Setting the Standard for Automation™

A Brief Review of the Need for Robust Smart Wireless Sensor Systems for Future Propulsion Systems, Distributed Engine Controls, and Propulsion Health Management

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Presenter

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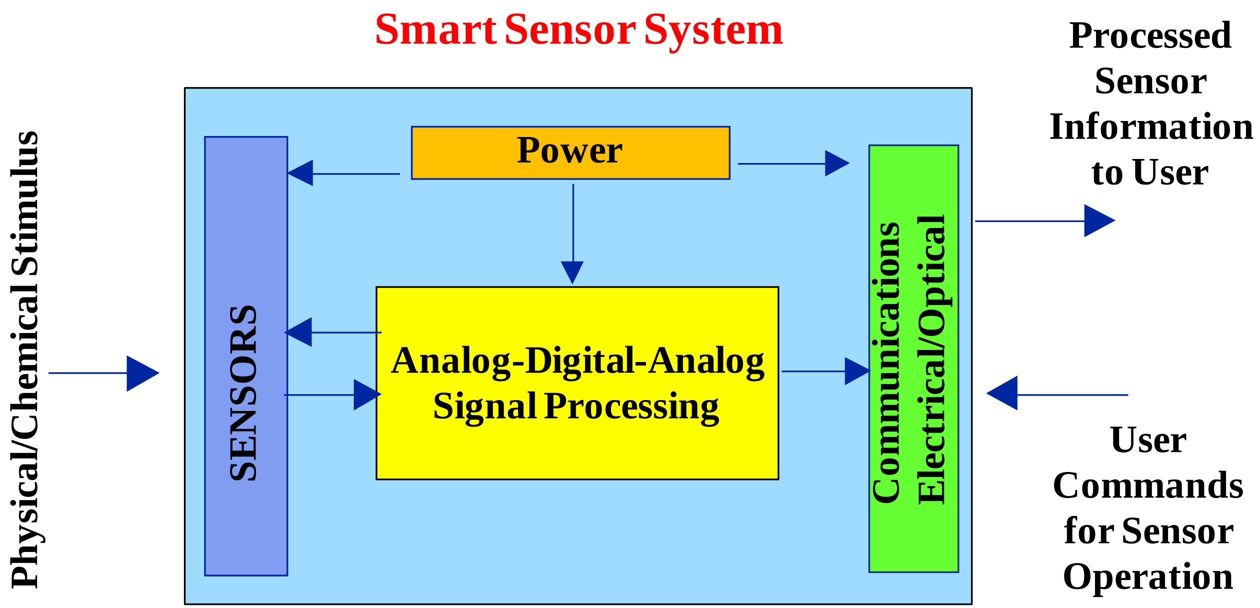
OUTLINE

- INTRODUCTION
- MOTIVATION TOWARDS WIRELESS SMART SENSOR SYSTEMS
- PROPULSION SYSTEM APPLICATIONS
- ROLE OF WIRELESS SMART SENSOR SYSTEMS
- EXAMPLE SMART WIRELESS SENSOR SYSTEMS DEVELOPMENT
- SUMMARY AND FURTHER WORK

MOTIVATION TOWARDS WIRELESS SMART SENSOR SYSTEMS

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



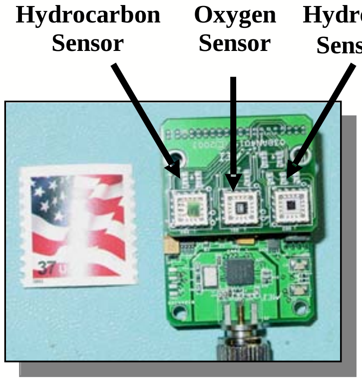
BASIC APPROACH:
MAKE AN INTELLIGENT SYSTEM FROM SMART COMPONENTS

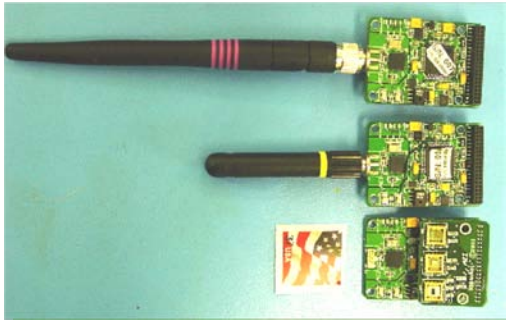
POSSIBLE STEPS TO REACH INTELLIGENT SYSTEMS

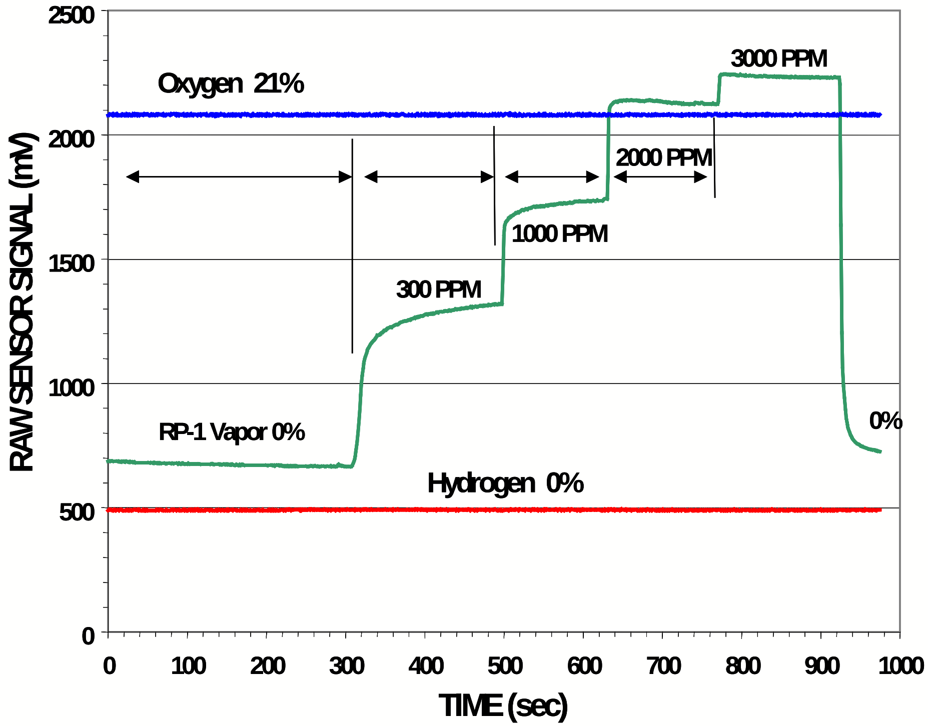
- **“LICK AND STICK” TECHNOLOGY (EASE OF APPLICATION)**
  - **Micro and nano fabrication to enable multipoint inclusion of sensors, actuators, electronics, and communication throughout the vehicle without significantly increasing size, weight, and power consumption. Multifunctional, adaptable technology 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 if it can be trusted.**
- **REDUNDANCY AND CROSS-CORRELATION:**
  - **If the systems are easy to install, reliable, and do not increase weight/complexity, the application of a large number of them is not problematic allowing redundant systems, e.g. sensors, spread throughout the vehicle. These systems will give full-field coverage of the engine parameters but also allow cross-correlation between the systems to improve reliability of sensor data and the vehicle system information.**
- ***ORTHOGONALITY:***
  - ***Systems should each provide a different piece of information on the vehicle system. Thus, the mixture of different techniques to “see, feel, smell, hear” as well as move can combine to give complete information on the vehicle system as well as the capability to respond to the environment.***

