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Siemens/ Wolfspeed | April 11th 2019

Novel Temperature Sensors and Wireless Telemetry for Active Condition Monitoring of Advanced Gas Turbines DOE Award: DE-FE-0026348

Acknowledgements: DOE NETL
Sydni Credle – DOE/NETL Project Manager

Deployment of Advanced Sensing Systems Enables Operational Based Assessment

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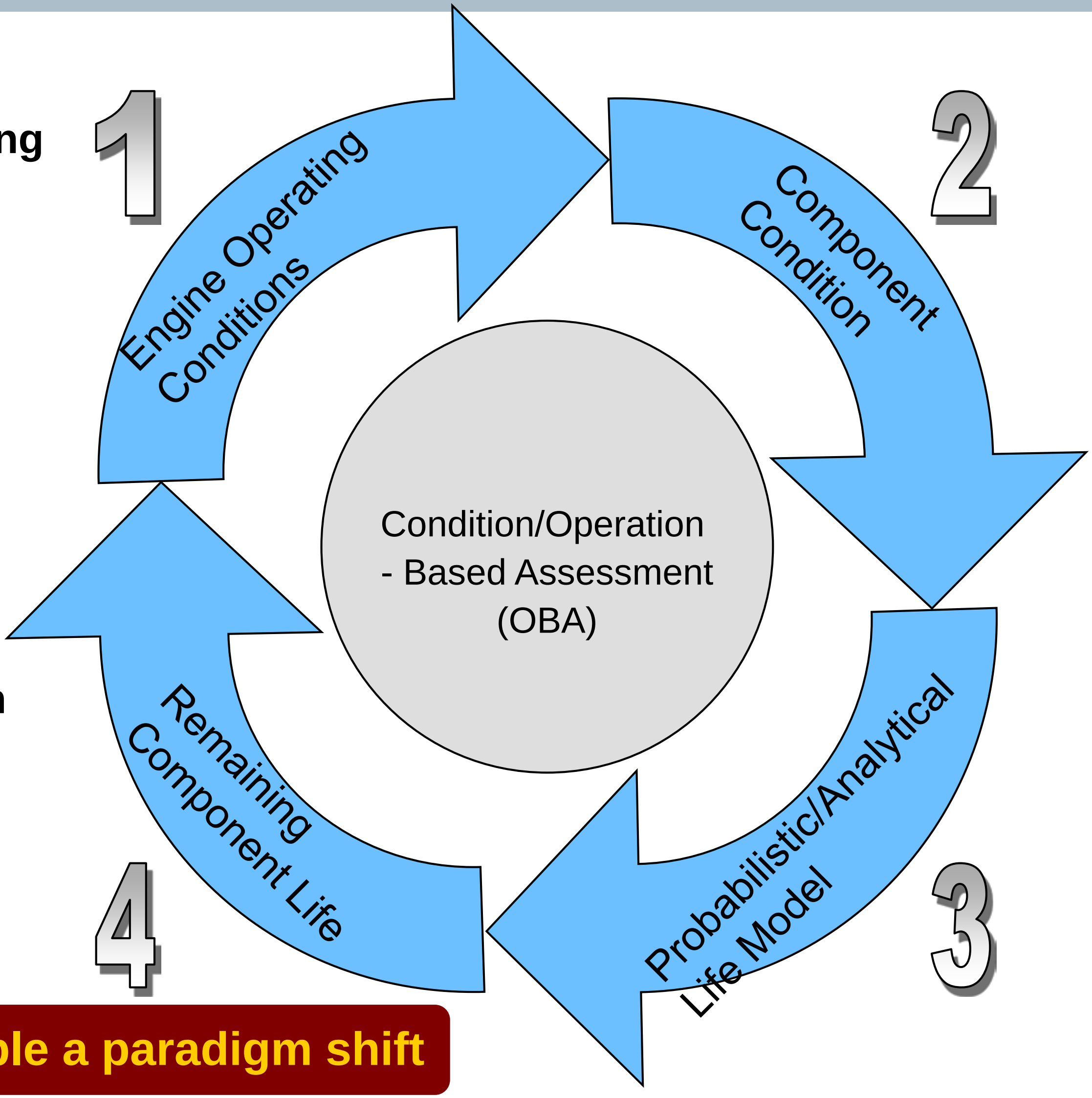
- **Harsh environment instrumentation provides critical information regarding component condition**
- **Such information provides data for:**
  - **Test engine evaluation**
  - **Design model validation**
  - **Engine performance**
  - **Engine diagnostics**
  - **Conditioned based assessment**
- **Improvements over existing instrumentation is required to obtain long life data from fleet engines.**
- **Enables a paradigm shift in engine operation**



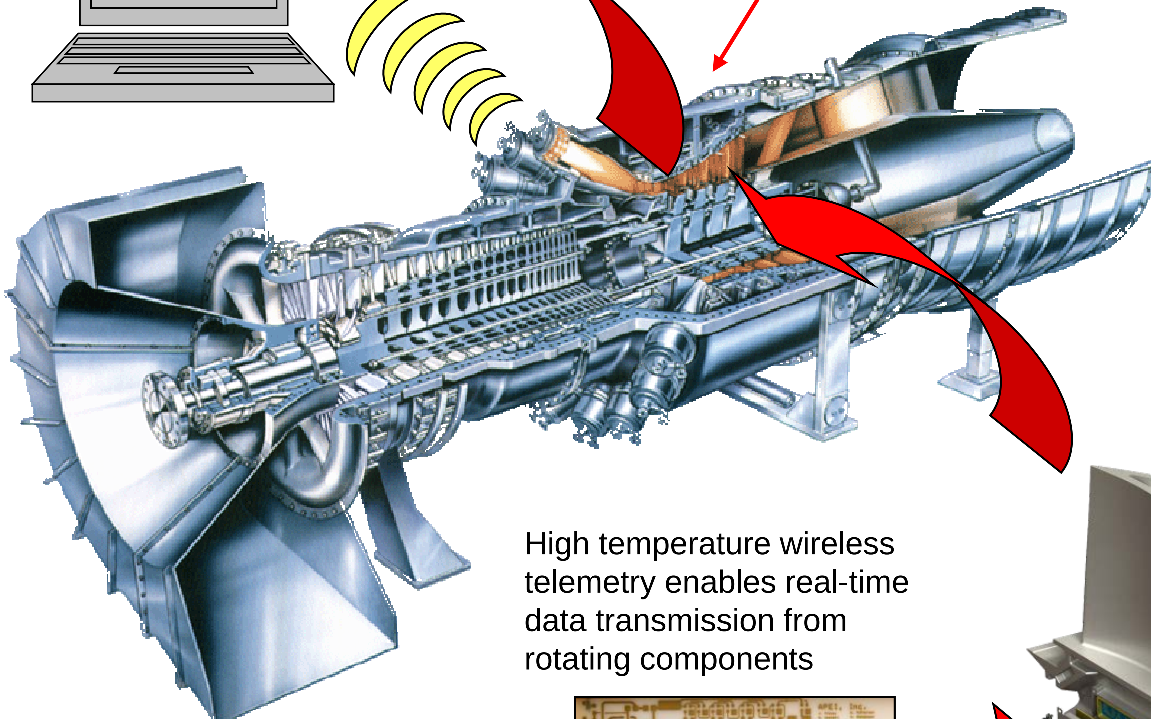
Advanced sensor systems enable a paradigm shift

Unrestricted

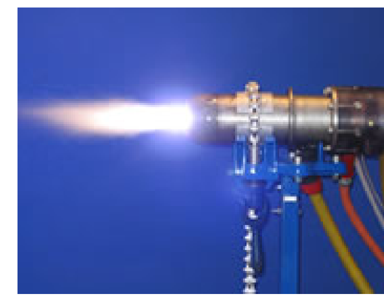
Anatomy of a Smart Component

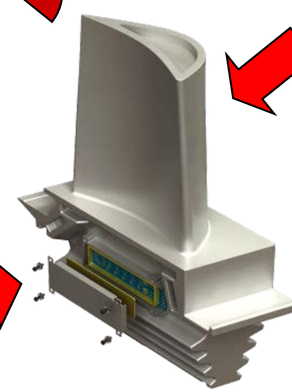
Data acquisition enables real-time input to life models

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

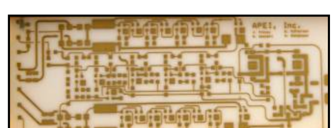


Thermal spray processes enable cost-effective, integrated sensors deposited on thermal barrier coatings (TBCs)





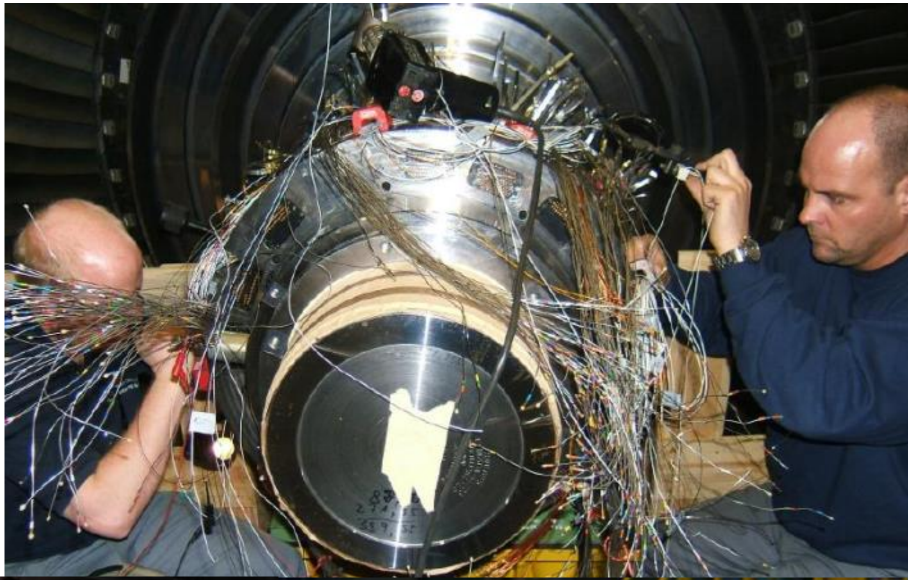
High temperature wireless telemetry enables real-time data transmission from rotating components

