Novel Temperature Sensors and Wireless Telemetry for Active Condition Monitoring of Advanced Gas Turbines

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DOE Award: DE-FE-0026348

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Ingenuity for life

Acknowledgements

This material is based upon work supported by the Department of Energy Award Number DE- DE-FE-0026348. Siemens would sincerely thank the support of Robie Lewis, DOE FPM for this project and also Sajib Roy and Dr. Alan Mantooth for dedicated efforts during the pandemic.

Deployment of Advanced Sensing Systems Enables Operational Based Assessment

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Condition Monitoring

Design Validation

System Testing, Simulation & Performance

Real time data, Field feedback & prognosis

In-situ Monitoring

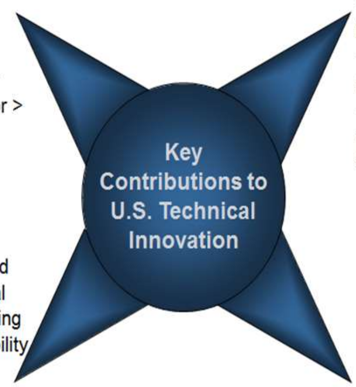
Remaining Life Calculation for Forecasting

- Instrumented components with relevant sensors
- Telemetry for data acquisition and transmission to signal processor
- System architecture for analyzing sensor data, perform statistical prediction analyses

- Harsh environment instrumentation provides critical information regarding component condition

Sensor Development
- Development of 1400C capable ceramic thermocouples
- Demonstration of sensor functionality operational for > 4000h operation

Wireless Telemetry
- Improving prototype 550°C transmitter
- Developing improved power system for 550°C
- Feasibility study for a 550°C wireless telemetry packaging at 16000 Gs



Operation based assessment model
- Artificial intelligence based model development for real time life assessment enabling improved operational flexibility
- Unified model integrating sensor data to intelligently predict consumed part life and risk reduction

Component scale-up, Testing & Validation
- Improve scaled-up deposition processes
- Develop heated spin test using active sensors and high temperature circuitry
- Demonstrate functionality and reduce risk for full-scale engine testing

Anatomy of a Telemetry System

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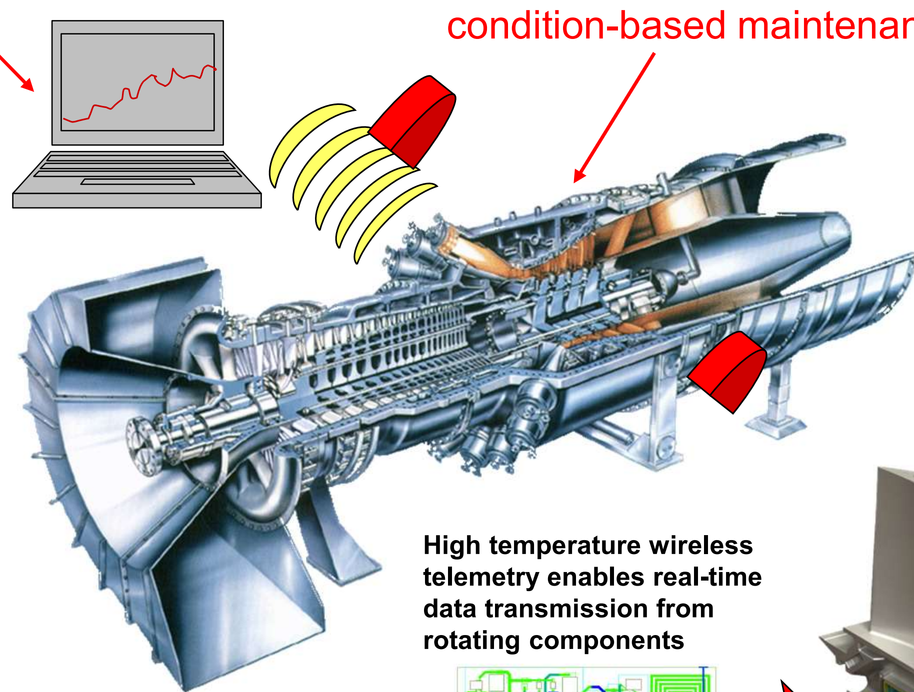
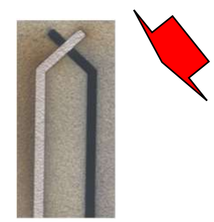
Data acquisition enables real-time input to life models

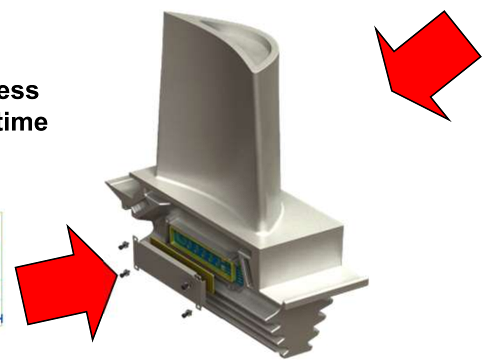
Real-time monitoring of component condition enables condition-based maintenance



Thermal spray processes enable cost-effective, integrated sensors



High temperature wireless telemetry enables real-time data transmission from rotating components



Current Blade Measurement Methodology

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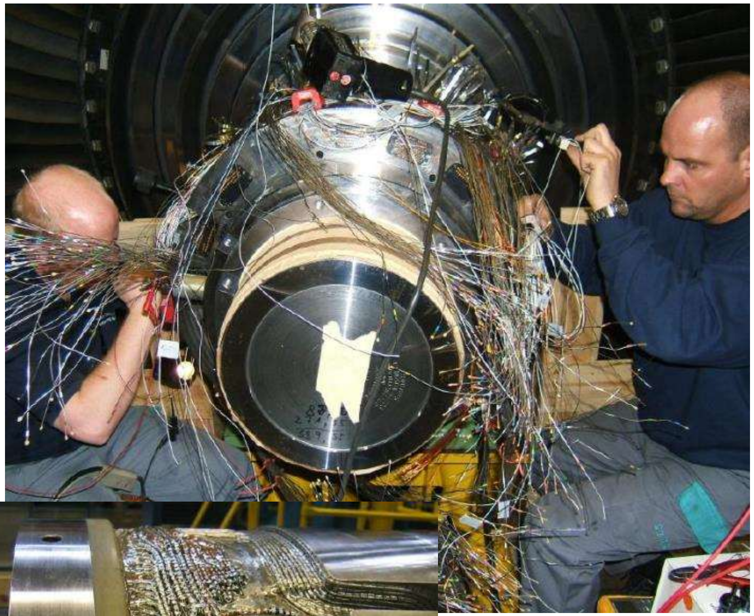
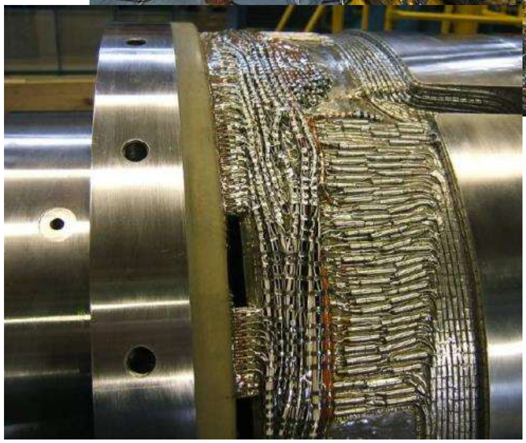
Current method of blade instrumentation

- Wires from blade rings down entire length of rotor
- Time consuming – 3-6 months per validation
- Expensive - $2-3 Million per validation
- Damages rotor; costly replacement





Paradigm Shift for Engine Monitoring

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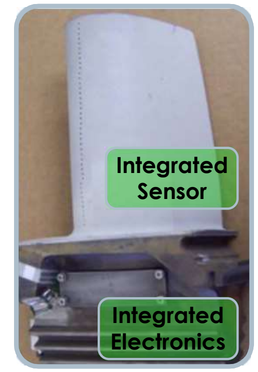
Increasing Engine Operating Temperatures
(Increased Efficiency, Reduced Emissions)

