

# AEROSPACE SENSOR SYSTEMS: FROM SENSOR DEVELOPMENT TO VEHICLE APPLICATIONS

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## **Abstract**

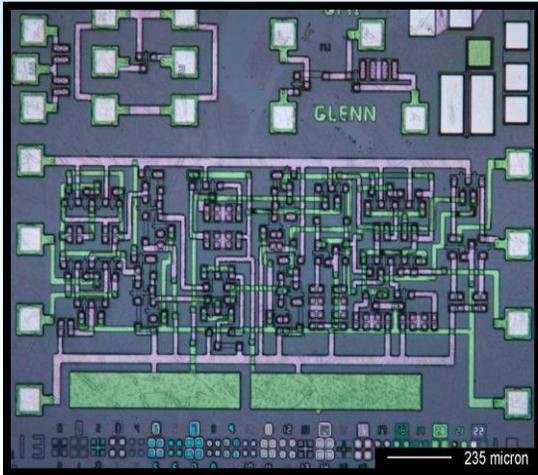
This paper presents an overview of years of sensor system development and application for aerospace systems. The emphasis of this work is on developing advanced capabilities for measurement and control of aeropropulsion and crew vehicle systems as well as monitoring the safety of those systems. Specific areas of work include chemical species sensors, thin film thermocouples and strain gages, heat flux gages, fuel gages, SiC based electronic devices and sensors, space qualified electronics, and MicroElectroMechanical Systems (MEMS) as well as integrated and multifunctional sensor systems. Each sensor type has its own technical challenges related to integration and reliability in a given application. The general approach has been to develop base sensor technology using microfabrication techniques, integrate sensors with “smart” hardware and software, and demonstrate those systems in a range of aerospace applications. Descriptions of the sensor elements, their integration into sensors systems, and examples of sensor system applications will be discussed. Finally, suggestions related to the future of sensor technology will be given. It is concluded that smart micro/nano sensor technology can revolutionize aerospace applications, but significant challenges exist in maturing the technology and demonstrating its value in real-life applications.

# **AEROSPACE SENSOR SYSTEMS: FROM SENSOR DEVELOPMENT TO VEHICLE APPLICATIONS**

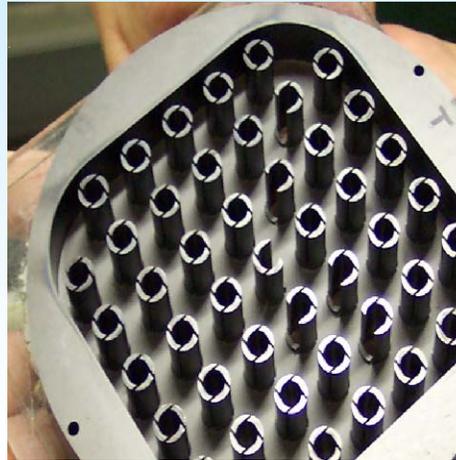
**Gary W. Hunter, Ph.D.  
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Sensors And Electronics Branch  
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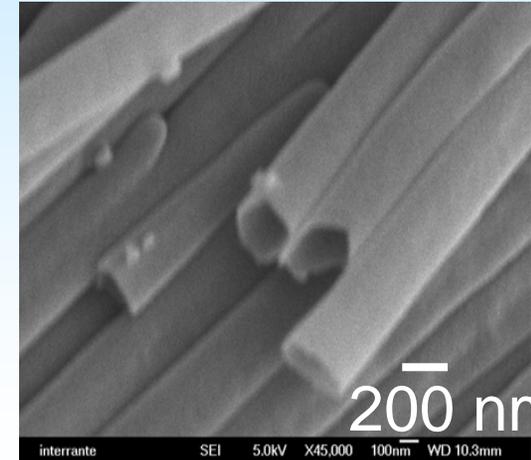
# Sensors and Electronics Branch: Scope of Work



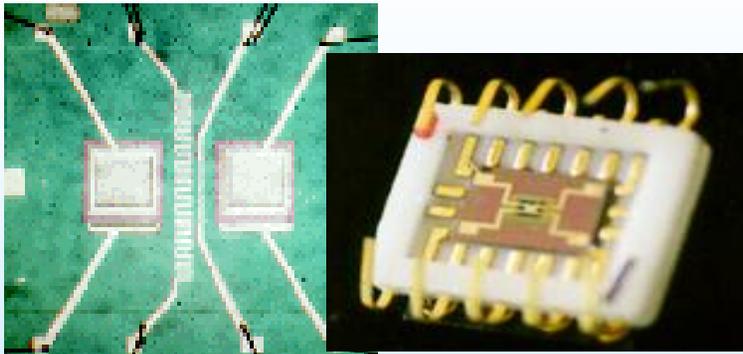
**High Temperature SiC Electronics**



**Micro-electromechanical Systems (MEMS)**



**Nanotechnology**

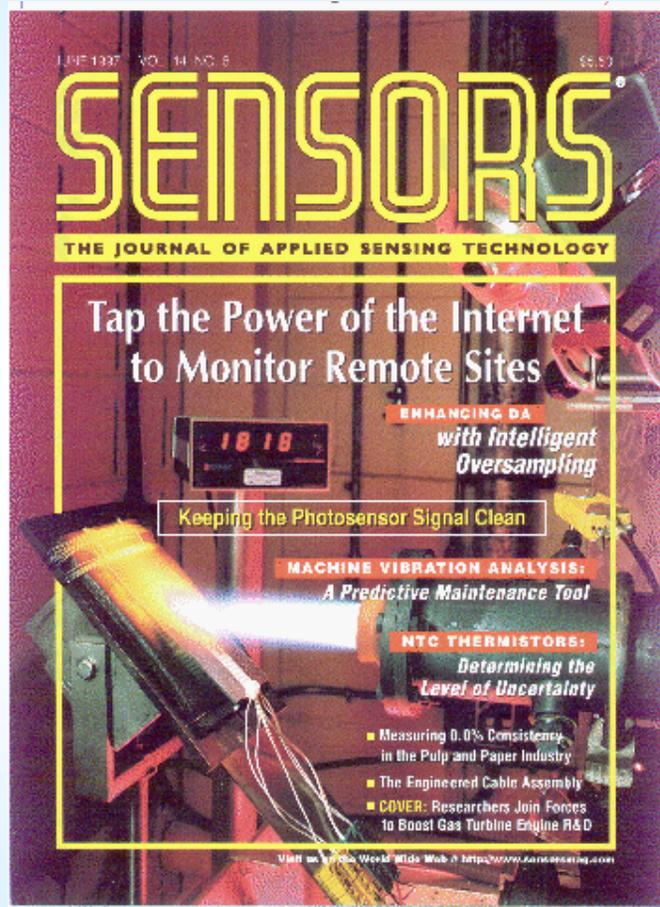


**Chemical Sensors**

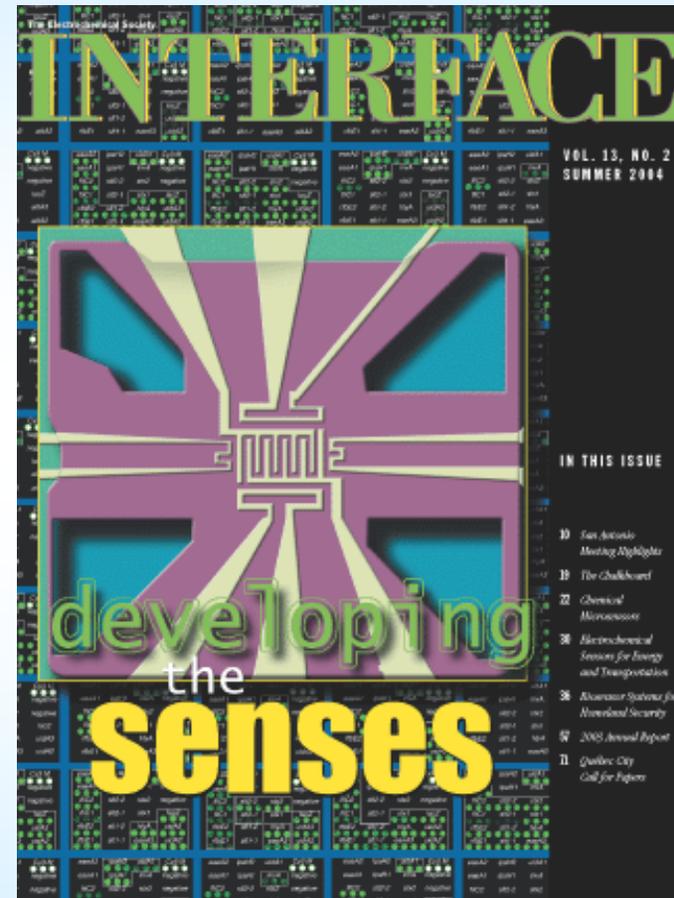


**Thin Film Sensors**

# A RANGE OF SENSOR AND SENSOR SYSTEM DEVELOPMENT



HARSH ENVIRONMENT SENSORS AND ELECTRONICS

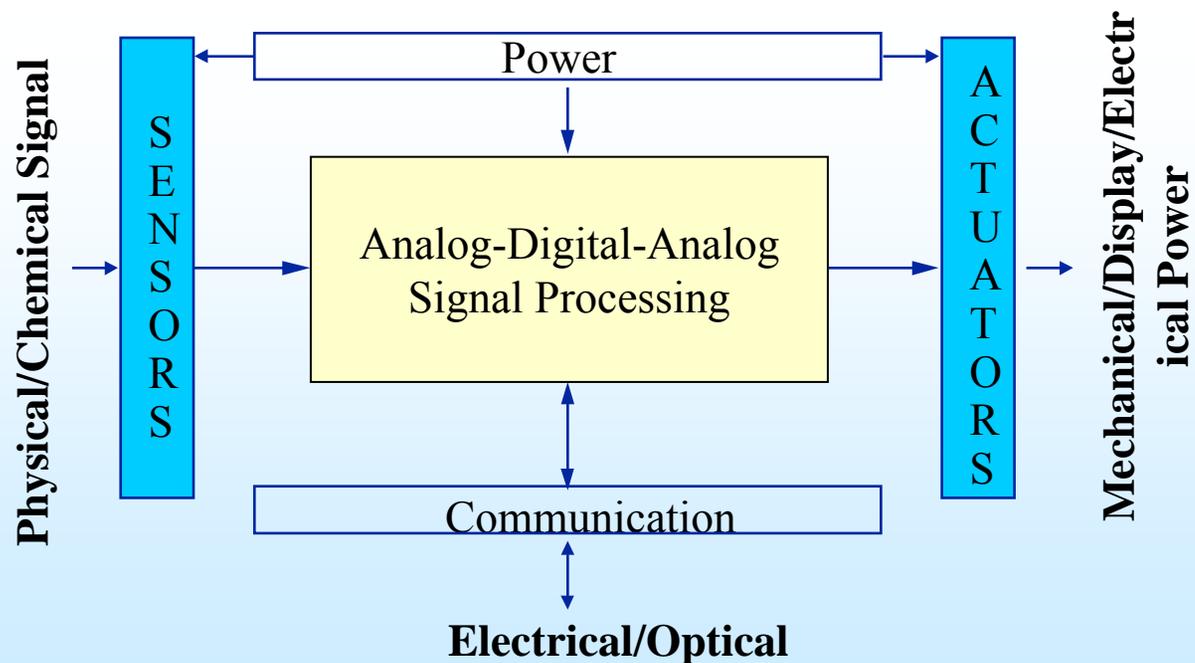


NASA GRC/CWRU O2 MICROSENSOR

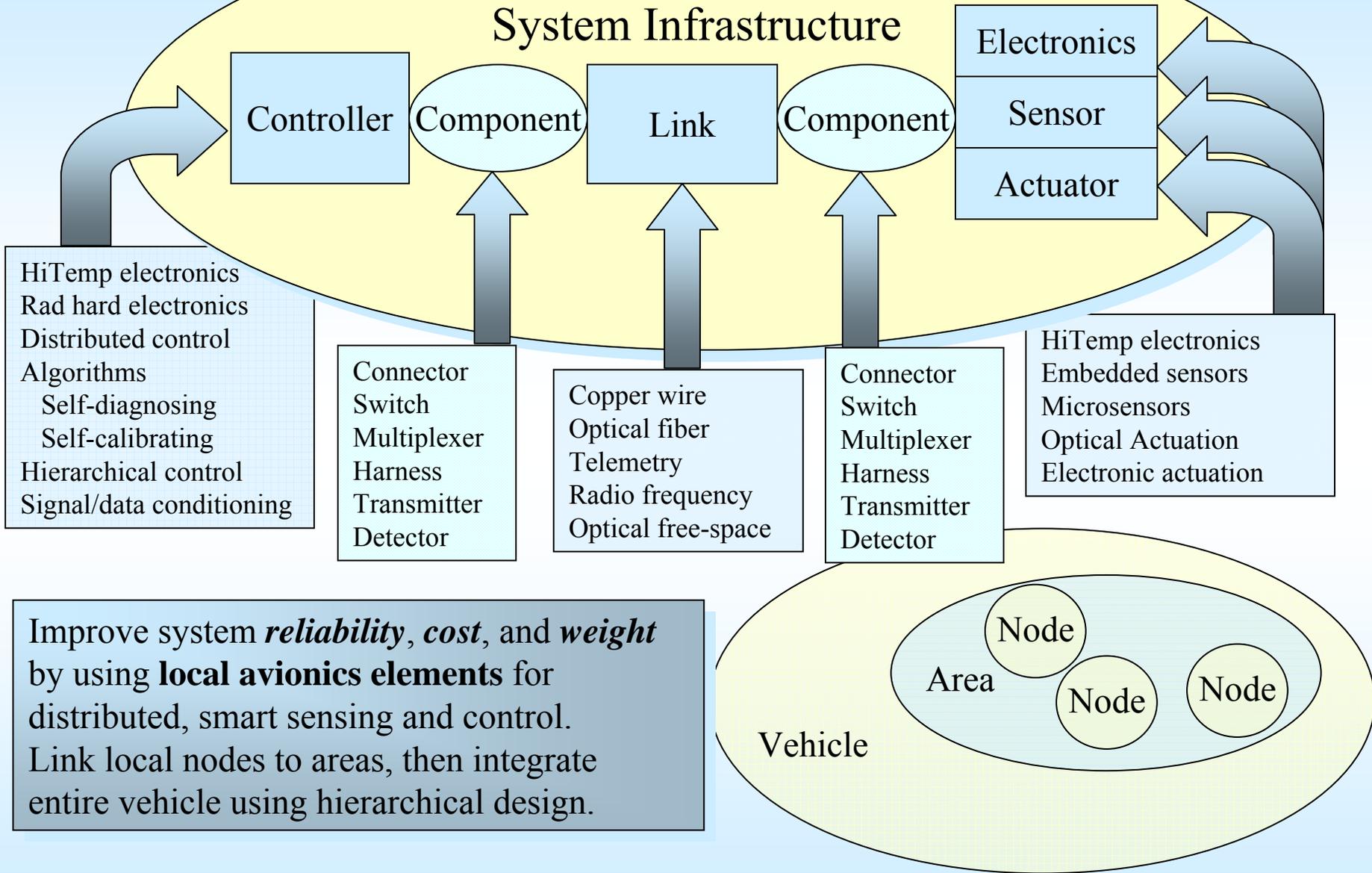
# MICROSYSTEMS TECHNOLOGY

- THIS PRESENTATION DISCUSSES A RANGE OF GAS SENSOR TECHNOLOGY
- EXAMPLES REVOLVE AROUND MICROSYSTEMS TECHNOLOGY
- EXAMPLES INVOLVE AEROSPACE APPLICATIONS BUT HAVE BROADER IMPLICATIONS
- BASIC APPROACH: DRIVE CAPABILITIES TO THE LOCAL LEVEL/DISTRIBUTED SMART SYSTEMS

## Microsystem Block Diagram



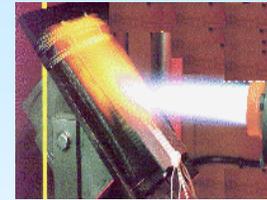
# Localized Avionics System Infrastructure



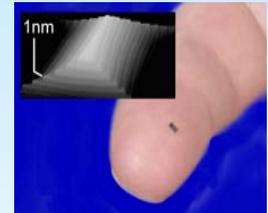
# HARSH ENVIRONMENT ELECTRONICS AND SENSORS APPLICATIONS

- **NEEDS:**

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



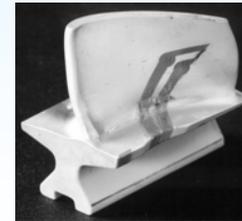
1998 R&D 100 Award



2004 R&D 100 Award

- **RESPONSE: UNIQUE RANGE OF HARSH ENVIRONMENT TECHNOLOGY AND CAPABILITIES**

- STANDARD 500C OPERATION BY MULTIPLE SYSTEMS
- TEMPERATURE, PRESSURE, CHEMICAL SPECIES, 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**

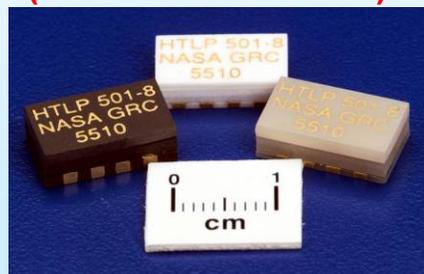
- **ENABLE EXPANDED MISSION PARAMETERS/IN-SITU MEASUREMENTS**

Range of Physical and Chemical Sensors for Harsh Environments



MICROFABRICATED SENSOR LOCATION

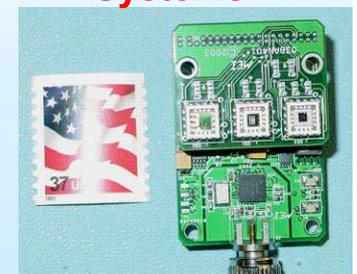
Harsh Environment Packaging (7000 hours at 500C)



High Temperature Signal Processing and Wireless



Long Term: High Temperature "Lick and Stick" Systems



# **BASIC APPROACH: MAKE AN INTELLIGENT SYSTEM FROM SMART COMPONENTS**

## **POSSIBLE STEPS TO REACH INTELLIGENT SYSTEMS**

### **•“LICK AND STICK” TECHNOLOGY (EASE OF APPLICATION)**

- **Micro and nano fabrication to enable multipoint inclusion of sensors, actuators, electronics, and communication throughout the vehicle without significantly increasing size, weight, and power consumption. Multifunctional, adaptable technology included.**

### **•RELIABILITY:**

- **Users must be able to believe the data reported by these systems and have trust in the ability of the system to respond to changing situations e.g. decreasing sensors should be viewed as decreasing the available information flow about a vehicle. Inclusion of intelligence more likely to occur if it can be trusted.**

### **•REDUNDANCY AND CROSS-CORRELATION:**

- **If the systems are easy to install, reliable, and do not increase weight/complexity, the application of a large number of them is not problematic allowing redundant systems, e.g. sensors, spread throughout the vehicle. These systems will give full-field coverage of the engine parameters but also allow cross-correlation between the systems to improve reliability of sensor data and the vehicle system information.**

### **•ORTHOGONALITY:**

- **Systems should each provide a different piece of information on the vehicle system. Thus, the mixture of different techniques to “see, feel, smell, hear” as well as move can combine to give complete information on the vehicle system as well as the capability to respond to the environment.**



# OUTLINE

- **INTRODUCTION**
- **SENSOR ELEMENT**
  - **TECHNOLOGIES AND CHALLENGES**
- **MICROFABRICATED GAS SENSORS**
  - **SENSOR PLATFORMS**
  - **SMART SENSORS SYSTEMS AND DEMONSTRATIONS**
- **SUPPORTING TECHNOLOGIES**
  - **HIGH TEMPERATURE ELECTRONICS EXAMPLE**
- **SYSTEM APPLICATION**
  - **MATURATION FOR ISS APPLICATIONS**
  - **SPACE QUALIFIED ELECTRONICS AND SENSORS**
  - **MOBILE SENSOR PLATFORMS**
- **SENSOR DATA QUALIFICATION**
- **FUTURE DIRECTIONS**
  - **NANOTECHNOLOGY**
- **SUMMARY**



**SENSOR ELEMENTS:**

**SPACE APPLICATIONS AND TECHNICAL  
CHALLENGES**

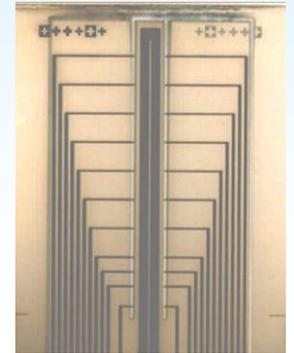
**TAILOR THE SENSOR TO THE APPLICATION**



# Thin Film Physical Sensors for High Temperature Applications

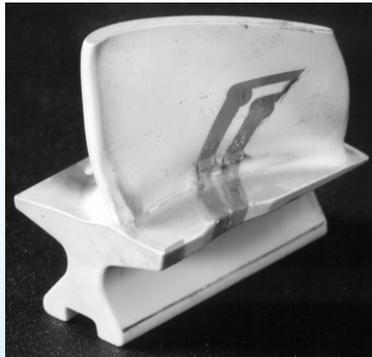
## Advantages for temperature, strain, heat flux, flow & pressure measurement:

- ◆ 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)



## Multifunctional smart sensors being developed

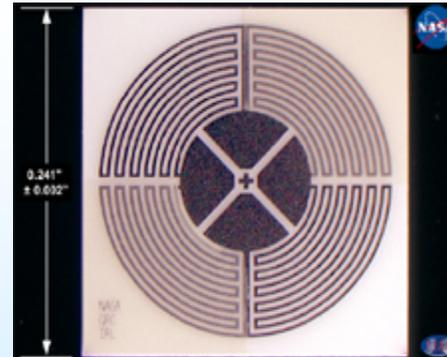
Flow sensor made of high temperature materials



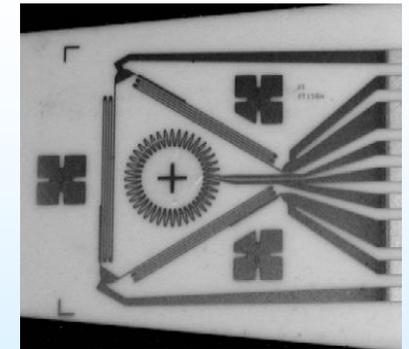
PdCr strain sensor  
to  $T=1000^{\circ}\text{C}$