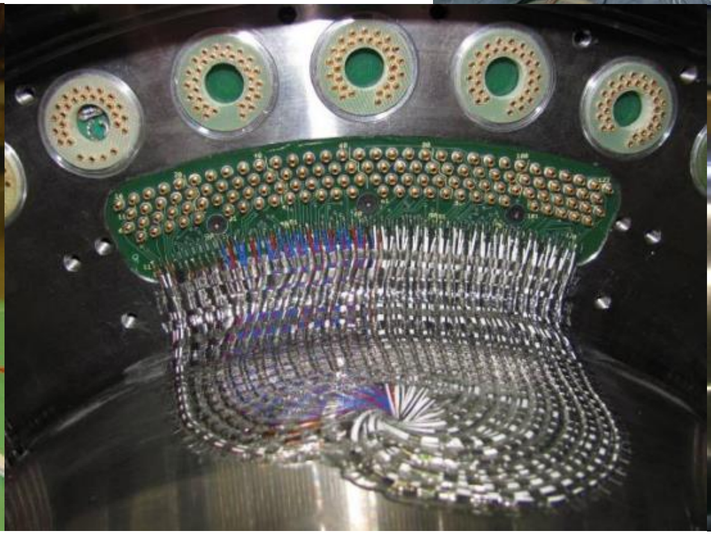


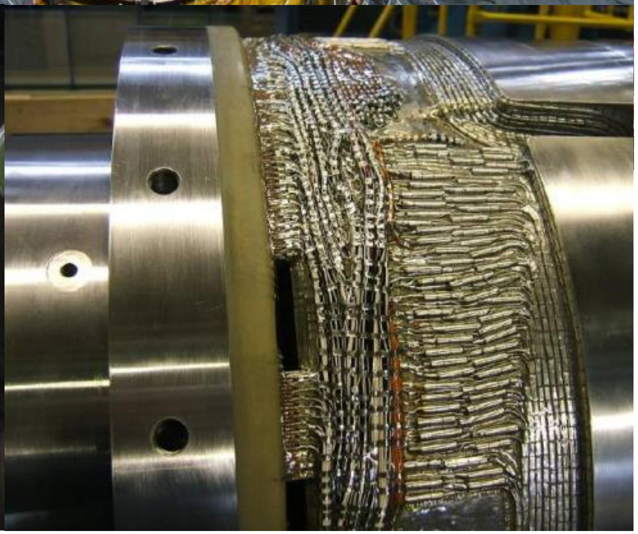
Current Blade Measurement Methodology

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







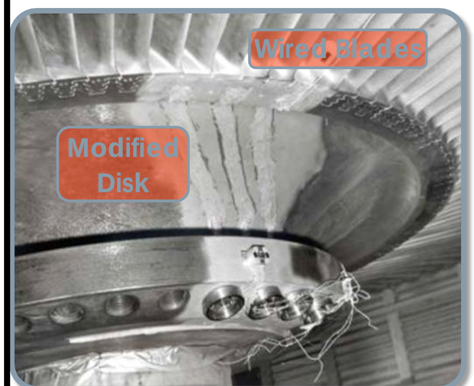
Paradigm Shift for Engine Monitoring

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

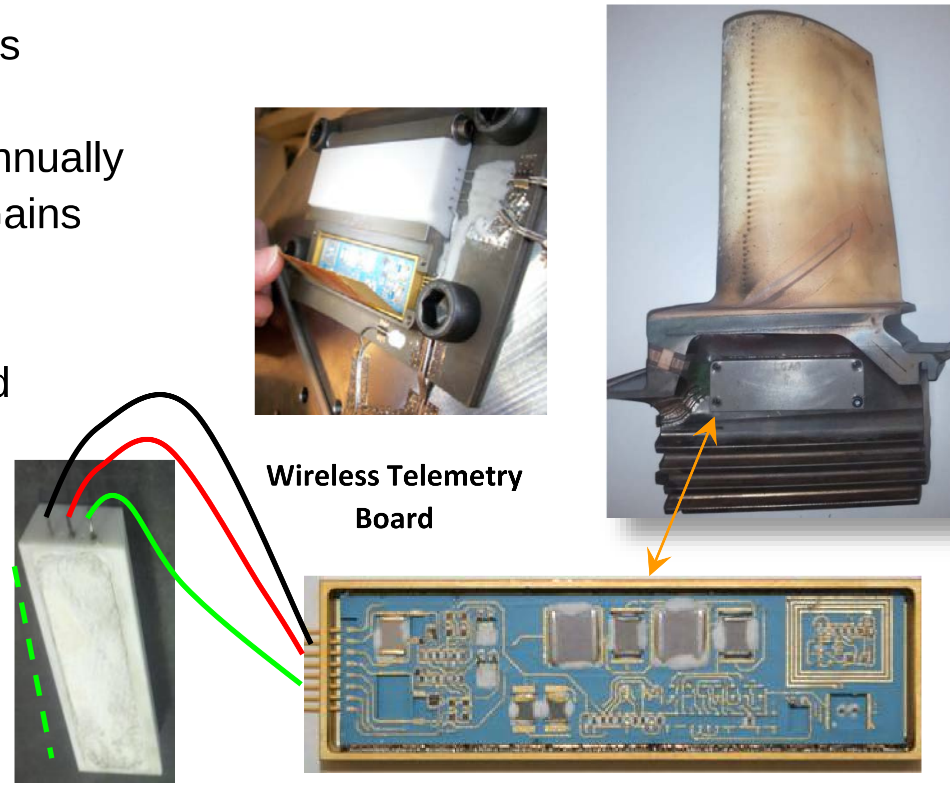
Benefits If Successful

Online Condition Based Monitoring

- Multi-Thousand Hour Lifetime
- Reduce component-life-based shutdowns
  - $1-2 Million savings
  - Machine on time increased 1-2% annually
- Online Engine Operation for Efficiency Gains

Feedback for Design Optimization

- Online Blade Condition more widespread
- No wires → higher accuracy
- Blade temperatures at critical locations



Summary

- Higher engine on-time
- More design feedback
- Multifunctional circuitry capabilities
- Online feedback → Operational optimization → higher engine efficiency
- Push forward extreme high temperature electronics

Novel Sensors- Wireless Telemetry System Team

HT Capable Thermally Sprayed Sensors

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

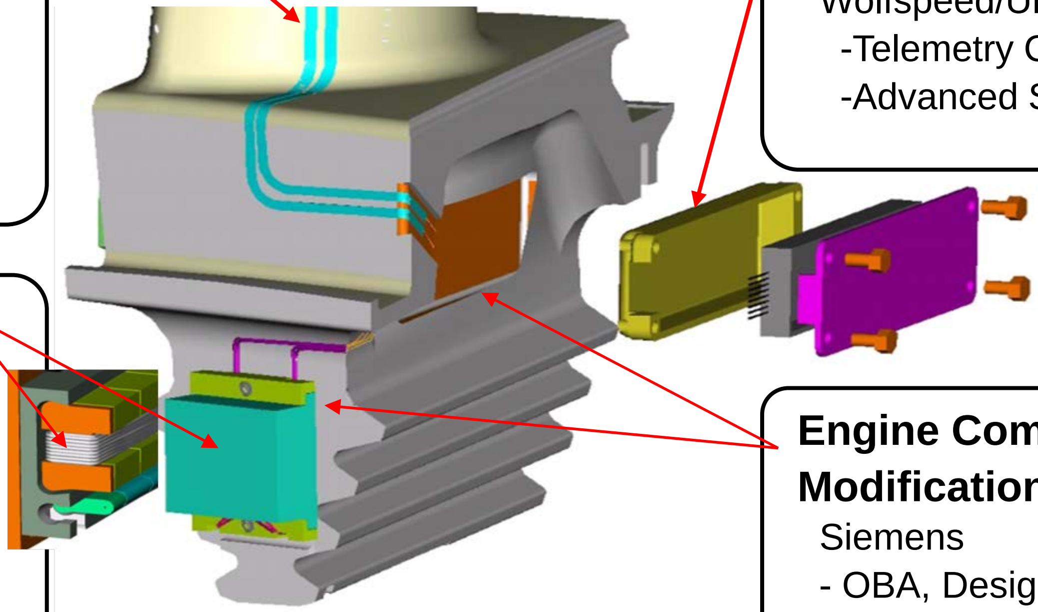
Curtiss Wright
- -Sensor Fabrication

Hitec Products
- -Attachments

HT Wireless Telemetry Transmitter Circuit Board

Siemens
- -Specification
- -Attachment Design

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



High Temperature Induced Power System

Siemens
- -Attachment design

Wolfspeed
- -Wireless Telemetry System

Aerodyn
- -High Temperature Spin Tests

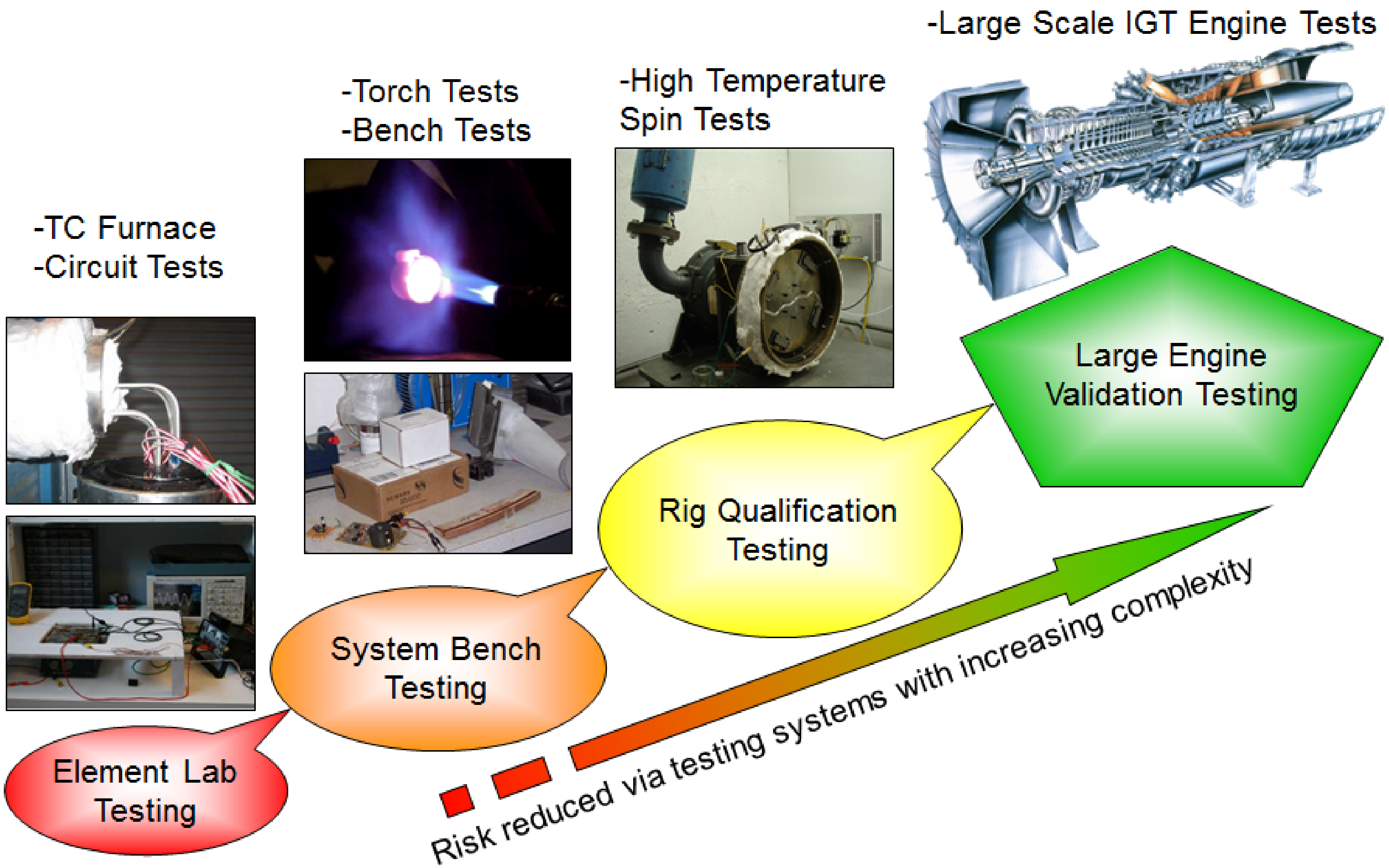
Engine Component Modification and Analysis

