ATOM*e*S:
Additive Topology Optimized Manufacturing with Embedded Sensing

DE-FE0012299

4-19-2016

2016 Crosscutting Research and Rare Earth Elements Portfolios Review

Award Number:	DE-FE0012299
Project Title:	ATOM*e*S: Additive Topology Optimized Manufacturing with embedded Sensing
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DOE Project Team:	DOE Contracting Officer- Robert Romanosky DOE Project Officer – Rick Dunst

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Acknowledgement

Opportunity and privilege to collaborate with researchers exploring relevant technical challenges.

NETL:

- Rick Dunst
- Paul Ohodnicki
- Doug Straub
- Benjamin Chorpening

UTRC:

- Paul Attridge, Sanjay Bajekal, Mike Klecka, Joe Liou, Joe Mantese, John Miano, Aaron Nardi, John Needham, Bill Rioux, Nick Soldner, Cagatay Tokgoz, Dan Viens, Xin Wu, Joe Zacchio

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Objective

This project aims to demonstrate an additive manufacturing process (guided by physics-based models) for seamlessly embedding a sensor suite into the airfoils of industrial natural gas turbines while maintaining their structural integrity and providing for wireless power, sensor interrogation, and real-time diagnostics through the employment of a health-utilization-monitoring system (HUMS).

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United Technologies Corporation – Immense Product Range

- Thermodynamic cycle management is a recurring theme
- Maximizing system efficiency
  - Energy, Performance, Cost
- Innovative and disruptive technologies

We have common interests

OTIS

UTC CLIMATE, CONTROLS & SECURITY

PRATT & WHITNEY

UTC AEROSPACE SYSTEMS

http://www.utc.com/Our-Businesses/Pages/At-A-Glance.aspx#pratt-whitney

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Overview

Industrial Power Turbine Application

- Performance cycle data improves efficiency
- Inlet guide vane – Low Temperature

Capabilities Demonstrated

- Additive manufacturing: DMLS, CS, TC Embedment Via LENS
- Simulation
  - Electromagnetic Field Interaction, LENS Welding – Processing Residual Stress
- Miniature electronics development
- Novel angular position sensing
- Multiple sensor integration into metal components
- Wireless power and data transmission
  - Final demonstration planning.

Reached For Greater Challenge Problem

- Collaboration opportunity with NETL – Morgantown, WV
- Raised the bar for temperatures
  - Corollary to guide vane

Continuing Development

- Envelope expansion

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Value in Monitoring a Range of Process Temperatures

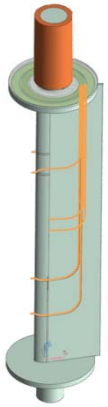
Common interest across industries

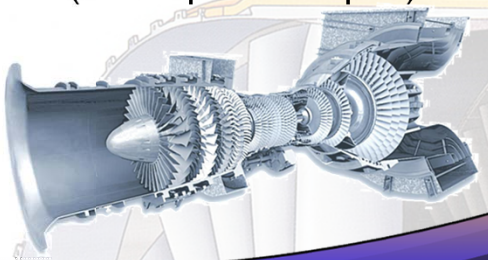
- Energy sector & aerospace

Team elected to take greater challenge

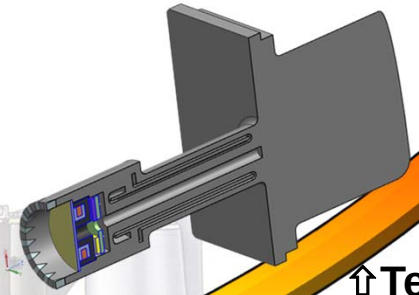
- Elevated temperatures
- Compact packaging

Land Based
Inlet Guide Vane(IGV)
(Concept Developed)





Mini Hydra Test
NETL
(Demonstrating)



