma Detection**
  - **Target Home Use as Well as Clinical Applications with a Hand-Held Unit**
- **Core Technology Adaptable to a Range of Applications**
  - **Correlation between Chemical Species and Human Health/Environmental Factors**

Breath Sensor System



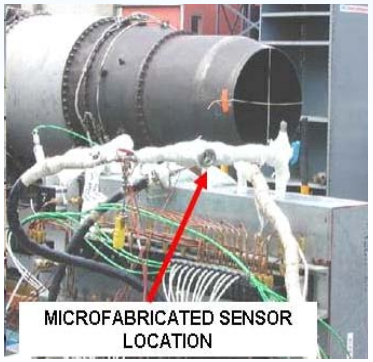
12 Sensor Array for Asthma Monitoring



International Breath Analysis Summit

A WIDE RANGE OF SYSTEM DEMONSTRATIONS AND APPLICATIONS
"LICK AND STICK" CORE HARDWARE

Jet Engines Emissions



Aircraft Fire Detection

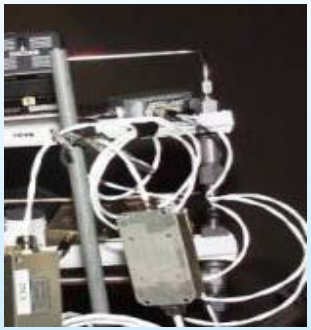
Breath Monitoring

NASA Helios Fuel Cells

International Space Station Safety System

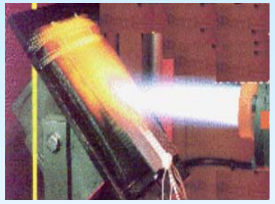
Rocket Engine Teststands

Environmental Monitoring

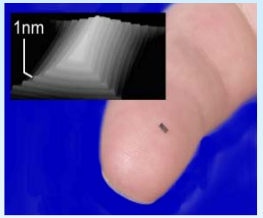


HARSH ENVIRONMENT ELECTRONICS AND SENSORS APPLICATIONS

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

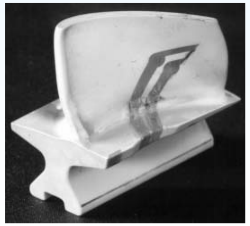


1998 R&D 100 Award



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, WIND FLOW AVAILABLE**
  - **HIGH TEMPERATURE ELECTRONICS TO MAKE SMART SYSTEMS**

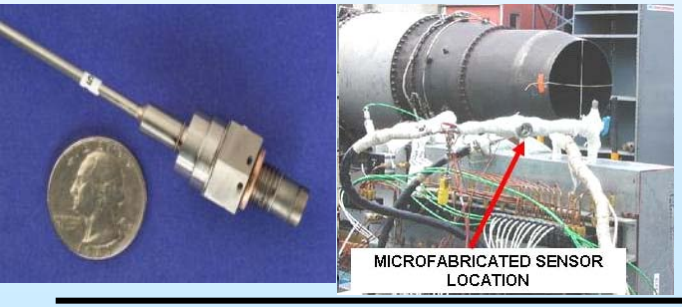


1995 R&D 100 Award

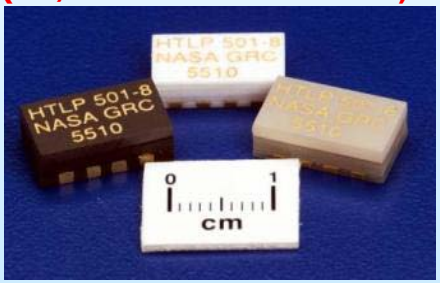
1991 R&D 100 Award

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

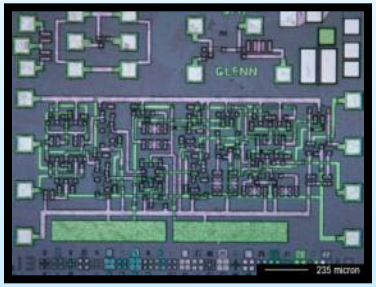
Range of Physical and Chemical Sensors for Harsh Environments



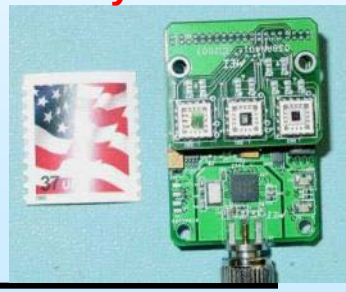
Harsh Environment Packaging (10,000 hours at 500˚C)