Siemens
- - OBA, Design and Analysis

Machining Vendors
- - Component Fab

The technical team is strong and has been working together for 12 years

Progressive Development Approach



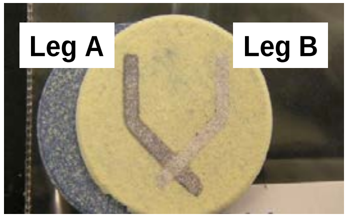
Rigorous testing and validation based on a thorough understanding of failure modes and improving final system performance

Thick Film Sensor Deposition via Thermal Spray

Thermal spray enables integral sensors to be deposited on coated and uncoated components with complex shape.

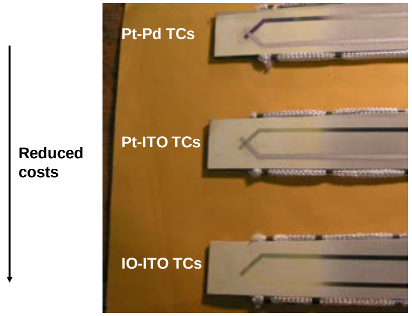
Sensors may be incorporated with minimal component and performance modifications.

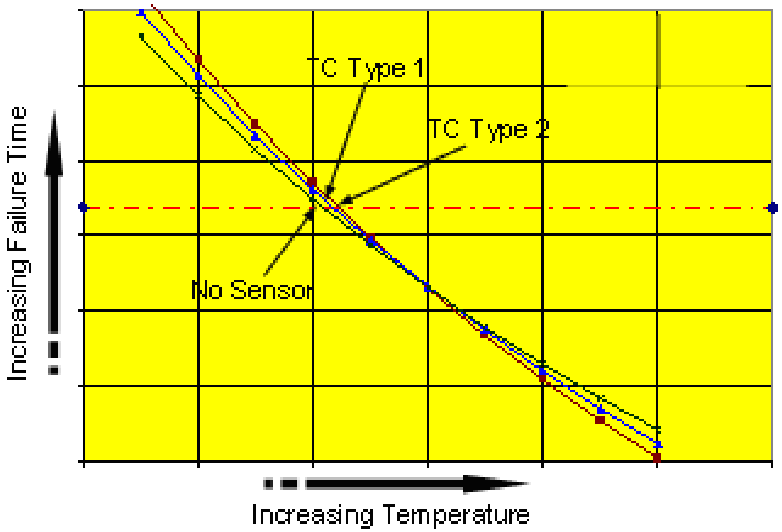
Specimen configuration tested.

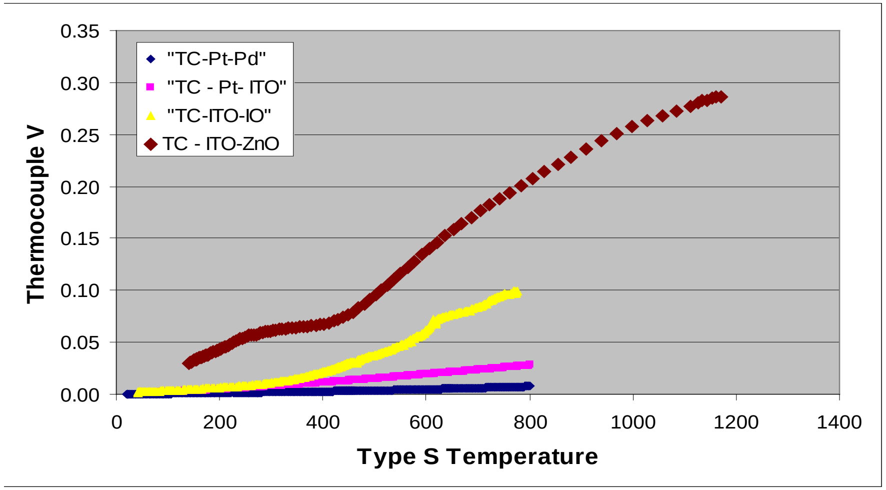


Thermocouple deposited on a furnace cycle test button.

Thermocouple deposited on a performance and calibration test bar.







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

Unrestricted

Isothermal Testing of ITO-LaSrCoO TC

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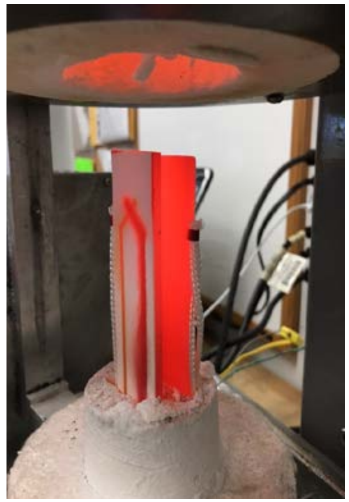
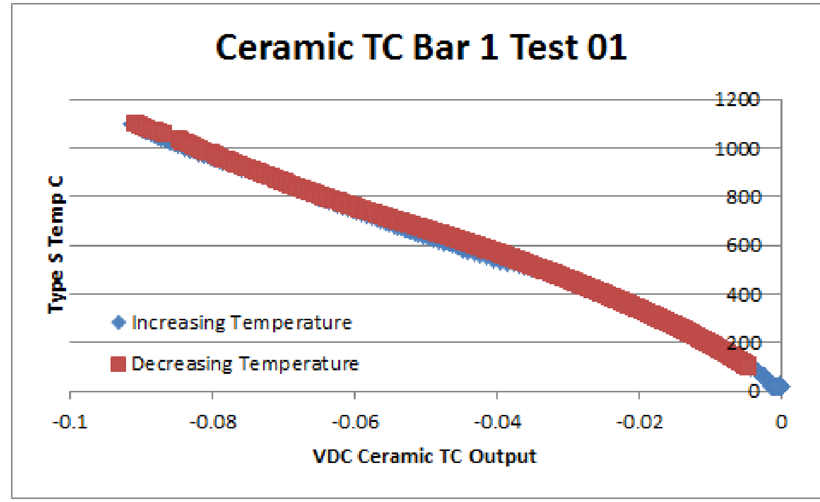
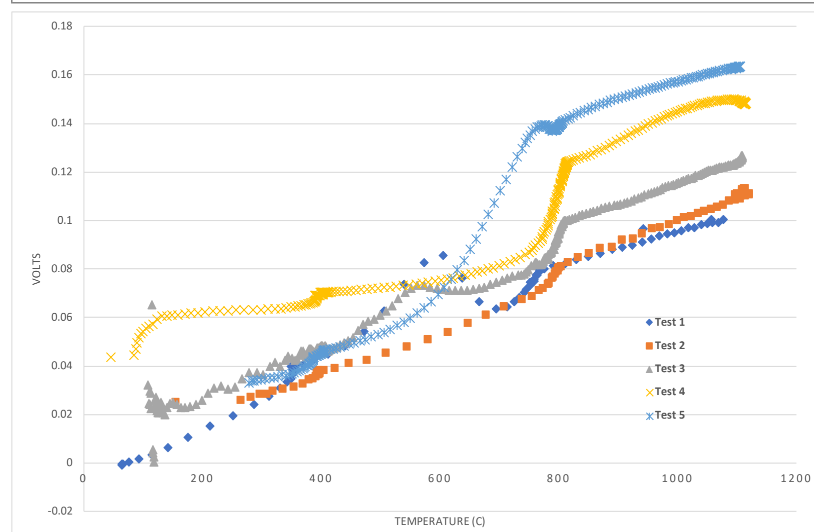
Isothermal heating with 2 TCs evaluation for reproducibility.





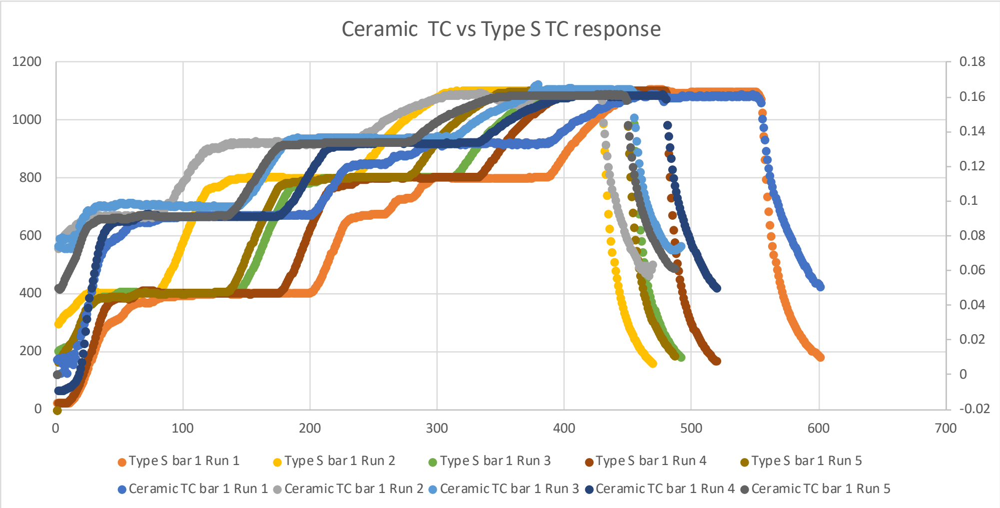
Calibration curve



- **Possibility of reactions between the 2 ceramic compositions that might be resulting in 60% increase in emf over 5 cycles.**
- **A stable ceramic composition is sought that doesn't reaction with the ITO leg. While we have a stable n-type thermocouple composition in Indium tin oxide, a very stable p type composition (Samarium-Calcium-Cobalt-Oxide) was produced.**

