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Ingenuity for life

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

DOE Award: DE-FE-0026348

Acknowledgements: DOE NETL
Robie Lewis – DOE/NETL Project Manager

Deployment of Advanced Sensing Systems Enables Operational Based Assessment

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Condition Monitoring

Design Validation

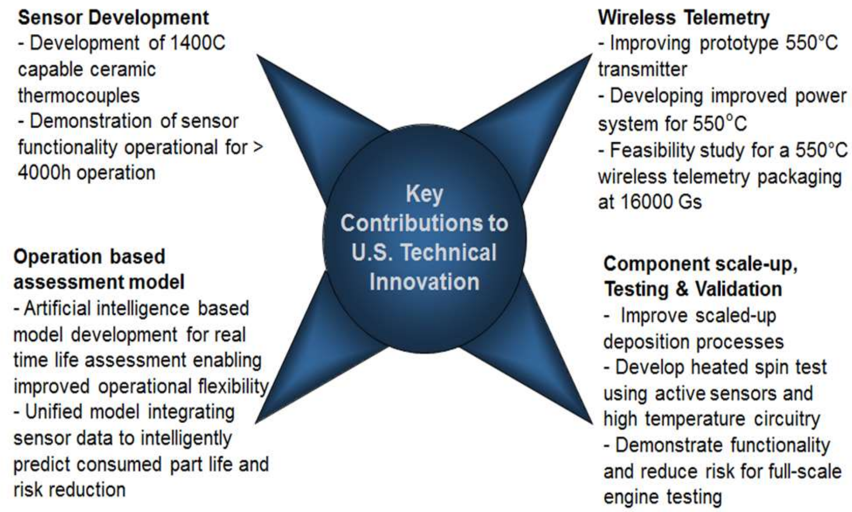
System Testing, Simulation & Performance

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

Anatomy of a Telemetry System

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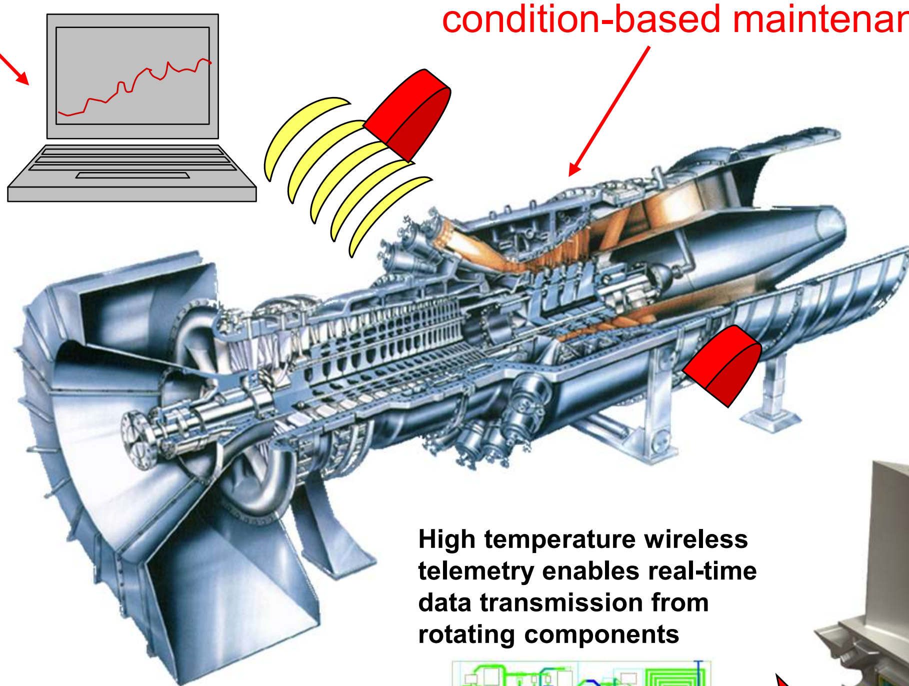
Data acquisition enables real-time input to life models



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

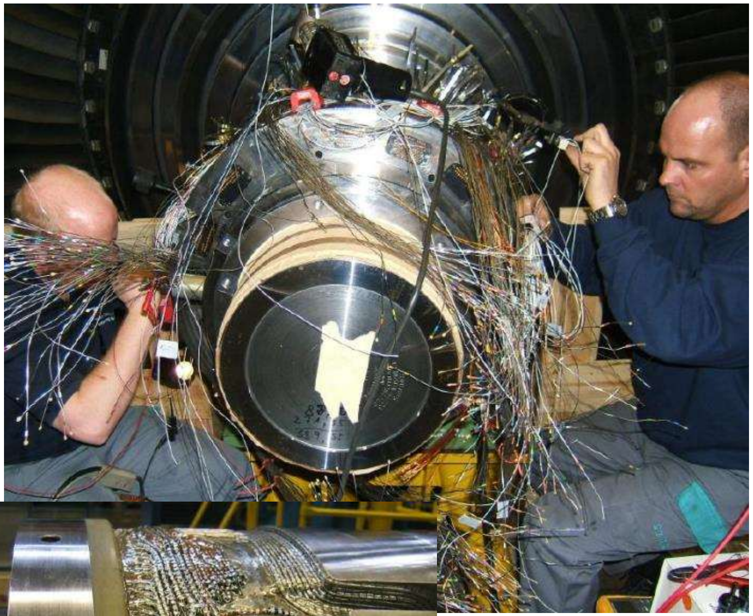
Thermal spray processes enable cost-effective, integrated sensors

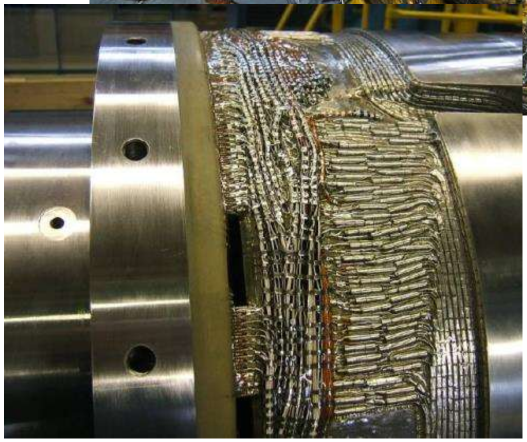
High temperature wireless telemetry enables real-time data transmission from rotating components

Current Blade Measurement Methodology

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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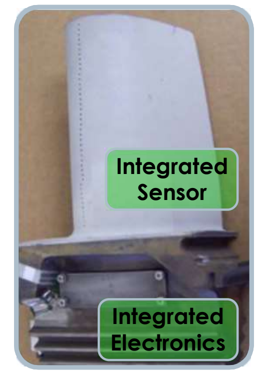
Increasing Engine Operating Temperatures
(Increased Efficiency, Reduced Emissions)

