



An Overview of the Development of High Temperature Wireless Smart Sensor Technology

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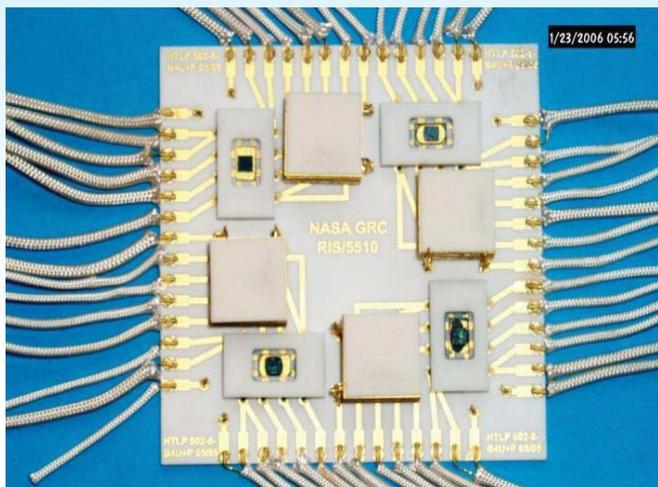


OUTLINE

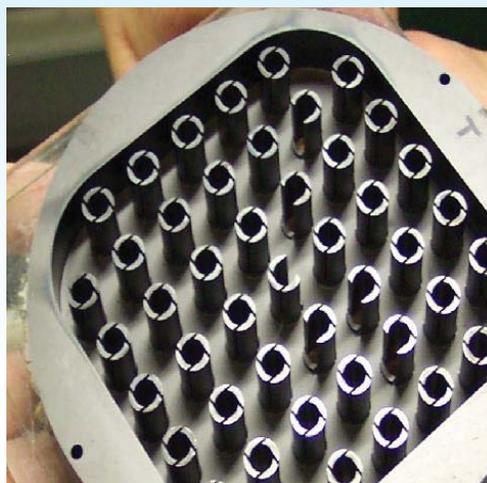
- **INTRODUCTION**
- **SMART SENSOR SYSTEMS**
- **HIGH TEMPERATURE SMART SENSOR APPLICATIONS**
- **PREVIOUS ACTIVITIES**
- **HIGH TEMPERATURE SMART SYSTEM DEMONSTRATION AT
NEAR 500°C**
- **NEXT GENERATION DEVELOPMENT AND DEMONSTRATION**
- **SUMMARY**



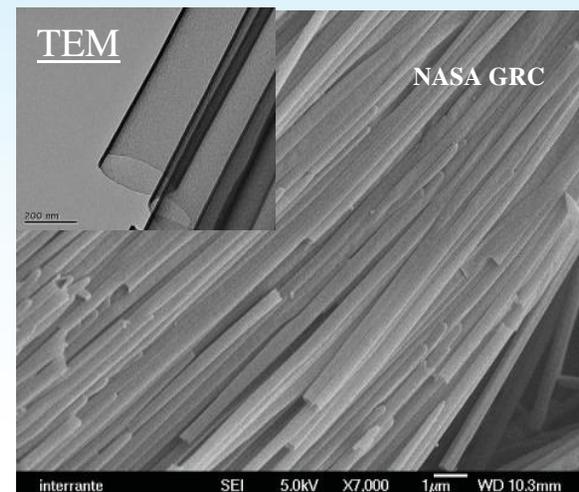
Smart Sensors and Electronics Systems Branch: Scope of Work



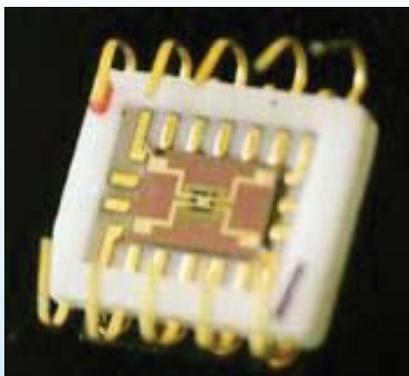
**High Temperature
SiC Electronics**



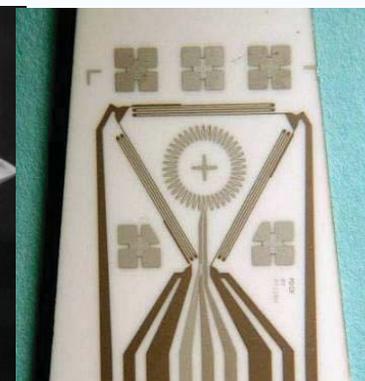
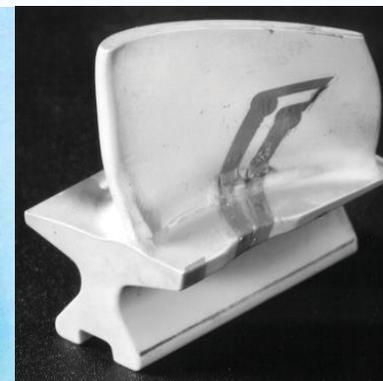
**Micro-Electro-Mechanical
Systems (MEMS)**



**Nanotechnology
SiC Nanotubes**



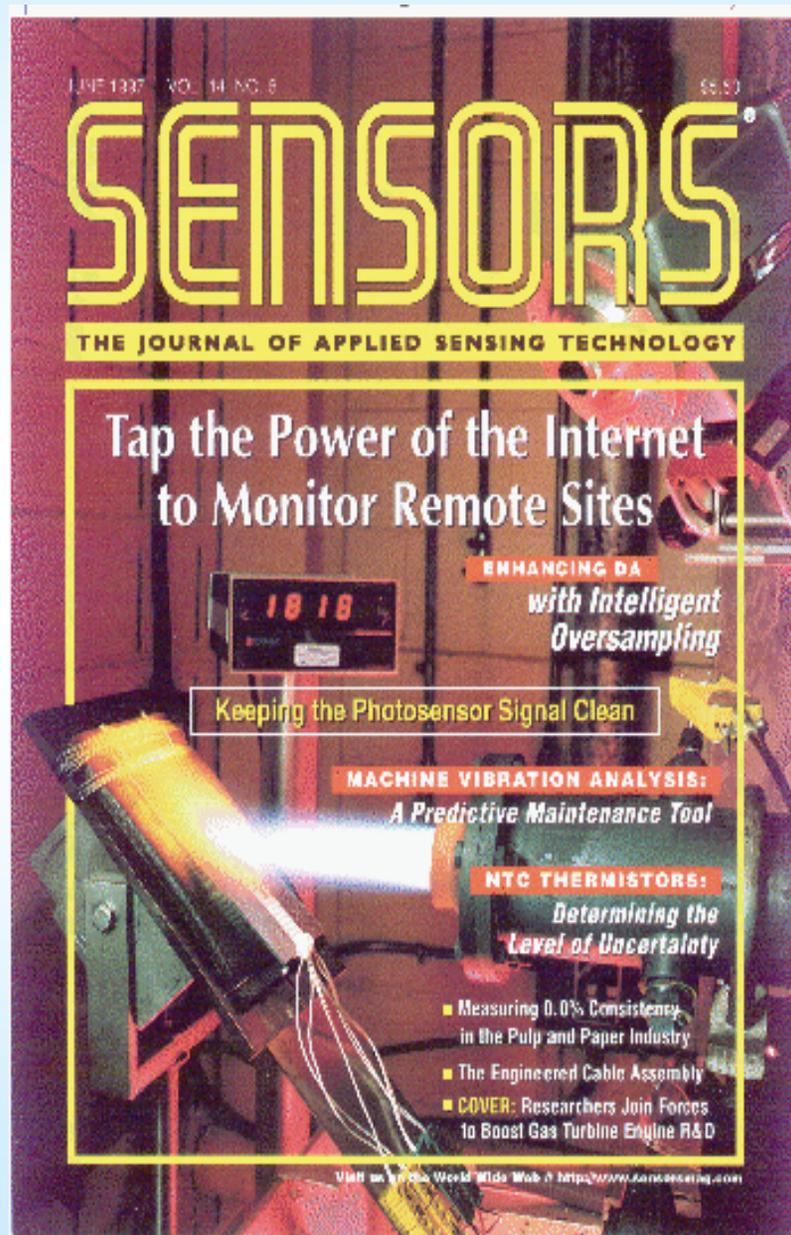
Chemical Sensors



Thin Film Sensors



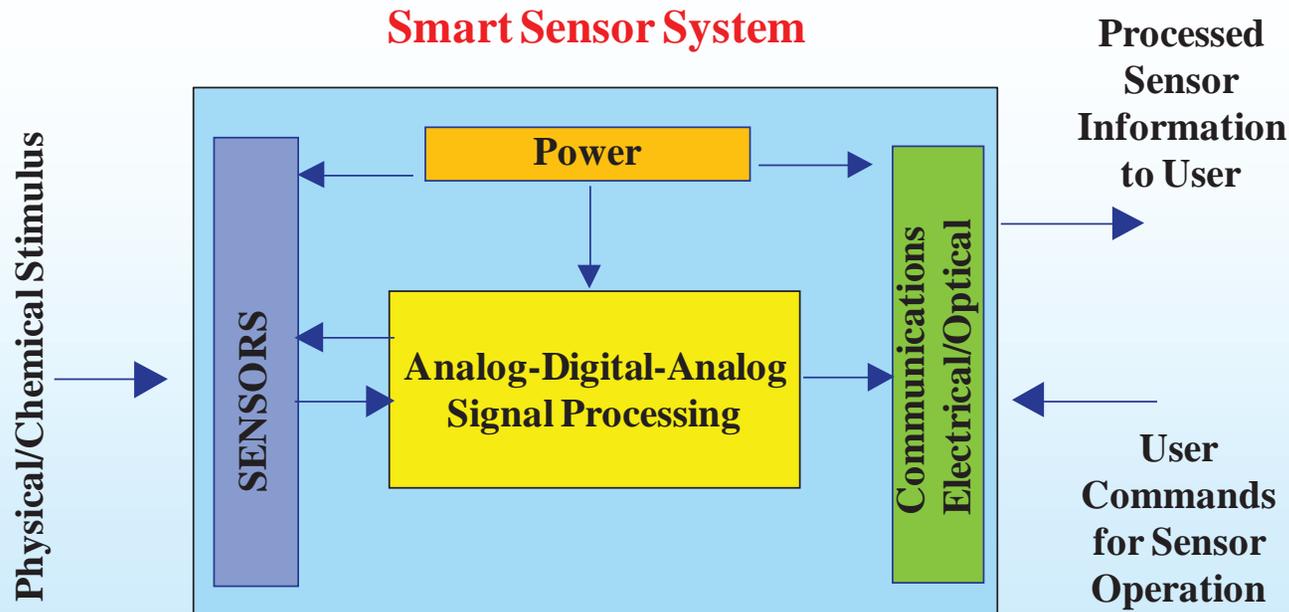
NASA GRC: DEVELOPMENT OF HARSH ENVIRONMENT SENSORS AND ELECTRONICS





