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Siemens/ Wolfspeed | March 20th 2017

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

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

Introduction: Rationale

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Condition Monitoring

Probabilistic Lifing

Design Validation

System Testing, Simulation & Performance

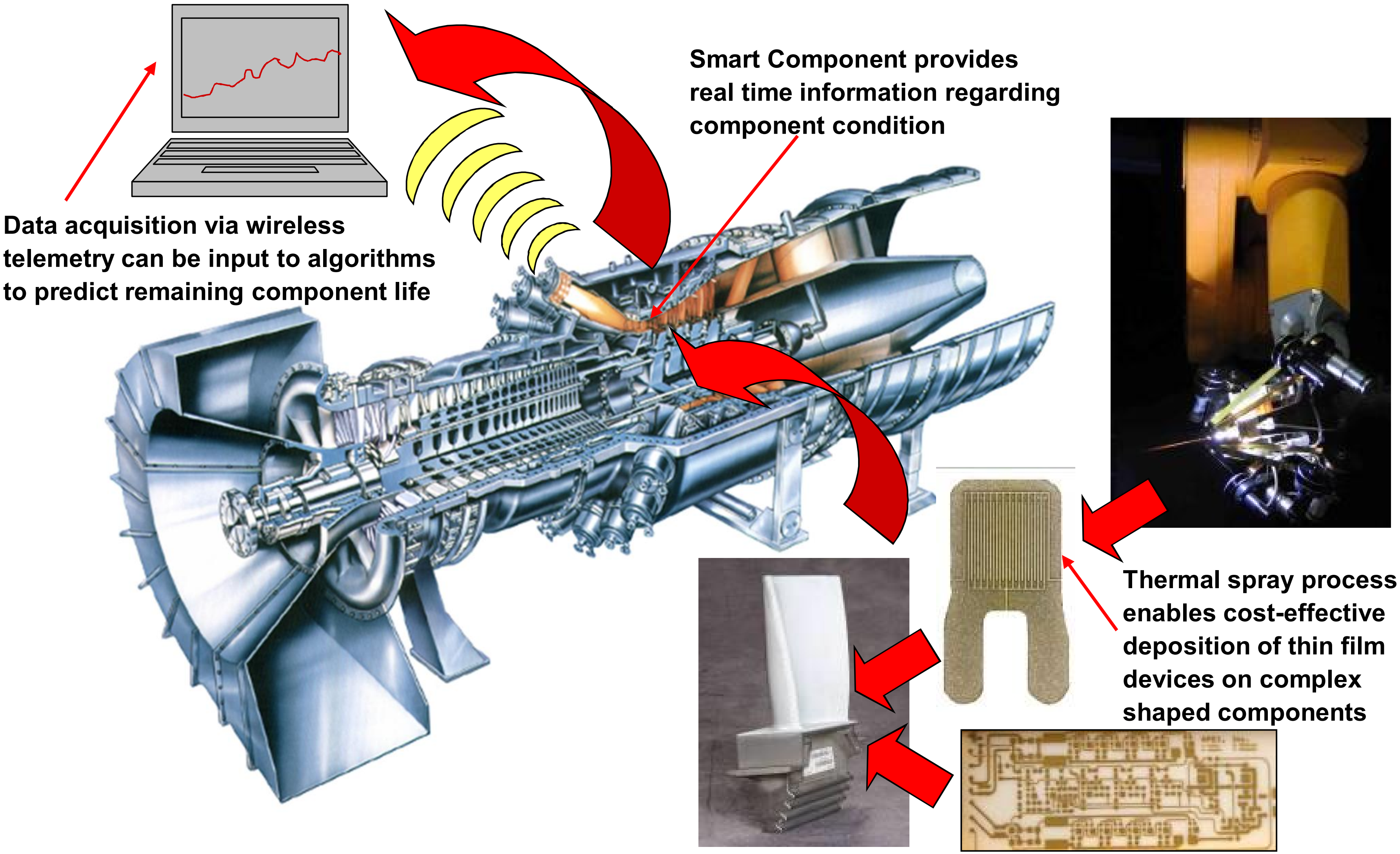
Real time data, Field feedback & prognosis

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

Anatomy of a Smart Component



Project Goals

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Most Challenging Measurements in Gas Turbines

- Turbine blade surface temperature
- Turbine blade heat flux
- Turbine blade dynamic strain
- Long life installation of above sensors

This System Will Measure All Three

- Long life flame-sprayed sensors
- High temperature, high g-load rotating electronics
- High temperature power transfer
- RF data transfer
- No destructive rotor wiring!

Online Condition Based Monitoring

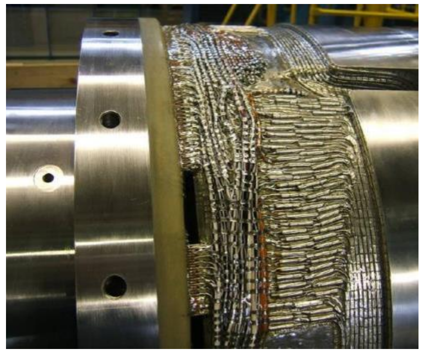
- Multi-Thousand Hour Lifetime
- Reduce component-life-based shutdowns
  - $1-2 Million savings
  - Machine on time increased 1-2% annually

Leverage Success from Previous Projects

- 350 C operation → 550 C operation
- Single channel boards → Multi-channel boards
- 500mW, high ripple power transfer → 2000mW, no ripple power transfer

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



Sensors - Wireless Telemetry System Team

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HT Capable Thermally Sprayed Sensors

