Silicon Carbide Microsystems Technology for Extreme Environments: Opportunities for Nuclear Applications

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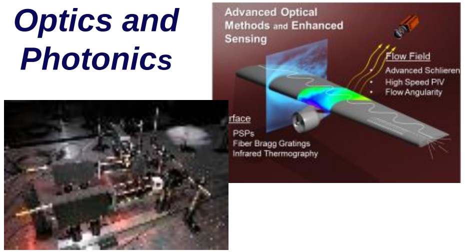
Communications and Intelligent Systems Division
NASA Glenn Research Center

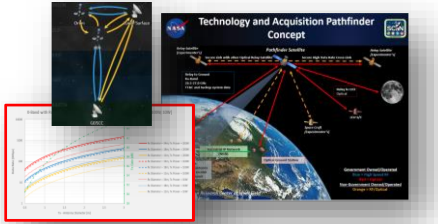
Division Capabilities

Optics and Photonics



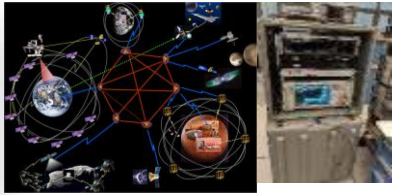
Optical Communications/Quantum Comm
Hyperspectral Imaging
Optical Instrumentation- Flow Diagnostics
Health Monitoring

Systems Architectures & Analytical Studies



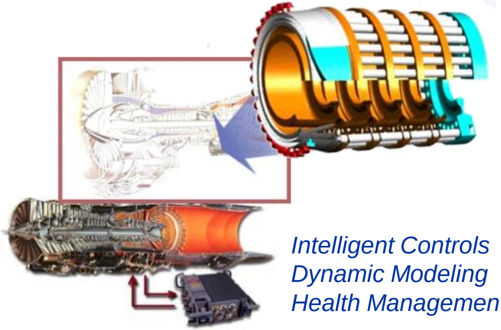
Communications System Architectures
Analytical System Studies, Mod & Sim
Spectrum Analysis

Secure Networks, System Integration and Test



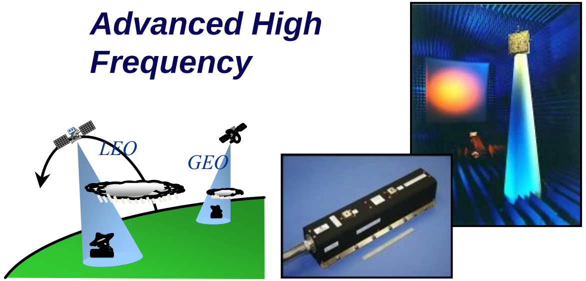
Network Research/Security
System
Integration/Test/Demo

Intelligent Control and Autonomy



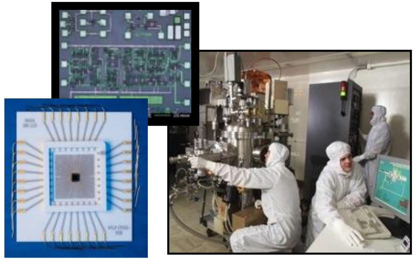
Intelligent Controls
Dynamic Modeling
Health Management

Advanced High Frequency



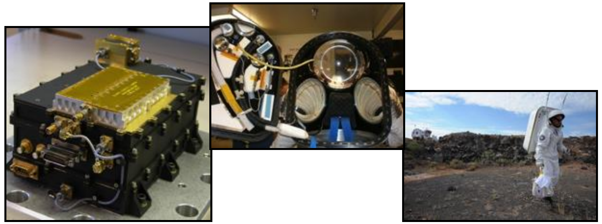
Antennas Design and Metrology
RF Systems and Components
3-D Electromagnetic Modeling
System Emulation

Smart Sensing and Electronics Systems



Extreme Environment Sensors & Electronics
Electro-Optical Sensing
Thin Film Physical Sensors

Cognitive Signal Processing

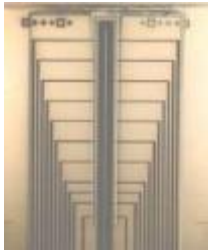


Radio Systems – SDRs,
Signal Processing and Cognition
Position, Navigation & Timing

Thin Film Physical Sensors

Applications: 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)