Pt- Pt/Rh temperature  
sensor to  $T=1200^{\circ}\text{C}$



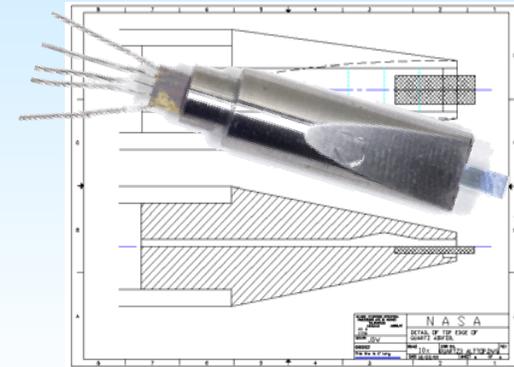
Heat Flux Sensor Array  
to  $T=1000^{\circ}\text{C}$



Multifunctional  
Sensor Array

# GRC's Physical Sensor Instrumentation Research History

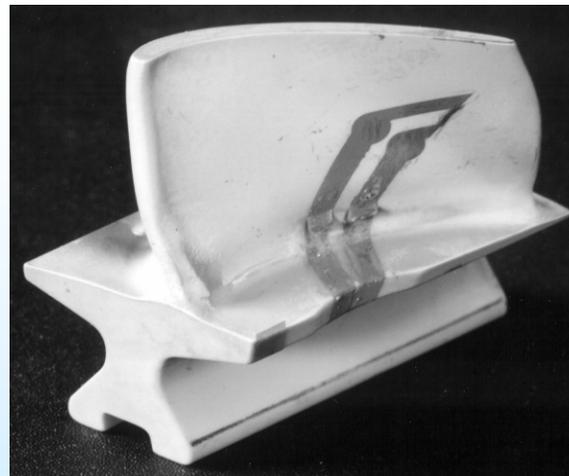
- R&D 100 Awards in 1991, 1995, and 1998
- NASA Group Achievement Award 2003
- Partnerships in Sensor Development:
  - Rolls-Royce, GE Aircraft Engines, Pratt & Whitney
  - Goodyear Tire & Rubber Company
  - University of Rhode Island
  - Air Force Research Lab (NDE Branch)



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



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



1995 R&D 100 Award  
PdCr thin film gauge applied on Allied-Signal Engines ceramic turbine blade



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 ( $>1500^{\circ}\text{C}$ )
  - 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

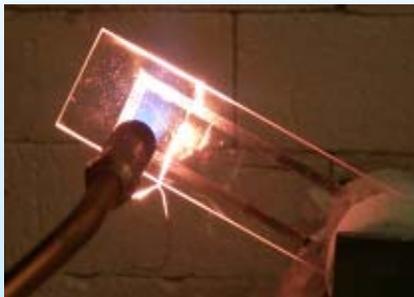
Sputtering System for Thin Film Sensor Fabrication



RTD on Fan Blade



Ceramic TC Sputtering Targets fabricated by the NASA GRC Ceramics Branch



Ceramic Thermocouple fabricated at University of Rhode Island

# CEV Interface Seals Instrumentation

## Thermal Protection System (TPS) Interface Seals

- Instrumentation for Interface Gap Heating Tests for CEV Heat Shield-to-Backshell Interface Seals
  - Design, fabrication and testing of a packaged miniature heat flux sensor
- Technology Challenge: Sensor Integration with Packaging
  - Leverage RTD Heat Flux Sensor development & Novel Thin Film Sensor effort



CEV Reentry w/ TPS Seal

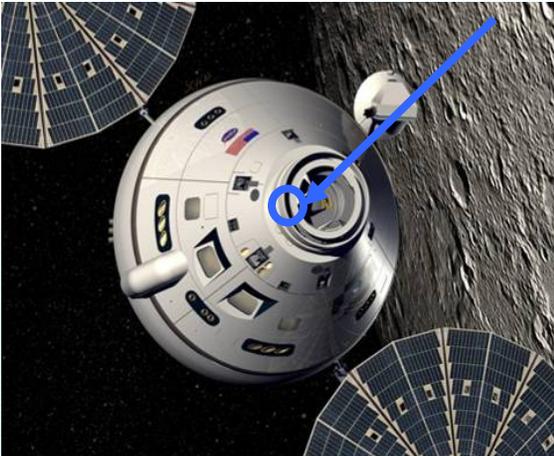
## Low Impact Docking System (LIDS) Interface Seals

- Instrumentation to Measure Pressure Between Two Seal Bulbs
  - Concept design, model and lab demonstration of pressure sensor
- Technology Challenge: Sensor Integration with Tight Size Tolerance
  - Miniature size so as to not interfere with the sealing function

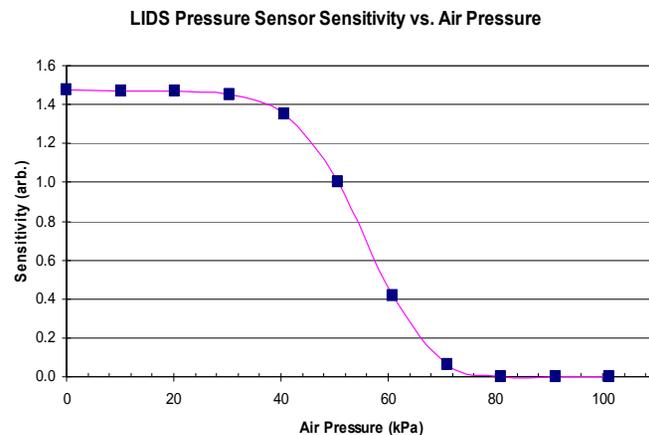
Fabricated Heat Flux Sensor Element



LIDS Pressure Sensor Concept Location

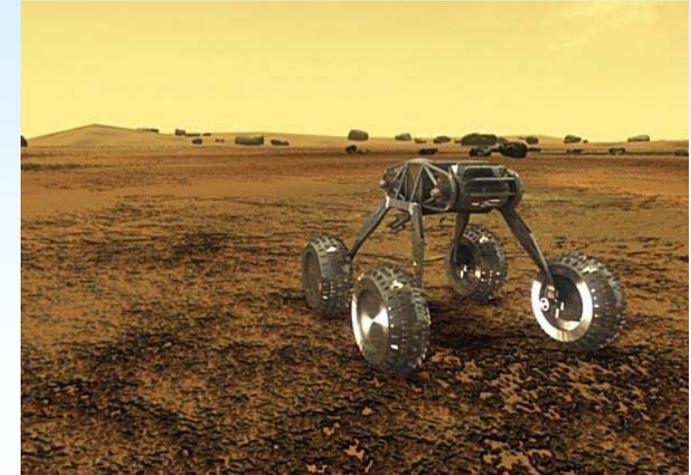


LIDS Pressure Sensor Concept Modeled

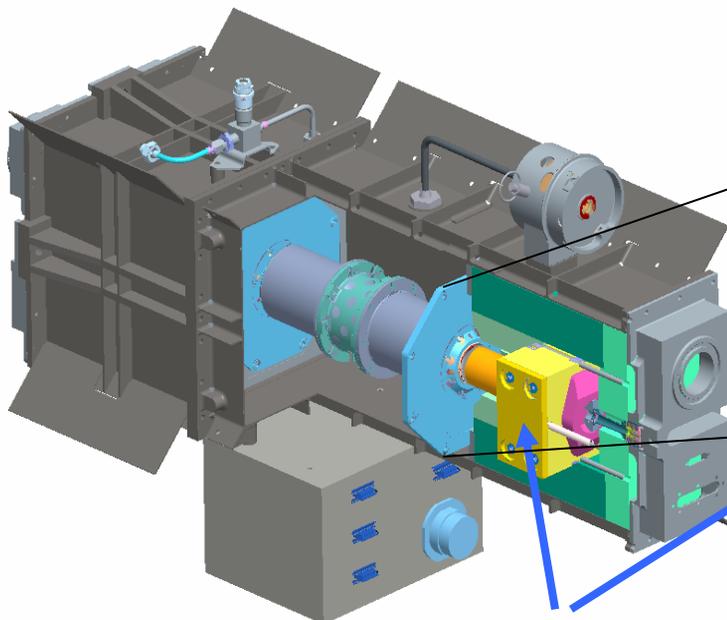


# Advanced Stirling Convertor (ASC) Sensors

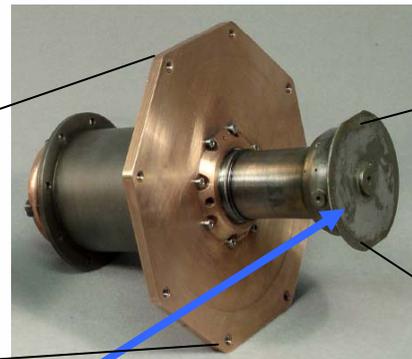
- Development of Heat Flux Sensors for ASC Units for measurement of thermal energy delivered into the converter
  - Allows for a direct measurement of thermal to electrical conversion efficiency in characterizing the ASC units
- Technical Challenge: Sensor Fabrication Methods Compatible with ASC Thermal and Structural Demands
  - Sensor Thermal Conductivity, Strength and Sensitivity satisfied with High Temperature Ceramics



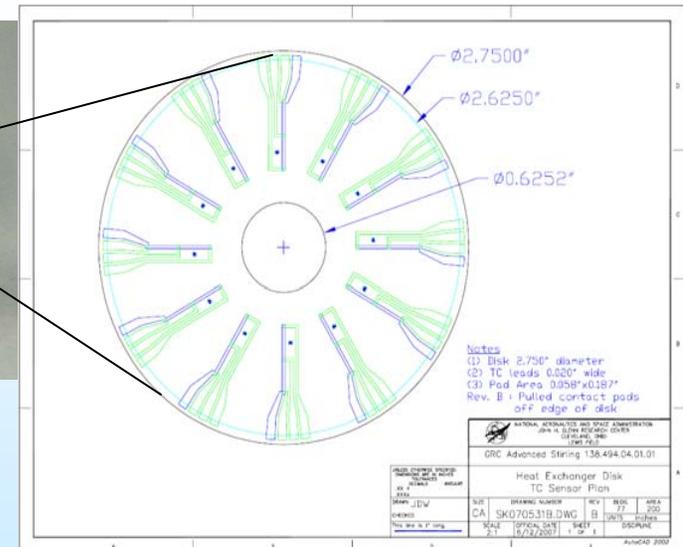
Venus Rover Concept with ASC Cooling



ASRG Engineering Unit with Planned Location of Heat Flux Sensors



ASC-E Converter



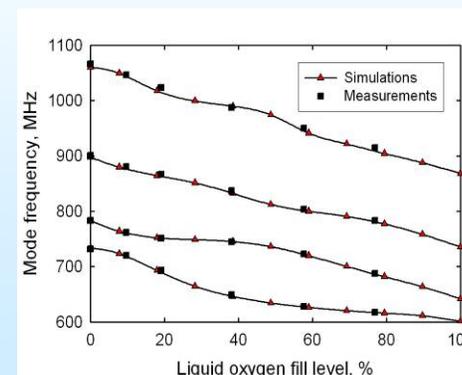
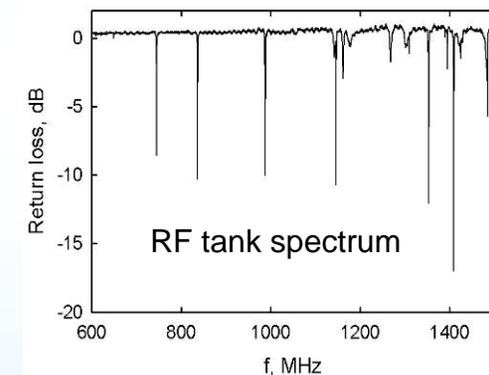
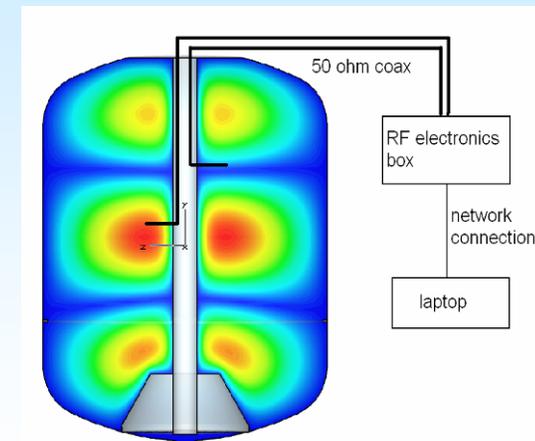
Heat Flux Sensor Design being Fabricated at NASA GRC



# Propellant gauging sensor

## Radio Frequency Mass Gauge (RFMG)

- Detects electromagnetic modes of a tank using an antenna and RF analyzer
- Mode frequencies are affected in a known way by liquid quantity
- Applicable to dielectric liquids such as liquid hydrogen, oxygen, methane.
- Tests in 58 cu. ft. liquid oxygen tank indicate high accuracy. RMS gauging uncertainty <1% full-scale.
- RFMG is being developed in-house at NASA GRC
- Potential application to EDS and Altair tanks
- Currently at TRL-5



POC: Greg.Zimmerli@nasa.gov

➤ **Future work is designed to push development of the RFMG to TRL 6-7.**

Risk	Mitigation Plan
Limited testing in methane/hydrogen.	Full-scale methane test planned for 2009. Small-scale H2 testing planned for 2008.
Unknown RFMG performance in larger scale tanks, and with other internal hardware.	Construct a full-scale mock LH2 Lander tank and test RF response with internal hardware (no cryo-fluid).
A high-fidelity flight-prototype instrument unit has never been tested.	Initiate development of a 2 <sup>nd</sup> generation Engineering Model. Goal is to meet typical thermal, vacuum, vibe, EMI spec's (will try to mimic spec's on Orion CEV).
The structural integrity of the antenna and RF connections has not been determined.	Need to identify/test appropriate connectors. Need to design & vibe-test flight-like antenna.
Performance in low-gravity is uncertain.	1g tilted tank tests. Possible low-gravity aircraft testing. Simulations.

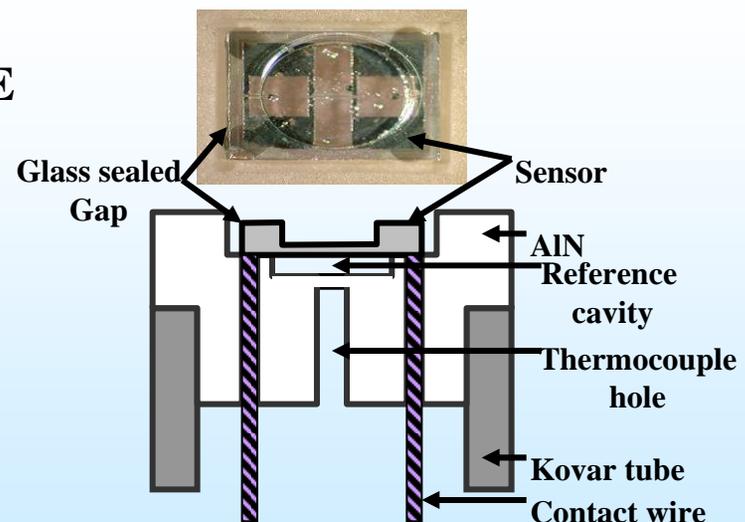


# SiC-BASED PRESSURE SENSORS

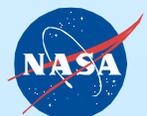
- **SiC HAS EXCELLENT MECHANICAL PROPERTIES FOR USE AS A HARSH ENVIRONMENT PRESSURE SENSOR (T > 500 °C, SILICON UNDERGOES PLASTIC DEFORMATION)**
- **FORM DIAPHRAM OF SiC AND INTEGRATE WITH ELECTRONICS**
- **WIDE RANGE OF APPLICATIONS**
  - **AERONAUTIC ENGINE APPLICATIONS**
  - **AUTOMOTIVE APPLICATIONS**
  - **WIND TUNNELS**
  - **MATERIAL PROCESSING**
- **ENGINE OPERATION DEMONSTRATED AT 500 C**
- **TECHNICAL CHALLENGES INCLUDE**
  - **SiC DIAPHRAM FORMATION (ETCHING)**
  - **PACKAGING**
  - **RELIABILITY TESTING**



500 °C SiC pressure sensor



**SENSOR PLATFORMS TO SMART SENSOR SYSTEMS:  
MICROFABRICATED GAS SENSORS**



# MICROFABRICATED GAS SENSORS



- **COLLABORATIVE EFFORT BETWEEN NASA GRC, CASE WESTERN RESERVE, and OHIO STATE UNIVERSITY**
- **SENSOR DEVELOPMENT RESULTING FROM:**
  - IMPROVEMENTS IN MICROFABRICATION AND MICROMACHINING TECHNOLOGY**
  - NANOMATERIALS**
  - DEVELOPMENT OF SiC-BASED SEMICONDUCTOR TECHNOLOGY**
- **GAS DETECTION IN:**
  - HARSH ENVIRONMENTS**
  - APPLICATIONS BEYOND CAPABILITIES OF**
  - COMMERCIAL SENSORS**
- **TECHNOLOGY DEVELOPS PLATFORMS FOR A VARIETY OF MEASUREMENTS**
  - SCHOTTKY DIODE**
  - RESISTANCE BASED**
  - ELECTROCHEMICAL**
- **TARGET DETECTION OF GASES OF FUNDAMENTAL INTEREST**
  - HYDROGEN (H<sub>2</sub>)**
  - HYDROCARBONS (C<sub>x</sub>H<sub>y</sub>)**
  - NITROGEN OXIDES (NO<sub>x</sub>) AND CARBON MONOXIDE (CO)**
  - OXYGEN (O<sub>2</sub>)**
  - CARBON DIOXIDE (CO<sub>2</sub>)**



# BASE PLATFORM 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

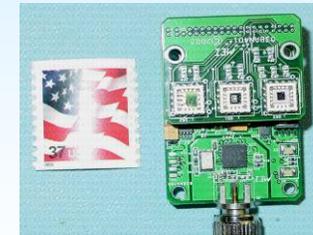
Multi Species Fire Sensors for Aircraft Cargo Bays and Space Applications



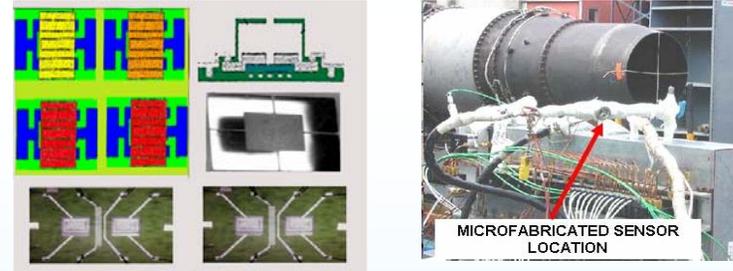
Environmental monitoring (ISS Whitesand Testing)



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



Aircraft Propulsion Exhaust High Temperature Electronic Nose

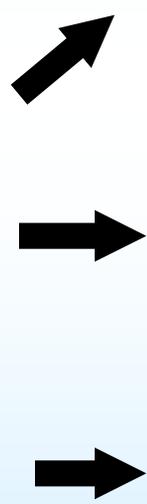


Oxygen Sensor

SiC Hydrocarbon Sensor

H2 Sensor

Nanocrystalline Tin Oxide NOx and CO Sensor



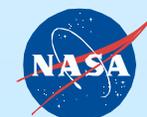
Hydrazine EVA Sensors (ppb Level Detection)

Sensor Equipped Prototype Medical Pulmonary Monitor

MEI Makel Engineering Inc.

