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INTEGRATED VEHICLE HEALTH MANAGEMENT

DETECTION DIAGNOSIS PROGNOSIS MITIGATION INTEGRITY ASSURANCE

Detection

John Lekki

Aviation Safety Program Retreat
March 26, 2009

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Technology Breakdown by Subsystem

- Aircraft Systems
  - Lightning
    - Detect Location on the aircraft and Intensity of Lightning Strike
  - Advanced Analytics
    - Data Mining
    - Damage signature detection

- Airframe
  - Icing
    - Sense airframe icing
  - Intelligent Sensing of Structural Damage
    - Develop sensor systems for the detection of airframe structural damage or degradation before it causes a flight problem
      - High Density Fiber Optic strain sensors – wide area
      - Surface Acoustic Wave sensors for Strain and Crack Detection – do not require power and are wireless
      - Carbon Nanotube Foil Strain sensors – biaxial strain at a point
      - Fuzzy Logic analytical approach for damage determination
  - Modeling of Sensor Performance
    - Sensor models will allow the sensors to be rapidly adapted to new application or requirements

Technology Breakdown by Subsystem

- Propulsion
  - Icing
    - Technologies that measure and detect atmospheric conditions associated with engine power loss
    - Total water content probe for sensing of airframe and engine icing buildup conditions – high density water content
  - Gas Path
    - Rotordynamics SHM
    - Self Diagnostic Accelerometer
    - Microwave Tip Clearance Sensor (1200 C)
    - High Temperature Fiber Optic Temperature Sensors (1000 C)
  - High Temperature Wireless Sensors (500 C)
    - Pressure and Emission Sensors
    - Electronics for Smart Sensors - process locally
    - Wireless communication
    - Power Harvesting – Thermoelectric

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Relevance

- Relevance of technologies in detection derived from multiple sources including
  - User community needs (Pull):
    - Research Papers
      - System analysis has collected and analyzed many papers / reports
      - Technology leads also provide references
    - Working Groups / Committees
      - Propulsion Instrumentation Working Group
      - Government / Industry Committees
        - » NASA, FAA, and NTSB for engine icing
  - Assessment of State of the Art
    - Literature / Product Review - comparisons from research papers generally include many caveats
    - Flight grade sensors?
- Impact / Relevance
  - Requires reasonable estimation of final system parameters
  - From this anticipated research results, the documented

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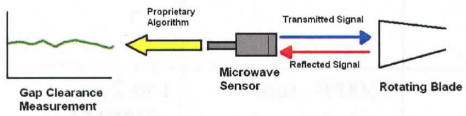
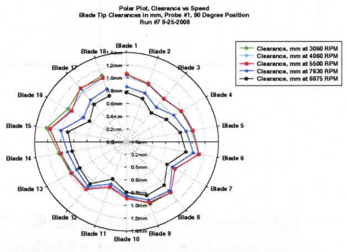
Microwave Tip Clearance Sensor Technology

- Microwave blade tip clearance sensor technology for use in turbine engines
  - Structural health monitoring – tip clearance and tip timing
  - Active closed loop clearance control - tip clearance



Microwave sensors installed on the NASA Turbofan Test Rig at the GRC's 9x15 LSWT

- Targeted for use in hot sections of turbine engines (High Pressure Turbine section)
  - Rated for use in high temperature environment, ~1200 ºC
  - Highly accurate, current goal of ~25um for this technology
  - Able to see through contaminants that exist in the engine flow
- Sensors have been used on several experiments at GRC to evaluate & demonstrate their performance. Goal is to use sensors on an actual aero engine.



Clearance data acquired on the NASA Turbofan Test Rig

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Microwave Tip Clearance Sensor Relevance

- Goal is to detect problems with blades before IFSD or for CBM
- Blade loss is one of the larger contributors to In flight Shut Down due to high vibration and power loss

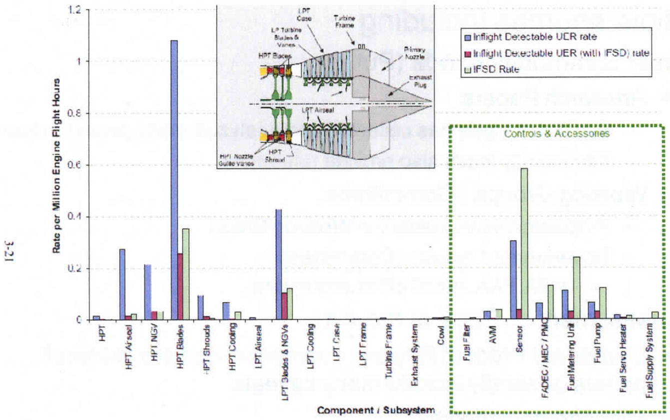

Figure 3-5. Engine Component Rates for Restrict Thrust Response Category (Continued)

Steve Clark, Grace Balut Ostrom, and Sam Clark, Engine Damage-Related Propulsion System Malfunctions, DOT/FAA/AR-08/24, December 2008.

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Advanced Turbine Engine Sensor Requirements for Blade Tip Clearance

Parameter Range:	Required Accuracy:	Environment:	Response:
.010 to .020 inches (0.25 to 0.50 mm)	0.001 inch (0.025 mm)	1600°F (un-cooled) (~870°C)	1 to 2 μs (500KHZ to 1MHZ)

Behbahani, A., and Semega, K., "Sensing Challenges for Controls and PHM in the Hostile Operating Conditions of a Modern Turbine Engine", AIAA-2008-5280, July 2008.