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

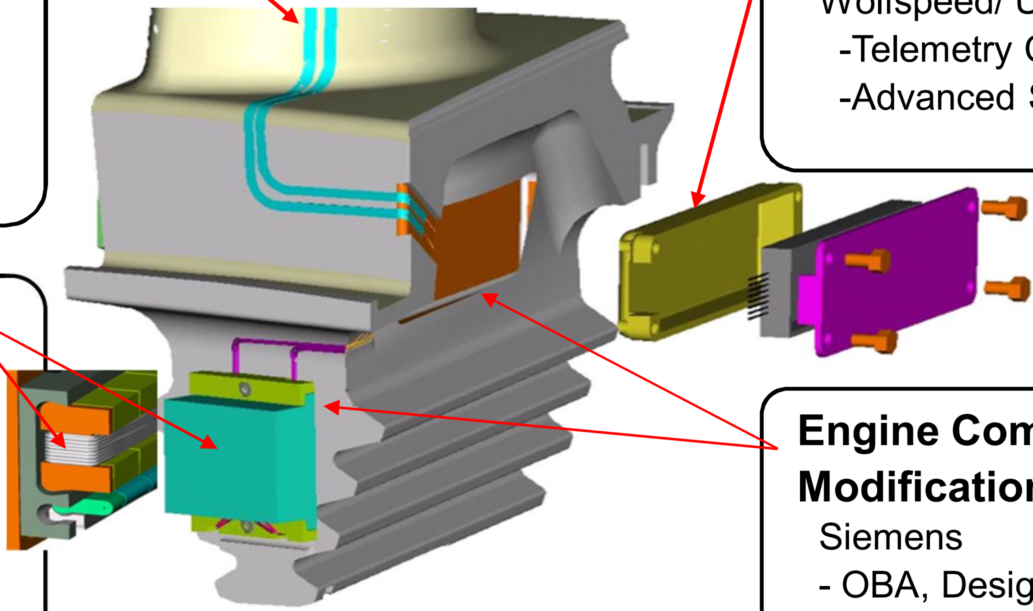
Curtiss Wright
- -Sensor Fabrication

Hitec Products
- -Attachments

HT Wireless Telemetry Transmitter Circuit Board

Siemens
- -Specification
- -Attachment Design

Wolfspeed/ Univ of Arkansas
- -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

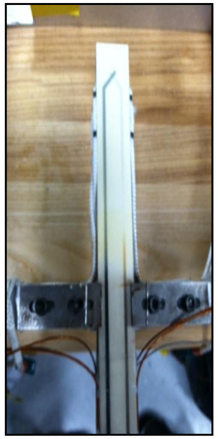
Siemens
- - OBA, Design and Analysis

Machining Vendors
- - Component Fab

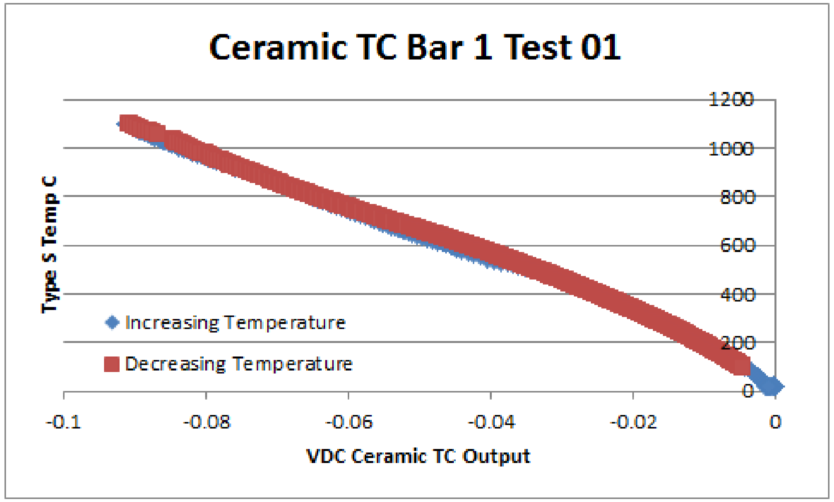
The technical team is strong and has been working together for 10 years

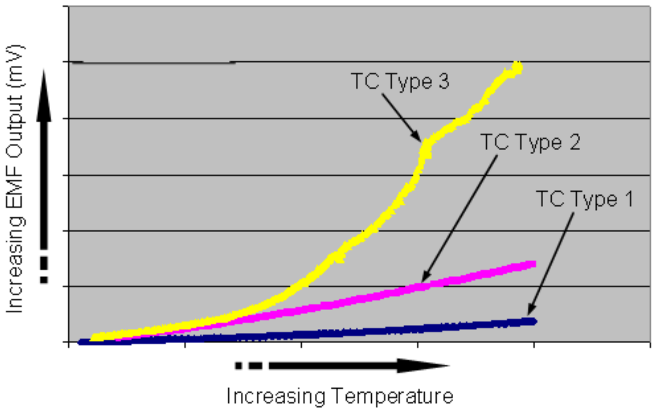
Isothermal Testing of ITO-LaSrCoO TC

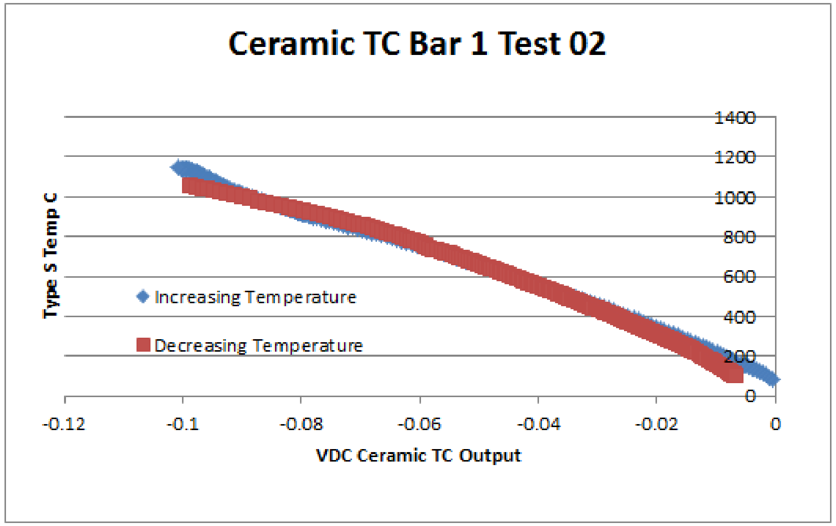
Isothermal heating with 2 TCs evaluation for reproducibility.