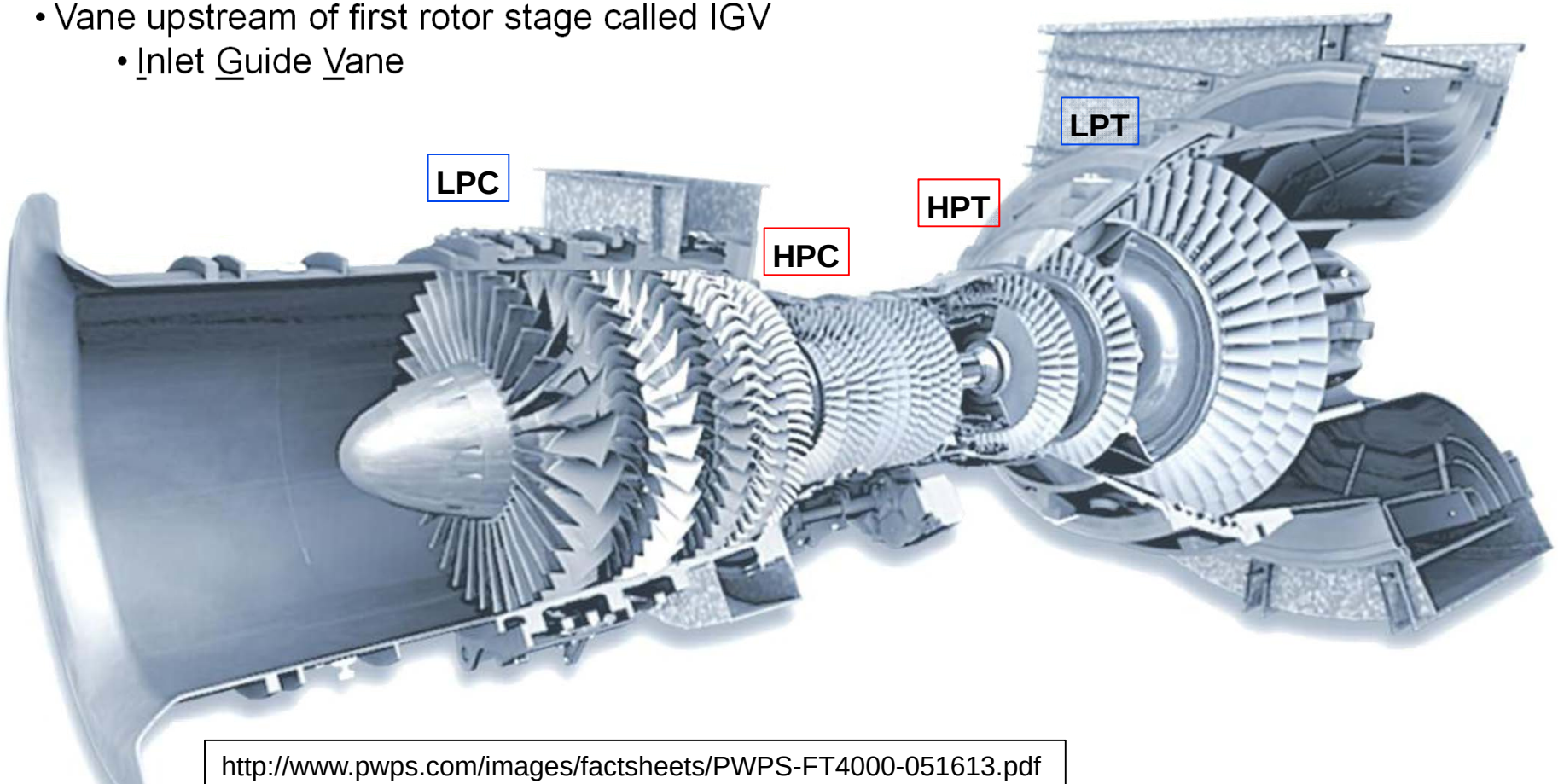
Combustor Exit
Turbine
Components

⇧Temperatures
⇩ Size
⇧ Integration Challenges

Image publicly available on P&W external website
http://www.pw.utc.com/Content/PW4000112_Engine/img/B-1-4-3_pw4000112_cutaway_high.jpg
http://www.pwps.com/images/factsheets/PWPS-FT4000-051613.pdf
http://www.pw.utc.com/Used_Serviceable_Material