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

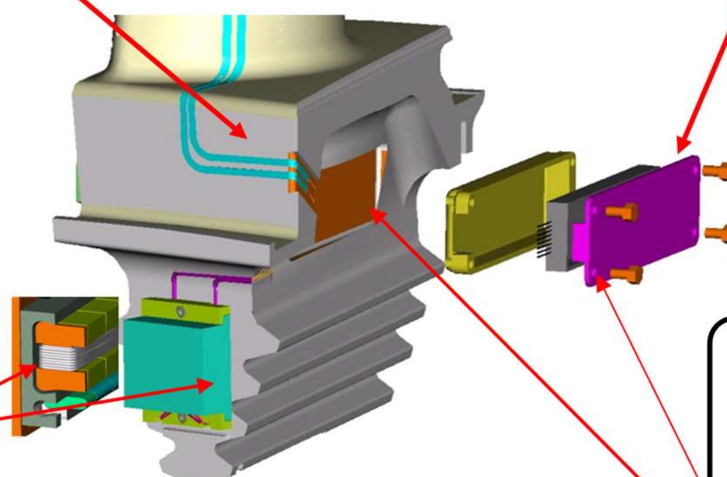
Siemens
- -Specifications
- -Ultra high temperature testing
- -Sensor optimization

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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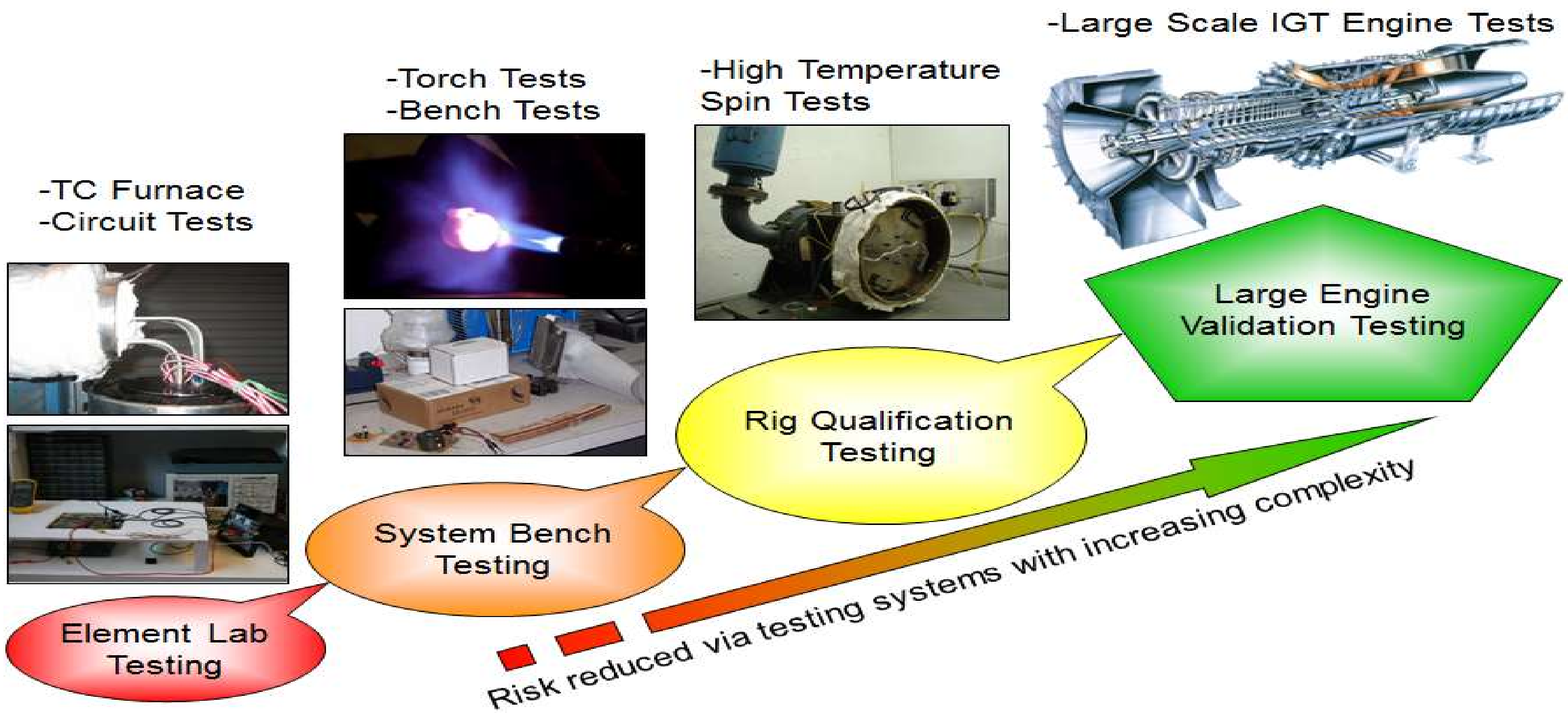
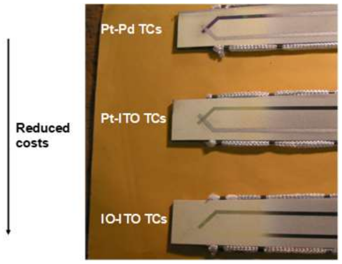


Rigorous testing and validation based on a thorough understanding of failure modes and improving final system performance

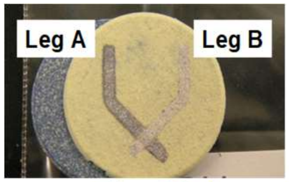
Thick Film Sensor Deposition via Thermal Spray

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.

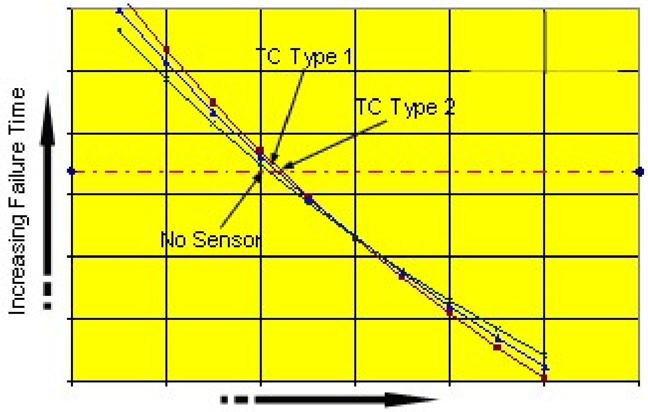
Thermocouple deposited on a performance and calibration test bar.