"LICK AND STICK" SENSOR SYSTEM
AVAILABLE IN STANDARD SILICON TECHNOLOGY

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







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

PROPULSION APPLICATIONS

PROPULSION SYSTEM GOALS

Motivation / Goals

Lower Cost

Technology Push / Pull

Simplify Upgrades

Add Customer Value

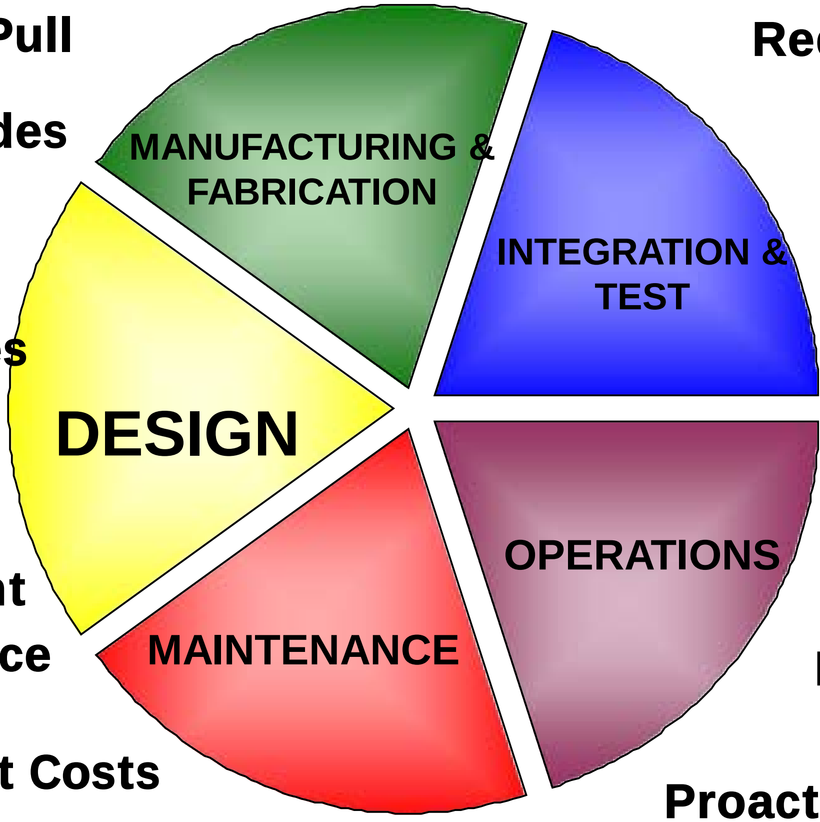
Time to Adapt
/ Add New Features

Adaptive Control
/ Flow Control

Reduce Weight

Mitigate obsolescence

Reduce Sustainment Costs



System Compatibility

Reduce Certification
Cost / Time

Capability Growth

Improve Reliability

Increase Availability

Real-time Life Tracking

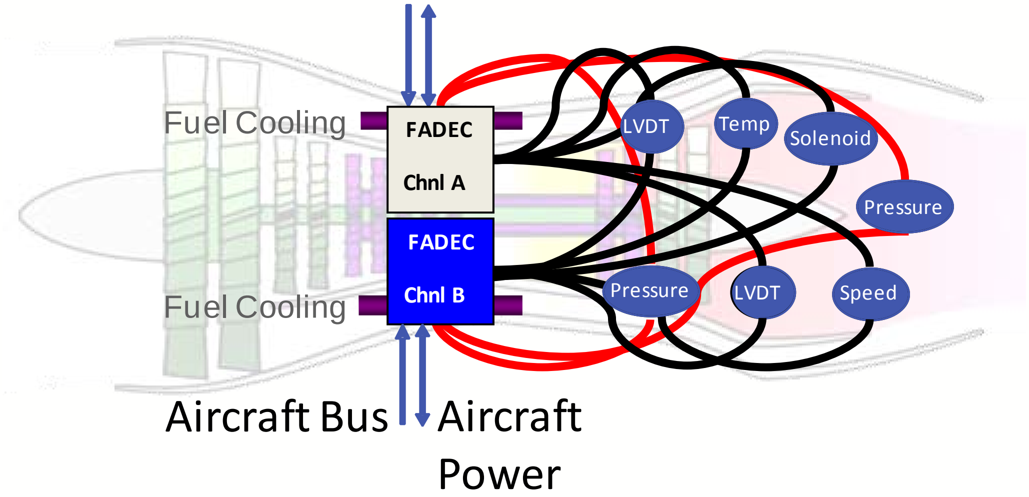
Mission Success

Prognostic Capability

Proactive Health Management

Performance, Time & Cost

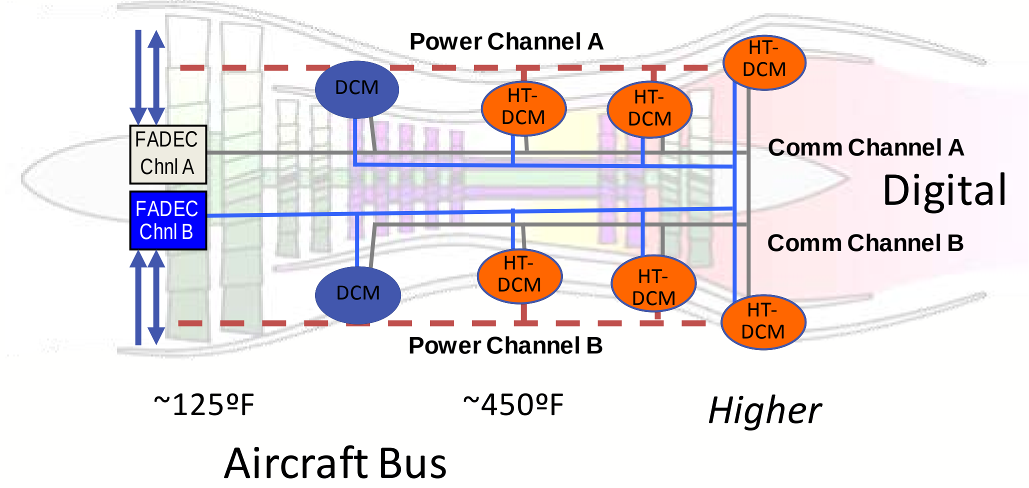
ENGINE CONTROL ARCHITECTURES



Centralized FADEC

Analog Sensor

Analog Power / Communication



Fully Distributed Control

DCM Low Temp Digital Control Module

HT-DCM High Temp Digital Control Module

Objective: Modular, Open, Distributed Engine Control

Technology Benefits

- **Increased Performance**
  - Reduction in engine weight due to digital signaling, lower wire/connector count, reduced cooling need
  - 5% increase in thrust-to-weight ratio
- **Improved Mission Success**
  - System availability improvement due to automated fault isolation, reduced maintenance time, modular LRU
  - 10% increase in system availability
- **Lower Life Cycle Cost**
  - Reduced cycle time for design, manufacture, V&V
  - Reduced component and maintenance costs via cross-platform commonality, obsolescence mitigation
  - Flexible upgrade path through open interface standards

Capability Needs

- **Open Systems Development, Modeling & Design**
  - Future systems requirements definition
  - Open industry interface standards definition
  - System modeling tools development
  - Modular system integration and test techniques
- **Hardware Systems Development**
  - High temperature integrated circuits and systems development
  - Improved electronic component availability
- **Software Systems Development**
  - Software system partitioning
  - Software design and modular test capability
  - Software distributed system V&V

Propulsion Health Management
Problem Statements

Existing Aircraft

- Although aircraft propulsion systems are highly reliable, propulsion malfunctions contributing to aviation accidents and incidents do occur.
- Degradation and damage that develops over time in hot section components can lead to catastrophic failure.
