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Siemens/ Wolfspeed | April 11th 2018

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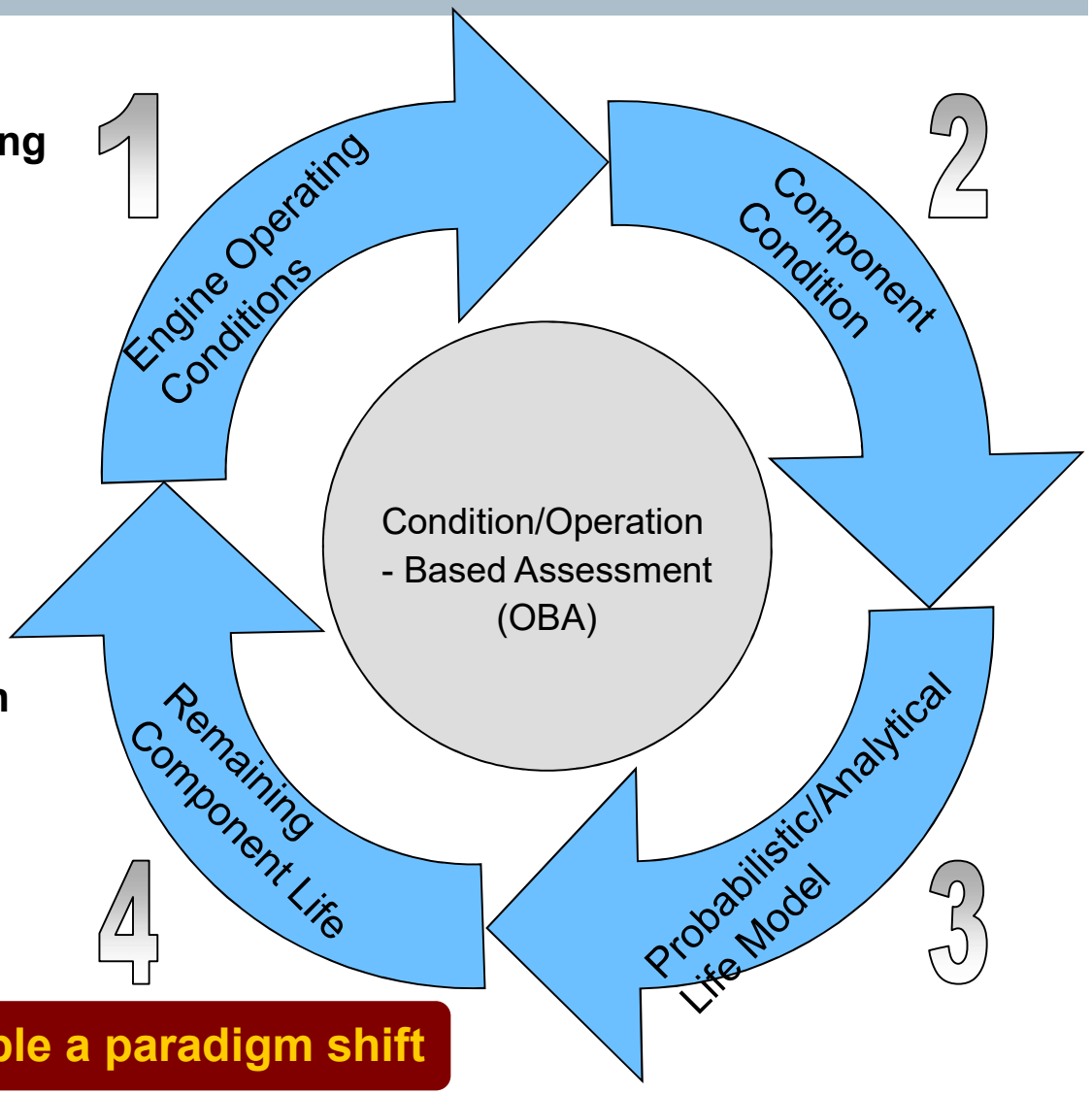
- Harsh environment instrumentation provides critical information regarding component condition
- Such information provides data for:
  - Test engine evaluation
  - Design model validation
  - Engine performance
  - Engine diagnostics
  - Conditioned based assessment
- Improvements over existing instrumentation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



Advanced sensor systems enable a paradigm shift

Anatomy of a Smart Component

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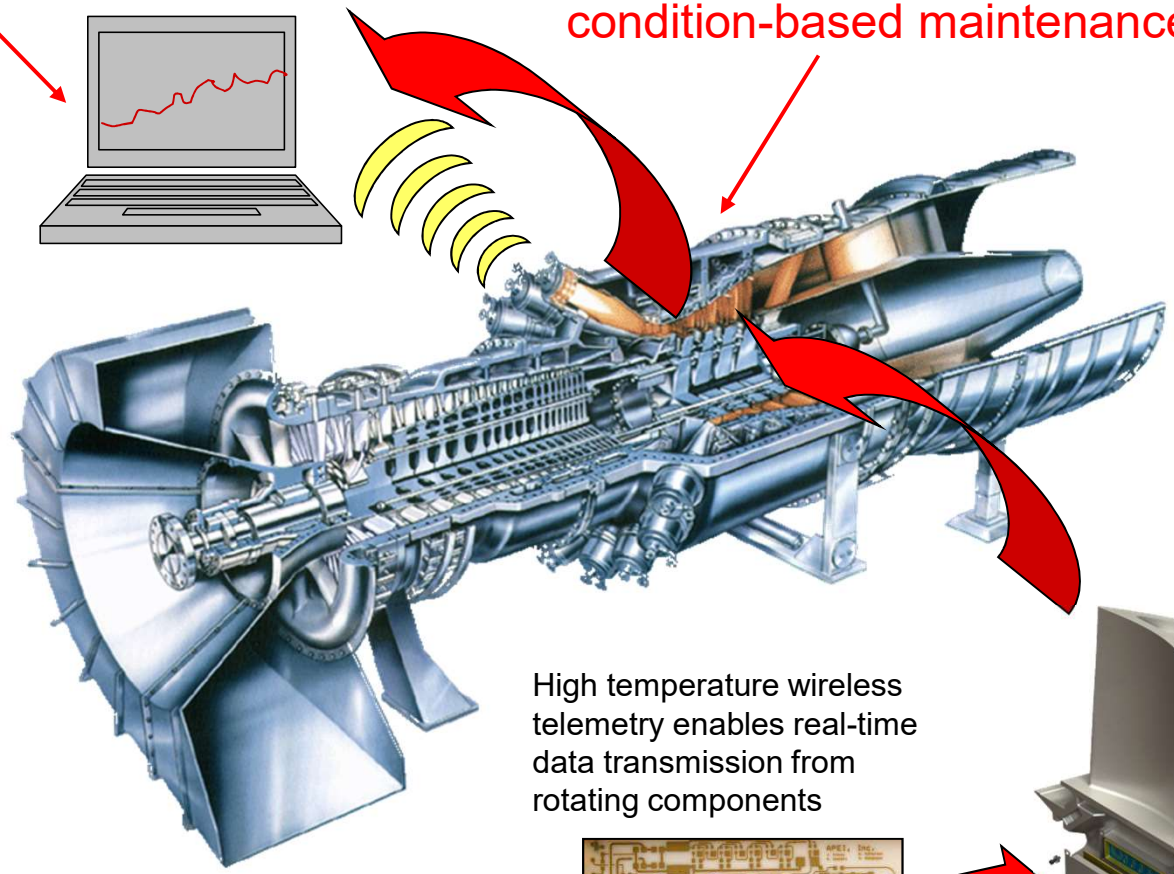
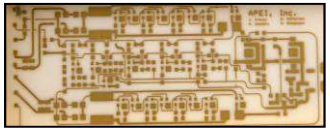
Data acquisition enables real-time input to life models