TC changes color after 1st run

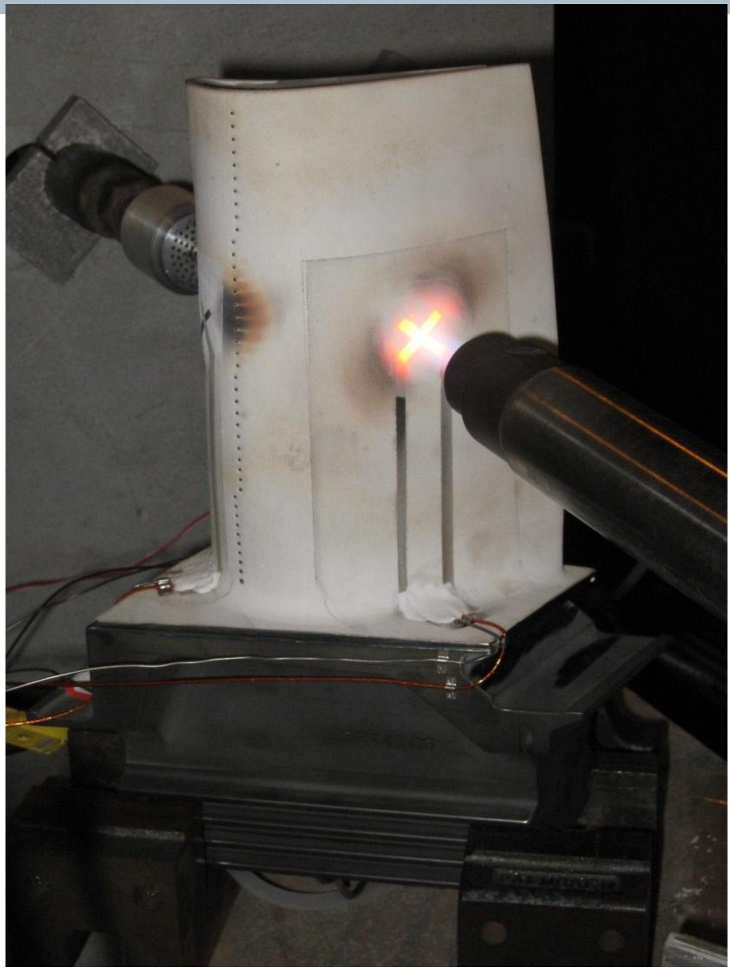


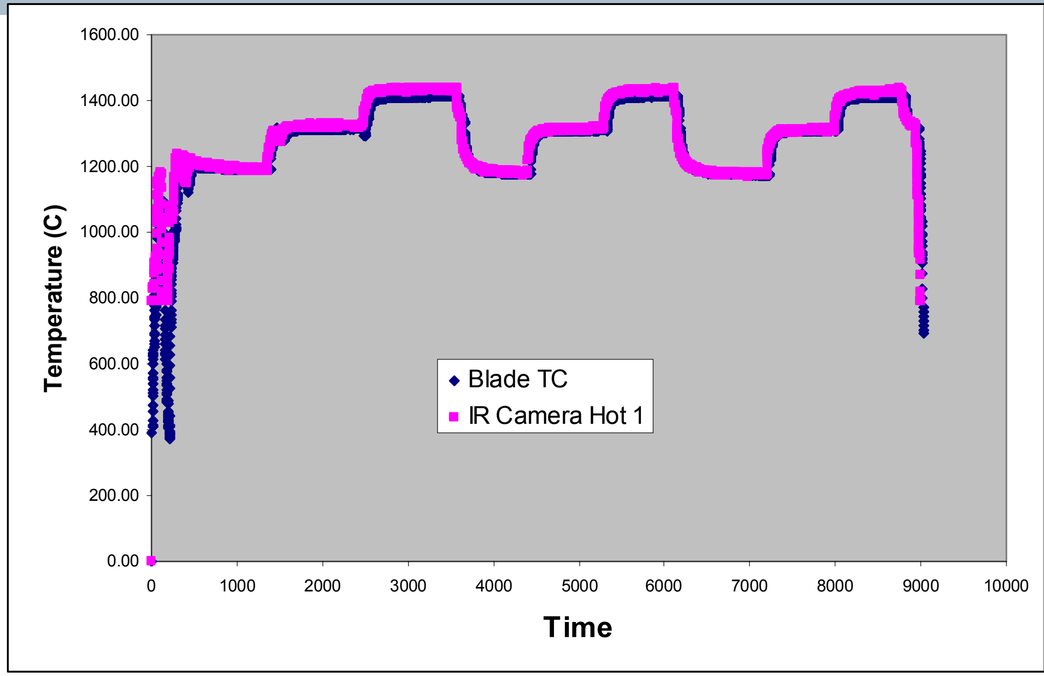




Ceramic thermocouple offers high signal to noise ratio at high temperatures

Flame Test on Actual GT Blade





	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	

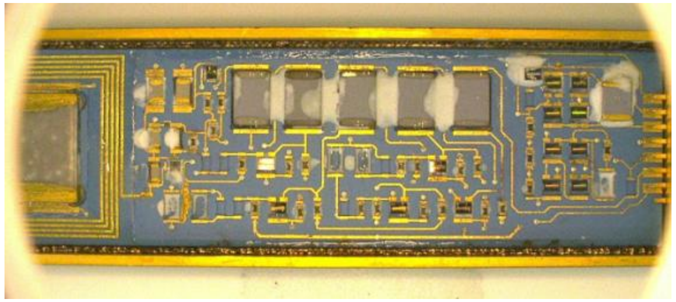
Type S TC – 5C between 1200-1400C

Excellent repeatability/reproducibility observed on a component

Design Challenges

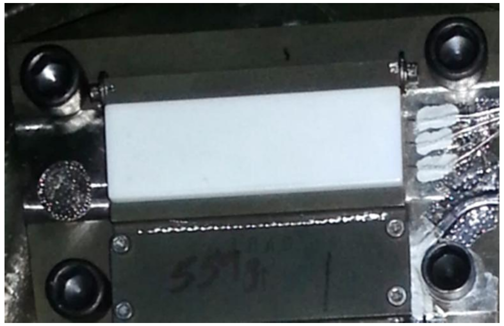
Electronics Boards

- 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

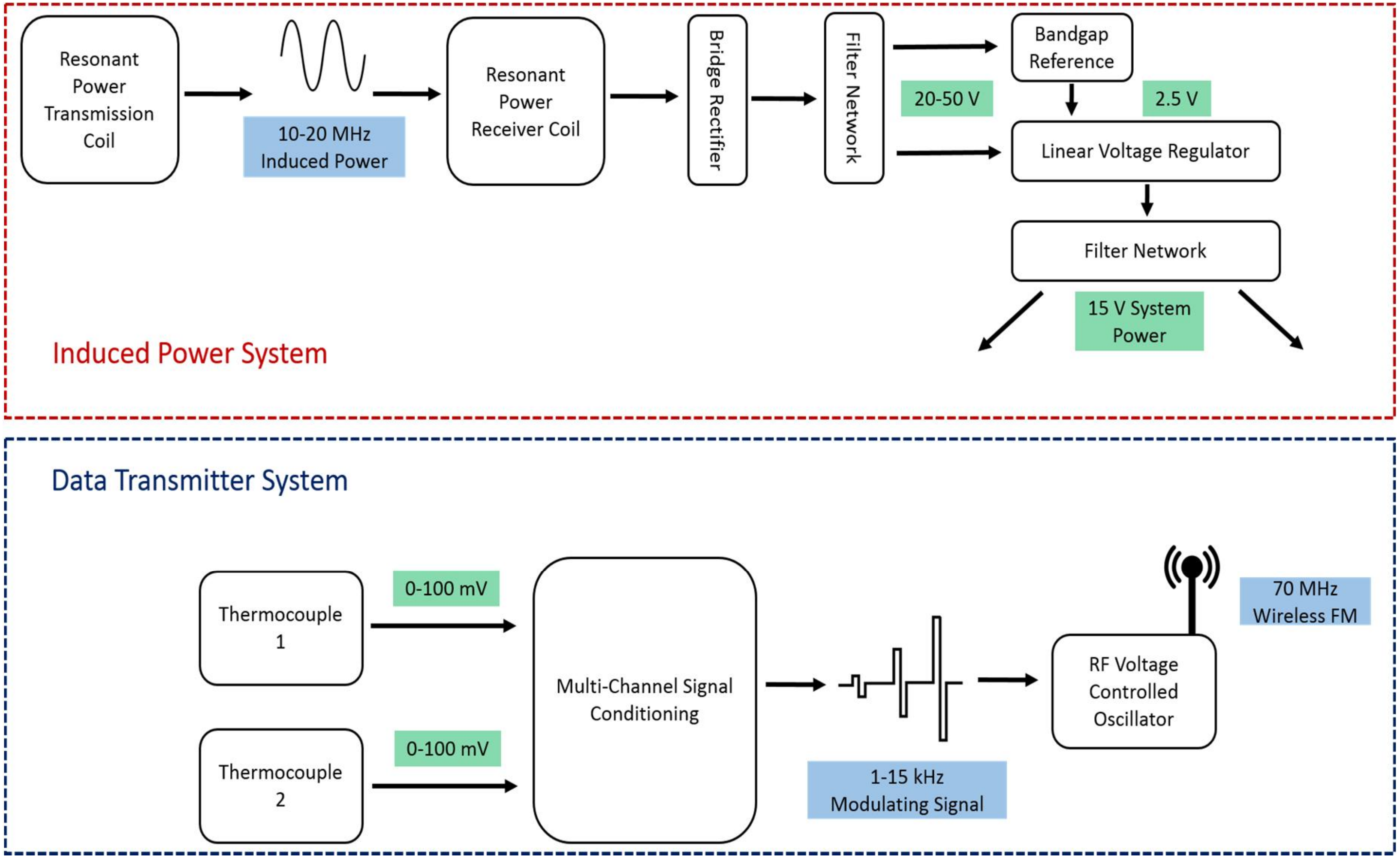