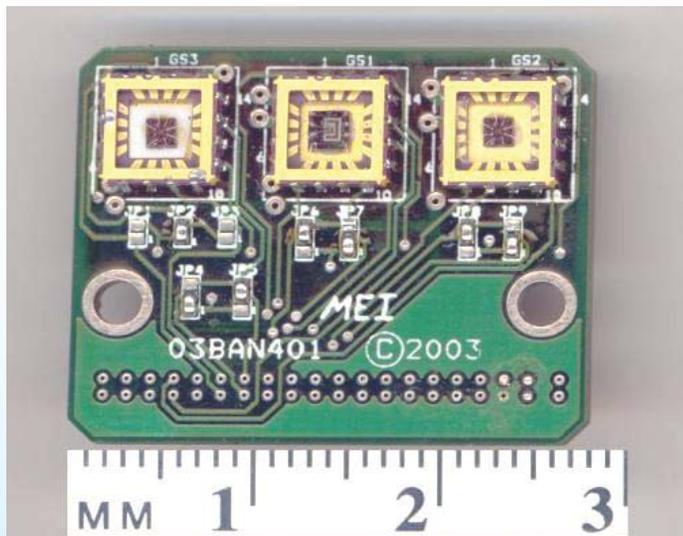
SMART SENSOR SYSTEMS BASED ON MICROSYSTEMS TECHNOLOGY

- 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
- BROAD RANGE OF APPLICATIONS
- MICROSYSTEMS TECHNOLOGY MOVING TOWARDS A RANGE OF APPLICATIONS
- ENABLE SYSTEM LEVEL INTELLIGENCE BY DRIVING CAPABILITIES TO THE LOCAL LEVEL USING DISTRIBUTED SMART SYSTEMS

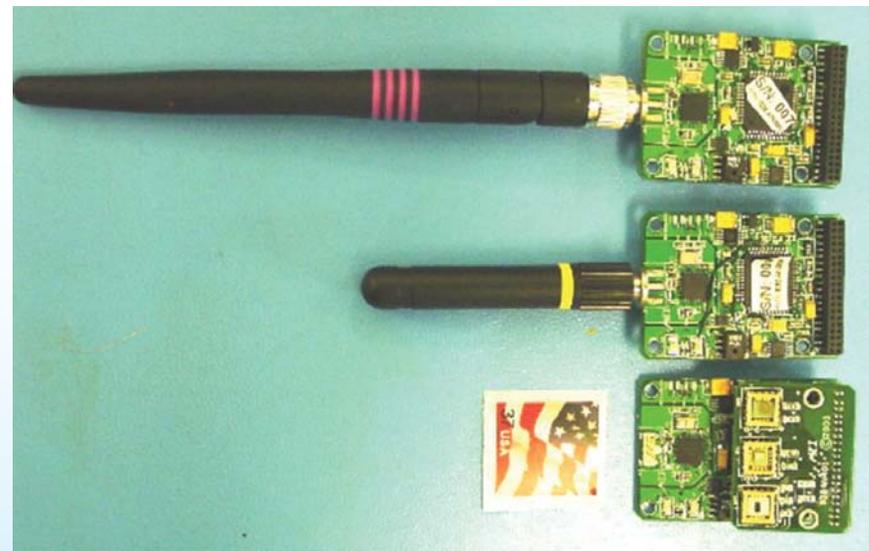


“LICK AND STICK” LEAK SENSOR SYSTEM

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



“Lick and Stick” Leak Detection Electronics and Three Sensors

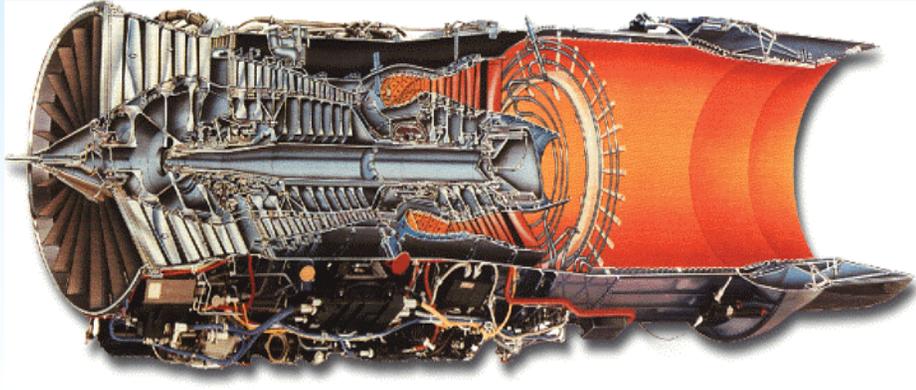


System configured with different wireless antennae.

