A Brief Overview of Silicon Carbide Based Smart Sensor System Technologies for Planetary and Aeronautics Applications

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Outline

- Introduction
- Sensor Development
  - Chemical
  - Physical
  - Pressure
  - Radiation Detectors
- High Temperature Electronics
- Applications
  - ➢ Planetary Science
  - ➢ Engine Monitoring
  - ➢ Fission Surface Power
- Summary

Smart Sensing 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**.

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

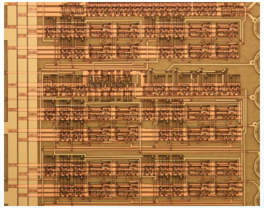
•Microfabricated thin-film physical sensors
- Temperature, strain, heat flux, flow, and radiation measurements

•Harsh environment nanotechnology
- Nano-based processing using microfabrication techniques

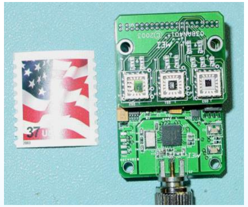
Microsystems Fabrication Facility

Facilities/Labs

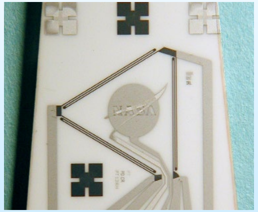
- Microsystems Fabrication Facilities
  - Class 100 Clean Room
  - Class 1000 Clean Room
- Chemical vapor deposition laboratories
- Chemical sensor testing laboratories
- Harsh environment laboratories
  - Nanostructure fabrication and analysis
  - Sensor and electronic device test and evaluation



SiC Signal Processing



Leak Detection Sensors

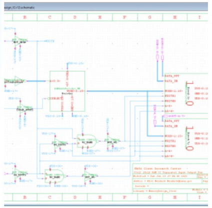


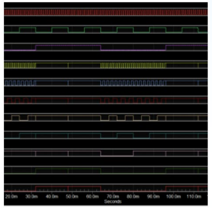
Thin Film Physical Sensors

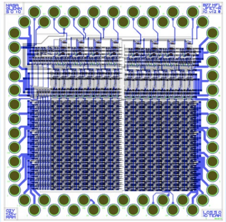
NASA Glenn Microsystems Fabrication Laboratory

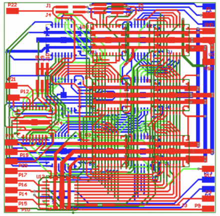
Vertically integrated design, prototyping, testing of extreme environment electronics & sensors

Design


Electrical Schematic Diagram of SiC Integrated Circuit

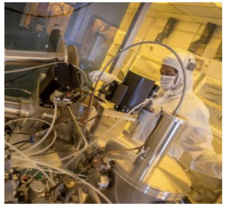

Electrical SPICE Circuit Simulation Waveforms of SiC Integrated Circuit


Mask Layout Design of SiC Integrated Circuit Chip


Design Layout of 4-level Multi-Chip Ceramic Circuit Board

Cleanroom Fabrication


Oxidation and Annealing Furnaces and Silicon Dioxide Low Pressure Chemical Vapor Deposition System


Reactive Ion Etcher

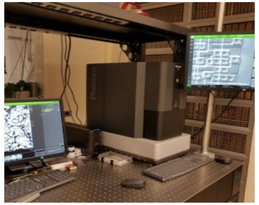

Rapid Thermal Annealer

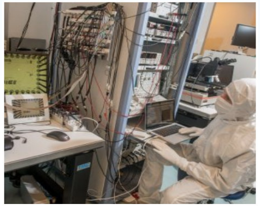

Wet Chemical Work Stations and Mask Aligner


Ultra High Vacuum Deposition System


Tantalum Silicide Sputter Deposition System

Test & Characterization


Scanning Electron Microscope with Energy Dispersive Spectroscopy


Electrical Probe Test Stations


High Temperature Ceramic Packaging Laboratory

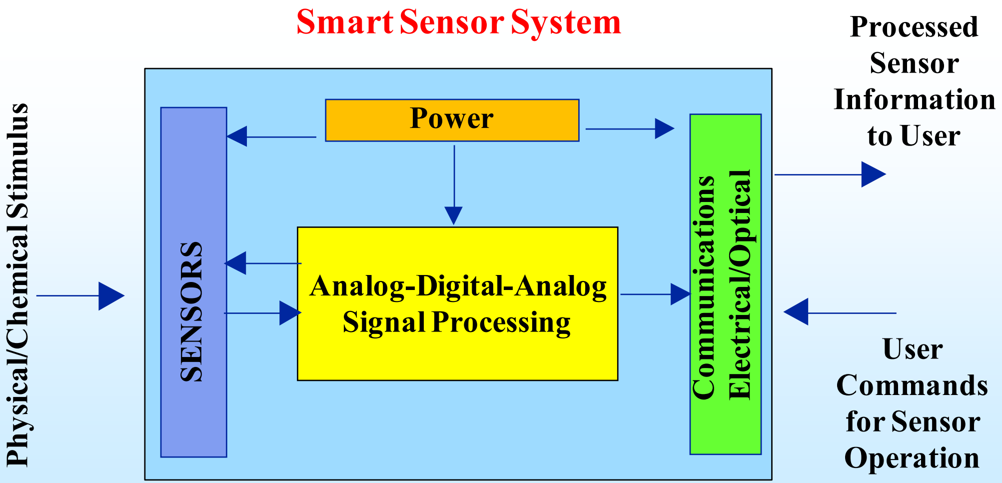

Insertion of SiC Chip on Ceramic Board Into Oven

The only facility to have built and demonstrated long-lived 500º C semiconductor ICs

https://www1.grc.nasa.gov/facilities/microfab/

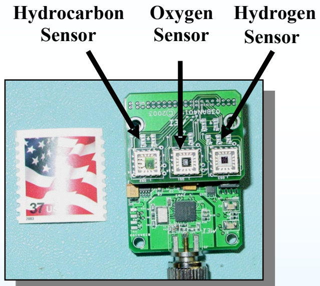
SMART SENSOR SYSTEMS BASED ON MICROSYSTEMS TECHNOLOGY

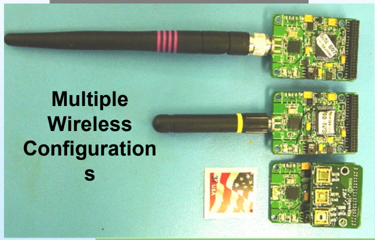
- A Range Of Sensor Systems Are Under Development Based On Microfabrication Techniques And Smart Sensor Technology
- Smart Sensor Systems Approach: Stand-alone, Complete Systems Including Sensors, Power, Communication, Signal Processing, And Actuation
- Microsystems Technology Moving Towards A Range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