- Must receive ~1 watt; only 10 cm long; 20mm gap
- Surrounded by grounded metal
- No metal enclosure (magnetic receiver)
- Metal-ceramic interfaces – high vibration and G-load
- Magnetic properties vary greatly over 0-550 ºC range



Stationary Power Inducing Ring

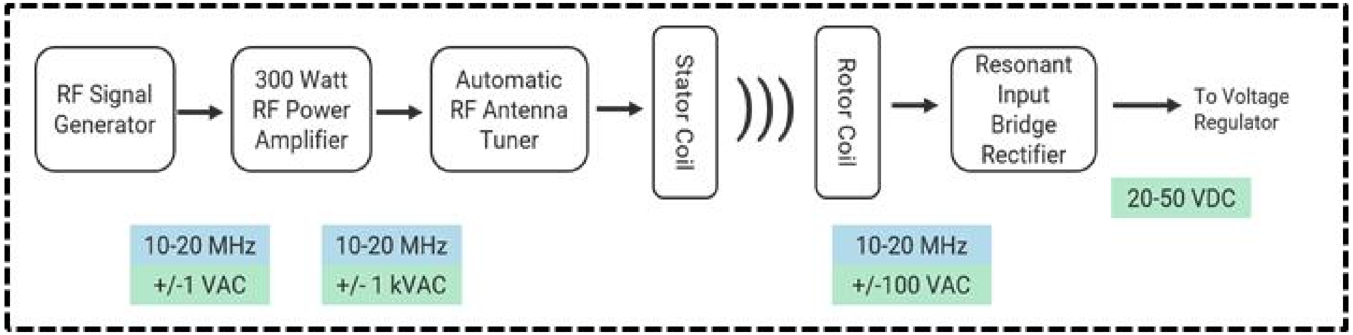
- Magnetic materials infeasible – too much variation in field strength over temperature
- Thermal expansion and vibration make electrical connections very difficult
- Mounted on grounded metal
- Ceramic/metal interface in high vibration environment
- Need 400 ºC, high frequency cables

