Smart Sensors System Development and Application for Harsh Environments

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Smart Sensors and Electronics Systems Branch (LCS)

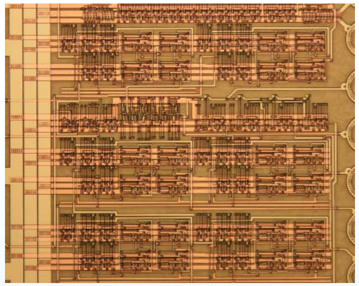
Description

Conducts research and development of **adaptable instrumentation to enable intelligent measurement systems** for ongoing and future aerospace propulsion and space exploration programs. Emphasis is on smart sensors and electronics systems for diagnostic engine health monitoring, controls, safety, security, surveillance, and biomedical applications**; often for high temperature/harsh environments**.

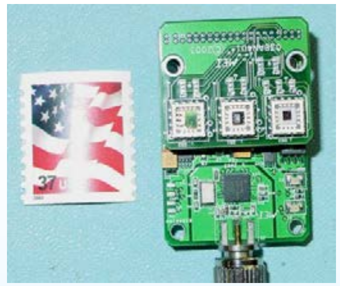
Microsystems Fabrication Facility

Facilities/Labs

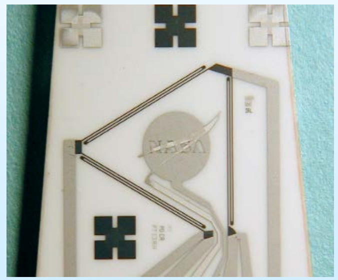
- Microsystems Fabrication Facilities
  - Class 100 Clean Room
  - Class 1000 Clean Room
- Chemical vapor deposition laboratories
- Chemical sensor testing laboratories
- Harsh environment laboratories
  - Nanostructure fabrication and analysis
  - Sensor and electronic device test and evaluation



SiC Signal Processing



Chemical Sensors



Thin Film Physical Sensors

Core Capabilities (technical areas)

- Silicon Carbide (SiC) - based electronic devices
  - Sensors and electronics for high temp (600°C) use
  - Wireless sensor technologies, integrated circuits, and packaging
- Micro-Electro-Mechanical Systems (MEMS)
  - Pressure, acceleration, fuel actuation, and deep etching
- Chemical gas species sensors
  - Leak detection, emission, fire and environmental, and human health monitoring
- Microfabricated thin-film physical sensors
  - Temperature, strain, heat flux, flow, and radiation measurements
- Harsh environment nanotechnology
  - Nano-based processing using microfabrication techniques
  - Smart memory alloys and ultra low power devices

APPROACH

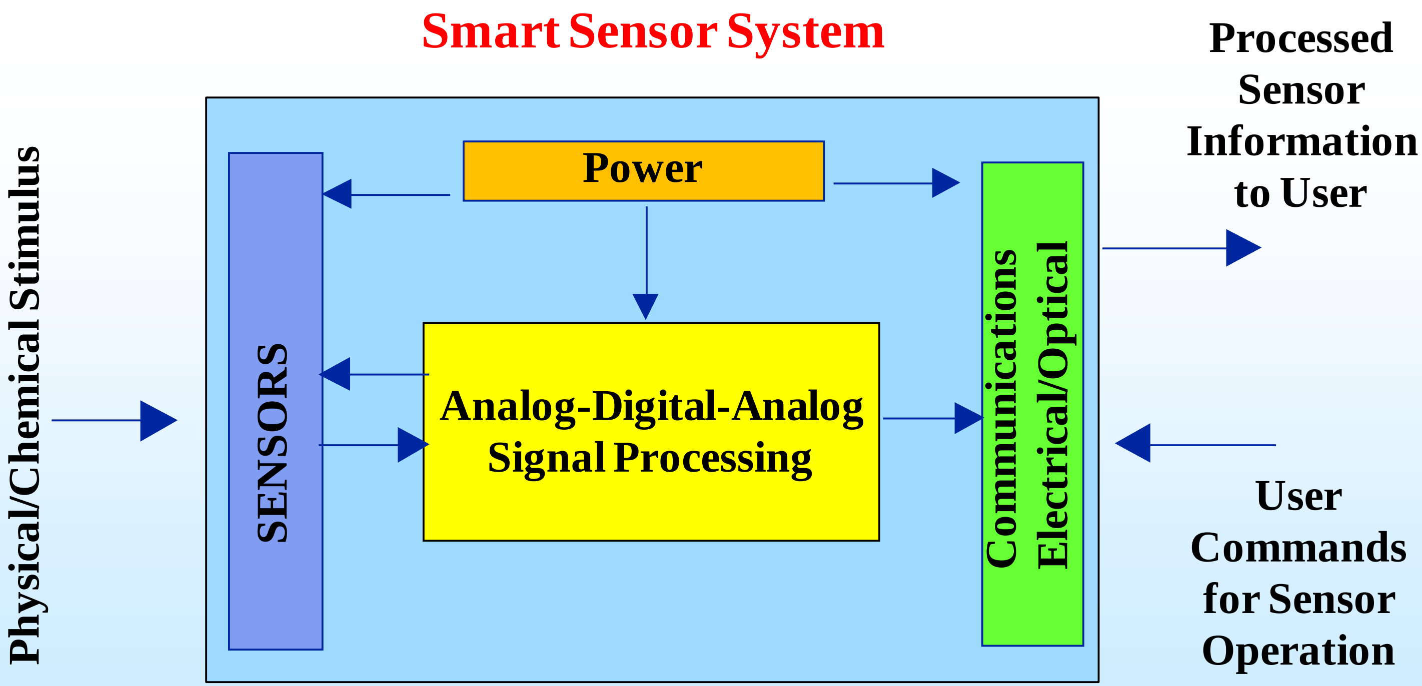
Interdisciplinary group of electronic engineers, chemists, materials engineers and physicists that can provide **Smart and Small Sensor Systems** to a broad range of aerospace applications.