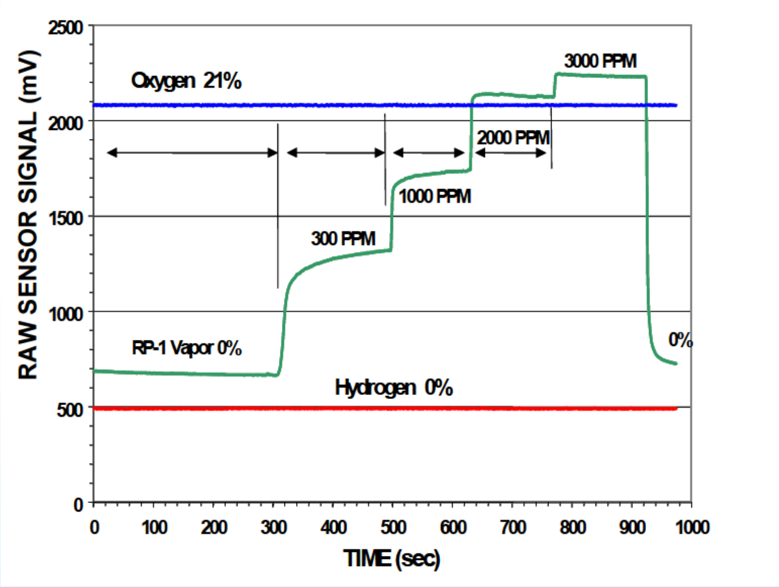
"LICK AND STICK" SENSOR SYSTEM

- SENSORS, POWER, AND TELEMETRY SELF-CONTAINED IN A SYSTEM NEAR THE SURFACE AREA OF A POSTAGE STAMP
- MICROPROCESSOR INCLUDED/SMART SENSOR SYSTEM
- ADAPTABLE CORE SYSTEM WHICH CAN BE USED IN A RANGE OF APPLICATIONS
- MULTIPLE CONFIGURATIONS AVAILABLE, INCLUDING BATTERY OR CONNECTED POWER
- IN-FLIGHT AND GROUND OPERATION APPLICATIONS





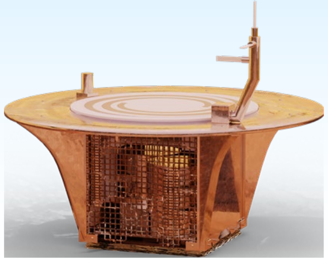
Wireless Data Transmission/Orthogonal Detection



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

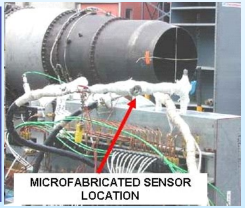
HARSH ENVIRONMENT ELECTRONICS AND SENSORS APPLICATIONS

- **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**

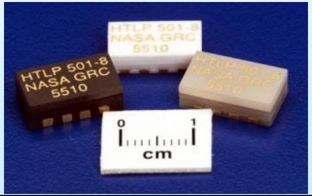


Long Lived In-Situ Surface Explorer (LLISSE)

Range of Physical and Chemical Sensors for Harsh Environments

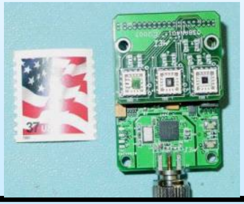


Harsh Environment Packaging (10,000 hours at 500˚C)



High Temperature Signal Processing and Wireless

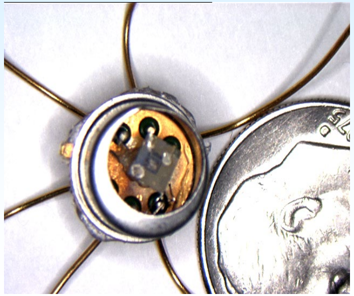
Moving Towards: High Temperature "Lick and Stick" Systems

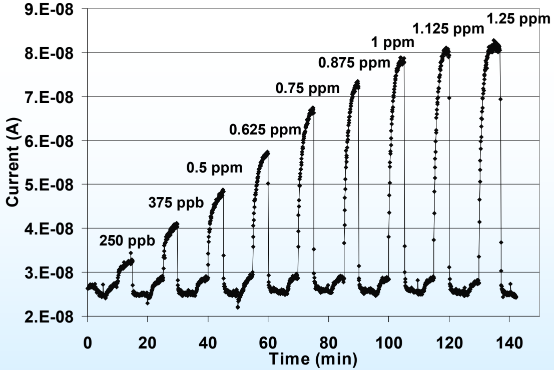


SiC-BASED GAS SENSOR DEVELOPMENT

- **The Use Of SiC Semiconductors Allows Operation At A Range Of Temperatures For Detection Of Hydrocarbons And NOx**
- **Selection of Sensing Alloy, Operating Temperature, and Filtering Can Allow Detection of a Range of Species**
- **Schottky Diode Design For High Sensitivity**
- **Wide Range Of Applications**
  - **Emissions Monitoring**
  - **Engine Health Monitoring**
  - **Hydrocarbon Fuel Leak Detection**
  - **Fire Safety and Environmental Monitoring**
- **Sensors Tested In Range of Environments including Engines**
- **Nominated Twice for NASA Invention Of The Year**

PACKAGED SiC-BASED SENSOR





OUTPUT CURRENT OF $Pd/PdO_X/SiC$ SENSOR TO HYDROGEN BIASED AT 0.45 V AT 180°C

LLISSE Chemical Sensors Status
Chemical Sensors Summary

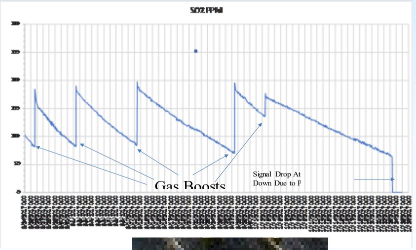
Background: ***Sensor Array Developed Under Completed NASA Phase I and Phase II SBIR***

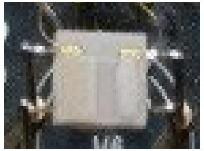
- ➢ Demonstrated Measurement of Key Species Including SO_2, H_2O, OCS, CO, HCl, and HF Under Relevant Conditions
- ➢ Sensors are selective to targeted species with minimal cross sensitivity to other species in Venus atmosphere

Current Status:

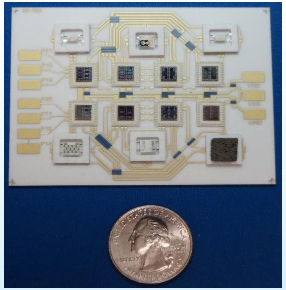
- Development of Chemical Sensors (including GRC sensors) Integrated with NASA GRC SiC Electronics On-Going in HOTTech project
  - ➢ Four Chemical Microsensors (SO_2, CO, OCS, HF) Tested for 60 days in Venus Simulated Conditions in GEER
    - All 4 Sensors Operated Nominally During 60 Day Test
    - First Demonstration of In-Situ SO_2 Tracking in GEER for Extended Periods
  - ➢ HF Sensor Integrated With Signal Transduction/Amplification SiC Electronics Monitored HF Boosts in GEER 10 Day Test
- Permanent installation as a monitoring system in GEER planned
- Modules being developed for measurement of volcanic gas emissions (SOx, CO, OCS, H_2O, NO, HF) using high temperature gas sensors and GEN-12A chemical sensor ASIC (single chip with all functions) near fissure/vent.