Ultra high-temperature wireless telemetry and advanced sensors

- Direct measurement of engine and component operating conditions
- Engine performance is directly determined based on measurements
- Component life predictions are calculated based on measured data
- Direct monitoring via minimally invasive high temperature wireless telemetry
- Key enabler for long life performance and condition monitoring



Current indirect gas path monitoring

- Indirect monitoring from gas path temperature sensors
- Engine performance indirectly calculated from available models
- Component life predictions are hours-based
- Monitoring of component integrity is practically non-existent
- Instrumentation, when used, is destructively invasive

Increasing Engine Reliability and Availability

Wireless Telemetry System Team

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HT Capable Thermally Sprayed Sensors

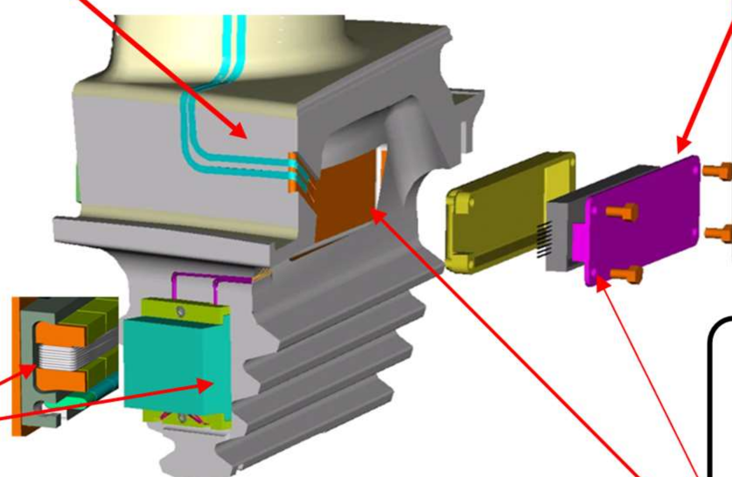
Siemens
- -Specifications
- -Ultra high temperature testing
- -Sensor optimization

High Temperature Induced Power System

Siemens
- -Attachment design

Wolfspeed
- -Wireless Telemetry System

Aerodyn
- -High Temperature Spin Tests



HT Wireless Telemetry Transmitter Circuit Board

Siemens
- -Specification
- -Attachment Design

Wolfspeed/Uni. Ark
- -Telemetry Circuit Board
- -Advanced SiC IC Devices

Engine Component Modification and Analysis

Siemens
- - OBA, Design and Analysis

Machining Vendors
- - Component Fab

Progressive Development Approach

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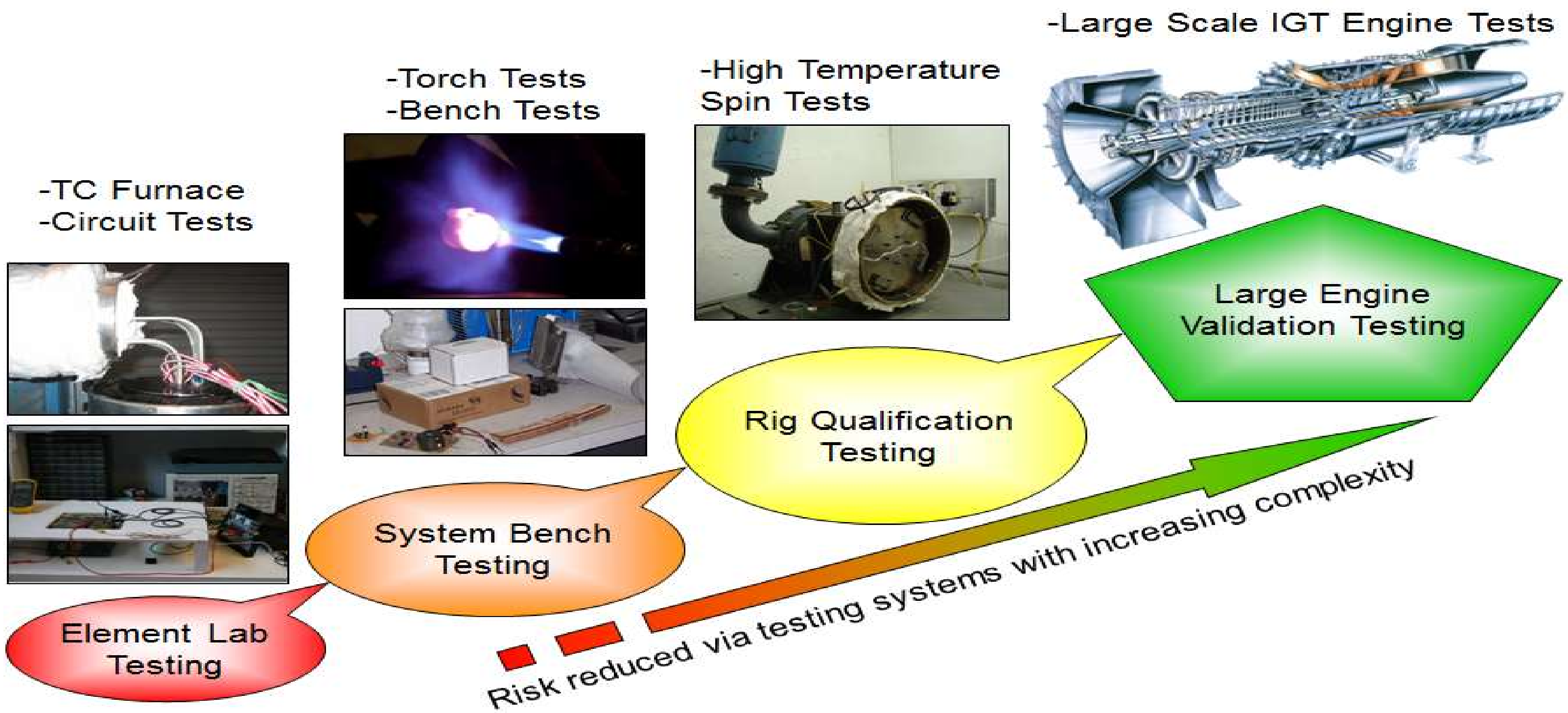

Rigorous testing and validation based on a thorough understanding of failure modes and improving final system performance

Thick Film Sensor Deposition via Thermal Spray

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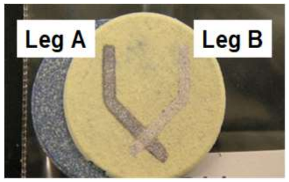
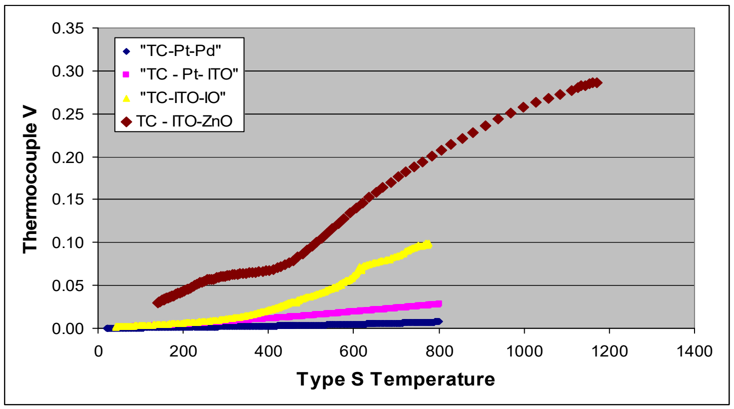
Thermal spray enables integral sensors to be deposited on coated and uncoated components with complex shape.
Sensors may be incorporated with minimal component and performance modifications.

Specimen configuration tested.





Thermocouple deposited on a performance and calibration test bar.