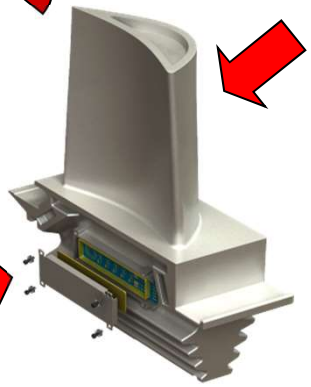
Real-time monitoring of component condition enables condition-based maintenance

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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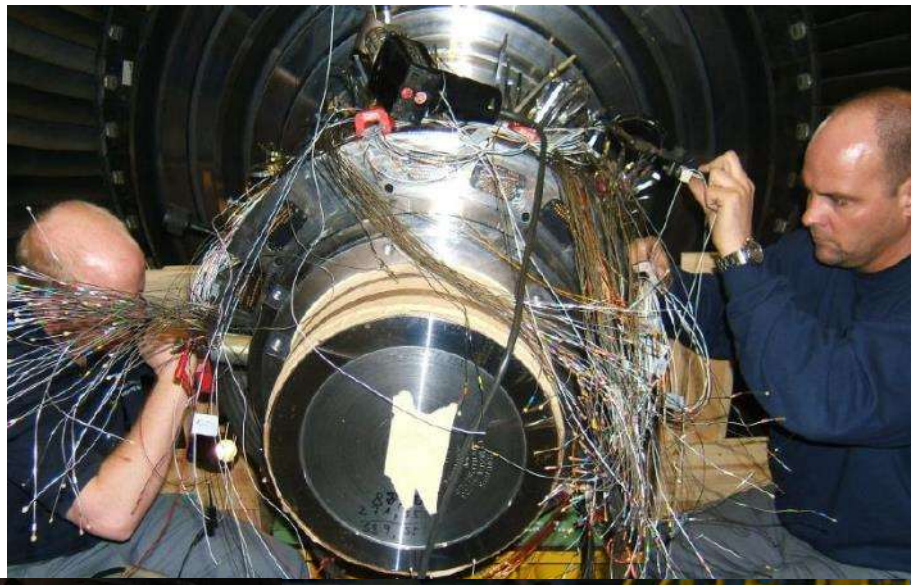
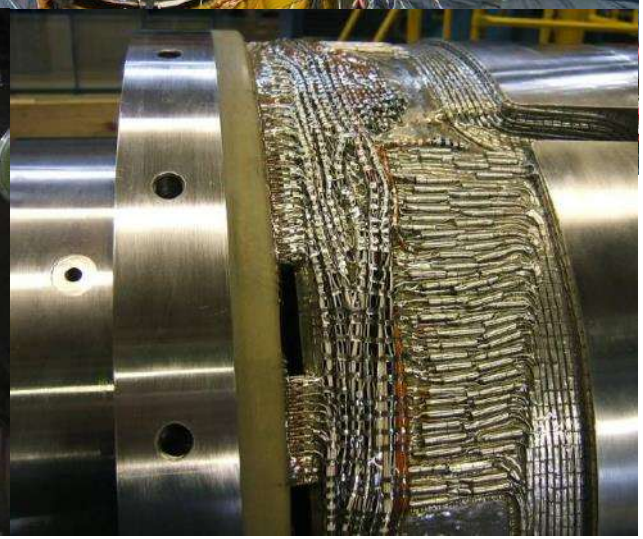
Current method of blade instrumentation

- 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





Benefits If Successful

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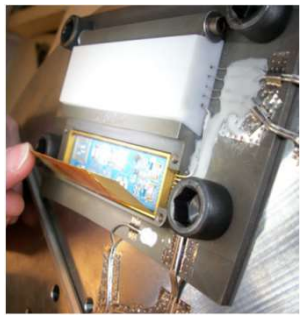
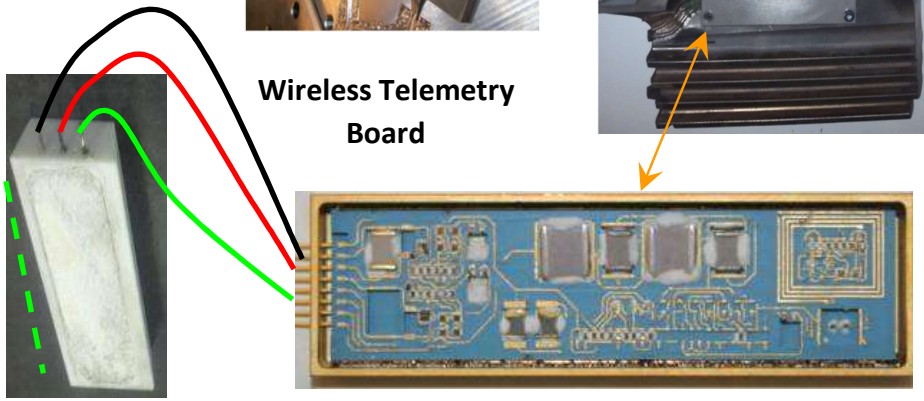
Online Condition Based Monitoring

- 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





Wireless Telemetry Board

Feedback for Design Optimization

- Online Blade Condition more widespread
- No wires → higher accuracy
- Strain amplitude error ± 30% → ± 5%

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

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HT Capable Thermally Sprayed Sensors

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

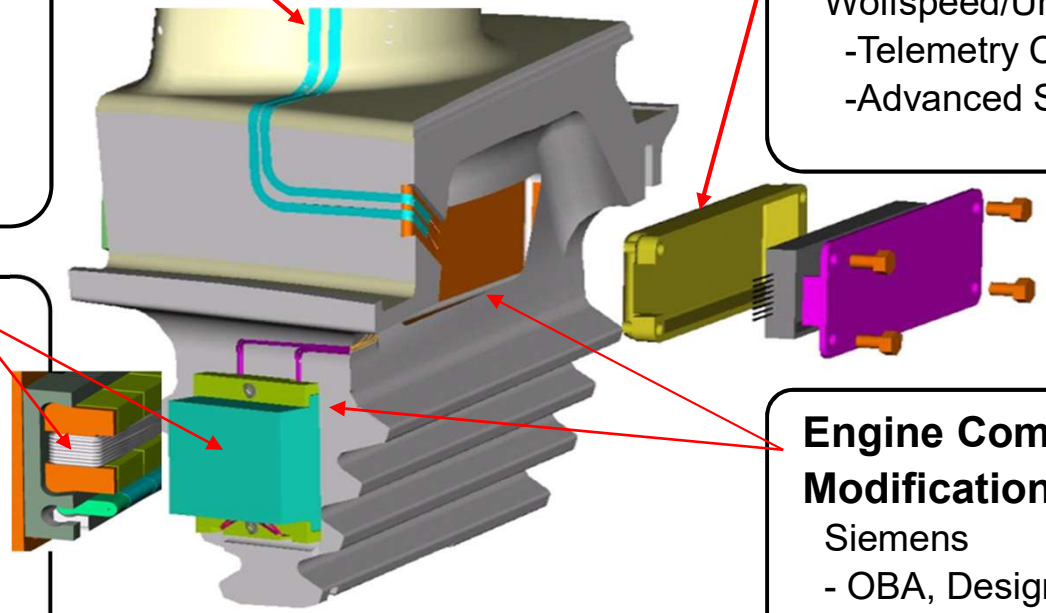
Curtiss Wright
- -Sensor Fabrication

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

Thick Film Sensor Deposition via Thermal Spray

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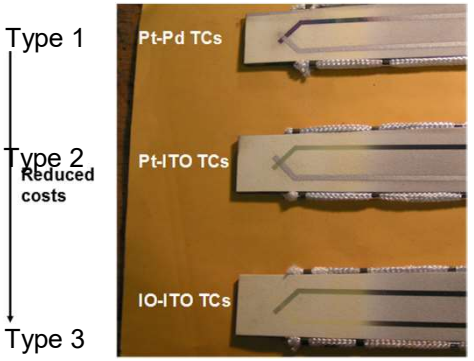
Thermal spray enables integral sensors to be deposited on coated and uncoated components with complex shape.

Sensors may be incorporated with minimal component and performance modifications.

The process can be done at high speeds, efficiently, and at low cost.