SO_2 Sensor Operation in GEER for 60 Days in Venus Simulated Conditions





SO_2 MicroSensor

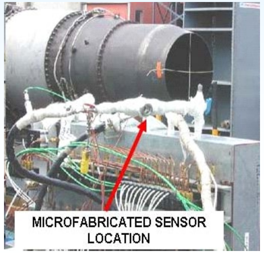


Compact "Credit Card" Format Board Single Sided

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

International Space Station Safety System

Jet Engines Emissions



Aircraft Fire Detection

Exercise Monitoring

NASA Helios Fuel Cells

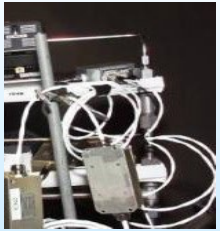
First Responder Monitoring

Human Health Breath Monitoring

Launch Vehicle Leak Detection

Rocket Engine Teststands

Environmental Monitoring



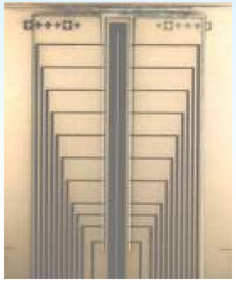
Cryogenic Fuel Line Monitoring

Long Lived Venus Surface Missions

Thin Film Physical Sensors for High Temperature Applications

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

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

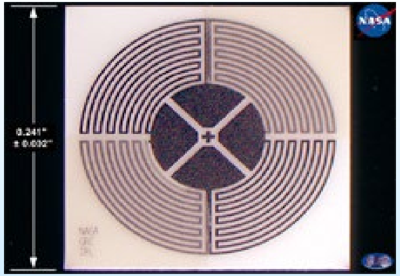


Flow sensor made of high temperature materials

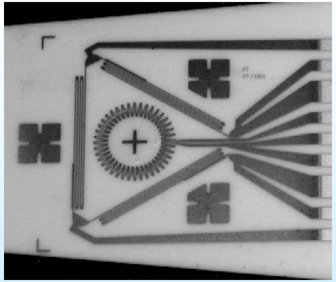
Multifunctional smart sensors being developed

PdCr strain sensor to T=1000°C

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



Heat Flux Sensor Array to T=1000°C



Multifunctional Sensor Array

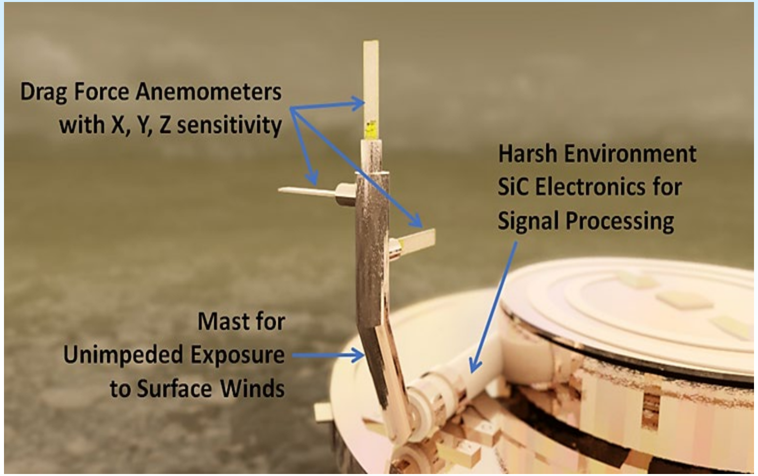
LLISSE Surface Wind Sensor

Background: ***Drag-force anemometer (cantilever) baseline approach with significant history of demonstrations in engine environments***

- Full-bridge strain gage approach allows flow measurements with minimal power consumption
- Force of wind bends cantilever; deformation measured using thin film strain gages
- Wind speed/direction determined using up to 3 perpendicular cantilevers along each axis

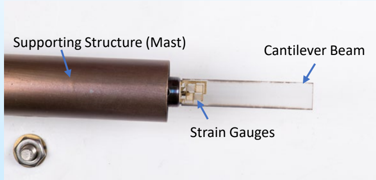
Current Status*: Wind sensor tested in wind tunnel and multiple times in GEER environment showing viability of approach*

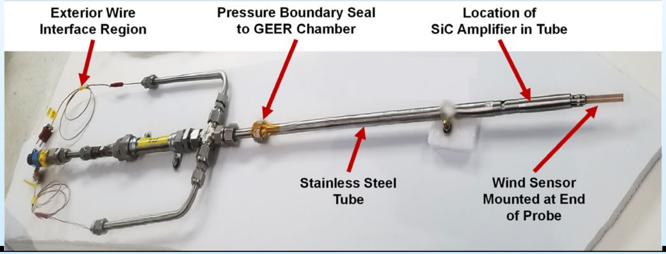
- Core material compatibility demonstrated
- Wind sensor integrated with electronic amplification has shown ability to track gas flow in GEER-simulated Venus surface conditions

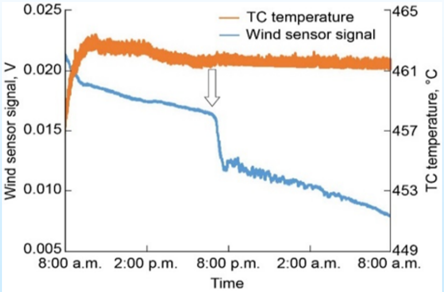


LLISSE Wind Sensor Approach

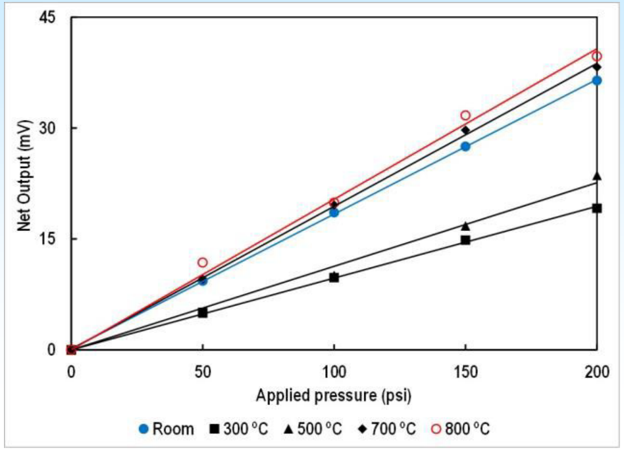
LLISSE Wind Sensor Assembly and Installation