Sensors on buttons for TBC spallation testing

Sensors at 3 locations on blade for conformality and high temperature (~1400C testing)

Sensors on bars for repeatability/reproducibility testing (~1100C)

Ceramic thermocouple offers high signal to noise ratio and no impact on TBCs

Isothermal Testing of ITO-SmCaCoO TC

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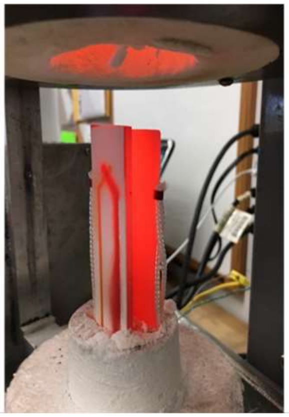
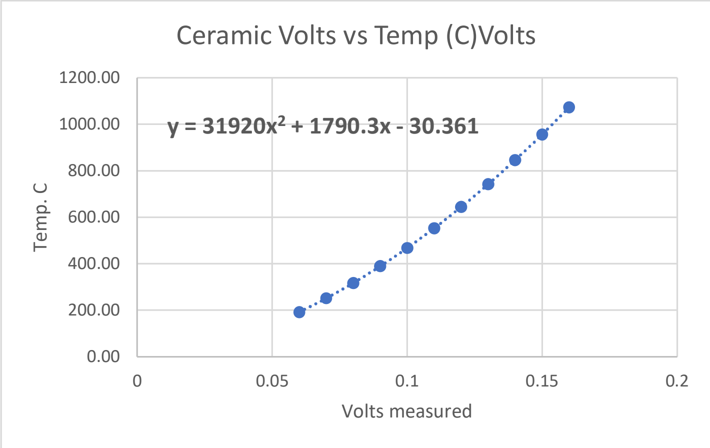
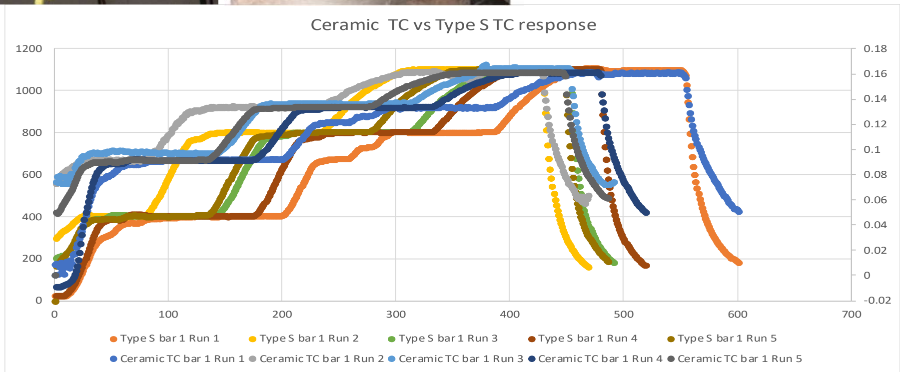


Isothermal heating with 2 TCs evaluation for reproducibility.

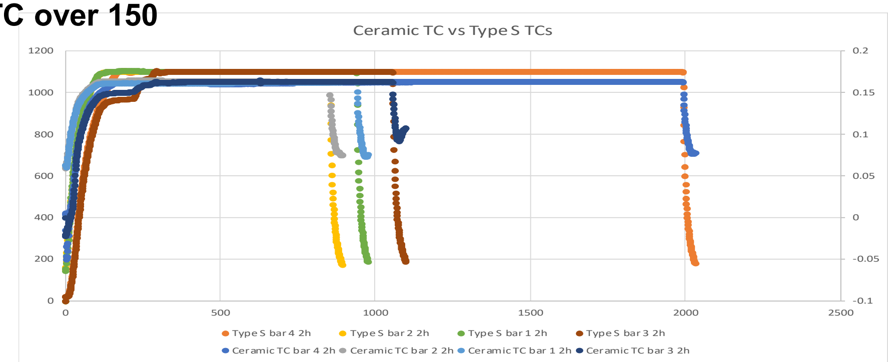
Calibration curve





New ceramic TCs show consistent emf output and correlation to Type S TC over 5 thermal cycles

4 TC bars show consistent emf output and correlation to Type S TC over 150 hours



Very consistent response from ITO-SmCaCoO TC for 10 repeat bars over 1.5 years

TBC/TC Testing of ITO-SmCaCoO TC

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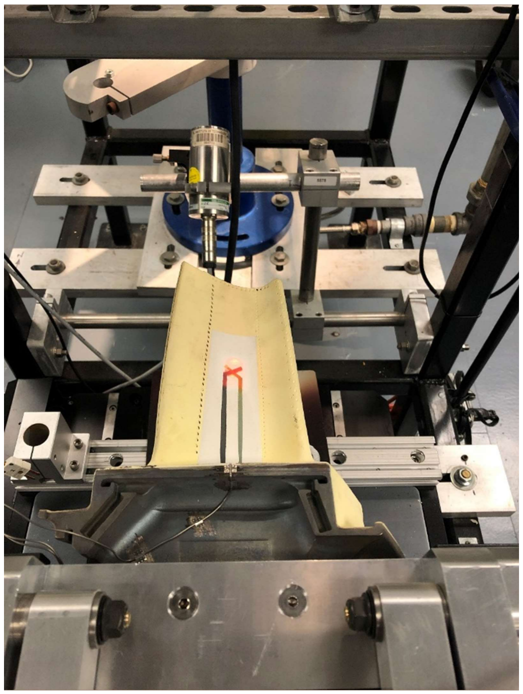
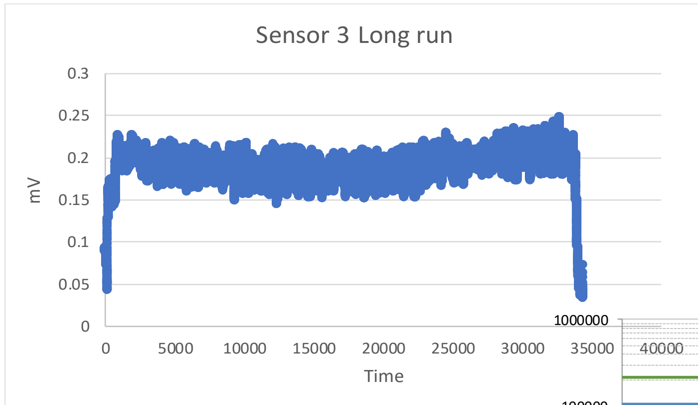
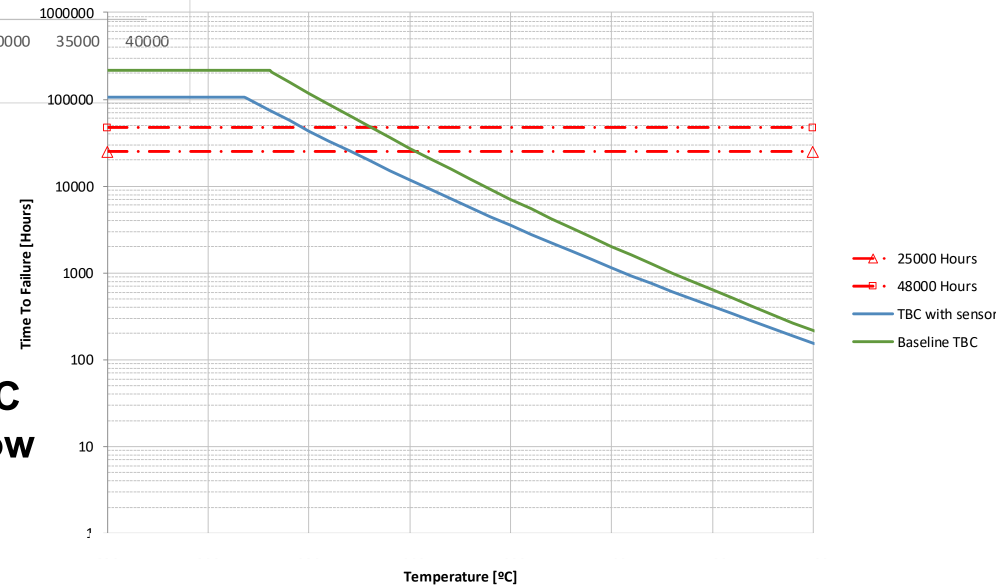


Laser rig testing done on bars and turbine blade



Testing at 1500C (10 hour testing)

TC testing upto 1500C shows stable TC response with 200 mV output.