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SOA Assessment for Microwave Tip Clearance

Technology	Accuracy (on range of .25")	Temperature	Status, Pros & Cons
Eddy Current	~0.001 (~0.5% FS)	~1000ºF (~540ºC) max	Based on magnetic coupling between sensor & blade. Temperature limited due to changes in magnetic properties of materials at high temperatures.
Capacitive	**~0.001 (~0.5% FS)**	**~1800ºF possibly up to 2550ºF (~1000ºC possibly up to 1400ºC)**	High temperature capacitive sensors have (or are) being developed by Fogale Nanotech from France and Capacitec from the US. These sensors specifications compete with the microwave sensor technology. **However, the highest frequency response indicated in the open literature for this technology is ~200KHZ.**
Microwave	**≤ 0.001 inch**	**~1652ºF (900ºC) un-cooled ~2200ºF (1200ºC) cooled**	Radatec (Vibro-Meter) and Hamilton-Sundstrand are developing this technology for use in aero turbine engines. Radatec first generation sensors are being used on large power generation turbines. Second generation sensors are being targeted for aero engines. **Greater than 1MHZ response is possible.**

Quality / Impact
Microwave Tip Clearance Sensor

- This is a detection capability that currently doesn't exist
- Successful technology development will lead to blade health detection in the hot section
  - bent blades
  - broken blades
  - blade vibration
- HPT / LPT blade failures have been identified as one the larger contributors to IFSD
- Tip clearance monitoring could also be an enabling technology for active closed loop clearance control

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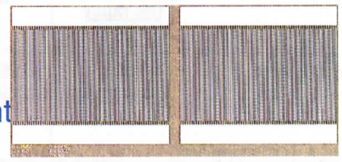
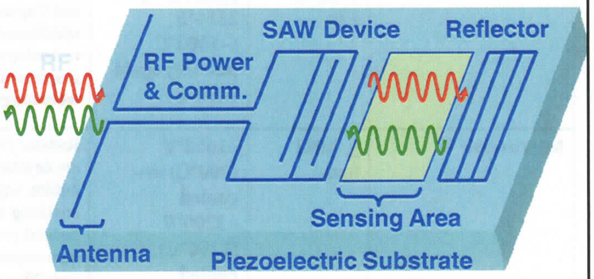
Surface Acoustic Wave (SAW) Devices

- Inexpensive
- Small (low mass and low volume)
- Extremely Low power (RF or Ambient
- Versatile
  - Signal Processing
  - Resonators
  - Filters
  - Strain sensors
  - Pressure sensors
  - Chemical sensors
  - Ultrasonic sensors
  - Temperature sensors





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Surface Acoustic Wave Strain Sensor Relevance

Technology Requirements and Needs	Adverse Events														
	Icing conditions in propulsion system	Fault of power electronics	Turbine engine bearing faults	Fatigue cracks on metallic airframe structure	Delamination in composites	Ball jam in EMA/Hydraulic actuator failures	A/C and pressurization faults	Oil/lubrication system failures	Wire chafing faults	Power system faults/Electrical distribution problems	Aileron, rudder, control surface faults	Instrumentation, communication, and navigation failure	Fuel system faults	Engine stall/Faults in turbomachinery	
# of Accidents	6	11	4	13	2	18			1	10	22	5	20	52	9
# of Incidents		417		343		516	408	463		738	620	1278	349	2312	2
Gas Pressure Measurement Technologies			X											X	
Surface Measurement Technologies	X		X											X	
Strain Measurement Technologies				X	X						X				
Harsh Environment Sensor Technologies			X					X					X	X	
Fluid Leak Detection Sensor Technologies			X				X	X					X		
Lightweight, Low Power Load Sensor Technologies				X	X					X	X				
Self-Powered Wireless Sensor Technologies		X							X	X					
Crack Detection/Monitoring in Blades and Disks	X		X											X	

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Surface Acoustic Wave Strain Sensor Relevance

- Aircraft operational loads monitoring has been in place for decades to determine airframe degradation
  - Christian Boller, "Structural Health Management of Ageing Aircraft and Other Structures", *Monograph on Structural Health Monitoring, Inst. of Smart Structures and Systems, Bangalore/India.*
  - Many references
- Standard strain gages have been used to detect cracks in aircraft
  - J. Tikka, R. Hedman, and A. Silijander, "Strain Gauge Capabilities in Crack Detection," in *Fourth International Workshop on Structural Health Monitoring*, Stanford, CA, 2003, pp. 812–819.
- A system with a resolution of 1 με has been demonstrated for crack monitoring
  - D. Banaszak, D. L. Brown, and D. J. Laird, "Antonomous Environmental Definition of C-130 Flap Well Skin Panel," *Journal of the IEST,* vol. 48, iss. 1, pp. 50-61, 2005.
- Crack detection sensitivity of 0.01mm has been demonstrated with strain gauges
  - S. Shanmugham and P. K. Liaw, "Detection and Monitoring of Fatigue Cracks," in *ASM Handbook: Fatigue and Fracture*, vol. 19: ASM International, 1996, pp. 210-223.