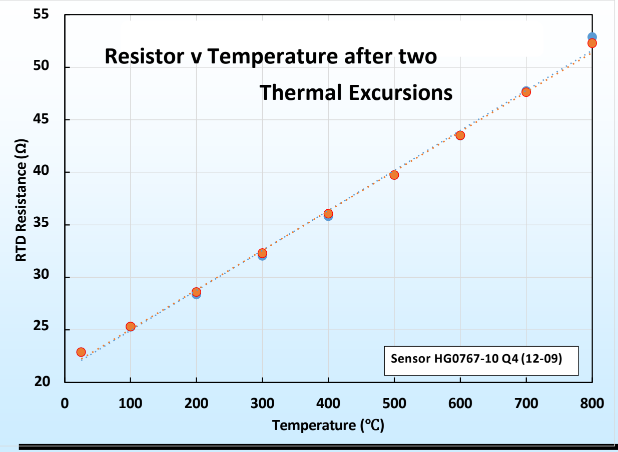






On-Chip Integrated Pressure/Temperature Sensor for 800°C Operation





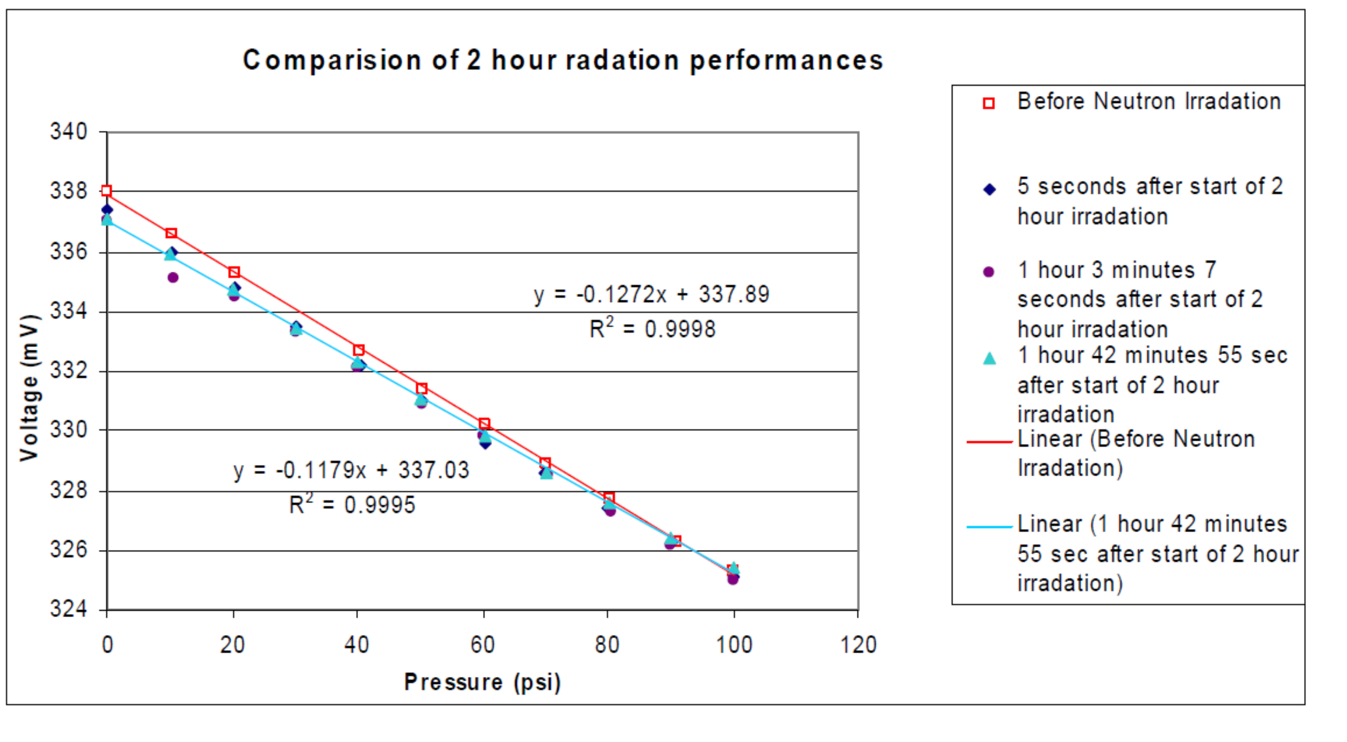
Integrated Pressure/Temp Sensors at 800 °C without Cooling

Accurate Pressure/Temp Relationship, Real-time Temperature Compensation and Voltage-Pressure Conversion.

Full-bandwidth Capture of Pressure Transient due to Direct Interaction with Flow-Field at High Temperature.

Neutron Irradiation of NASA GRC SiC Piezoresistive Sensors*

1 MeV equivalent neutron fluence in SiC of 10^{15} n-cm^{-2}



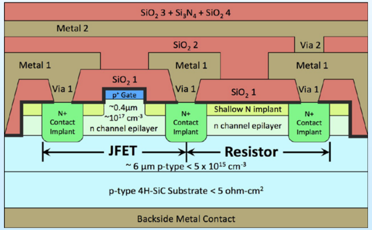
**Master's Thesis: Debra A. Goodenow, The Ohio State University 2007*

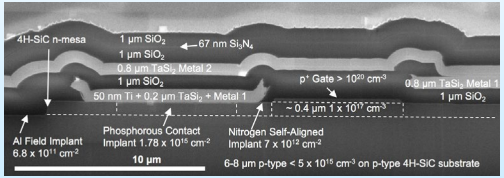
High Temperature Electronics Advancements

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 ~1000 of Junction Field Effect Transistors (JFETs); An order of magnitude beyond a few JFETs previously demonstrated
- 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

Cross-sectional illustrations of NASA Glenn 4H-SiC JFET-R devices with two levels of interconnect. (a) Simplified device structure drawing. (b) Scanning electron micrograph of Generation 10 JFET source and gate region



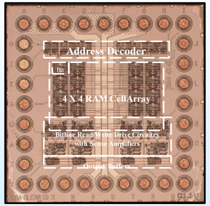


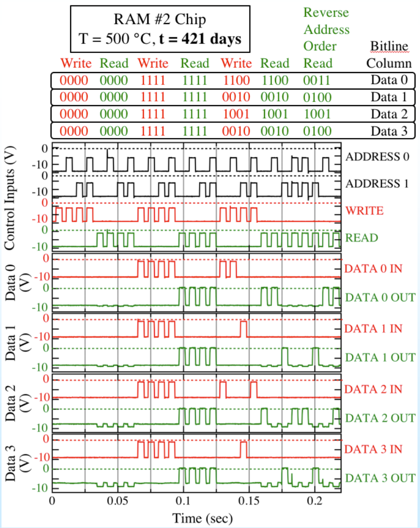
NASA GRC Electronics Development

2017 NASA Glenn SiC JFET IC “Version 10”
1+ year of operation in Earth air oven at 500 ° C Achieved

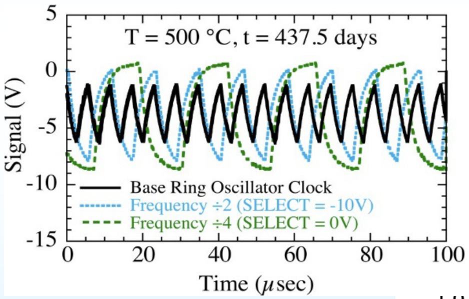
Version 10 ICs set high temperature durability world records in T ≥ 500 °C Earth-atmosphere oven testing.

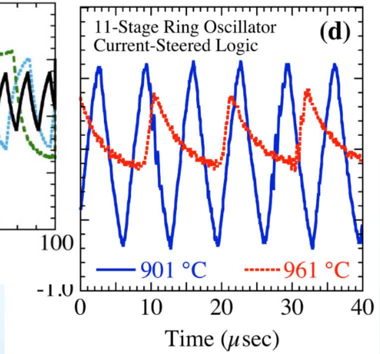
Complex ICs Operating more that 1 Year at 500 °C[1]

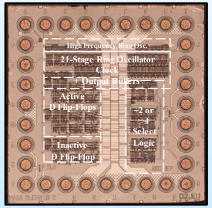




ICs Operating at World Record 961 °C[2]







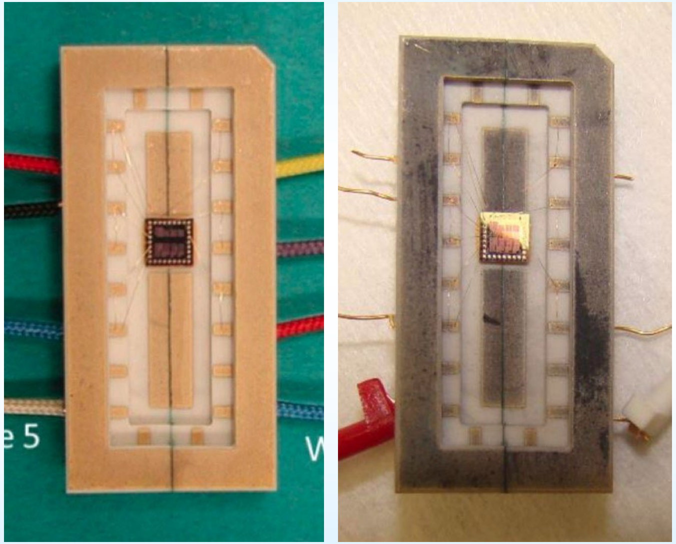
[1] 2018 Int. Conf. High Temperature Electronics p. 71
[2] IEEE Electron Device Letters vo. 38 p. 1082 (2017).