- Ground-based testing may not identify problems occurring in-flight, or due to damage or degradation in harsh environment conditions during operation.
- Information related to the engine health state is limited due to the harsh environment operational conditions.
- Examples of malfunctions include uncontained rotor failures, in-flight engine shutdowns, and restricted thrust response.
- Examples of underlying causes include turbomachinery damage, controls and accessory faults, and environmental effects such as volcanic ash and ice ingestion.

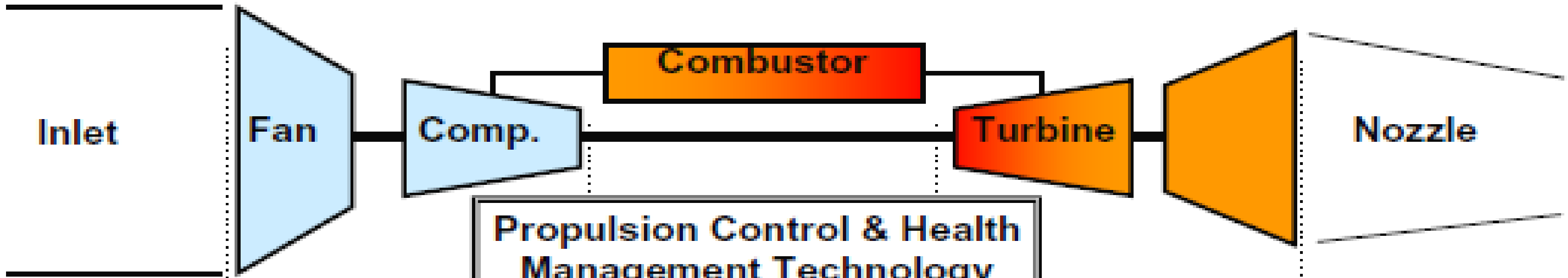
Future Aircraft

- It is desired that new materials and capabilities be incorporated future aircraft to improve fuel efficiency and reduce noise and emissions while safety is maintained at existing levels. System-level effects of integration of new flight technologies is unclear.
- One way to incorporate these technologies and maintain safety is through health monitoring, but for an engine the operational environments mean limited information is available.
- One example is that changes in the operation of an engine system, for example by increased operating temperatures, may have long-term effect on engine conditions and safety. Knowing these problems as they develop, rather than when they manifest themselves in an accident, is desired.

Propulsion Health Management Demonstrated Needs Include:

- Advances in algorithms and data analysis are necessary to keep pace with increased data acquisition capabilities.
- Sensor system integration improvements and new functionality can be a means to address existing safety issues and also facilitate the introduction of new flight technologies.
- One way to monitor engine systems, and mitigate potential issues is through small, low weight sensors, such as fiber optics or wireless, which can be integrated easily. An objective is to avoid costly retrofits while maintaining safety.
- Advances in sensors and electronics are critical for enhancing engine health assessments.
- Engine sensor reliability and limited measurement capability are major challenges to increased situational awareness.
- Very difficult to model some engine parameters, e.g., turbine blade temperatures, strains, heat fluxes; measurements are needed
- Measurement and diagnostics of the engine should be viewed as a integrated, whole field problem and not a collection of individual technologies.
- Engine tests provide rare and much needed opportunities to demonstrate propulsion health management technology.