Gas Turbine Review – FT4000 Land Based Industrial Gas Turbine

- Use high and low pressure spools
- Emphasis on shaft power extraction to generator
- Variable pitch vanes also in LPC
- Vane upstream of first rotor stage called IGV
  - Inlet Guide Vane



http://www.pwps.com/images/factsheets/PWPS-FT4000-051613.pdf

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PW4000 112-Inch Fan Engine

- **High pressure spool** aerodynamically coupled to **Low Pressure**
- Inter-shaft bearing supports
- Variable pitch vanes in HPC only.
- Chemical Energy → Thrust

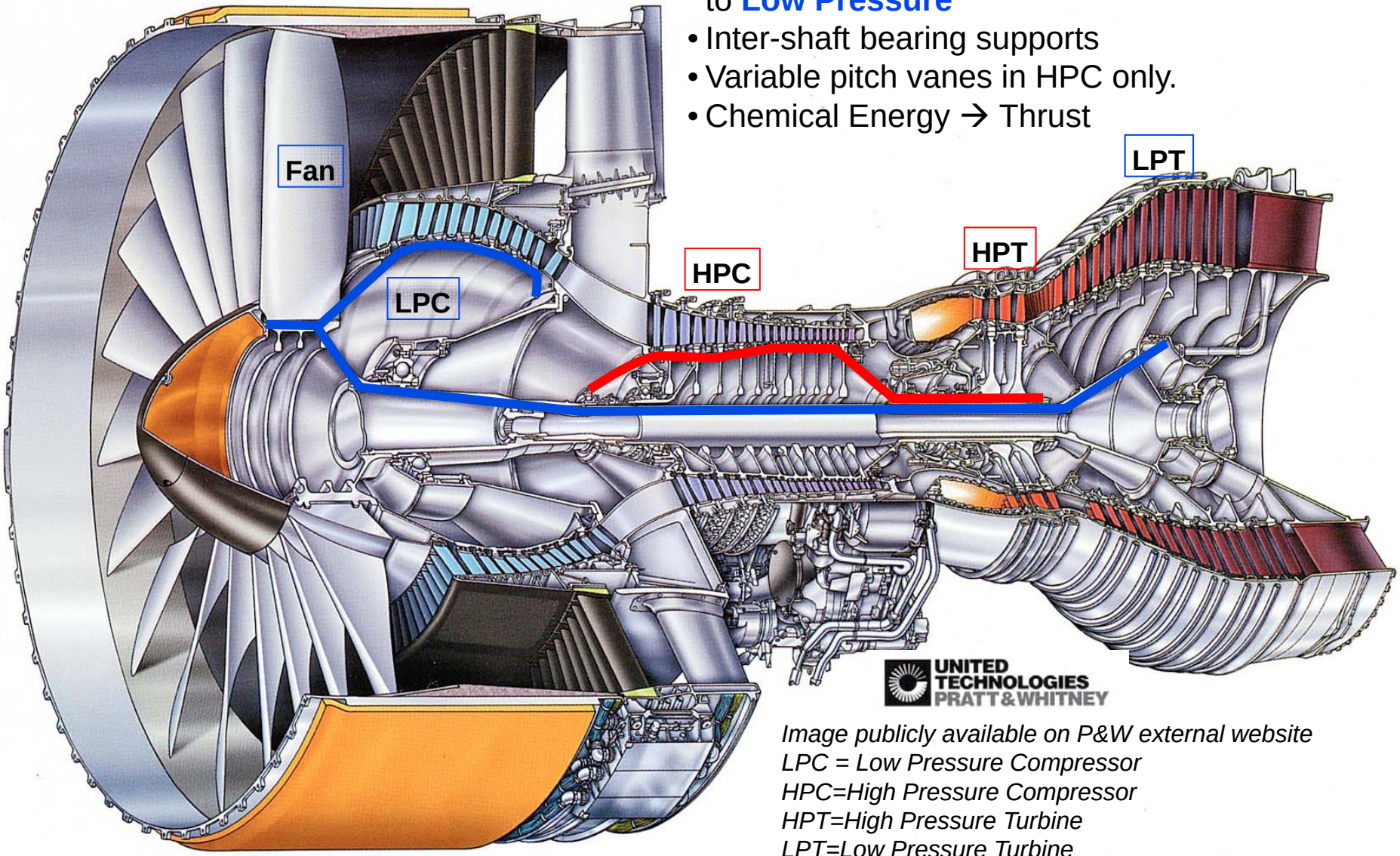

Image publicly available on P&W external website
LPC = Low Pressure Compressor
HPC=High Pressure Compressor
HPT=High Pressure Turbine
LPT=Low Pressure Turbine

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Variable Pitch Stator Vanes

- Process monitoring variable pitch stators provides efficiency through precision control.