HIGH TEMPERATURE ELECTRONICS AND SENSORS BENEFITS TO NASA MISSIONS



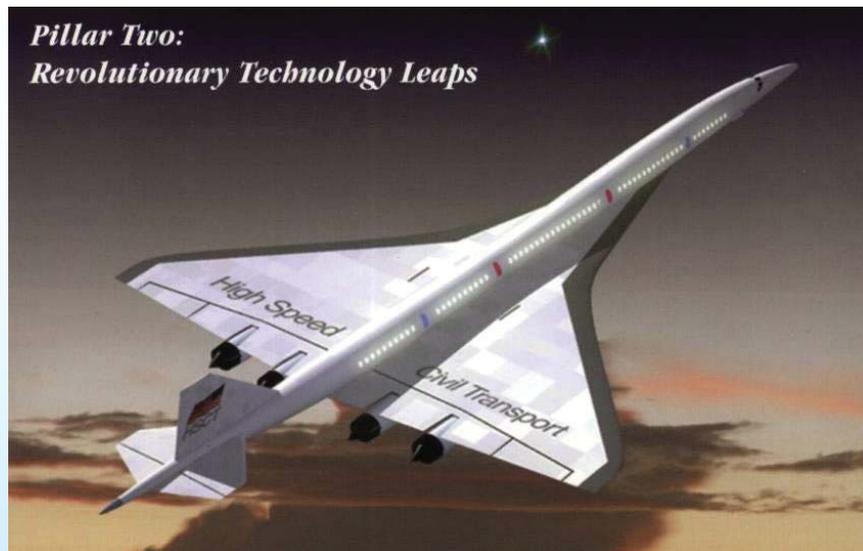
Intelligent Propulsion Systems



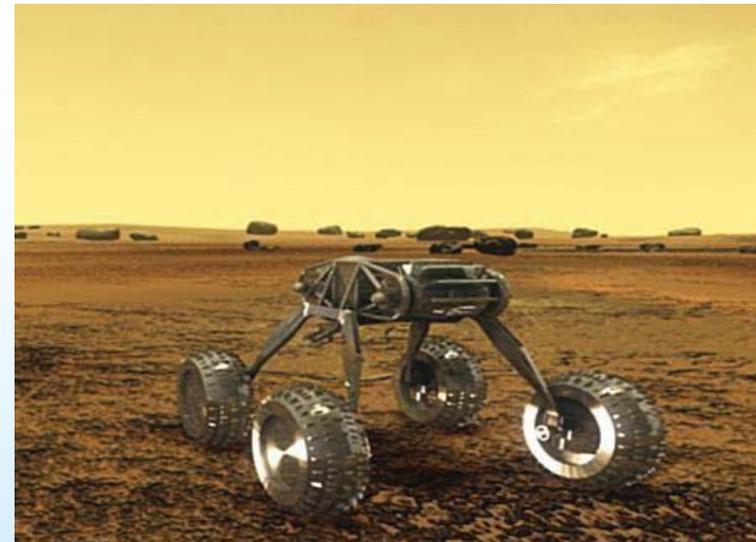
Space Exploration Vision



More Electric + Distributed Control Aircraft

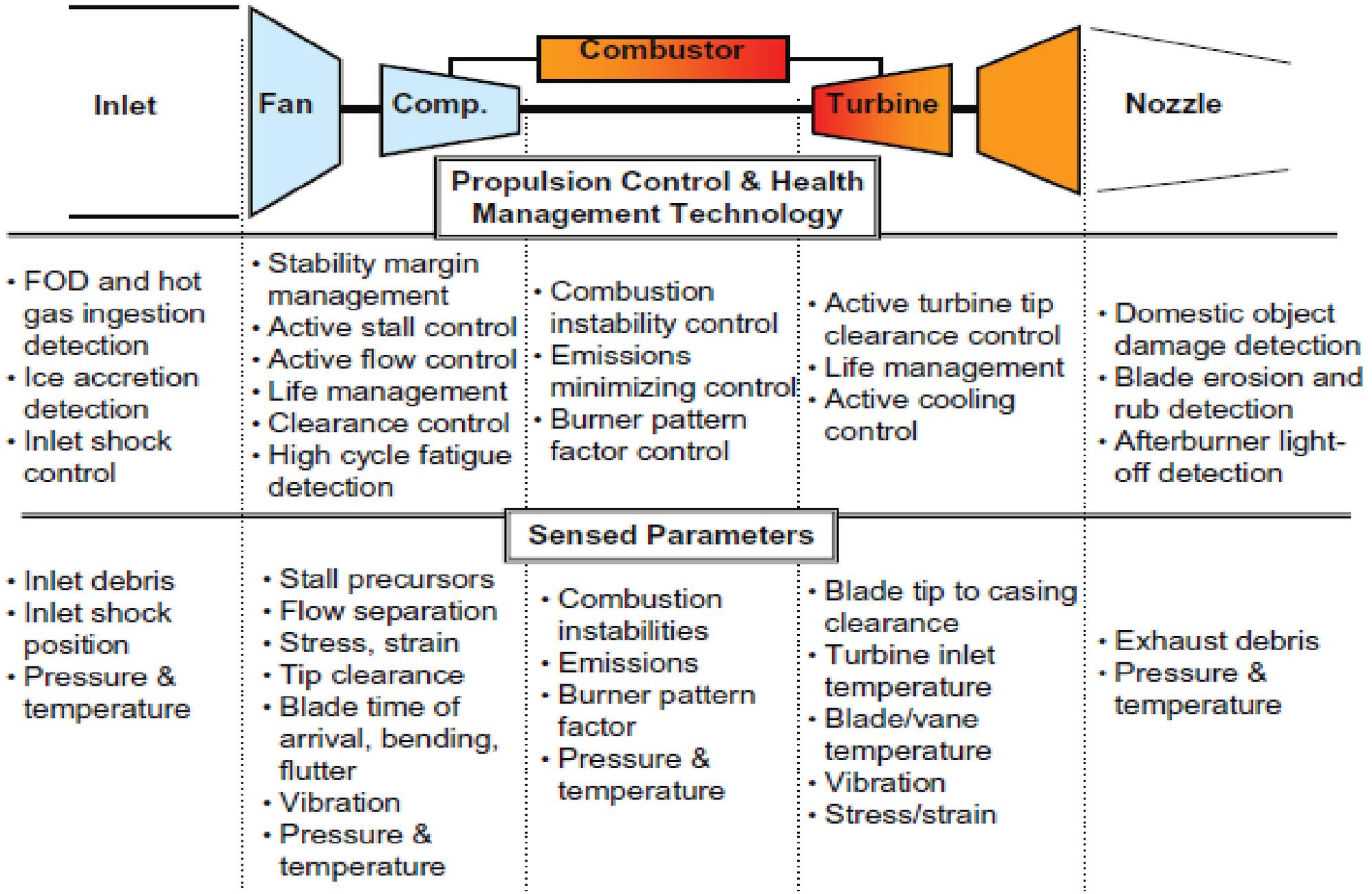


Venus Exploration





PROPULSION CONTROL AND HEALTH MONITORING TECHNOLOGIES ASSOCIATED SENSE PARAMETERS



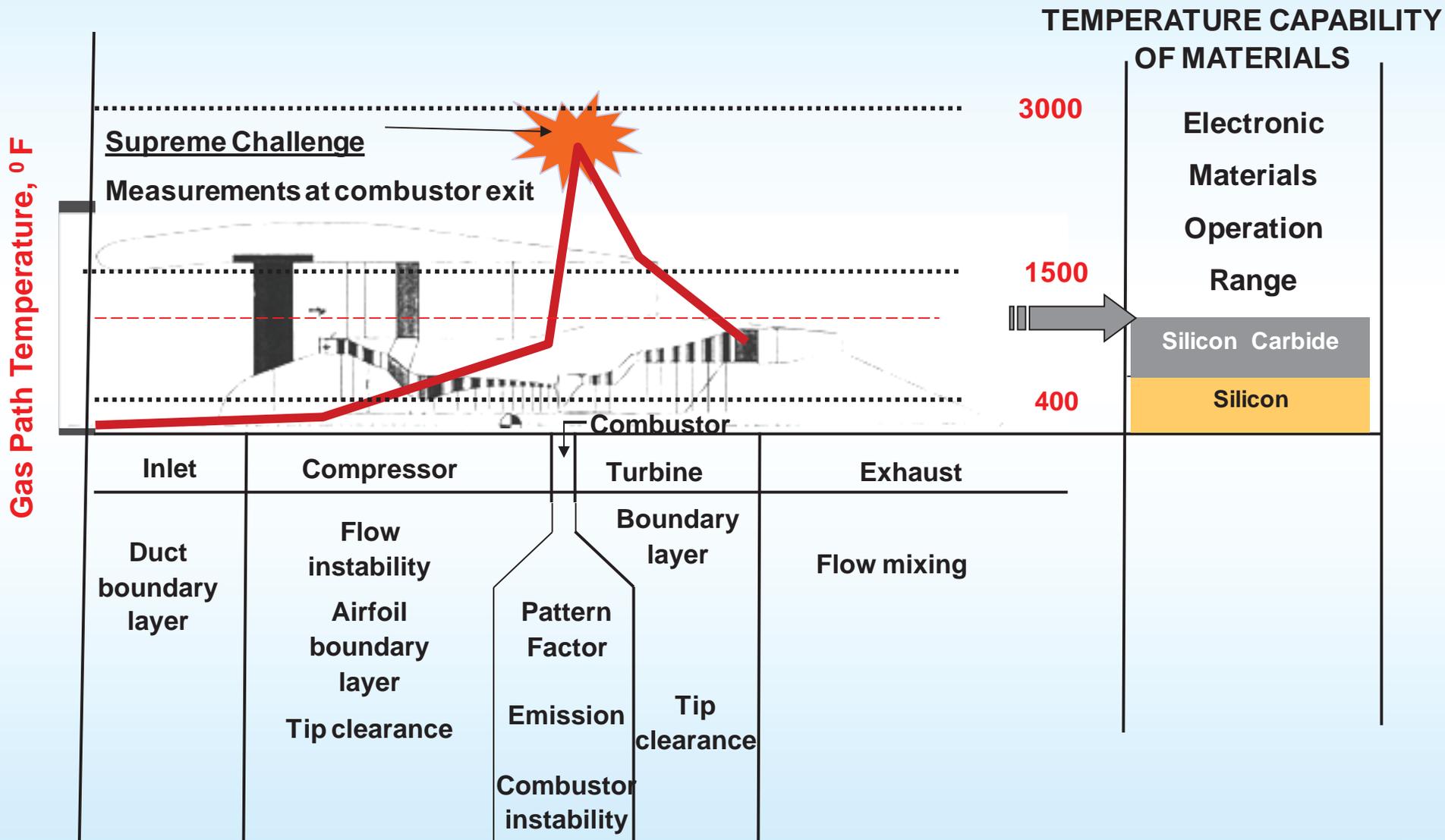


High Temperature Wireless Smart Sensor Systems

- **Sensors should go where they are needed, even in the harshest of environments**
- **Wires add weight, complexity, and are one of the main causes of sensor failure**
- **Future implementation of sensor technology can be significantly enhanced by:**
 - **Improving the ease of integration.**
 - **Decreasing the burden on the vehicle by decreasing the wire count.**
 - **Improving reliability by minimizing one of the major causes of sensor failure.**
- **Processing at the source can significantly enhance resulting information**
 - **Improve the fidelity of the information (e.g. signal amplification)**
 - **Select information to be transmitted/Decrease the amount of information that needs to be sent routinely**
- **Drive intelligence to the local level**
 - **Local processing to allow component level diagnostics**
 - **Decrease burden on the FADEC**
- **Major Drivers**
 - **Suitable security of the information exchange is critical for their use, especially in control systems.**
 - **Reliability of the radio connection is fundamental for control purposes**
 - **Operation in Engine Environments**
- **Objective: High temperature Smart Sensor Systems with wireless telemetry and distributed electronics operable over the broad operating temperature range and conditions of the engine**



CORRELATION OF POSITION WITHIN THE ENGINE TO TEMPERATURE LIMITATION ON ELECTRONIC MATERIALS

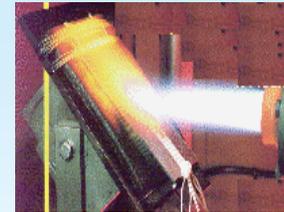




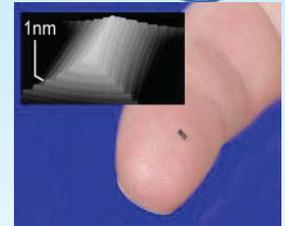
HARSH ENVIRONMENT ELECTRONICS AND SENSORS APPLICATIONS

• NEEDS:

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



1998 R&D 100 Award



2004 R&D 100 Award

• RESPONSE: UNIQUE RANGE OF HARSH ENVIRONMENT TECHNOLOGY AND CAPABILITIES

- STANDARD 500°C OPERATION BY MULTIPLE SYSTEMS
- TEMPERATURE, PRESSURE, CHEMICAL SPECIES, WIND FLOW AVAILABLE
- HIGH TEMPERATURE ELECTRONICS TO MAKE SMART SYSTEMS



1995 R&D 100 Award



1991 R&D 100 Award

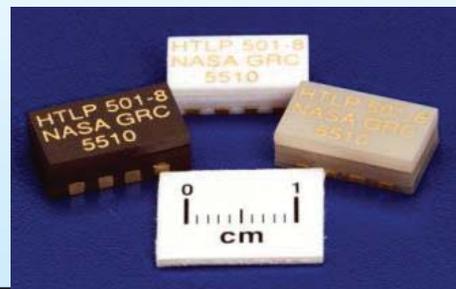
• ENABLE EXPANDED MISSION PARAMETERS/IN-SITU MEASUREMENTS

• LONG LIVED HIGH TEMPERATURE ELECTRONICS AT 500°C: **TOP DISCOVERY STORY IN 2007**

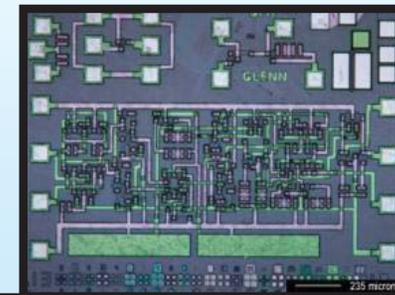
Range of Physical and Chemical Sensors for Harsh Environments