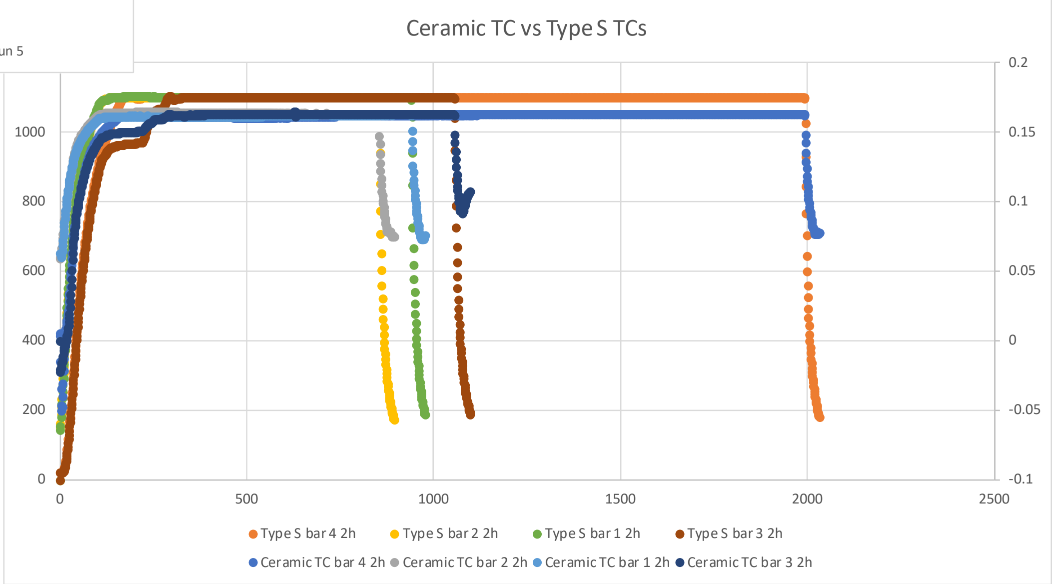
Continued search of stable P-type ceramic composition

Isothermal Testing of ITO-SmCaCoO TC



- 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 2 hours



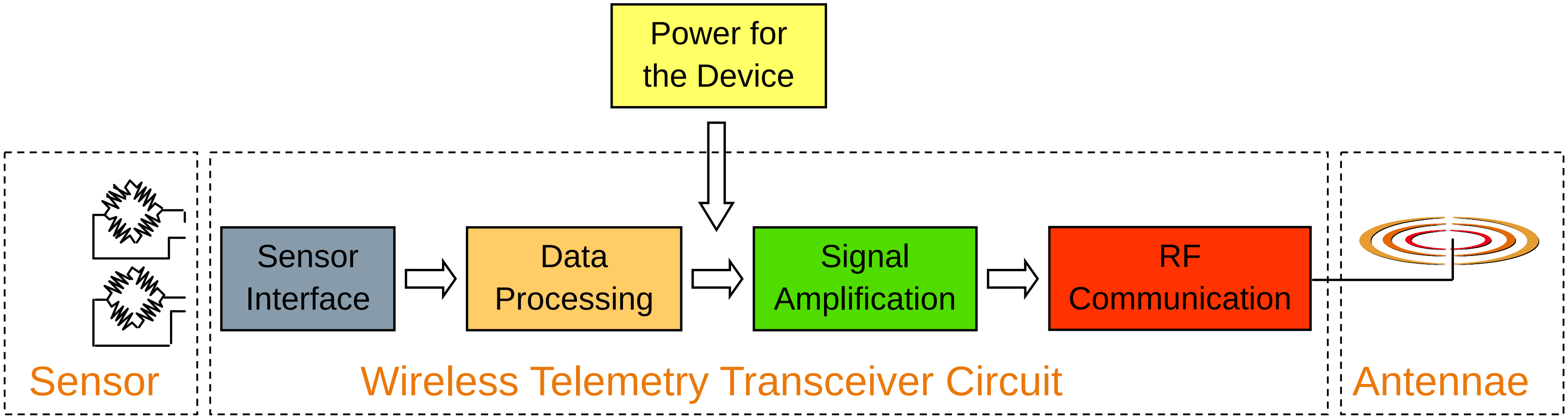
New ceramic TCs show consistent emf output and correlation to Type S TC over 5 thermal cycles

Next steps:

- Long term testing at 1400C planned
- TC bar sent to Wolfspeed for integration to wireless telemetry board

Very consistent response from ITO-SmCaCoO TC, long term testing underway

Structure of a Wireless Telemetry System

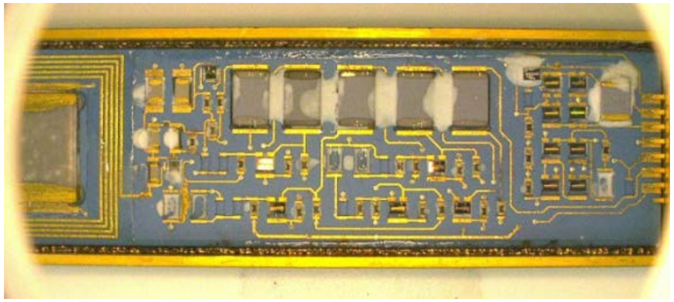


- **Hardwiring rotating parts through rotor is expensive and time consuming.**
- **Wireless telemetry has been used for many years, but not uncooled at high ambient temperatures.**
- **Antennae, circuit board, and electrical run materials, die attach and wire bond processes all must be optimized for 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.**

Design Challenges

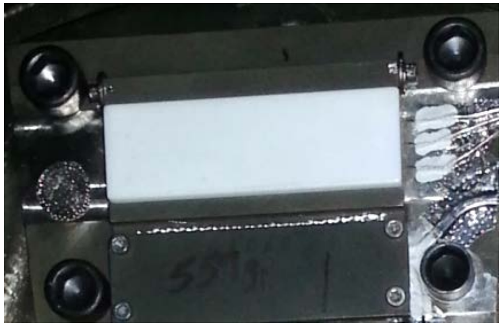
Electronics Boards

- Operating temperature 200+ ºC higher than silicon technology can survive
- Thermal expansion and 16,000 g load make electrical connections very difficult
- Vibration and g-load cause cracking of ceramic boards
- Thermal cycling causes metal trace delamination
- Bond wire failures (breaking and g-load flexing)



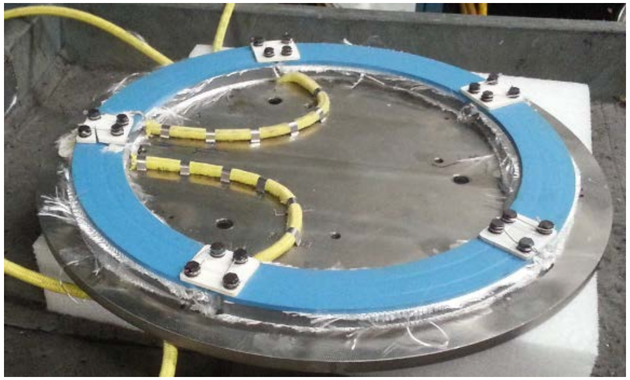
Rotating Antenna

- Must receive ~1 watt; only 10 cm long; 20mm gap
- Surrounded by grounded metal
- No metal enclosure (magnetic receiver)
- Metal-ceramic interfaces – high vibration and g-load
- Magnetic properties vary greatly over 0-400 ºC range

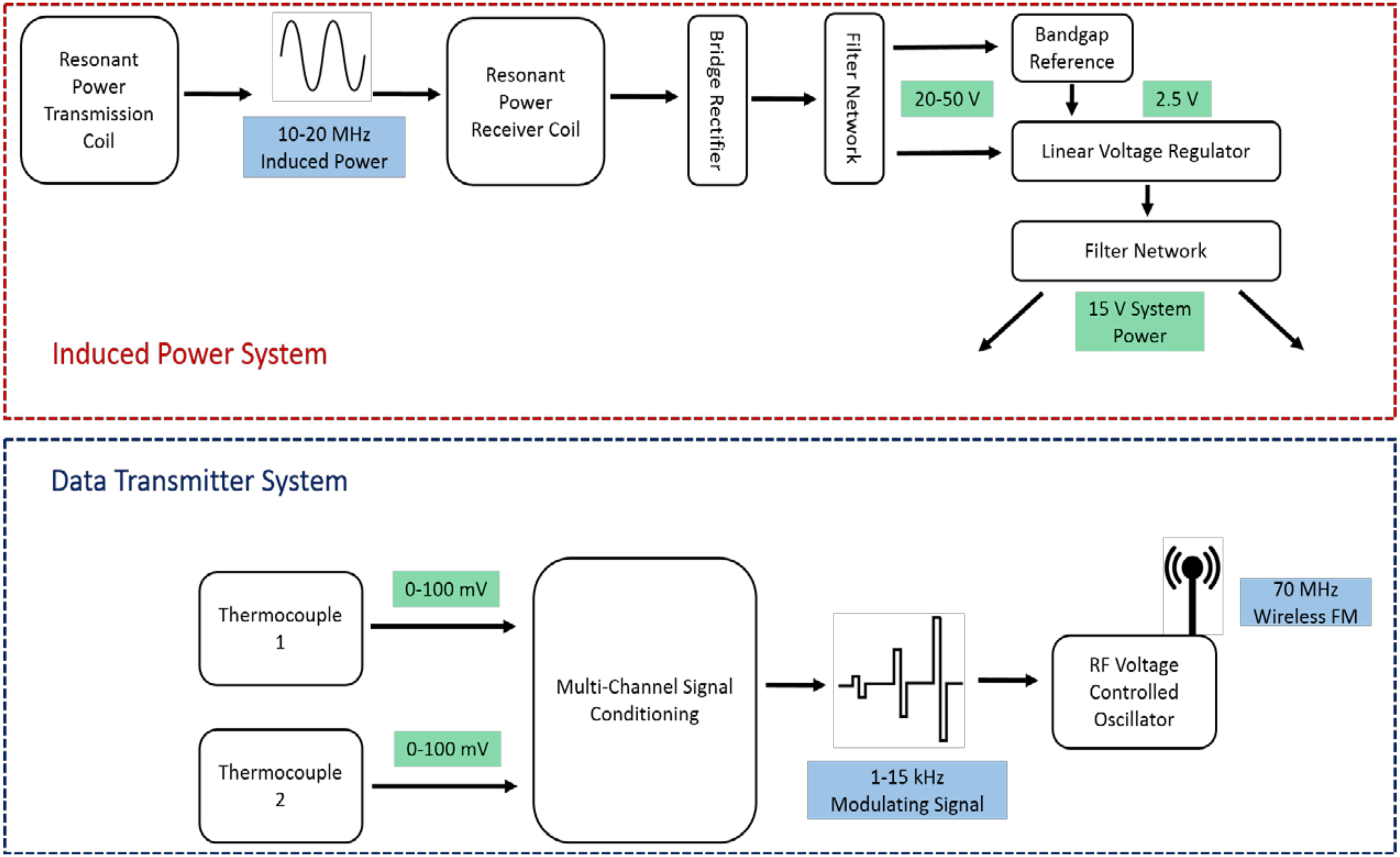


Stationary Power Inducing Ring

- Magnetic materials infeasible – too much variation in field strength over temperature
- Thermal expansion and vibration make electrical connections very difficult
- Mounted on grounded metal
- Ceramic/metal interface in high vibration environment
- Need 400 ºC, high frequency cables