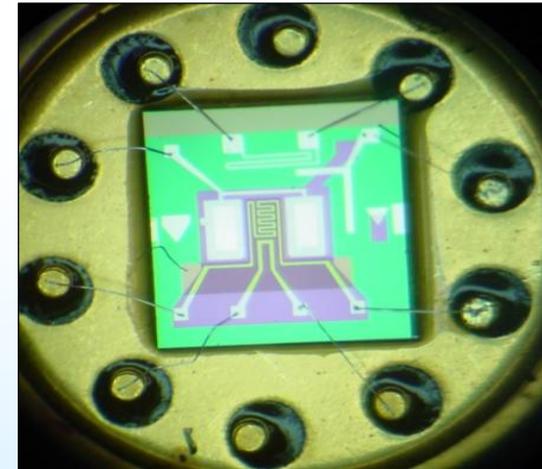
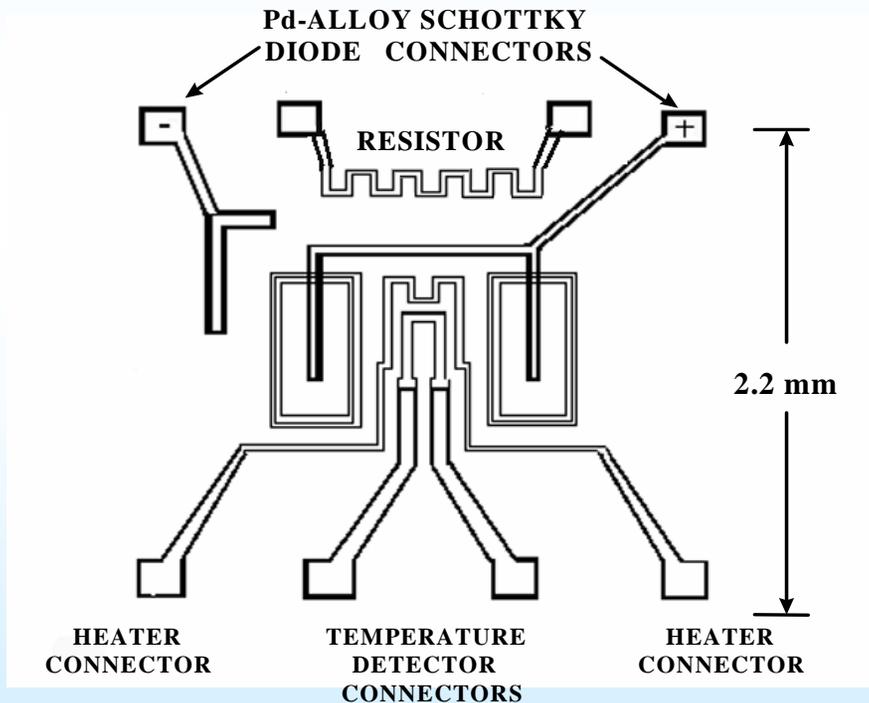


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# HYDROGEN LEAK SENSOR TECHNOLOGY

- MICROFABRICATED USING MEMS-BASED TECHNOLOGY FOR MINIMAL SIZE, WEIGHT AND POWER CONSUMPTION
- HIGHLY SENSITIVE IN INERT OR OXYGEN-BEARING ENVIRONMENTS, WIDE CONCENTRATION RANGE DETECTION
- TWO SENSOR SYSTEM FOR FULL RANGE DETECTION: FROM PPM LEVEL TO 100%



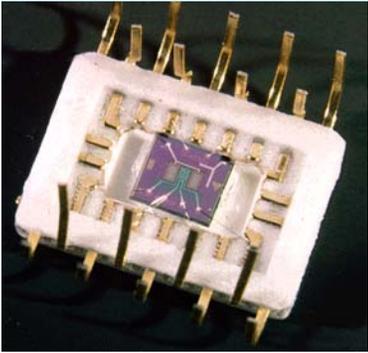
**MEI** *Makel Engineering Inc.*



Glenn Research Center



# HYDROGEN LEAK SENSOR TECHNOLOGY



- STATUS: OPERATIONAL SYSTEM ON ISS WITH ASSOCIATED HARDWARE
- BEING PREPARED FOR CLV IMPLEMENTATION

**1995 R&D 100 AWARD WINNER**

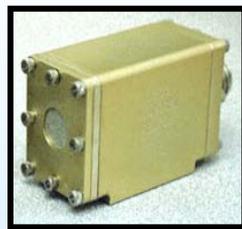
**NASA 2003 TURNING GOALS INTO REALITY SAFETY AWARD**

Shuttle



Aft Compartment  
Hydrogen Monitoring

X33



Hydrogen Safety  
Monitoring

X43



Hydrogen Safety  
Monitoring

Helios



Fuel Cell Safety and  
Process Monitoring

ISS



Life Support Process  
and Safety Monitoring

**MEI** Makel Engineering Inc.



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# **SiC-BASED GAS SENSOR DEVELOPMENT**



- **THE USE OF SiC SEMICONDUCTORS ALLOWS SENSOR OPERATION AT TEMPERATURES WHICH ALLOW THE DETECTION OF HYDROCARBONS AND NO<sub>x</sub>**
- **INERT MATERIAL OPERATIONAL IN HIGH TEMPERATURE, CORROSIVE ENVIRONMENTS**
- **SCHOTTKY DIODE DESIGN FOR HIGH SENSISTIVITY**
- **TEMPERATURE DETECTOR AND HEATER INCLUDED/OPERATION AT A RANGE OF TEMPERATURES**
- **WIDE RANGE OF APPLICATIONS**
  - EMISSION MONITORING**
  - ENGINE HEALTH MONITORING**
  - ACTIVE COMBUSTION CONTROL**
  - HYDROCARBON FUEL LEAK DETECTION**
  - FIRE SAFETY**
- **PROTOTYPE SENSOR PACKAGE FABRICATED/TESTED IN ENGINE ENVIRONMENTS**
- **APPROACHES**
  - ALLOY ON SiC SUBSTRATE**
  - REACTIVE INSULATOR APPROACH**
  - BARRIER LAYER**
  - ATOMICALLY FLAT SiC**

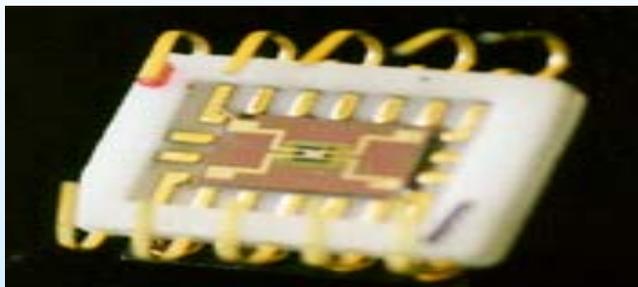
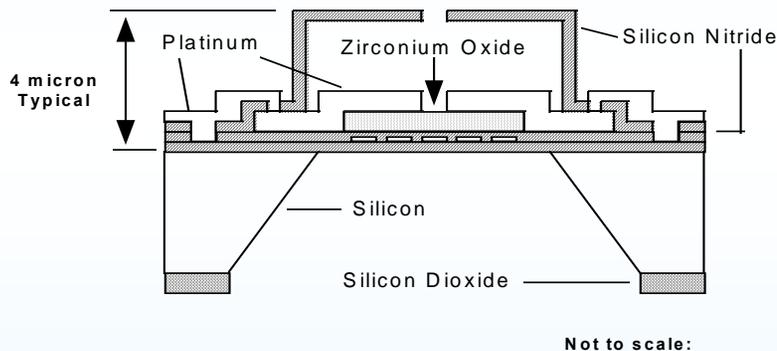
**PACKAGED SiC-BASED SENSOR**



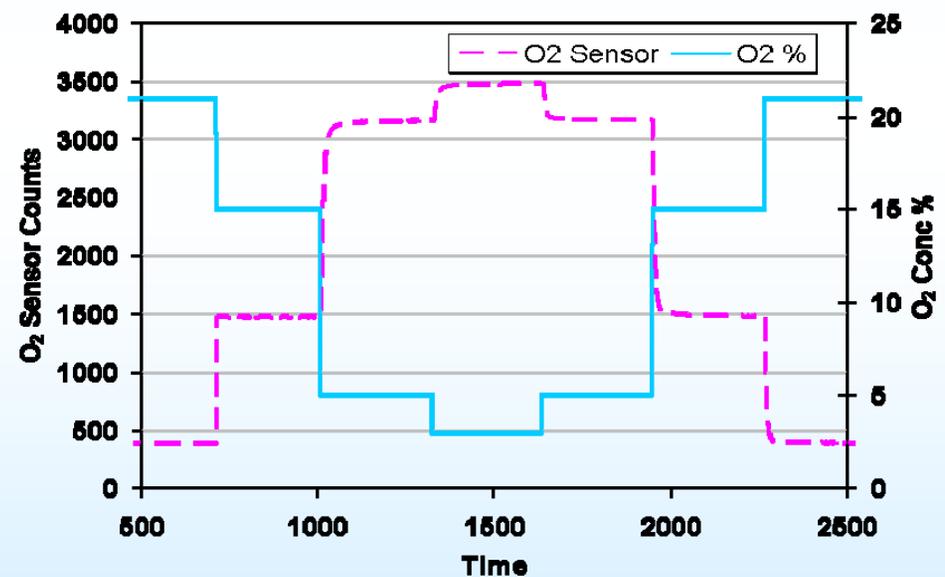
# MICROFABRICATED OXYGEN SENSOR TECHNOLOGY



- MICROFABRICATED AND MICROMACHINED FOR MINIMAL SIZE, WEIGHT AND POWER CONSUMPTION (NEAR 100 mW FOR ~500 C OPERATION)
- AMPEROMETRIC OPERATION ALLOWS MEASUREMENT OF OXYGEN OVER A WIDE CONCENTRATION RANGE (0-100%)
- CHAMBER STRUCTURE CONTROLS OXYGEN DIFFUSION RATE
- RELATIVELY MATURE TECHNOLOGY/PACKAGING COULD BE IMPROVED TO DECREASE POWER CONSUMPTION



ZrO<sub>2</sub> Oxygen Sensor

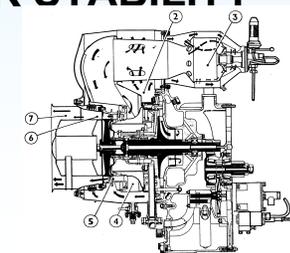
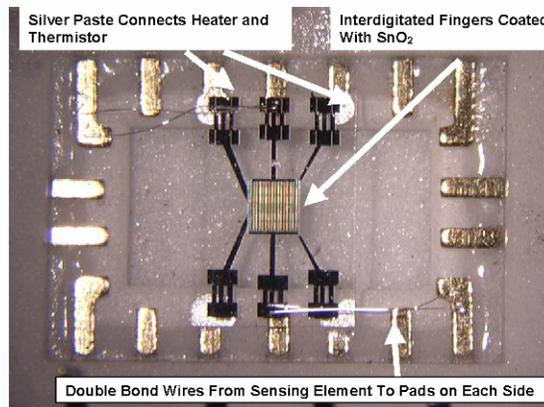
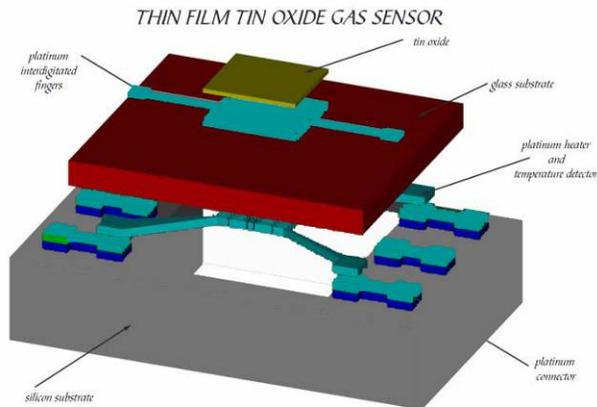


Zirconia Based Oxygen Microsensor Response To Various Oxygen Concentrations



# MICROFABRICATED TIN OXIDE BASED NO<sub>x</sub> AND CO SENSOR TECHNOLOGY

- MICROFABRICATED FOR MINIMAL SIZE, WEIGHT AND POWER CONSUMPTION
- MICROMACHINED TO MINIMIZE POWER CONSUMPTION AND IMPROVE RESPONSE TIME
- TEMPERATURE DETECTOR AND HEATER INCORPORATED INTO SENSOR STRUCTURE
- NANOFABRICATION OF TIN-OXIDE TO INCREASE SENSOR STABILITY

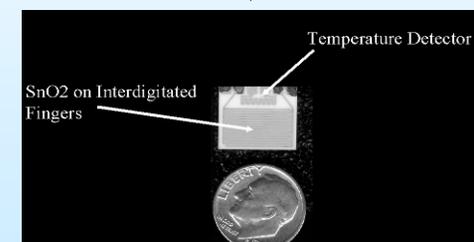


50 Hp Gas Turbine

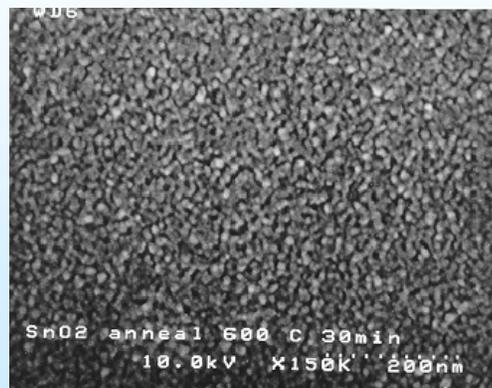


Industry Standard  
Continuous Emission  
Monitoring Equipment

**REPLACE INSTRUMENT RACK  
SIZED SYSTEM WITH DIME SIZED  
SENSOR AND ACCOMPANYING  
ELECTRONICS**



**Nanocrystalline  
Tin Oxide**



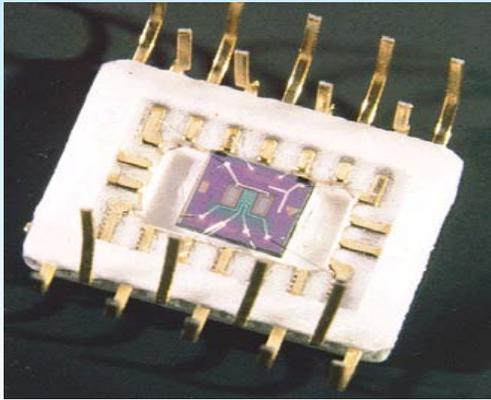
# SENSOR SYSTEM DEVELOPMENT

- EACH SENSOR PLATFORM PROVIDES QUALITATIVELY VERY DIFFERENT TYPES OF INFORMATION ON THE ENVIRONMENT
- SENSOR ARRAY VARIES WITH APPLICATION/MICROFABRICATION TECHNIQUES MANDATORY
- BASIS CHEMICAL SENSOR FEATURES:
  - RESPONSE TIME, SENSITIVITY, SELECTIVITY, STABILITY
  - BATCH FABRICATION, PROCESSING REPRODUCIBILITY, CONTROL OF STRUCTURE
  - TAILOR SENSOR SYSTEM FOR THE APPLICATION
- SUPPORTING TECHNOLOGIES NECESSARY
  - PACKAGING (OFTEN UP TO 70% OF OVERALL SENSOR COST)
  - SIGNAL CONDITIONING AND PROCESSING
  - SOFTWARE (E.G. NEURAL NET PROCESSING, MODELING)
  - POWER AND COMMUNICATION

See for example: G. W. Hunter, C.C. Liu, D. Makel, Microfabricated Chemical Sensors For Aerospace Applications, MEMS Handbook Second edn, Design and Fabrication, CRC 2006, Press LLC, Boca Raton, Ch. 11.



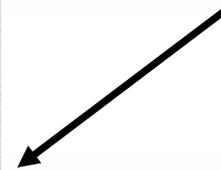
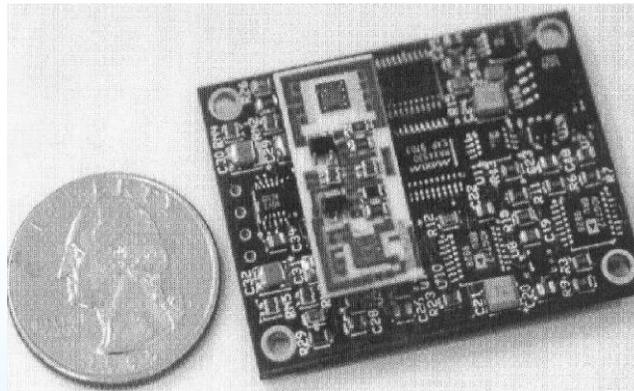
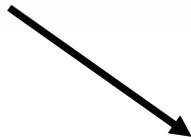
# MINIATURIZED SMART LEAK SENSOR SYSTEM



**MICROFABRICATED HYDROGEN  
SENSOR**



**HYDROGEN SENSORS ON SPACE  
SHUTTLE**



**PROTOTYPE HYDROGEN/OXYGEN SENSOR SYSTEM WITH ELECTRONICS**

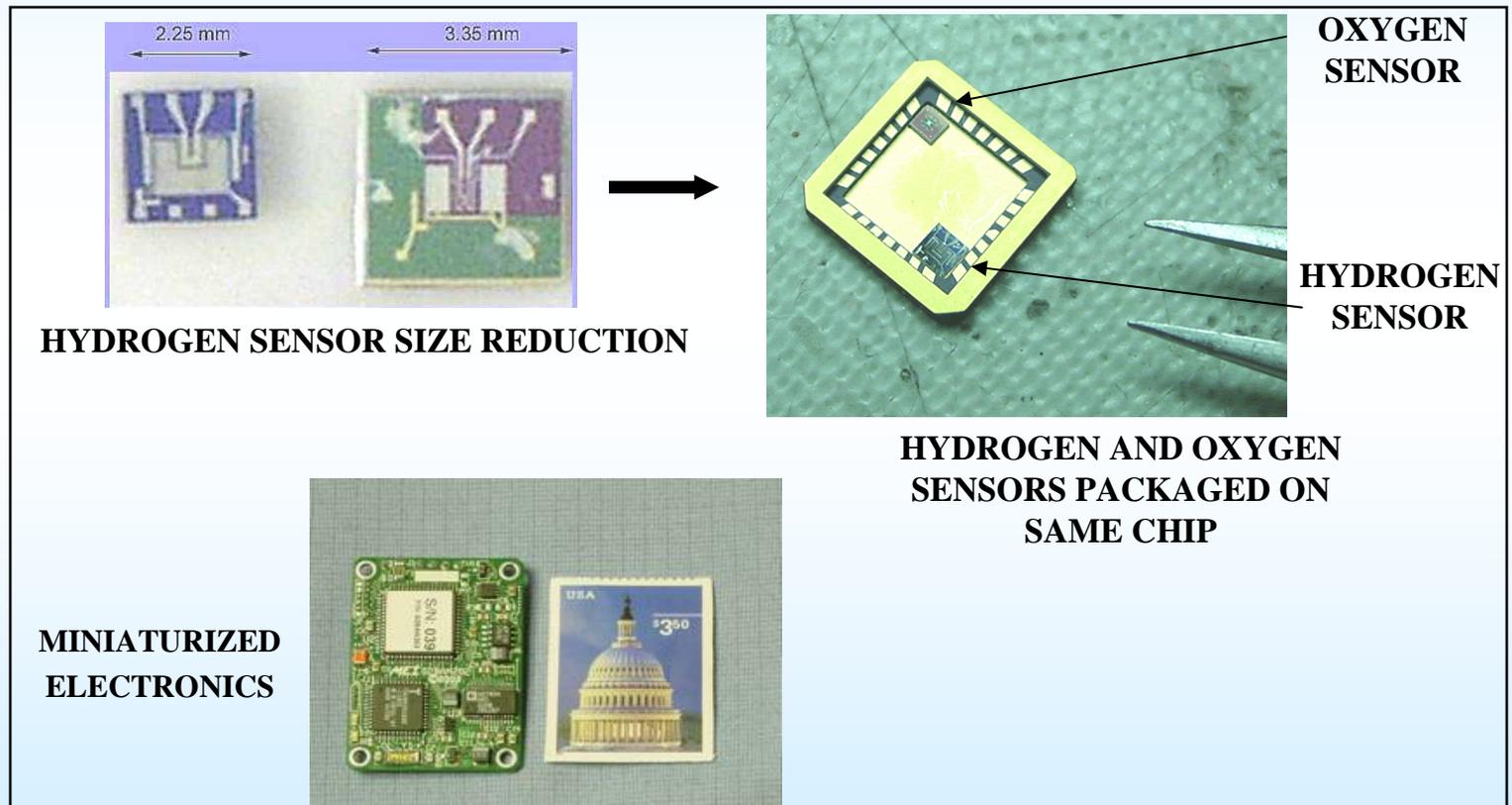


**DEMONSTRATE STAND-ALONE SMART LEAK DETECTION SYSTEM  
WITH A SURFACE AREA THE SIZE OF POSTAGE STAMP**

# “LICK AND STICK” LEAK SENSOR SYSTEM

- COMBINE FUEL (HYDROGEN, HYDROCARBON) WITH OXYGEN IN AN ARRAY: DETERMINE EXPLOSIVE COMBINATIONS
- SELF-CONTAINED SYSTEM WHICH CAN BE IMPLEMENTED WHEREVER, WHENEVER NEEDED WITHOUT REWIRING OR SIGNIFICANT POWER DRAIN TO THE VEHICLE
- ON-GOING ACTIVITY: DECREASE SIZE AND POWER OF SENSORS/ELECTRONICS

**FIRST STEP:  
COMBINE  
SMALLER  
SENSORS WITH  
SMALLER,  
SMART  
ELECTRONICS**



**MEI** Makel Engineering Inc.

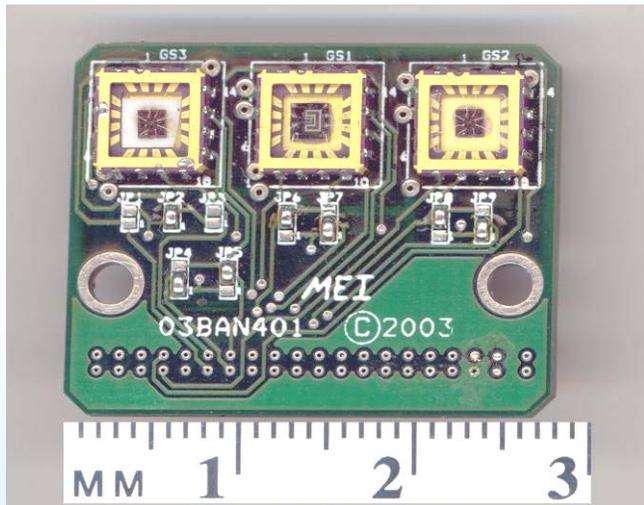


**Glenn Research Center**

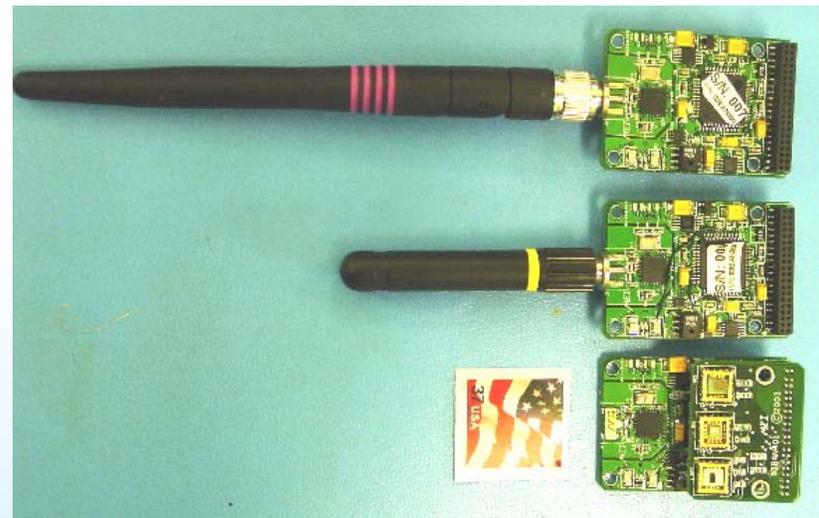


# “LICK AND STICK” LEAK SENSOR SYSTEM

- **SENSORS, POWER, AND TELEMETRY SELF-CONTAINED IN THE NEAR THE SIZE OF A POSTAGE STAMP**
- **MICROPROCESSOR INCLUDED/SMART SENSOR SYSTEM**
- **VERIFY SYSTEM COMPATIBILITY WITH SPACE APPLICATIONS**
- **ADAPTABLE CORE SYSTEM WHICH CAN BE USED IN A RANGE OF APPLICATIONS**
- **MULTIPLE CONFIGURATIONS AVAILABLE**