- Using unique in-house capabilities, we produce ,cutting edge sensor system technologies that provide critical information (data), thus, enabling vastly improved decision-making capability, whether it be regarding designs, operations, the environment, or hazards.
- Our work, to quote Galileo, is to *"Measure what is measurable, and make measurable what is not so".*
- In this modern era, making a measurement does not just involve a sensor element (like a thermocouple), but rather a whole sensor system that provides:
  - Multiparameter information needed to understand the problem;
  - Local processing to optimize the quality and relevance of that information ;
  - Communication of that information in a manner that best fits the application; and
  - Tailoring of each integrated sensor system to meet the needs of the application.
- **We provide micro/nano-based tools and capabilities to enable:** Physical measurements; Chemical sensor platforms; High temperature electronic devices and communication, Harsh Environment Smart Sensors and Actuators and Integrated Sensor Systems

In this Information Age, our small, smart sensor system technologies are the enabling first step in acquiring information (data) about an aerospace system and/or an environment, leading to cognition and decision-making capabilities.

SMART SENSOR SYSTEMS BASED ON MICROSYSTEMS TECHNOLOGY

- A Range Of Sensor Systems Are Under Development Based On Microfabrication Techniques And Smart Sensor Technology
- Smart Sensor Systems Approach: Stand-alone, Complete Systems Including Sensors, Power, Communication, Signal Processing, And Actuation
- Microsystems Technology Moving Towards A Range Of Applications
- Enable System Level Intelligence By Driving Capabilities To The Local Level Using Distributed Smart Systems



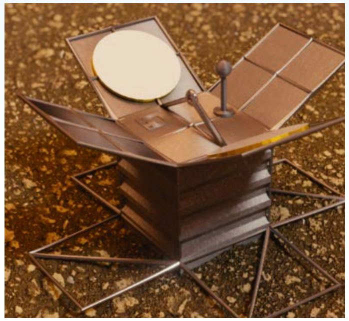
BASIC APPROACH: MAKE AN INTELLIGENT SYSTEM FROM SMART COMPONENTS

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 the number 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.

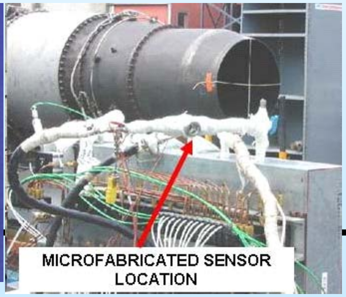
HARSH ENVIRONMENT ELECTRONICS AND SENSORS APPLICATIONS

- **Needs:**
  - **Operation In Harsh Environments**
  - **Range Of Physical And Chemical Measurements**
  - **Increase Durability, Decrease Thermal Shielding, Improve In-situ Operation**
- **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**
- **Enable Expanded Mission Parameters/In-situ Measurements**
- **Long Lived High Temperature Electronics At 500˚C**

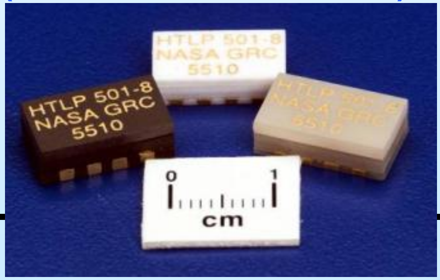


Long Lived In-Situ Surface Explorer (LLISSE)