PROPULSION CONTROL AND HEALTH MONITORING TECHNOLOGIES ASSOCIATED SENSE PARAMETERS



Propulsion Control & Health Management Technology

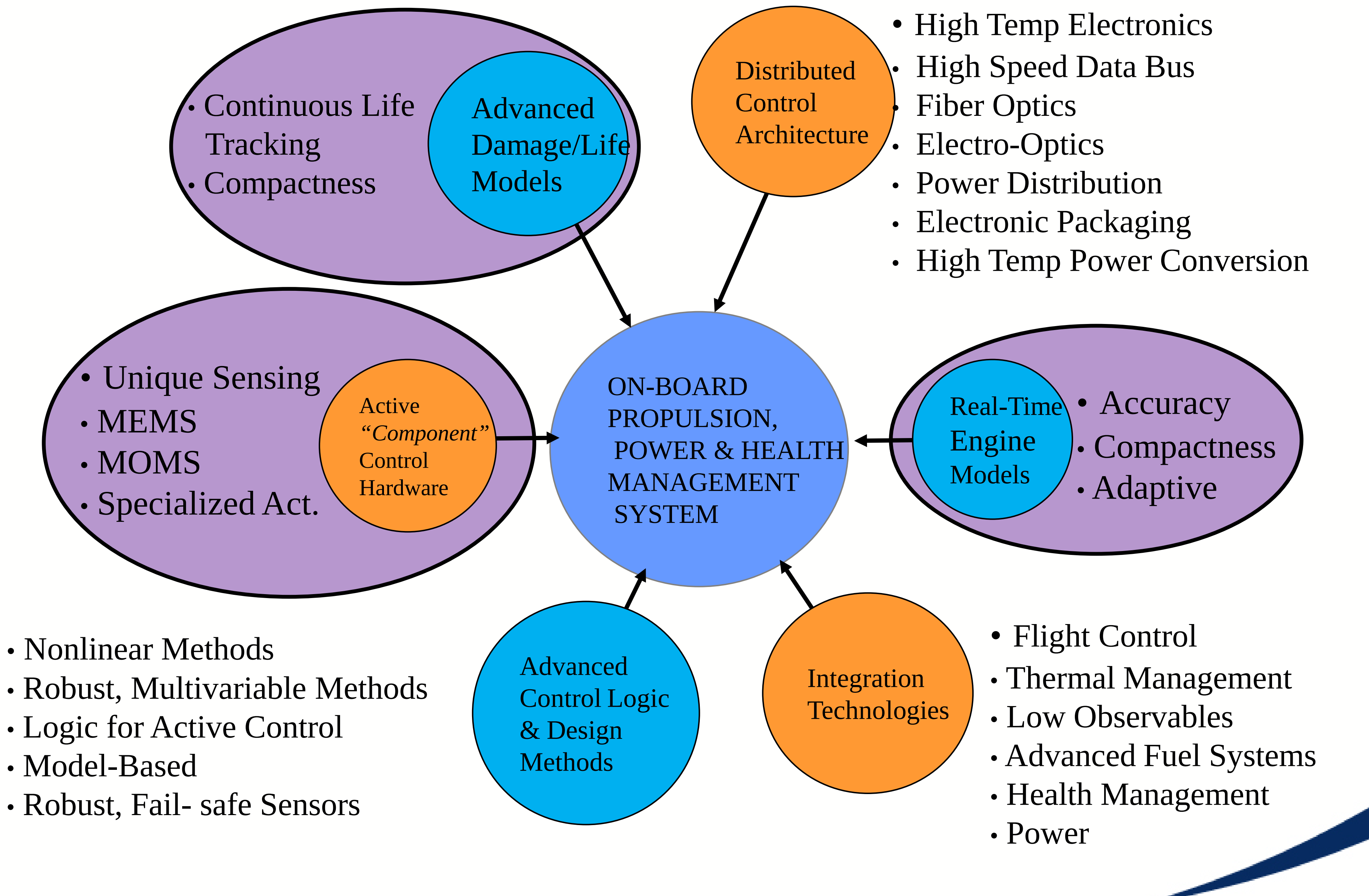
• FOD and hot gas ingestion detection • Ice accretion detection • Inlet shock control	• Stability margin management • Active stall control • Active flow control • Life management • Clearance control • High cycle fatigue detection	• Combustion instability control • Emissions minimizing control • Burner pattern factor control	• Active turbine tip clearance control • Life management • Active cooling control	• Domestic object damage detection • Blade erosion and rub detection • Afterburner light-off detection

Sensed Parameters

• Inlet debris • Inlet shock position • Pressure & temperature	• Stall precursors • Flow separation • Stress, strain • Tip clearance • Blade time of arrival, bending, flutter • Vibration • Pressure & temperature	• Combustion instabilities • Emissions • Burner pattern factor • Pressure & temperature	• Blade tip to casing clearance • Turbine inlet temperature • Blade/vane temperature • Vibration • Stress/strain	• Exhaust debris • Pressure & temperature

Technologies Associated with Both Distributed Engine Controls and Propulsion Health Management