Sensors on TBC surface pose low risk to TBC Spallation life

Top Level Design Principles

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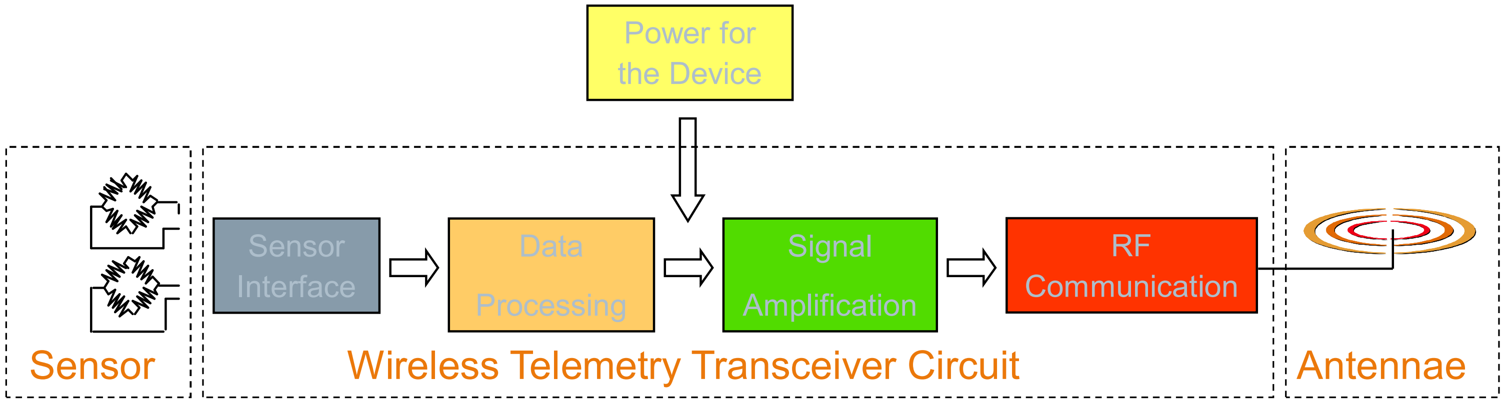

- **Hardwiring rotating parts through rotor is expensive and time consuming.**
- **Wireless telemetry has been used for many years, but not uncooled at high ambient temperatures.**
- **Antennae, circuit board, and electrical run materials, die attach and wire bond processes all must be optimized for functionality and stability at elevated temperatures and high g-loads.**
- **The active devices used on the circuit board must be capable of operation at high temperatures (devices such as SiC, AIN, etc. are required).**
- **A source of power must be provided to the circuit at high temperature.**

High Temperature Electronics System Block Diagram

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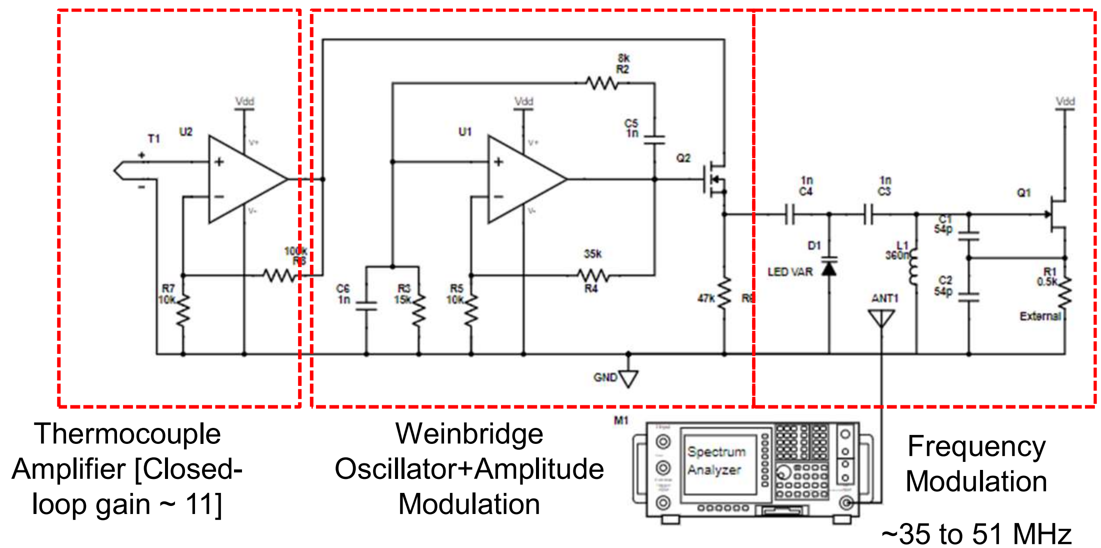
- System Level Block Diagram include Bridge Rectifier, Voltage Rectifier, FDM, and FM transmitter. Operates at 20Mhz Power input and Communicates data back at with FM 70Mhz.



System Level Schematics of LTCC board

Circuit and Components tested to 550 °C

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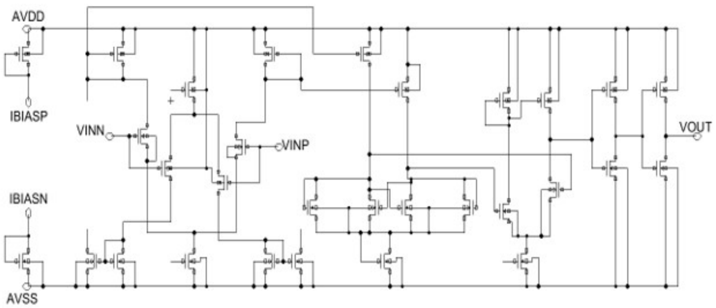
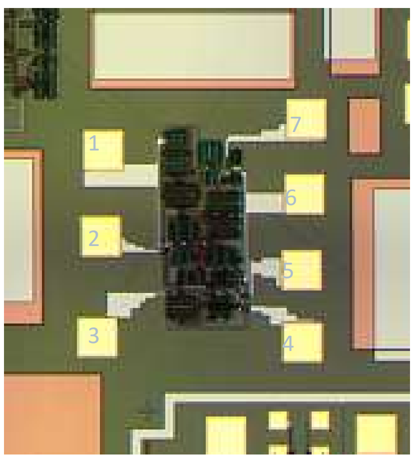
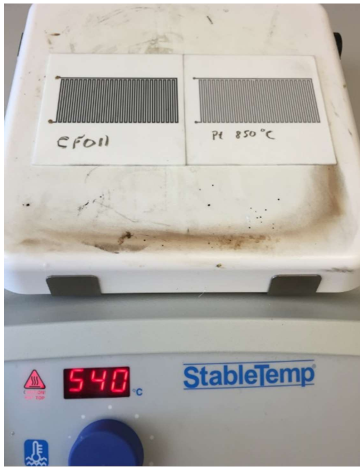
SiC IC Testing @ 550 °C (OpAMP Comparator)

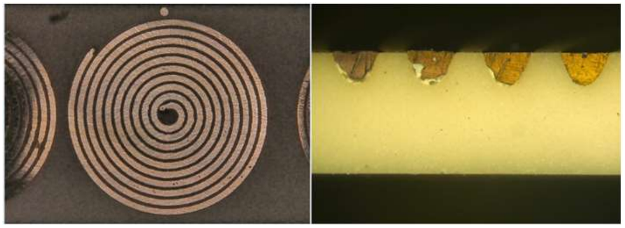


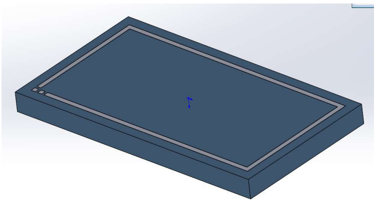


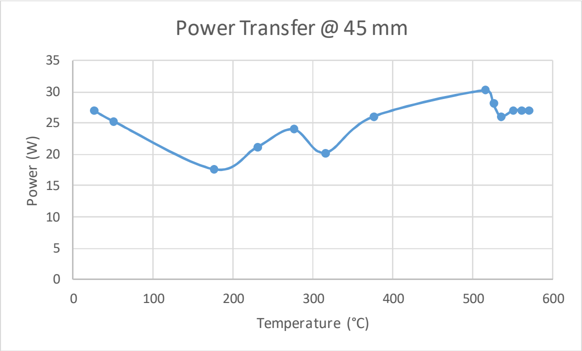


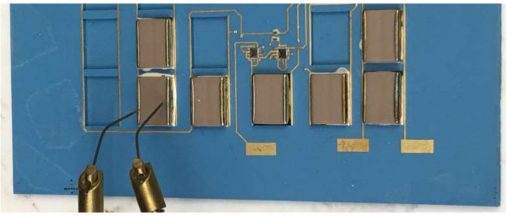
Various Resistor Pastes increase resistance from 20 – 200% from room temperature to 540 °C