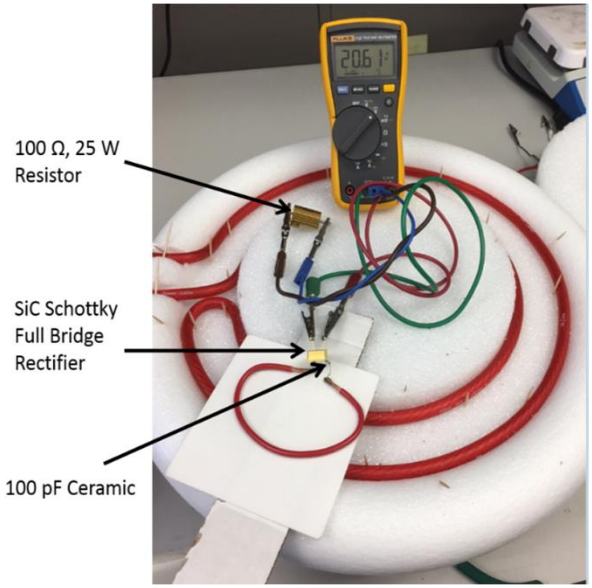
Wireless Telemetry System



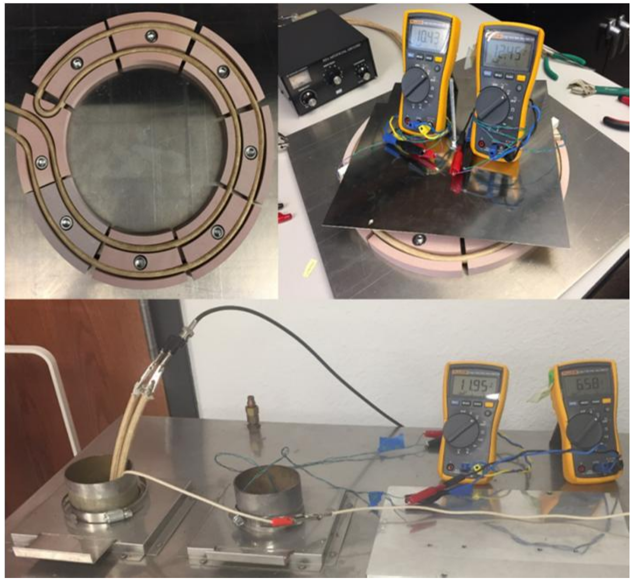
Antennae, circuit board, and electrical run materials, die attach and wire bond processes all being optimized for functionality and stability at 550C and high g-loads

Revised Power System





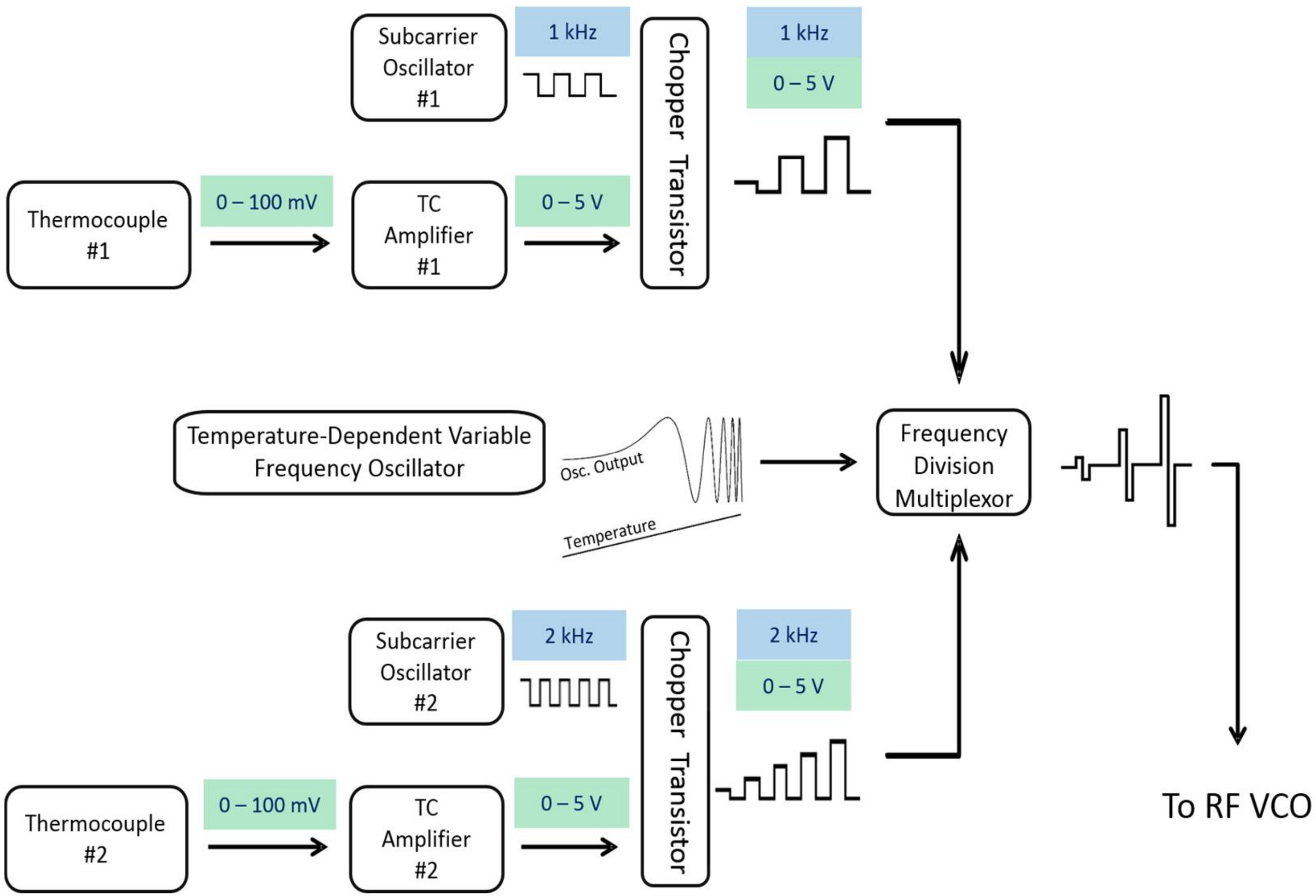
Room Temp Prototype



> 550 ° C Prototype

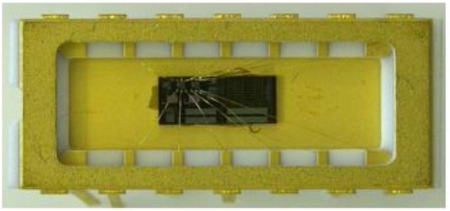
Improved system results in > 10X in power transfer due to increased quality factor of the resonant system, and enhanced coupling efficiency of the induced power setup.

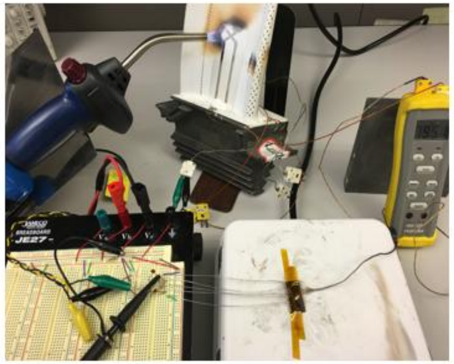
Multi-Channel Signal Conditioning Design



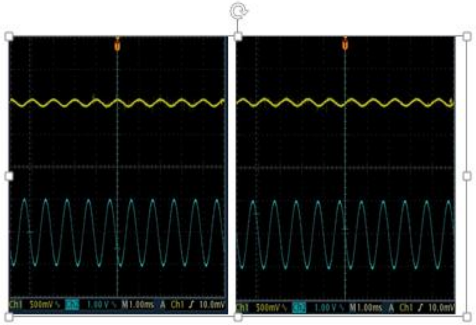
Multi-channel signal processing a must for multiple sensors on a turbine component