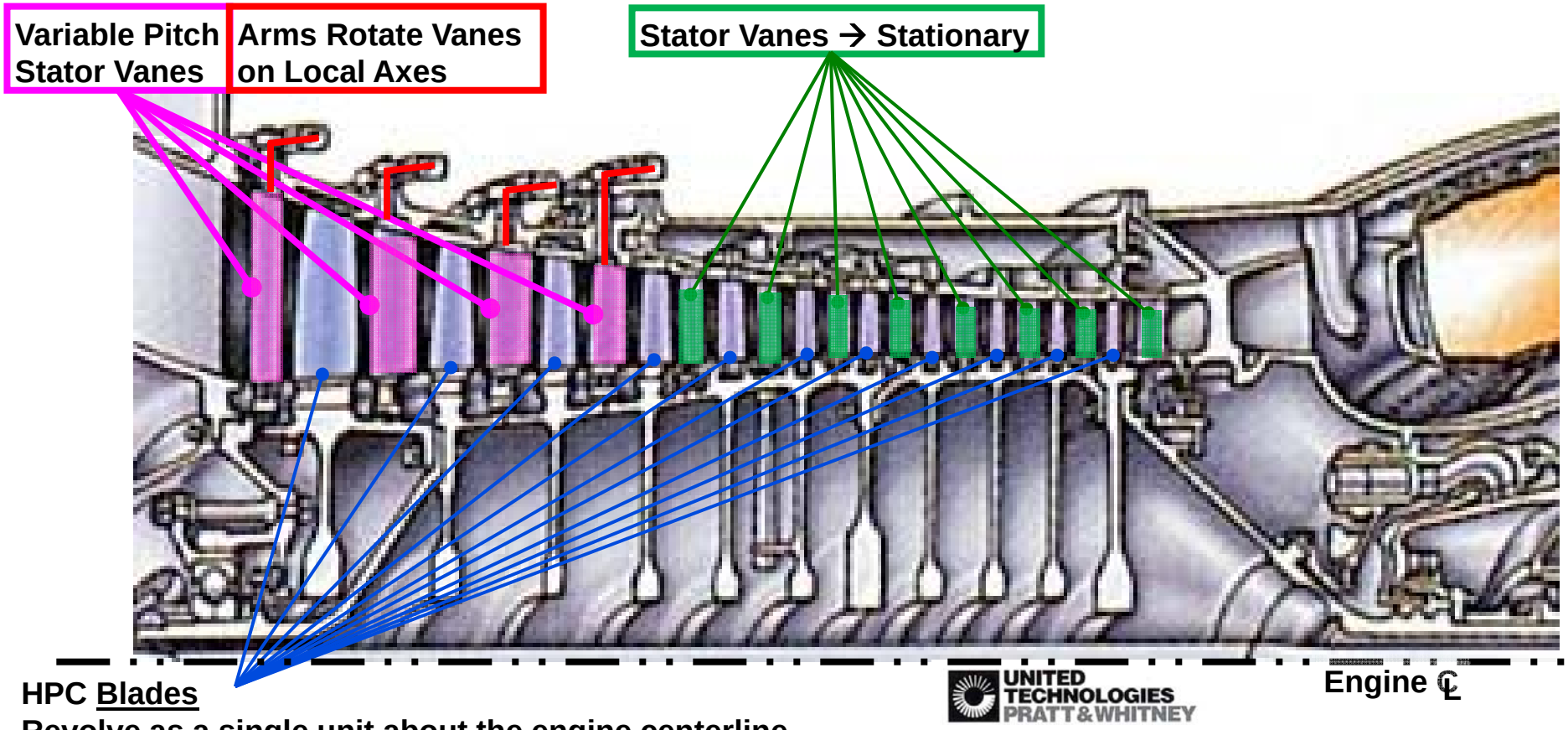

Image publicly available on P&W external website

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Methodology and Requirements