Surface Acoustic Wave Sensor SOA Assessment

Sensor	Sensitivity	Weight	Power	Size
COTS Wireless strain gauge	+/-1.0 με	46 g	Battery	73.89 cm^3
SAW	+/- 0.25 με	<4.6 g	Passive	<8 cm^3

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Surface Acoustic Wave Strain Sensor Impact / Quality

- Improved environmental load / fatigue monitoring enabled by SAW sensors
  - More airframe coverage for a given power / weight of sensor system
  - Improved sensitivity
  - Improved sensor integration because wireless and no battery to change
- The capability of detecting airframe cracks 0.01mm is anticipated

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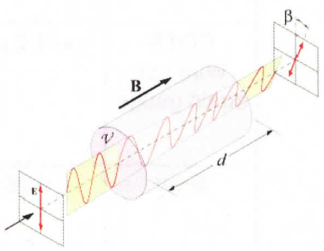
Aircraft Lightning Detection

- **Rationale: Lightning strikes on composite aircraft have potential of deeper magnetic flux penetration into avionic wiring and higher structural IR voltages.**
- **Intended Results:**
  - **Determine the total energy transferred from a lightning strike**
  - **Propagation path of the lightning current along the fuselage to support IVHM diagnosis and prognosis assessments of structural damage and avionic system health**
- **Optical Lightning Sensors based on Faraday Effect use the rotation of the plane of polarization of the light in the dielectric to determine the intensity of the magnetic field. This technology offers flexible designs with wide bandwidth and large dynamic range in small, light weight packages. They are immune to lightning and will not saturate like ferrites.**



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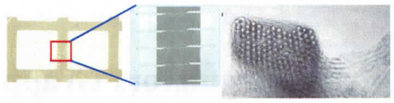
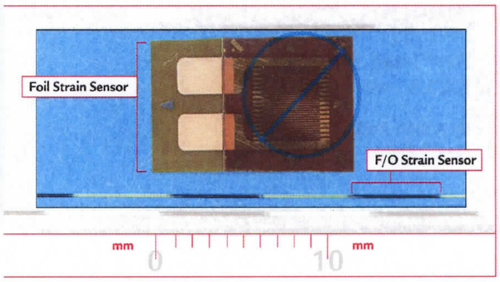
Development of Advanced Airframe Sensors

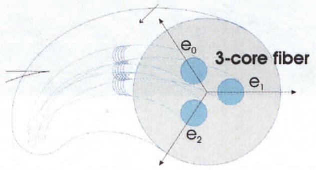
Goal: Development of advanced sensors and sensory materials to detect the onset of structural damage / degredation

Carbon Nanotube-Based Sensors
Small, highly sensitive strain sensor array



Fiber-Bragg Grating F/O Sensors
- **Strain / temperature sensing**
- **10,000 sensors/lb in one fiber**
- **Replaces foil strain sensors**
- **Multi-core Fiber Optic Shape Sensors**





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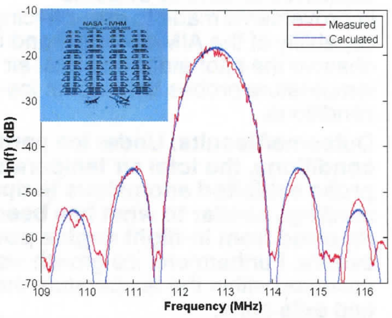
SAW Sensor Prototype Fabrication and Modeling completed

- SAW can be used for Strain, Temp, Pressure, Chemical, etc
- Wireless Communication and Self Powered
- A first order multi-physics model of MEMS based SAW sensor has been developed. The model incorporates electrical, mechanical, and acoustical domain behavior.
- All of the devices were within the 90% modeling accuracy when compared to the experimental data.
- Accurate models will
  - reduce the uncertainty associated with prototyping process
  - give a better understanding of the sensing mechanism and how it can be exploited to create better sensors



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THE WALL STREET JOURNAL. ONLINE

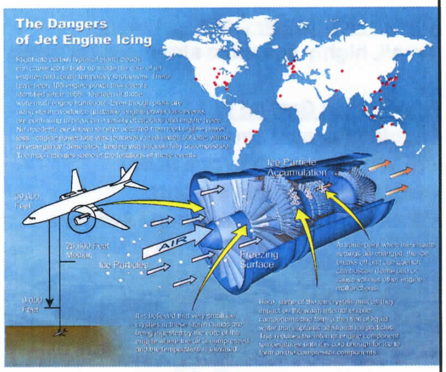
April 7, 2008

PAGE ONE

Airline Regulators Grapple With Engine-Shutdown Peril

Investigators Find New Icing Threat; FAA Proposes Rules

By ANDY PASZTOR
April 7, 2008



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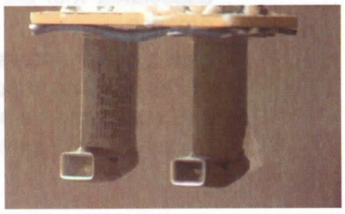
Wind Tunnel Testing of Instrumentation For Ice Crystal Engine Icing

- **Description:**
  An Aircraft Integrated Meteorological Measurement System (AIMMS-20) probe and two pitot-static and total temperature probes were tested in the NASA Icing Research Tunnel. The AIMMS-20 probe will provide measurements of the wind velocities, gusts, and updrafts during atmospheric sampling of icing clouds that lead to engine power loss. The test objectives of were to evaluate improvements made to the anti-icing capability of the AIMMS probe and to observe the pitot-static and total air temperature probes behavior in ice particle conditions.
- **Outcome/Results: Under ice particle conditions, the total air temperature probe exhibited anomalous temperature readings similar to what has been reported from in-flight engine power loss events.** Furthermore, ice growth was observed within the temperature probe inlet and exits ports.

AIMMS-20 probe after 5 minutes of heavy icing conditions. Probe tip remained clear of ice.

Total air temperature probes during ice crystal encounter. Note ice buildup in inlet and exits



Recent Technical Accomplishment

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High Temperature Sensors, Electronics, And Communications

Enable New Capabilities ...