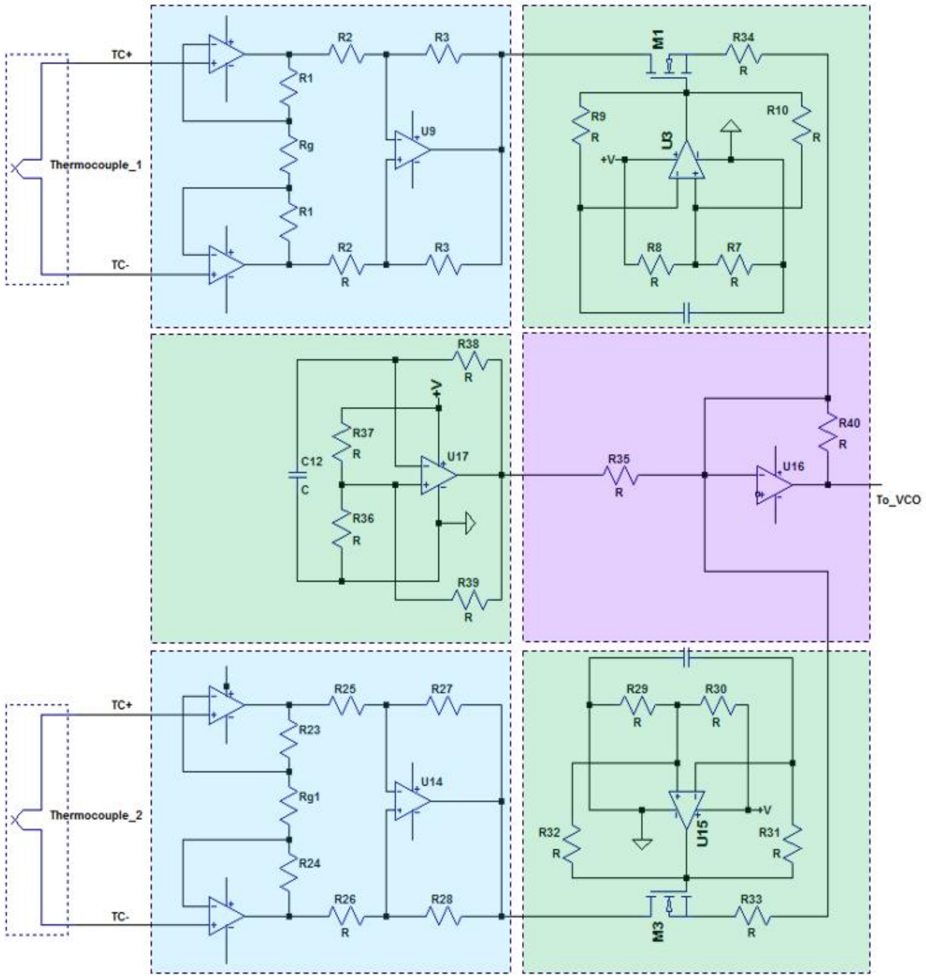
Signal Conditioning SiC ASIC





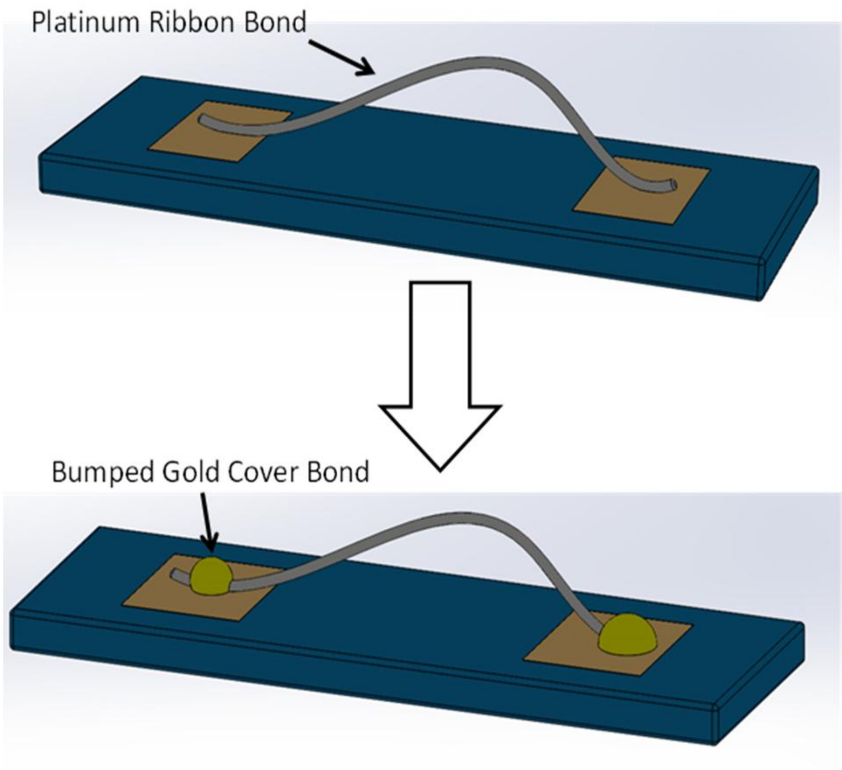
- **First initial feasibility demonstrated in a laboratory environment**