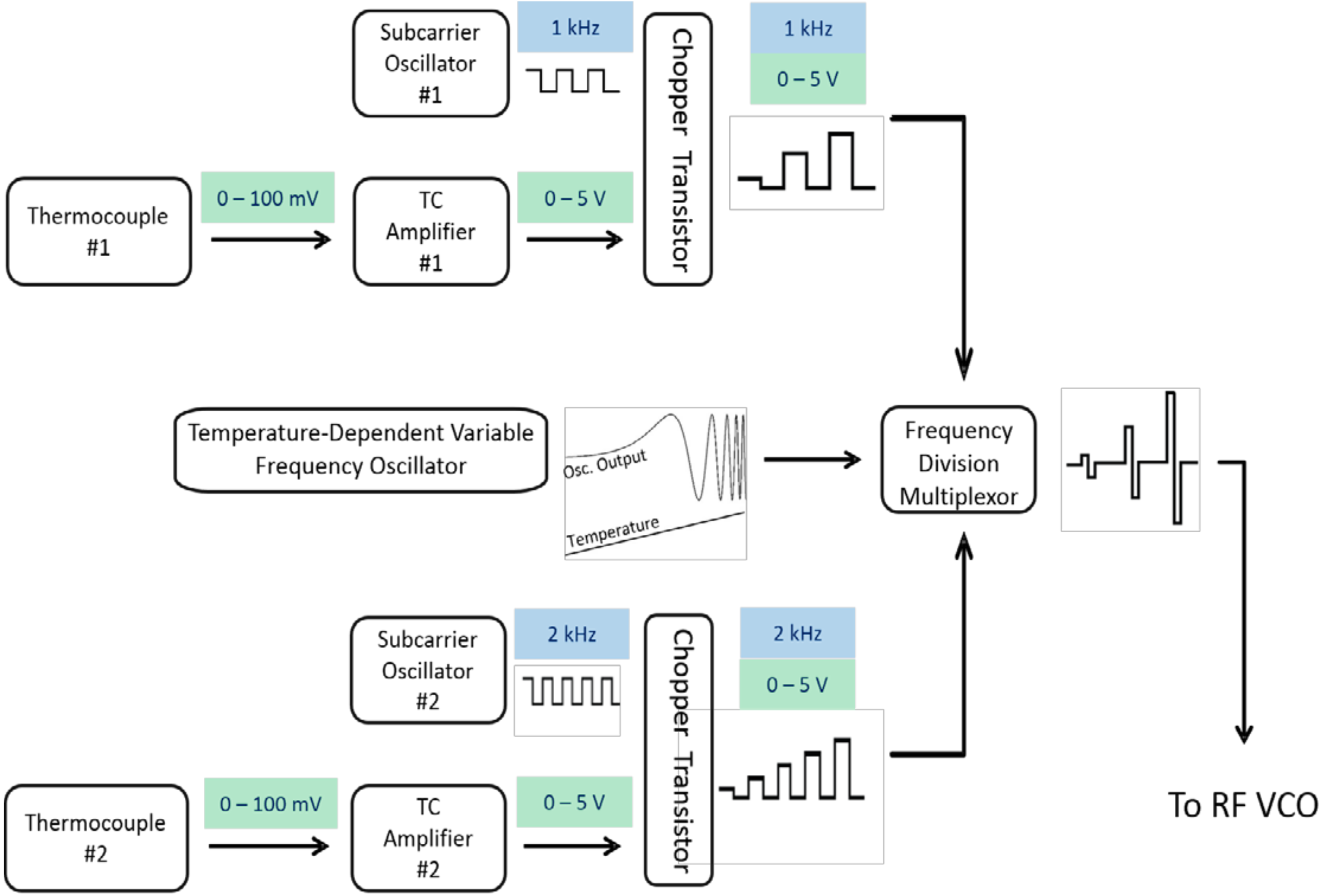


Wireless Telemetry System



Antennae, circuit board, and electrical run materials, die attach and wire bond processes all being optimized for functionality and stability at 550C and high g-loads

Multi-Channel Signal Conditioning Design



Multi-channel signal processing a must for multiple sensors on a turbine component

Circuit and Components tested to 550 ° C

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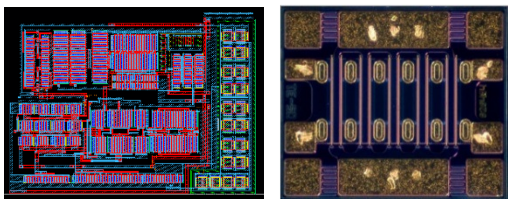
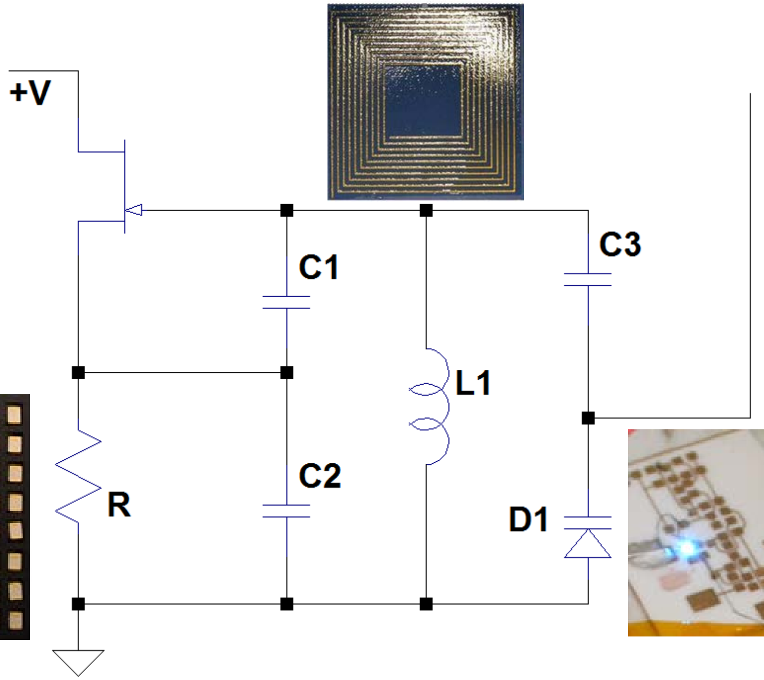
$$y(t) = A_c cos(2\pi f_c t + \frac{A_m f_\Delta}{f_m} sin(2\pi f_m t))$$

Op-Amp



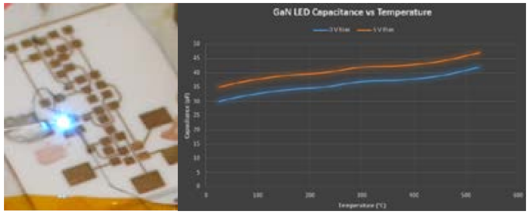


Baseband Signal

$$f_c = \frac{1}{2\pi\sqrt{L}}$$

$$f_\Delta \propto \frac{1}{2\pi\sqrt{\Delta C}}$$

Capacitor



Varactor

- **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**

SiC Integrated Circuits – Process BJT (KTH Stockholm)

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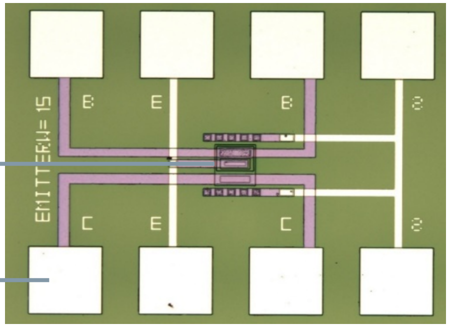
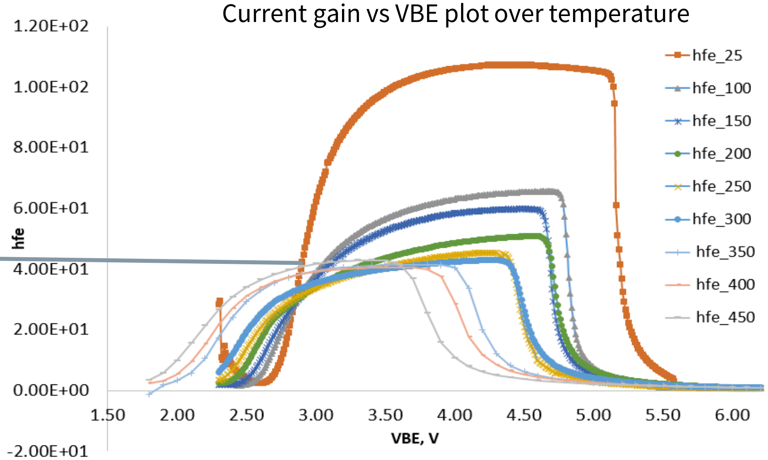
- Fabrication started on four wafers, out of eight wafer slots
  - Rest of the wafers are kept for second fabrication run
- UARK reticle size was 10 mm by 5 mm
  - All circuits were designed using 40 **µm by 15 µm emitter width NPN devices**
  - Reticle was diced into 5 mm by 5 mm dies
  - I/O PAD size was 100 **µm by 100 µm**
- Characterization for the devices were performed over temperature
  - Current gain dropped from 105 at 25 °C to 47 at 450 °C.