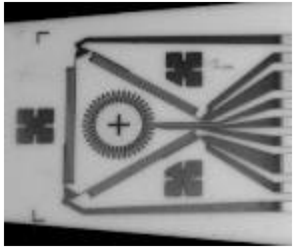


Flow sensor made of high temperature materials

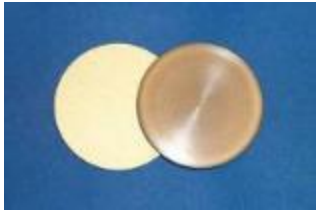
PdCr strain sensor to T=1000°C

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

Heat Flux Sensor Array to T=1000°C

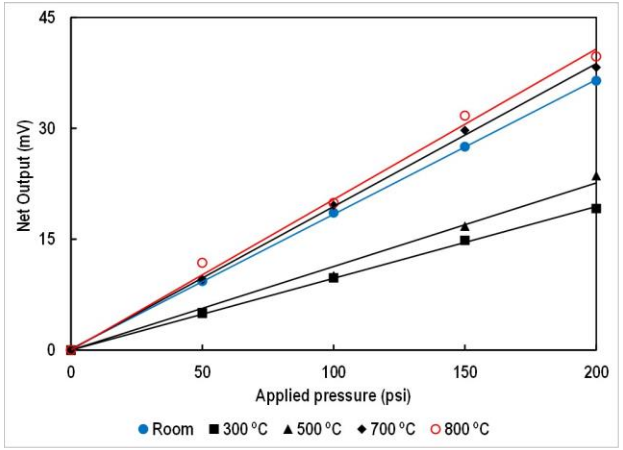


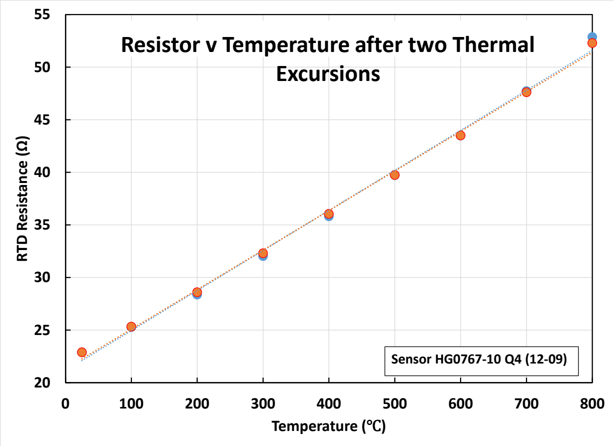
Multifunctional Sensor Array



Ceramic Thermocouple fabricated at University of Rhode Island

Integrated Pressure/Temperature Sensor for 800 °C Operation





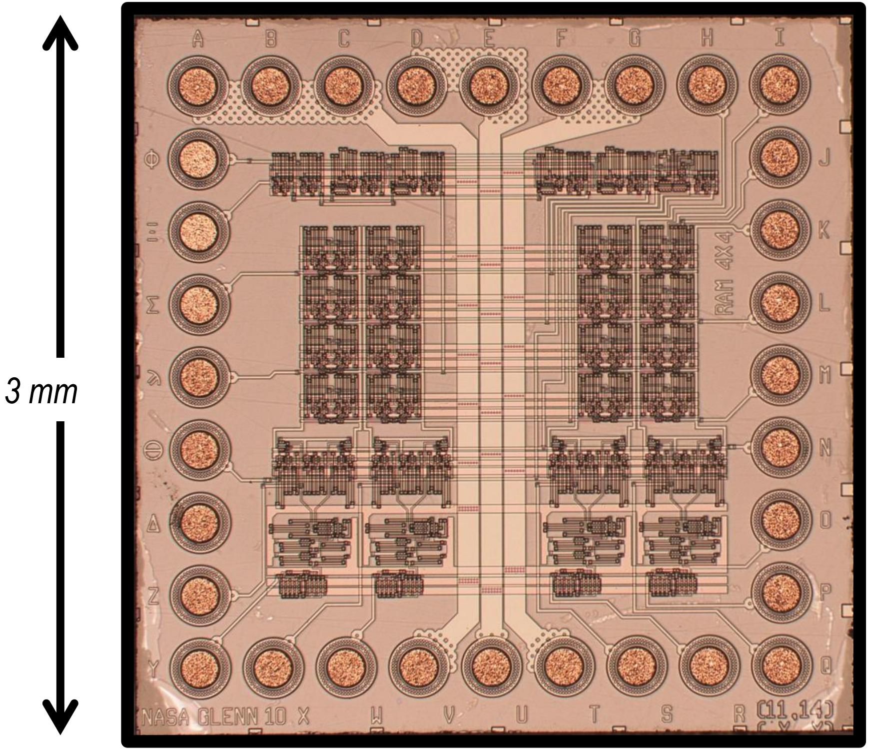
Integrated Pressure/Temp Sensors at 800 °C without Cooling

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

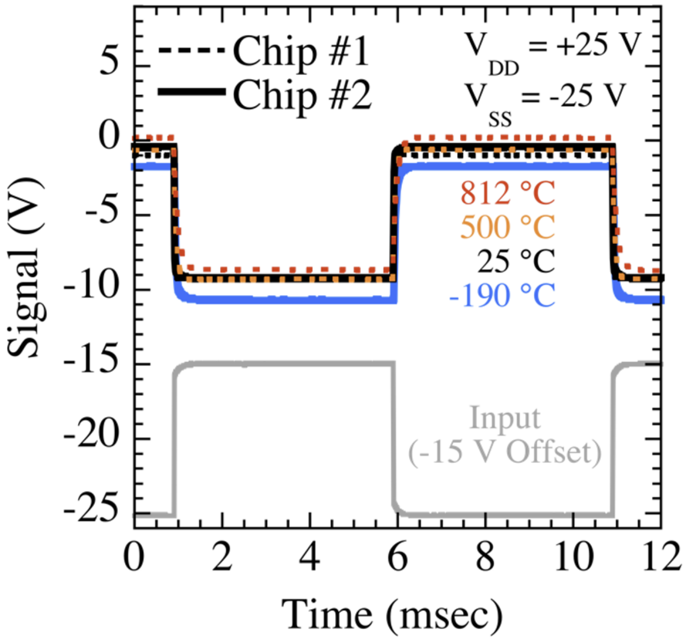
Full-bandwidth Capture of Pressure Transient due to Direct Interaction with Flow-Field at High Temperature.