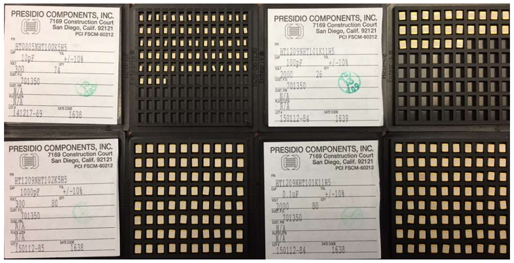
Power System Testing @ 550 °C





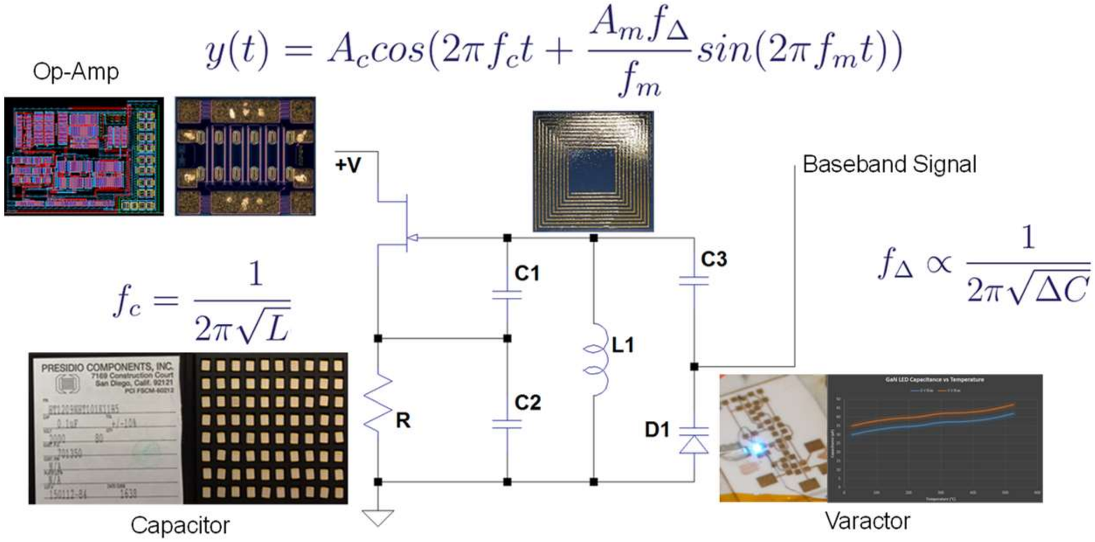






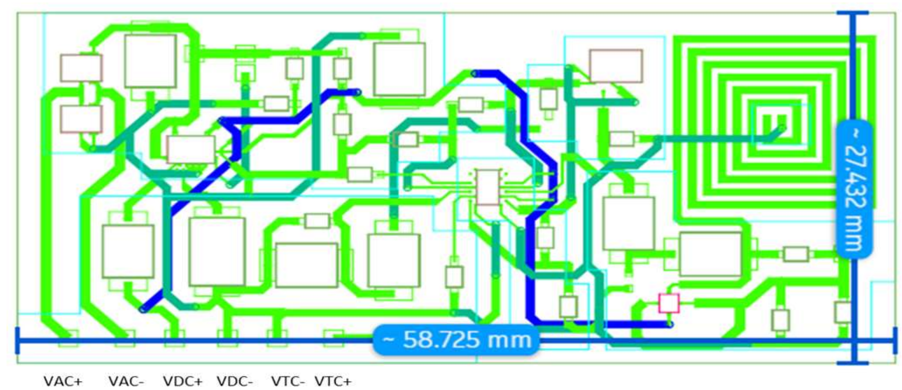
Capacitors functional but decline in capacitance by ~ 20% at 550 °C

High Temperature Electronics – Raytheon Chips



- **Components with CMOS from Raytheon UK provided much better performance with a DC input voltage**
- **Raytheon shut their fab down, Team had to start from scratch making circuits on two separate fab lines**

UARK's LTCC carrier board for high temperature SiC electronics



- Raytheon UK design utilized for R1 Vane.
- Device can utilize VAC power input from inductor coil for telemetry.
- Supports one TC input.
- Can be powered from 15 VDC for non-telemetry operation.
- Board made from LTCC.
- Die-Pad metallization consists of stacked titanium-aluminum.

RUK Modules: Individual Device/Circuit Blocks Temperature testing and Spin Testing

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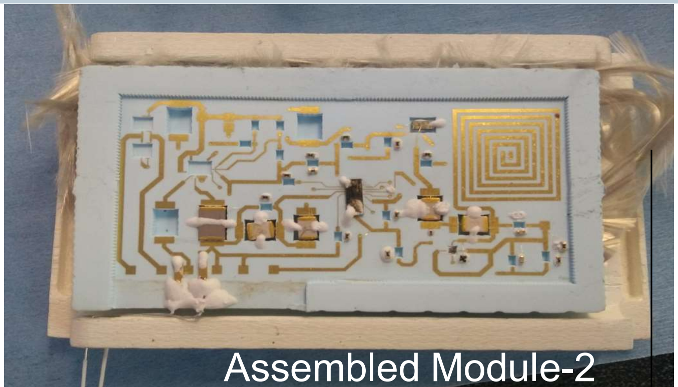
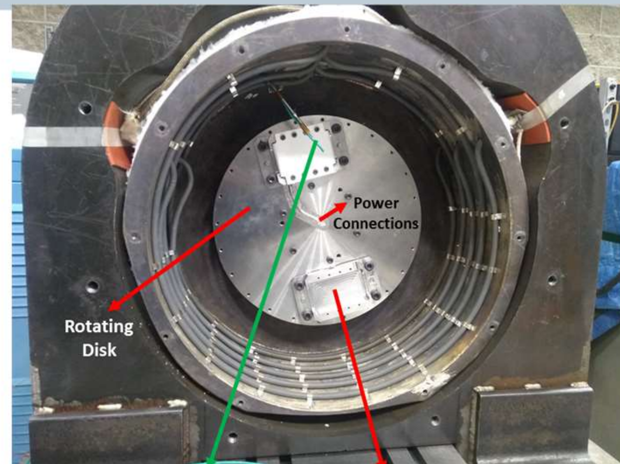


Nextel fiber glass underneath the module to eliminate any movement of the module inside the CMC housing

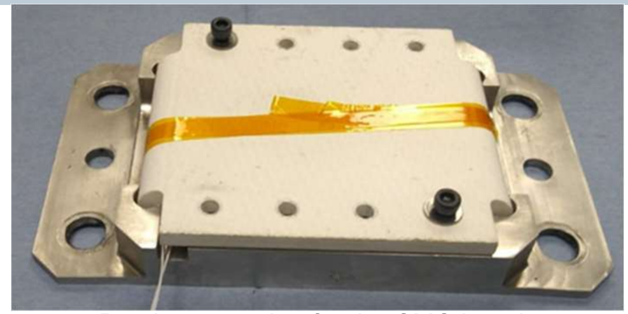
- All passives included two wirebonds for each nodes/terminals to account for wirebond tear
- Spun at 10,920 RPM or 16,000 G-load
- System operated and provided signal transmission , observed on a real-time spectrum analyzer
- Power delivered to the circuits through wires
- No cracks observed on the LTCC module



Bare wire to serve as antenna for signal reception

Counter-weight (made of Inconel material, other option could be stainless steel)

Active Components	Tested at Max. Temperature	Method
SiC Opamp	350°C	PCB (bench-top)
SiC NFET	350°C	Thermal Chuck (probe-station)
GaN Diode	350°C	Thermal Chuck (probe-station)
GaN HEMT	500°C	Thermal Chuck (probe-station)