Range of Physical and Chemical Sensors for Harsh Environments

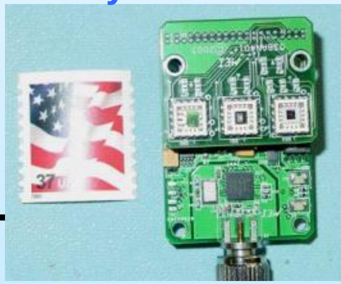


Harsh Environment Packaging (10,000 hours at 500˚C)



High Temperature Signal Processing and Wireless

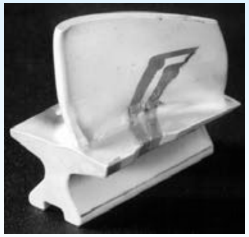
Moving Towards: High Temperature “Lick and Stick” Systems

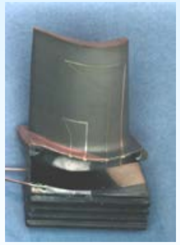


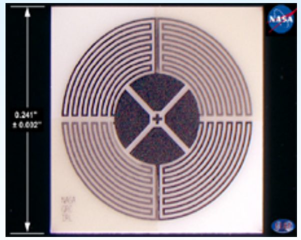
Microfabricated Thin-Film Physical Sensors

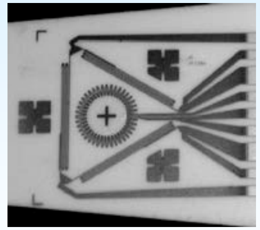
Temperature, Strain, Heat Flux, Flow, and Radiation


Strain Sensor at 1000˚C


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

Description of Technology

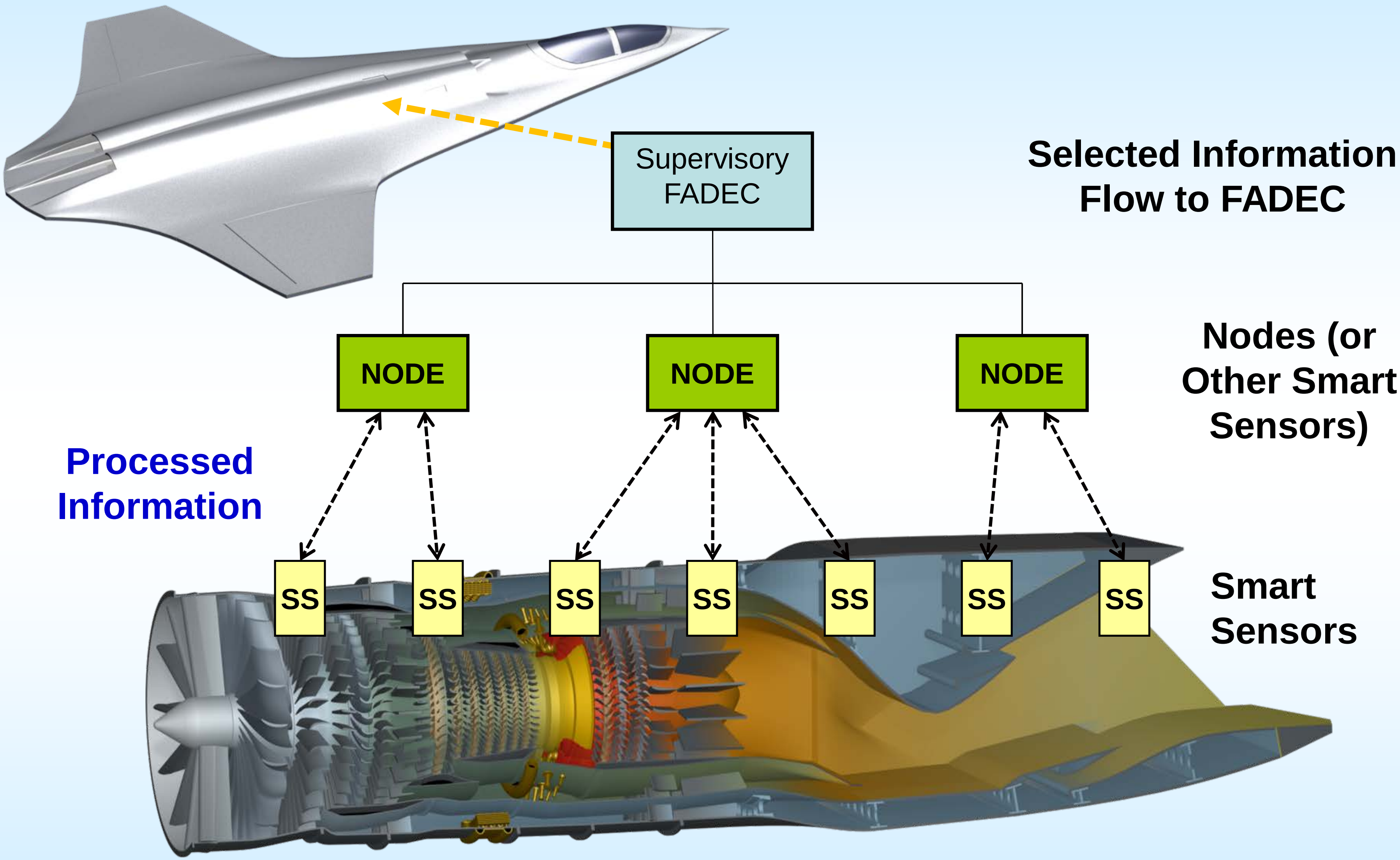
- Traditional (larger) sensor systems can interfere with the measurements and be difficult to implement.
- Thin film sensor technology can be directly deposited onto the surface of the component.
- Capable of operation to very high temperatures (>1500˚C).
- Sensor types include temp, strain, heat flux and flow.
- A multifunctional sensor can provide multiple parameters within the ranges of: strain (1 to 10 microstrain); heat flux (0.1 to 1 W/ sq cm); temperature (up to 1500°C).