*The solution is not just software! New **hardware** capabilities are required!*

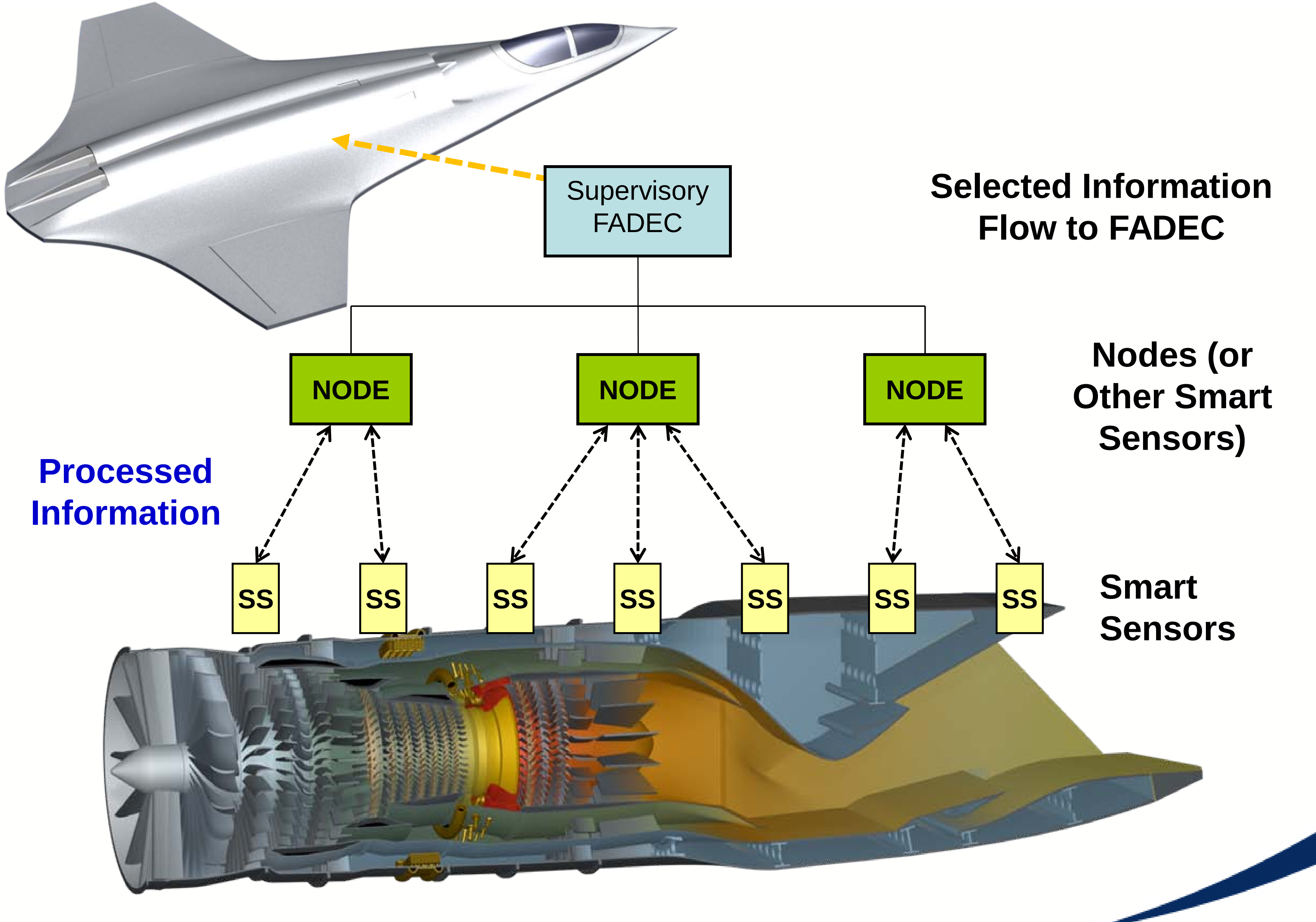


ROLE OF WIRELESS SMART SENSOR SYSTEMS

High Temperature Wireless Smart Sensor Systems

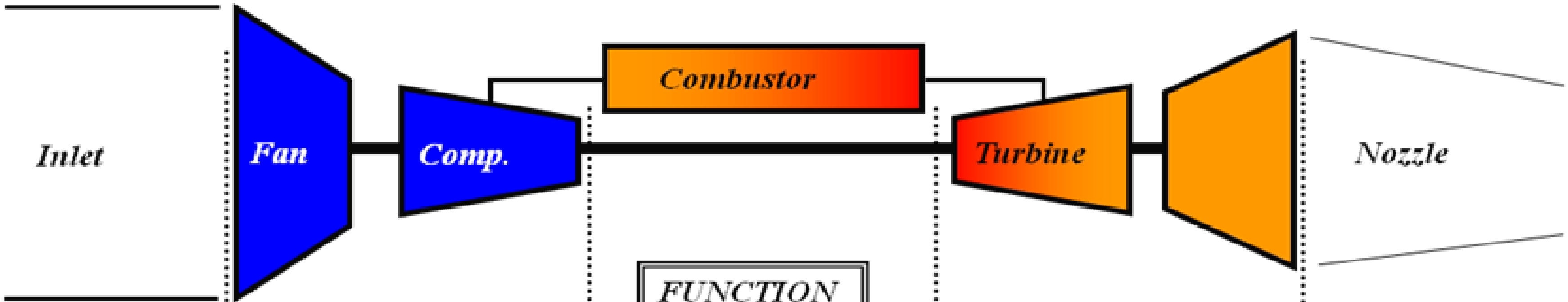
- Sensors should go where they are needed, even in the harshest of environments
- Wires add weight, complexity, and are one of the main causes of sensor failure
- Future implementation of sensor technology can be significantly enhanced by:
  - Improving the ease of integration.
  - Decreasing the burden 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
- Objective: High temperature Smart Sensor Systems with wireless telemetry and distributed electronics operable over the broad operating temperature range and conditions of the engine

Implementation of Distributed Engine Controls with Smart Wireless Sensors



Sensors and their functions in Turbine Engine Controls and PHM

Dual Purposes/Wide Application Environment Range



FUNCTION

Inlet	Fan / Comp.	Combustor	Turbine	Nozzle
•FOD Detection	•Stall/Surge Avoidance •Tip Clearance Control •Life Management •HCF Detection & Cntl.	•Life Management	•Life Management •Tip Clearance Control	

SENSORS REQUIRED

Inlet	Fan / Comp.	Combustor	Turbine	Nozzle
•Inlet Debris Monitoring System (IDMS)	•Disk Crack Sensor •Tip Clearance •Adv. Press. Sensor •Vibration	•Vibration •T41 Sensor •Erosion Detection •Corrosion Detection	•Disk Crack Sensor •Tip Clearance •Vibration •T41 Sensor •TBC Spalling Detection •Corrosion Detection	•Exhaust Debris Monitoring System (EDMS) •Acoustic Sensor •Emissions Sensor