Sensor deposition may be performed using masking and conventional thermal spray hardware

Thermocouple deposited on a performance and calibration test bar.

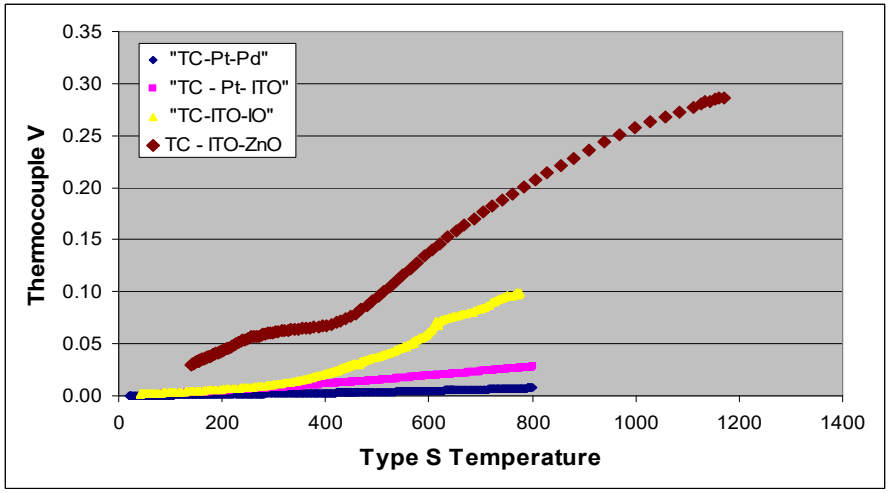


Thermocouples with various compositions are being developed and tested.

The greater the EMF output, the better the signal-to-noise (S/N) ratio of the sensor.

The metallicTCs are the least sensitive, but are nearest to production ready. The more advanced compositions will be phased in as their development status matures.

Multiple ceramic compositions being evaluated for p type thermocouple, ITO is a stable n type thermocouple



Ceramic thermocouple offers high signal to noise ratio at high temperatures

Isothermal Testing of ITO-LaSrCoO TC

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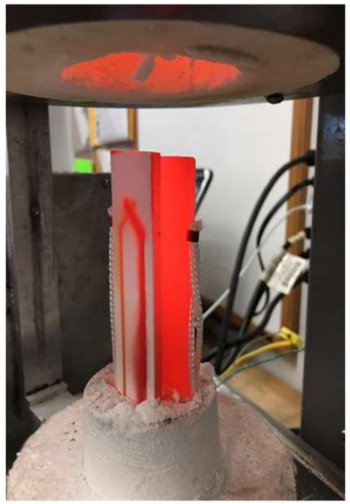
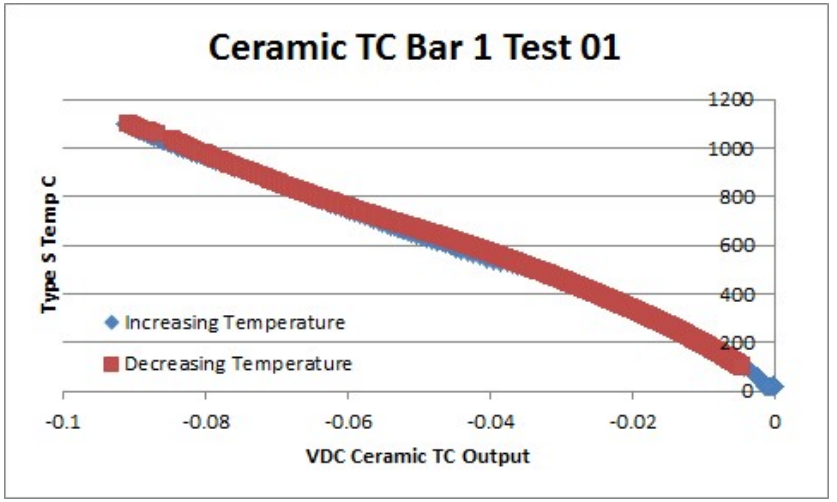
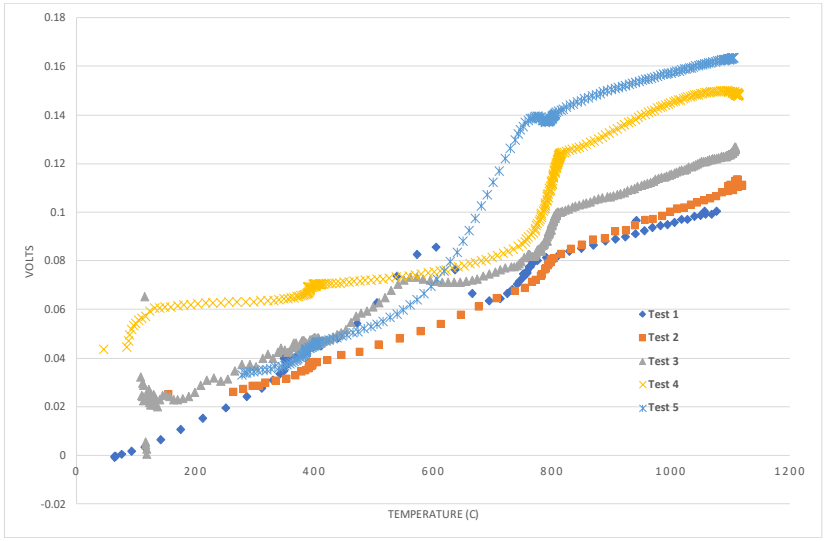
Isothermal heating with 2 TCs evaluation for reproducibility.



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

Flame Test on Actual GT Blade/ Wireless Telemetry

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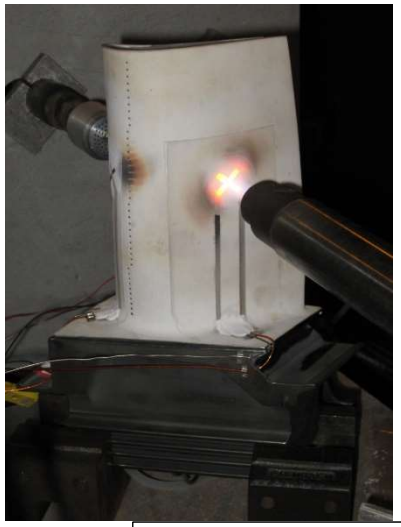
Type S TC – 5C between 1200-1400C



	1200C	1300C	1400C
Concave	-3.1	1.0	4.1
Ldng Edge	-4.7	-2.9	1.5
Convex	-2.6	-3.1	1.6
Grand Average		-0.9	
Std. Dev. of Grand Ave.		3.0	
Random Uncertainty		6.9	95% Conf.
	d.f.	8.0	