Applications

- Structural health and life prediction monitoring of engine systems as well as high temperature structures.
- Monitoring and controlling high temperature processes (aeronautic and industrial).
- Characterization of new and developing materials.
- Flow measurement distribution above a surface.
- Thermal energy measurements of systems (tire to operation of a Stirling converters.)
- In-situ monitoring of thin film coating systems.
- Medical diagnostics; in-situ monitoring of bone healing.

National Aeronautics and Space Administration

Implementation of Distributed Engine Controls with Smart Wireless Sensors



Hunter, G. W. and Behbahani, A. “A Brief Review of the Need for Robust Smart Wireless Sensor Systems for Future Propulsion Systems, Distributed Engine Controls, and Propulsion Health Management”, Proceeding of the 58th International Instrumentation Symposium, Hyatt Regency La Jolla, San Diego, California, 4–7 June 2012

VIPR Overview

Vehicle Integrated Propulsion Research (VIPR) engine tests to support the research and development of Engine Health Management Technologies for Aviation Safety

Engine testing is a necessary and challenging component of Aviation Safety technology development.

Partnerships make it possible.

Test Objectives:

Demonstrate capability of advanced health management technologies for detecting and diagnosing incipient engine faults before they become a safety impact and to minimize loss of capability

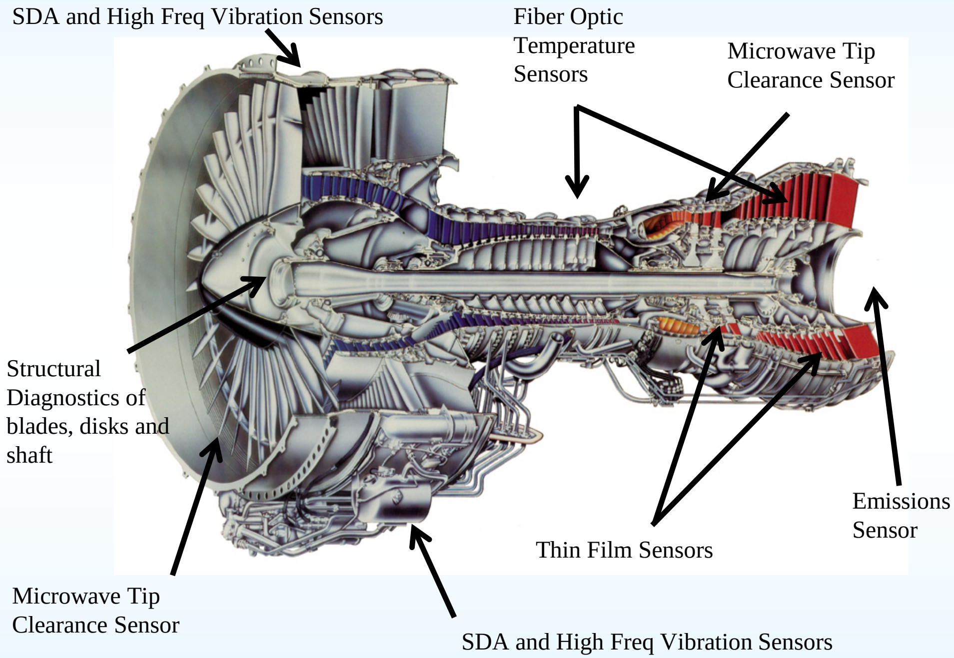
Approach:

Perform engine ground tests using large bypass transport engine

- Normal engine operations
- Seeded mechanical faults
- Seeded gas path faults
- Accelerated engine life degradation through volcanic ash ingestion testing

Partnerships:

- NASA
- Air Force
- Federal Aviation Administration
- Pratt & Whitney
- GE
- Rolls-Royce
- United States Geological Survey
- Boeing
- Makel Engineering
- Others in discussion



Model-based gas path diagnostic architecture

Thin Film Thermocouple

OBJECTIVE

•Enable improved dynamic temperature measurements at higher temperatures using thin film sensor technology

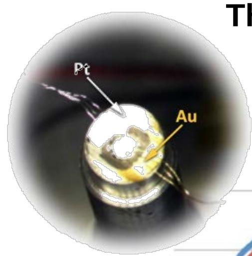
APPROACH

•Thin film sensors have negligible mass, are minimally intrusive, and can be applied to a variety of materials including ceramics
•Two high temperature prototype thermocouple probe designs fabricated and demonstrated
•Each sensor probe design demonstrated different thin film thermocouple types and packaging approaches

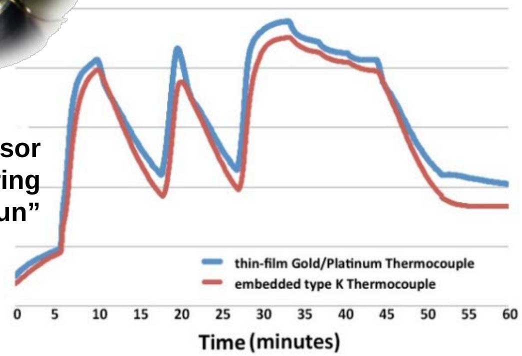
SIGNIFICANCE

•Operation of thin film thermocouple sensor prototypes validated as installed in bleed-air borescope ports
•Sensors tracked dynamic engine temperature changes through multiple power cycles with faster response than embedded thermocouples
•Data included monitoring VAE performance trends
•Tracked performance changes were observed elsewhere in engine
•Application not limited to bleed-air borescope ports
•Part of information fusion to better understand the overall health state of the engine

VIPR 2 Design: Metal Probe / Au-Pt Thermocouple



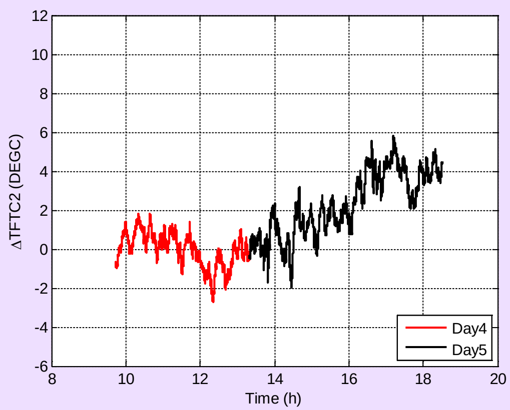
Sensor tip with 0.003” wires attached to deposited thin films



Thin Film Sensor Operation During “Green Run”