High Temperature Signal Processing and Wireless

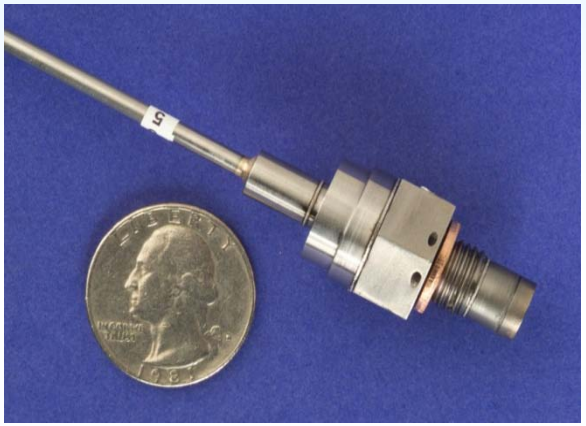


Long Term: High Temperature "Lick and Stick" Systems



•SiC-BASED PRESSURE SENSORS

- SiC HAS EXCELLENT MECHANICAL PROPERTIES FOR USE AS A HARSH ENVIRONMENT PRESSURE SENSOR (T > 500 °C, SILICON UNDERGOES PLASTIC DEFORMATION)
- FORM DIAPHRAM OF SiC AND INTEGRATE WITH ELECTRONICS
- WIDE RANGE OF APPLICATIONS
  - ➢ AERONAUTIC ENGINE APPLICATIONS
  - ➢ AUTOMOTIVE APPLICATIONS
  - ➢ MATERIAL PROCESSING
- ENGINE OPERATION DEMONSTRATED AT 500 C
- CAN BE INTEGRATED WITH FLOW VELOCITY AND TEMPERATURE

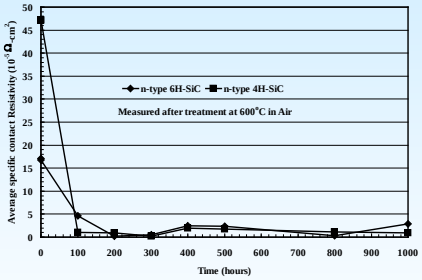


500 °C SiC pressure sensor

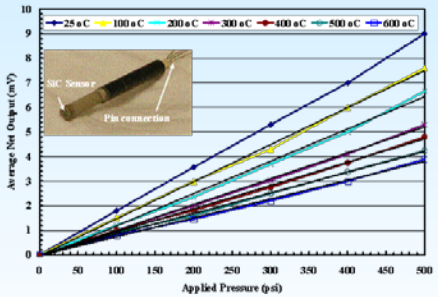
SiC High Operating Temp. Probe (HOTProbe): SiC chip to simultaneously measure flow velocity, pressure, and temperature;

Real World Application: Pressure Sensor Installed in Engine Test

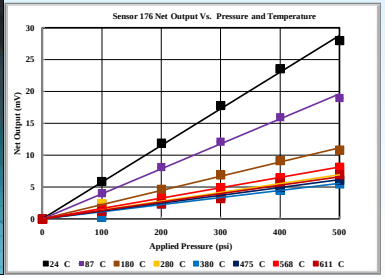
High Temperature (600 °C) SiC Pressure Sensor Development



Thermally stable ohmic contact to n-type SiC durable at 600 °C in air for over 1000 hours.



2nd generation manufacturable MEMS-DCA SiC pressure transducer. Patent application filed.



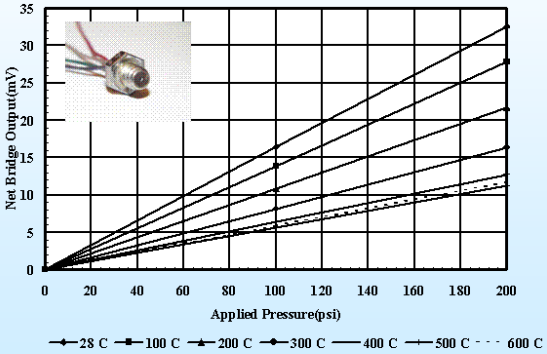
Technology Transfer

1999 (TRL-1) — **2000** — **2002 (TRL-3)** — **2007 (TRL-4)**

2001 (TRL-2) — **2005** — **2010 (TRL-5)**

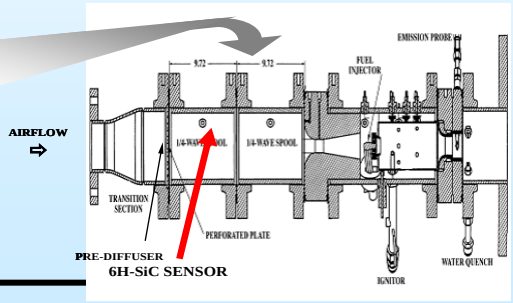
High Temperature Pressure Concept Funded by GMI. (Spring 99)

1st generation MEMS-DCA SiC pressure transducer demonstrated.