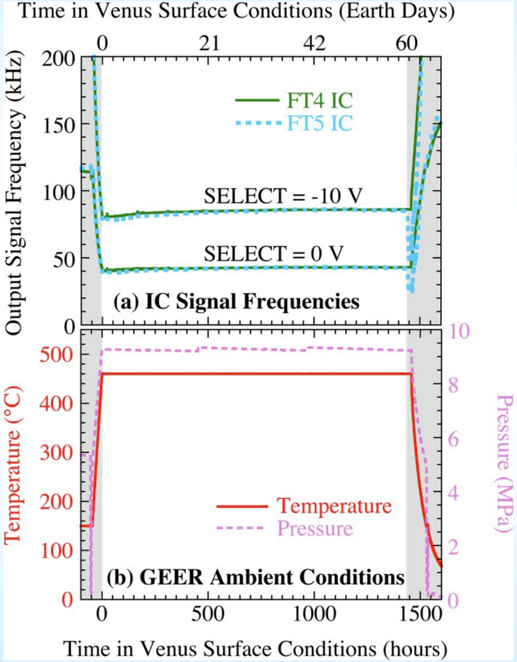
60-Day Venus Environment IC Test (in GEER)[1,2]

Two IC Version 10 ÷2/÷4 Clock ICs (175 JFETs/chip) successfully operated in GEER Venus surface conditions for 60 days duration

Before GEER

After 60 days GEER





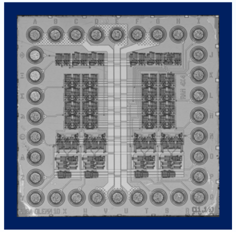
[1]Neudeck et al., IEEE J. Electron Devices Soc., vol. 1, p. 100 (2018).

[2]Chen et al., Proc. 2018 Int. High Temperature Electronics Conf.

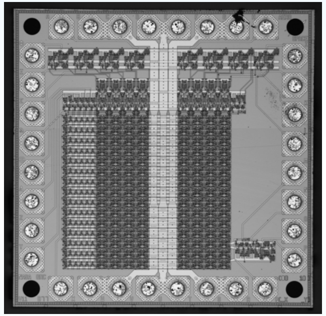
NASA Glenn SiC JFET IC Technology Progress

“Learn by doing” fabricating and testing **successive upscaled generations** of prototype IC wafers/chips

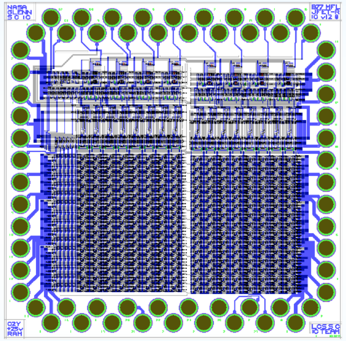
“IC Gen. 10” (2017)
(16-bit RAM, 195 SiC JFETs)
2 prototype 75 mm diameter SiC epi-wafers
6 μm gate length, 6 μm resistor width
3 mm x 3 mm, 32 I/O Bond Pads



“IC Gen. 11” (2018)
(120-bit RAM, ~ 1000 SiC JFETs)
4 prototype 75 mm diameter SiC epi-wafers
6 μm gate length, 3 μm resistor width
4.65 mm x 4.65 mm, 32 I/O Bond Pads



“IC Gen. 12”
(248-bit RAM, ~ 2000 SiC JFETs)
6 prototype 100 mm diameter SiC epi-wafers
3 μm gate length, 2 μm resistor width
5 mm x 5 mm, 62 I/O Bond Pads



Wafer fabrication in progress

Key IC Version 10 Accomplishments*

- **400+ days stable 500 °C electrical operation**
- **60 days stable Venus surface environment electrical operation**
- 961 °C electrical operation (short-term)
- -190 °C cryogenic electrical operation
- Radiation immunity through 7 Mrad(Si) ionizing dose and 86 MeV-cm^2/mg heavy ions (25 °C)

Key IC Version 11 Accomplishments

- **5-fold reduction in logic gate power**
- **First ICs designed for LLISSE**
- 500 °C 8-bit Analog to Digital converter
- Few days 500 °C ~1 kbit ROM operation

*Published results, see https://www1.grc.nasa.gov/research-and-engineering/silicon-carbide-electronics-and-sensors/technical-publications/

Advanced Space Radiation Instrumentation Research

Problem:

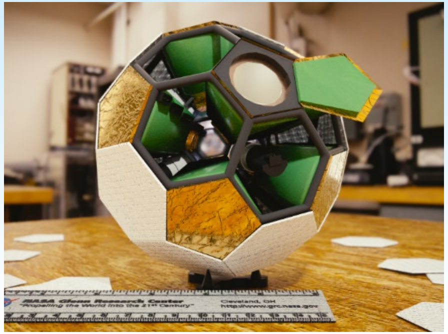
- Awareness of space radiation critical in missions beyond LEO (i.e., Moon, Mars, NEOs, etc.) requiring:
  - Embedded instrumentation to provide feedback for “smart”, adaptive systems
  - Precision instrumentation to provide improved data to space radiation modeling efforts
  - Compact instrumentation for more complete, real-time situational awareness on small platforms (e.g., CubeSats)
- Current technology limiters are radiation hardness, noise floor, thermal stability, and detector geometry.

Solution:

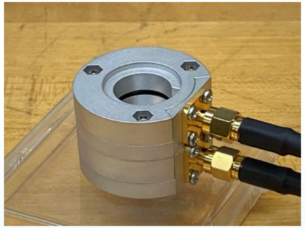
- Compact integrable detectors with low noise, solid state components allowing spherical geometry enabled by the application of Wide Band Gap semiconductors as radiation detectors

Approach:

- Variety of detector development:
  - SiC LET Detectors & Charged Particle Telescope
  - Low Power Charged Particle Counter
  - Fast Wide Band Gap Cherenkov Detector
- Leverage GRC Expertise and Facilities in:
  - Harsh Environment Thin Films
  - SiC Devices & Harsh Environment Packaging
  - Micro-Optics
  - Flight Electronics

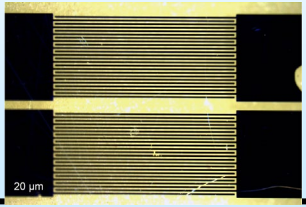


Compact Full-field Ion Detector System (CFIDS) Concept
(US Patents 7,872,750 & 8,159,669)



Large Area SiC LET Detectors & Charged Particle Telescope

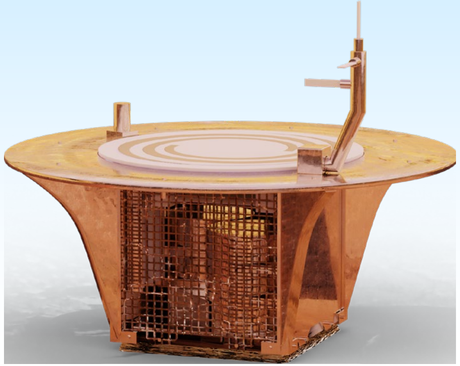
Fast, Large Area, Wide Band Gap Cherenkov Detector
(U.S. Patent 10,054,691)