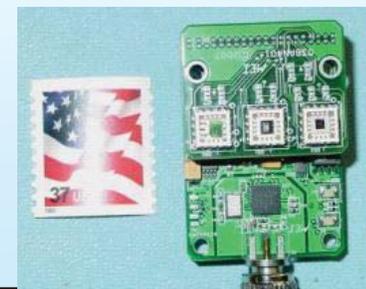
Harsh Environment Packaging (10,000 hours at 500°C)



High Temperature Signal Processing and Wireless



Long Term: High Temperature "Lick and Stick" Systems

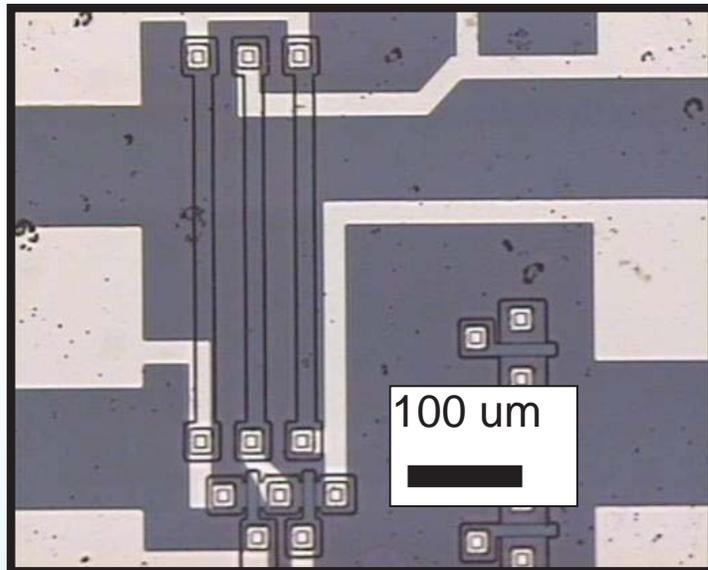


NASA Glenn Silicon Carbide Differential Amplifier

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

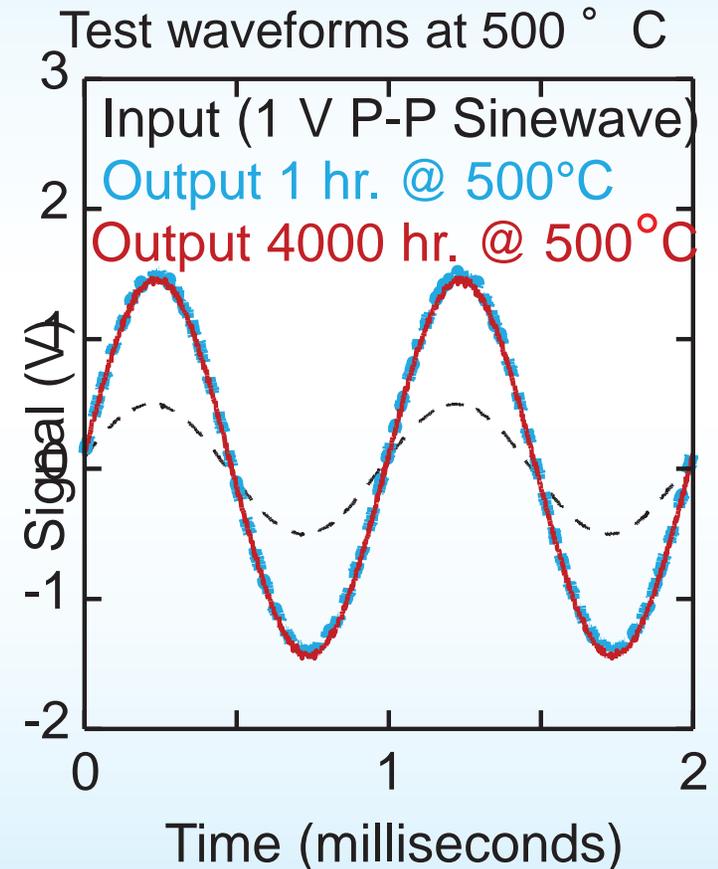
Demonstrates CRITICAL ability to interconnect transistors and other components (resistors) in a small area on a single SiC chip to form useful integrated circuits that are durable at 500°C.

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.

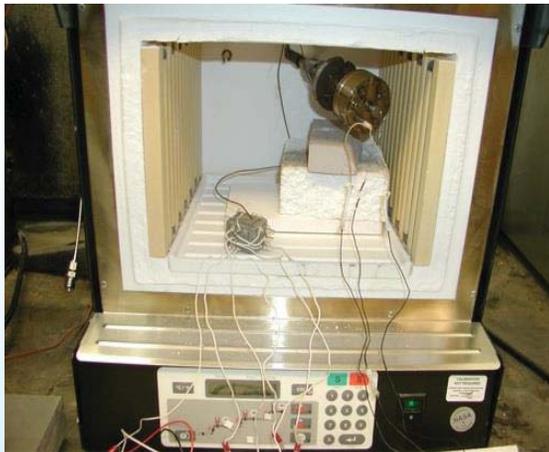


Less than 5% change in
operating characteristics during
4000 hours of 500°C operation.

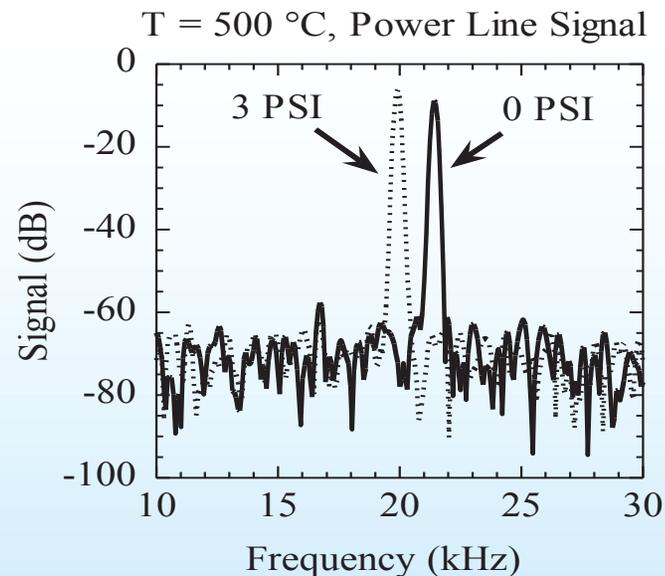
High Temperature Wireless

Parallel RF sensor data signal transmission at 500°C

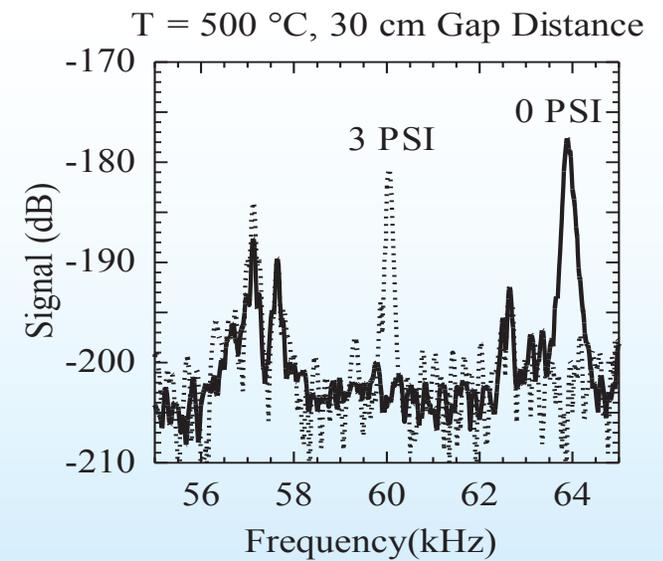
- Based On NASA SiC Components Previously Demonstrated For Long-life Operation
- Modulation Of Oscillator Output Frequency As A Function Of Applied Pressure At 500°C
- Sensor Data Transmission Across A Power Wire Of A Complete System At 500°C Has Been Demonstrated For 1 Hour
- Demonstration Of Wireless Sensor Transmission At 500°C At A Distance Of 30 cm Has Been Achieved With An External Antenna
- Both Are Considered World Firsts And Building Blocks For Future Technology Demonstrations



SiC Ring oscillator stack and capacitive pressure sensor system components in oven for 500°C testing



Transmission through power wire at 500°C over more than 1m

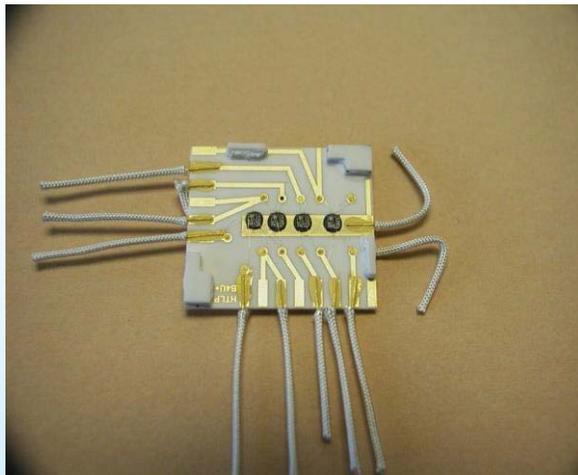


Wireless Transmission at 500°C with external antenna at 30 cm

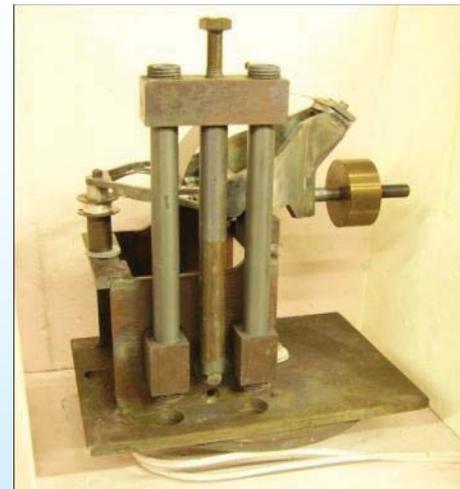


Venus Seismometer

- **INTEGRATION OF NASA GRC SiC ELECTRONICS, CAPACITORS, AND CIRCUIT DESIGN WITH SEISMOMETER MECHANISM**
 - **SIGNIFICANT ADVANCES IN COMPONENT PARTS FOR CIRCUIT DESIGN**
 - **MODIFICATION OF SENSING MECHANISM TO ALLOW IMPROVED CIRCUIT RESPONSE**
- **OPERATION OF COMBINED SYSTEM AT NEAR 500°C FOR 24 DAYS THUS MEETING A PROJECT OBJECTIVE**
- **WIRELESS TRANSMISSION OVER 2 METERS OF RESULTING SIGNAL**
- **SECOND GENERATION SEISMOMETER MECHANISM FABRICATED; PLANS TO BE INTEGRATED WITH ELECTRONICS**