MEMS-DCA Pressure transducer patent 6,845,664 awarded. Licensing agreements in process.

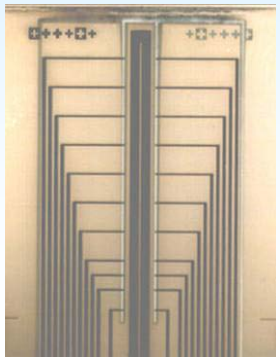
Field Application



Thin Film Physical Sensors for High Temperature Applications

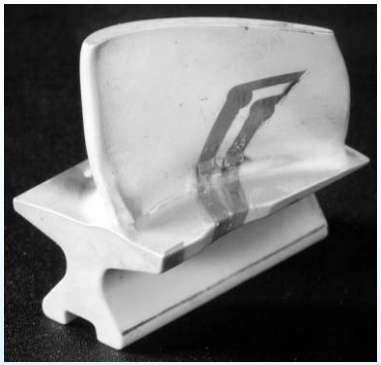
Advantages for temperature, strain, heat flux, flow & pressure measurement:

- 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)



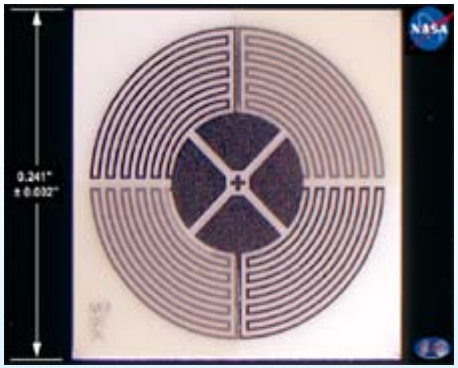
Flow sensor made of high temperature materials