500 °C Durable NASA Glenn SiC JFET-R RAM Chip

SiC JFET-R RAM Chip



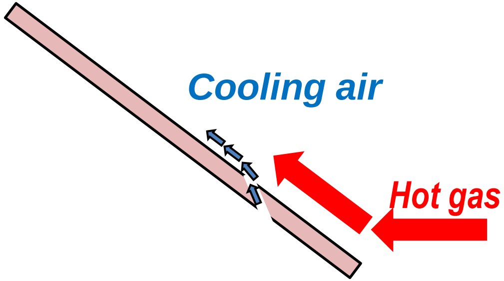
Made possible by advance robust contact metallization, packaging, and fabrication process

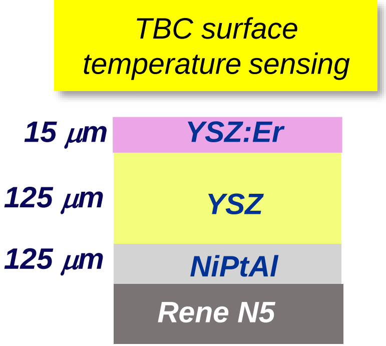


-190 ℃ to +812 ℃ SiC JFET-R NOT Gate Testing

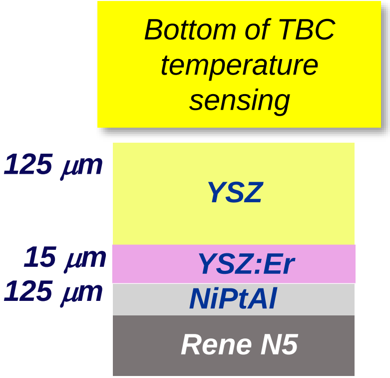
- 1000 °C temperature span WITHOUT changing signal/supply input voltages!
- Cold environments WITHOUT "cold start" issues.
- Temperature-accelerated 800 °C lifetime testing for long-duration 500 °C missions.

Luminescence-Based Temperature Measurements





Used for mapping temperatures above and below Thermal Barrier Coating during air-film cooling. Compare air film cooling effectiveness above and below TBC.



Luminescence-Based Temperature Measurements

Blowing ratio (measure of cooling air flow)

0.57

Increasing cooling air flow

0.95

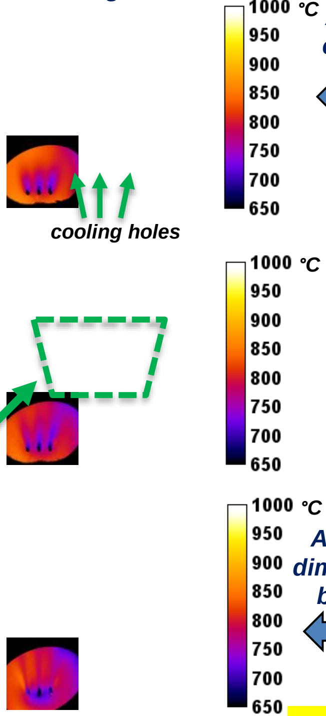
1.66

Above TBC

Air film cooling dominates at low blowing ratios.

Below TBC

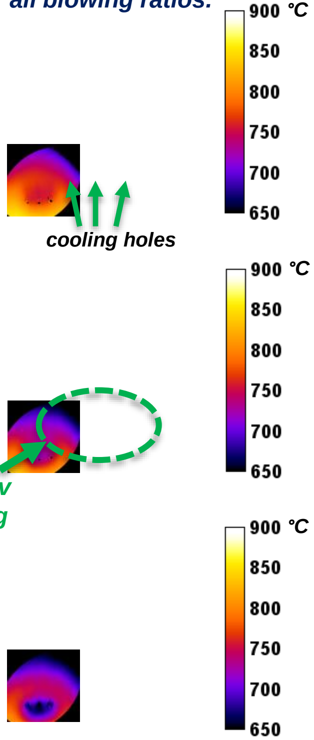
In-hole convective cooling dominates at all blowing ratios.



Air jet film cooling

Air film cooling effective at TBC surface.

In-hole convective cooling dominates at metal surface.



In-hole convective cooling

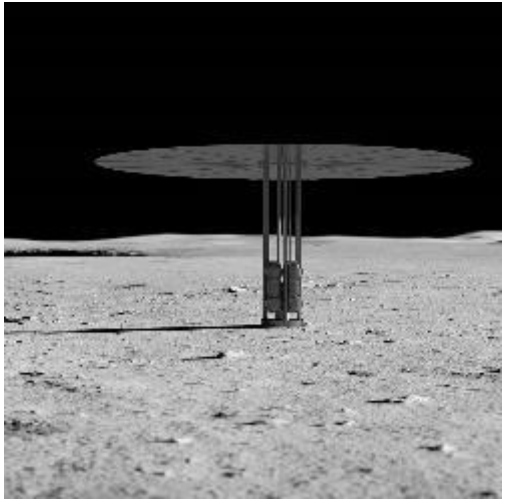
Reactor Remote Temperature Visual Inspection?

Air film cooling diminishes at high blowing ratios

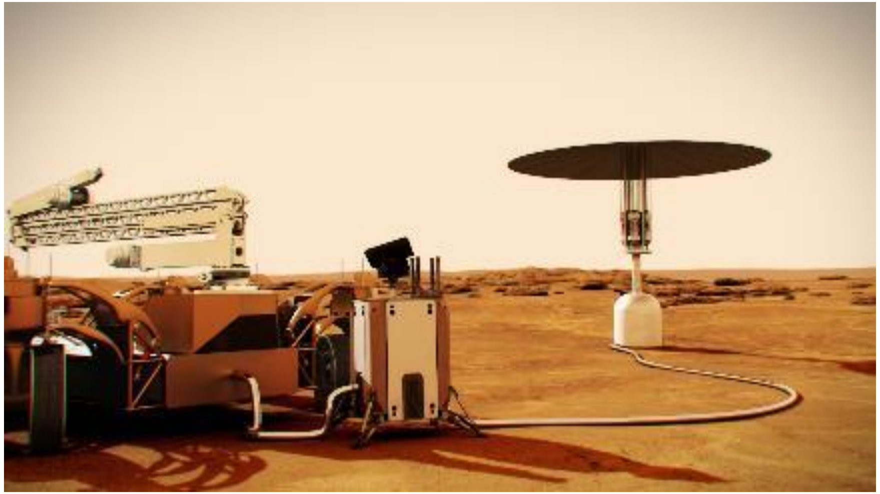
In-hole convective cooling continues to dominate

Important implications for cooling hole design.