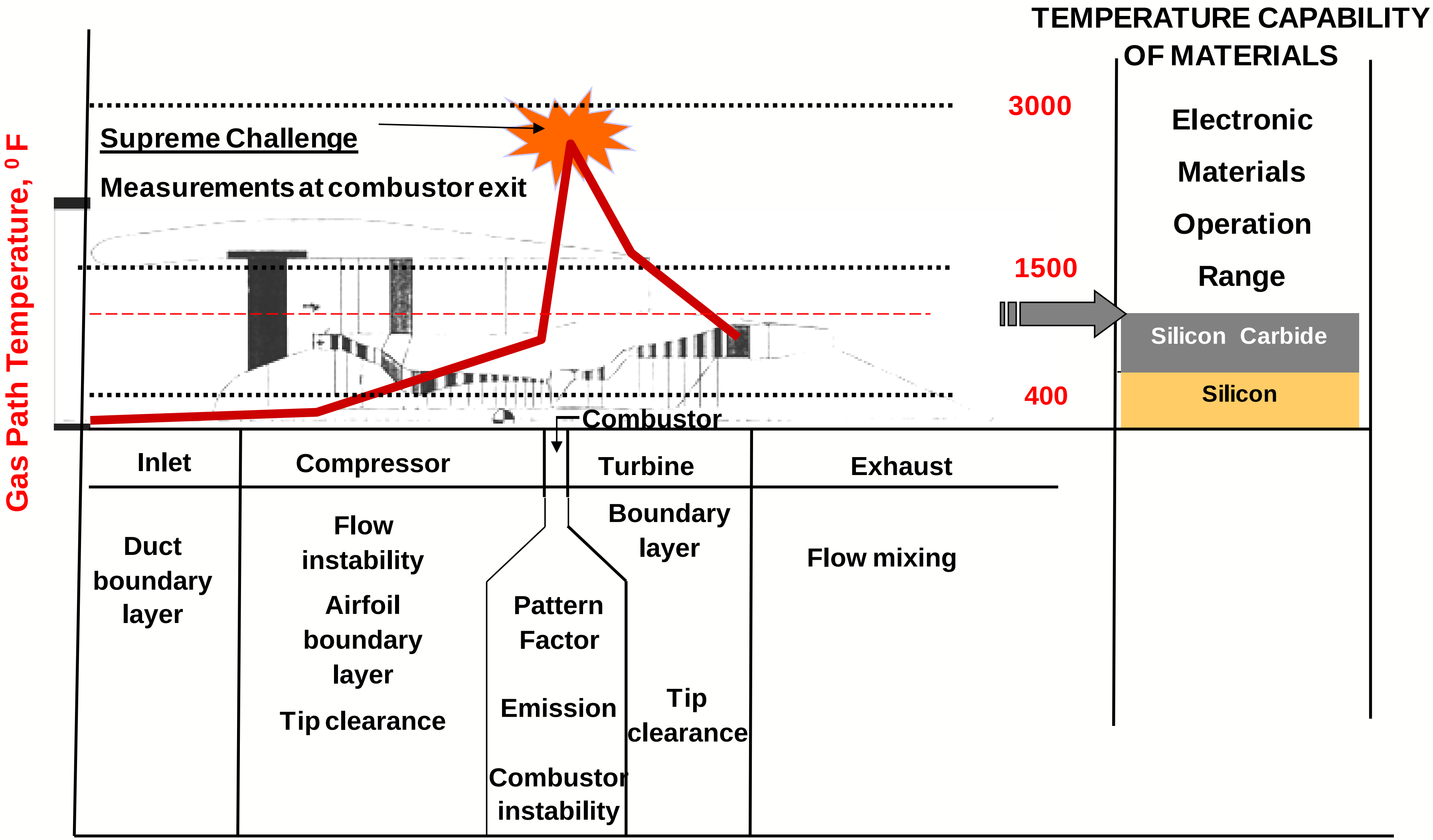
Black: Real Time Diagnostics Red: Advanced On-Wing Inspection Technique

Green: Both Real Time Diagnostic and Advanced On-Wing Inspection

Blue: New Real Time Performance Measurement Required

CORRELATION OF POSITION WITHIN THE ENGINE TO TEMPERATURE

LIMITATION ON ELECTRONIC MATERIALS



Technical Requirements for Smart Sensors in Distributed Controls and Propulsion Health Management

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**

Related Drivers:

Physical Drivers for Smart Sensors/Distributed Control System Designs

- Thermal Environment
- Externals Packaging
- Rapid Reconfiguration / Upgradability
- Generic Physical/Functional Interface
- Environmental Requirements
- Certification Impact
- Integration Testing
- Need to integrate electronics onto or within existing hardware

Environmental Requirements

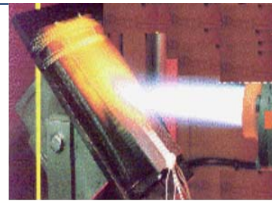
- Design for existing ambient temperatures and vibration environments
- Don’t drive cost/complexity into the DCM to withstand unrealistic margins
- Design electronics to withstand existing hardware thermal conditions
- Recognize limitations of typical industry materials