High Temperature Wireless Resonator Unit

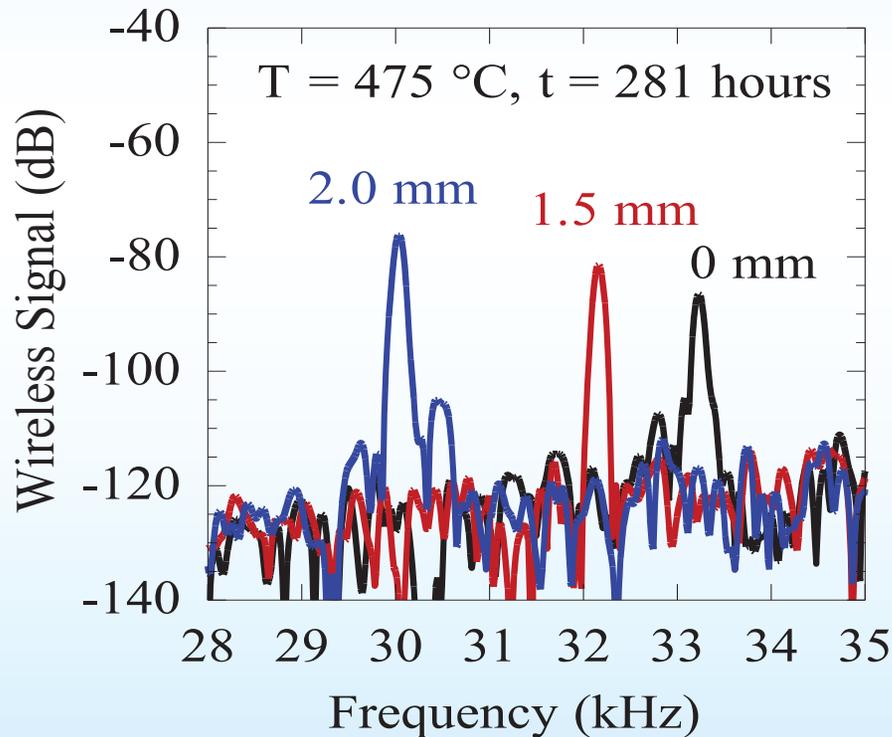


High Temperature Seismometer Mechanism

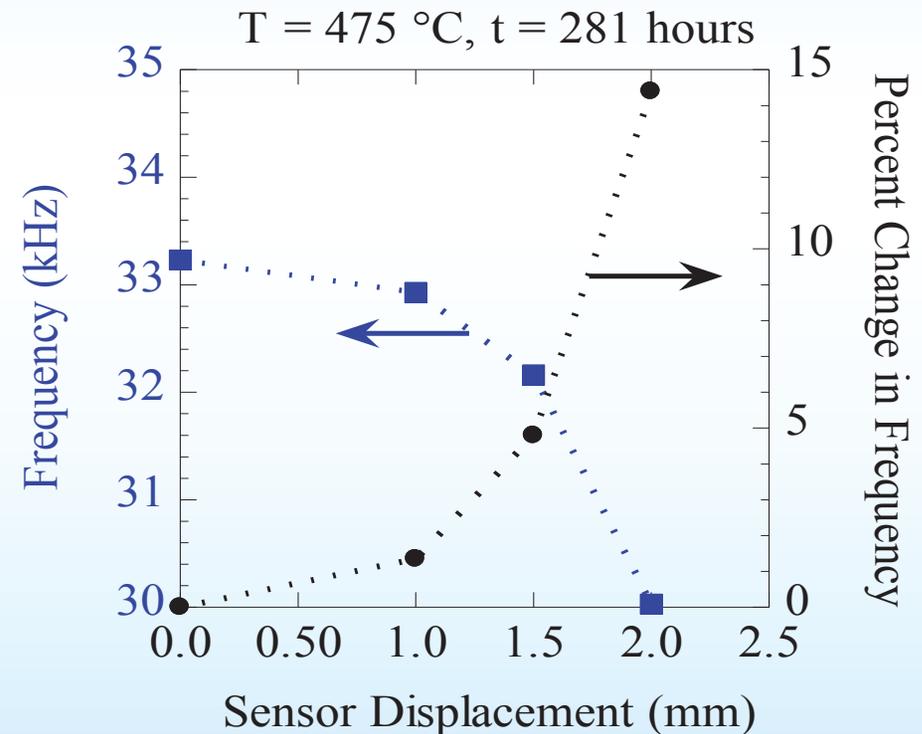


Venus Seismometer Operation at High Temperatures

- WIRELESS SIGNAL SPECTRA FOR SENSOR DISPLACEMENTS AT 475° C
- ANTENNA DISTANCE ~ 2 METERS
- FURTHER ASPECTS OF DEVICE PERFORMANCE TO BE EXAMINED
- LONG TERM DIRECTION: TESTING IN VENUS RELEVANT ENVIRONMENTS



Capacitive sensor element and oscillator circuit with output buffer in oven at 475 °C.



Wireless signal frequency as a function of capacitive sensor element displacement



OBJECTIVE :
MOVE TOWARD HIGHER DEGREES OF COMPLEXITY
ALLOWING HARSH ENVIRONMENT SMART SENSOR SYSTEMS
FULL SYSTEM APPROACH TOWARD HARSH ENVIRONMENT SMART
SENSOR SYSTEMS

- **Milestone: Demonstrate High Temperature Sensing, Wireless Communication, and Power Scavenging for Propulsion Health Management**
- **Metric: Demonstrate integrated self powered wireless sensor system at 500 °C with data transmission with operational life of at least 1 hr**

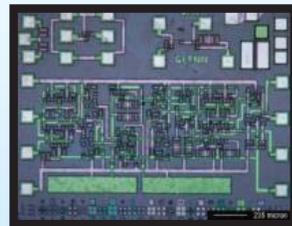
Significant wiring exists with present sensor systems



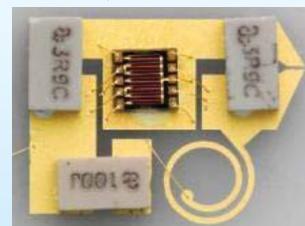
Allow Sensor Implementation by Eliminating Wires



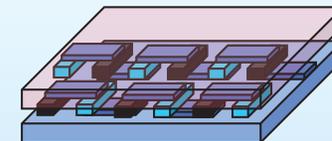
High Temperature Sensor Systems



World Record High Temperature Electronics Device Operation



High Temperature RF Components



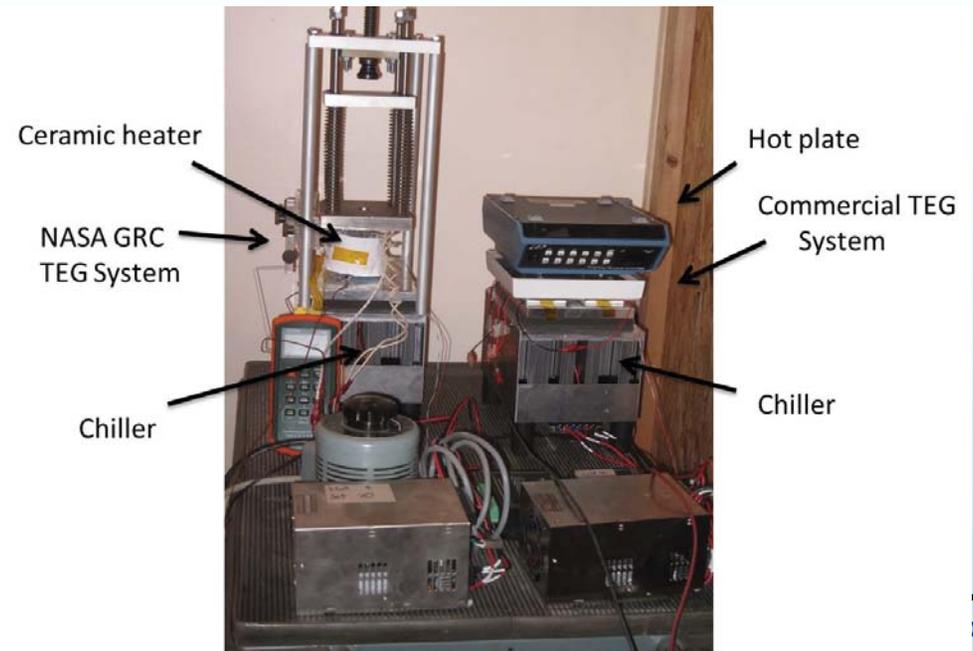
Energy Harvesting Thin Film Thermoelectrics



POWER SCAVENGING

- **POWER SCAVENGING FROM BOTH 300°C (COMMERCIAL) AND 500°C (SiGe-BASED) THERMAL ELECTRIC GENERATION (TEG) SOURCES**
- **THE TRANSISTOR DRAIN VOLTAGE, V_{DS} , WAS HELD CONSTANT AT 10 V AND THE DRAIN CURRENT, I_{DS} , WAS HELD CONSTANT AT 90 MA.**
 - **APPROXIMATELY 2.7 V WAS SUPPLIED BY A DC POWER SUPPLY TO THE DRAIN**
 - **REMAINDER FROM THE TEG ACCOUNTING FOR APPROXIMATELY 73% OF THE POWER TO THE TRANSISTOR**
- **IT SHOULD BE NOTED THAT THIS CONFIGURATION IS MEANT TO SHOW BASIC FUNCTIONALITY**
 - **FURTHER MINIATURIZATION AND INTEGRATION IS POSSIBLE AND DEPENDS ON THE APPLICATION ENVIRONMENT**
 - **MUCH OF THE INFRASTRUCTURE USED REPRODUCED A THERMAL GRADIENT ENVIRONMENT**

Power scavenging test system used to generate a temperature gradient over the thermoelectric generators and generate scavenged power.