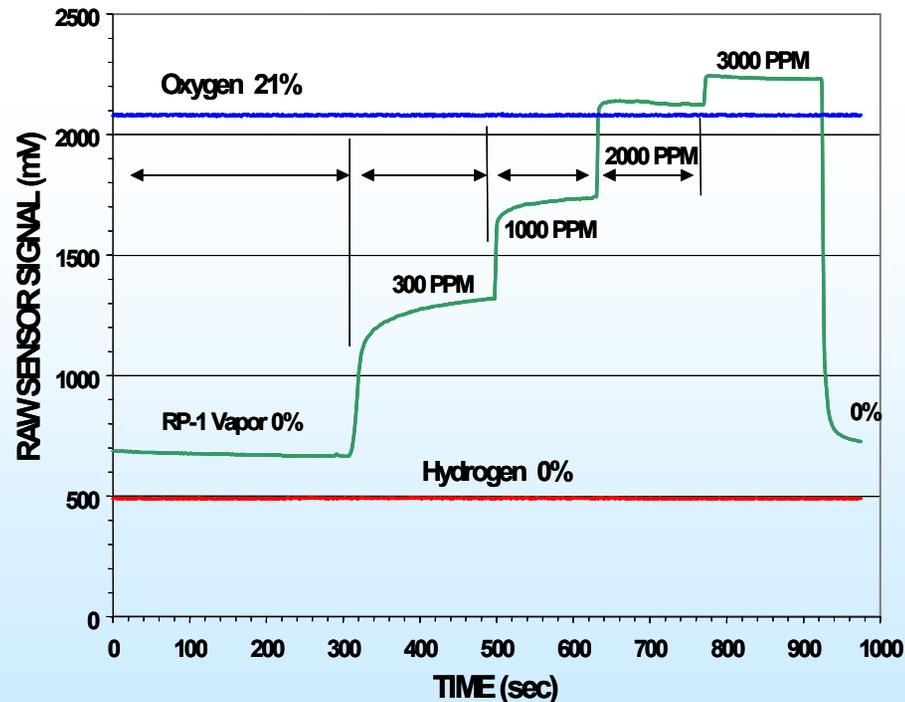
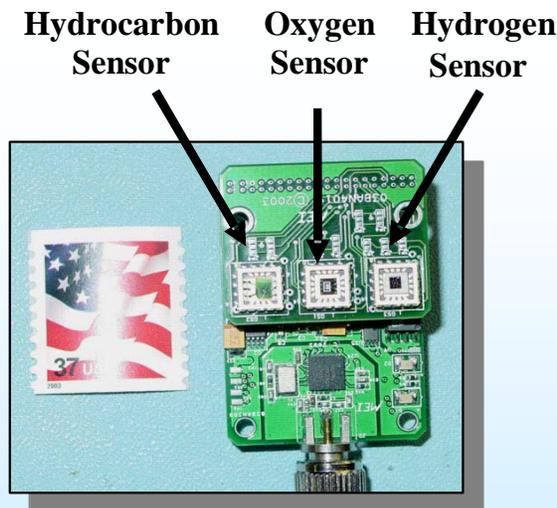
**“Lick and Stick” Leak Detection Electronics and Three Sensors**



**System configured with different wireless antennae.**

# “LICK AND STICK” LEAK SENSOR SYSTEM DEMONSTRATION

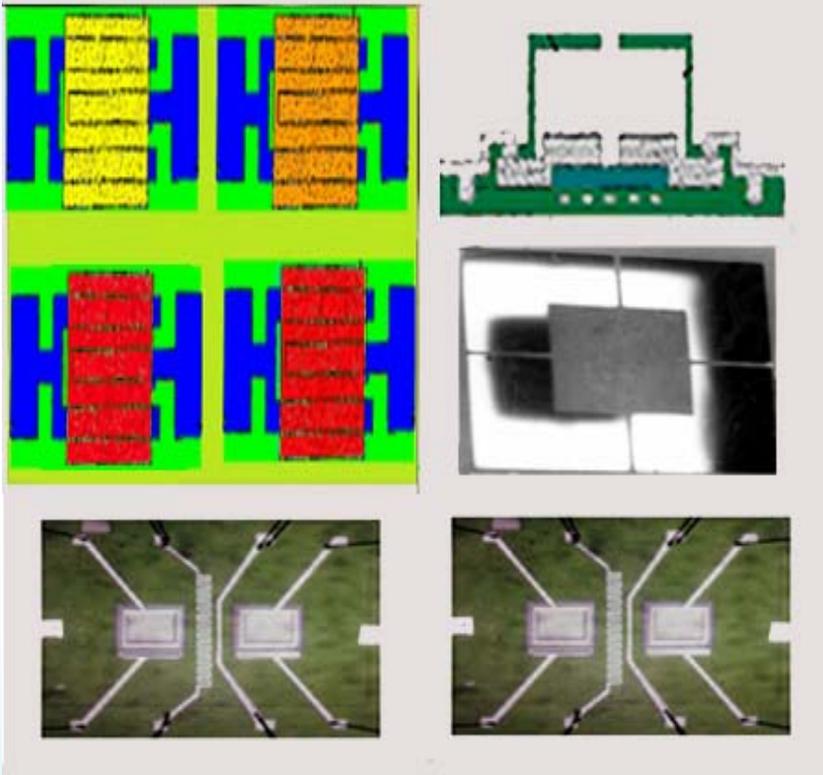
- WIRELESS DEMONSTRATION OF 3 SENSOR SYSTEM ACHIEVED
- BASELINE: ZIRCONIA BASED O<sub>2</sub> SENSOR (ALTHOUGH NAFION BASED ROOM TEMPERATURE SYSTEM BEING MATURED FOR USE)
- LONGEVITY OF SENSOR SYSTEM LIFE ON A BATTERY IS A LIMITATION IN SOME APPLICATIONS
- MOVE FROM HIGH TEMPERATURE SENSOR TECHNOLOGY TO LOWER TEMPERATURE SENSORS
- BEING QUALIFIED FOR CREW LAUNCH VEHICLE APPLICATIONS (HARDWIRED) FOR HYDROGEN DETECTION ONLY



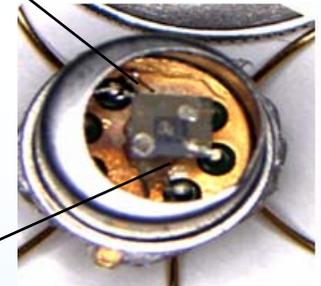
# HIGH TEMPERATURE GAS SENSOR ARRAY HIGH TEMPERATURE ELECTRONIC NOSE

SnO<sub>2</sub> Resistor      TiO<sub>2</sub> Resistor      Electrochemical Oxygen Sensor

Selectively Filtered SnO<sub>2</sub> Resistors



SiC-Based Pressure Sensor



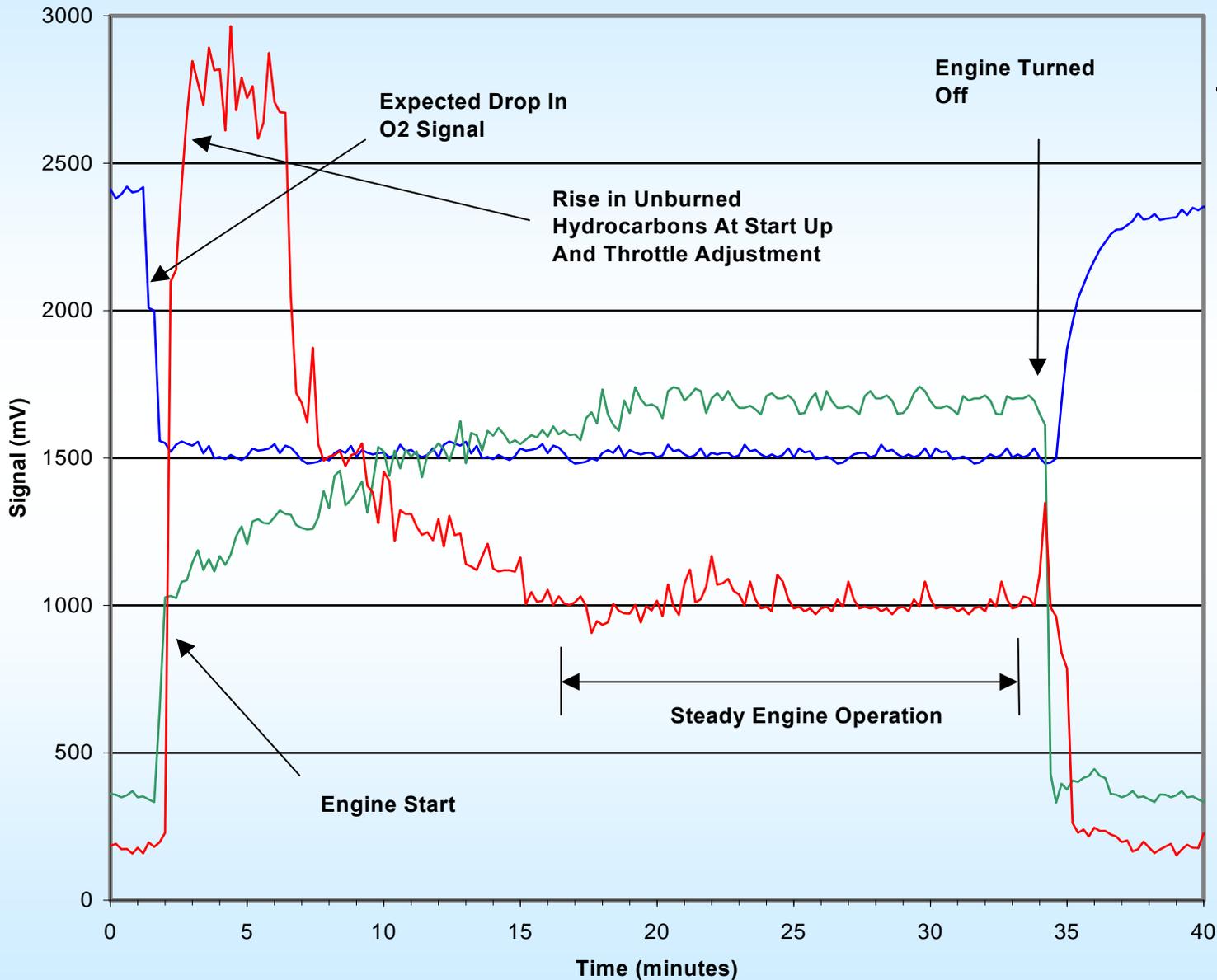
Metal-SiC Schottky diodes

Metal-Reactant Insulator SiC Schottky diodes

# Harsh Environment Demonstration Testing



1.9 liter, four cylinder HC/CI at U.C. Berkeley (propane/air)



**Makel Engineering, Inc.**

Exhaust Gas Temperature = 337 °C  
Phi= 0.35  
O2=14%  
NOx<5 PPM  
CO =1400 PPM  
UHC =1200 PPM

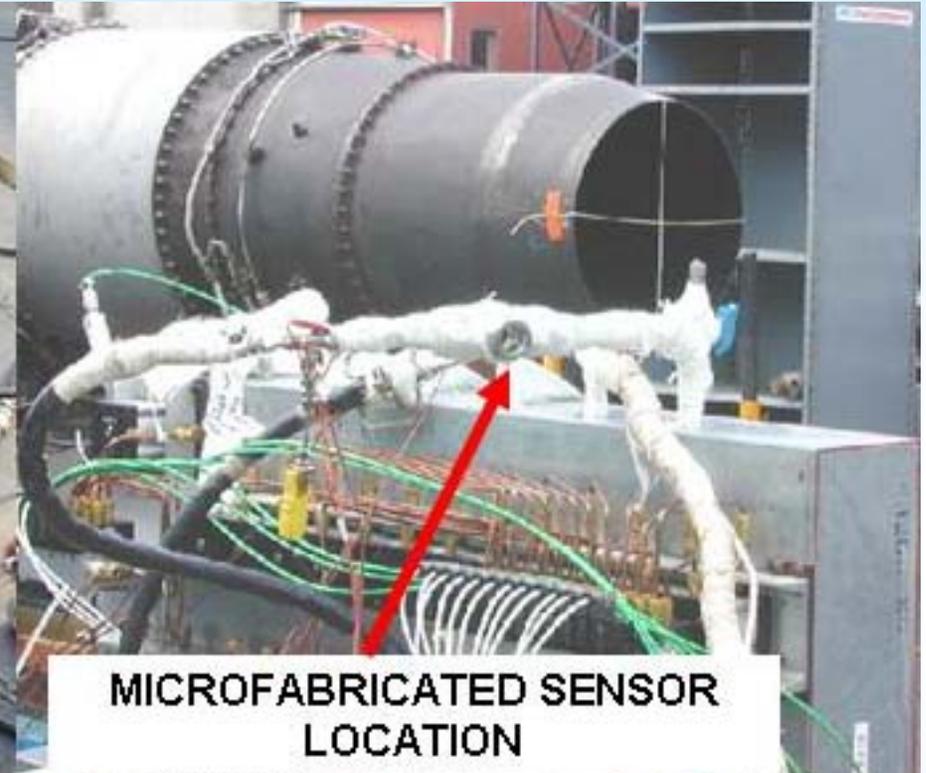
- Oxygen Sensor
- SnO2 Sensor
- SiC Hydrocarbon Sensor



Glenn Research Center



# MICRO SENSORS TESTED AT OUTLET OF THE JT-12 JET ENGINE



**MICROFABRICATED SENSOR LOCATION**

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

**Location Of The Sensors In The Flow Stream Of The Rake**

**HIGH TEMPERATURE OPERATIONAL CAPABILITY AND OF THE SENSORS ALLOW PLACEMENT SIGNIFICANTLY CLOSER TO THE ENGINE OUTLET THAN TRADITIONAL EQUIPMENT.**

# Micro-Fabricated Gas Sensors for Low False Alarms

**2005 R&D 100 AWARD WINNER**

**NASA 2005 TURNING GOALS INTO REALITY AA's CHOICE AWARD**

## FEATURES

### •MICROFABRICATED CO/CO<sub>2</sub> GAS SENSOR ARRAY

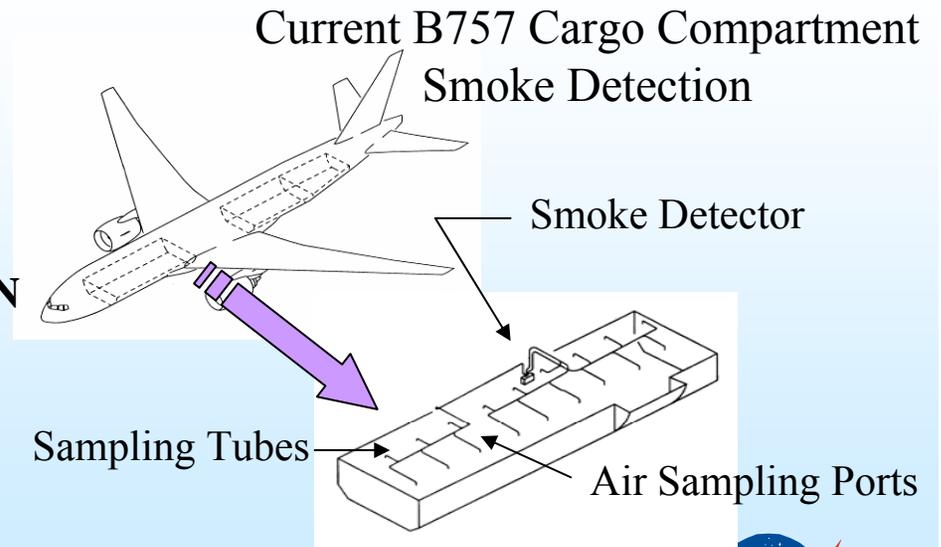
- AIM TO DECREASE FALSE ALARM RATE WHICH IS AS HIGH AS 200:1
- CENTRAL TO APPROACH
- NANOCRYSTALLINE MATERIALS (IN CO SENSOR) PRODUCE MORE SENSITIVE, STABLE SENSORS
- TWO APPROACHES TO CO<sub>2</sub> DETECTION
- MINIMAL SIZE/WEIGHT/POWER

### •CHEMICAL GAS SENSORS PROVIDE GASEOUS PRODUCT-OF-COMBUSTION INFORMATION

- SENSOR ARRAY CAN DETECT RANGE OF GAS SPECIES
- TO BE COMBINED WITH INTELLIGENT SOFTWARE FOR PATTERN RECOGNITION

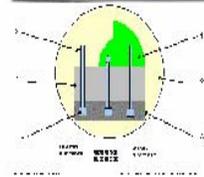
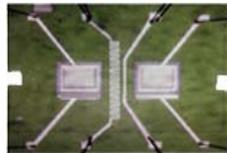
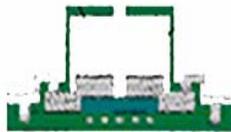
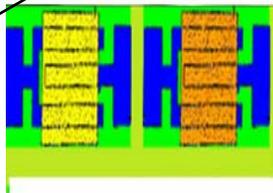
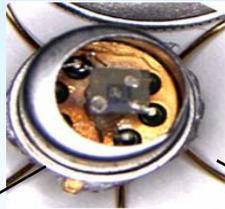
### •BENEFITS

- DISCRIMINATE FIRES FROM NON-FIRES

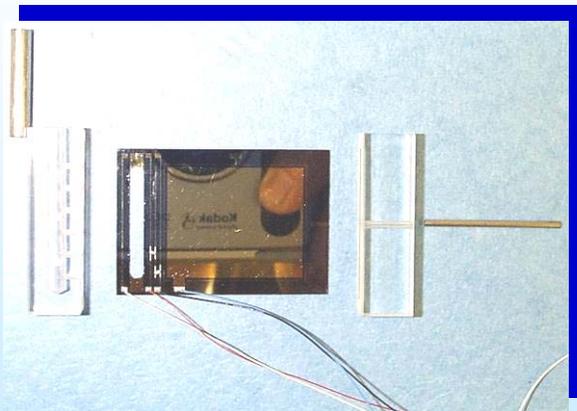


# OVERALL FIRE DETECTION APPROACH FOR SPACE APPLICATIONS:

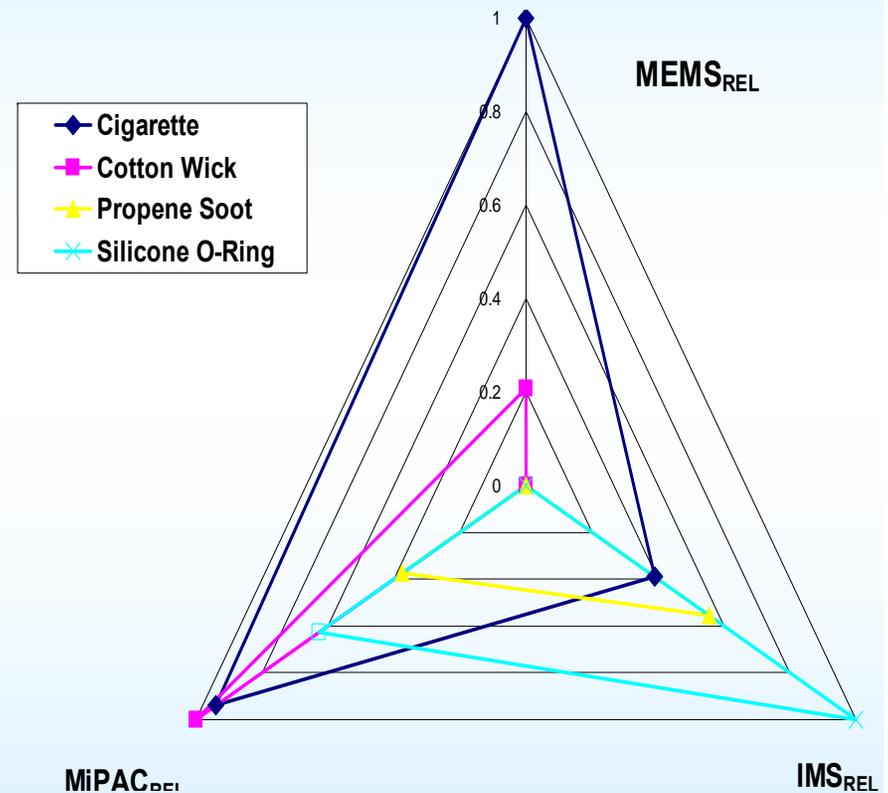
- COMBINED MEMS-BASED CHEMICAL SPECIES AND PARTICULATE
- ORTHOGONAL DETECTION AND CROSS-CORRELATION SIGNIFICANTLY REDUCES FALSE ALARMS



MEMS-Based  
Chemical  
Species  
Detection



MEMS-Based  
Particulate  
Detector

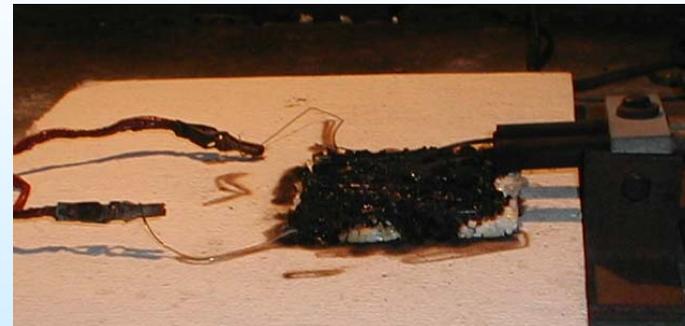
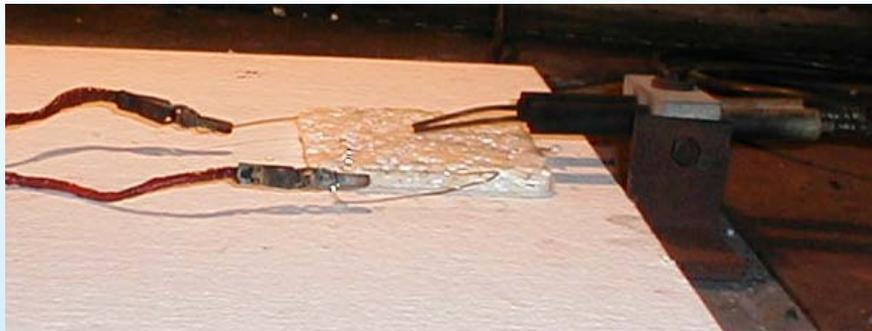
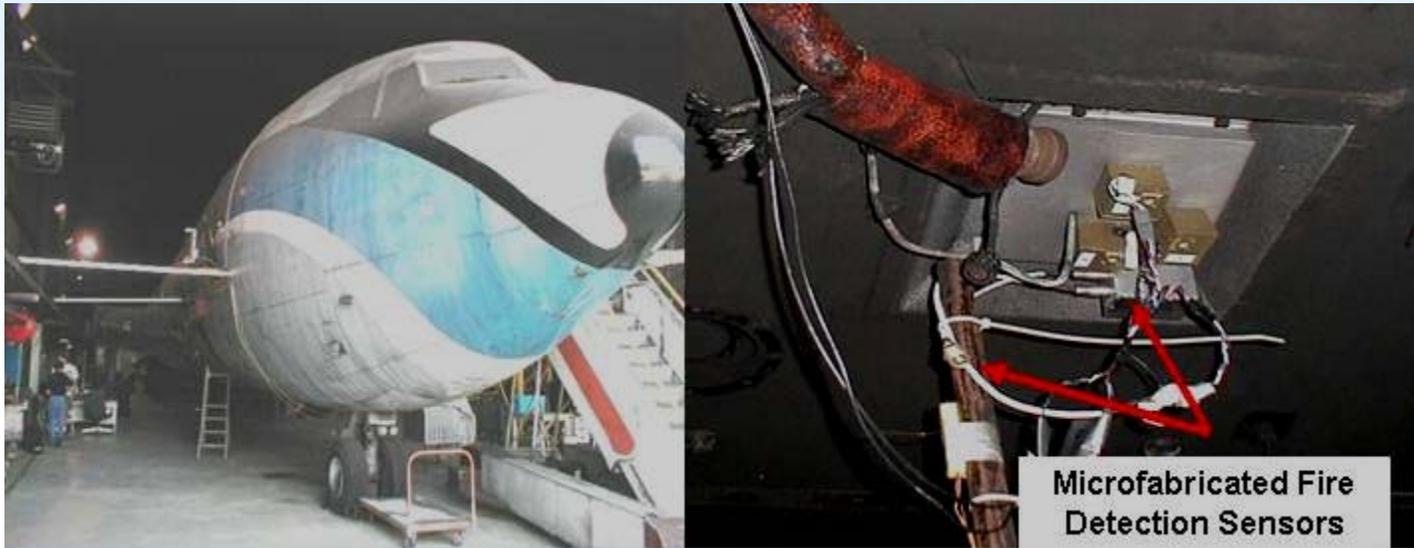


Makel Engineering, Inc.