Bracket mounting for the CMC housing with the module inside

- The RUK module uses wired supply to power the active circuits via slip rings
- The RUK active devices/circuits used in the module have been tested for maximum temperature of 350°C due to epoxy temperature limitation
- The GaN HEMT used for Colpitts oscillator/RF tranmisttor was tested at 500°C

Third Spin Test: At high-temperature and high rotational speed

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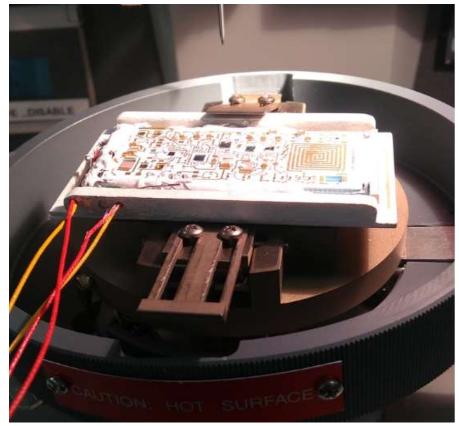
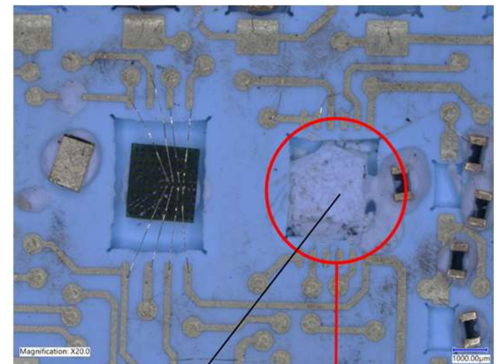
- Wireless supply tested:
  - Air gap between the power transmission coil frame and module ≈ 17 mm
  - Output power measure from the on-module regulator output node, VDD and VSS, equaled 7.14 V at 72F with the PA setting at 33 dBm with applied power signal of 11.9 MHz (5 Vpk-to-pk) from function generator
- Frequency modulation functionality failed the moment speed crossed 5000 rpm. Wireless power transfer also failed to work
- At 426.7°C temperature, module functioned at speed 5000 rpm
- At 5500 rpm the module failed to operate due to detachment of OpAmp die from the module

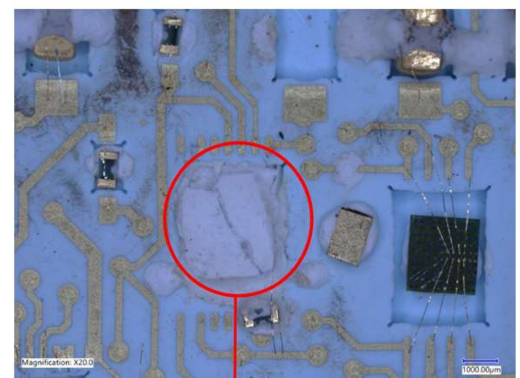


Fraunhofer module used for third spin testing (k-type thermocouple cable used)

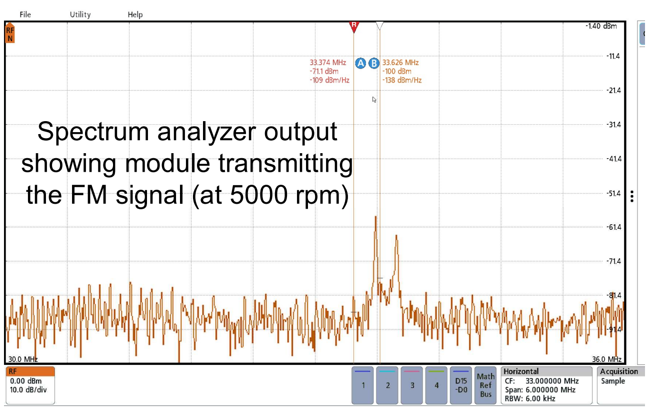


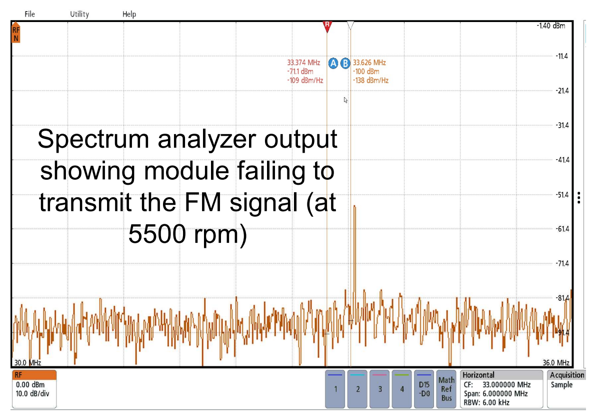
The white substance is the ceramic epoxy

Thermocouple opamp pulled-off from the module cavity



Wien-Bridge oscillator opamp pulled-off from the module cavity



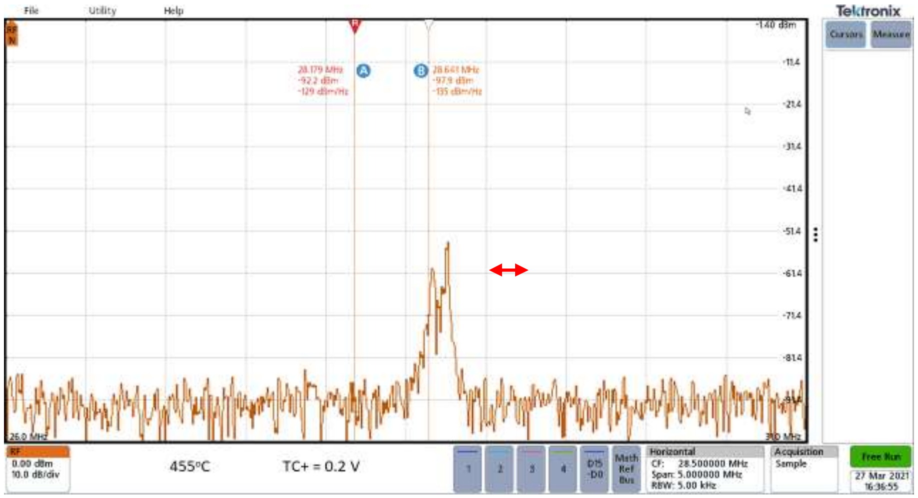


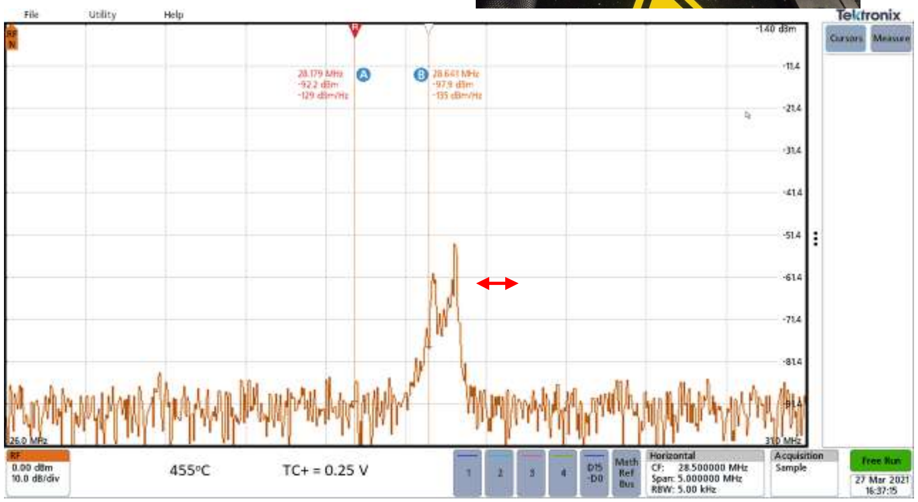
Fourth (Final) Spin Test

To be carried between the date of **May 26-June 4, 2021**. Finalized date will be decided after discussion with Aerodyn

Will be performed on the new assembled Fraunhofer module (module image on the right)