Fabricated NPN device

Current gain vs VBE plot over temperature



Further Optimization needed to maintain Current gain

SiC Integrated Circuits – Process CMOS (Fraunhofer)

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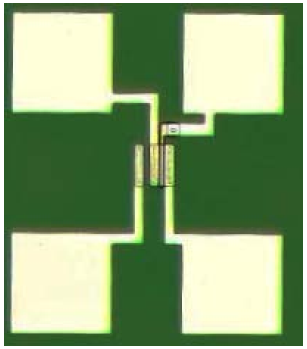
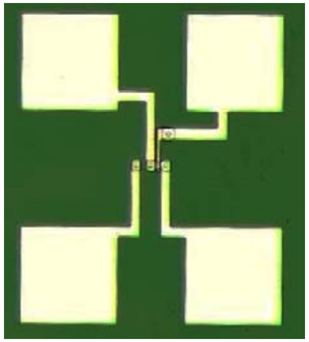


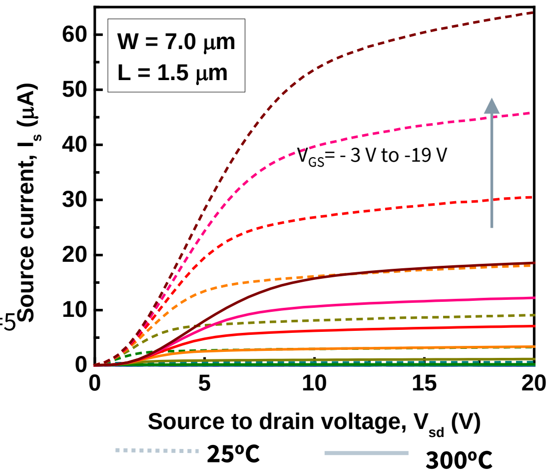
Fabricated PFET Device (W=7 µm, L= 1.5 µm)



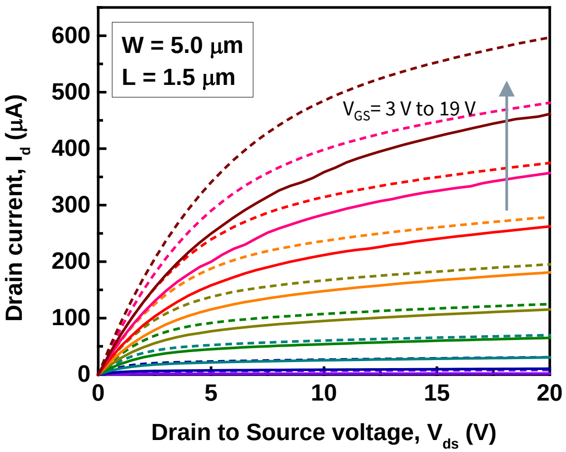
Fabricated NFET Device (W=5 µm, L= 1.5 µm)

- Reticle size was 20 mm by 15 mm
  - Characterization on the devices were performed over temperature
- Wafer resolved the poly patterning issue
  - NFET showed acceptable I-V characteristics
    - VTH drops significantly over temperature
  - PFET provided poor I-V results
    - Due to higher P+ contact resistance

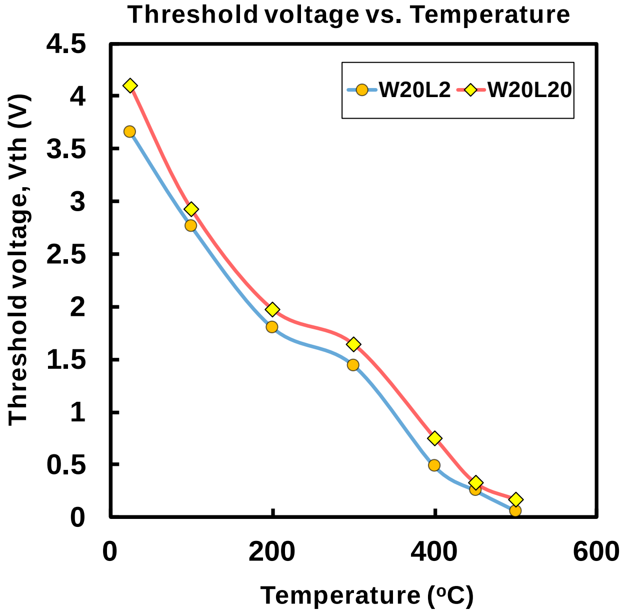
DC output characteristics of PFET



DC output characteristics of NFET

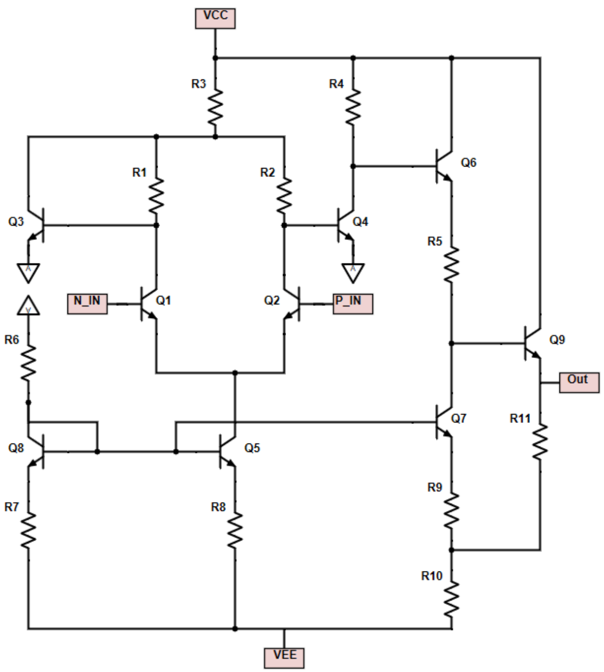


Threshold voltage drop of NFETs over temperature

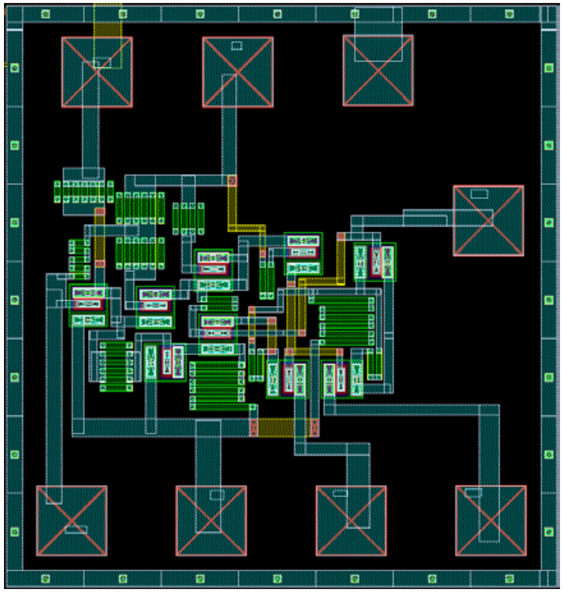


Optimization of PFET with new Reticle sizes

SiC Signal Conditioning Block: Circuit Testing - OPAMP



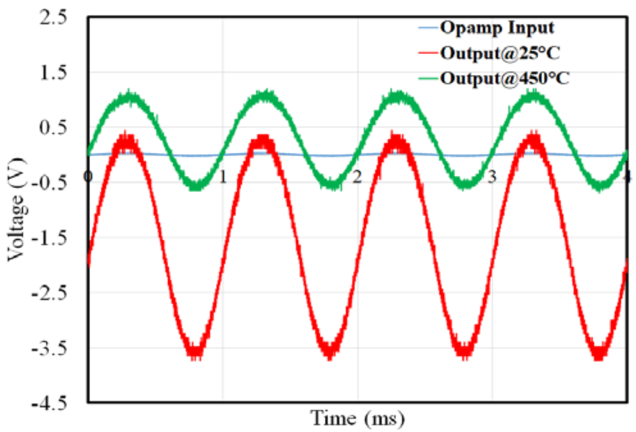
OPAMP Schematic



OPAMP Layout

Test Method:

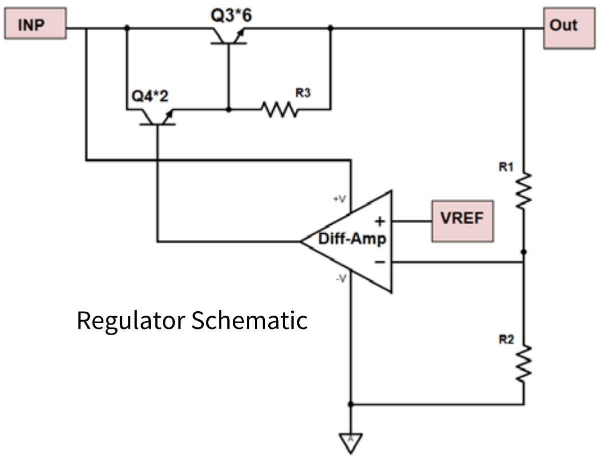
- Device was placed on the Signatone™ thermal chuck
- DC power supply provided VCC and VEE, which were 10 V and -4V respectively
- Inverting input (N_IN) was set to 0 V and non-inverting input (P_IN) was fed from a function generator
  - 1 kHz 50 mV_{Pk-Pk} sinudoidal-signal
  - Input signal offset set to 0 V
- Opamp output was observed from oscilloscope with 13 pF capacitance



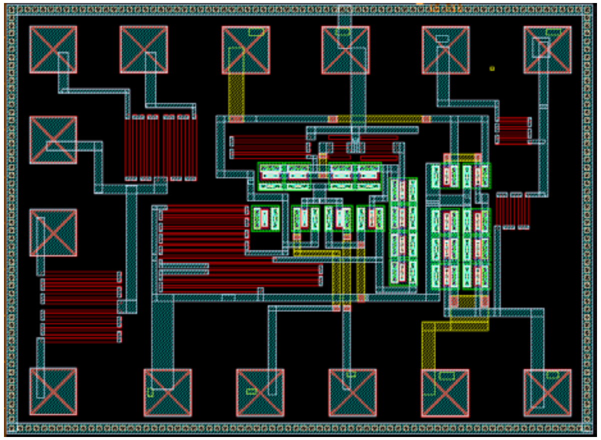
OPAMP Output at 25°C and 450°C

- **Opamp input base current equals 5 µA at 25°C**
  - **At 450°C base current increases to 10 µA**
- **Input resistance of the opamp equals 9 kΩ (needs to be in MΩ)**

SiC Signal Conditioning Block: Circuit Testing - Regulator



Regulator Schematic



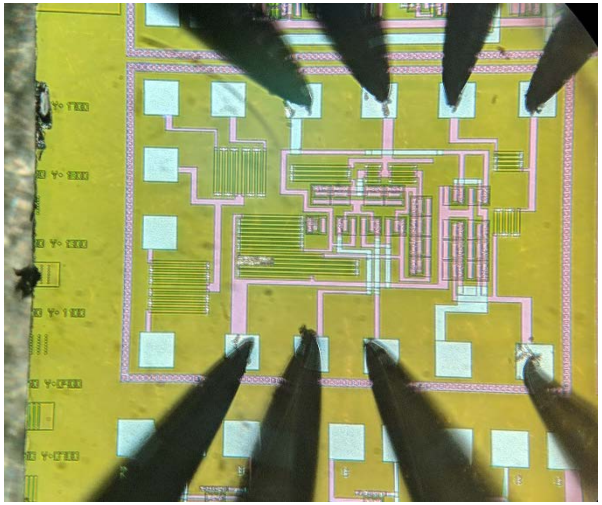
Regulator Layout

Test Method:

- Device was placed on the Signatone™ thermal chuck
- Applied voltage on the INP node varied from 20 to 40 V
- Applied reference voltage was 4.5 V
- Output load current varied from 0 mA (no load) to 18 mA (full load) using potentiometer
- Output was measured using multimeter

Temperature (°C)	Regulator output @ No Load (V)	Regulator output @ 18 mA load (V)	Load Regulation (in V/mA - low is better)
25	9.13	8.46	0.037
450	9.72	8.79	0.0517

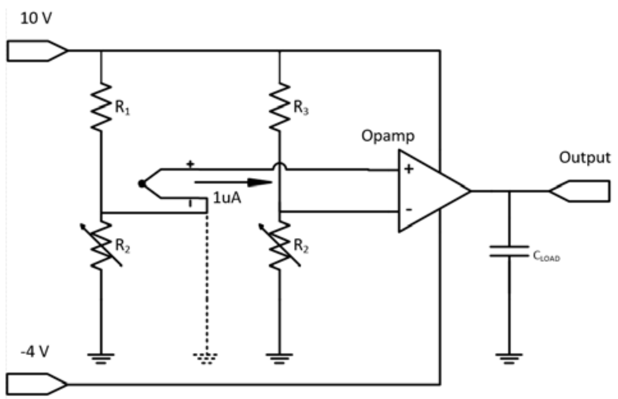
Load Regulation at 25°C and 450°C



Regulator Die on the Chuck at 450°C

Acceptable Load Regulation

SiC Signal Conditioning Block Testing



Schematic showing TC connection to the SiC opamp in open-loop configuration

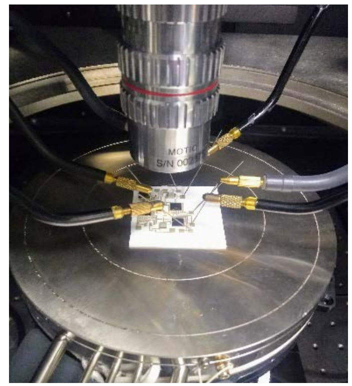
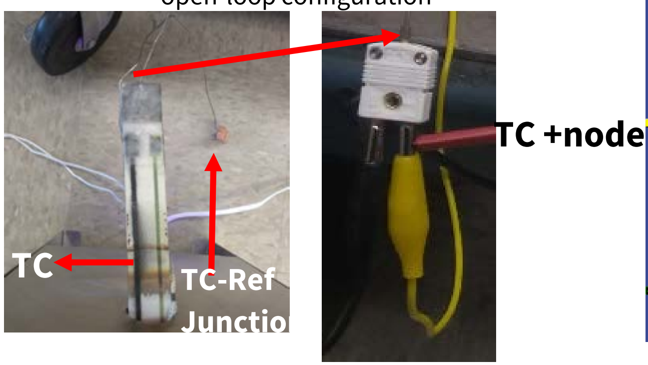
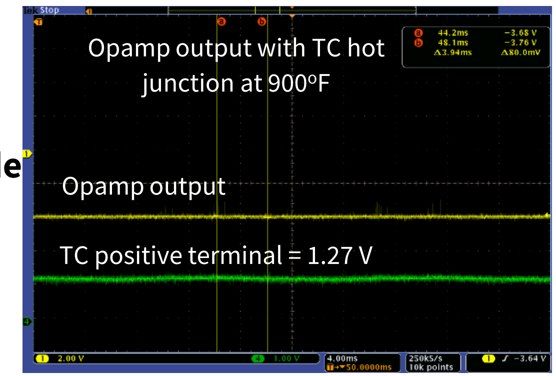
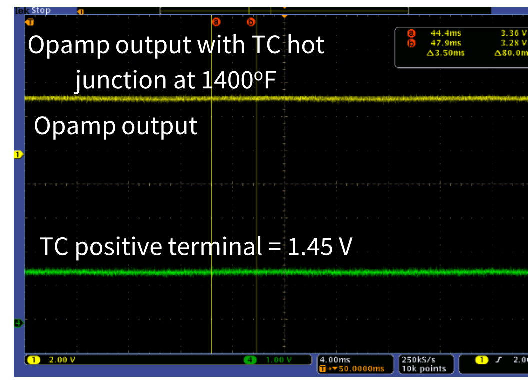


Image of the LTCC board probed on the chuck

Image of the Tabletop oven

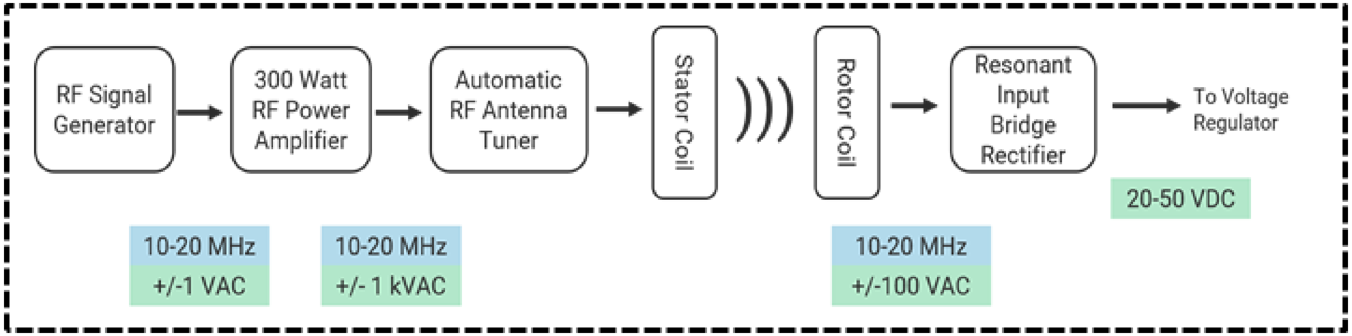


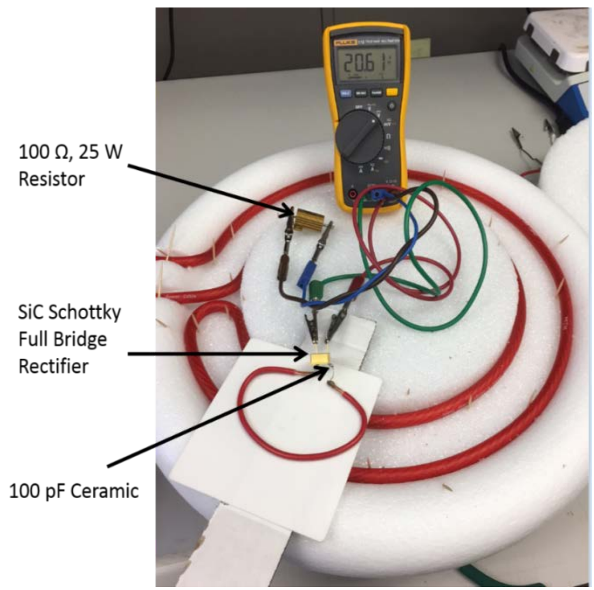




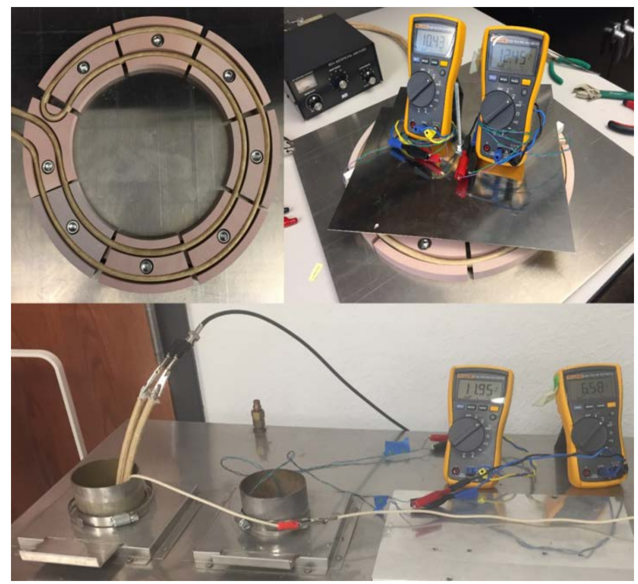
- The TC provides 1 μA but leaks from BJT based working circuit need to be addressed
- Increasing the opamp input impedance would resolve this issue by lowering the base current
- The opamp has high negative swing when INV node is higher. Currently, redesigning the output stage of the opamp

Revised Power System





Room Temp Prototype



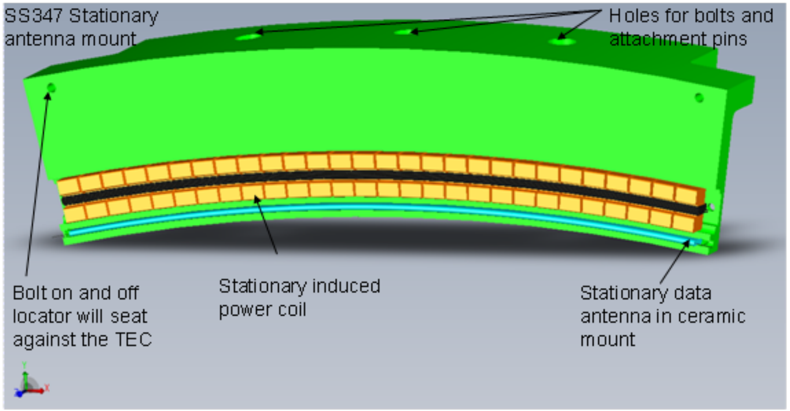
> 550 ° C Prototype

Improved system results in > 10X in power transfer due to increased quality factor of the resonant system, and enhanced coupling efficiency of the induced power setup.