Glenn Research Center



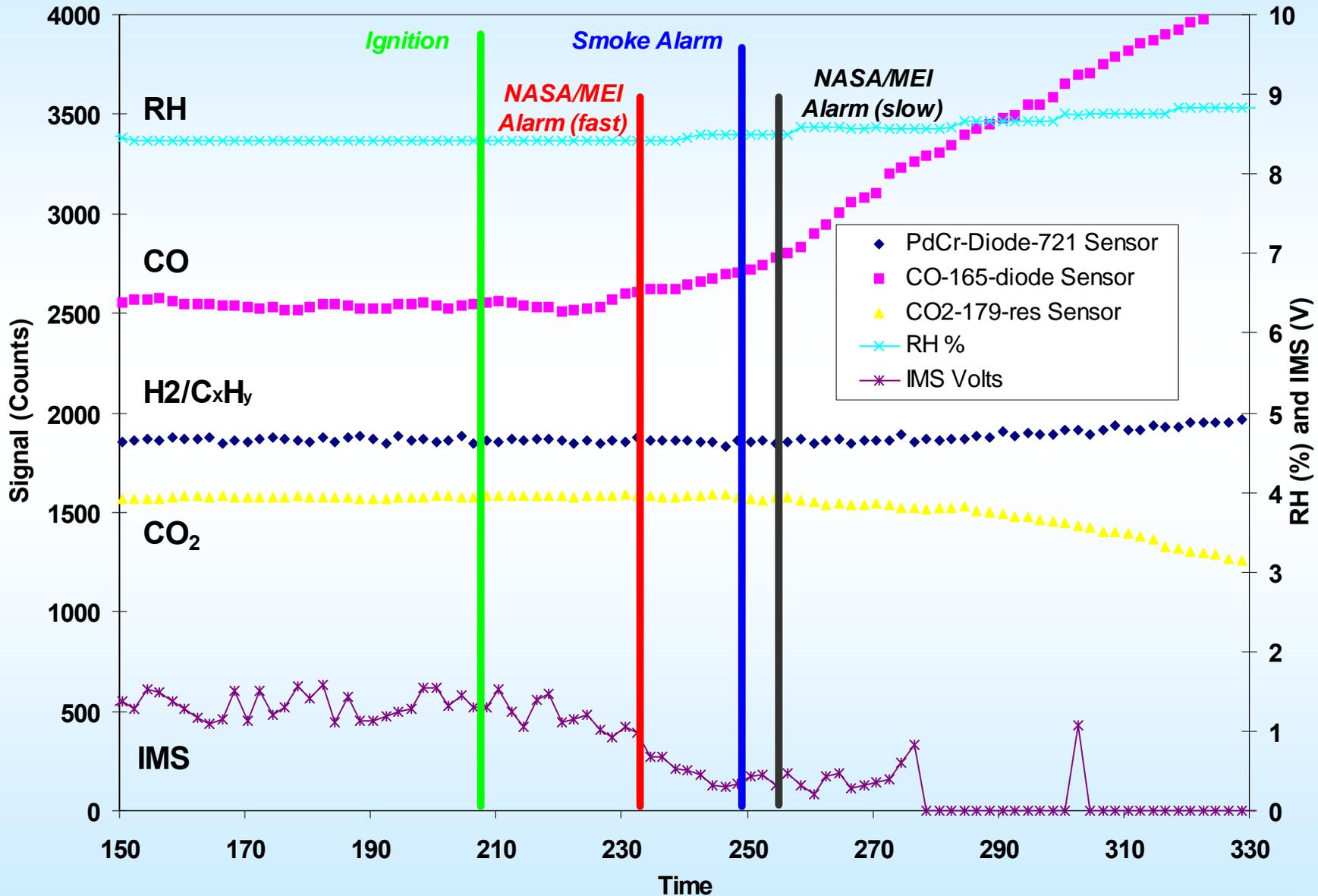
# FAA Cargo Bay Fire Simulation Testing Boeing 707 luggage compartment and the FAA “Biscuit”



# FAA Cargo Bay Fire Testing

## No False Alarms/Consistent Detection of Fires

### Transitioning to Space Fire Applications



## **SUPPORTING TECHNOLOGIES**

**SUPPORTING TECHNOLOGIES OFTEN DETERMINE  
SUCCESS OF SYSTEM**

**HARSH ENVIRONMENT SYSTEMS**



# High Temperature Wireless Development

## OBJECTIVES:

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

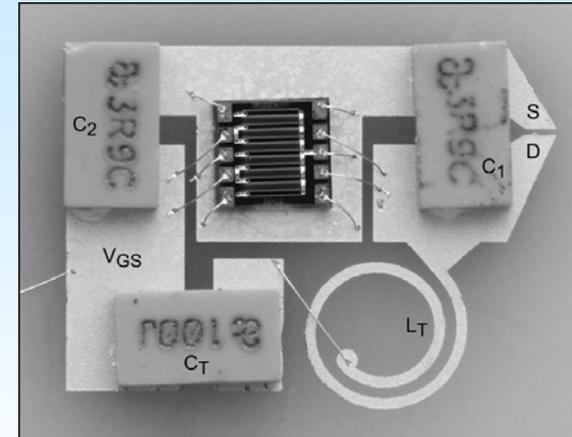
## TECHNICAL CHALLENGES:

- 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

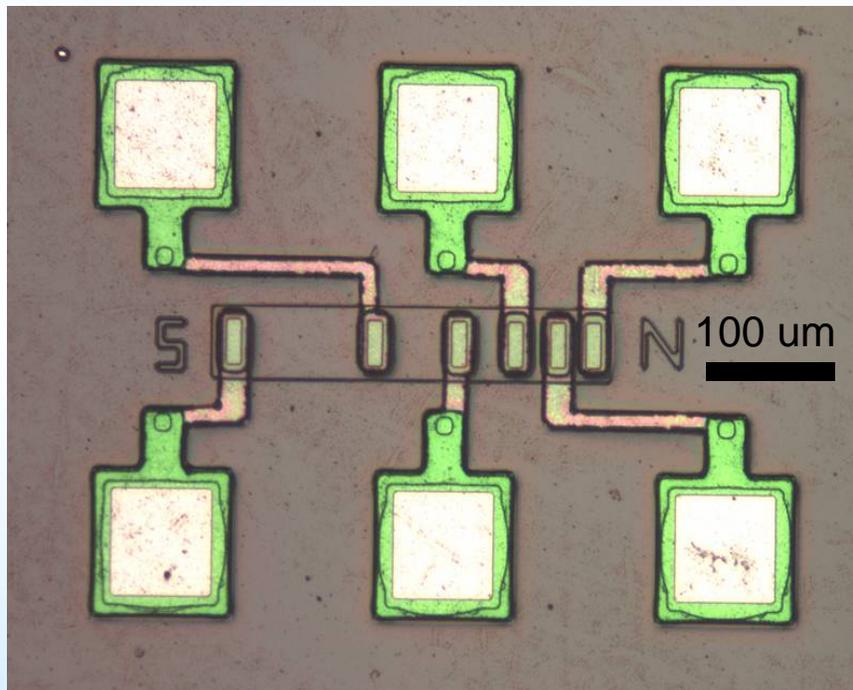


Wires from 1000 Sensors

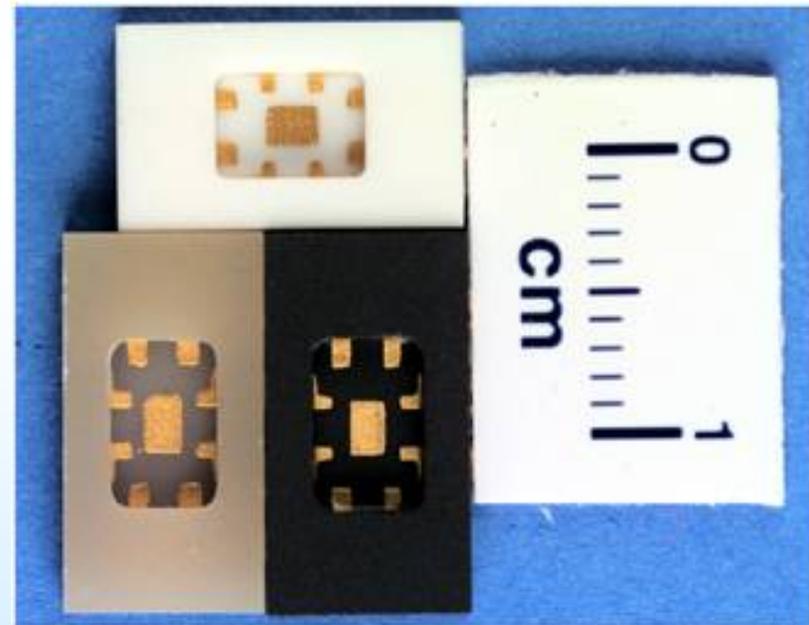
## Previous Key NASA Glenn Advancements

**Key fundamental high temperature electronic materials and processing challenges have been faced and overcome by systematic basic materials processing research (fabrication and characterization).**

500 ° C Durable Metal-SiC Contacts  
(R. Okojie, 2000 GRC R&T Report)



500 ° C Durable Chip Packaging  
And Circuit Boards  
(L. Chen, 2002 GRC R&T Report)

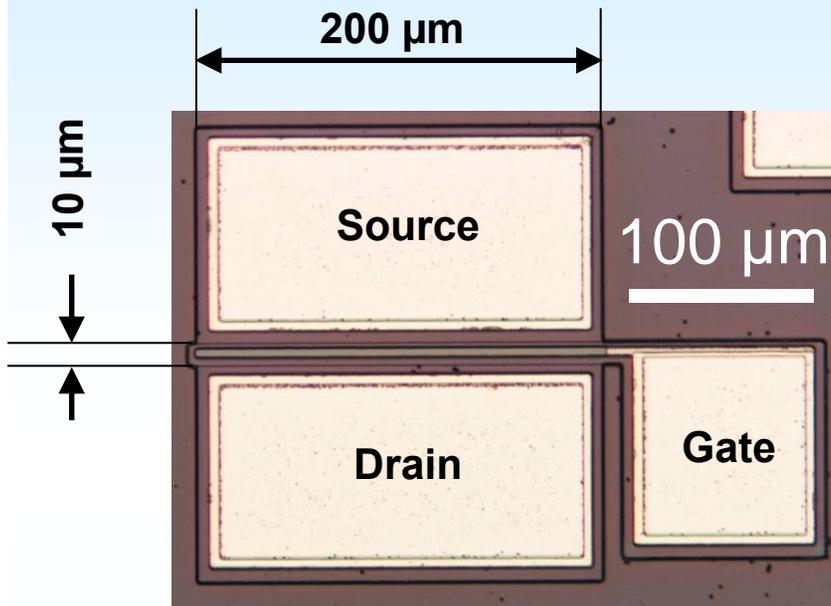


Additional advancements in device design, insulator processing, etc. also made.

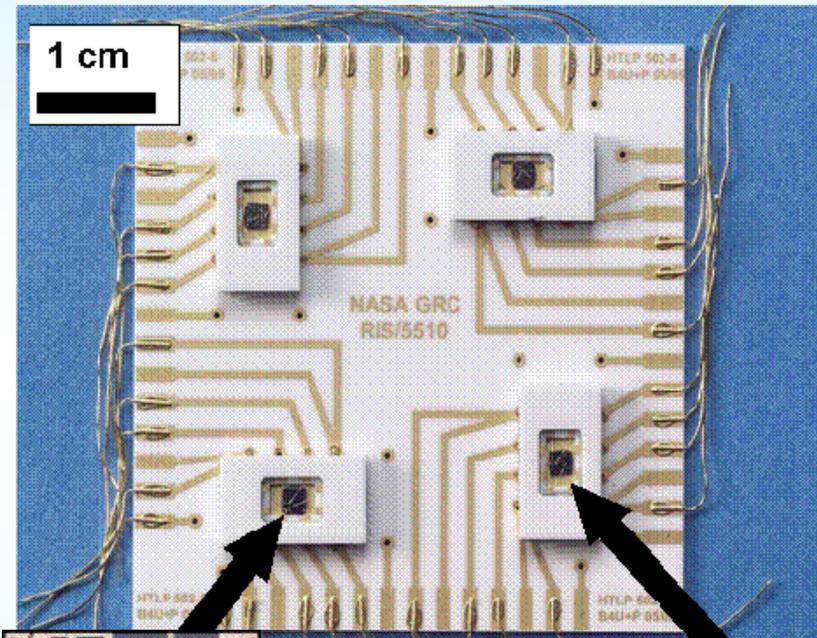
# 6H-SiC Junction Field Effect Transistor (JFET) Fabricated by NASA Glenn Research Center

Tech Accomplishments  
(IVHM v1.5 MS 1.3.5)

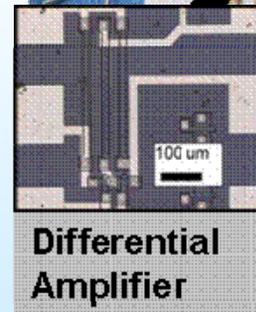
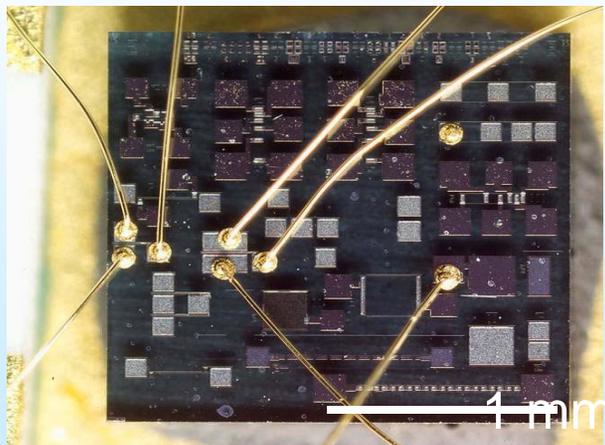
### 200 $\mu$ m/10 $\mu$ m 6H-SiC JFET



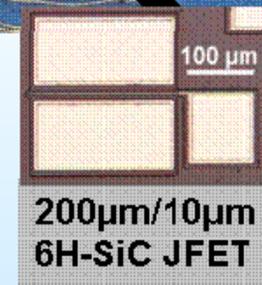
### Multiple devices in Ceramic Packaging



### Packaged with bond wires



### Differential Amplifier



### 200 $\mu$ m/10 $\mu$ m 6H-SiC JFET

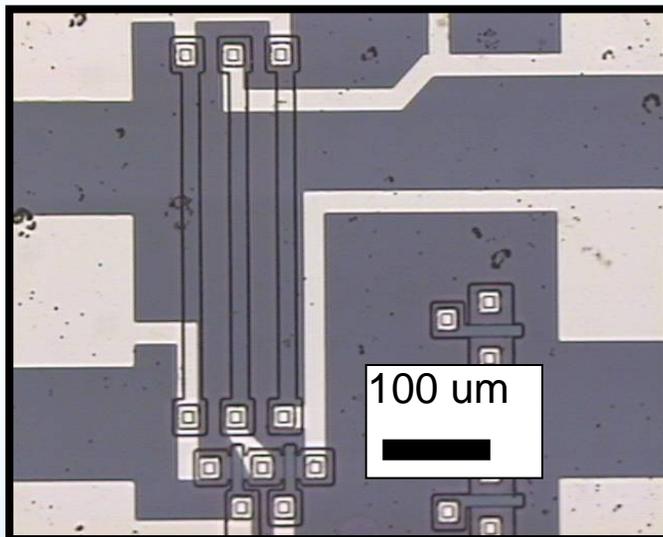
# NASA Glenn Silicon Carbide Differential Amplifier

Tech Accomplishments  
(IVHM v1.5 MS 1.3.5)

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

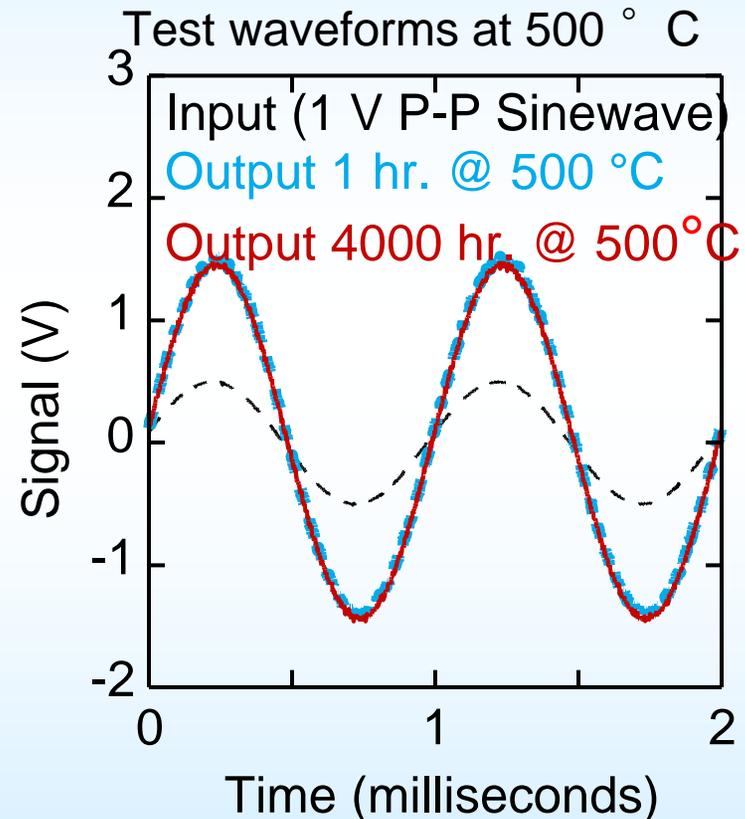
Demonstrates CRITICAL ability to interconnect transistors and other components (resistors) in a small area on a single SiC chip to form useful integrated circuits that are durable at 500 ° C.

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.

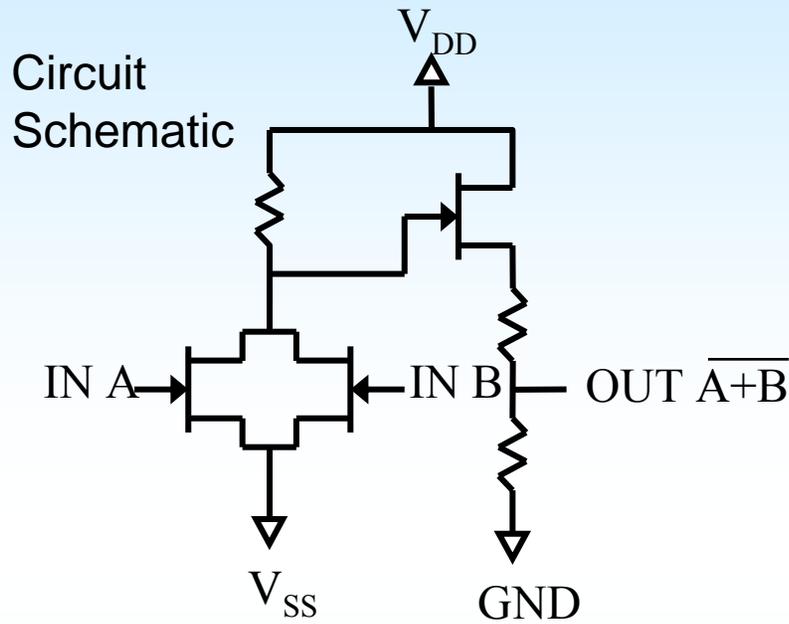


Less than 5% change in operating characteristics during 4000 hours of 500 ° C operation.