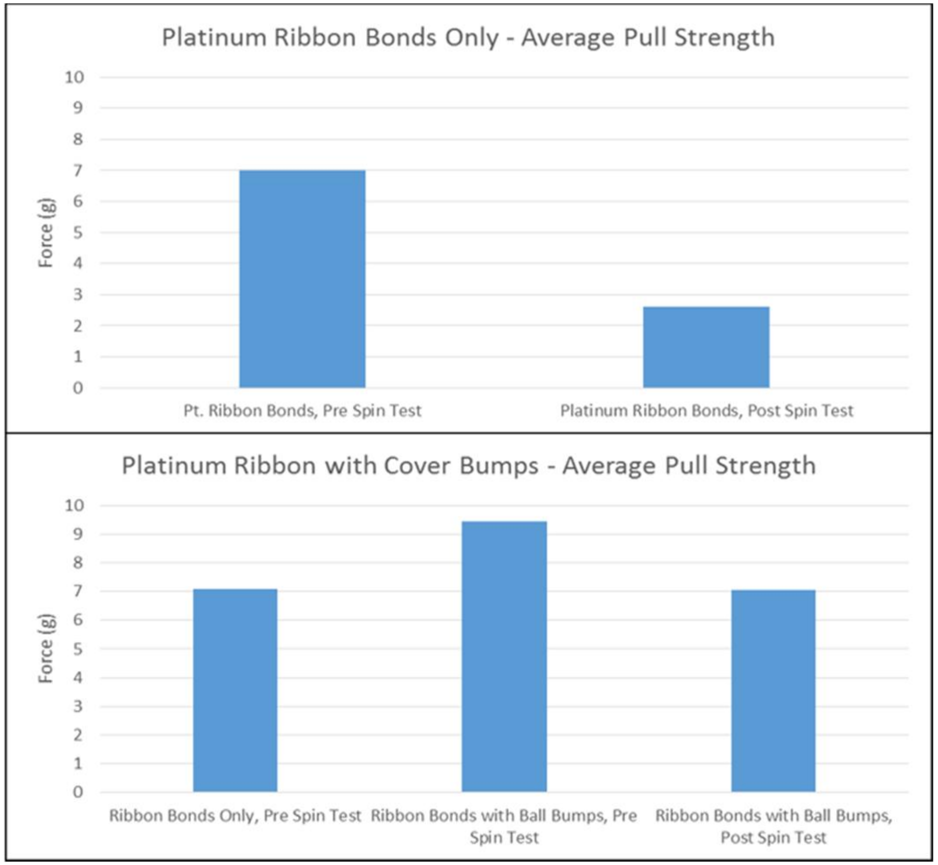




Milestone: Single chip SiC application-specific integrated circuit (ASIC), comprising the entire signal conditioning chain and the power conditioning circuitry

Advanced Bond-wire Interconnection Schema





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

Progressive Development Approach

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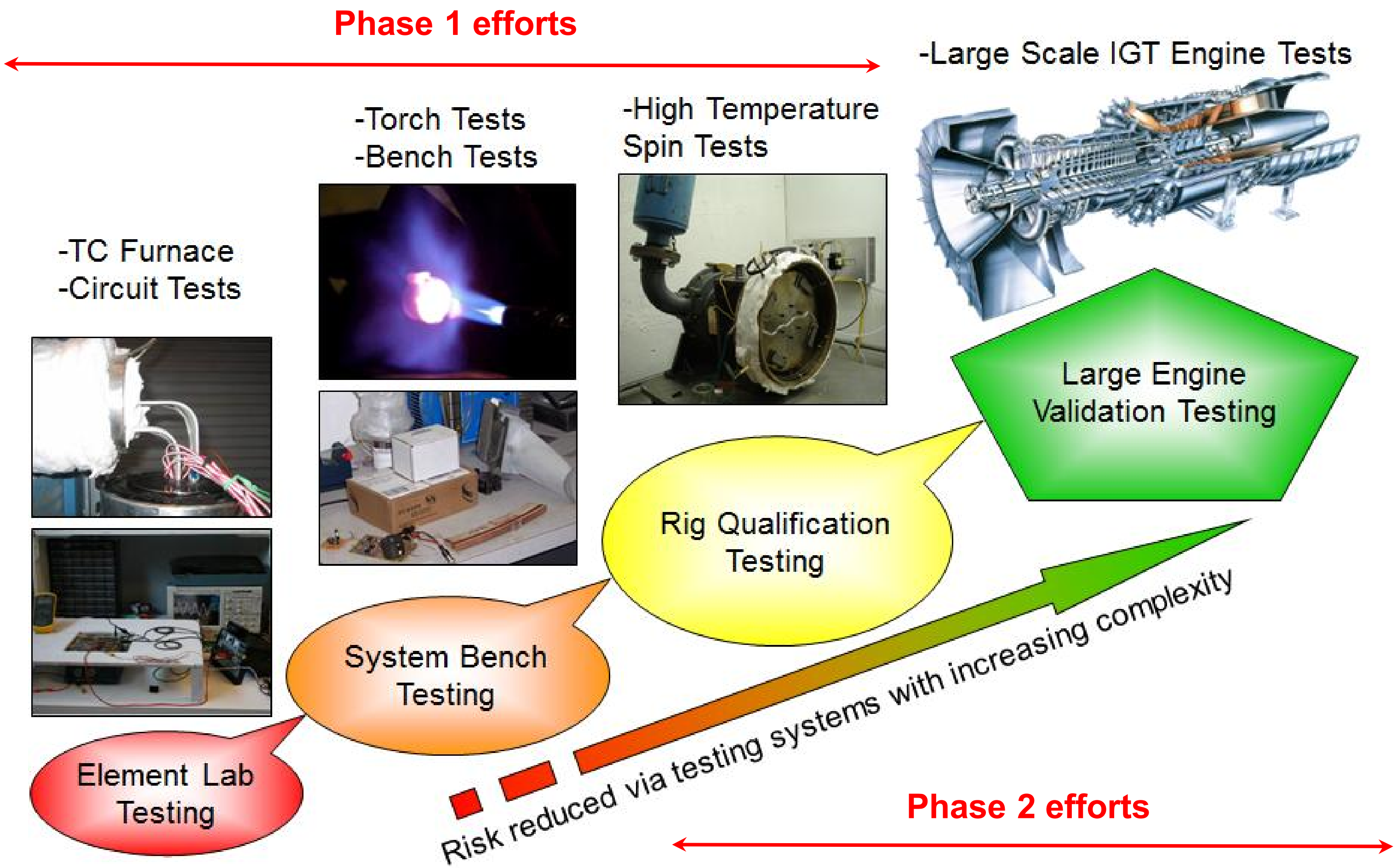
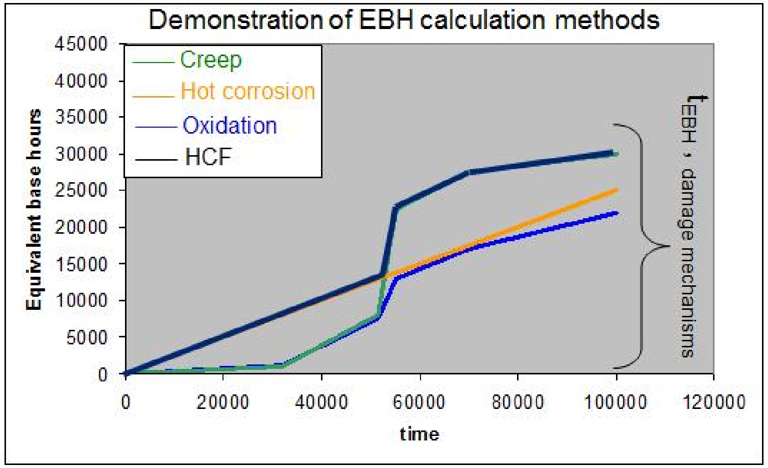