NASA Emerging Radiation Resilient Sensors and Electronics



Conceptual fission surface power system on the Moon



Conceptual fission surface power system on Mars

- NASA, DOE, and industry designing a 40-kW fission power system – enough to continuously run 30 households for ten years.
- Future lunar demonstration will pave the way for sustainable operations and even base camps on the Moon and Mars. (https://www.nasa.gov/mission_pages/tdm/fission-surface-power/index.html)

NASA Lunar/Martian Fission Surface Power (FSP)

Attributes	Challenges on Instruments
Compact	Instruments must have small form factor
Unmanned	Agile accident response
10 –year Operational Life	Maintenance and replacing faulty parts
2029 Delivery Date	Instrumentation performance validation

Key Take Away

- No luxury of replacing faulty parts!
- Instrumentation with reduced form factor
- Instrumentation likely to reside near the reactor core.
- Invest in emerging innovative I&C systems to address FSP instrumentation risks.

Traditional Instrumentation and Controls Structure in an NPP

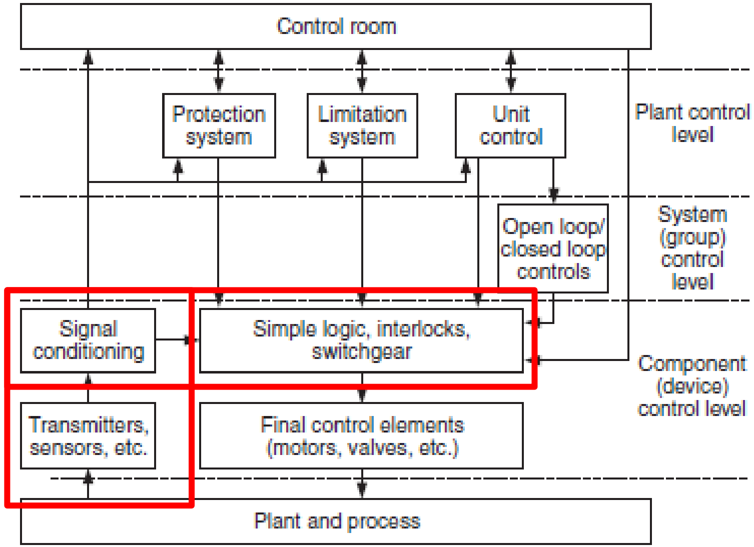


FIG. 15.2. Structure of I&C in an NPP.

Red box is our areas of interest that aligns with our core capabilities

Vision (path to innovation):

- *Integrate discrete functionalities on a single chip*
- *Co-located on a common platform*
- *Vertical integration*

Quantifiable Outcomes!

Reduced form factor, robustness, radiation resiliency, support 10-year longevity as prescribed, while retaining performance

Why Silicon Carbide?

Sublimation Temperature (~2600 °C)

Near Inert Surface Chemistry Translates to Less Reaction with Surrounding Materials

Wide bad gap (3.2 eV)

Nitrogen Dopants with Small Absorption Cross-Sections.

Relatively Mature Semiconductor Resulted in Realization of Micro Sensors and Electronics for Harsh Environment Applications

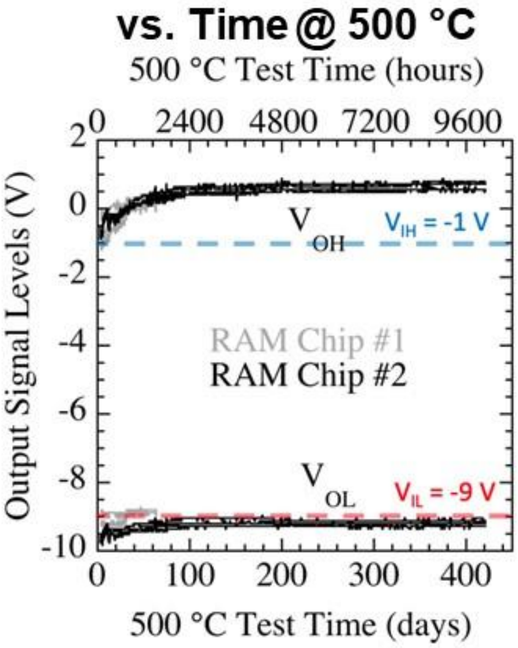
Targeted Operation between 500-1000 ^{o}C while Mounted on Reactor Structure

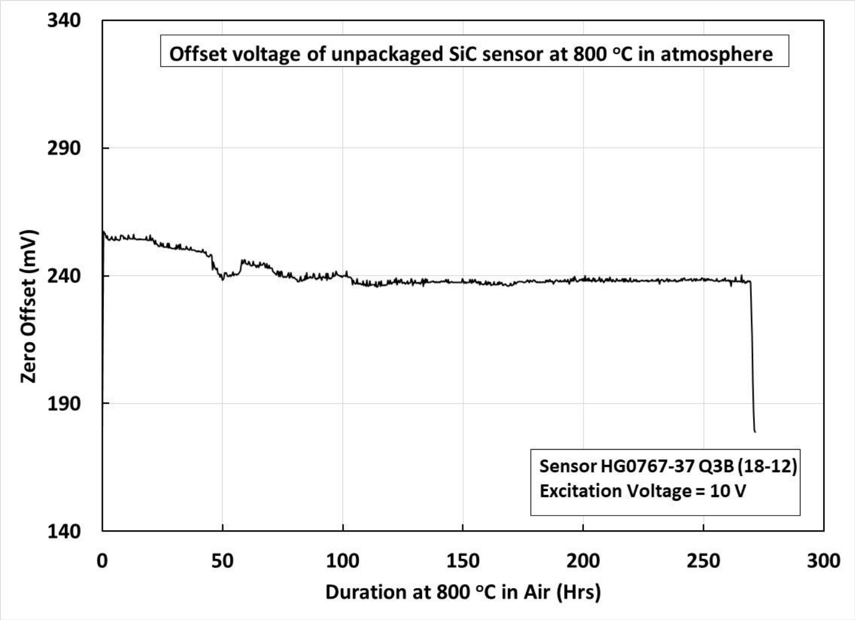
Minimal Shielding Translates to Reduced Form Factor and Volume