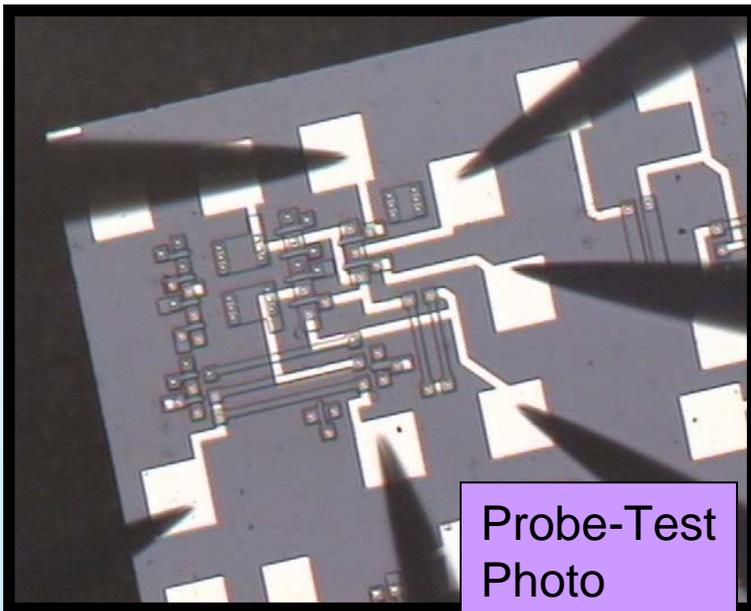
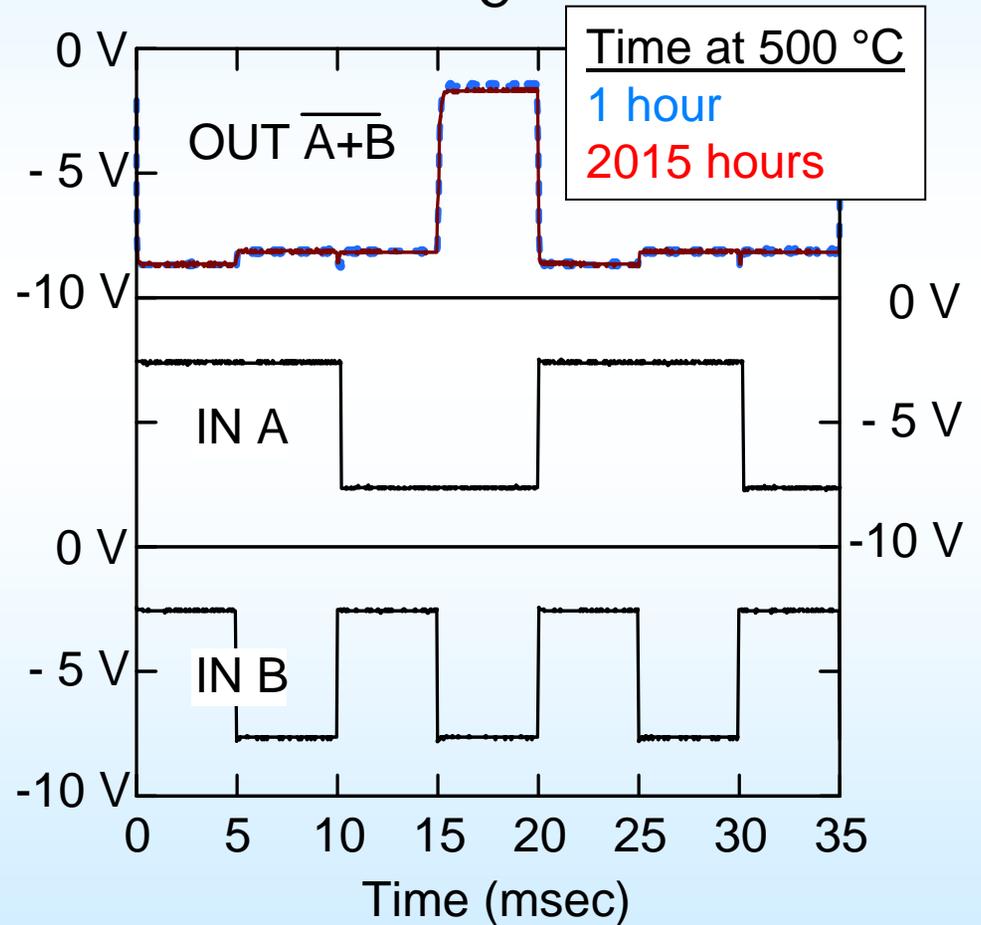
# NASA Glenn SiC JFET NOR Gate IC

Tech Accomplishments  
(IVHM v1.5 MS 1.3.5)

**World's First Semiconductor Digital IC to  
Surpass 2000 hours of 500° C Operation**



Waveforms of **packaged**  
NOR (= "Not OR") gate at 500  
° C



Probe-Test  
Photo

Glenn Research Center



***SIGNIFICANCE OF RECENT ELECTRONICS RESULTS  
THE BASIC HARDWARE TOOLS FOR HIGH TEMPERATURE DATA PROCESSING  
HAVE BEEN FABRICATED***

- ◆ **THESE RESULTS HAVE BEEN THE SUBJECT OF A HIGH LEVEL OF VISIBILITY  
E.G. NASA TOP 10 DISCOVERY STORIES FOR 2007**
- ◆ **DURABLE HIGH TEMPERATURE IC'S WILL ENABLE IMPORTANT NEW  
CAPABILITY**
  - Enabled by fundamental electronic materials research.
  - **World record IC durability at 500 ° C (> 400-fold improvement).**
  - Inherently up-scalable to high circuit complexity while remaining physically small.
- ◆ **THIS DEMONSTRATION SHOWS THAT IT IS NOW POSSIBLE TO CONSTRUCT  
MORE COMPLEX CIRCUITS OPERATING AT 500 °C AND MINIATURIZED.**
- ◆ **LOGIC GATES GENERATE FLIP-FLOPS THAT CAN GENERATE STATE-  
MACHINES TO ENABLE:**
  - Creation Of Control Electronics For An “Intelligent” Fixed Or Mobile Agent
  - The Configuration Of Intelligent Data Transmission Methods Allowing For Unambiguous Demodulation Of Signals Uniquely Associated With Each Sensor/Transmitter In A Network.



**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**

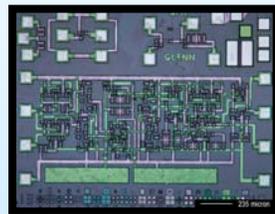
**Milestone: Demonstrate High Temperature Sensing, Wireless Communication,  
and Power Scavenging for Propulsion Health Management  
8/30/2011**

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

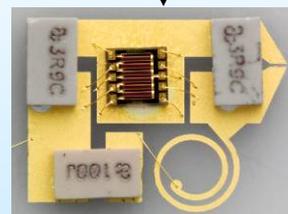
Significant wiring  
exists with present  
sensor systems



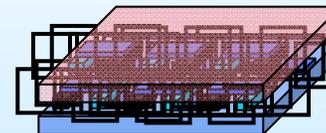
**Allow Sensor Implementation by Eliminating Wires**



World Record High  
Temperature Electronics  
Device Operation



High Temperature RF  
Components



Energy Harvesting  
Thin Film  
Thermoelectrics

**SENSOR SYTEM APPLICATION**  
**SYSTEM TESTING TO MOBILITY**



**FUTURE APPLICATIONS  
LICK AND STICK SYSTEMS  
BRIEF LIST OF LAUNCH, IN-SPACE, AND LUNAR APPLICATIONS**

**LAUNCH**



**Propellant Leaks  
Toxic Gas Leaks**

**IN-SPACE**



**Propellant Fuel Leaks  
Toxic Gas Leaks  
Environmental Monitoring  
Fire Detection  
EVA**

**LUNAR**



**Propellant Fuel Leaks  
Toxic Gas Leaks  
Environmental Monitoring  
Fire Detection  
EVA/ISRU Applications**

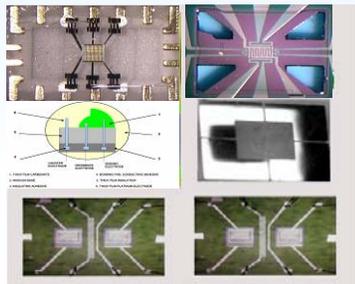


# SUMMARY

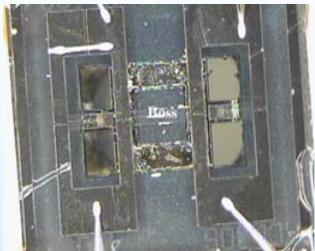
## TOOLS TO ENABLE NEW MISSIONS

### EXAMPLE POSSIBLE MISSION: Venus Integrated Weather Sensor (VIWS) System

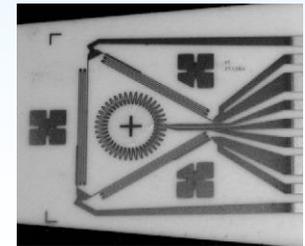
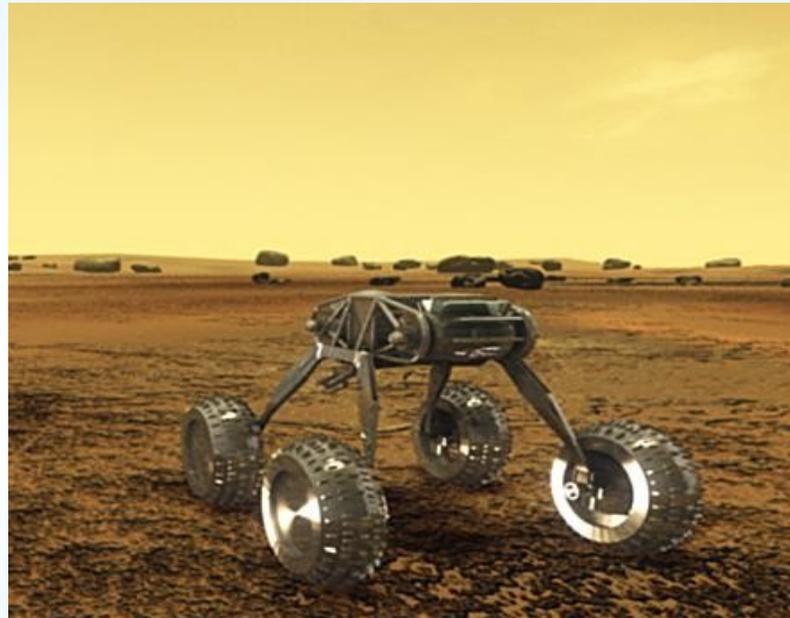
Sensor Suite to Monitor Venus Weather Conditions including: **Data Processing and Communication, Wind Flow, Seismic, Pressure/Temperature/Heat Flux, Chemical Environment**



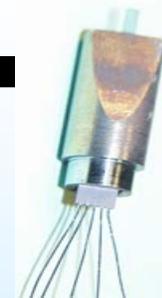
**HIGH TEMPERATURE  
ELECTRONIC NOSE  
(Chemical Species)**



**Hi-g SiC  
ACCELEROMETER  
(Seismic Activities)**



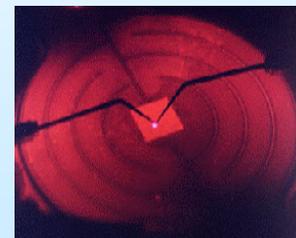
**MULTIFUNCTIONAL  
PHYSICAL SENSOR ARRAY  
(Temperature, Heat Flux)**



**HOTProbe  
(Wind flow,  
Pressure,  
Temperature)**



**PRESSURE  
SENSOR  
(Pressure)**



**SiC ELECTRONICS  
(Data Processing  
and Com)**



# One Potential Vision: “Smart” Suit

- Development of a “Smart” Suit which has self-monitoring, caution and warning, and control capabilities with high levels of reliability, durability, and safety.
- Small, lightweight, low power sensor systems, with increased packaging flexibility, will improve the effectiveness and extensibility of the EVA suits.
- Seamless integration of sensors throughout EVA system improving reliability and capability without significantly increasing system wiring and power.
- Monitor Both Inside And Outside the EVA Suit for Astronaut Health and Safety\Suit Maintenance
  - **Inside: For Example, Monitor Suit CO<sub>2</sub>, O<sub>2</sub>, Flow to Allow Metabolic Measurements**
  - **Outside: For Example, Monitor Dust/Toxic Gas/Dangerous Conditions Before Brought Back Into Airlock Or Can Affect Astronaut Safety**
- Include Ability to Determine Astronaut Health by Monitoring of Breath

A “**Smart**” Suit Needs To Monitor Both Internal And External Conditions



Breath Sensor System – includes mouthpiece for breath collection, Nafion drying tube in sample line, sensor manifold with PDA interface, and mini sampling pump



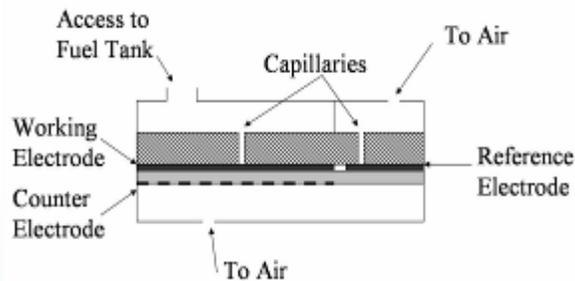
## SENSOR SYSTEM IMPLEMENTATION

- **OBJECTIVE: A SELF-AWARE SYSTEM COMPOSED OF SMART COMPONENTS MADE POSSIBLE BY SMART SENSOR SYSTEMS**
- **SENSOR SYSTEMS ARE NECESSARY AND ARE NOT JUST GOING TO SHOW UP WHEN NEEDED/TECHNOLOGY BEST APPLIED WITH STRONG INTERACTION WITH USER**
- **SENSORS SYSTEM IMPLEMENTATION OFTEN PROBLEMATIC**
  - **LEGACY SYSTEMS**
  - **CUSTOMER ACCEPTANCE**
  - **LONG-TERM VS SHORT-TERM CONSIDERATIONS**
  - **SENSORS NEED TO BUY THEIR WAY INTO AN APPLICATION**
- **SENSOR DIRECTIONS INCLUDE:**
  - **INCREASE MINIATURIZATION/INTEGRATED INTELLIGENCE**
  - **MULTIFUNCTIONALITY/MULTIPARAMETER MEASUREMENTS/ORTHOGONALITY**
  - **INCREASED ADAPTABILITY**
  - **COMPLETE STAND-ALONE SYSTEMS (“LICK AND STICK” SYSTEMS)**
- **POSSIBLE LESSONS LEARNED**
  - **SENSOR SYSTEM NEEDS TO BE TAILORED FOR THE APPLICATION**
  - **MICROFABRICATION IS NOT JUST MAKING SOMETHING SMALLER**
  - **ONE SENSOR OR EVEN ONE TYPE OF SENSOR OFTEN WILL NOT SOLVE THE PROBLEM: THE NEED FOR SENSOR ARRAYS**
  - **SUPPORTING TECHNOLOGIES OFTEN DETERMINE SUCCESS OF A SYSTEM**



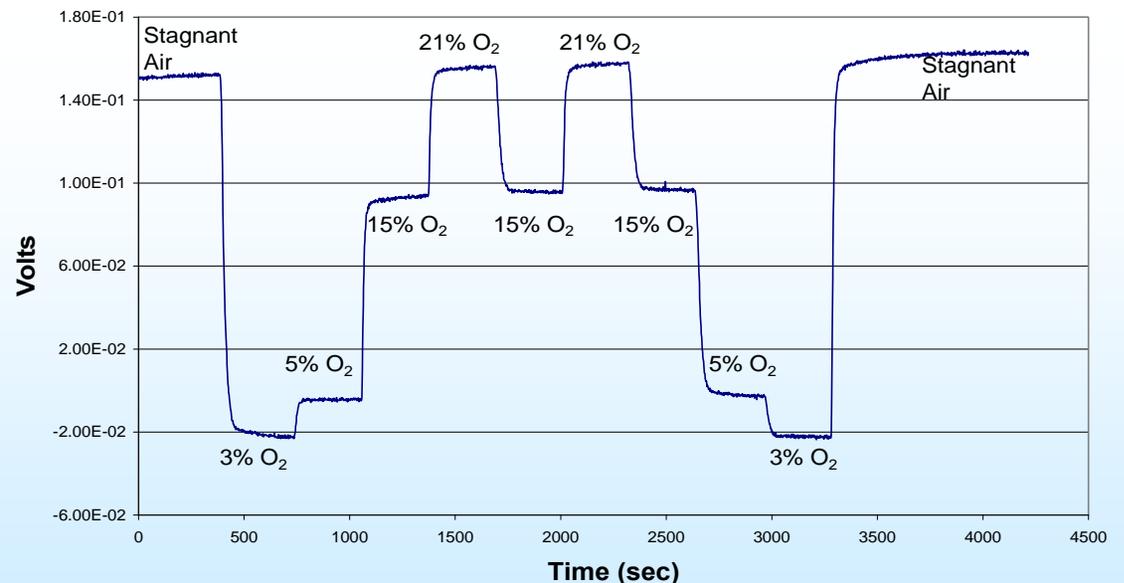
# ROOM TEMPERATURE O<sub>2</sub> SENSOR TECHNOLOGY

- POSSIBLE REPLACEMENT FOR PRESENT LIQUID ELECTROCHEMICAL CELL TECHNOLOGY
- VIABILITY FOR SPACE BASED APPLICATIONS MUST BE VERIFIED THROUGH AN EXTENSIVE TEST PROGRAM.
- ONE SIGNIFICANT LESSON OF PREVIOUS ISS IMPLEMENTATION IS THAT TESTING IN RELEVANT ENVIRONMENTS OVER THE REQUIRED SENSOR LIFE IS MANDATORY
- FIND THE ISSUES ON THE GROUND OR LAB AND NOT AFTER IT HAS BEEN DEPLOYED ON THE VEHICLE IN SPACE
- TEST TO FAILURE AND ANALYZE THE FAILURE IF POSSIBLE



NAFION O<sub>2</sub> Sensor Structure

200ccm dry O<sub>2</sub> with N<sub>2</sub> balance - O<sub>2</sub> potentiostat



Preliminary NAFION O<sub>2</sub> Sensor Data

# WHITE SANDS TEST FACILITY O2 SENSOR TESTING

- TESTING OCCURRED SIDE BY SIDE WITH EXISTING ISS SENSOR SYSTEMS FOR ISS ENVIRONMENTAL MONITORING AT WHITE SANDS TEST FACILITY
- TESTING OCCURRED OVER A RANGE OF PRESSURES AND O2 CONCENTRATIONS INTEGRATED WITH ELECTRONICS AND PRESSURE COMPENSATION
- REPEATED CYCLES OVER SEVERAL TEST PERIODS APPROXIMATED ~8 YEARS OF ISS OPERATION
- ACCURACY OF CALIBRATION, REPEATABILITY OF DATA, RESPONSE TIME WERE MAJOR OF EVALUATION CRITERIA
  - THIS IS A CRIT 1 (RELATED TO LIFE OF CREW) FUNCTION WITH STRICT CALIBRATION/PERFORMANCE REQUIREMENTS (+/-0.8%)
- MAJOR FINDING: SENSOR FAILURE MECHANISMS IDENTIFIED

Present commercial  
ISS O2 sensors



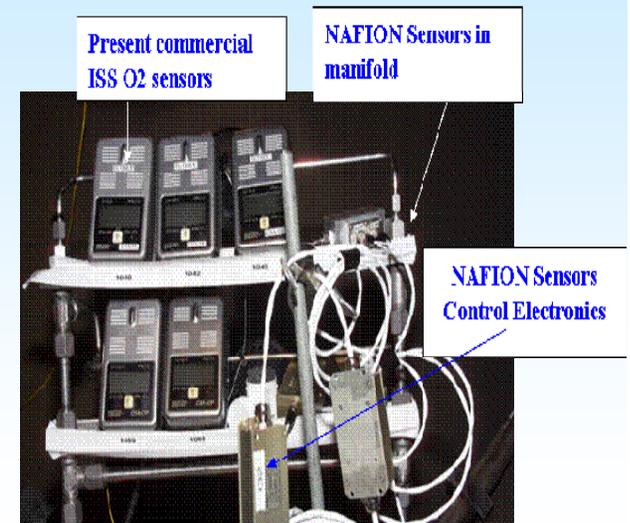
NAFION Sensors in  
manifold

NAFION Sensors  
Control Electronics

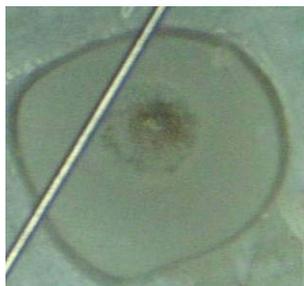
NAFION based oxygen sensor (left) and sensors during piggyback testing with NASA CSA-O2 systems

# PROGRAM RESULTS: ROOM TEMPERATURE O2 SENSORS CHANGES IN RESPONSE TO WHITE SANDS TESTING

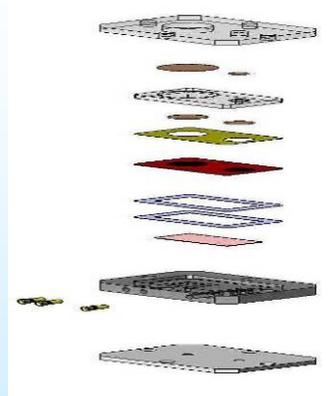
- 2.5 YEARS OF LIFE DURING BENCH TESTING/8 YEARS OF EQUIVALENT PRESSURE TESTING
- ROOM TEMPERATURE O2 SENSORS VIABLE FOR CRIT 1 ISS FUNCTION
  - SENSOR RESPONSE TIME, SENSITIVITY, CALIBRATION CAPABILITY
- LIFETIME OF O2 SENSORS WAS DETERMINED/PRIMARY GOAL OF PROJECT
  - FAILURE MODE WAS THAT THE O2 SENSORS STARTED DRIFTING OUTSIDE OF ALLOWABLE CRIT 1 TOLERANCES FOR O2 PERCENTAGE.