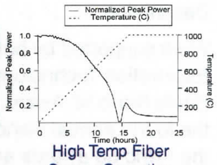
- Propulsion Structural Health Monitoring
- High-temperature Pressure Sensors and
- High-temperature Wireless Communications And Energy Harvesting Technologies

Technical Approach:

- Propulsion structural health monitoring including smart accelerometers, and optical strain and blade tip-timing sensors.
- Pressure sensors for incorporation into gas-path trending and fault diagnostic models to infer turbine health.
- Integration of sensor technology with high temperature wireless communications and energy harvesting to enable a smart systems operable at high temperatures.
  - High-temperature wireless communications based on SiC electronics and rugged RF passive components
  - Energy harvesting systems focusing thermo-electric and photo-voltaic materials for generation of power for remote sensors.

High Temperature Pressure Sensor

Self Diagnostic Accelerometer

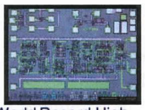


High Temp Fiber Sensor Operation

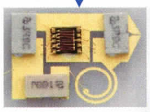
Provide a New Generation of Sensor Technology

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

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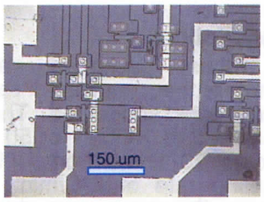
World Record High-Temperature Circuit Demonstration

Description:

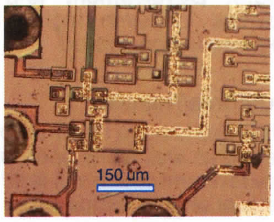
Electronics circuits fabricated from silicon carbide have been tested and operated a world record times at 500° C. The circuits have included differential amplifiers, logic circuits, and discrete JFET's.

Outcome/Results:

The lifetime of the differential amplifier in its present design was determined to be 7337 hours of 500 C electrical operation. This is over 10 months of operation and over a factor of 700 improvement over previous devices. Two discrete JFET's (with no interconnect) on this circuit board remain functional past 10000 hours of 500 C electrical operation.



As-fabricated



After Failure

Figure 1: Optical photographs of SiC JFET logic IC chips (top) before packaging and (bottom) after thousands of hours of 500 C testing.

Recent Technical Accomplishment

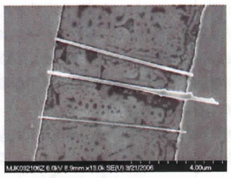
NASA Selected for Nano 50 Award

- Description:

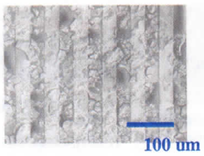
Work supported by both the Integrated Vehicle Health Management Project and NASA Exploration Technology Development Program and has been selected for the 2008 Nanotech Briefs Nano 50 Award. "The Novel Carbon Dioxide Microsensor" has been named a winner in the fourth annual Nanotech Briefs Nano 50 Awards in the Technology category. The winners of the Nano 50 awards are the "best of the best" – the innovative people and designs that will move nanotechnology to key mainstream markets."

- Outcome/Results:

Carbon dioxide (CO_2) is one of the major combustion products that can be measured for emissions monitoring. In this invention, a novel sensing material, nanocrystalline tin oxide (SnO_2) doped with copper oxide (CuO), has been developed to detect CO_2. This microsensor has been fabricated using MEMS technology and sol-gel nanomaterial-synthesis processes.



Other nanotechnology based emissions sensors work is ongoing

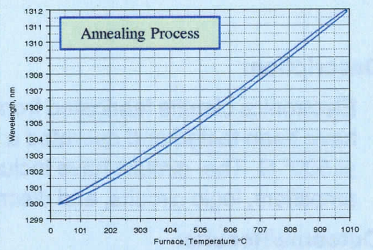


Picture of doped film sensing material

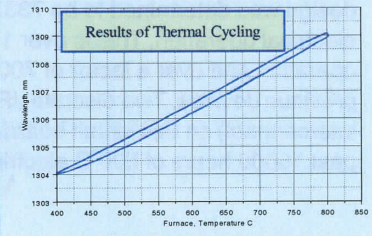
Development of High Temperature Optical Sensors

Description:
A robust packaged version of a high temperature optical sensor has been constructed and tested. The device was annealed at 1000°C for 50 hours and thermally cycled 20 times from 400°C to 800°C at a heating rate of 2°C/min. During the thermal cycling the sensor was also kept at 800°C for 2 hours. Development and testing of similar devices for even higher thermal operational regimes is considered

Outcome/Results:
The results have shown robustness of the device as well as its operability in harsh thermal environment which will lead to higher accuracy / density engine temperature measurement.



1 Cycle; 2°/min Heating Rate;
Room Temp. – 1000°C; 50 Hrs Hold @ 1000°C



20 Cycles; 2°/min Heating Rate;
400°C – 800°C Cycling Range; 2 Hrs Hold @ 800°C

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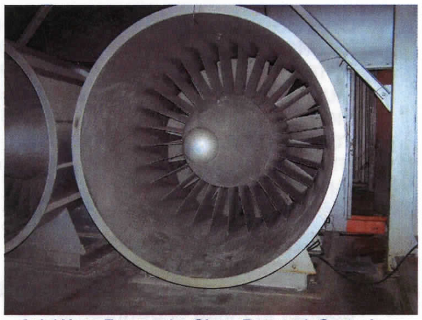
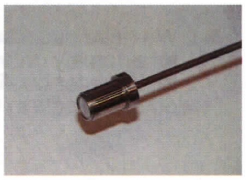
Microwave Tip Clearance Probe Tested On a Axial Vane Fane

- **Description:** Tested the microwave tip clearance measurement system (developed by the former Radatec under Phase II SBIR) on a large axial vane fan located at the 10x10 Wind Tunnel Facility. Acquired clearance measurements for several configurations.
- **Outcome/Results:** Tip clearance data provides important information on the structural health of rotating blades. In previous testing the probe was temperature tested up to 1200 C.