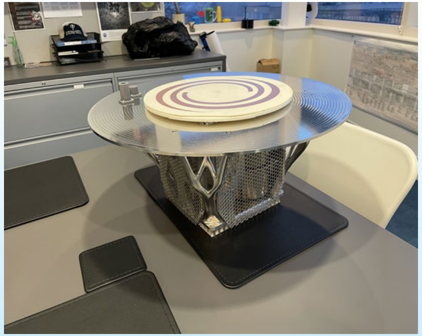


Low Power Charged Particle Counter
(U.S. Patent 10,429,521)

Long-lived lander In-Situ Solar System Explorer (LLISSE)

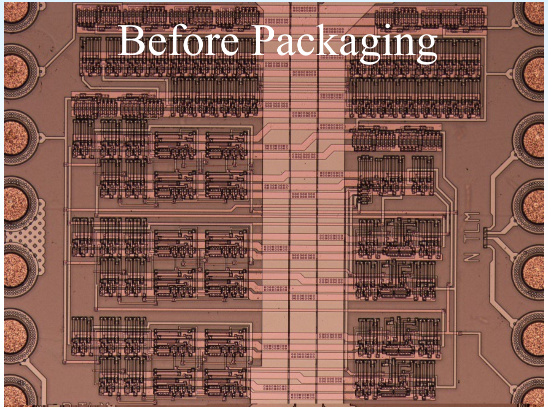
- LLISSE is a small long-duration lander for Venus
  - Designed to be an independent platform with all the needed subsystems (power, communication, sensors, etc..).
- Enable compelling science by returning first ever temporal Insitu data: Meteorology (temp, pressure, radiance, winds) as well as atmospheric specie abundances and their variability
- Operates for 60 days or more on Venus (> Solar day)
- Transmits measurements to a supporting orbiter, which is needed to relay the data to Earth
- LLISSE is a platform that can be expanded to achieve more or other targeted science

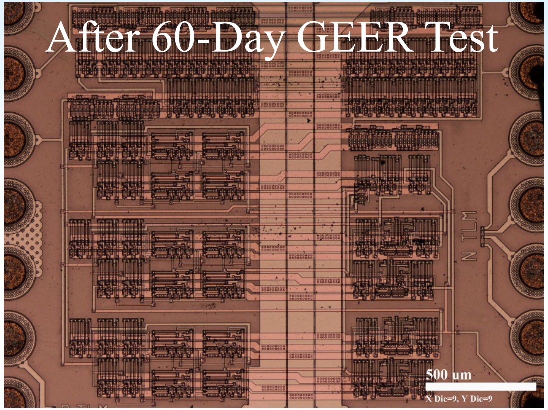




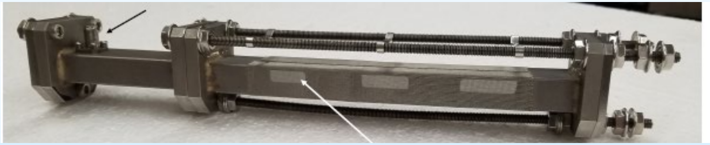
Material Choice (and GEER Testing) Matters

SiC Clock IC Chip Optical Microscope Photos
(These IC Materials Work - Chip operated for 60 days)