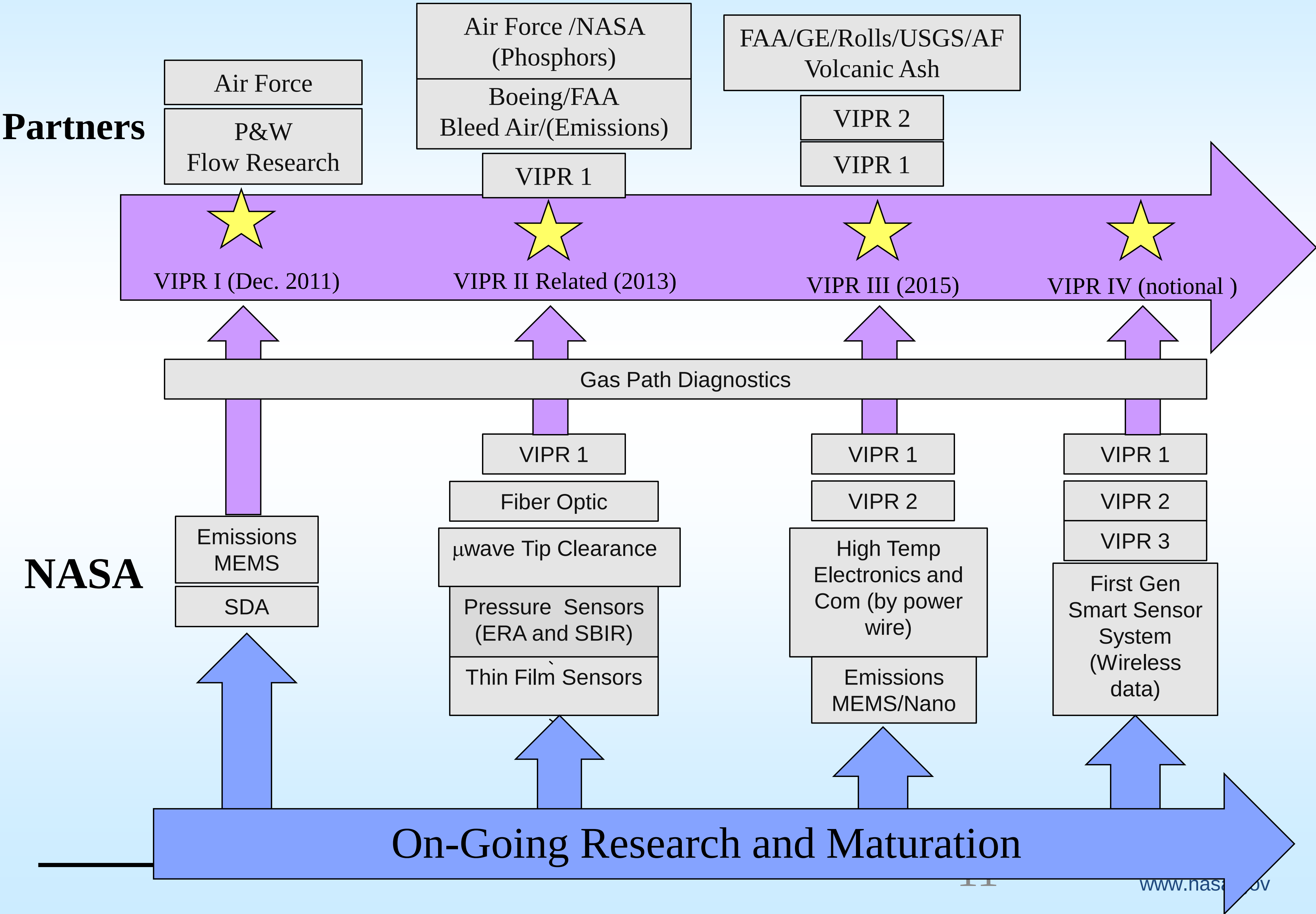
VIPR 3 Design: Spark Plug / Pt-Pd Thermocouple

Thin film deposition processing on “Spark Plug” sensor tip



Thin Film Sensor Data: Volcanic Ash Runs Day 4-5

Vehicle Integrated Propulsion Research
Engine Testing as Part of Technology Development



High Temperature Electronics Advancements

R&D 100 Award 2018

- *Unique capabilities have produced the World's First Microcircuits at moderate complexity (Medium Level Integration) that have the potential for long-lived operation at 500˚C*
- **Circuits contain 10's to 100's of JFETs; An order of magnitude beyond a few JFETs previously demonstrated in the last decade**
- **Significant step towards more complex electronics operation in harsh environments and Smart Engine Systems**
- **Enables a wide range of sensing and control applications *at High Temperatures***
  - **In-package signal conditioning for smart sensors**
  - **Signal amplification and local processing**
  - **Wireless transmission of data**
- **A tool-box of signal conditioning, processing, and communications circuits are being developed and demonstrated (both analog and digital)**

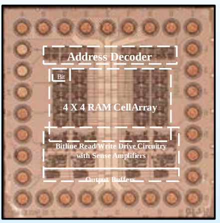
Electronics Development

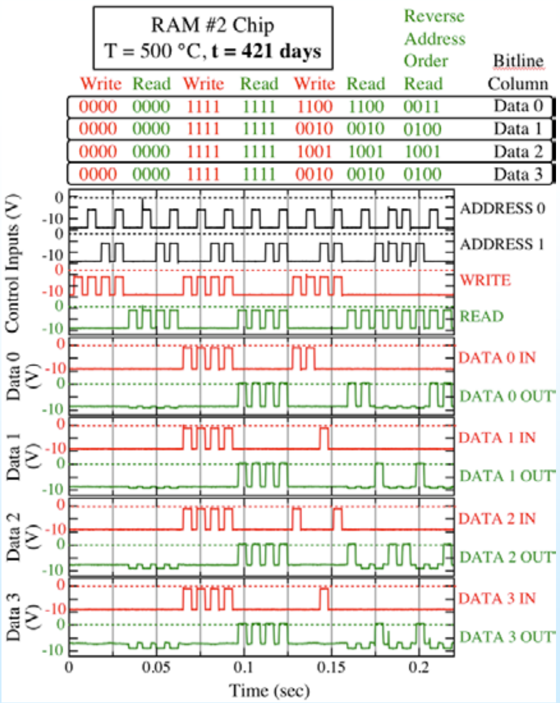
2017 NASA Glenn SiC JFET IC "Version 10"