Axial Vane Fane at the Glenn Research Center's 10x10 Wind Tunnel

Microwave Tip Clearance Probe



Recent Technical Accomplishment

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Advanced Analytics for Detection

- Substantial flight-related data to learn from
  - Aircraft-produced: Sensor data, flight-related data (e.g., origin, destination), covering many flights over many years.
  - Other: Safety reports, simulation results
  - Data distributed over many sites
- Transform data into fault detection tools
  - Anomaly detection, fault classification
  - Return measure of uncertainty in detection result
  - Accuracy (false positive, false negative) and speed appropriate to situation
  - Levels ranging from component-level to national air space level

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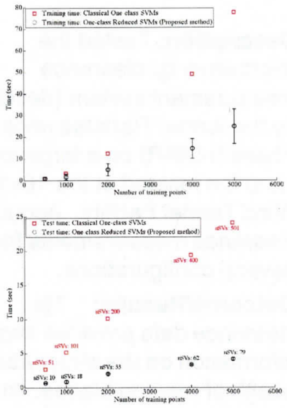
Advanced Analytics: One-Class Reduced Support Vector Machines (OCRSVM)

- One-class Support Vector Machines (SVMs) perform anomaly detection by mapping the original data into a much higher dimensional space and then finding a small fraction of the training data (anomalies) that can be linearly separated from the remainder.
- OCRSVM achieves comparable accuracy to standard one-class SVMs using much less (about one-quarter in initial experiments) training time and time for classifying new examples.
- We have successfully used SVMs for anomaly detection in ADAPT tests, water quality monitoring, and other projects in the past.



TOP. Comparison of training times of OCRSVM and standard one-class SVMs.
BOTTOM. Comparison of times for classifying new test points for OCRSVM and standard one-class SVMs.

Recent Technical Accomplishment www.nasa.gov 27

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Conclusion

- Novel Detection technologies are being developed to help address significant issues for Aviation Safety
- Very Significant progress has been made
  - Complete detection system being addressed
    - Sensors
    - Communications
    - Power Scavenging
    - Advanced Analytics
- Sensor system integration and robustness concerns are being addressed across the project
  - Sensors Small / Low Weight
  - Sensors Self Powered
  - Minimal wiring through utilization of fiber optics or wireless
  - Sensor Diagnostics

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OVERVIEW OF PROPULSION HEALTH MANAGEMENT RESEARCH IN NASA AERONAUTICS

G. W. Hunter, J. Lekki, P. G. Neudeck, T. Bencic, G. E. Ponchak, E. Clark, D. Simon, S. Arnold, and G. M. Beheim

NASA Glenn Research Center at Lewis Field
21000 Brookpark Road
Cleveland, OH 44135

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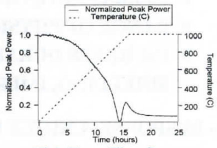

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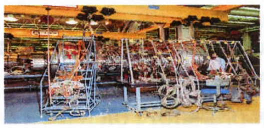
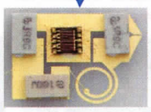


Allow Sensor Implementation by Eliminating Wires

World Record High Temperature Electronics Device Operation



High Temperature RF Components

Energy Harvesting Thin Film Thermoelectrics

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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 is it can be trusted.
- REDUNDANCY AND CROSS-CORRELATION:
  - If the systems are easy to install, reliable, and not increase weight/complexity, the application of a large number of them is not problematic. This allow 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.

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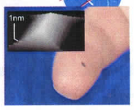
HARSH ENVIRONMENT ELECTRONICS AND SENSORS APPLICATIONS

- 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 500C OPERATION BY MULTIPLE SYSTEMS
  - TEMPERATURE, PRESSURE, CHEMICAL SPECIES, WIND AVAILABLE
  - HIGH TEMPERATURE ELECTRONICS TO MAKE SMART SYSTEMS
- ALL-IN-ONE SHOP FOR HARSH ENVIRONMENT SYSTEM APPLICATIONS
- ENABLE EXPANDED MISSION PARAMETERS/IN-SITU MEASUREMENTS

1998 R&D 100 Award



2004 R&D 100 Award

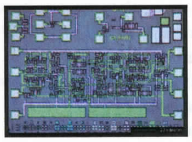
1995 R&D 100 Award

1991 R&D 100 Award

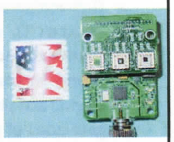
ange of Physical and Chemical Sensors for Harsh Environments

Harsh Environment Packaging (2000 hours at 500C)

High Temperature Signal Processing and Wireless



Long Term: High Temperature "Lick and Stick" Systems



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Global and Local Structural Diagnostics

Global vibration based structural health monitoring (SHM) of propulsion systems

Localized SHM

Utilize small PZT patches that ride on rotors for assessing localized damage (ultrasonics and impedance based SHM for monitoring turbine shafts and disks)

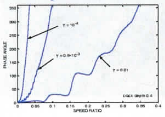
Structural Diagnostics/Prognostics of Propulsion System Components (e.g., turbine shafts and disks)

Theoretical models

$$M\ddot{q}+C\dot{q}+K_s q=\begin{Bmatrix} M\varepsilon(\Phi^2\cos\theta+\dot{\Phi}\sin\theta) \\ M\varepsilon(\Phi^2\sin\theta-\dot{\Phi}\cos\theta)\end{Bmatrix}+\begin{Bmatrix} Mg \\ 0 \end{Bmatrix}$$

$$(J_p+M\varepsilon^2)\ddot{\theta}+M\varepsilon(-\ddot{z}\sin\theta+\ddot{y}\cos\theta)=T_e$$