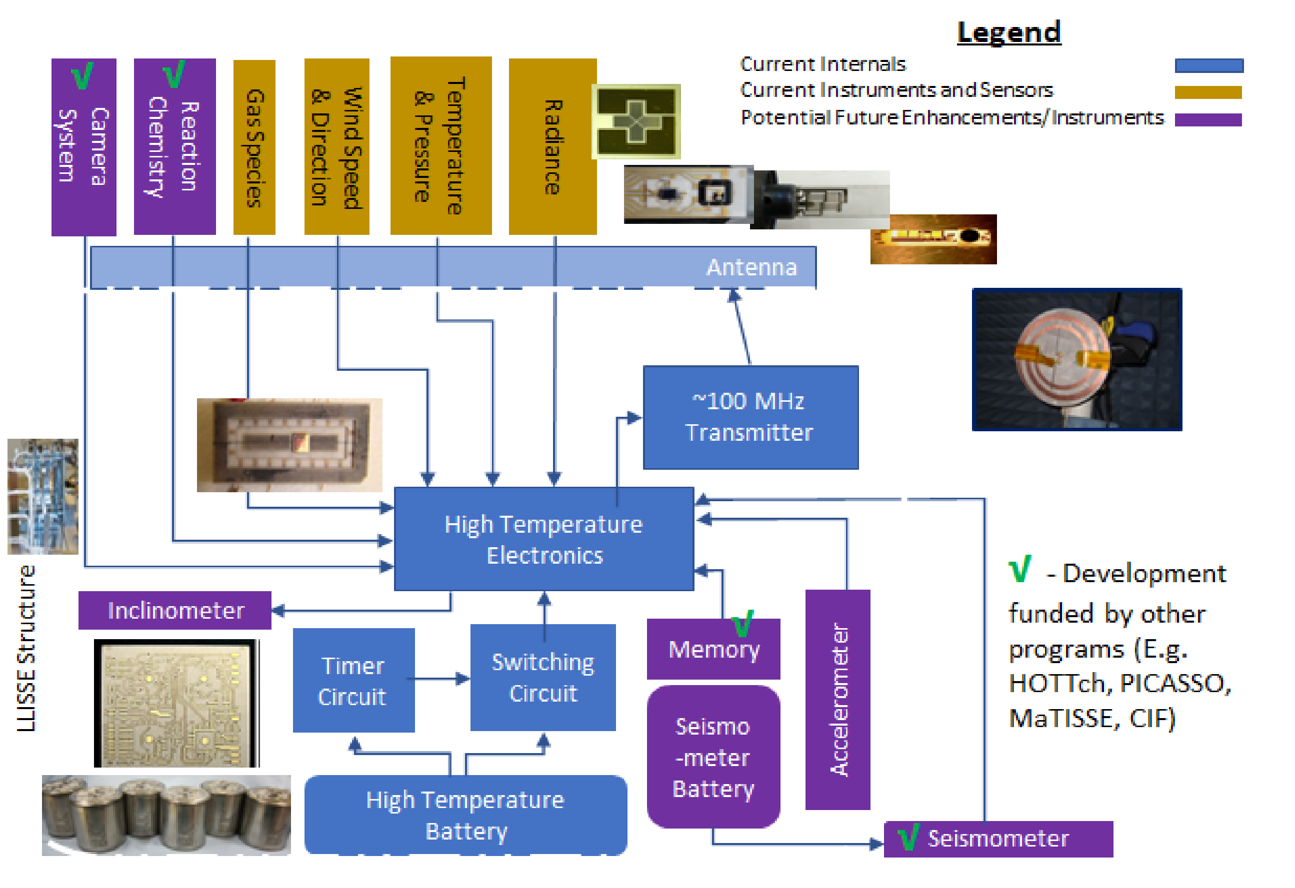




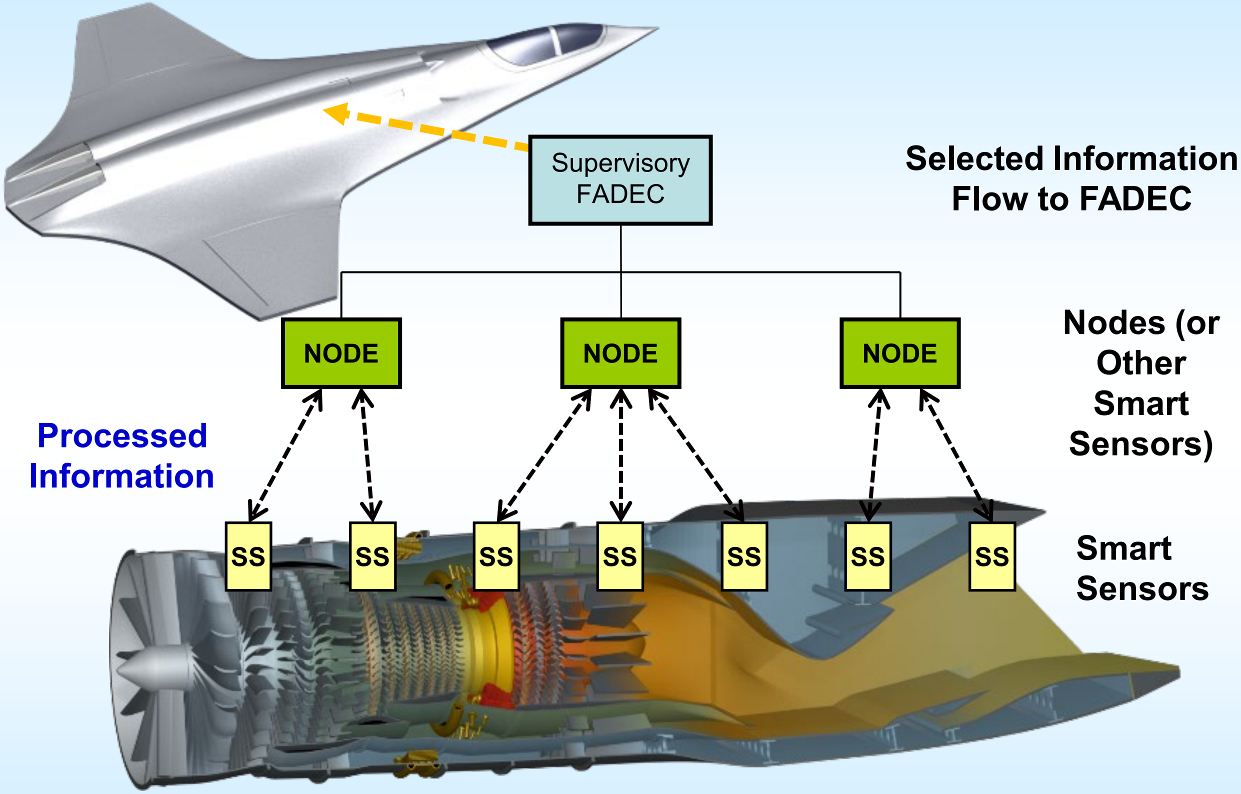
Wave Guide Before and After 60 Days of GEER Testing
(These materials react – grow crystals – will NOT work)



LLISSE Block Diagram



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

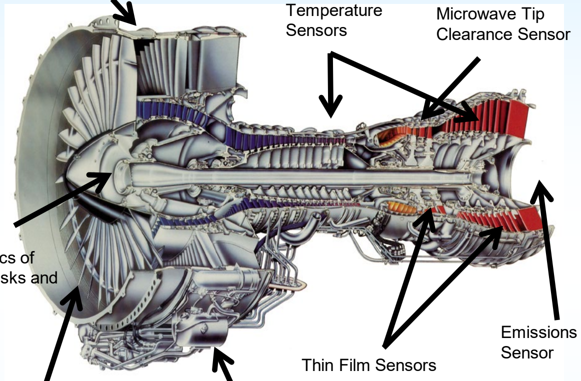
Approach:

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

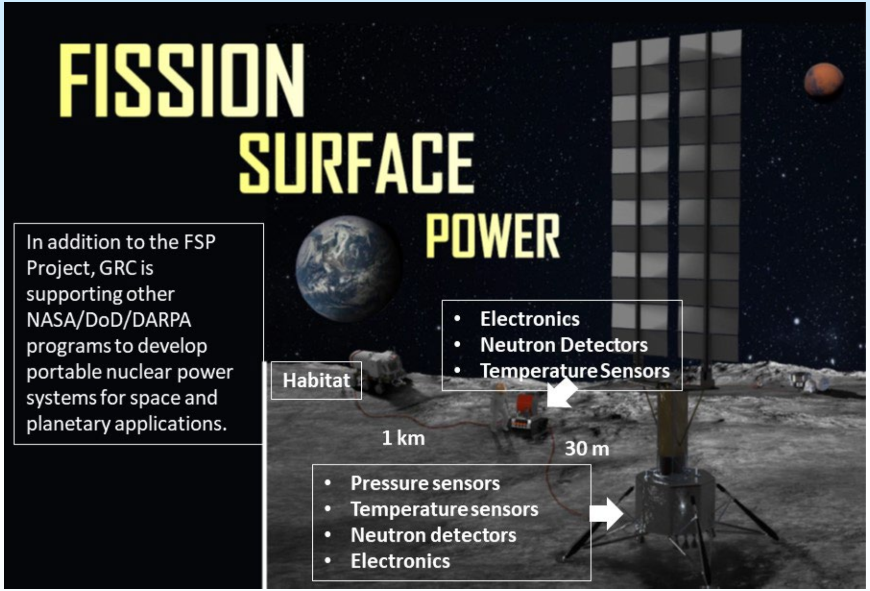
Partnerships:

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



Model-based gas path diagnostic architecture

Leveraging GRC Intrinsically Radiation Hardened SiC Sensor Technology



FSP Attributes	Challenges for Instrumentation
Compact	Instruments must have small form factor: Multifunctional integration
Unmanned	Agile in accident response
10 –year Operational Life	No luxury of replacing/maintenance faulty parts: Reliability

Current Activity (STMD funded): Ready to conduct accelerated irradiation of integrated SiC Pressure/Temperature sensors to quantify the meantime to failure, thereby developing a reliability prediction physics to support sustainable and reliable 10-yr Lunar FSP operation.

SUMMARY

We can enable the Information Age for hardware in aerospace by enabling Smart SensorSystems that work where they need to work

- **Aerospace Applications Require A Range Of Smart Sensing Technologies**
- **NASA GRC Has Unique Capabilities To Address These Needs Including A Range Of SiC-Based Technologies**
- **Facilities For Microfabricated Sensors/Electronics Fabrication And Characterization**
- **A Range Of Sensor and Sensor System Technologies Being Developed**
- **Drive System Intelligence To The Local (Sensor) Level: Distributed Smart Sensor Systems**
- **Sensor And Sensor System Development Examples:**
  - **Chemical Sensors, Pressure Sensors, Thin-film Physical Sensors, Radiation Detectors**
  - **High Temperature Electronics**
- **Core Microsystems Technology Applicable To A Range Of Application Environments**
  - **Venus Surface Applications**
  - **Engine Monitoring**
  - **Fission Surface Power**

SMART, SMALL, ADAPTABLE, AND RUGGED

Backup Slides

Surface Technology Development Overview

- Technologies relevant for Venus surface applications may often have their origin in other harsh environment applications e.g., aeronautics or industrial processing
- Material systems and engineering approaches standardly used for even harsh environment terrestrial applications may not be viable for Venus missions
- A major challenge is operation in Venus surface conditions without significant degradation and for extended periods of time
- Testing of proposed technologies in first at high temperature leading up to Venus simulated conditions include relevant chemistry, is core to technology advancement
- The status of Venus technology development is in some cases at the level of 1970's to 1980's technology; at these levels significant science can be accomplished.
- A mission needs a complete compliment of relevant technologies for success