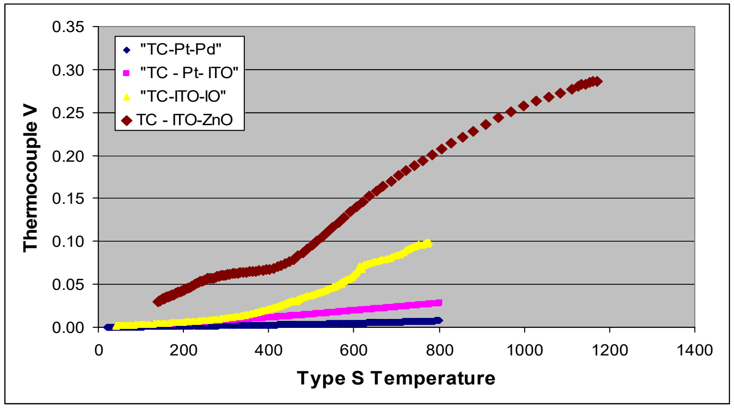


Specimen configuration tested.



Thermocouple deposited on a furnace cycle test button.





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

Isothermal Testing of ITO-SmCaCoO TC

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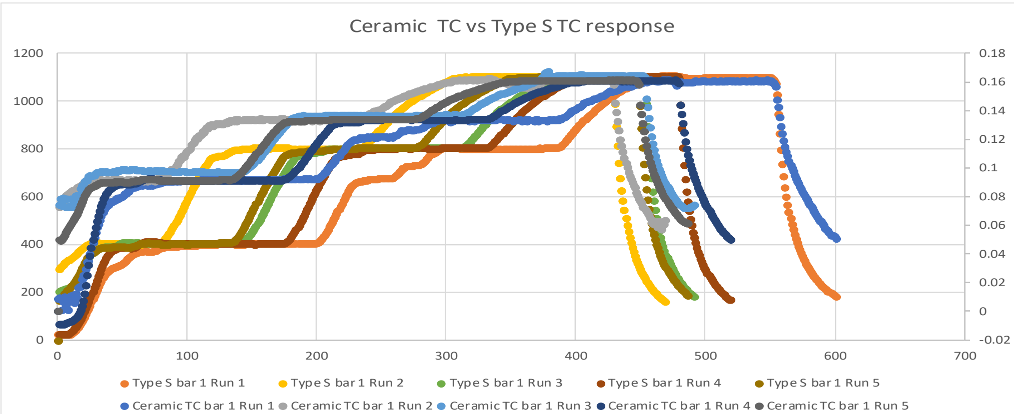
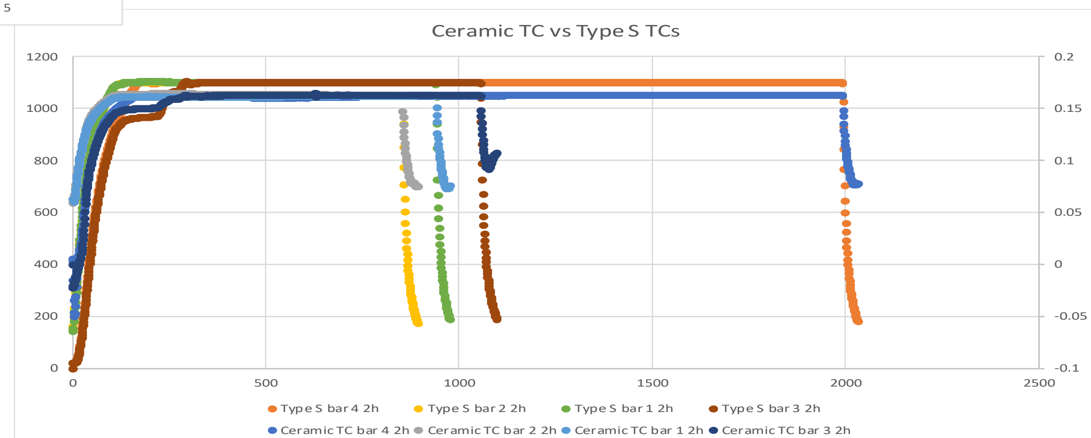


- **Isothermal testing upto 1100C**
- **170 mV @1100C output**
- **No reactions or increase in emf observed with thermal cycles**

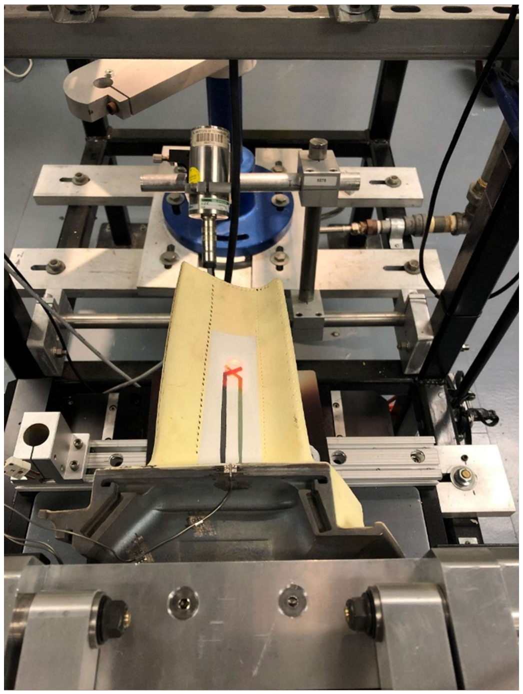
4 TC bars show consistent emf output and correlation to Type S TC over 150 hours

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



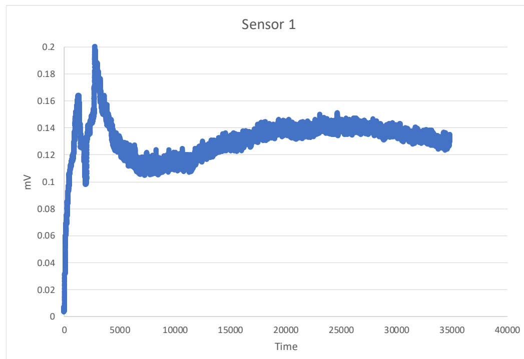
Very consistent response from ITO-SmCaCoO TC for 10 repeat bars over 1.5 years

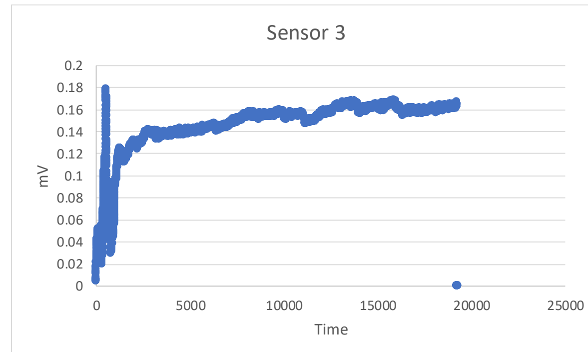
Laser Rig Testing of ITO-SmCaCoO TC



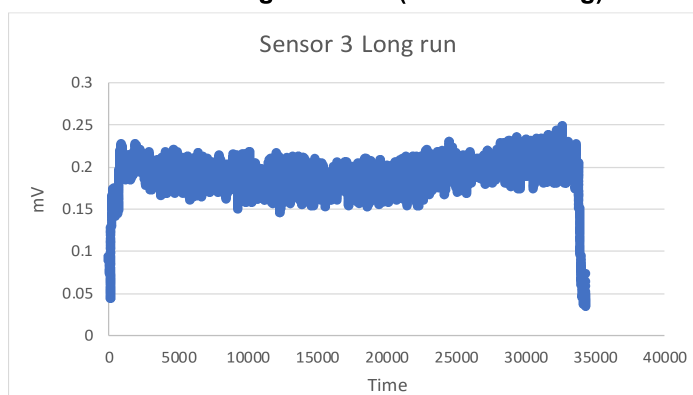
Laser rig testing done on bars and turbine blade