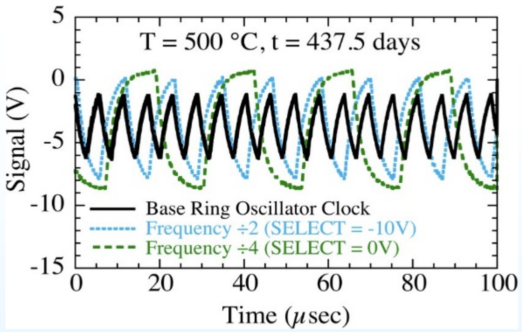
1+ year of operation in Earth air oven at 500 ° C Achieved

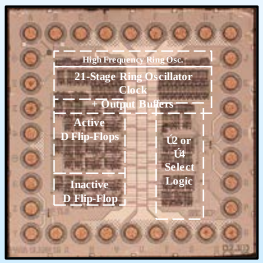
Version 10 ICs set high temperature durability world records in T ≥ 500 °C Earth-atmosphere oven testing.

Complex ICs Operating more that 1 Year at 500 °C[1]

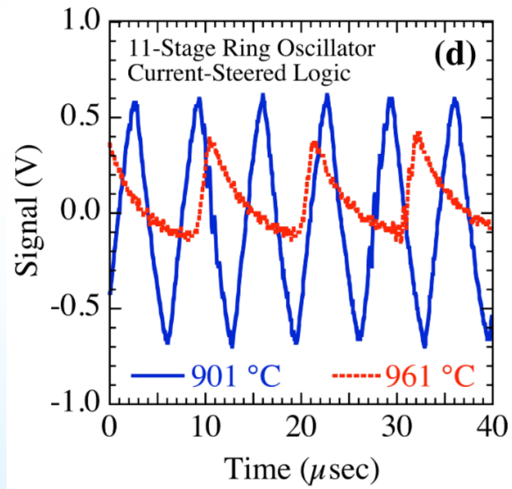








ICs Operating at World Record 961 °C[2]



[1] 2018 Int. Conf. High Temperature Electronics p. 71
[2] IEEE Electron Device Letters vo. 38 p. 1082 (2017).

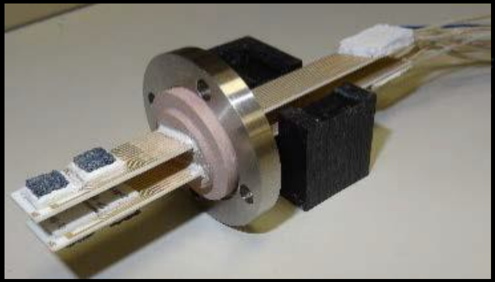
LONG-LIVED IN-SITU SOLAR SYSTEM EXPLORER (LLISSE)

- LLISSE is a small (~10kg) probe being developed to acquire and transmit simple but important science measurements for extended periods from the surface of Venus
- Three key elements leveraged
  - Recent developments in high temperature electronics
  - Focused, low data volume measurements
  - Novel operations scheme
- Operations Goals:
  - Operate for a minimum of one Venus “daylight period” and day/night transition (~60 Earth days)

LLISSE Sensors

Broad Array Sensor Technology for Venus Applications Leveraged From Aeronautics Development

- Active development of harsh environment smart sensors systems for engine test stand, health management, and intelligent engine systems
- Demonstration/Application in Multiple Applications/Commericalized System

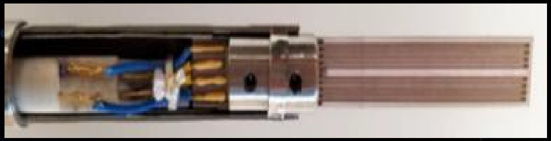


Chemical Sensor Array for GEER chamber Simulated Venus Surface testing

Courtesy of D. Makel, Makel Engineering, Inc.