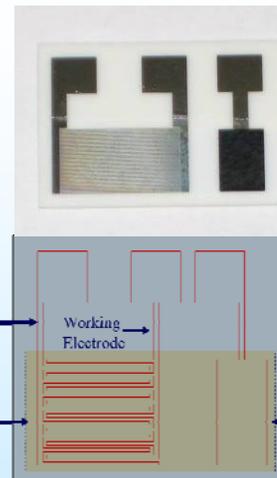
TESTING AT WHITE SANDS



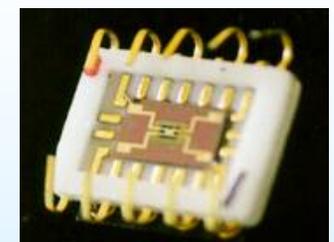
Example Failure Mechanism: Diffusion Hole Breakdown



Present Sensor Structure



Sputtered Based Three Electrode System



Batch Processed MEMS based Packaged Sensor

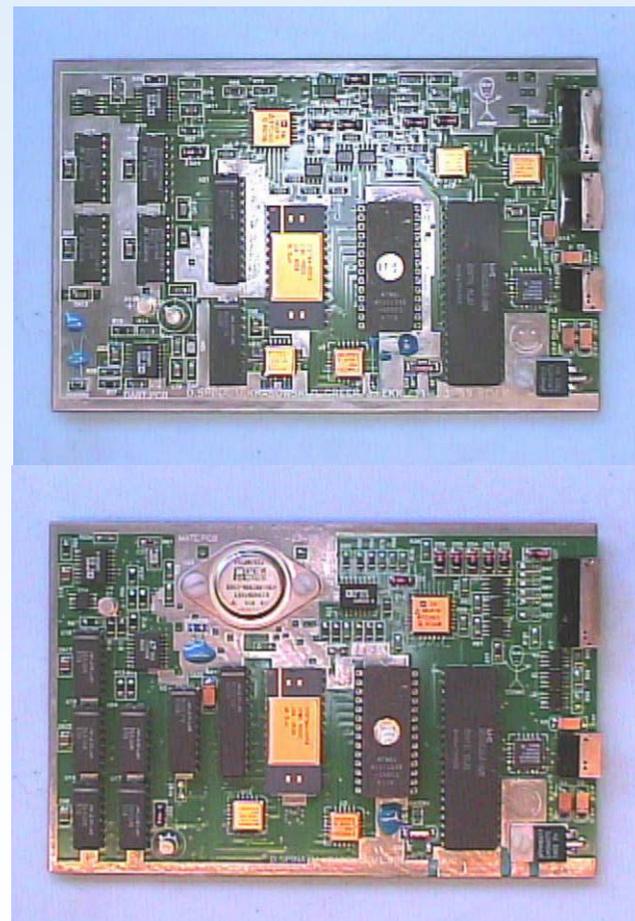
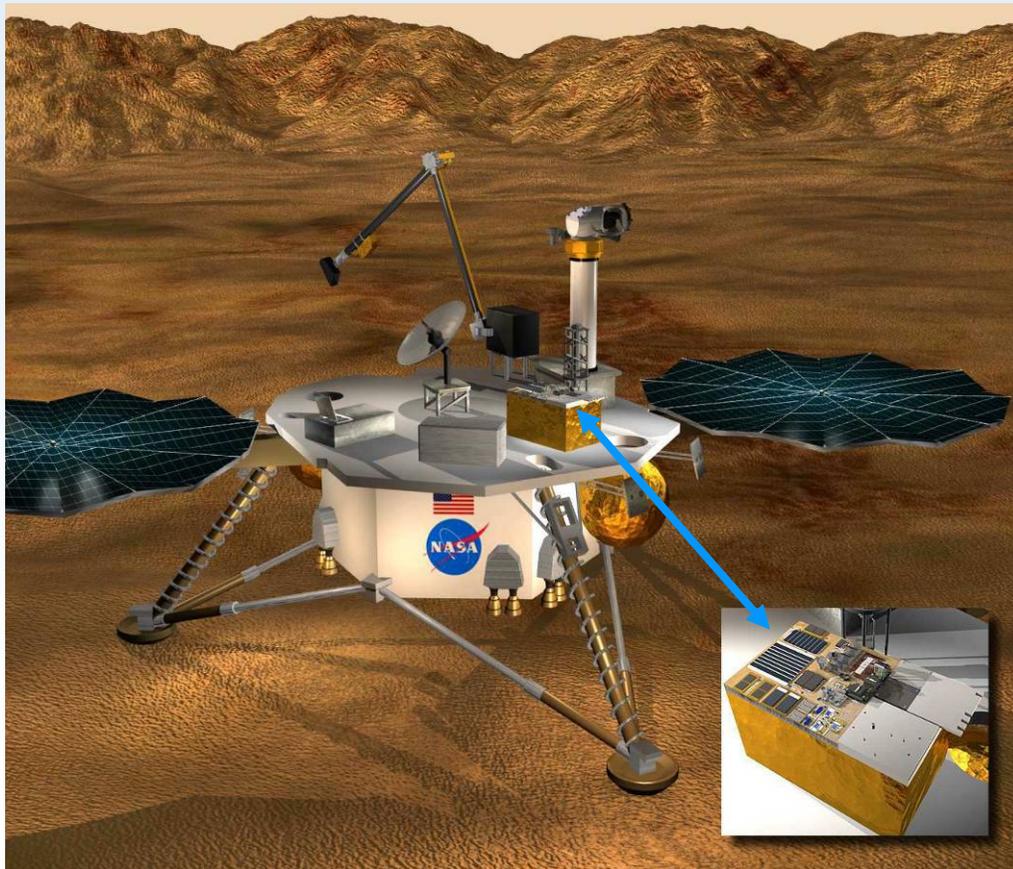




# GRC Instrumentation For Space

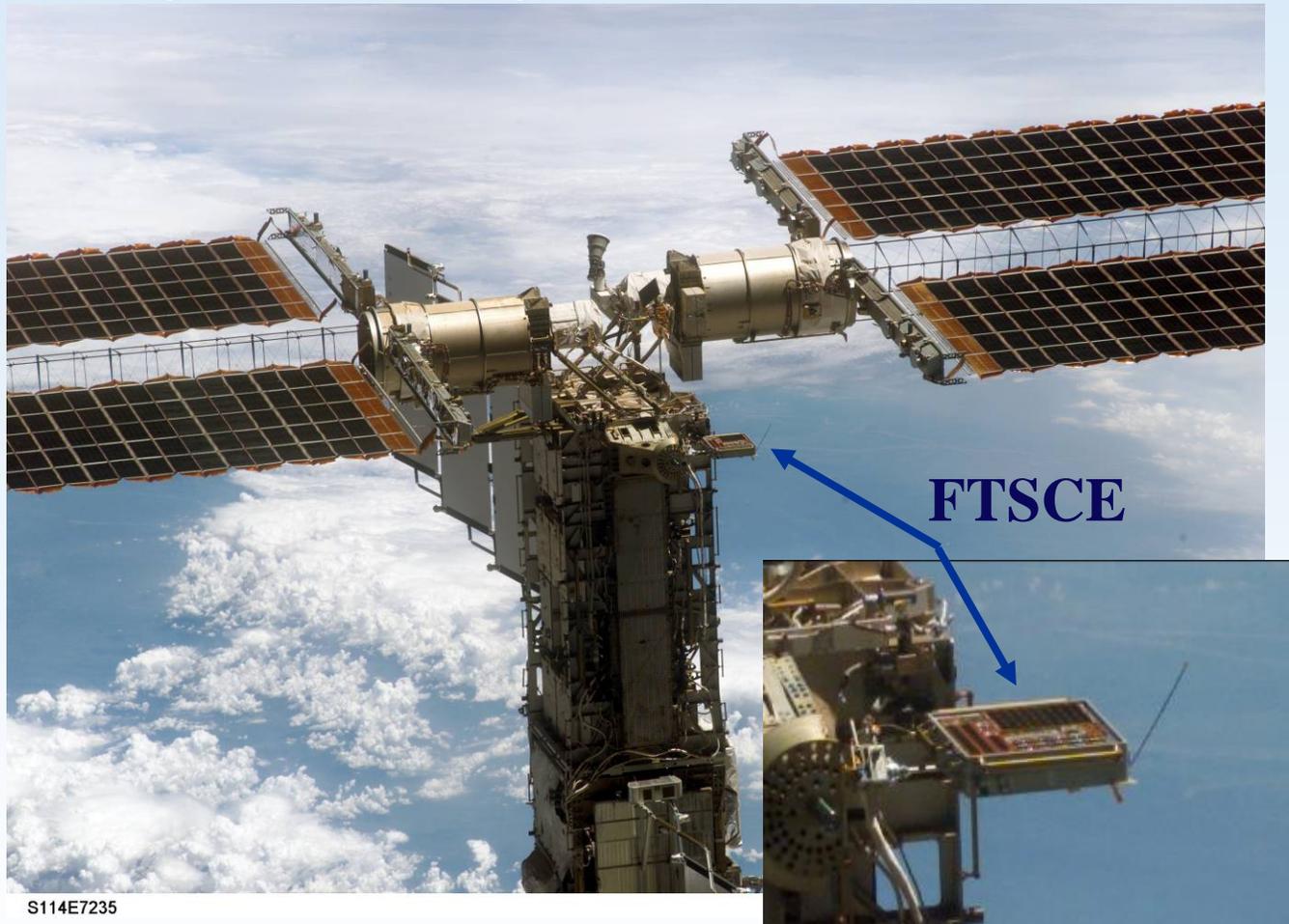
Designed, Built, Programmed & Qualified In-House

- 2001 – **Mars In-Situ Propellant Precursor (MIPP): Mars Array Technology Experiment and Dust Accumulation and Removal Technology (MATE & DART)**
  - Complete MIPP experiment top plate and circuit board set development to characterize multiple solar cell technologies and perform dust characterization and mitigation.



# GRC Instrumentation For Space

Designed, Built, Programmed & Qualified In-House



Forward Technology Solar Cell Experiment (FTSCE) as part of 5th Materials on the International Space Station Experiment (MISSE-5)  
Attached to the P6 Solar Panel Strut

# GRC Instrumentation For Space

Designed, Built, Programmed & Qualified In-House

- July 2005 – **Forward Technology Solar Cell Experiment (FTSCE)** as part of 5th Materials on the International Space Station Experiment (**MISSE-5**)
  - **First Ever Active Experiment in MISSE Series**
  - 36 present and new solar cell technologies being exercised while directly exposed to Low Earth Orbit
  - Various temperature, sun position and radiometry sensors
  - **Operating through ground command radio link and autonomously through internal schedule, sun position and temperature**
  - **After a successful one year mission, FTSCE was returned to Earth and will be refurbished at GRC and flown again on MISSE-7**



# GRC Mobile Sensor and Instrumentation Platforms

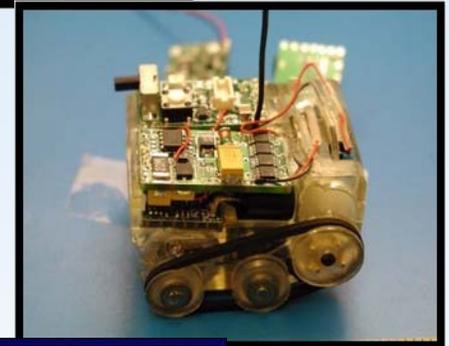
## First Generation sensor platform:

- video
- packetized one way command link



## Second Generation size shrink

- with two way command and data path
- real time video
- multi-agent slotted network protocol



## Telerobotics

- Sensor Platform Area Network (SPAN)
- two agent control over the Internet
- streaming video
- each agent owns state vector of the other

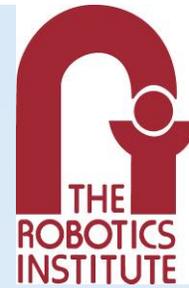


## Group Awareness and Behavior

- sensing the presence and position of other robot(s)
- near field sensing and communications channel
- mimics weakly electric fish



# Highlander Lunar Rover Initiative



**“Cratos” - Lunar Rover Test Mule  
Operating at NASA GRC**

**NASA GRC and The Robotics Institute  
at Carnegie Mellon University Co-  
Developing Tracked Rovers Capable of  
Autonomous Descent and Ascent of  
Crater Walls**

**Carnegie Mellon Highlander Design  
Benefits From Instrumentation and Motion  
Control Electronics and Algorithms  
Designed, Built and Tested in Cratos at  
GRC.**

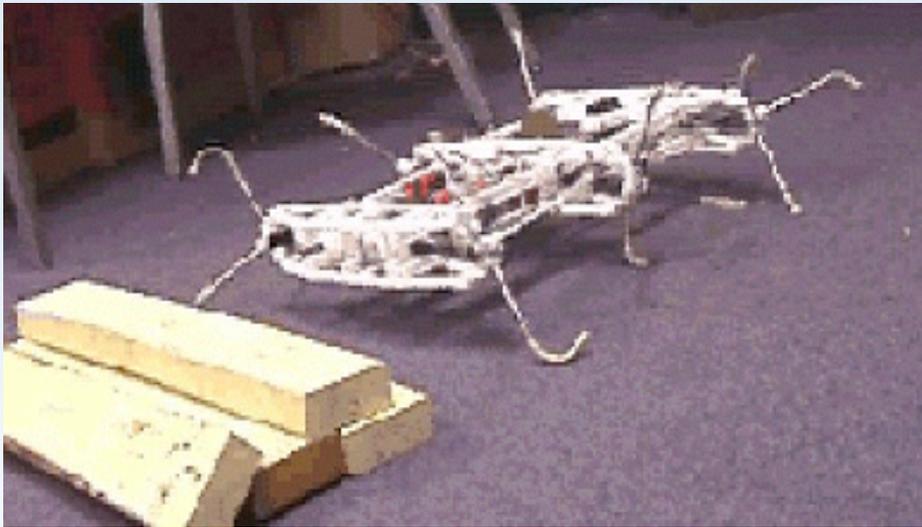


**CMU Highlander Rover**



## GRC and Case Western Reserve University Collaborative Effort In Biologically Inspired Robots: Whegs™

Whegs™ robots combine the advantages of combining wheels and legs and mimic the tripod gate used by the common Cockroach. Whegs allow a robot to climb over objects that are much higher than could be overcome using wheels.



An experimental Whegs in the laboratory

<http://biorobots.cwru.edu/projects/whegs/>



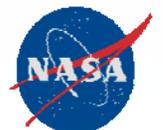
A step in environmentally hardening a Wheg

**Whegs™ can also be hardened to swim on or under water and would make superb lake bottom crawlers**

**GRC and CWRU are hardening Whegs™ as potential Lunar, Mars and terrestrial sensor platforms**

**HOW DOES ONE MAKES SENSE OF ALL THIS**

**SENSOR DATA QUALIFICATION**



# Sensor Implementation Considerations

## For Ares I Crew Launch Vehicle

- **Each abort algorithm requires detection and confirmation of the condition**
  - Requires multiple hardware redundant measurements of the same property (homogeneous sensors)

OR

- Require analytical redundancy with correlation of sensors measuring different, but related properties (heterogeneous sensors)
- **Flight Computer Software must provide data qualification on all flight critical sensors.**
  - Due to design constraints (e.g. cost, weight and heritage hardware) utilization of existing homogeneous and heterogeneous redundant sensors may be required



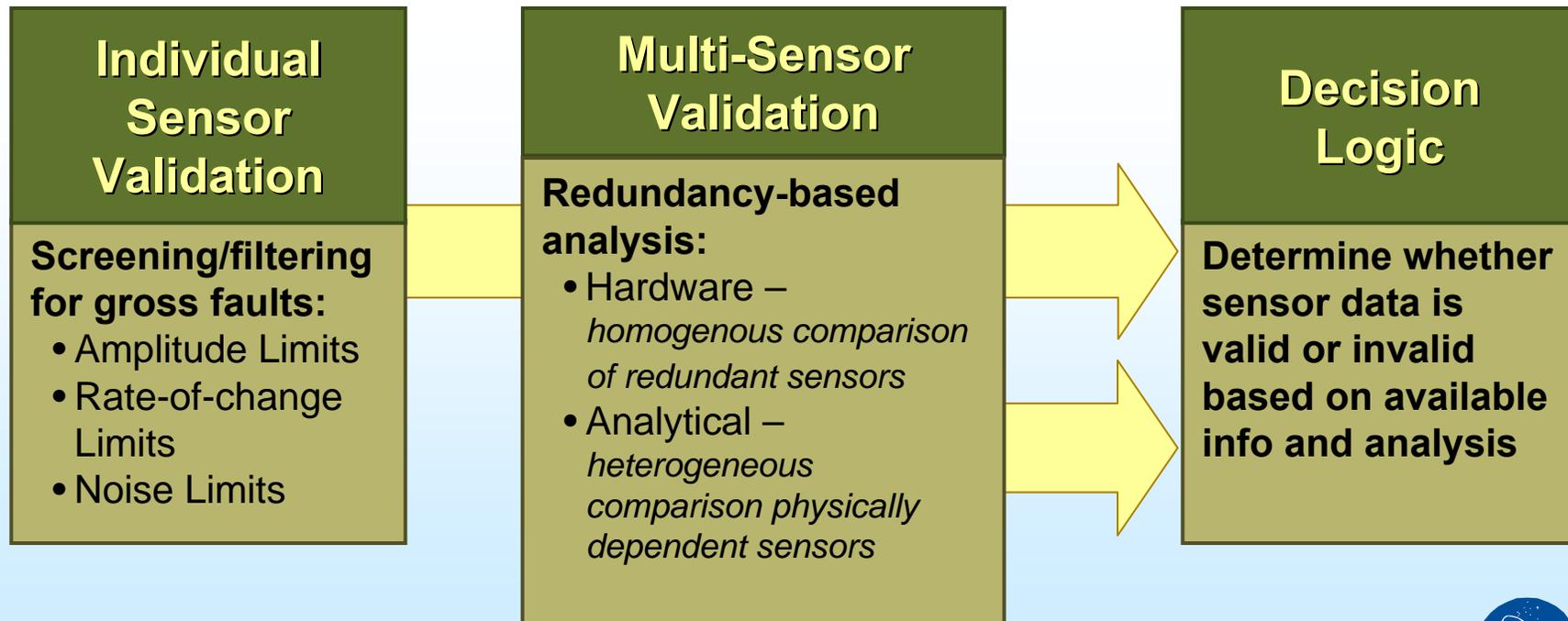
# Data Qualification

- ◆ **Provides control and diagnostic systems with qualified sensor information**
  - Reduces probability that actions or operational decisions will be based upon faulty information
  - Increases confidence in measurements from unfailed sensors
  
- ◆ **Supports Launch Commit Criteria flexibility by identifying sensor faults versus system failures**
  
- ◆ **Screen faulty sensor data in performance data on-board prior to compression and transmission to ensure accurate information**
  
- ◆ **Software solution – requires no additional mass/weight**
  - Potential benefit of additional redundancy (through analytical relationships) without weight/complexity of additional sensors.
  - Adding more sensors may not be an option.



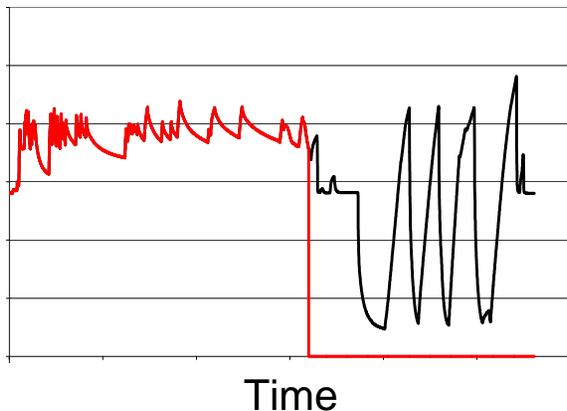
# Solution ⇨ Sensor Data Qualification System (SDQS)

- ◆ An algorithmic approach for continuously monitoring/analyzing sensor data at the flight computer to determine whether or not data values are within normal operating limits.
  - Sensor data is considered qualified if the SDQS determines that values are within the bounds of normal operation for a given sensor
  - Sensor data fails qualification if the SDQS determines that a values are outside the bounds of normal operation for a given sensor over a set time period
- ◆ Data qualification performed in three stages:

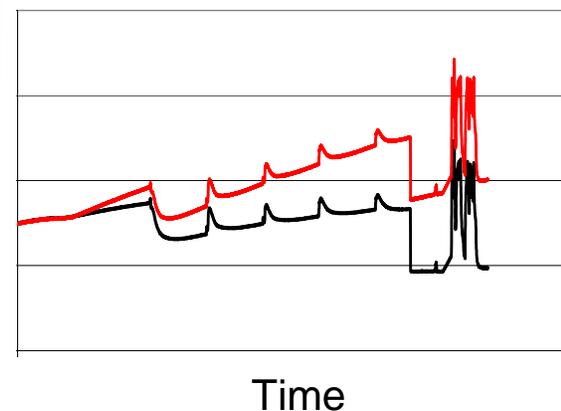


# Types of Sensor Failure Modes Targeted

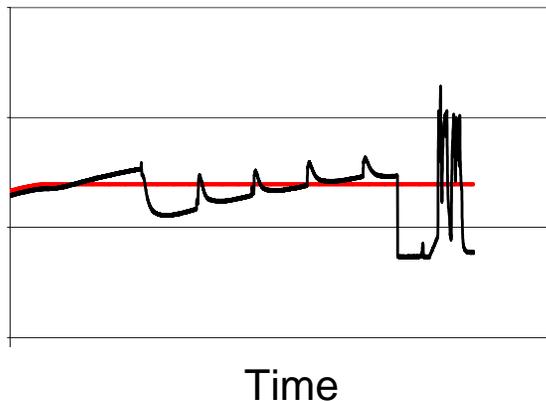
Hard Failure  
(open/short circuit)



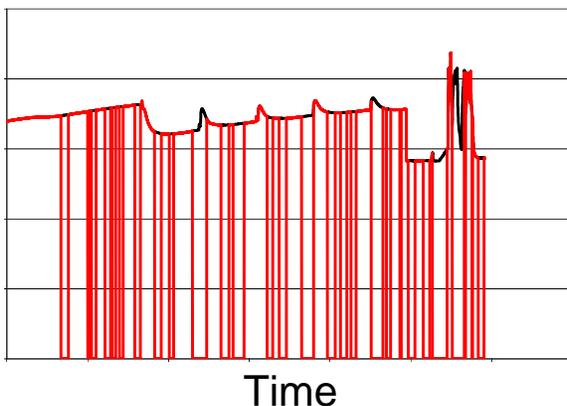
Drift Failure  
(thermal/resistance change)



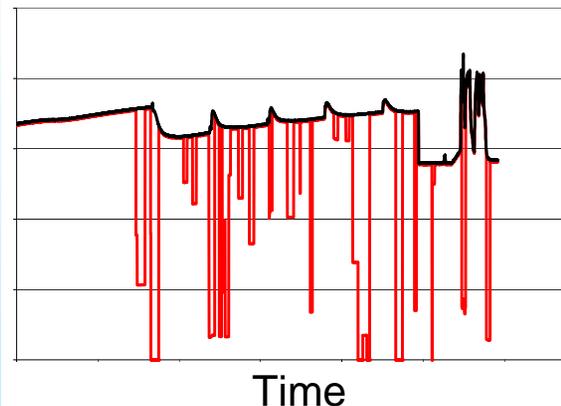
Iced-Up Failure  
(sensor value locked)



Intermittent-Binary  
(loose connector)