Testing at 1400C (10 hour testing)





Testing at 1500C (10 hour testing)



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

Impact of sensor on TBC Spallation life

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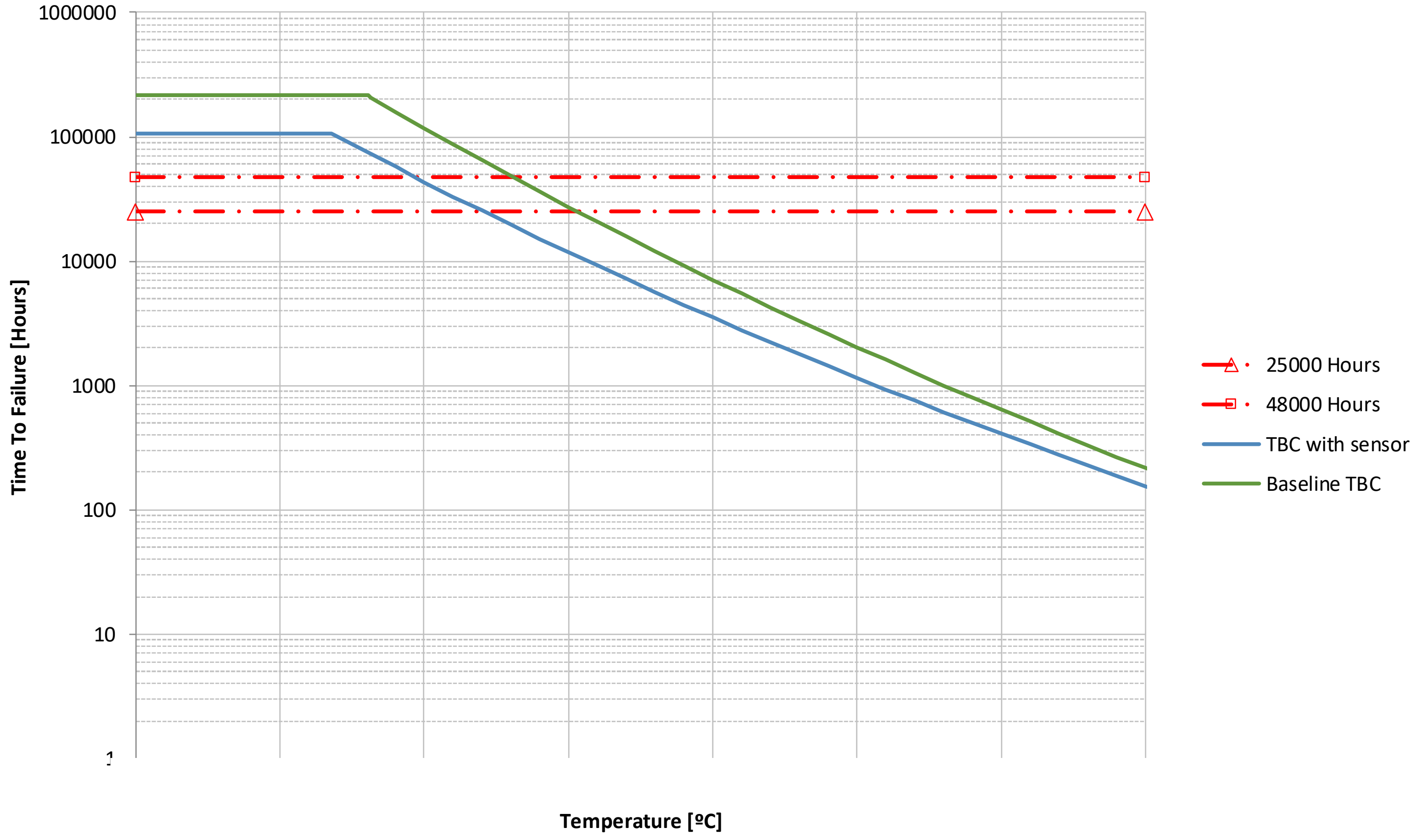

Sensors on TBC surface pose low risk to TBC Spallation life

Top Level Design Principles

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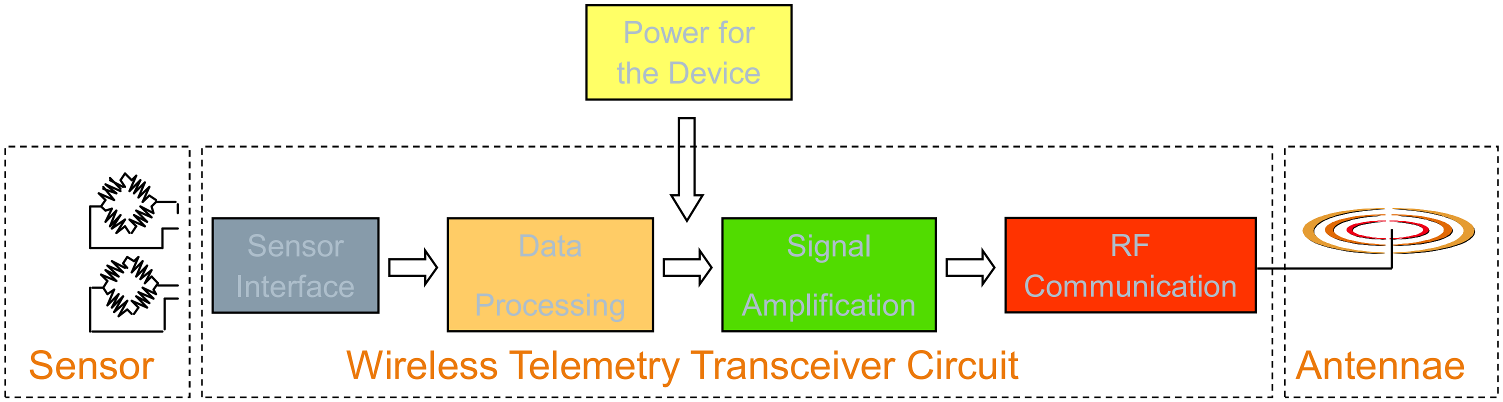