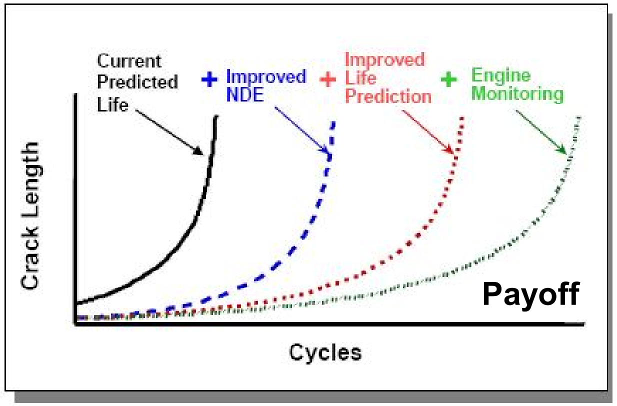
Rigorous testing and validation based on a thorough understanding of failure modes and improving final system performance

Operational Based Assessment

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

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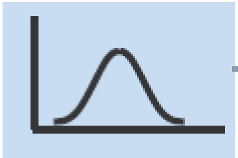
Surrogate Model based Probabilistic Analysis

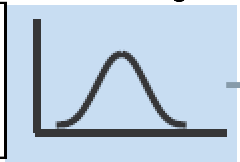
Fleet / Individual Data from Sensors

Temporal Blade Path Temperature Variation



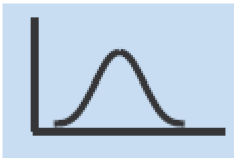
Historical Statistics from Manufacturing Variability

TBC Coating Uniformity



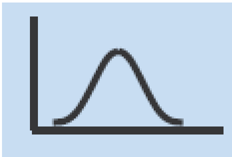
Test Data

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

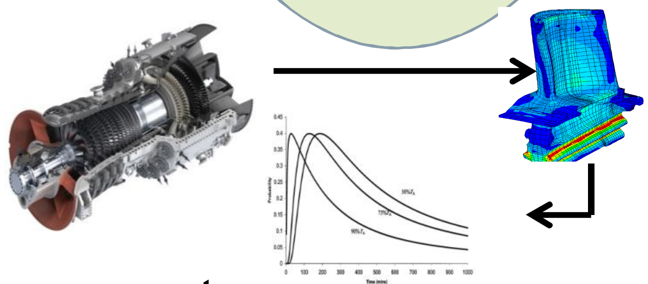
Blade Path Analysis Conjugate Heat Transfer

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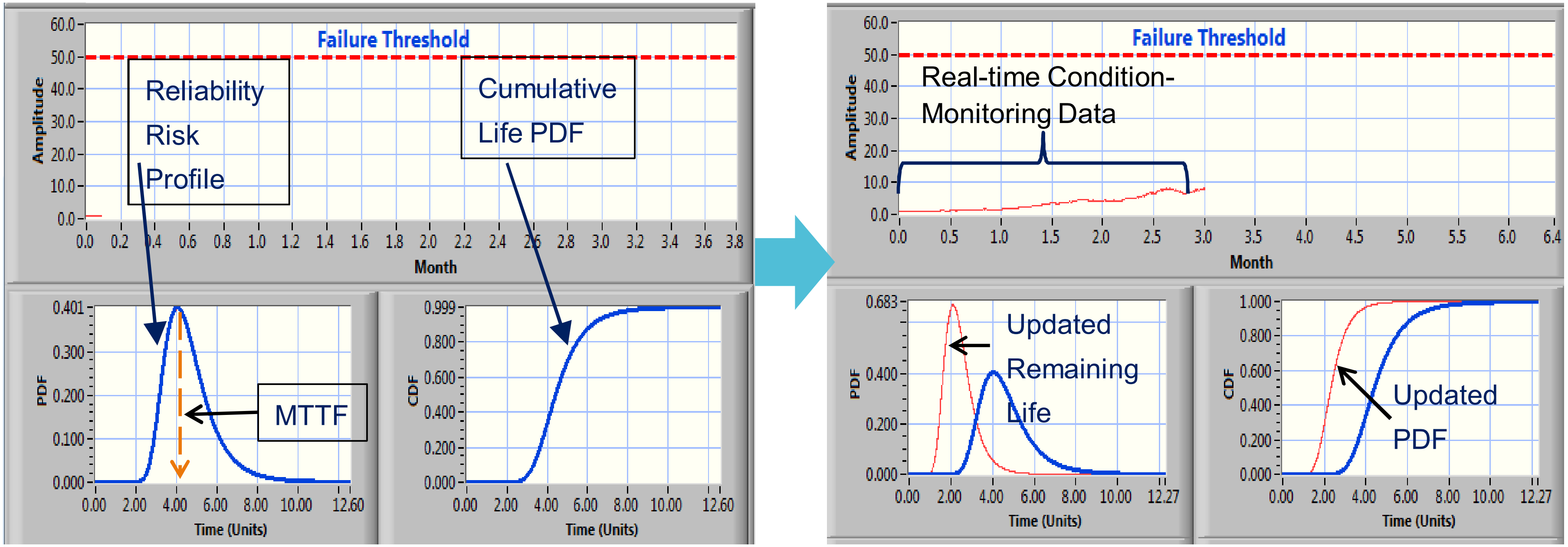
From Probabilistic Design Life Assessment to Operations-Based Remaining Life Prediction



- 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

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 achievements include: a) Demonstration of ceramic thermocouples that showed > 4x improvement in voltage (emf) output compared to metallic thermocouples (100 mV to 25 mV at 1200C), b) Demonstration of a cutting edge single chip silicon carbide (SiC) integrated circuits (IC) operational amplifier based system to perform analog signal and power conditioning of the sensor signal c) Development of a new induced power driver and receiver geometry capable of transferring 5W of power over 17 mm, which constitutes an order magnitude increase in power as compared to 0.5-1 W obtained from original designs, d) 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 validation testing of sensor-wireless telemetry package in gas turbine engine and advanced operation-based assessment (OBA) model utilizing artificial intelligence