Development Approach:

- Miniaturized sensor systems produced by microfabrication techniques and high temperature compatible materials
- Parallel Development of Multiple Sensor Types
  - Pressure
  - Temperature
  - Wind (3 directions)
  - Multiple Chemical Species
  - Radiance
- Each sensor has targeted specifications and associated electronics requirements



Drag force anemometer (wind sensor)

Status

- Multiple sensors interface with electronics demonstrated in Venus Simulated Conditions.
- Demonstration of reliable, responsive SO_2 detection for 60 days in Venus simulated conditions

SUMMARY

Smart, Small, And Rugged

- AEROSPACE APPLICATIONS REQUIRE A RANGE OF SENSING TECHNOLOGIES
- DRIVE SYSTEM INTELLIGENCE TO THE LOCAL (SENSOR) LEVEL
    - ➢DISTRIBUTED SMART SENSOR SYSTEMS
- FACILITIES FOR MICROFABRICATED SENSOR AND ELECTRONICS FABRICATION AND CHARACTERIZATION
- MICROFABRICATION AND MICROMACHINING TECHNOLOGY USED TO FORM A RANGE OF HARSH ENVIROMENTS SENSORS
- UNIQUE HIGH TEMPERATURE ELECTRONICS ENABLE PROCESSING AND WIRELESS SYSTEMS
- HARSH SMART SENSOR SYSTEM DEVELOPMENT: COMBINATION SENSORS AND INTEGRATED INTELLGENCE
- CORE ENABLING TECHNOLOGY WITH APPLICATION FROM A JET ENGINE TO THE SURFACE OF VENUS

BACKUP SLIDES

Facilities and Laboratories

Microsystems Fabrication Facility (Class 100 Cleanroom Facility)

Features:

3000 square feet class 100 and class 1000 cleanroom space, Photolithography tools suitable for 2 micrometer linewidths
Chemical work stations for substrate cleaning and wet etching
Physical vapor thin film deposition systems, Plasma etchers, including deep reactive ion etcher for SiC micromachining
Low pressure chemical vapor deposition system for silicon dioxide films
Annealing and oxidation furnaces, Rapid thermal annealers

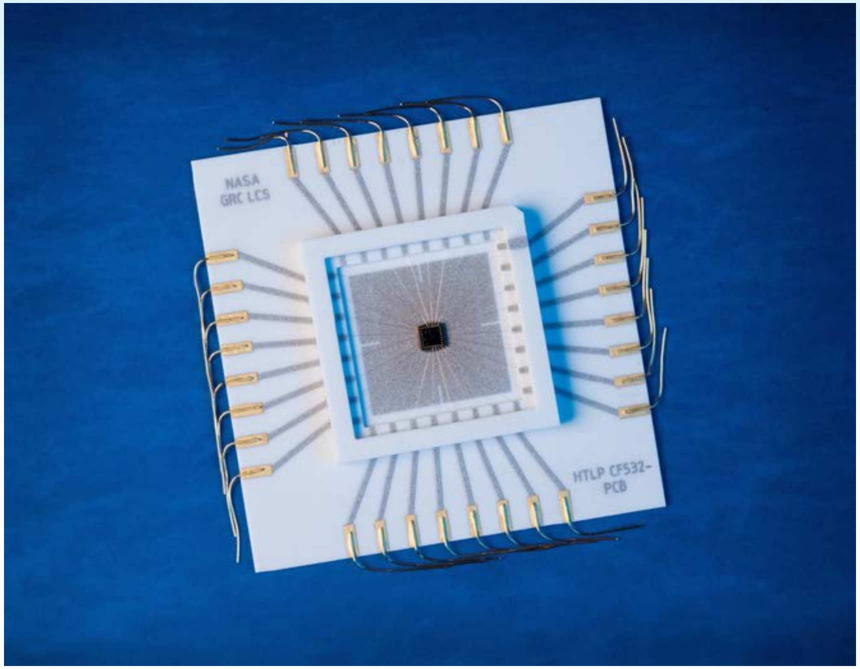
Research Projects:

SiC electronic devices –worlds first 500˚C integrated circuit
High temperature wireless sensors using 500˚C SiC electronics
Thin film sensors in-situ monitoring of high temperature processes
Chemical sensors for active emissions control and health monitoring
High temperature SiC pressure sensors for active combustion control
SiC microactuators for control of fuel flow to minimize combustion instability

SENSOR SYSTEM IMPLEMENTATION

- Objective: A Self-aware Intelligent 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
- Sensor 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)

High-T packaging example[1,2] (32 pins)



- Package durability and leakage characterized.
- Packages NOT sealed, chips are subjected to ambient atmosphere (Earth or Venus) during high temperature testing.

[1] L. Chen, et al., Proc. IMAPS High Temperature Electronics Conference, 2016, pp. 66-72.
[2] P. G. Neudeck, et al., IEEE Electron Device Lett. 38 (2016) 1082-1085.