- **Hardwiring rotating parts through rotor is expensive and time consuming.**
- **Wireless telemetry has been used for many years, but not uncooled at high ambient temperatures.**
- **Antennae, circuit board, and electrical run materials, die attach and wire bond processes all must be optimized for 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, AlN, etc. are required).**
- **A source of power must be provided to the circuit at high temperature.**

High Temperature Electronics

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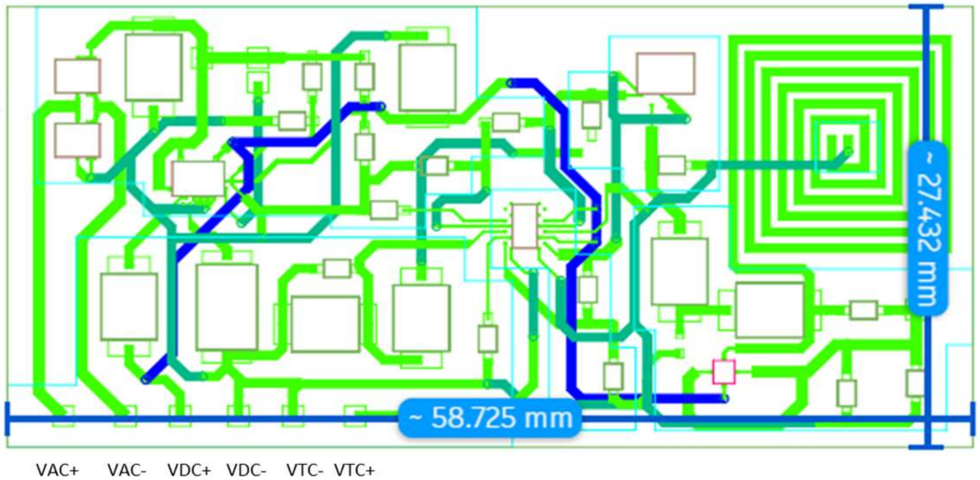
- Raytheon UK design utilized for R1 Vane.
- Device can utilize VAC power input from inductor cc for telemetry.
- Supports one TC input.
- Can be powered from 15 VDC for non-telemetry operation.
- Board made from LTCC.
- Die-Pad metallization consists of stacked titanium-aluminum.



UARK’s LTCC carrier board for high temperature SiC electronics.

High Temperature Electronics System Block Diagram

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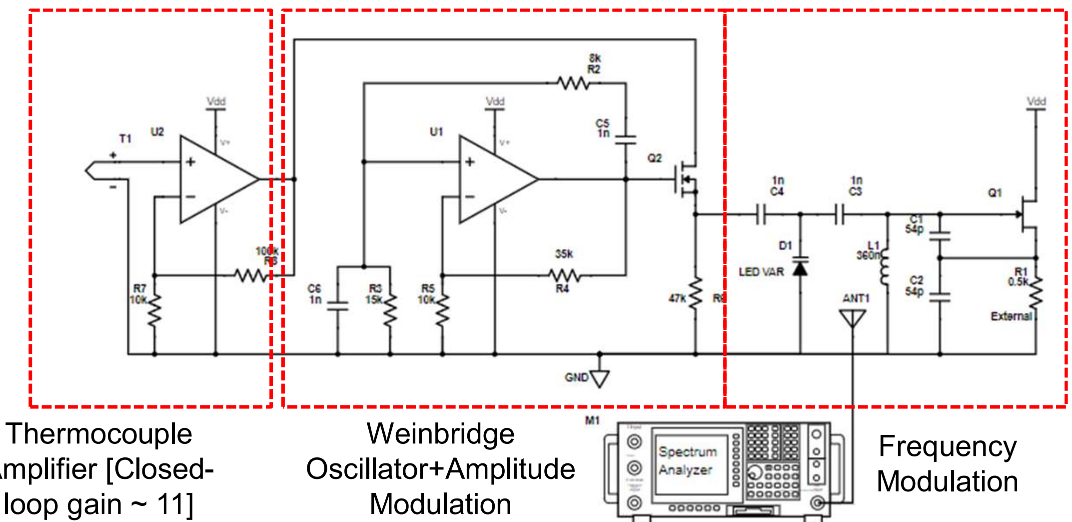
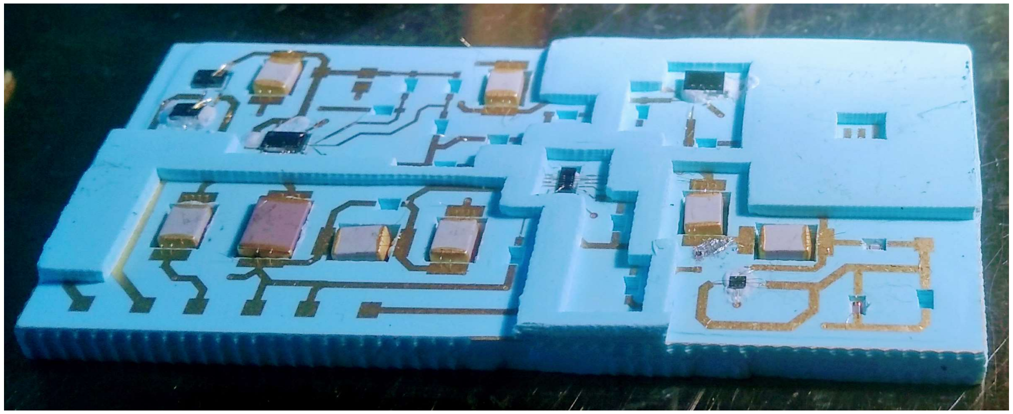
- System Level Block Diagram include Bridge Rectifier, Voltage Rectifier, FDM, and FM transmitter. Operates at 20Mhz Power input and Communicates data back at with FM 70Mhz.



System Level Schematics of LTCC board

High Temperature Electronics Operating Conditions

- Raytheon Op-Amp can amplify thermocouple signal with a biasing current set to 125uA using 100kOhm thick film resistor.
- Colpitts Oscillator observed from Spectrum Analyzers to have center frequency of 51 Mhz.
- Operating temperature 200+ ºC higher than silicon technology can survive
- Operation at 15VDC or 70-80VAC @ 20MHz.
- Must receive ~1 watt; only 10 cm long; 20mm gap
- Surrounded by grounded metal
- Need 400 ºC, high frequency cables for stationary power inductor



Fabricated LTCC in assembly Process.