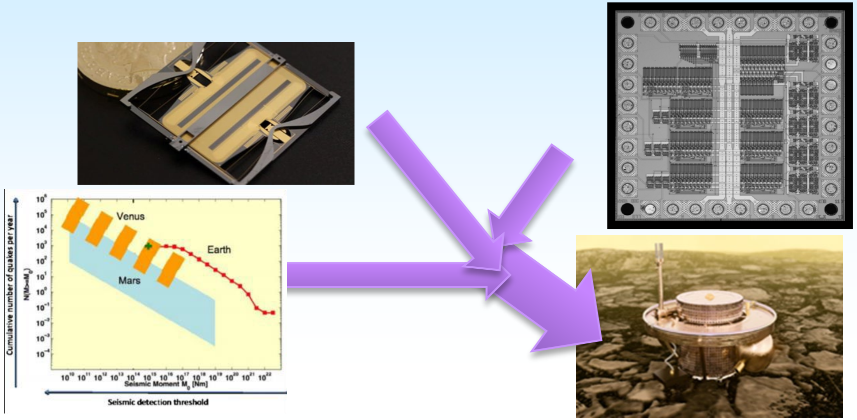
GEER: 92 atm, 465 °C + chemical composition found at the surface of Venus (CO_2, N_2, SO_2, H_20, CO, OCS, HCl, HF, and H_2S)

Evolving "Handbook" of What Works in Venus Ambients

https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2017EA000355

Tested Materials with Corresponding Outcomes		
Devices	**Materials**	**Outcome**
Electronics Packaging	Pb	PbS
	Al_2O_3	No reaction
Insulation	CaO	$CaSO_3$, $CaSO_4$
SiC Electronics	Pt	PtS; fibers when present as thin film
	Pt (in the presence of Au)	PtS spheres
	Au	No reaction, but mobile
	Ir	No reaction, but mobile
	SiC	No reaction
	SiO_2	No reaction
Feedthrough Materials	Cu	Cu_2S crystals
	Ni	NiS crystals
	CuBe	Cu_2S crystals; Cl found on surface
SiC Pressure Sensor	Kovar (Ni-Co-Fe)	NiS, Fe_xO_y
	AlN	No reaction
	Ag-Cu Braze	Segregation into Cu_2S and Ag; Ag mobile
GEER Components	Inconel 625 (Ni-Cr-Mo-Fe)	NiS, Cr_xO_y
	304 SS	Mirror finish, low corrosion rate
	Al foil/Mg doped	MgO on surface, MgF inner layer, Al bulk no reaction
New Materials	Sputtered Aluminum	Reacts with HF to form AlF_3
	Titanium	Oxide on surface decreasing into bulk

High-Temperature MEMS based seismometer



Team Member(s)/Institution(s)

T. Kremic / PI	NASA Glenn Research Center (GRC)
D. Spry / CO-I	GRC
M. Krasowski / CO-I	GRC
R. Herrick /Science PI	Univ. of Alaska/Fairbanks (UAF)
Michael West / CO-I	UAF
T. Pike / Collaborator	Imperial College of London

Technology Overview/Description

<u>Overall objective:</u>

Leverage existing MEMS seismic sensor, recent developments in high-temperature electronics and sensors, terrestrial analogues and Venus seismicity studies, and an expert team to design and mature a MEMS based seismometer suitable for use on long-duration Venus landers, like SAEVe.

Accomplishing this involves:

- Assessing / modifying existing MEMS seismic sensors that may be suitable for Venus applications
- Developing driving/interfacing electronics to support required operations and interfaces of a notional lander
- Design and fabricate a 1-axis instrument (but readily scalable to 3 axis) and verify performance via tests and analysis. Iterate.
- Mature instrument and demonstrate performance of breadboard system in Venus surface conditions against model-based predictions and reach a TRL of 4 or greater

Technology Goals

1. Develop science-based requirements for a Venus seismometer that consider the Venus unique operations circumstances
2. Assess MEMS seismic sensors, modify as required, and fabricate and test under Venus conditions
3. Analysis and the sensor / electronics system and design, fabricate and test a 1 axis system that meets requirements and is consistent with expected Venus mission applications
4. Demonstrate operations of breadboard 1 axis instrument in Venus conditions

Starting TRL: 2 Ending TRL: 4

VIPR Ground Testing Overview

VIPR 1 (December 2011):

Modify a heavily instrumented F117 /PW2000 engine with an advanced suite of sensors, confirm sensor operation, characterize nominal engine operation parameters and validate gas path models.

VIPR 2 (July 2013):

Employ selected sensors to detect and characterize impacts of certain seeded faults and validate off-nominal gas path models. Faults are expected to include intentional operation with contaminated and/or inadequate lubrication, operation with intentional rotor or turbine imbalances, and other intentionally inserted and known faults.

VIPR 3 (2015):

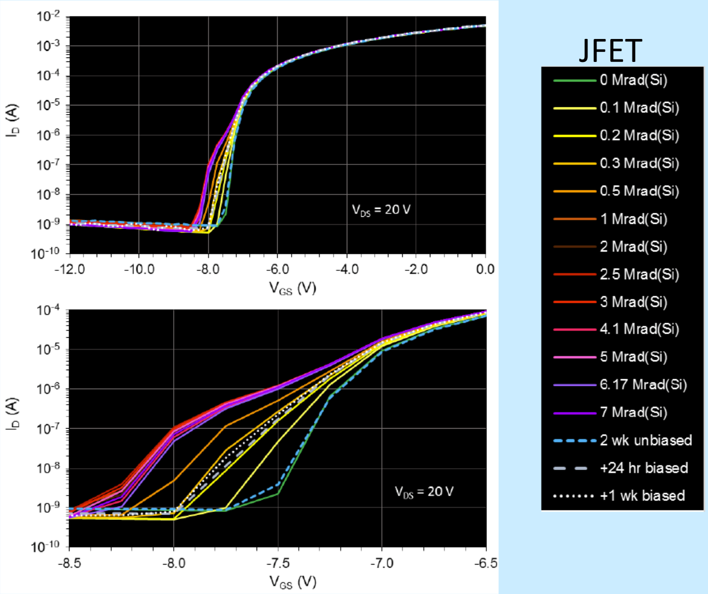
Determine capability of advanced detection and diagnostic systems to characterize engine performance, and identify fault modalities, during rapid engine degradation caused by the ingestion of volcanic ash.

All VIPR ground testing conducted on an Air Force C-17 aircraft at Edwards AFB, California.

Radiation Testing of NASA Glenn JFET ICs[1]

Generation 10 JFETs, Oscillators, Flip-Flops, Op-Amps tested by NASA Goddard

Total Ionizing Dose Hard (Gamma > 7 Mrad)



Single Event Effects (Heavy Ion Strike through Au)

Ring Oscillator

- No destructive effects at LET(Si) = 86 MeV-cm²/mg
- Only small glitches recorded

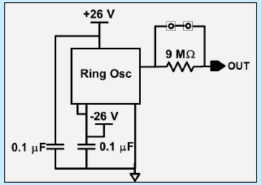


Fig.16. Ring oscillator test circuit.

Summary

Prototype 4H-SiC JFET ICs developed & fabricated at NASA GRC for harsh Venus conditions demonstrate potential for Jovian-type environments as well:

- **> 7 Mrad(Si) TID tolerance**
- **No destructive SEE at LET(Si) = 86 MeV-cm²/mg**
- **SEUs occurred in the clock circuit**
  - **3.5 MeV-cm²/mg ≤ onset LET(Si) ≤ 9.6 MeV-cm²/mg**

[1]Lauenstein et. al., 2019 IEEE Radiation Effects Data Workshop (REDW)
https://ntrs.nasa.gov/citations/20190031951