EXAMPLE HIGH TEMPERATURE SMART

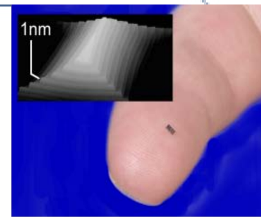
SYSTEM DEVELOPMENT

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**

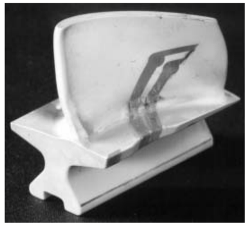


1998 R&D 100 Award



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

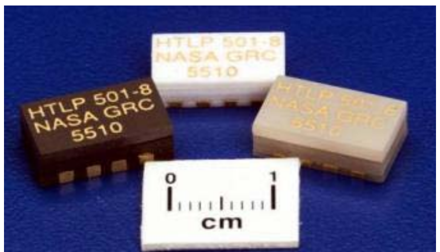
1991 R&D 100 Award

- **ENABLE EXPANDED MISSION PARAMETERS/IN-SITU MEASUREMENTS**

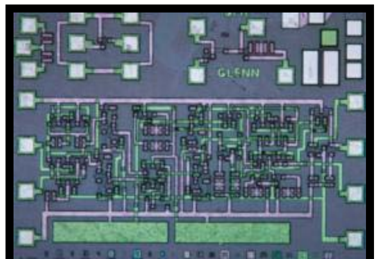
- **LONG LIVED HIGH TEMPERATURE ELECTRONICS AT 500˚C: TOP DISCOVERY STORY IN 2007**

Range of Physical and Chemical Sensors for Harsh Environments

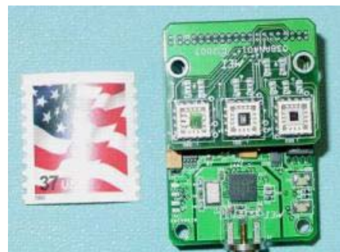
Harsh Environment Packaging (10,000 hours at 500˚C)



High Temperature Signal Processing and Wireless



Long Term: High Temperature "Lick and Stick" Systems

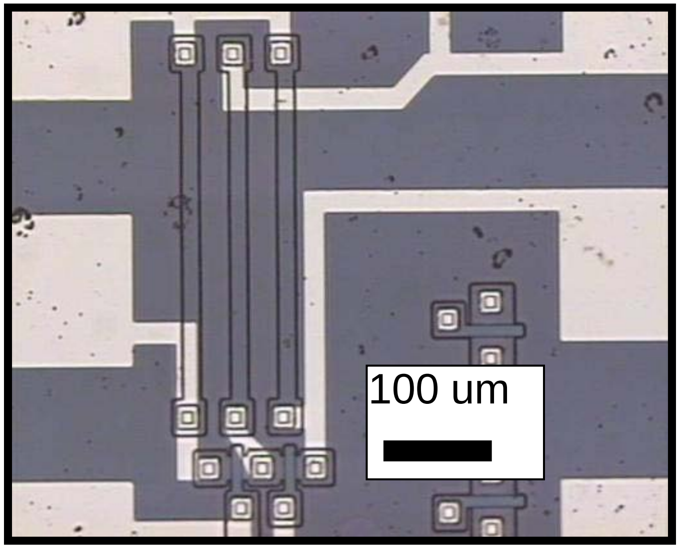


NASA Glenn Silicon Carbide Differential Amplifier

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

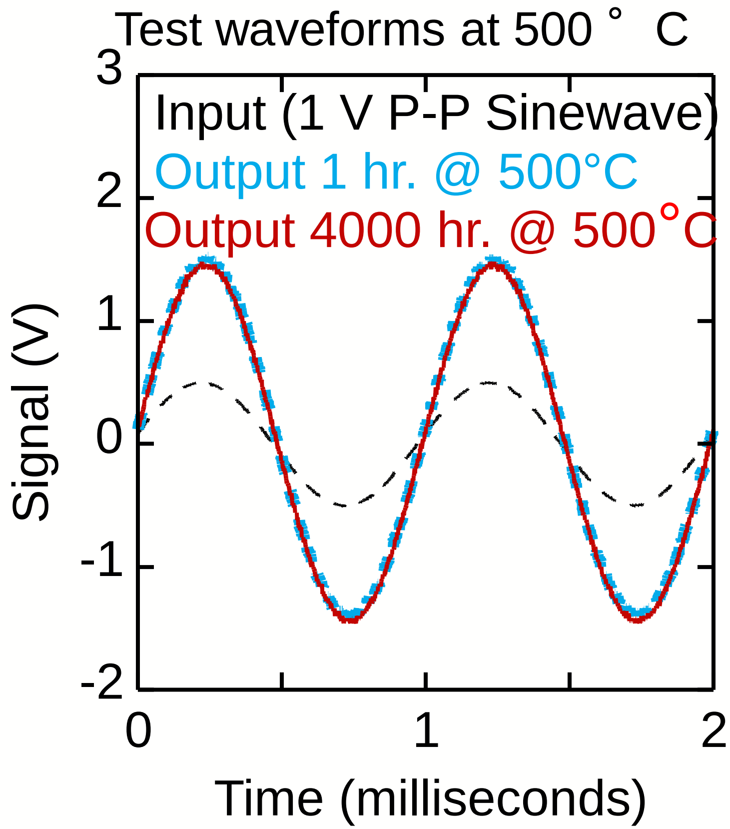
Demonstrates CRITICAL ability to <u>interconnect transistors</u> and other components (resistors) in a small area on a single SiC chip to form useful integrated circuits that are durable at 500°C.

Optical micrograph of demonstration amplifier circuit before packaging



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

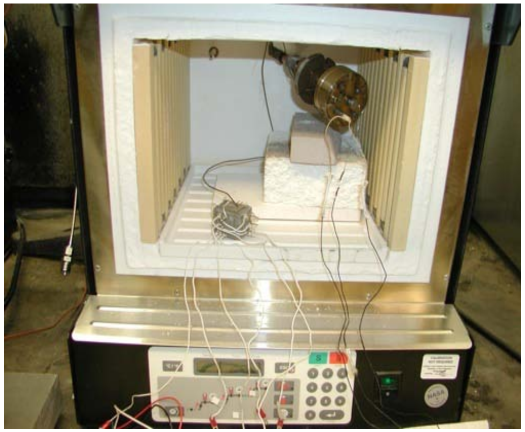
Single-metal level interconnect.