Excellent repeatability/ reproducibility observed on a component

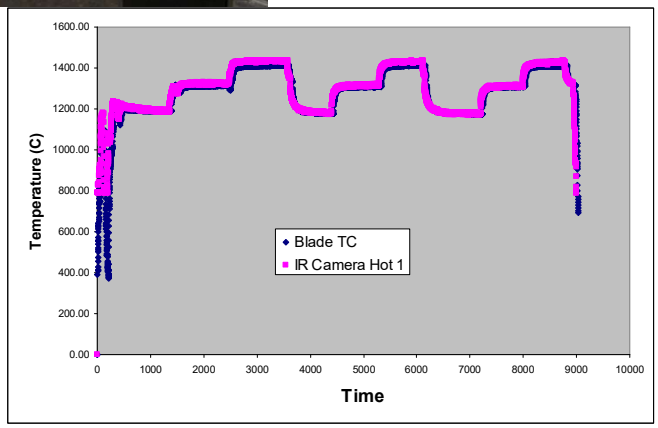
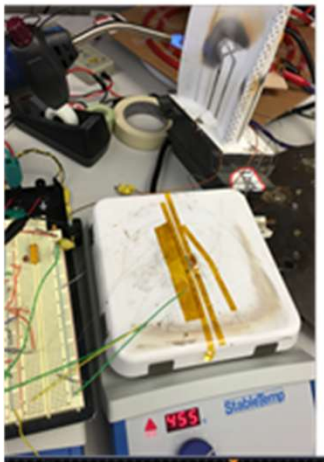
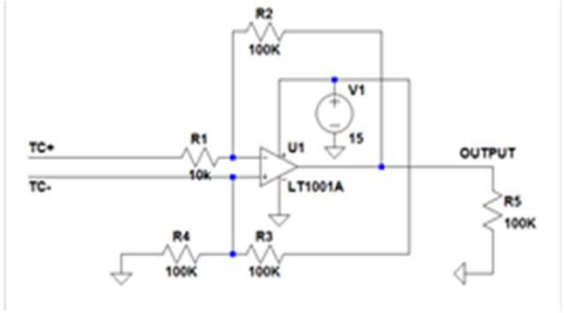
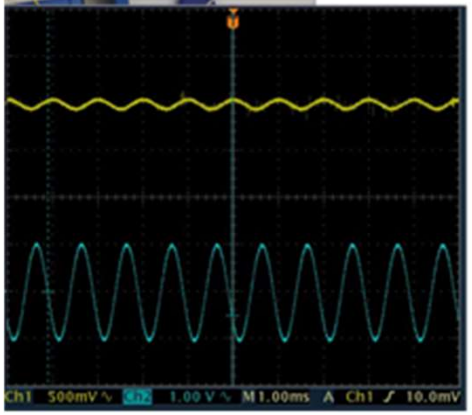


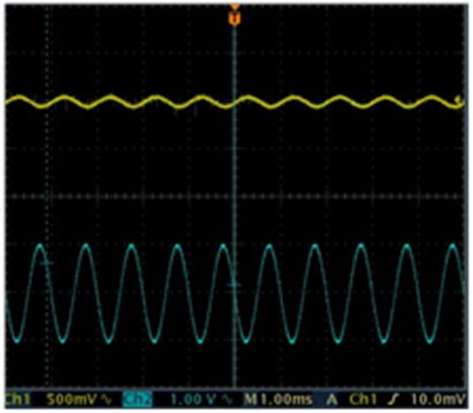
Table top testing with Wireless telemetry





TEMPERATURE (°C)	25	250	450
OUTPUT for 0 mV TC Input	7.5	7.49	7.49
OUTPUT for 3 mV TC Input	7.458	7.451	7.450
DC GAIN (V/V)	14	13	13.3





To showcase the gain performance and linearity, the room temperature (bottom left) and 450 C (bottom right) response of the same circuit to a low voltage sinusoid is shown. In both the DC and AC responses, the gain is between 13 and 14 V/V, which is same as simulated values with a silicon opamp model.

Structure of a Wireless Telemetry System

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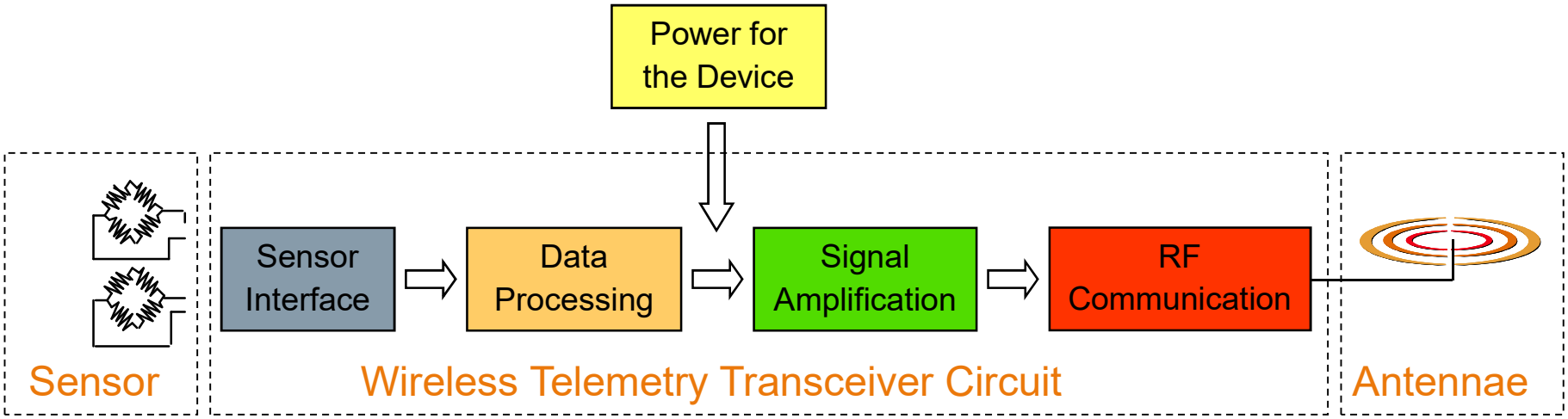

- **Hardwiring rotating parts through rotor is expensive and time consuming.**
- **Wireless telemetry has been used for many years, but not uncooled at high ambient temperatures.**
- **Antennae, circuit board, and electrical run materials, die attach and wire bond processes all must be optimized for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

Structure of a Wireless Telemetry System

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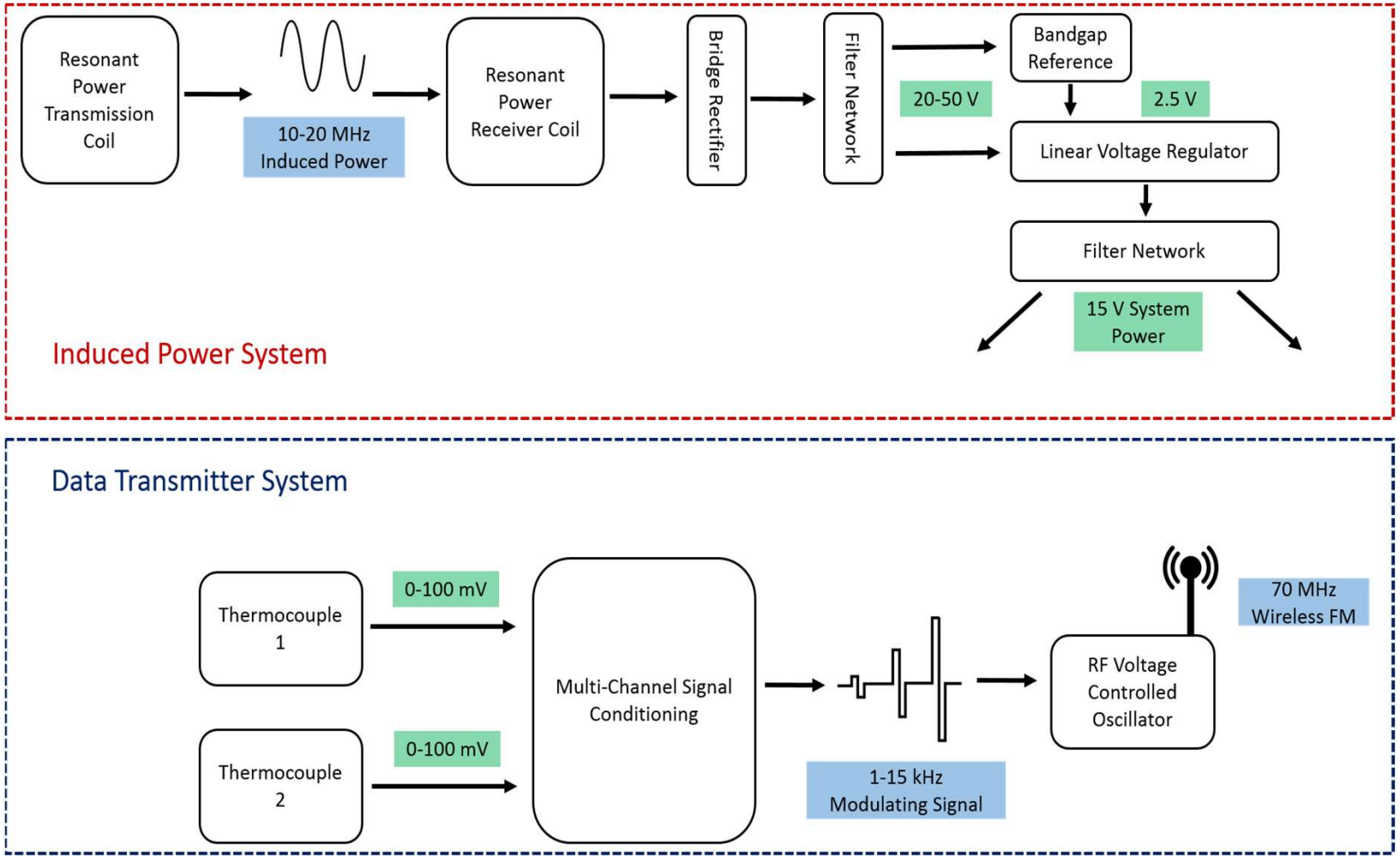