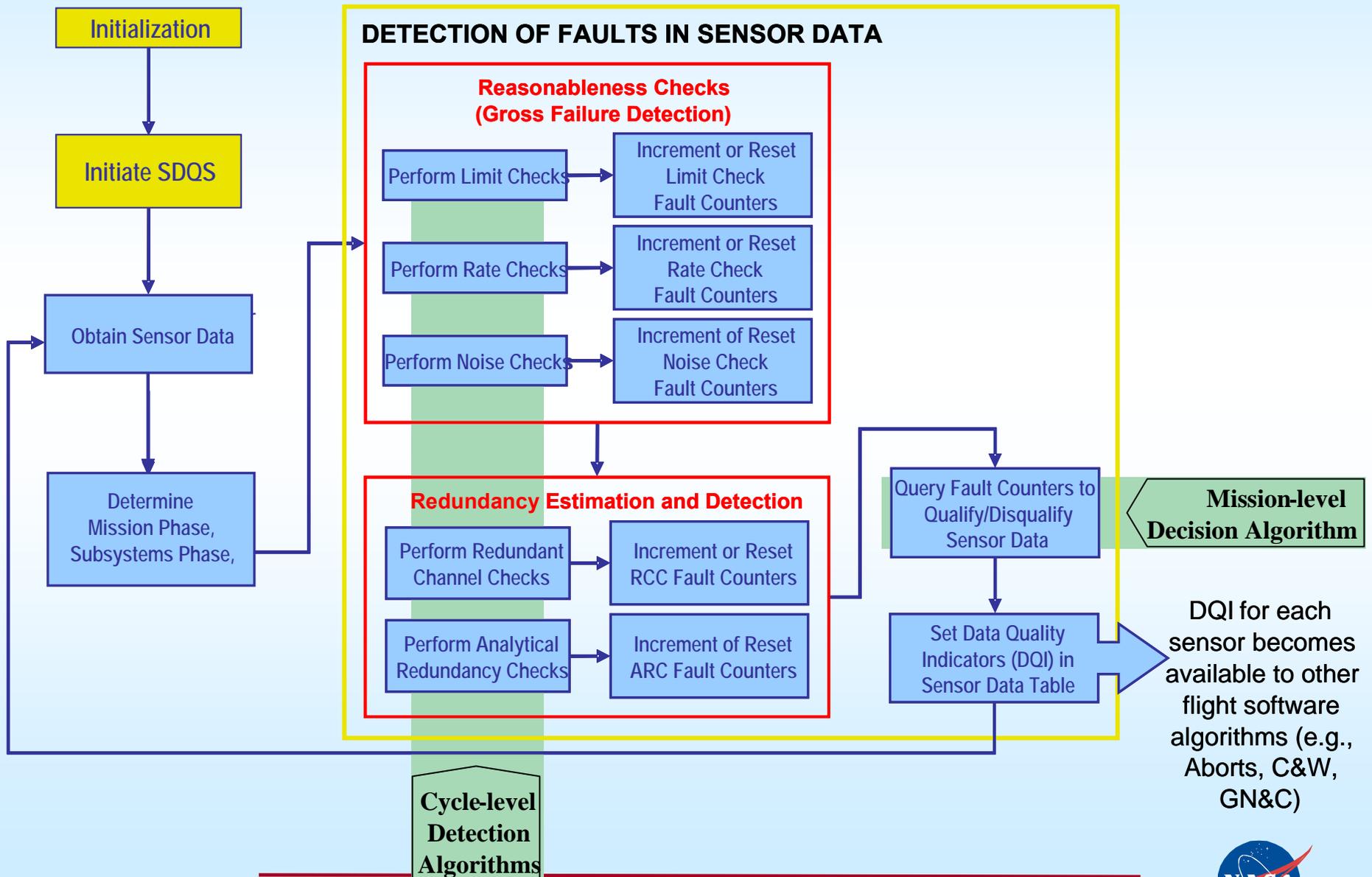
Intermittent-Filtered  
(cracked solder joint)



## Legend

- Good Sensor
- Failed Sensor

# Sensor Data Qualification System (SDQS) Functional Flow



# Portable Health Algorithms Test (PHALT) System

The **PHALT** System was developed for use in rapid prototyping and testing of diagnostic algorithms in real-time hardware

- ◆ **Portable**

Laptop (development platform) and industrial, rack-mount PC (real-time target) provide portability to support on-the-road demonstrations and real-time testing

- ◆ **Diagnostic Algorithms**

- ◆ Currently limited to data validation
- ◆ Capability to add a variety of diagnostic & prognostic health management algorithms

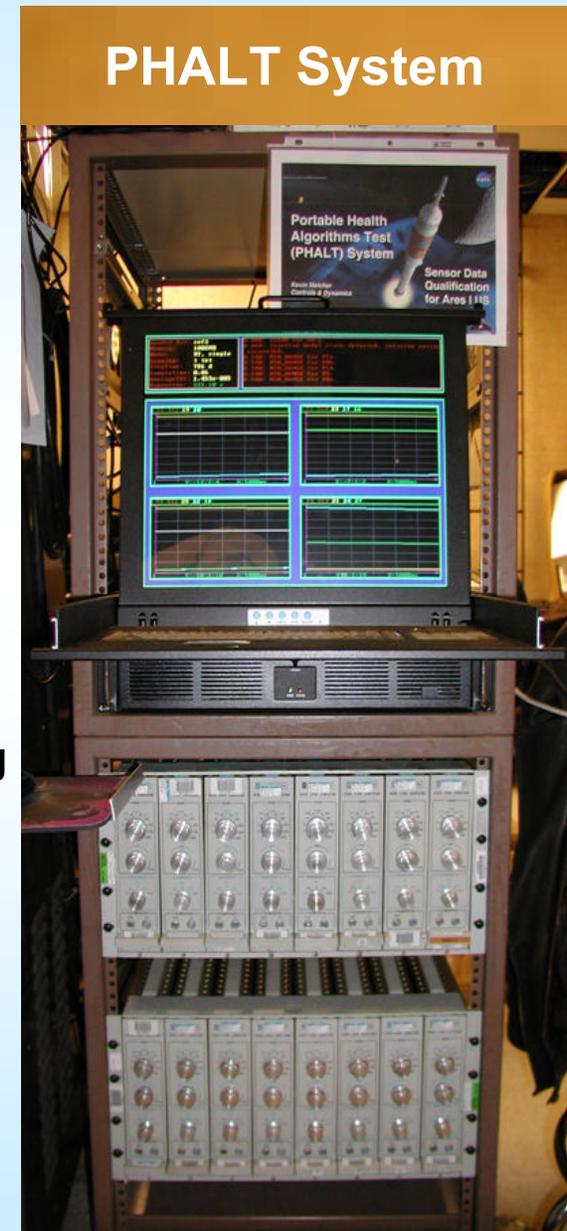
- ◆ **Test**

- ◆ Matlab/Simulink xPC software provides capability for rapid prototyping and seamless generation of real-time applications.
- ◆ Industrial PC with real-time I/O supports real-time testing of algorithms with broad spectrum of available test rigs.

Real-time  
Target with  
GUI & I/O



Anti-aliasing  
Filters



# PHALT System Demonstration Results

## Data Qualification Testbed Demonstrations

- PHALT System tied onto the Electrical Power System (EPS) Power Distribution Unit (PDU) Controller Area Network (CAN) Bus Card
  - 25 of 26 Simulated Sensor failures were caught by the qualification network being demonstrated.
    - The Undetected Failure Was a Drift That Would Have Been Caught if Allowed to Continue.
- PHALT System implemented within a Combustion Valve Test Rig
  - Real-time hardware sensor failures produced
  - Conducted demonstration of sensor failures with closed-loop control sensors
  - Demonstrated viability of software approach
  - Tests and evaluate of detection software are on-going



## **TRANSITION OF SENSOR SYSTEMS TO FLIGHT: SOME AREAS OF CONSIDERATION**

- **DEVELOPMENT OF A FULL LIFE-CYCLE PLAN FOR THE PRODUCT IS FUNDAMENTAL**
  - **TEAM COMPOSED OF THE PRODUCT DEVELOPER, THE END-USER, AND FLIGHT VEHICLE AND/OR GROUND SUPPORT . EXPERTS FROM SAFETY, RELIABILITY, LOGISTICS, SYSTEM INTEGRATION AND PROJECT MANAGEMENT.**
- **DETAILED SET OF REQUIREMENTS CRITICAL VERY EARLY IN THE PROCESS TO AVOID UNNECESSARY DELAYS AND/OR COSTLY REDESIGNS. INCLUDED ARE:**
  - **PERFORMANCE CONSIDERATIONS**
  - **PHYSICAL CONSIDERATIONS**
  - **ENVIRONMENTAL CONSIDERATIONS**
  - **SAFETY AND RELIABILITY CONSIDERATIONS**
- **FAILURE MODES EVALUATION ANALYSIS CONDUCTED DURING THE QUALIFICATION OF THE PRODUCT.**
- **EXTENSIVE TESTING EVEN TO FAILURE**



## SYSTEM LEVEL SUGGESTIONS

- **SENSORS SYSTEMS BE INCLUDED INTO THE VEHICLE IN THE DESIGN PHASE.**
- **STUDY THE VEHICLE SYSTEM TO DETERMINE OPERATIONAL FUNCTION AND CRITICALITY OF VARIOUS SENSOR SYSTEMS AND HOW TO OPTIMIZE CROSS FUNCTIONALITIES.**
- **INSTRUMENT THE VEHICLE SYSTEM TO ALLOW MEASUREMENTS TO ENABLE DAMAGE/DEGRADATION PREDICTION AT A LEVEL TO ALLOW AUTONOMOUS OPERATION.**
- **DEMONSTRATE SENSOR RELIABILITY AND DURABILITY BEFORE INCLUSION OF SENSOR SYSTEM INTO VEHICLE.**
- **PERFORM SENSOR MEASUREMENTS TO OPTIMIZE MEASUREMENT OF MULTIPLE PARAMETERS SIMULTANEOUSLY TO IMPROVE FULL-FIELD SYSTEM INFORMATION AND MEASUREMENT RELIABILITY**
- **DEVELOP SENSOR SYSTEMS WHICH INCLUDE INTEGRATED INTELLIGENCE WHILE MINIMIZING SIZE, WEIGHT, AND POWER CONSUMPTION.**
- **AT MINIMUM, CRIT 1 SYSTEMS, I.E. THOSE WHOSE FUNCTION CAN AFFECT LOSS OF CREW AND/OR VEHICLE, SHOULD BE MONITORED NO MATTER THE EXTREME CONDITION INHERENT IN SUCH MONITORING**



**FUTURE DIRECTIONS**

**NANOTECHNOLOGY**



# **NANOTECHNOLOGY DEVELOPMENT**

## **NANO DIMENSIONAL CONTROL PREVALENT IN CHEM/BIO SENSORS**

- **NANO CONTROL OF CHEMICAL SENSOR STRUCTURES STRONGLY PREFERRED EVEN IF SENSOR ISN'T LABELED A "NANO SENSOR"**
  - **WE ARE MEASURING VARYING NUMBERS OF MOLECULES**
- **IF NANOTECHNOLOGY ALREADY PRESENT IN CHEM/BIO SENSOR DEVELOPMENT, THEN:**
  - **WHAT STAYS THE SAME AND WHAT'S NEW?**
  - **WHAT ARE THE CHALLENGES IN NANOTECHNOLOGY DEVELOPMENT?**
  - **WHAT IS THE ROLE/ADVANTAGE OF NANO TECHNOLOGY**

### **SAME**

- **APPLICATIONS DON'T CARE THAT IT IS NANO, NEED IMPROVED CAPABILITIES**
- **STANDARD SENSOR TECHNOLOGY REQUIREMENTS, POTENTIAL, AND DIRECTIONS SET BY THE ADVENT OF MICRITECHNOLOGY REMAIN CONSTANT**
- **SENSITIVITY, SELECTIVITY, STABILITY, RESPONSE TIME, TAILOR FOR THE APPLICATION, "LICK AND STICK", ETC.**
- **PACKAGING STILL SIGNIFICANT COMPONENT OF SYSTEM**
- **AS WITH MICRO, CAN ONLY GO AS FAR AS THE SUPPORTING TECHNOLOGIES**
- **MULTIPLE SENSOR PLATFORMS MAY STILL BE NECESSARY DEPENDING ON THE APPLICATION/ENVIRONMENT**

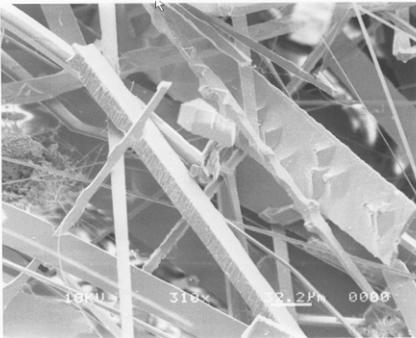
### **TARGETED TECHNOLOGY DEVELOPMENT**

- **MICRO-NANO CONTACT FORMATION**
- **NANOMATERIAL STRUCTURE CONTROL**
- **OTHER NANO OXIDE MATERIALS**

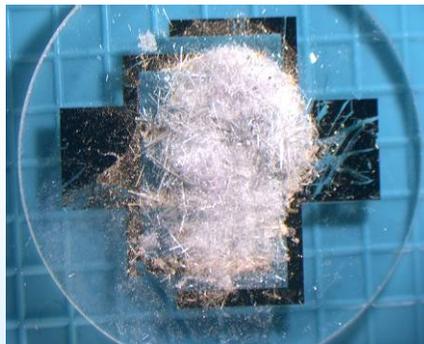


# EXAMPLE NANOTECHNOLOGY CHALLENGE: MICRO-NANO CONTACT FORMATION

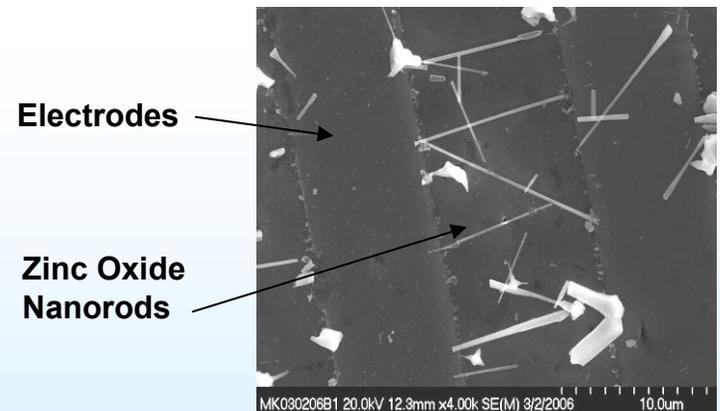
- NO MATTER HOW GOOD THE SENSOR, IF YOU CANNOT MAKE CONTACT WITH IT, THEN IT WILL NOT BE INEFFECTIVE
- MICRO-NANO INTEGRATION/CONTACTS
  - MAJOR QUESTION FOR NANOSTRUCTURED BASED SENSORS: HOW ARE THE NANOSTRUCTURED MATERIALS INTEGRATED INTO A MICROSTRUCTURES
- MANUAL METHODS GENERALLY INVOLVE REPEATABILITY ISSUES E.G.
- BASIC WORK ON-GOING TO IMPROVE MICRO-NANO CONTACTS E.G. USE OF DIELECTROPHORESIS TO ALIGN NANOSTRUCTURES
- BRING THE LEVEL OF PROCESS CONTROL PRESENT IN MICROSYSTEMS TO NANOTECHNOLOGY



**NANOSTRUCTURE  
FABRICATED BY THERMAL  
EVAPORATION-  
CONDENSATION PROCESS.**



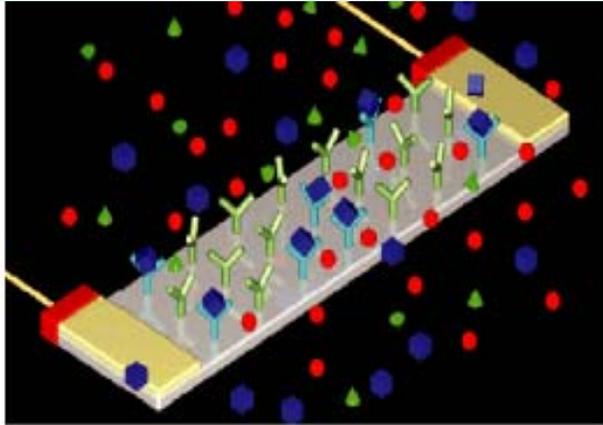
**NANORODS CONTACTED  
WITH THE SUBSTRATE VIA  
A SILVER EPOXY**



**ZINC OXIDE NANORODS AFTER  
DIELECTROPHORESIS ACROSS  
INTERDIGITATED FINGERS**

# “LOCK AND KEY” CHEMICAL SENSORS USING NANOSTRUCTURES

- **OBJECTIVE: DEMONSTRATE THE FUNDAMENTAL ABILITY TO ASSEMBLE THE ULTIMATE “LOCK AND KEY” CHEMICAL SENSOR DETECTION SYSTEM**
- **STATE OF THE ART:**

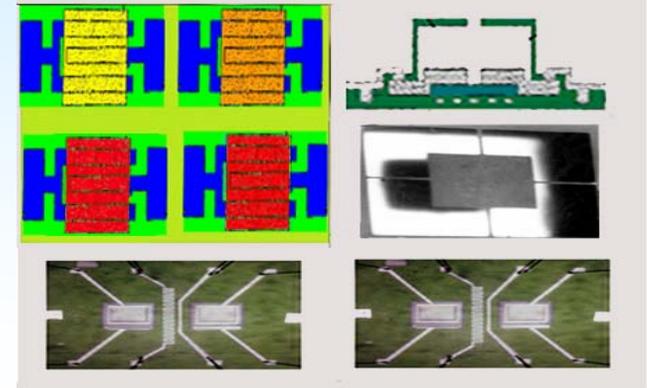


Limited Chemical Selectivity by use  
“Lock and Key” Approach



Many Species,  
Complex Structures  
Lead to Limited  
Ability For Species  
Identification

## NASA GRC HIGH TEMP NOSE APPROACH



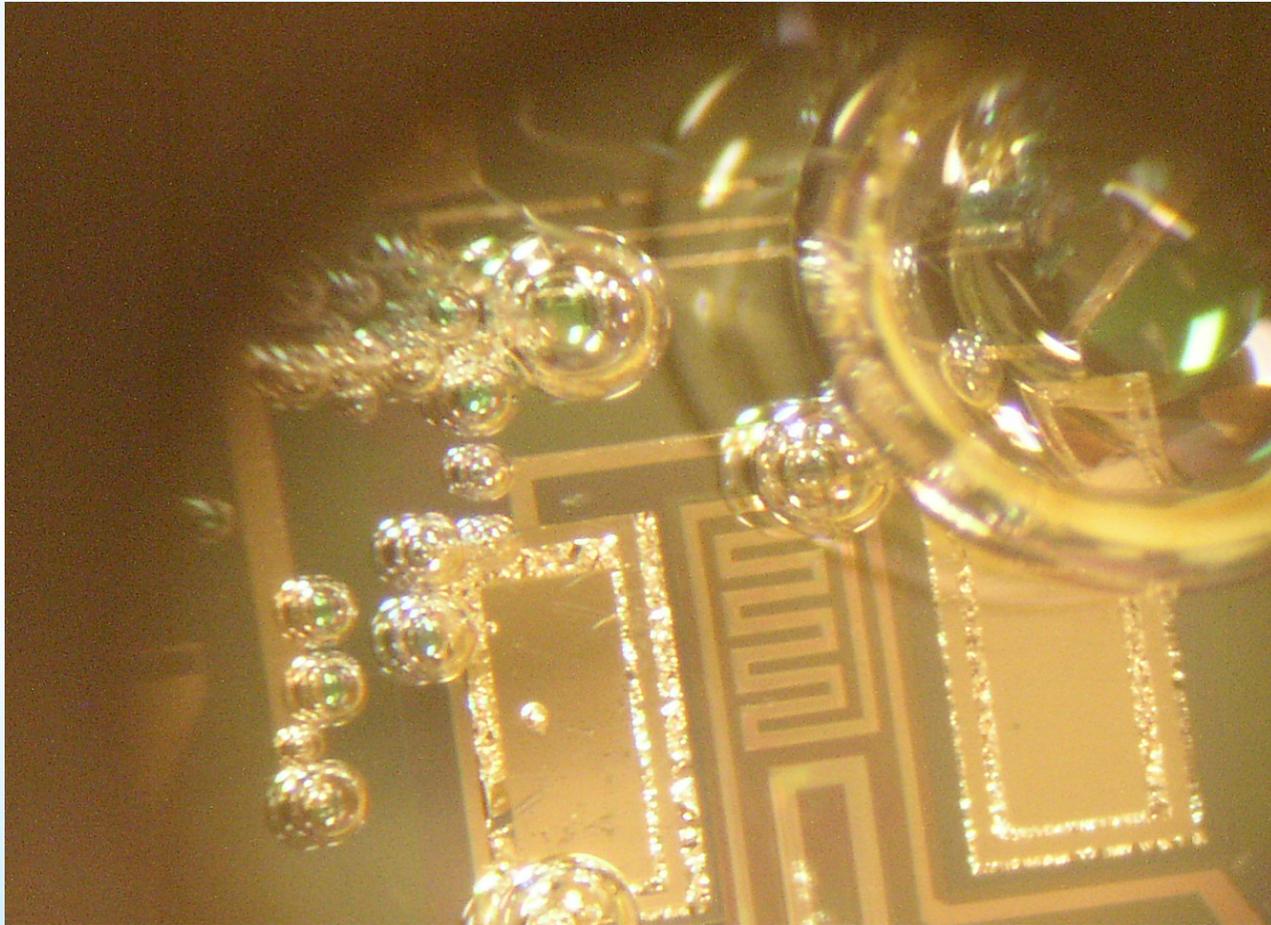
Nose Approaches necessary to attempt to understand environment but still limited in species identification: multispecies identification, closely related species, significant false positives

- **TECHNICALLY ADDRESS THE FUNDAMENTAL QUESTION “WHAT IS NANO GOOD FOR?” IN THE AREA OF CHEMICAL SENSORS:**
  - **NOT SMALL NANO STRUCTURES FOR BILLION MOLECULE MEASUREMENTS/ IN SUCH APPLICATIONS MAY CONSIDER THIN FILMS OR ALTERNATE SENSOR PLATFORMS**
  - **INSTEAD USE NANOSTRUCTURES FOR DETECTION ON MOLECULAR LEVEL**
- **ARRANGE THE CHEMICAL SENSOR STRUCTURE TO “FIT” THE MOLECULE IN QUESTION**
- **VERIFY THE PRESENCE OF THE MOLECULE WITH AN ELECTROCHEMICAL SIGNATURE**
- **FABRICATE “DESIGNER” CHEMICAL SENSORS**

**SENSORS HAVE WIDE VARIETY OF APPLICATIONS BUT CANNOT  
WORK IN EVERY ENVIRONMENT**

***RIGHT SENSOR FOR RIGHT APPLICATION***

**H<sub>2</sub> SENSOR OPERATION UNDER WATER**



## SUMMARY

- **AEROSPACE APPLICATIONS REQUIRE A RANGE OF SENSING TECHNOLOGIES**
- **A RANGE SENSOR AND SENSOR SYSTEM TECHNOLOGY BEING DEVELOPED TO MEET THESE NEEDS USING:**
  - **MICROFABRICATION AND MICROMACHINING TECHNOLOGY**
  - **SMART SENSOR SYSTEMS**
- **TECHNOLOGY BEST APPLIED WITH STRONG INTERACTION WITH USER/TAILOR SENSOR FOR NEEDS OF APPLICATION/SUPPORTING TECHNOLOGIES MANDATORY**
- **SUPPORTING TECHNOLOGIES NECESSARY**
- **DRIVE SYSTEM INTELLIGENCE TO THE SENSOR LEVEL**
- **LONG-TERM: INTELLIGENT SYSTEMS**
  - **RELIABILITY**
  - **REDUNDANCY**
  - **ORTHOGONALITY**
  - **CROSS-CORRELATION**
- **SENSOR IMPLEMENTATION**
  - **A NUMBER OF BARRIERS**
  - **A TEAM APPROACH SUPPORTED BY TESTING**
- **NANOTECHNOLOGY**
  - **SIGNIFICANT PROMISE BUT TECHNOLOGY BARRIERS EXIST**
  - **LONG-TERM FULLY ENABLE “LICK AND STICK”**



## **ACKNOWLEDGEMENTS**

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