Engine Test Preparation

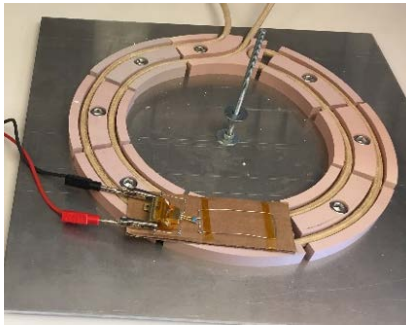
Old design:

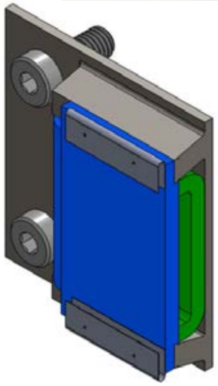
Complex wound magnets, Heavy magnetic holders
Many insulated windings next to each other; shorting ruins a whole section.
Insulation of windings was stiff ceramic coating
Insulation of outside-to-inside cables was not vibration resistant

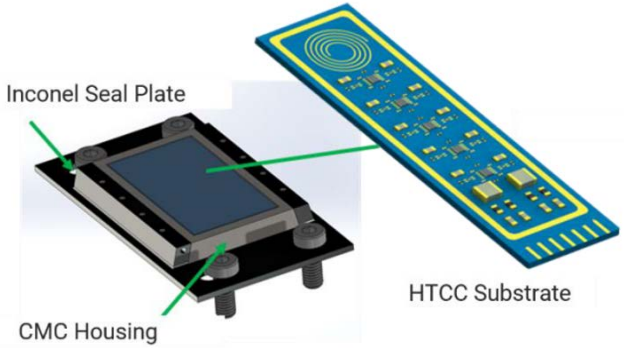


New design:

No magnets, A single cable, wound in a circle twice
Rests inside insulating fixture, doesn't touch so won't short
ZERO electrical connections inside turbine
Mass of "holder" is much, much lower, comprised of CMC
Power transfer is 8x higher, and very temperature independent
Tests up to 650 ° C show good power transfer (Aerodyne spin rig)







Design efforts initiated for engine test insertion of row 1 blade/vane for June 2020

Operational Based Assessment

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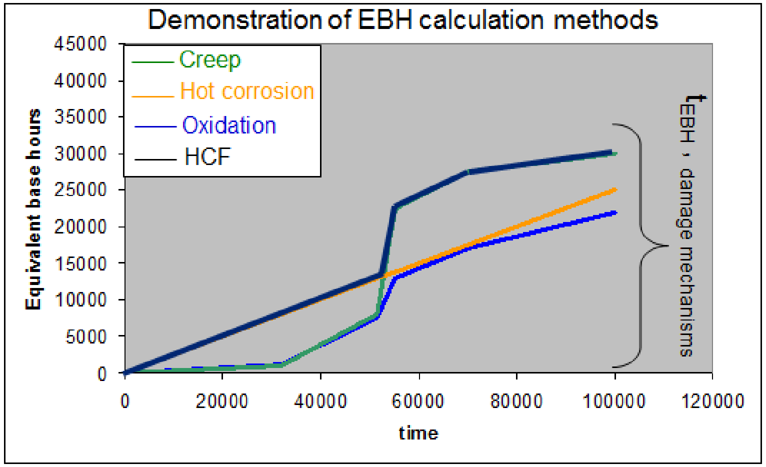
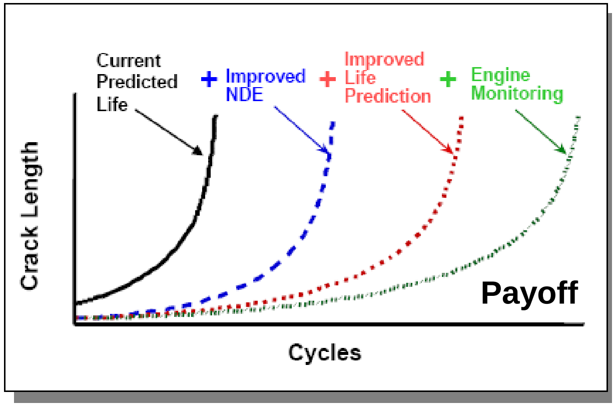
Prognostic health monitoring system comprises (a) instrumented components with relevant sensors, (b) telemetry for data acquisition/transmission to electronics for processing sensor signals, and (c) system architecture for analyzing sensor data, perform statistical prediction analyses for health forecasting.

Onset of Failure modes





Materials System Testing, Simulation and Performance [Design, Materials]

In-situ Monitoring [Materials, Instrumentation, NDE, Diagnostics]

Multi-disciplinary effort

Physics-based Probabilistic Life-Prediction Models

(Near) Real time data, Field feedback, analysis and prognosis [Service, Materials]

Remaining Life Calculation for Forecasting [Team]

Utilizing Engine Feedback to Materials design/life forecasting

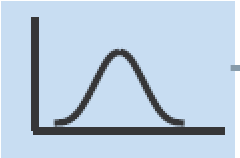
Stochastic Methods for Turbine Component Life Estimation

SIEMENS

Surrogate Model based Probabilistic Analysis

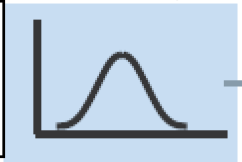
Fleet / Individual Data from Sensors

Temporal Blade Path Temperature Variation



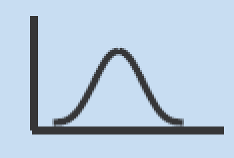
Historical Statistics from Manufacturing Variability

TBC Coating Uniformity



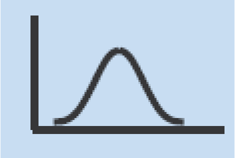
Test Data

Material Properties



Statistical Correction to Models from Past Analytical Estimations

Model Correlations



PDFs of Variables

Surrogate Model-based Probabilistic Life Estimation

- Adaptive Sampling
- Dimensionality Reduction using Auto Encoders
- Artificial Neural Network based Multi-variate Meta-model
- Bayesian Optimization for fast convergence
- Monte-Carlo sampling of the meta-model to predict probability of failures and convert to fleet reliability

Automated Simulation Scripts

Deterministic Tool Chain

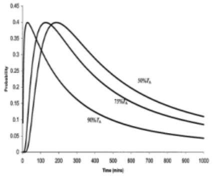
Blade Path Analysis Conjugate Heat Transfer

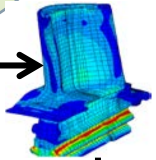
Thermomechnical 3D FEA

Life Prediction (creep, LCF/HCF, corrosion.)

Benefits

- Stochastic Prediction of Reliability, Life EBH
- Hierarchy of Contributing Factors
- Quantifiable risk level across all operating space





Close the loop on using service data for design improvements

Operations-based Predictive Analytics (use case: Life Estimation)

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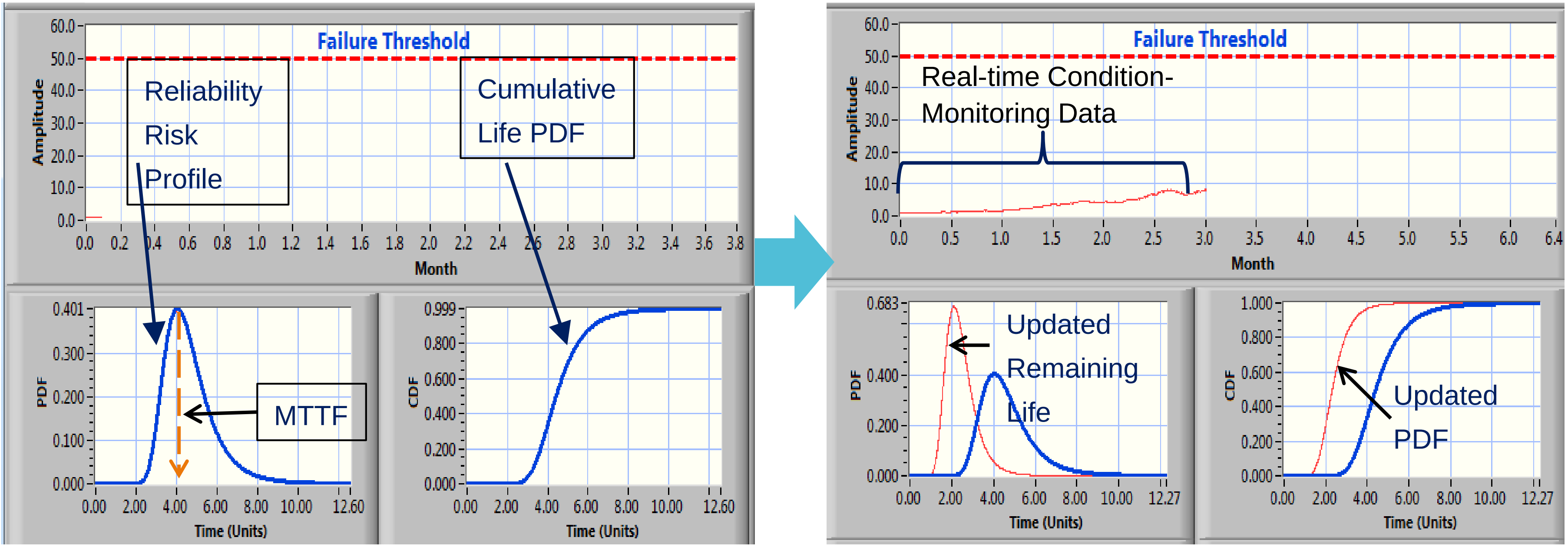
From Probabilistic Design Life Assessment to Operations-Based Remaining Life Prediction



- Collect/Organize Maintenance Records
- Visualize and Analyze Failure Events
- Probability Distribution & Reliability Metrics
  (MTTF & MTBF etc.)
- Fleet-wide metric – cannot be individualized

- Identify & Collect Historical/ Real-time Data
- Visualize & Define Baseline Patterns
- Integrated Life Consumption Calculations from Meta-models
- Remaining Life Estimation
- Stochastic Prediction of Future Life for user-defined Operations
  (What-if scenarios)

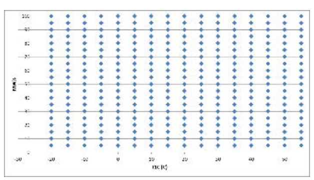
Design of strategic architecture to assess the current state of the machine and predict the future state based on predicated continued operation

Case Study of TBC Life for Row 1 Blade

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.

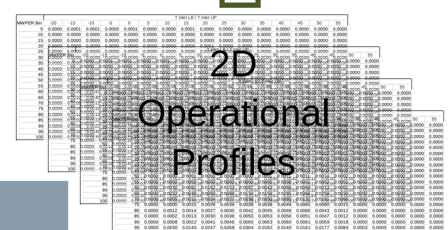
Each existing engine's operation conditions and operation hours (OH) in service have been analyzed and summarized into an operational profile by two parameters: normalized power load (MW%) and compressor inlet temperature (T1C)

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

Unrestricted

Summary

- **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 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**
- **Since the power and telemetry are both integrated on the same substrate, the method for mounting the board had to be completely re-imagined.**
- **Initial insights into duty cycle life assessment utilizing operational profiles for turbine components**