Antennae, circuit board, and electrical run materials, die attach and wire bond processes all being optimized for functionality and stability at 550C and high g-loads

Revised Power System

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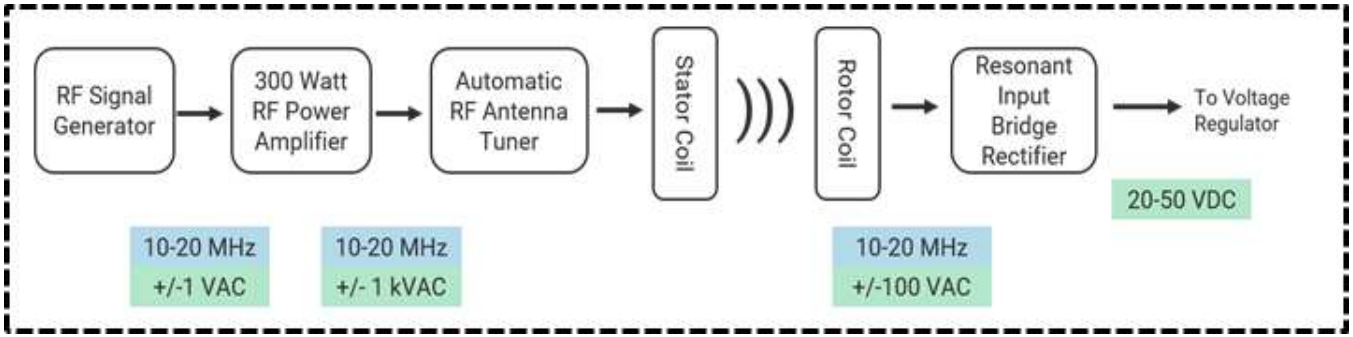
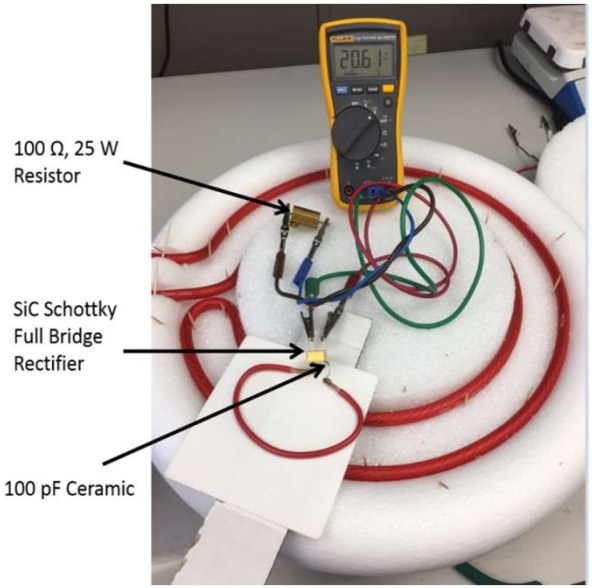
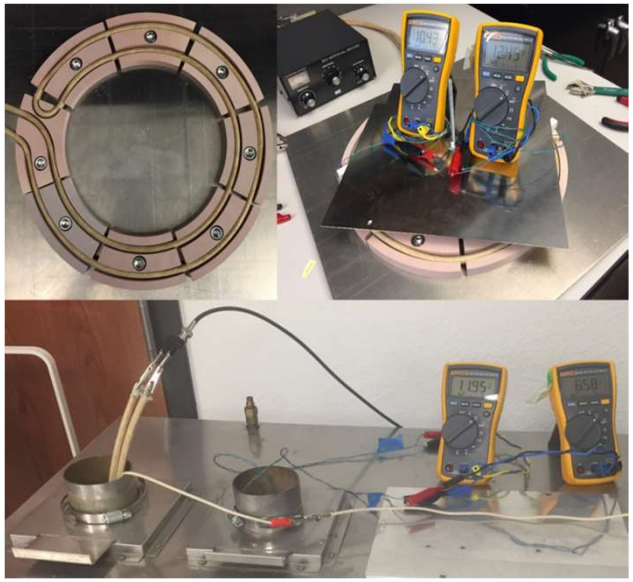




Room Temp Prototype



> 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.

Multi-Channel Signal Conditioning Design

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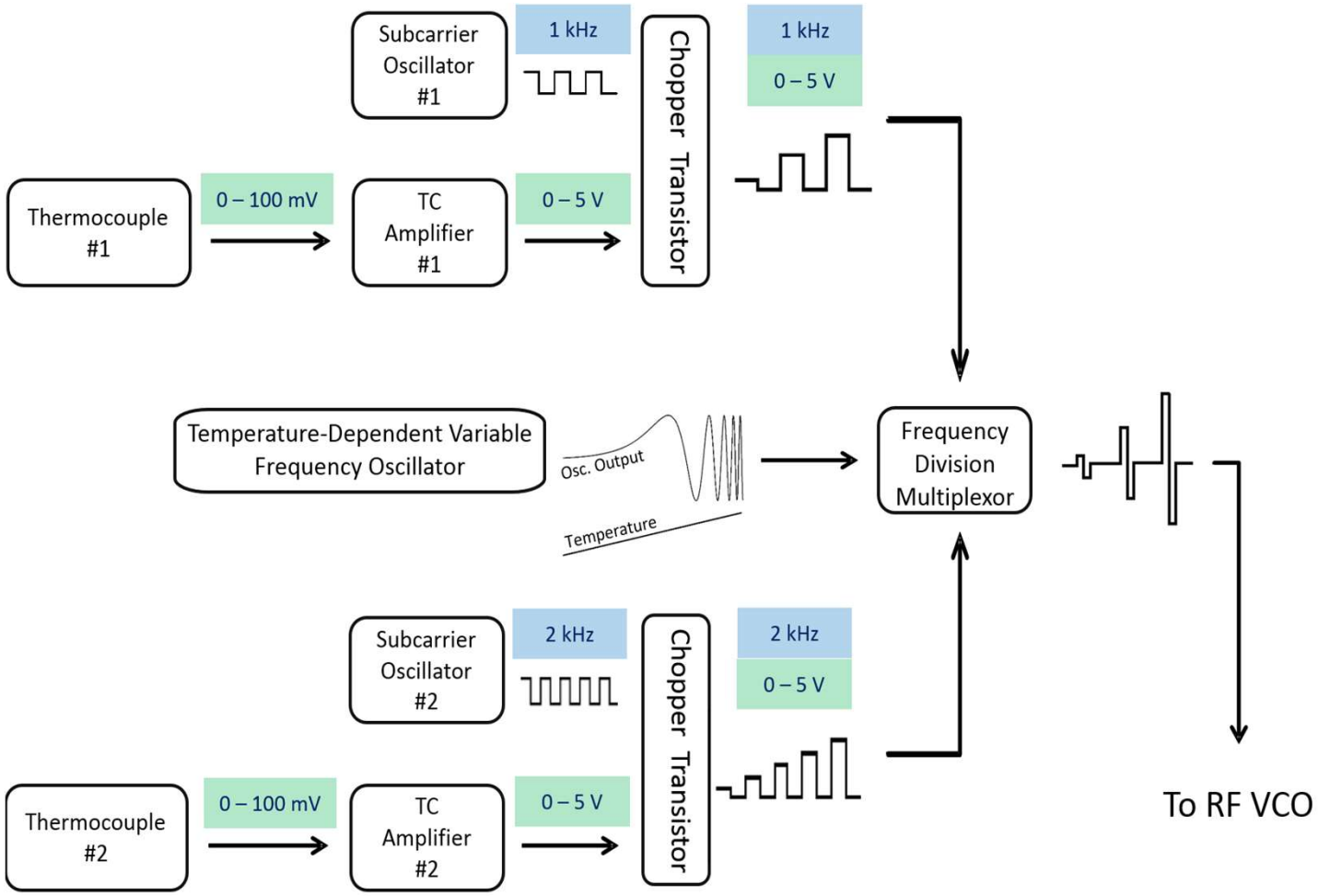