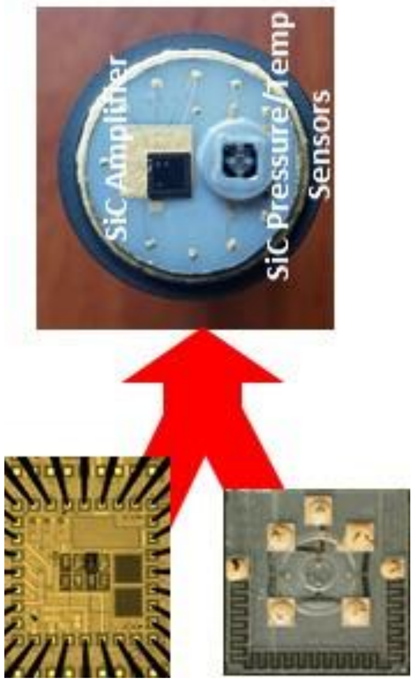
GRC Potential Solutions

What We Have Done!

- 800 C Pressure/Temperature and Electronics Operation-Proximity to reactor core.
- Long Term Reliability at Temperature-Toward prescribed 10-yr Operation.
- Miniaturization (Reduced Form Factor)-Toward reduced form factor and weight.





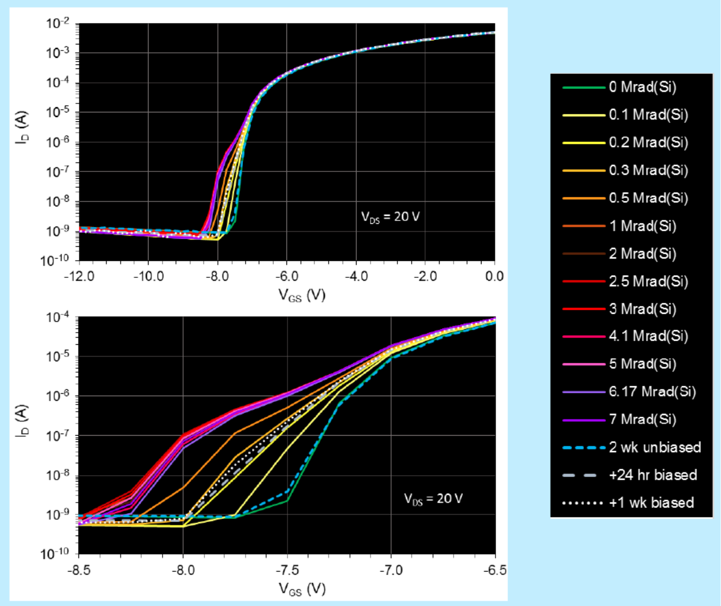


GRC Potential Solutions

FSP Notional Distance/Radiation Tolerances [1]

Item	Distance (m)	Radiation Tolerance
Stirling Components	**1**	**Neutron: 5x10^{14} n-cm^{-2} (>100 keV)** **Gamma:25 Mrad (Rad Si)**
Electronics	**10**	**Neutron: 5x10^{11} n-cm^{-2}** **Gamma: 25 krad (Rad Si)**
Humans (Crew)	**10^3**	**Total 5 rem/yr., Gamma+Neutron (100 % occupancy; 1 km wide)**

NASA Glenn JFETs, Oscillators, Flip-Flops, Op-Amps tested by NASA Goddard [2]



Total Ionizing Dose Hard (Gamma > 7 Mrad) Surpasses Notional Tolerances

1. Predecisional Compass Final Report CD-2021-187: 40kW Fission Surface Power System (FSPS) Deployability.
2. *Lauenstein et. al., 2019 IEEE Radiation Effects Data Workshop (REDW)*

Electronic Component Dose Degradation Limitations

	Neutron Displacement Damage [1]		Total Ionization Dose (TID) Damage [2]	
	Max Fluence (n/cm^2)	Displacement effect	TID (rad)	TID effect
Diodes/ Photodiodes	10^{13}-10^{15}	↑ leakage current; ↑ forward voltage threshold	10^6-10^8	↑ photocurrents
LEDs	10^{12}-10^{14}	↓ light intensity	10^7-10^8	0.25 dB attenuation
BJTs	10^{13}	Current gain degradation	10^5-10^7	Current gain degradation; ↑ leakage current
JFETs	10^{14}	↑ channel resistivity; ↓ carrier mobilities	>10^8	Minimal effects
SiC JFETs	10^{16}	↑ channel resistivity; ↓ carrier mobilities	>10^8	Minimal effects
MOSFETs	10^{15}	↑ channel resistivity; ↓ carrier mobilities	10^6	↑ threshold voltage; ↑ leakage current
CMOS	10^{15}	↑ channel resistivity; ↓ carrier mobilities	10^8	variations in threshold voltage; variations in leakage current