Circuit and Components tested to 550 °C

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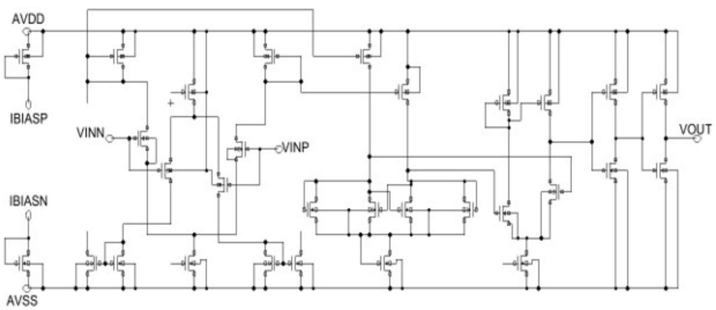
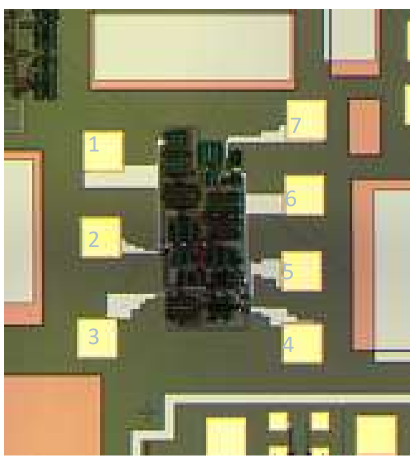
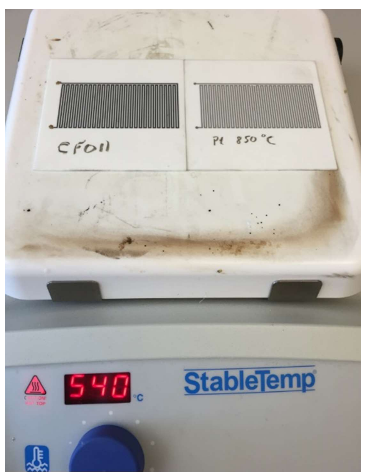
SiC IC Testing @ 550 °C (OpAMP Comparator)

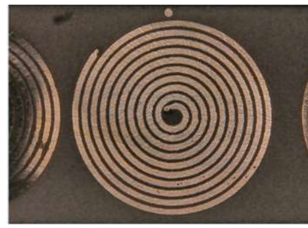


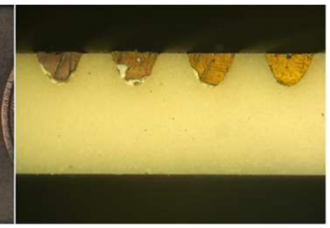


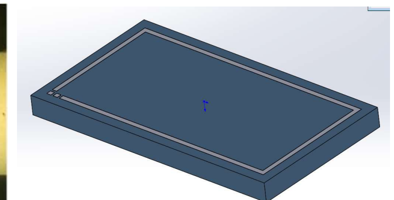


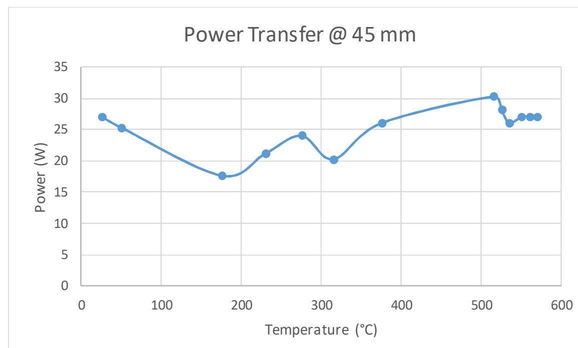
Various Resistor Pastes increase resistance from 20 – 200% from room temperature to 540 °C

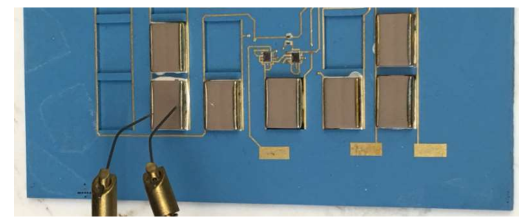
Power System Testing @ 550 °C

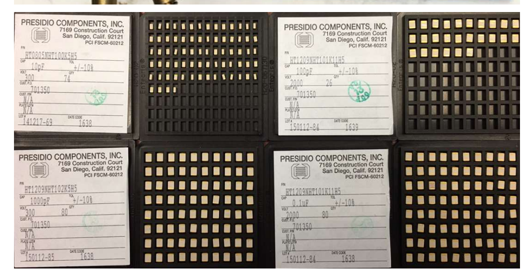












Capacitors functional but decline in capacitance by ~ 20% at 550 °C

Mechanical Package

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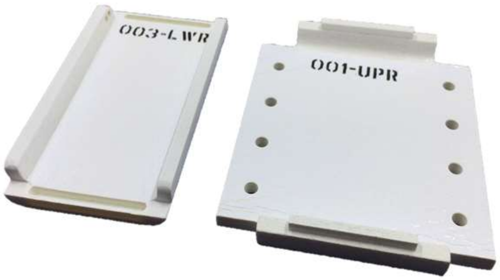
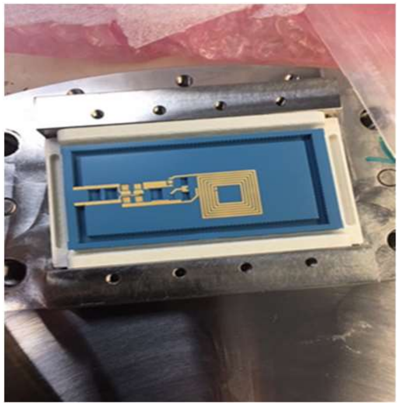
- Drilled holes for wire feed-through
- Wires Bonded with high temperature solder or capacitively welded to Board pads.
- Strain Relief on high temperature cables will prevent pulling forces.





LTCC Board installed inside CMC housing. Drills for Wire Feed-Thru (top). CMC Packaging as manufactured (bottom left). LTCC board placed inside of CMC package on spin test rig (bottom right)

Assembly Plan for RUK module

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- Scheduling is on the UARK and CREE side. These dates need to coincide with scheduling from Siemens for engine test.
- Assembly of RUK module will be completed by end of September 2020.
- After verification of the design under testing conditions, external hardline cables will be bonded to the board.

Activities delayed by 2 months due to COVID-19

Task	Schedule	Completed?
Layout Modification	May 13, 2020	✓
New Screens Ordered	May 19, 2020	✓
New Screen Received	May 22, 2020	✓
LTCC Fabrication	May 29, 2020	✓
Assembly and wire-bonding of Raytheon Die and HT capacitor parts	June 05, 2020	✓
Expected arrival of thick-film resistors (significantly delayed due to COVID)	June 30, 2020	
Assembly and wire-bonding of thick-film resistor	July 2, 2020	
Room temperature functionality testing of the thermocouple amplifier, weinbridge oscillator and FM transmitter (under probe station)	July 06, 2020	
High-temperature (350°C-500°C system-level functionality testing of LTCC board	July 10, 2020	
Spin testing of spare LTCC board with partial assembly	TBD	
Welding of external cables on the board pads and system-level testing	July 17, 2020	