Multi-channel signal processing a must for multiple sensors on a turbine component

Signal Conditioning SiC ASIC

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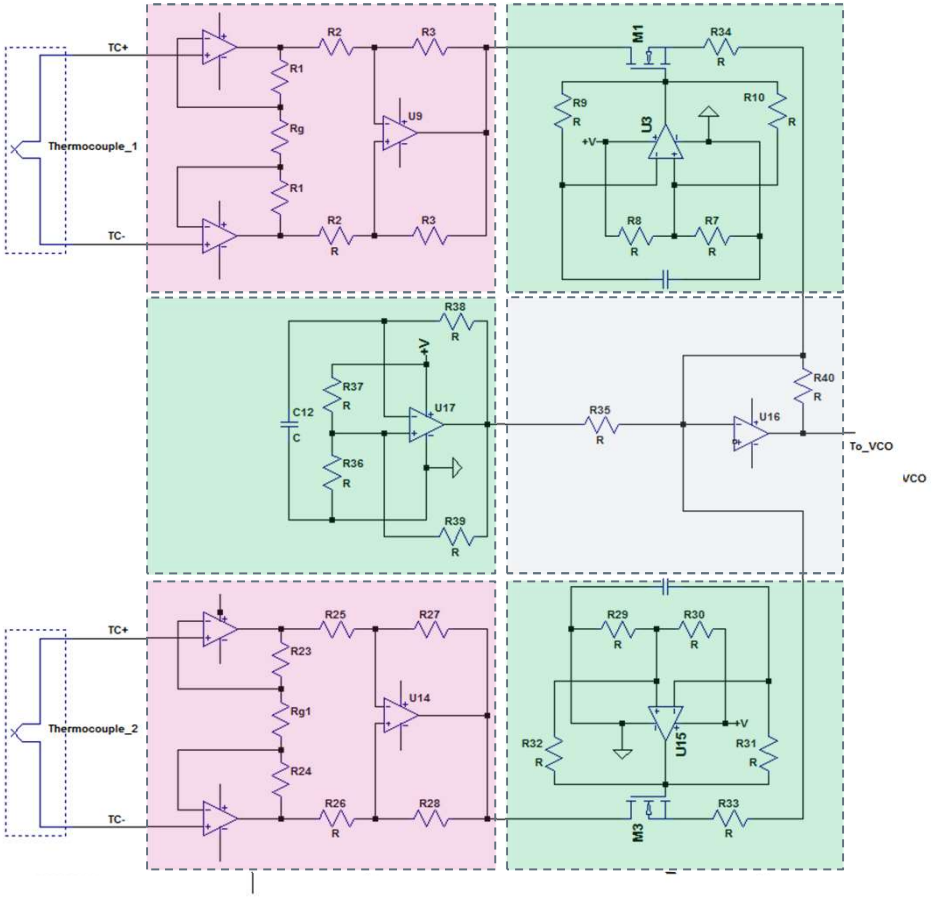

SiC application-specific integrated circuit (ASIC), comprising the entire signal conditioning chain (and eventually including the power conditioning circuitry as well)

Advanced Bond-wire Interconnection Schema

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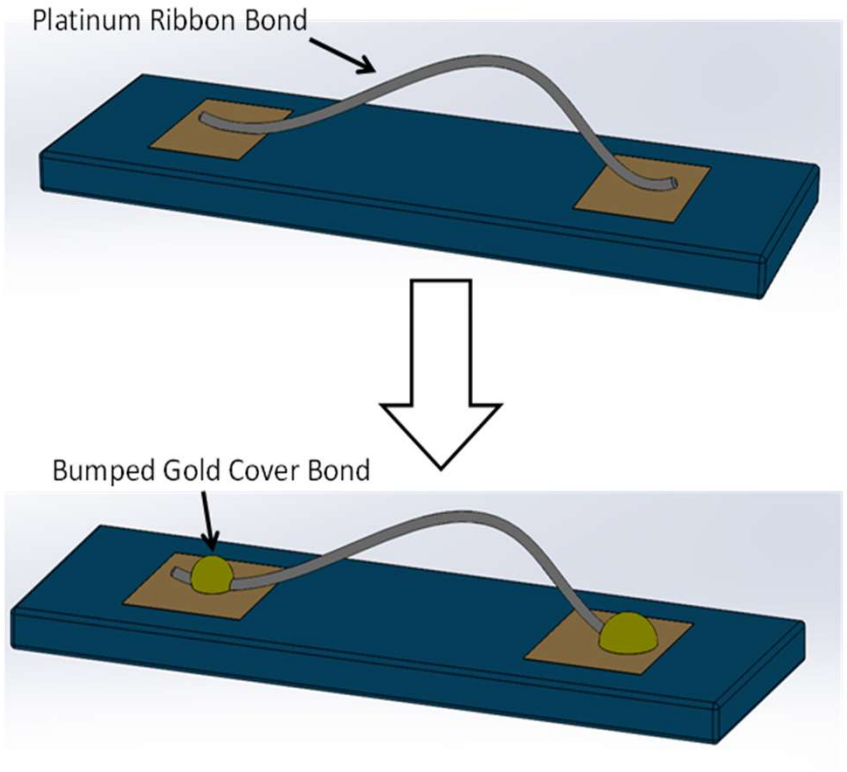

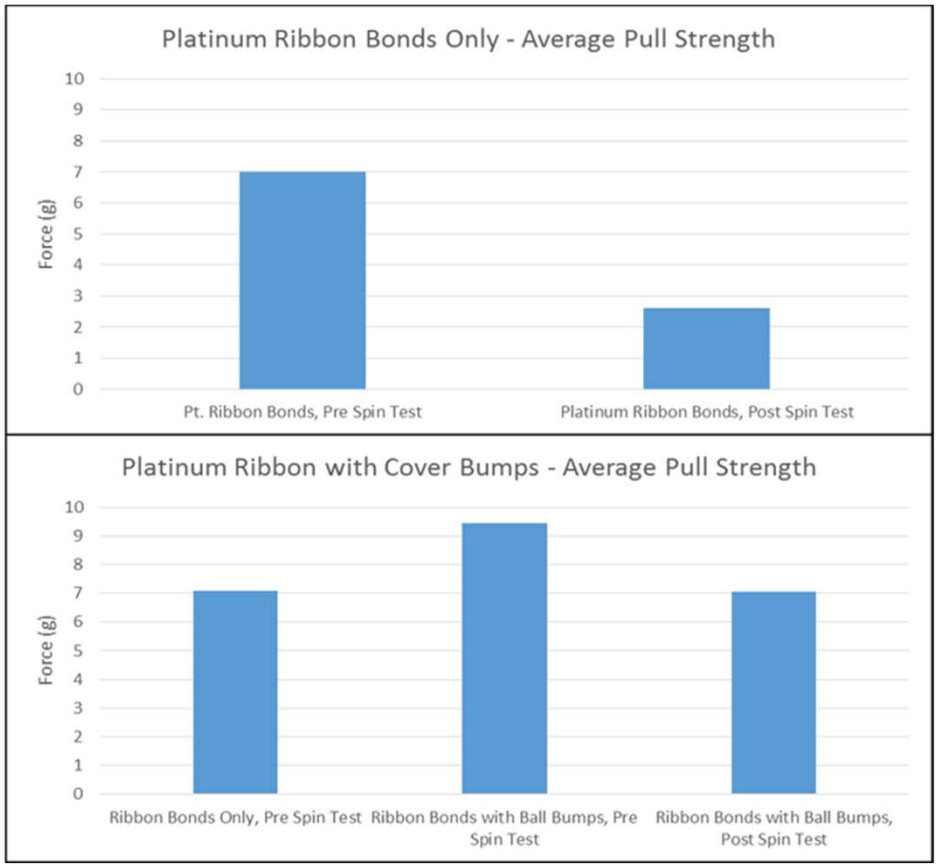

Increased reliability of the wire bond interconnections necessary to electrically connect the semiconductors to withstand both high temperatures and high g-forces simultaneously