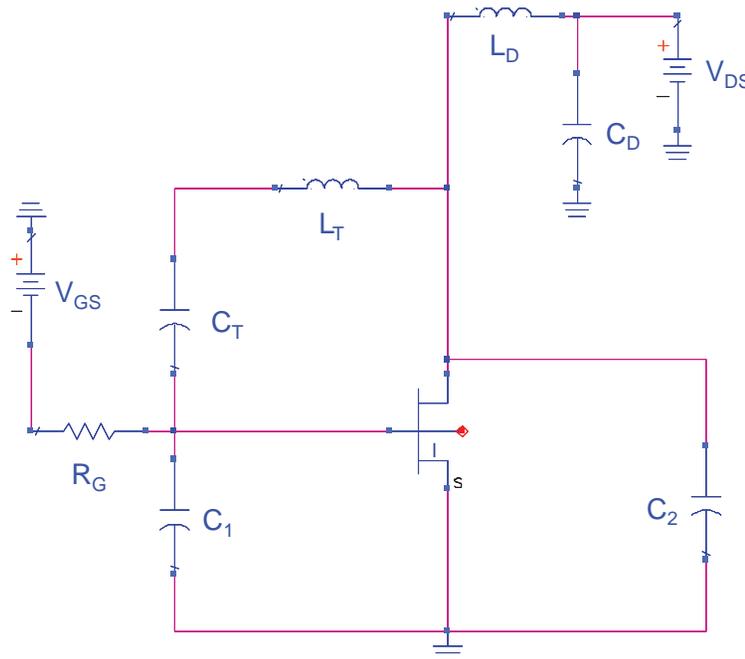




HIGH TEMPERATURE WIRELESS CIRCUIT

- **WIRELESS SENSING CIRCUIT DESIGN ENCOMPASSES MULTIPLE COMPONENTS**
 - **CAPACITIVE PRESSURE SENSOR (SPORIAN MICROSYSTEMS)**
 - **SIC METAL–SEMICONDUCTOR FIELD EFFECT TRANSISTOR (MESFET) ANTENNA**
 - **MULTIPLE PASSIVE COMPONENTS SUCH AS CAPACITORS.**
- **THE CIRCUIT IS COMPOSED OF A CLAPP-TYPE OSCILLATOR DESIGN**
 - **MESFET: CREE CRF24010D**
 - **L_T IS A 2-TURN THIN FILM SPIRAL INDUCTOR, WHICH ALSO PROVIDES MAGNETIC COUPLING FOR WIRELESS SIGNAL TRANSMISSION**
 - **C_1 AND C_2 ARE CERAMIC CHIP CAPACITORS**
 - **C_T IS THE CAPACITIVE PRESSURE SENSOR**

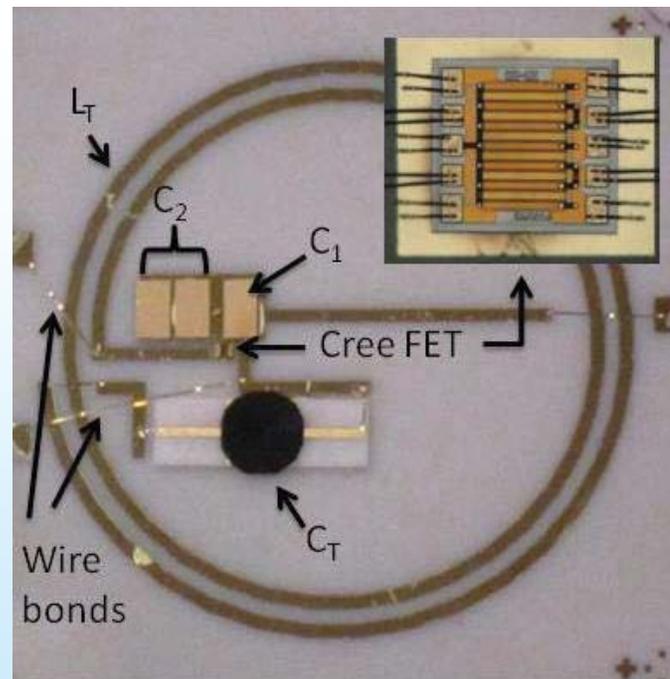
Schematic of the circuit using a Clapp-type oscillator design.



SiC HIGH TEMPERATURE CIRCUITRY

- **CIRCUIT INTEGRATED FOR INSERTION IN A PRESSURE/TEMPERATURE CHAMBER**
 - **DESIGNED TO OPERATE AT 130 MHZ**
 - **ALUMINA SUBSTRATE**
 - **THE METALLIZATION CONSISTS OF A TITANIUM/GOLD (TI/AU) LAYER,**
 - **DEPOSITED USING THIN FILM MICROFABRICATION PROCESSING TECHNIQUES**
 - **WIRE BONDS WERE USED TO MAKE ELECTRICAL CONNECTIONS BETWEEN COMPONENTS AND PADS**
- **THIS CIRCUIT FORMED A HIGH TEMPERATURE WIRELESS PRESSURE SENSOR WITH POWER PROVIDED BY BOTH POWER SCAVENGING AND AN EXTERNAL POWER SOURCE.**

Photograph of the wireless sensing circuit showing the Cree SiC MESFET, capacitive pressure sensor, antenna, and capacitors.

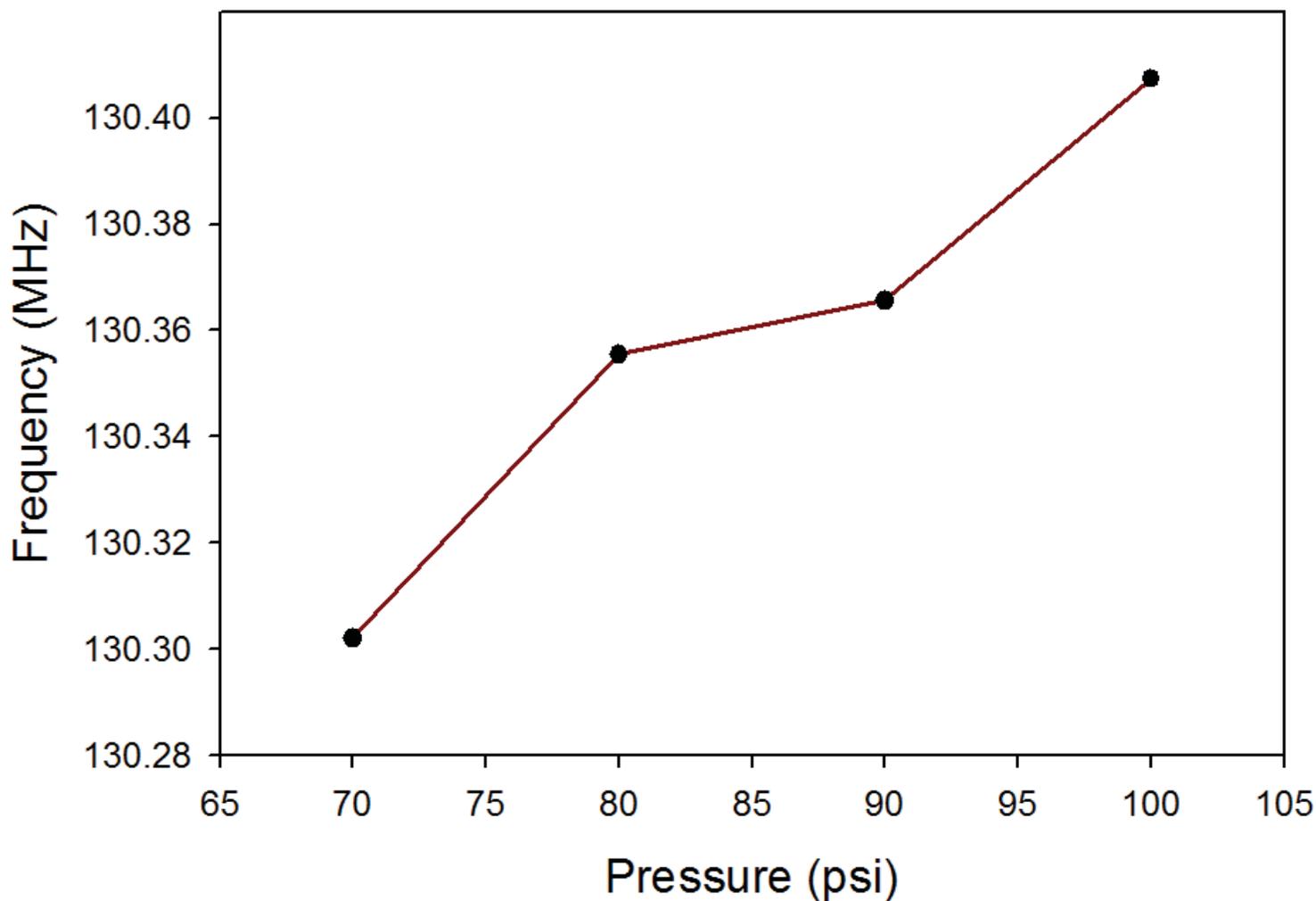




TESTING RESULTS

(Data Below 475°C presented in other papers)