Theoretical Nonlinear phase response of damaged rotor



Sub-scale experimental verification

Modulator (top), Wireless Slip Ring (center) and Analog Demodulator (bottom)

Sensors use wireless capacitive slip-ring for communicating

High temperature rotor test frame for verification testing

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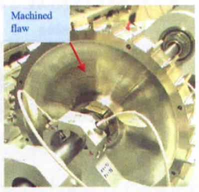
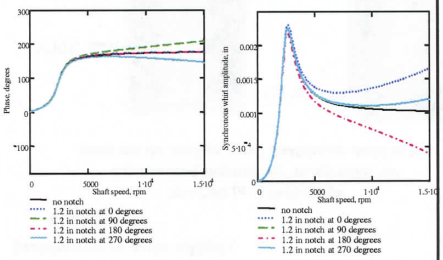
Rotodynamic Model Demonstrated

- **Developed rotordynamic model of notched disk to predict whirl response of system**
  - **Modeled current experimental set-up**
  - **Characterized using experimental data and finite element results**
  - **Whirl response is function of rotor speed and notch characteristics in agreement with Model**

Integration of Sensors in Rotodynamic Teststand With Implanted Flaw



Rotor Model Developed: Modified Jeffcott Amplitude and Phase Bode plots



Model Equations Developed

Whirl amplitude and phase

$$r_{whirl}=\frac{r^2\sqrt{e_0^2+e_{cr}^2+2e_0e_{cr}\cos\beta}}{\sqrt{(1-r^2)^2+(2\xi r)^2}}$$

$$(\theta+\alpha)=\tan^{-1}\left(\frac{2\xi r}{1-r^2}\right)+\tan^{-1}\left(\frac{e_{cr}\sin\beta}{e_0+e_{cr}\cos\beta}\right)$$

Equations of motion

$$\ddot{x}+2\xi\omega_n\dot{x}+\omega_n^2x=e\omega^2\cos\omega t$$

$$\ddot{y}+2\xi\omega_n\dot{y}+\omega_n^2y=e\omega^2\sin\omega t$$

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Rotating Structural HM using Microwave Tip Clearance Sensing

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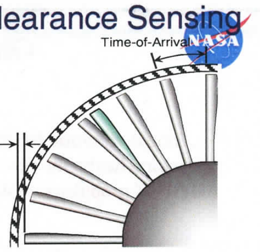
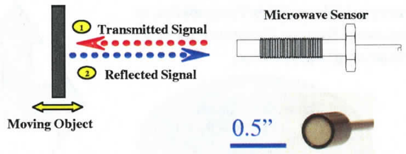
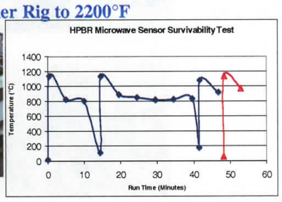
- Developed by Radatec Inc under SBIR program
- Non-contact measurements
  - Tip clearance
  - Blade time of arrival
- Key Technology Features
  - Use in all areas including first stage turbine environment (1300°C+ gas path using bleed air cooling)
  - Ability to "See through" combustion products, flames, steam, including ceramics and composites, etc.
  - Individual measurements from every blade

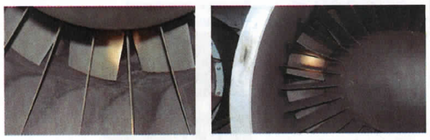




Microwave probe evaluated for survivability and operation in a combustion environment using jet fuel in GRC High Pressure Burner Rig to 2200°F



Current installation and testing of tip clearance and structural stability in fan at 10X10 wind tunnel facility



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Metal Oxide Nanostructures for Chemical Sensor Development

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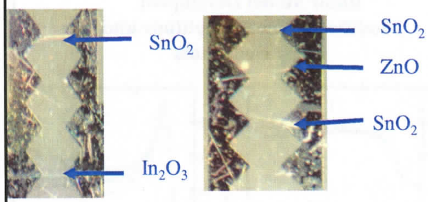
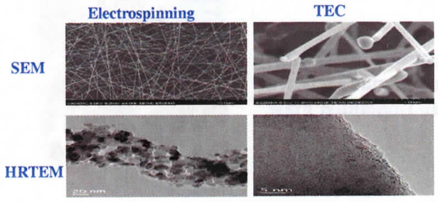
- **Move From Nanocrystalline Materials To Nanostructure e.g. Tubes, Rods, Ribbons**
- **Develop Basic Tools To Enable Fabrication Of Repeatable Sensors Using Nanostructures**
- **Approach 3 Basic Problems In Applying Nanostructures As Chemical Sensors**
  - ***Micro-Nano Contact Formation***
  - ***Nanomaterial Structure Control***
  - ***Range Of Nano Structured Oxides Available***

IMPROVE NANOSTRUCTURE TO MICROELECTRODE CONTACTS



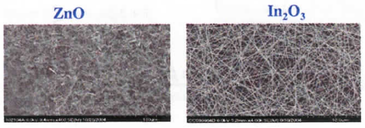
Three nano structured oxide aligned on the same microplatform. Separation between the electrodes is 30 microns

NANOMATERIAL STRUCTURE CONTROL



Different Processing of nanostructures produces different crystal structures

EXPAND RANGE OF NANOSTRUCTURES AVAILABLE



Multiple oxide nanostructured materials have been fabricated

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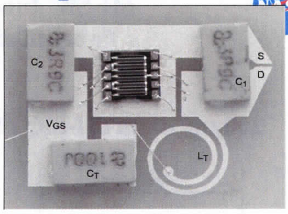
High Temperature Wireless Development