Subcomponents tested to 540-550 ˚ C

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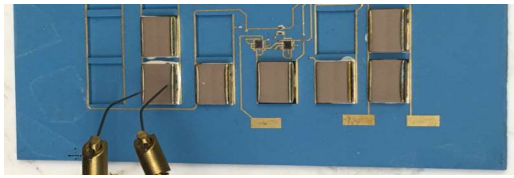
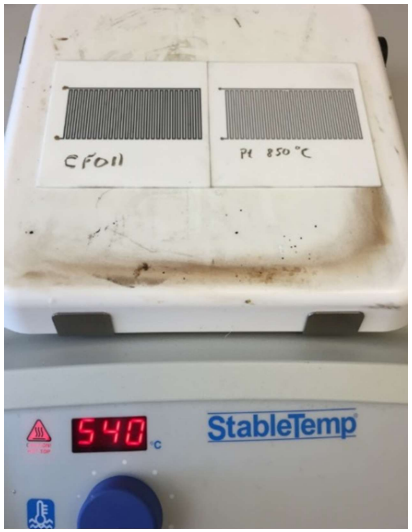
Varactor testing for FM circuit for 550 °C Operation

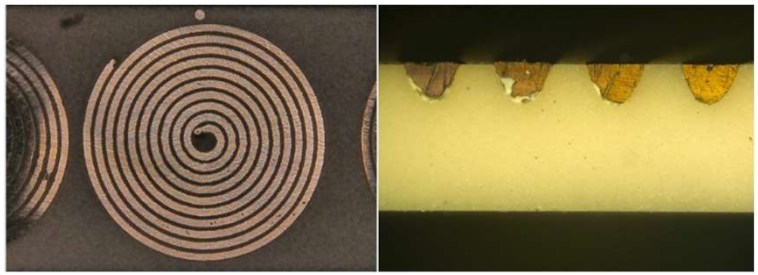


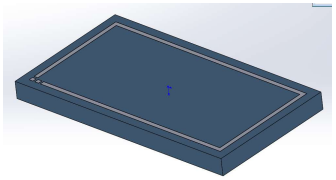
Capacitors functional but decline in capacitance by ~ 20% at 550 °C

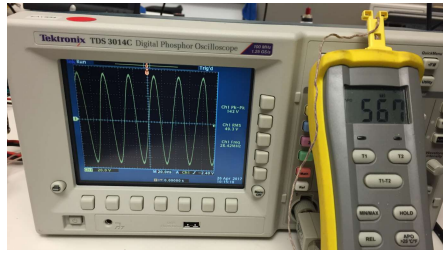
Various Resistor Pastes increase resistance from 20 – 200% from room temperature to 540 °C

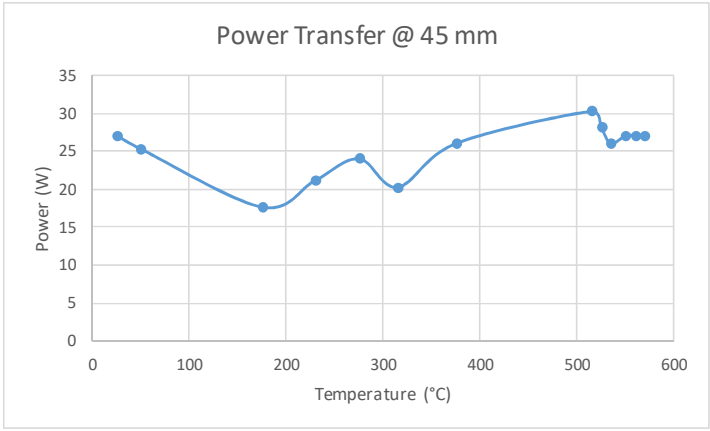


Power system testing @550 °C









Need to optimize each individual component for high temperature performance

Resonant Inductive Coupled Prototype Testing

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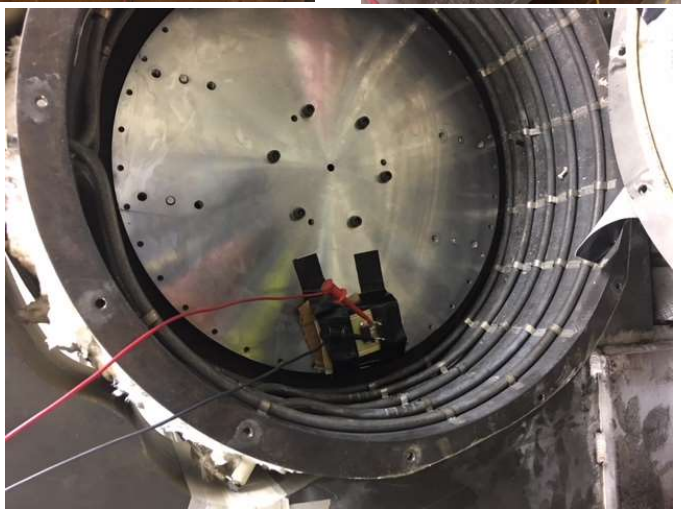
- **Transfer of 5 W at 20 mm distance with resonant inductive coupled system when installed in the actual spin test rig**
- **The RF ground of the system has a significant influence on the automatic tuning of the power transfer system, so a mockup of the system was installed in the spin rig to ensure a full heated spin test would be electrically functional**



Electrical functionality of inductive coupled system was demonstrated in spin rig