Schedule of System Assembly and Testing of High Temperature Electronics

Enablers of the Engine Test

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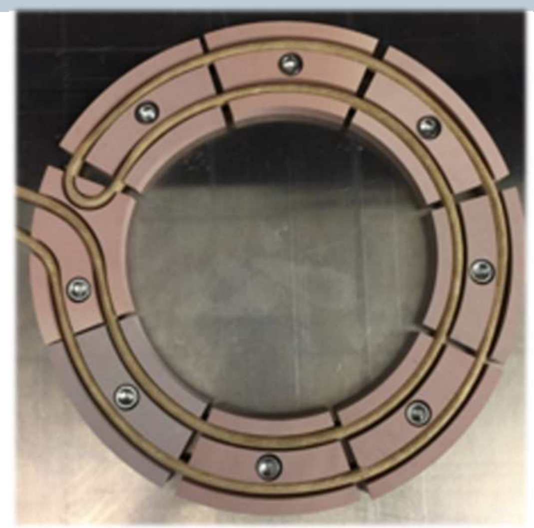
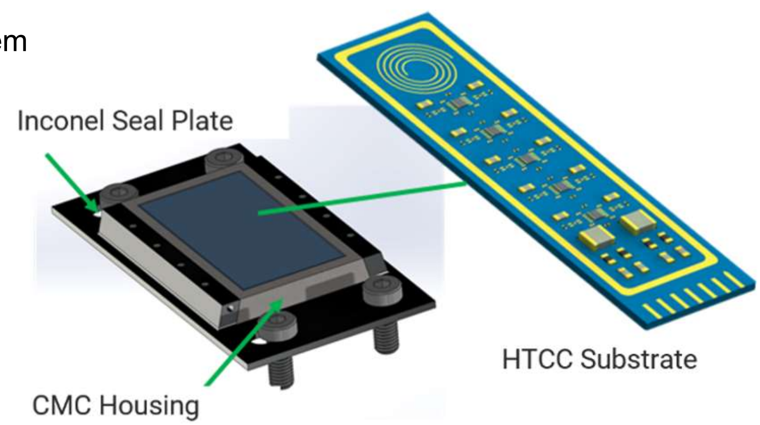
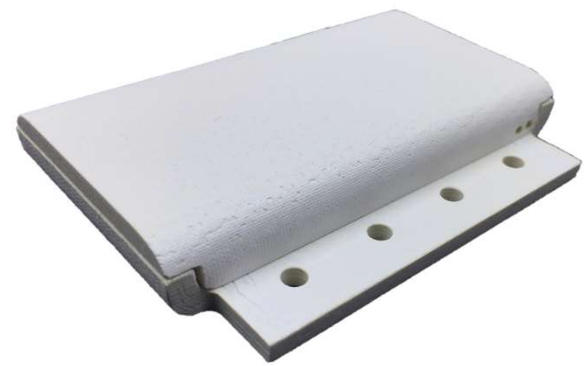
The Siemens-Led Team is in preparation to demonstrate the broad suite of sophisticated technologies which allow for on-blade, real-time temperature measurements.

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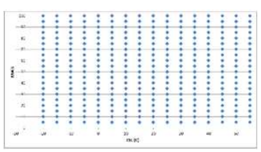
Challenging market situation requires a competitive design life. Current lifing approach is based on assumed single design points (Baseload hot and iso conditions for the full life time), not based on fleet operational data.

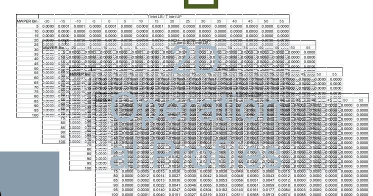
Each existing engine's operation conditions and operation hours (OH) in service have been analyzed and summarized into an operational profile by two parameters: normalized power load (MW%) and compressor inlet temperature (T1C)

Operation conditions (MW%, T1C) → Calculate Interstage Conditions → Calculate Local conditions → Calculate Duty Cycle Life → Fleet Duty Cycle Life Distribution