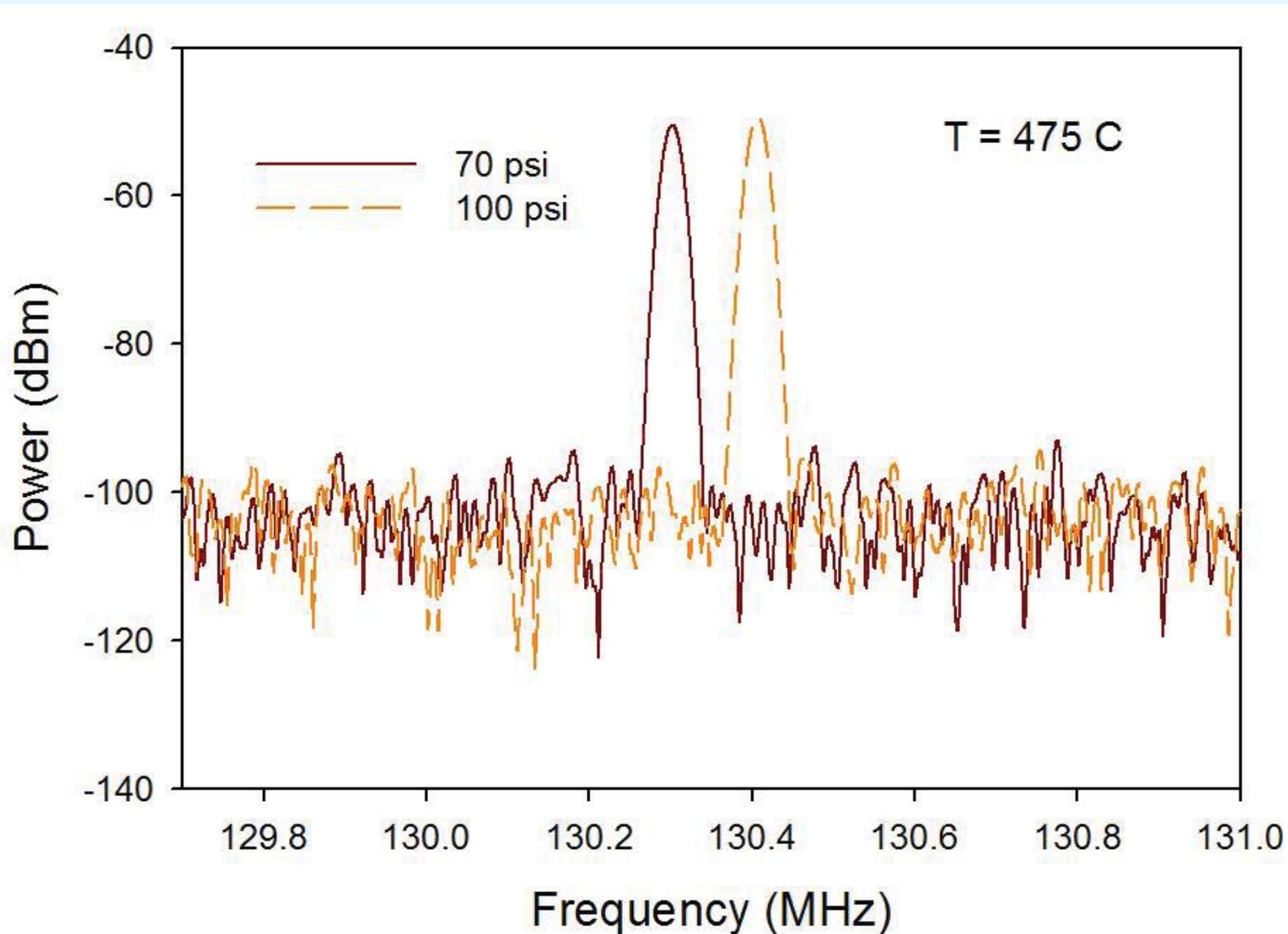
WIRELESS PRESSURE SENSOR RESPONSE DUE TO CHANGES IN PRESSURE AT A TEMPERATURE OF 475°C





TESTING RESULTS

SPECTRUM RESPONSE AT 475°C OF THE WIRELESS PRESSURE SENSOR AT 70 AND 100 PSI.





Approach: More Complex Systems Moving Toward Engine Applications Smart Sensor Systems

Milestone: Demonstrate High Temperature Sensing, Wireless Communication, and Power Scavenging for Propulsion Health Management

Date: 6/30/2012

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

Basic smart sensor demonstration approach

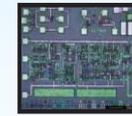
Significant wiring exists with present sensor systems



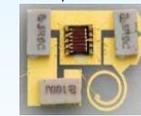
Allow Sensor Implementation by Eliminating Wires



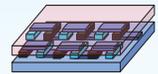
High Temperature Sensor Systems



World Record High Temperature Electronics Device Operation



High Temperature RF Components



Energy Harvesting Thin Film Thermoelectrics

Move Toward Higher Degrees Of Complexity Allowing Harsh Environment Smart Sensor Systems

High Temp Electronics and Comm Demo planned for VIPR 3

Next generation of high temperature circuit technology (FY14)

Circuit	Inputs	Outputs	Transistors, I/O Pads	Comments
4-Bit A/D	Analog voltage signal, optional external clock, output type select	4 bit parallel digital latch, pulse width modulated (PWM)	203 JFETs, 23 I/Os	Internal ring-oscillator clock circuit
2X2 Bit Static RAM	Read, Write, Data Lines, Address Lines	4 bit parallel digital latch, pulse width modulated (PWM)	220 JFETs, 30 I/Os	Address decoder, sense amplifiers
Source Separation Sensor Signal Transmitter	Capacitive sensor	Frequency modulated with address code	301 JFETs, 20 I/Os	Each sensor signal is tagged with unique address code
Ring Oscillators	Capacitive sensors	Frequency modulated signals (up to 500 MHz)	10-12 JFETs, 6 I/Os	On-chip large transistors for power amplification
Binary Amplitude Modulation RF Transmitter	Low power binary signal	High-Power RF signal to antenna		Could connect with PWM from A/D
Op Amp, 2-Stage	Differential	Voltage gains to 50 w/ on-chip resistors	10 JFETs	For piezoelectric SiC pressure sensors
4-Bit D/A	4 digital	1 analog	20 JFETs	

Milestone: Demonstrate 1st generation smart sensor system off-nominal engine sensing

Date: 8/30/2016

Metric: Show first demonstration of a limited smart high temperature wireless data sensor system to detect engine faults

Integration of a range of technologies is needed for Smart Sensor Systems

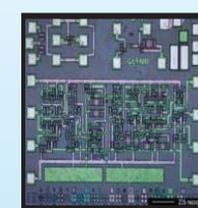
Range of Physical and Chemical Sensors for Harsh Environments



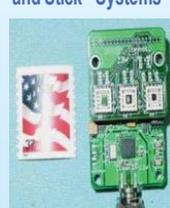
Harsh Environment Packaging (10,000 hours at 500°C)



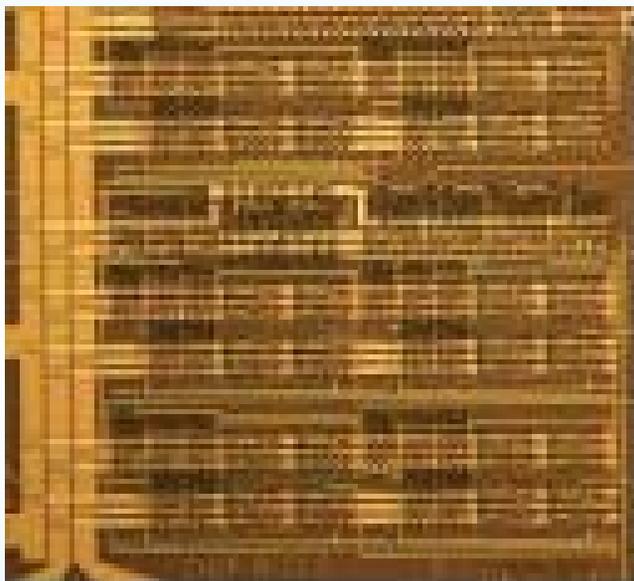
High Temperature Signal Processing and Wireless



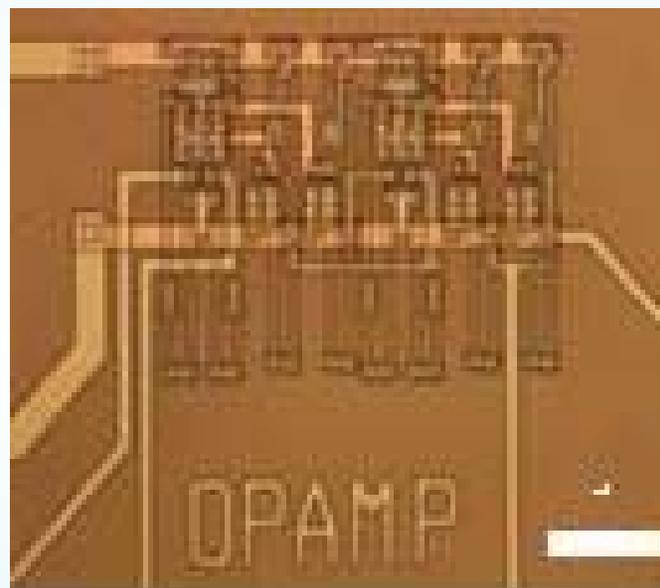
Long Term: High Temperature "Lick and Stick" Systems



Development Towards More Complex Electronics for Smart Sensor Systems



**4-bit Analog To Digital
Converter**



Op-amp integrated circuit



VIPR Overview

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

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

Partnerships make it possible.