Progressive Development Approach

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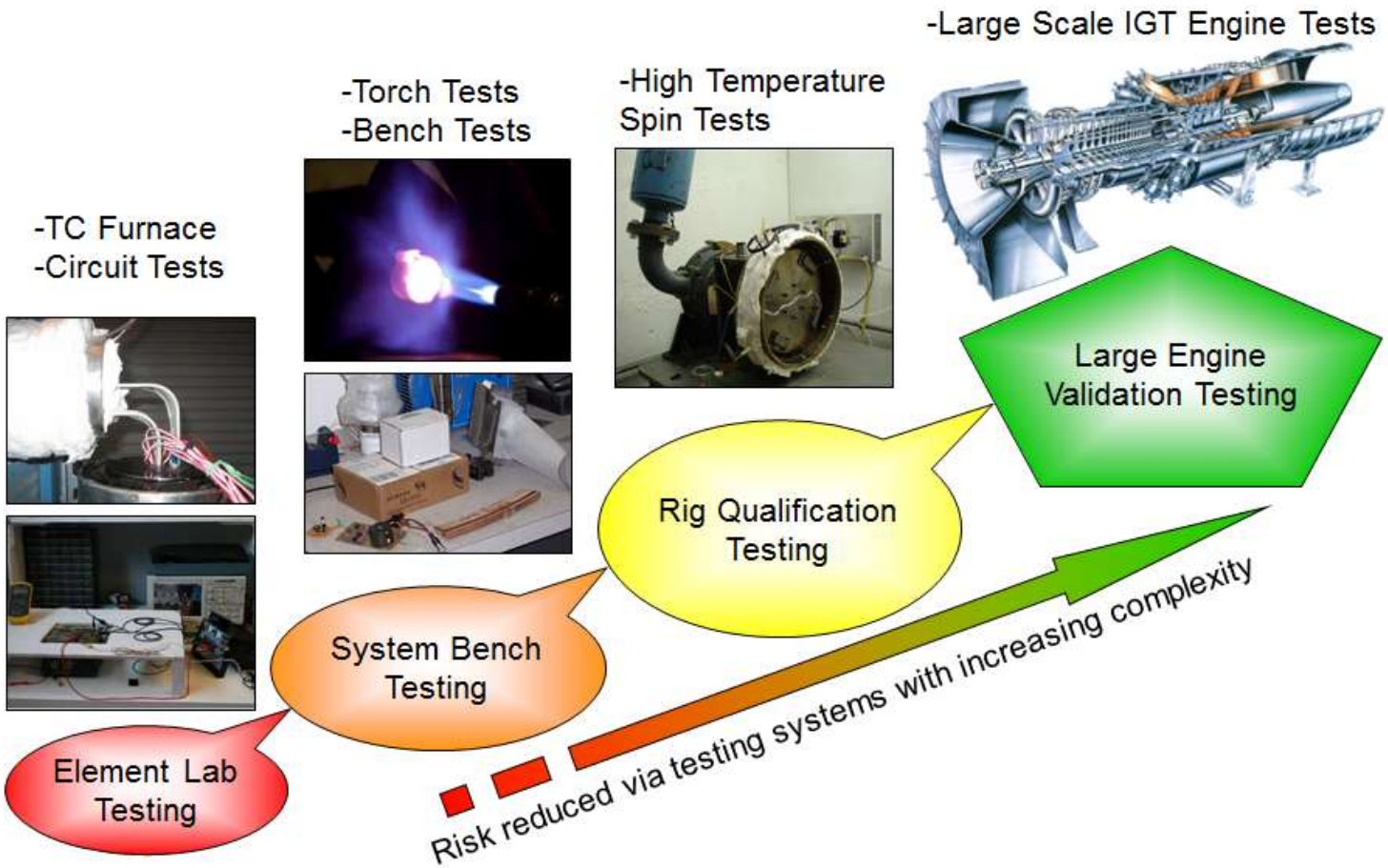

Rigorous testing and validation based on a thorough understanding of failure modes and improving final system performance

Artificial Intelligence, Machine Learning and Deep Learning

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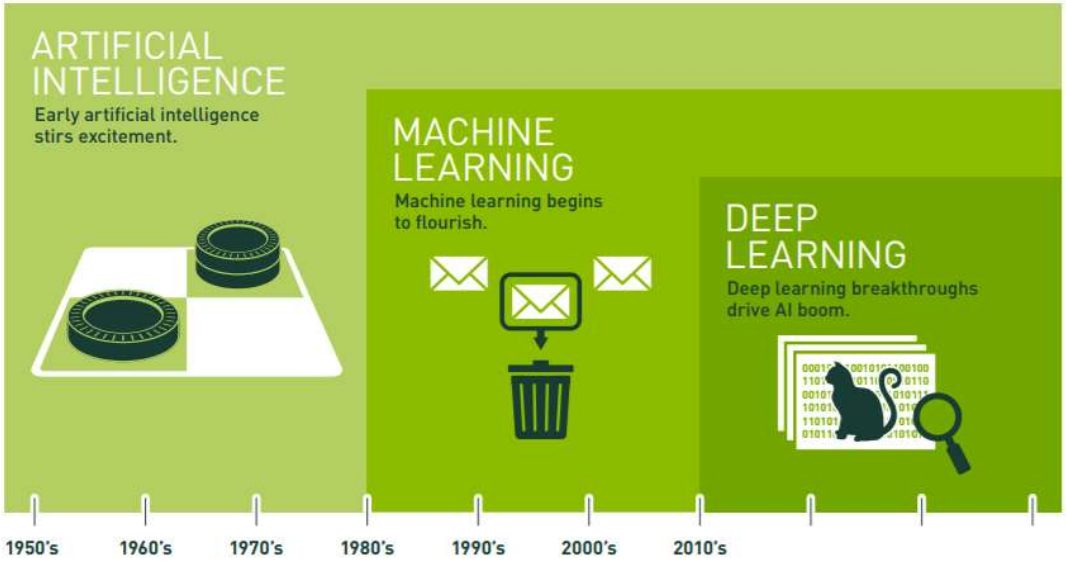
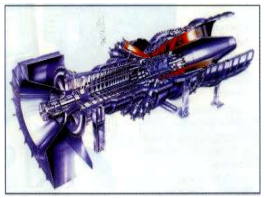
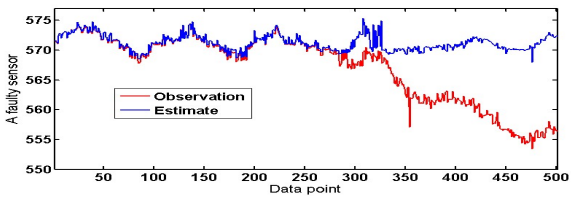


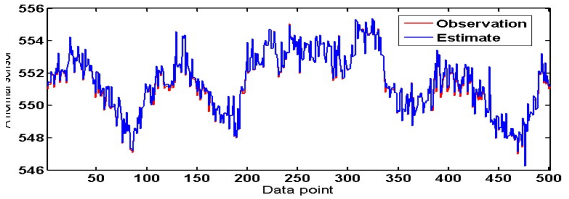
- Artificial intelligence addresses the use of computers to mimic the cognitive functions of humans
- Machine learning (ML) is a subset of AI and focuses on the ability of machines to receive a set of data and learn for themselves, changing algorithms as information is processing.
- Deep Learning is a subset of ML. It is based on neural networks, needs a very large amount of data to train and follow a conceptual model of the brain.

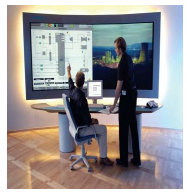
New Recurrent Denoising AutoEncoder

- Recurrent neural network (RNN) enables feedback loop structure
- Denoising algorithm is robust against sensor signal failures/deviations
- Deep nonlinear network









Predictions are more accurate by using time series history

Stochastic Methods for Turbine Component Life Estimation

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Surrogate Model based Probabilistic Analysis

Fleet / Individual Data from Sensors

Historical Statistics from Manufacturing Variability

Test Data

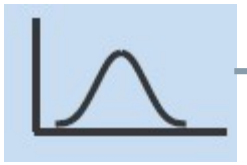
Statistical Correction to Models from Past Analytical Estimations

Temporal Blade Path Temperature Variation

TBC Coating Uniformity

Material Properties

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

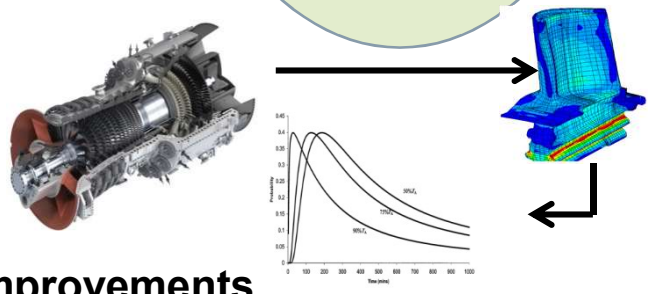
Automated Simulation Scripts

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

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.
- Phase 1 had demonstrated improved emf for ceramic thermocouples, cutting edge single chip silicon carbide (SiC) integrated circuits, ew induced power driver and receiver geometry capable of transferring 5W of power over 17 mm, Improved wire-bond design capable of withstanding high centrifugal loading, and e) Successful lab test of integrated sensor-wireless telemetry package on a gas turbine blade.
- Phase 2 program will focus on optimization and long term stability of functionality, followed by performance demonstration of individual subsystems in test rigs.
- Data collection of service experience for row 1 blade underway for advanced operation-based assessment (OBA) model utilizing artificial intelligence.
- Multiple opportunities available for validation testing of sensor-wireless telemetry package in small and large gas turbine engines.