- This module has been tested at 455°C on a probe-station. Results are shown for 0.2 V and 0.25 V applied input to the module at 455°C
  - As TC+ increases from 0.2 V to 0.25 V, the gap between the frequency peaks increases, indicating the change in the frequency modulated signal. The transmission center frequency also shifts due to change in capacitor values of the LC-tank oscillator circuit on the module





Fourth (Final) Spin Test: Measures taken for combined high-temperature and high rotational speed test

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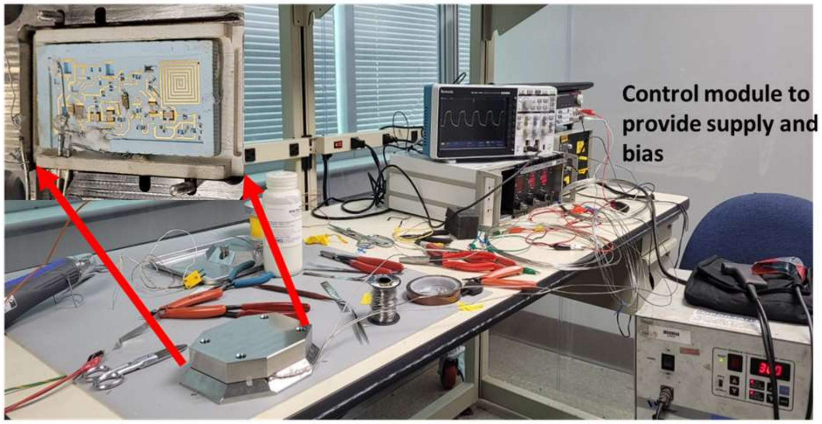
- Additional ceramic epoxy added on the die during assembly to allow further strength on the die attachment to the module's LTCC material: to avoid die detachment as seen on the third spin test
- The regulator circuit die on the module has multiple bond wires added on the supply and ground pads to avoid circuit operation failure due to bond wire tear
- The Fraunhofer module has separate input pads(TC+ and TC-) for the thermocouple opamp to allow compensating for the opamp offset
- Ramp in rotational speed (above 5000 rpm) will be carried out once spin-rig temperature reaches 500°C

Engine test preparations:

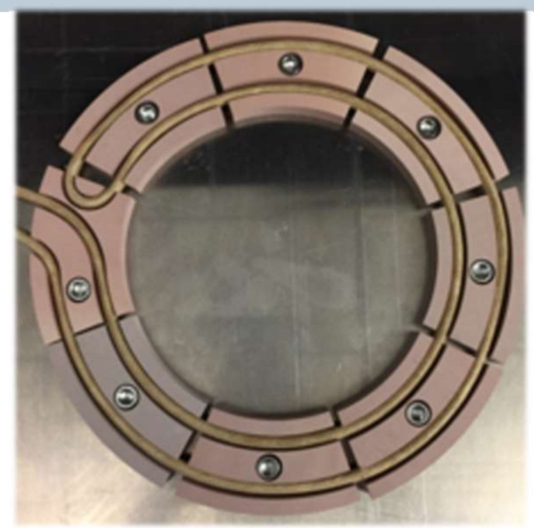
- RUK module-3 assembled on the Inconel bracket at UA CSRC facility. Stainless-steel jacketed cables with nickel wire have been used for supply and signal reception
- The module-3 has been temperature cycled three times (tested at temperature above 425°C) resulting in the module-3 thermocouple opamp offset shifted to 2.2 V
- To check the variation on the offset over temperature , the module-3 was tested on a hot-plate up to 505°C. Applied supply voltage was 9 V

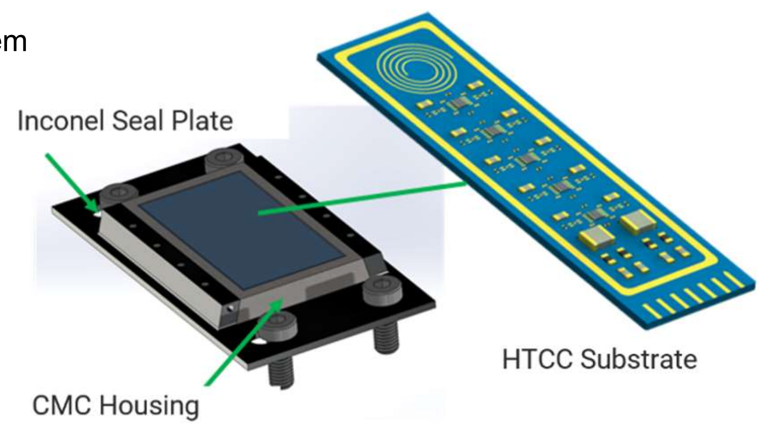


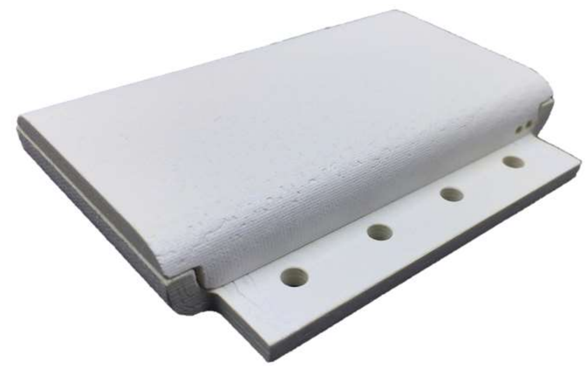
Enablers of the Engine Test

The Siemens-Led Team is in preparation to demonstrate the broad suite of sophisticated technologies which allow for on-blade, real-time temperature measurements.

- Novel, rugged spray-on blade thermocouples with superior lifetimes
- 500 ºC on-blade electronics to take in thermocouple data
- 500 ºC on-blade electronics to RF wirelessly transmit the thermocouple data
- 500 ºC on-blade electronics to receive wireless power
- Magnetically transparent on-blade Ceramic Matrix Composite electronics holder
- 600 ºC Wireless Power Transfer of up to 5 watts to power the rotating electronics board
- Auto-matching wireless transfer driver system







Kulkarni/ Siemens

Case Study of Thermal Barrier Coating Life for Row 1 Vane of Gas turbine

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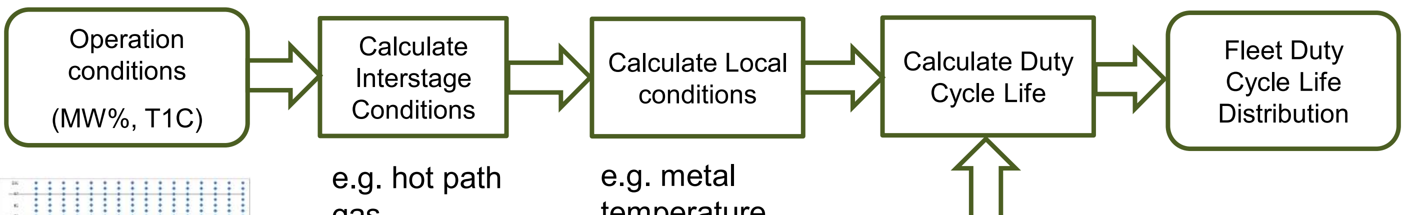
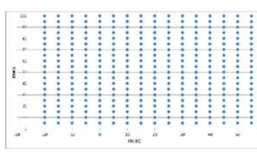
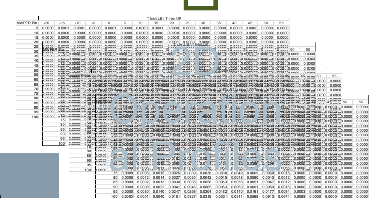
Challenging market situation requires a competitive design life. Current lifing approach is based on assumed single design points (Baseload hot and iso conditions for the full lifetime), not based on fleet operational data.