Test Objectives:

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

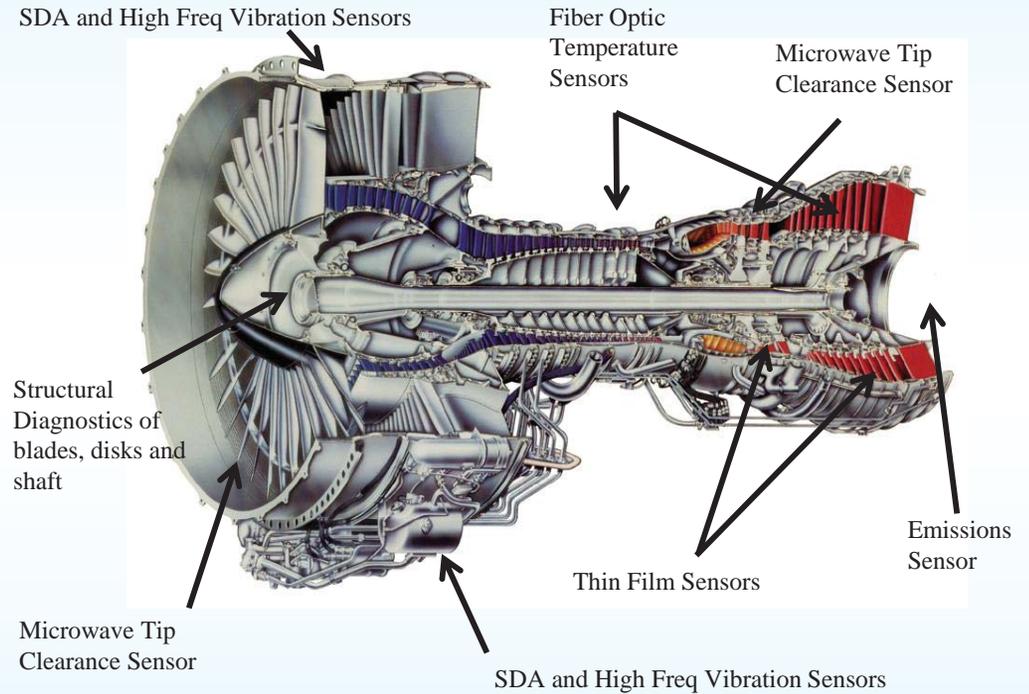
Approach:

Perform engine ground tests using large bypass transport engine

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

Partnerships:

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



Model-based gas path diagnostic architecture





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.



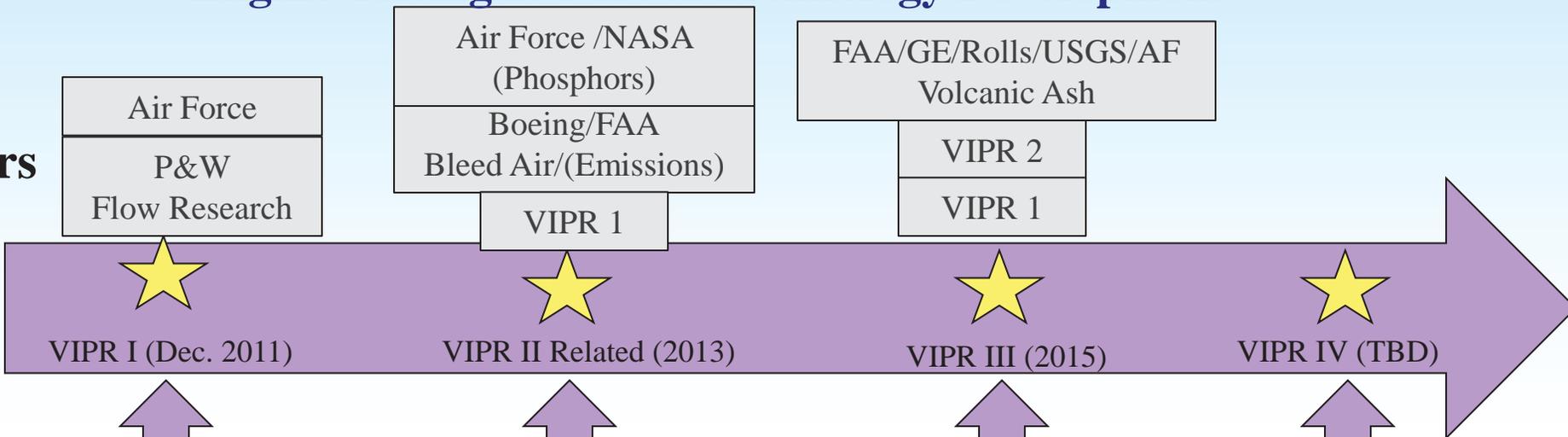
All VIPR ground testing is planned to be conducted on an Air Force C-17 aircraft at Edwards AFB, California.



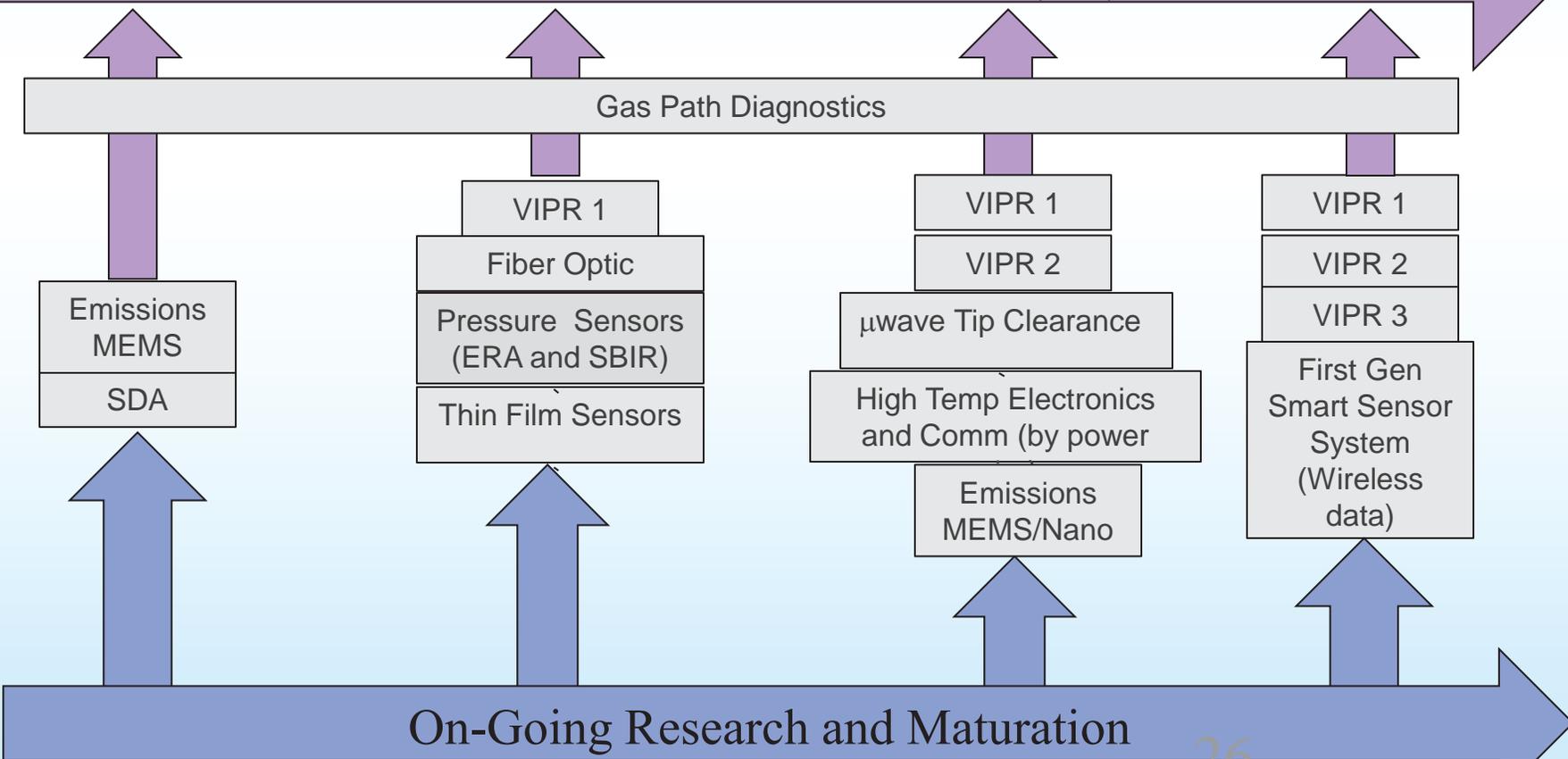
VIPR Overview

Engine Testing as Part of Technology Development

Partners



NASA



SUMMARY



- **SMART SENSOR SYSTEMS HAVE A RANGE OF APPLICATIONS**
 - **INTEGRATED SYSTEM OF PROCESSING, COMMUNICATIONS, SENSORS, AND POWER**
 - **SMART TECHNOLOGY IS BECOMING INCREASING DOMINANT IN COMMERCIAL APPLICATIONS**
 - **“LICK AND STICK” TECHNOLOGY AVAILABLE AT NEAR ROOM TEMPERATURES**
- **PROPULSION HEALTH MANAGEMENT AND DISTRIBUTED ENGINE CONTROL APPLICATIONS**
 - **CHALLENGED BY HARSH ENVIRONMENT CONDITIONS AND LACK OF OPERATIONAL ELECTRONICS**
- **MULTIPLE HIGH TEMPERATURE TECHNOLOGIES INTEGRATED**
 - **PRESSURE SENSOR, POWER SCAVENGING, SiC CIRCUITY, WIRELESS CIRCUIT**
 - **SYSTEM INTEGRATION**
 - **TESTING SYSTEM**
- **FUTURE WORK: TRANSITION OF TECHNOLOGIES TOWARDS MORE COMPLEX ELECTRONIC SYSTEMS**