Multifunctional smart sensors being developed

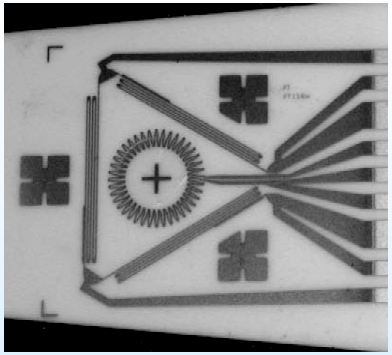


PdCr strain sensor to T=1000°C

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



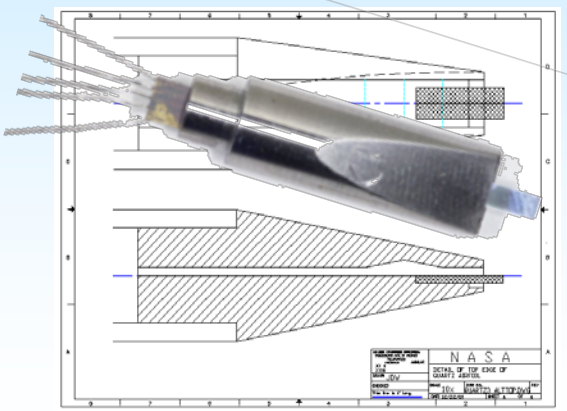
Heat Flux Sensor Array to T=1000°C



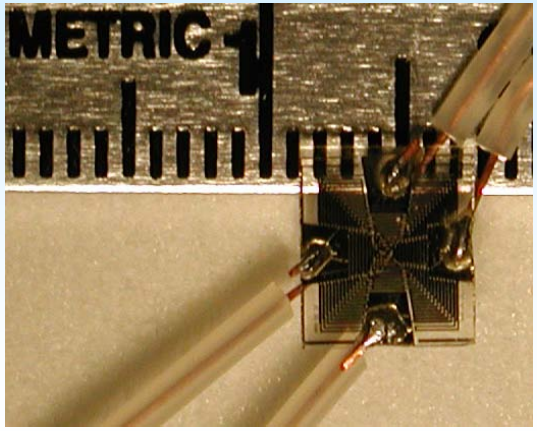
Multifunctional Sensor Array

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



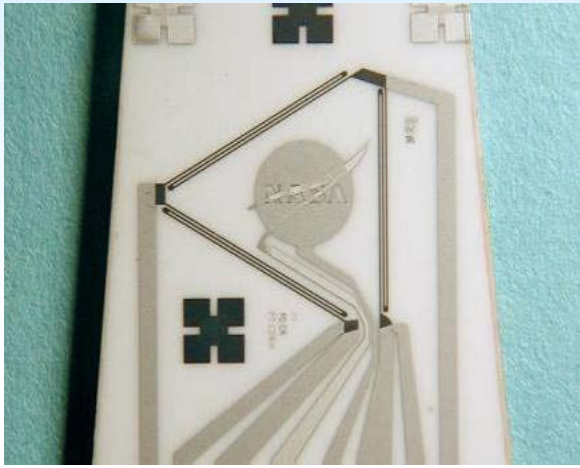
2008 NASA Tech Briefs Create the Future Design Contest - Machinery & Equipment
Flexible Small Area Heat Flux Sensor developed for Goodyear Tire & Rubber Co.

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

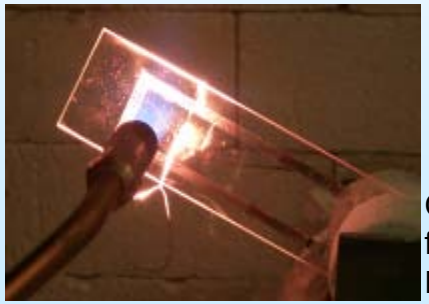
Novel Thin Film Sensor Technology Development

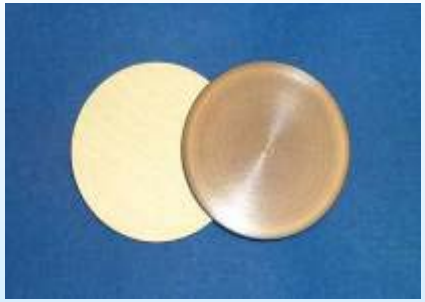
- Development of Thin Film Sensors with Ceramic, Laminate and Nanostructured Materials
  - Improve techniques for applying high temperature sensors onto complex structures
  - Develop thin film sensors to measure temperature, strain, and heat flux for hot section components
- Technology Challenge: Survivability 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

High Temperature Wireless Development

OBJECTIVES:

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

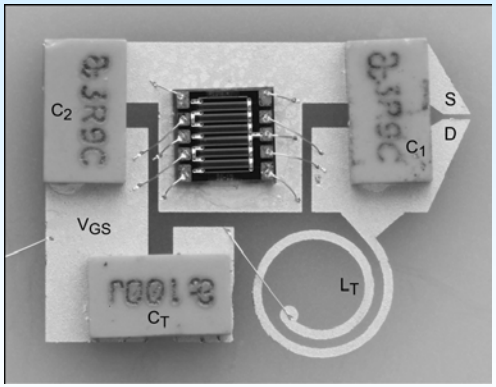
TECHNICAL CHALLENGES:

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

GOALS SUPPORTED:

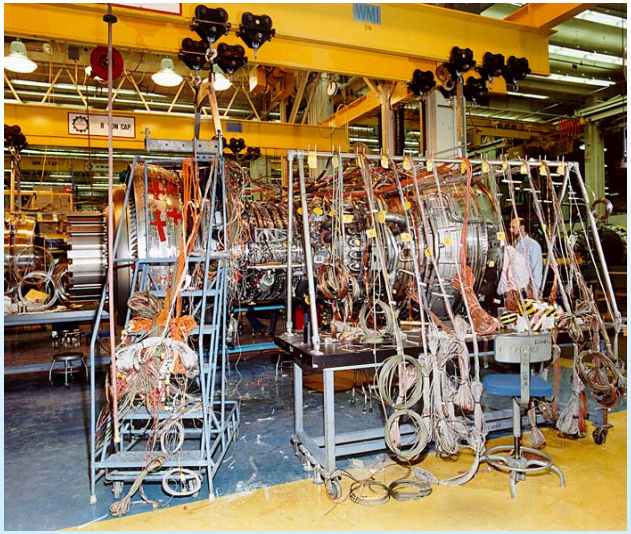
- **ENHANCE PERFORMANCE**
- **SIGNIFICANTLY REDUCE COST**