FSP Notional Radiation Tolerance @10 m

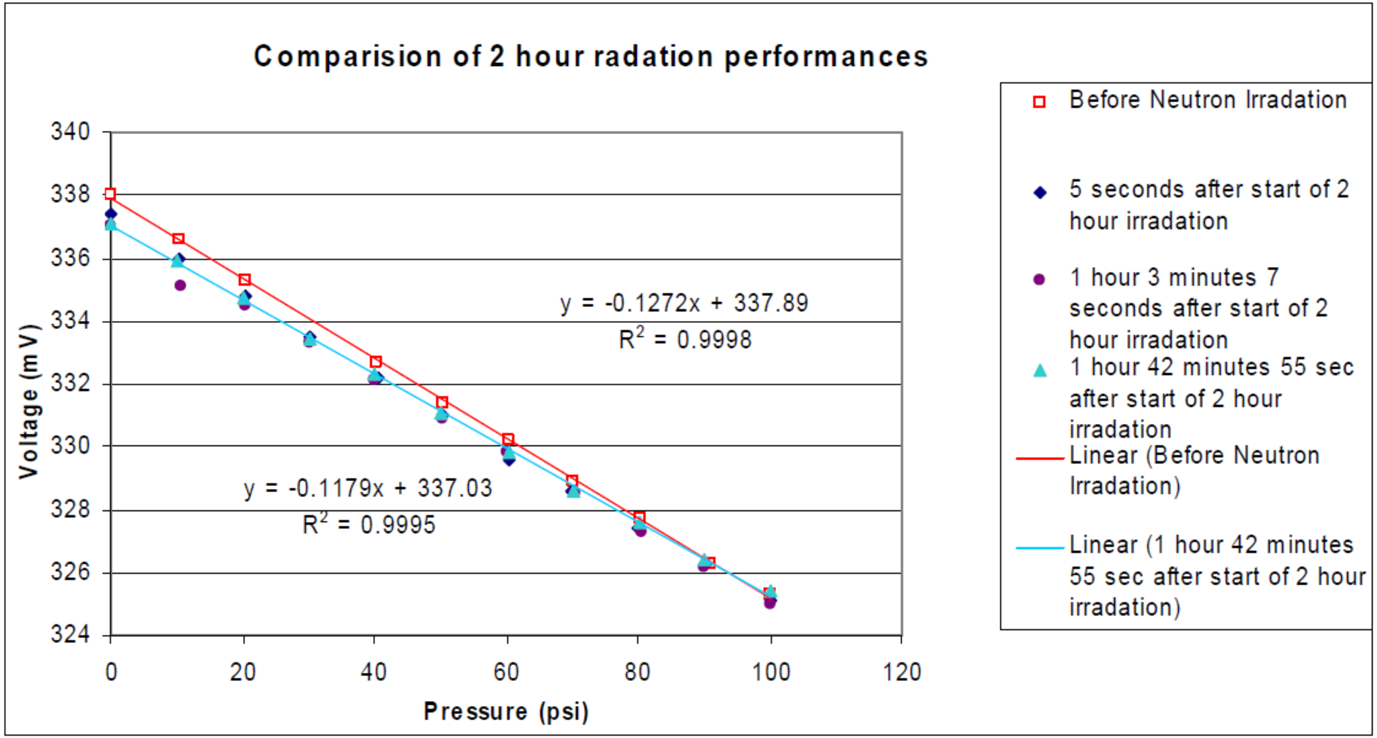
Neutron: 5x10^{11} n-cm^{-2}

Gamma: 25 krad (Rad Si)

[1] Neamen, Donald A. Semiconductor physics and devices: basic principles. New York, NY: McGraw-Hill,, 2012.
[2] H. Spieler, "Introduction to radiation-resistant semiconductor devices and circuits." AIP Conference Proceedings. Vol. 390. No. 1. American Institute of Physics, 1997.

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

Advanced Space Radiation Instrumentation Research

Problem:

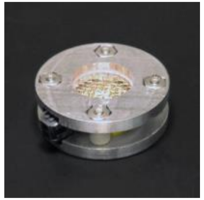
- Awareness of space radiation critical in missions beyond LEO (i.e., Moon, Mars, NEOs, etc.) requiring:
  - Embedded instrumentation to provide feedback for “smart”, adaptive shielding systems
  - Precision instrumentation to provide better data to space radiation modeling efforts
  - Compact instrumentation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

Solution:

- Compact integrated detectors with low noise, solid state components allowing spherical geometry

Approach:

- GRC Expertise and Facilities in:
  - Harsh Environment Thin Films
  - SiC Devices & Harsh Environment Packaging
  - Micro-Optics
  - Flight Electronics
- These strengths are combined into GRC’s Advanced Space Radiation Instrumentation Research effort

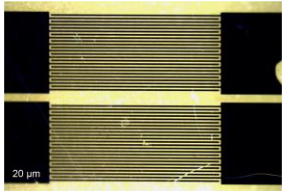


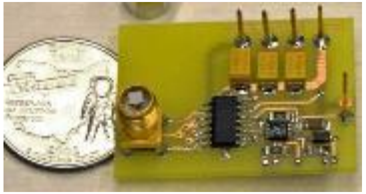
Large Area SiC LET Detectors

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

Low power charged particle counter (U.S. 10,429,521)

Fast, Large Area, Wide Band Gap UV Photodetector (U.S. 10,054,691)