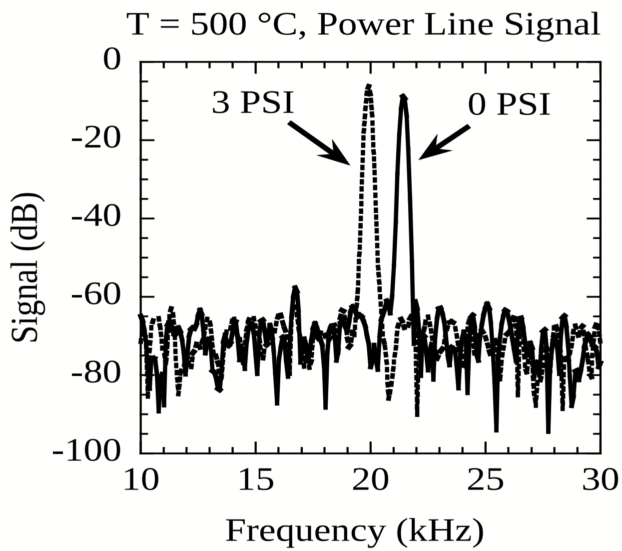
Less than 5% change in operating characteristics during 4000 hours of 500°C operation.

High Temperature Wireless
Parallel RF sensor data signal transmission at 500 °C

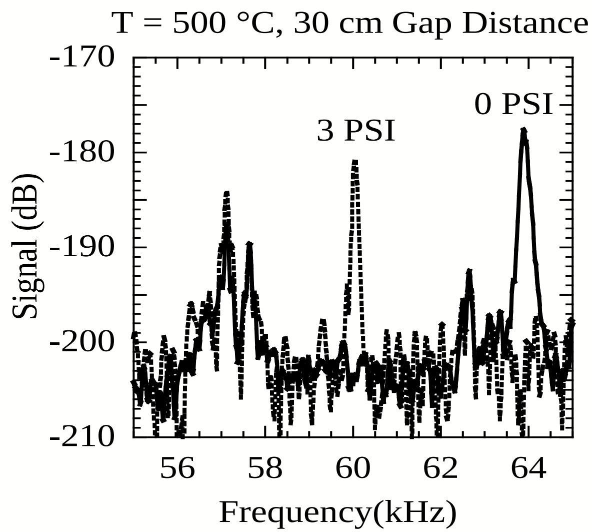
- **Based On NASA SiC Components Previously Demonstrated For Long-life Operation**
- **Modulation Of Oscillator Output Frequency As A Function Of Applied Pressure At 500°C**
- **Sensor Data Transmission Across A Power Wire Of A Complete System At 500°C Has Been Demonstrated For 1 Hour**
- **Demonstration 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

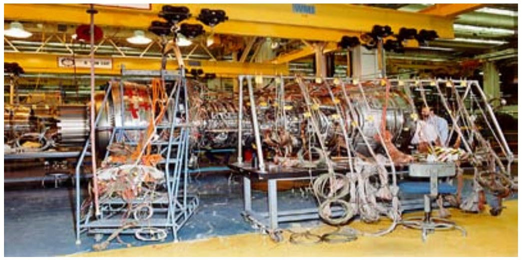
OBJECTIVE :
MOVE TOWARD HIGHER DEGREES OF COMPLEXITY ALLOWING HARSH ENVIRONMENT SMART SENSOR SYSTEMS

NASA AVIATION SAFETY PROGRAM: FULL SYSTEM APPROACH TOWARD HARSHENVIRONMENT SMART SENSOR SYSTEMS

Milestone: Demonstrate High Temperature Sensing, Wireless Communication, and Power Scavenging for Propulsion Health Management FY2013

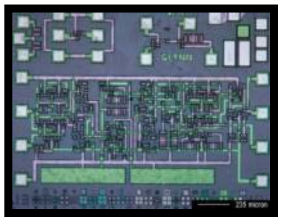
Metric: Demonstrate integrated self powered wireless sensor system at 500 ˚C with data transmission with operational life of at least 1 hr

Significant wiring exists with present sensor systems

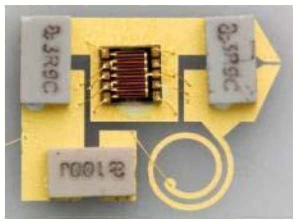


Allow Sensor Implementation by Eliminating Wires

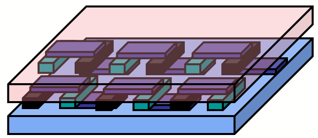
High Temperature Sensor Systems



World Record High Temperature Electronics Device Operation



High Temperature RF Components



Energy Harvesting Thin Film Thermoelectrics

SUMMARY

- SMART SENSOR SYSTEMS HAVE A RANGE OF APPLICATIONS
  - INTEGRATED SYSTEM OF PROCESSING, COMMUNICATIONS, SENSORS, AND POWER
  - SMART TECHNOLOGY IS BECOMING INCREASING DOMINANT IN COMMERICAL APPLICATIONS
  - APPLICATIONS FOR PROPULSION SYSTEMS
- DISTRIBUTED ENGINE CONTROL APPLICATION INCLUDES:
  - PERFORMANCE, TIME, COSTS
  - OPTIMIZED SYSTEMS ENGINEERING APPROACHES, AND IS MORE POWERFUL, FLEXIBLE, AND SCALEABLE
- PROPULSION HEALTH MANAGEMENT MOTIVATION INCLUDES:
  - RELIABILITY OF SENSOR SYSTEMS, INCREASED SENSOR COVERAGE, IMPROVED ABILITY TO UNDERSTAND VEHICLE HEALTH (LOCAL PROCESSING)
- BOTH APPLICATION AREAS SHARE COMMON TECHNOLOGY NEEDS
  - SECURITY
  - RELIABILITY
  - OPERATION IN ENGINE ENVIRONMENTS
- EXAMPLE OF HIGH TEMPERATURE DEVELOPMENT: SiC BASED INTEGRATED SYSTEM
- IMPLEMENTATION WILL LIKELY BE BASED FIRST ON MORE MATURE TECHNOLOGY MORE BENIGN ENVIRONMENTS, FOLLOWED BY SELECTED IMPLEMENTATION IN HARSH ENVIRONMENTS FOR MORE CRITICAL APPLICATIONS
- THIS IS A CORE TECHNOLOGY OF WIDE AND SIGNIFICANT IMPACT THAT NEEDS FURTHER DEVELOPMENT