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

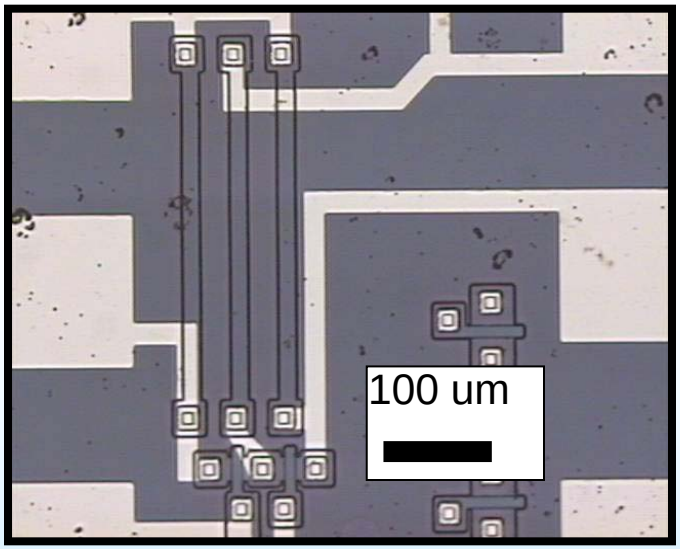
NASA Glenn Silicon Carbide Differential Amplifier

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

NASA Top Discovery Story 2007

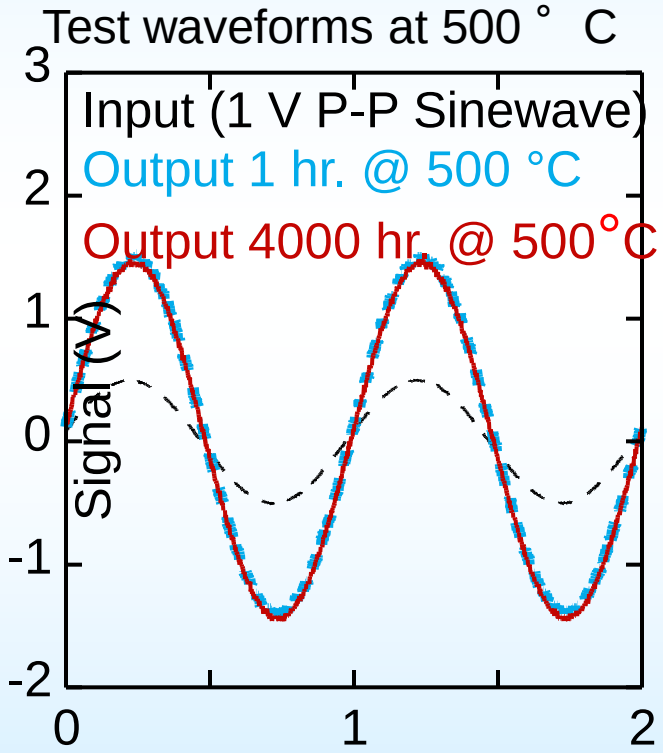
Demonstrates CRITICAL ability to interconnect transistors and other components (resistors) in a small area on a single SiC chip to form useful integrated circuits that are durable at 500ºC.

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.



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

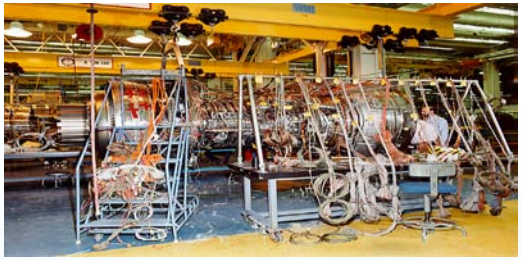
OBJECTIVE :
MOVE TOWARD HIGHER DEGREES OF COMPLEXITY ALLOWING HARSH ENVIRONMENT SMART SENSOR SYSTEMS

FULL SYSTEM APPROACH TOWARD HARSHENVIRONMENT SMART SENSOR SYSTEMS

- **Milestone: Demonstrate High Temperature Sensing, Wireless Communication, and Power Scavenging for Propulsion Health Management FY2013**

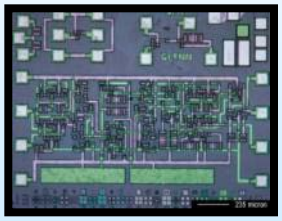
- **Metric: Demonstrate integrated self powered wireless sensor system at 500 ˚C with data transmission with operational life of at least 1 hr**

Significant wiring exists with present sensor systems

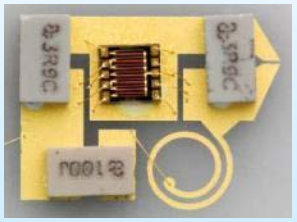


Allow Sensor Implementation by Eliminating Wires

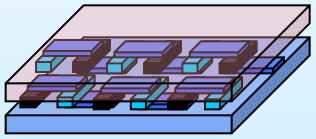
High Temperature Sensor Systems



World Record High Temperature Electronics Device Operation



High Temperature RF Components



Energy Harvesting Thin Film Thermoelectrics