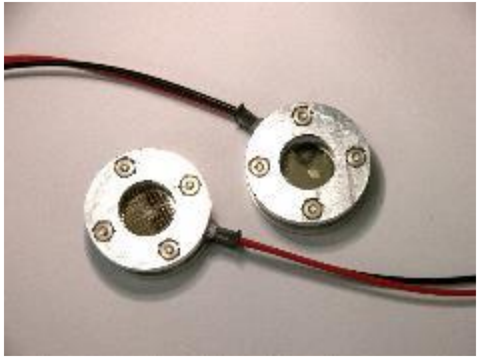




ETDD SiC Dosimeter Prototype

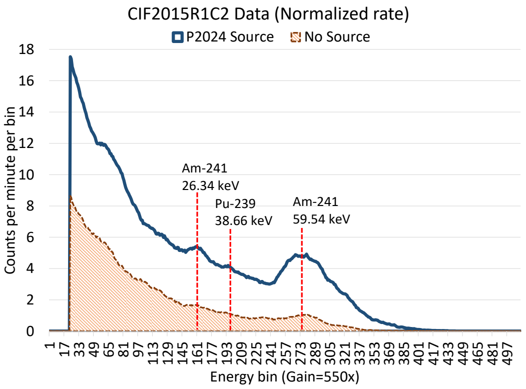
WBG LET Detectors

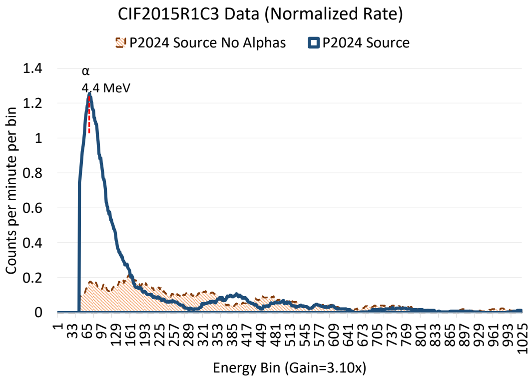
- Proof-of-concept SiC LET detectors developed under a Center Innovation Fund award competed through NASA STMD
- As-Built Detector Specs:
  - High Purity Semi-Insulating 4H-SiC
  - Active Area: 200 mm^2
  - Active Thickness: 0.348 mm
  - Top Contact: 2000 Å Pt/Ti (Schottky)
  - Bottom Contact: 7000 Å Pt/TaSi/Ti (ohmic)
  - Die Size: 325 mm^2 square
  - Package Size: 4.13 cm dia. x 1.25 cm
  - Capacitance: 65±5 pF
  - Leakage: 4.5 nA at 100 VDC bias



WBG LET Detectors

- Checked response at high gain and low gain on multichannel analyzer for gamma, alpha peaks of Pu-239 sources
  - Response time limited to 36 counts per second (27.78 ms/count)
  - Should stop 8 MeV/u ions and less; measure E, calculate LET (=E/x)
  - Observed peaks down to 26.3 keV or LET ≥ 75.7 eV/µm
  - Noise floor ≈ 60 eV/µm (20.7 keV), Uncertainty ±30 eV/µm, dE/E = 20% in air
  - Estimate of minimally ionizing proton (3 GeV p) LET = 543 eV/µm in SiC (detectable)
- Characteristic Proof of Concept – validation of key parameters

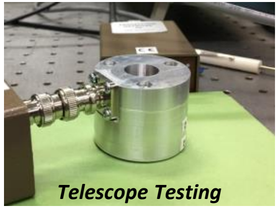




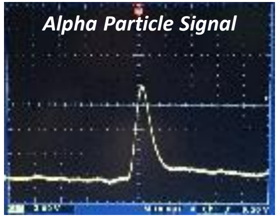
WBG LET Detectors

- **Improvements to the detector design currently underway through Individual Research and Development (IRAD) effort**
  - **Phase I designed, fabricated, packaged and tested four LET detectors singly and configured as telescope pairs, documenting improved performance and stable operation of the telescope design**
  - **Phase II currently underway to accommodate smaller connectors and measure a spectra**
- **Phase I Telescope Specs:**
  - **Telescope Size: 4.375 cm dia. x 3.50 cm tall**
  - **Aperture Size: 200 mm^2**
  - **Geometric Factor: 0.5 sr·cm^2**
  - **Field of View: 62°**
  - **Detector: HPSI 4H-SiC, 1000Å Pt/Ti (anode), 1000Å Ni/Ti (cathode)**
  - **Die Size: 1.778 cm x 1.778 cm square**
  - **Capacitance: 56.7 ± 1.5 pF**
- **Plans beyond Phase II include integrating charge amplifiers into the package and accelerator beam line tests**

iC Charged Particle Telescope



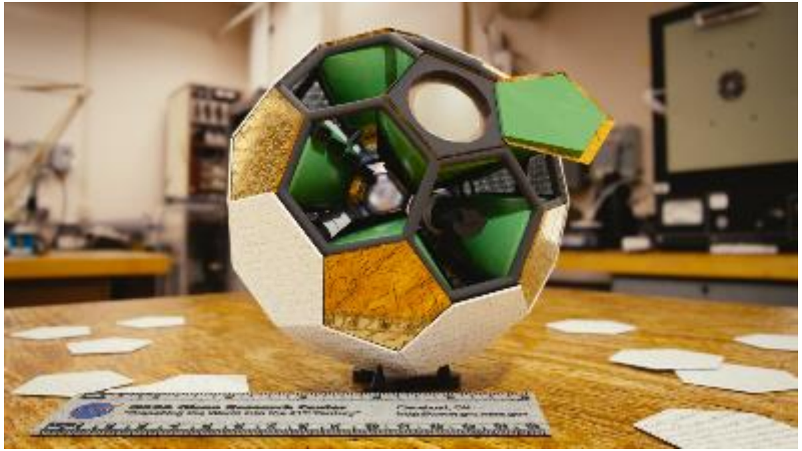
Telescope Testing



Alpha Particle Signal

Future Concept: Compact Full-Field Ion Detector System (CFIDS)

- Mapping of heavy ions > 100 MeV/amu
  - Integrated system with solid-state Cherenkov detector and large area detectors in surrounding wedges
- High radiation flux rates for 10+ year missions
  - Precision rad-hard, thermally stable wide band gap detectors used
- Low noise, multi-directional measurements at single locations
  - Compact, spherical detector system