Prototype Oscillator Circuit

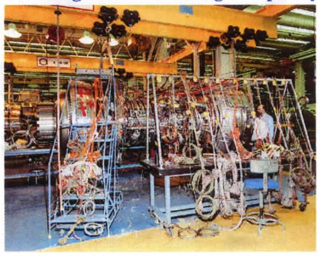
OBJECTIVES:
- HIGH TEMPERATURE WIRELESS TELEMETRY, DISTRIBUTED ELECTRONICS OVER A BROAD OPERATING RANGE

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

Example: Gas Turbine Engine Development Requires Extensive Instrumentation Yielding Extensive Wiring Complexity

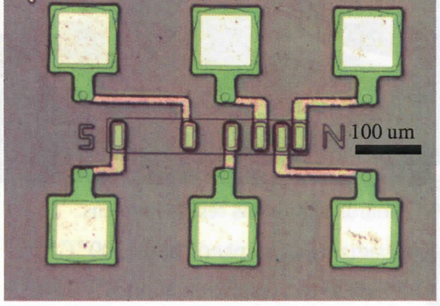


Wires from 1000 Sensors

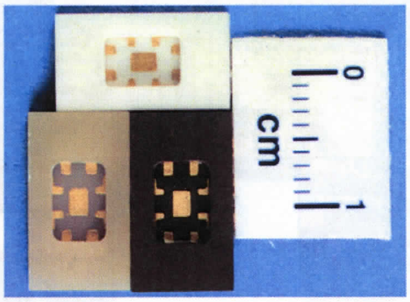
Previous (to IVHM) Key NASA Glenn Advancements

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.

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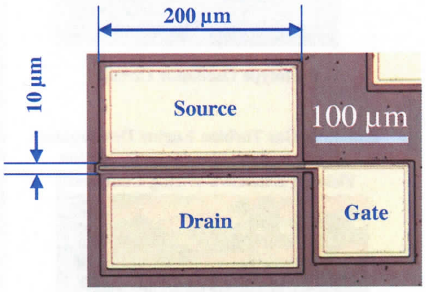
Tech Accomplishments (IVHM v1.0)

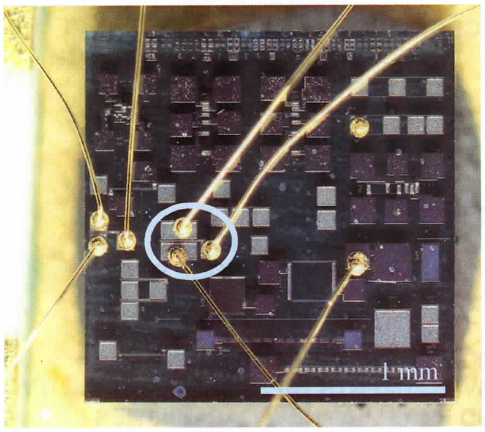
6H-SiC Junction Field Effect Transistor (JFET) Fabricated by NASA Glenn Research Center

200µm/10µm 6H-SiC JFET



Optical micrograph of device before packaging

Packaged with bond wires



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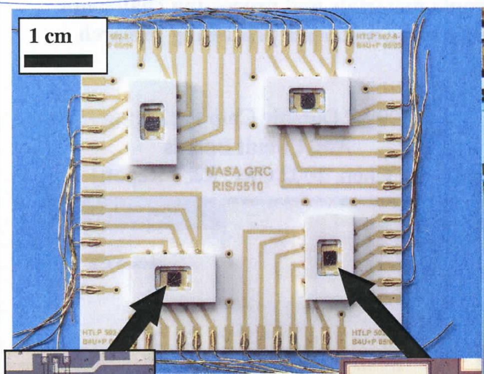
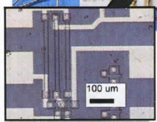
Tech Accomplishments (IVHM v1.0)

Packaged Devices and Test Setup

Parallel fabrication and testing of both single-transistors and IC's





Differential Amplifier

200µm/10µm 6H-SiC JFET

Boards with chips reside in ovens.

Oxidizing atmospheric air at 500 °C.

Wires to test instrumentation.

Continuous electrical testing at 500 °C.

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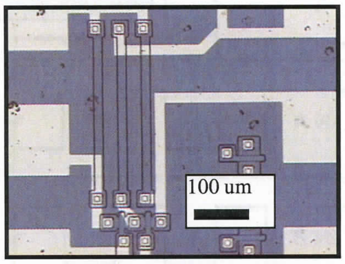
Tech Accomplishments (IVHM v1.)

NASA Glenn Silicon Carbide Differential Amplifier

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.

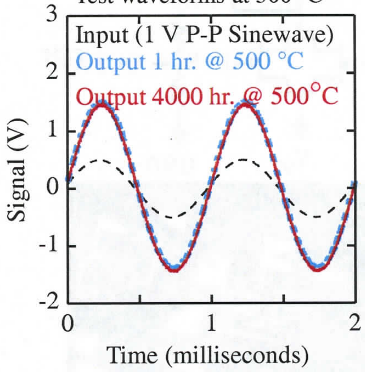
Optical micrograph of demonstration amplifier circuit before packaging



2 transistors and 3 resistors integrated into less than half a square millimeter.

Single-metal level interconnect.

Test waveforms at 500 °C



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

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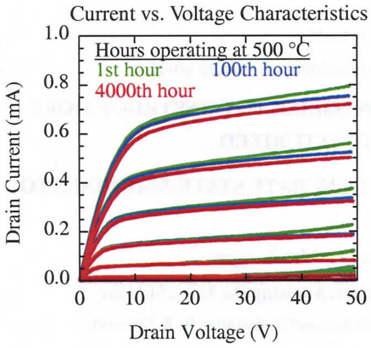
Tech Accomplishments (IVHM v1.)