e.g. hot path gas temperature, mass flow

e.g. metal temperature, stress



	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

Current efforts focused on creep life of row 4 blade material

Design Requirements: Connection Diagram

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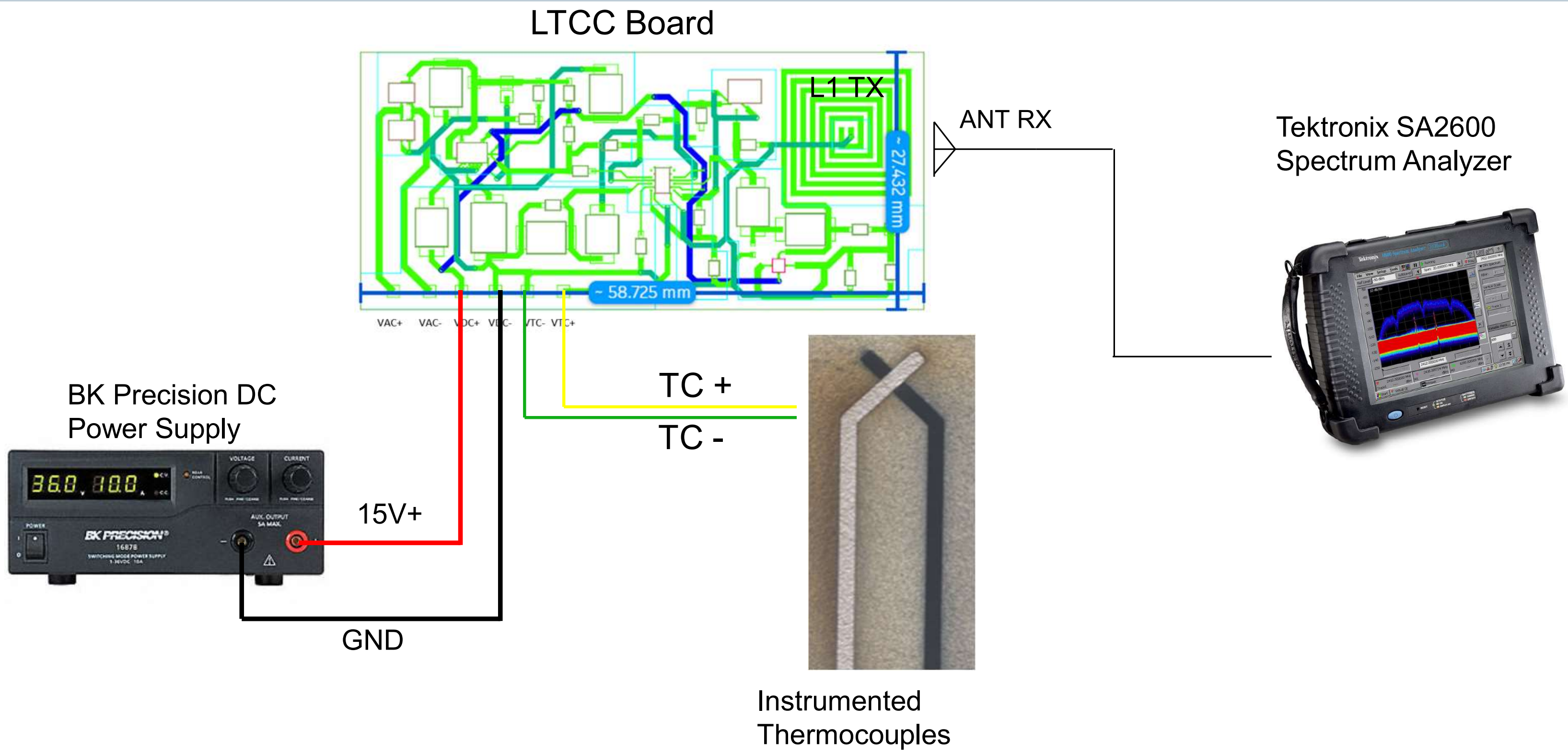
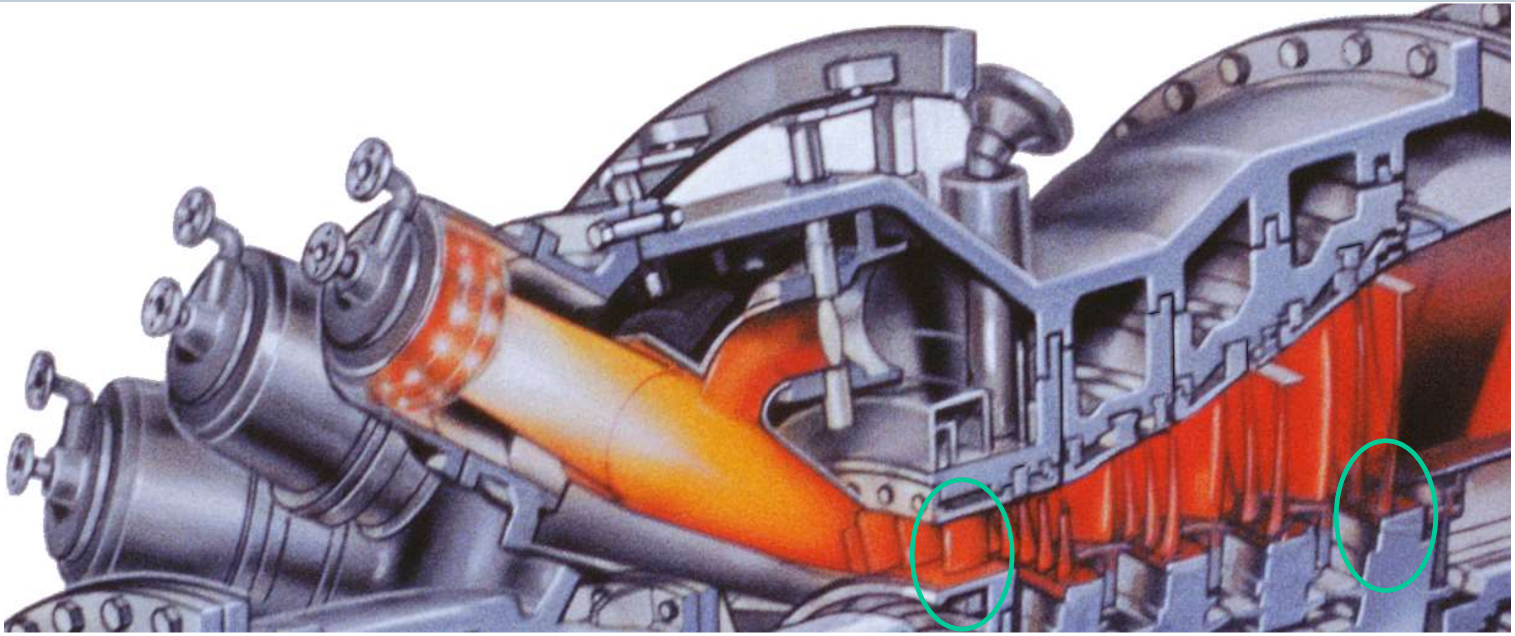


Connection Layout of Various Components of Row 1 Telemetry System

Engine Test on Siemens 9HL at Duke Energy site in NC



Team in design review process for technology demonstration in 2 locations in the engine

- **Row 1 vane with stationary wireless telemetry – made from chips from Raytheon, UK**
- **Row 4 blade with rotating wireless telemetry – made from chips from Fraunhofer Germany/KTH Sweden**
- **Stationary chips undergo electrical test end of April and chips for rotating hardware undergo spin rig testing in May 2020 to meet the august deliverable of instrumented hardware to engine site**

Potential to test the technology in Siemens' newest engine at Duke Energy site in Lincoln County, NC

Schedule of the Test

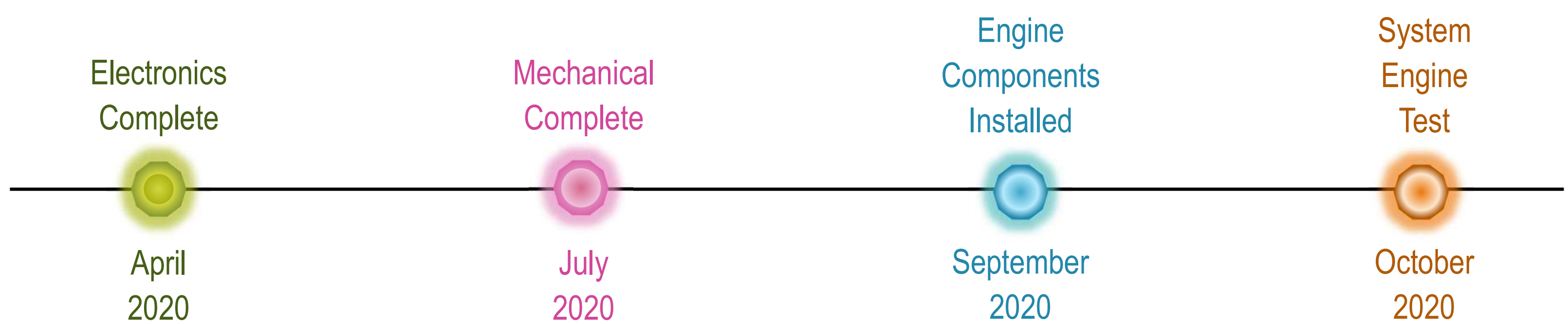
Siemens currently has a test campaign on its newest gas turbine SGT-9000HL at Lincoln county site of Duke Energy

Concurrently, engine integration work, mechanical spin testing verification, cable testing, and seal plate design will occur.

Final integration review and approvals were completed August 19h 2020

Row 1 vane received for instrumentation and integration with wireless telemetry during summer 2020

Testing will occur in October 2020.



Program running on 3 month delay due to COVID-19

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 first engine test component will utilize Raytheon chip for wireless telemetry**
- **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.**