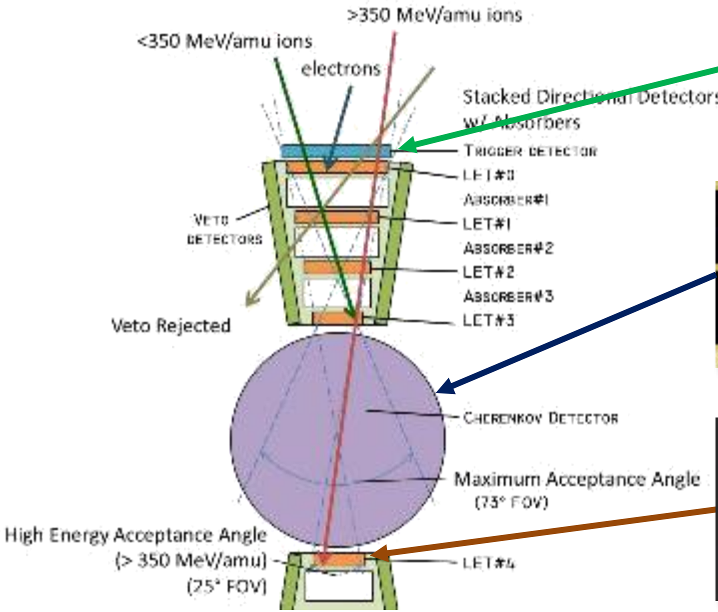


Concept illustration of the CFIDS detector assembly (cables, electronics not shown)

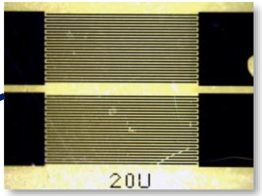
Space radiation detector with spherical geometry

- *Technology covered by U.S. Patents 7,872,750 (January 18, 2011) and 8,159,669 (April 17, 2012)*

Future Concept: Compact Full-Field Ion Detector System (CFIDS)



GaP Diode for Solid-State Trigger/Veto Detectors
(U.S. Patent 10,429,521)

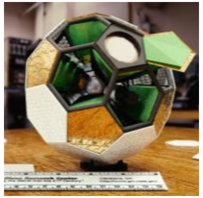


ZnO UV Sensor for Solid-State Cherenkov Detector
(U.S. Patent 10,054,691)

Large Area SiC LET Detectors

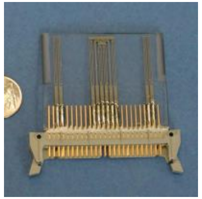
CFIDS comprised of a spherical Cherenkov detector surrounded by stacked LET detectors with absorbers, Coincidence/Anticoincidence detectors

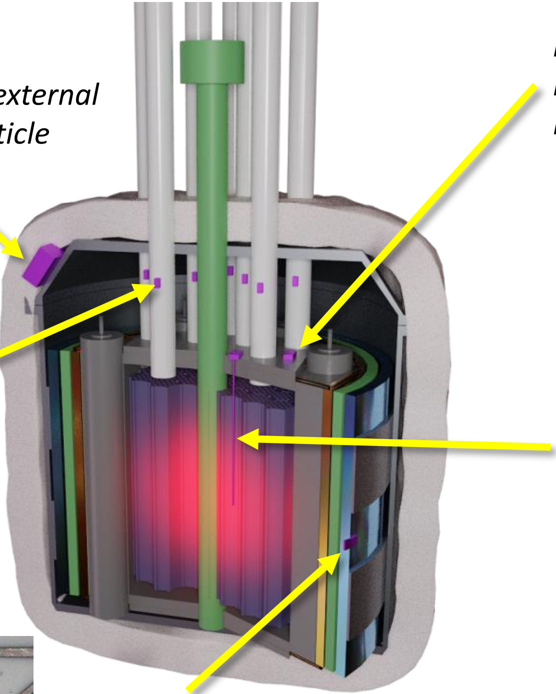
GRC Sensors Technology for Advanced Reactors



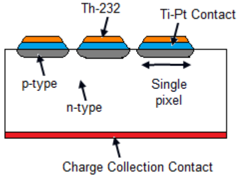
Low-noise external charge particle monitoring

High Temperature Caustic Flow Sensors

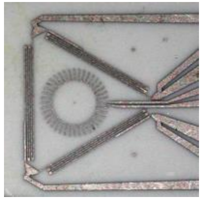




High Temperature Fast Neutron Flux Monitor



Fast, In-Core Thin Film Thermocouple



Embedded Multifunctional Gauges containment deformation and heat flux monitoring

GRC Sensors Technology for Advanced Reactors *(References)*

- Thin films (µm-thick) tailored for operation in high temperature (>1300K), high radiation, corrosive environments
- Embedded Sensors: On-component fabrication for in-situ operations
- Temperature: Thin Film Thermocouple and/or Multifunctional Sensor
  - J.Wrbanek, et al. (2020) “Development of a Venus Surface Wind Sensor Based on a Miniature Drag-Force Anemometer” NASA TM-20205007616
  - R. Meredith, et al. (2014) “Design and operation of a fast, thin-film thermocouple probe on a turbine engine” AIAA 2014-3923
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Conclusion

GRC has demonstrated micro sensors and electronics performances that are moving in direction of FSP instrumentation risk mitigation.

- **High temperature (500-1200 C)-proximity placement to core**
- **Reduced from factor (minimal packaging, reduced weight, mass, and volume)-proportionally scaled to meet FSP reactor compactness.**
- **Long term reliability at temperature-addresses maintenance challenges**

Published data demonstrated the radiation resiliency of SiC sensors and electronics over conventional semiconductor devices.

- **Extensive radiation tests required to determine maximum fluence limit.**
- **Opportunity for innovative solutions to increasing maximum fluence limit.**