Each existing engine's operation conditions and operation hours (OH) in service have been analyzed and summarized into an operational profile by two parameters: normalized power load (MW%) and compressor inlet temperature (T1C)







	Service calculated by design (Hours)	Duty Cycle Method (Hours)	Difference (%)
Projected Life (Hours)	55314	56973	+3.00%
	59726	57045	-4.49%

Surrogate modeling enabled design life calculations are within 5% of projected service life

Awaiting sensor data from engine to validate model assumptions and TBC life

Design Requirements: Connection Diagram

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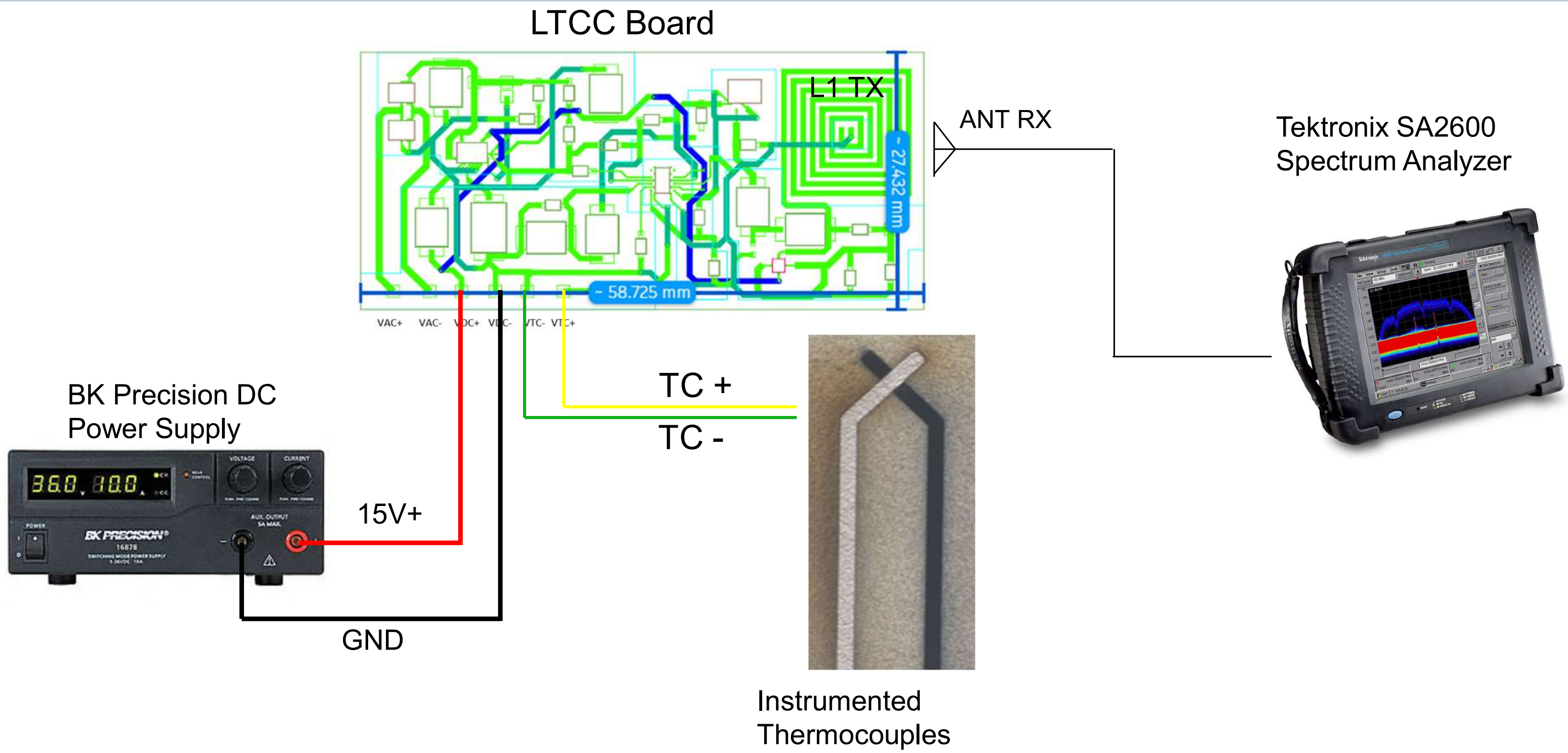

Connection Layout of Various Components of Row 1 Telemetry System

Proposal for Instrumentation of Test engine
Instrumentation Scope

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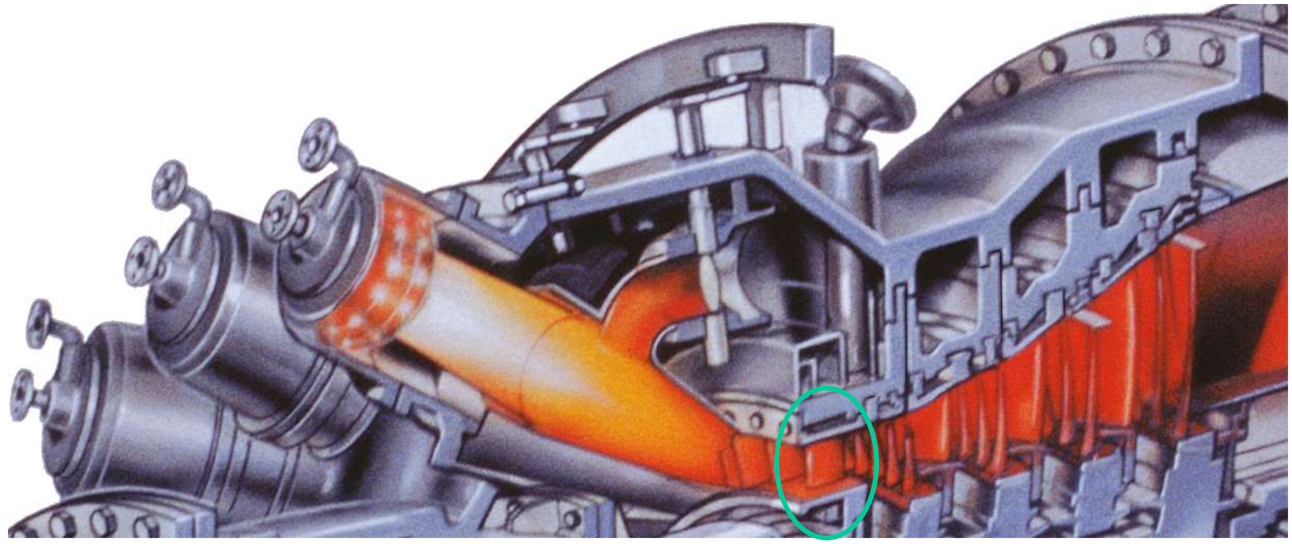
Spray Coated TCs and High Temperature Telemetry Module

- Spray Coated TCs and Reference TCs routed to Row 1 Vane
- Device module bolted to Bulkhead seal with M10 Bolts, reinforced by Wire-Tie
- Temperature range for Electronics is up to 600C
- Pressure Range for Electronics is up to 300 PSI
- Spray Coated TCs operate up to 1400C for up to 200hours and 1100C indefinitely
- Target duration of testing is 100 hours under load
- Row 1 Vane will be seated in position #9 and routed through port #4



Team cleared the design review process for technology demonstration on row 1 vane

- **Row 1 vane with stationary wireless telemetry – made from chips from Raytheon, UK**
- **Multiple iterations to address wireless board functionality for successful transmission of data**
- **Instrumented R1 vane installed along with bolting of wireless telemetry to demonstrate wireless transmission at > 500C during Outage from April 19th to April 27th .**

Summary

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- Siemens and its partners are developing Smart Component systems to provide real-time information for stationary and rotating components to enable a transition to condition-based maintenance.
- Ceramic thermocouple comprising n-type Indium tin oxide and p-type Samarium-Calcium-Cobalt-Oxide) has demonstrated excellent sensor functionality and repeatability. Long term and high temperature testing underway.
- Wireless team had to re-invent SiC IC designs with in two different IC technologies, SiC CMOS at Fraunhofer IISB, and SiC BJTs at KTH Stockholm due to shutdown of Raytheon UK chip manufacturing.
- The instrumented row 1 vane with RUK chip wireless telemetry package installed at Duke site on April 10th 2021. Final spin rig testing of Fraunhofer chip telemetry package planned for end of May.
- The telemetry board substrate has been migrated to a 'high temperature co-fired ceramic' (HTCC) board, increasing the strength of the substrate by 2x over the former LTCC based board
- Initial insights into duty cycle life assessment utilizing operational profiles for turbine components, will be validated with data from the engine test.