NASA Glenn SiC JFET : First Transistor to Surpass 4000 Hours of Stable Electrical Operation at 500 °C

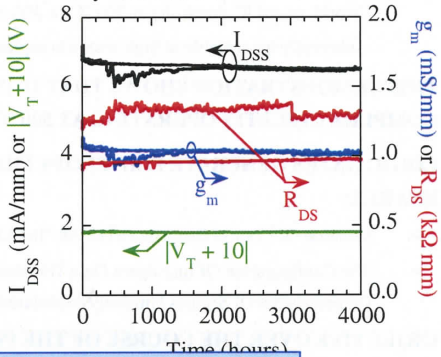
Current-voltage characteristics are very good and stable after 4000 hours.
- Enables realization of analog integrated circuits (amplifiers, oscillators).

Excellent turn-off characteristics, large ON to OFF current ratio (> 1000).
- Enables realization of digital logic circuits.

Current vs. Voltage Characteristics



Key Parameters vs. Time @ 500 °C



Less than 10% change occurs during 4000 hours at 500 °C (most during 1st 100 hrs).
- 10% variation is smaller than listed on most silicon transistor spec. sheets.

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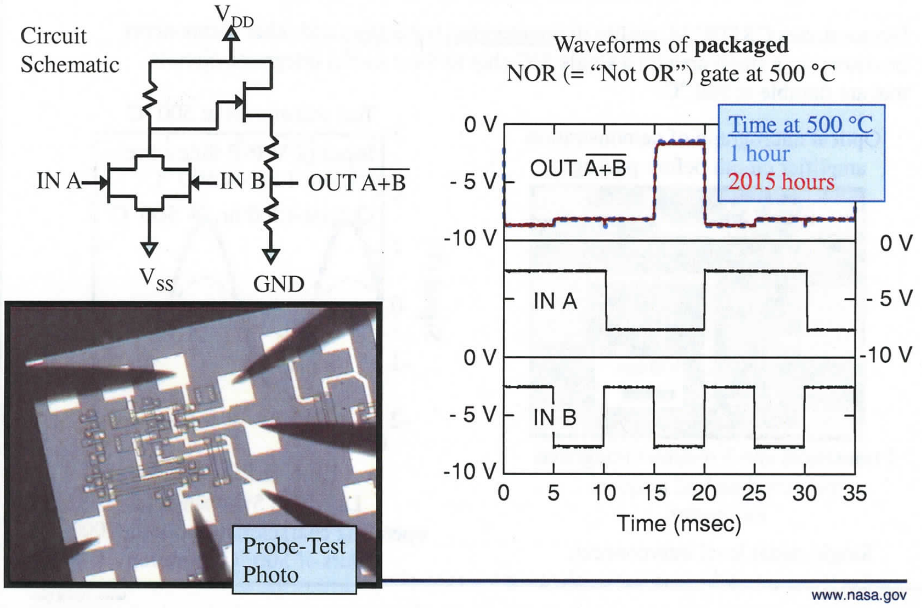
Tech Accomplishments (IVHM v1.3)

NASA Glenn SiC JFET NOR Gate IC

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



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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 OVER THE COURSE OF THE IVHM PROJECT: TO MOVE TOWARD HIGHER DEGREES OF COMPLEXITY ALLOWING WIRELESS TRANSMISSION**

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SUMMARY AND FUTURE PLANS

A WIDE RANGE OF HIGH-TEMPERATURE SENSORS AND ELECTRONICS BEING DEVELOPED IN IVHM

SiC Electronics Summary

- Durable high temperature electronics is enabling important new capability highly relevant to advancing IVHM.
- This work has demonstrated over 100-fold improvement in 500 °C operational durability for a semiconductor integrated circuit chip.
  - Enabled by fundamental electronic materials research.
  - Simple amplifiers and logic gates working at 500 °C.
  - Approach rapidly up-scalable while remaining physically small.

SiC Electronics Short Term Plans

- How long will the chips last at 500 °C?
- Analyze failure mechanisms (after circuits finally fail).
- Revise process to further increase 500 °C circuit durability.
- Test more chips, test at 600 °C (accelerated failure testing).
- Test for thermal cycling (begun with Inverting Amplifier), thermal shock, vibration, etc.

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 over 1 m distance minimum and operational life of at least 1 hr

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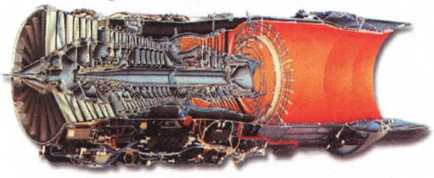
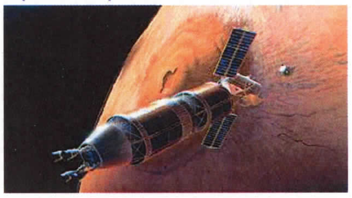
HIGH TEMPERATURE ELECTRONICS AND SENSORS BENEFITS TO NASA MISSIONS

Intelligent Propulsion Systems

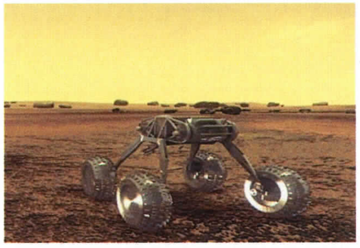


Space Exploration Vision PMAD



More Electric + Distributed Control Aircraft

Venus Exploration



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