Exploit UTC investment in additive manufacturing

- Topology optimization
- Process modeling
- Suite of additive manufacturing (AM) processes

No wires

RF based power and communications

COTS components – wireless and sensors

Sensor and RF components embedded in a metallic or semi-metallic covering to protect components from harsh environment

Communication distances (for now) < 1cm

Temperature <100°C

Communication rate ~100kbs

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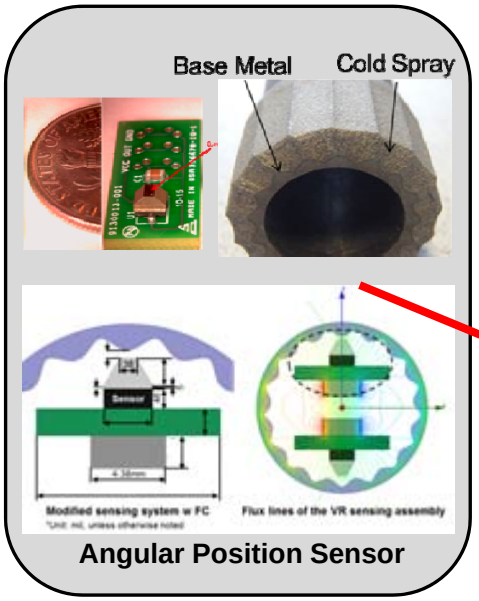
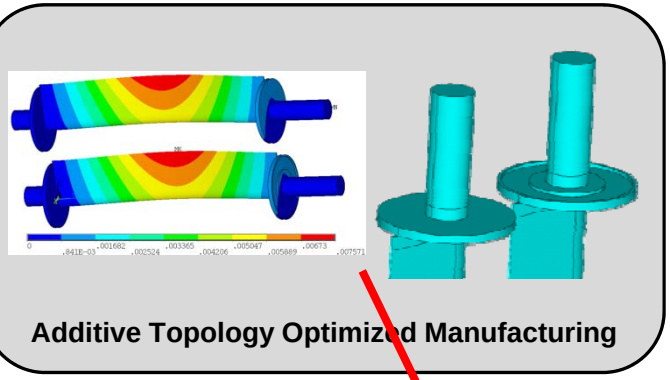
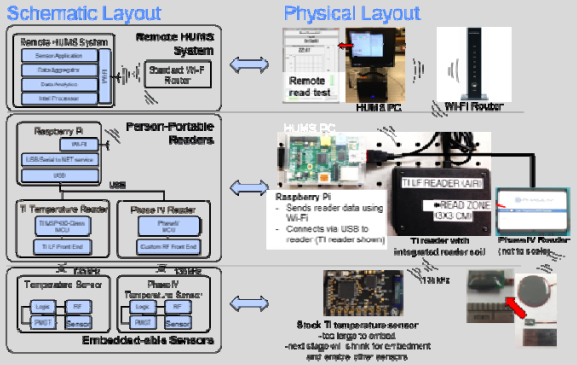
Technology Capability Flow



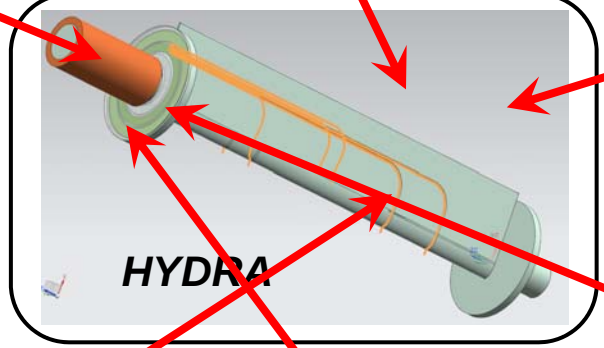
Angular Position Sensor

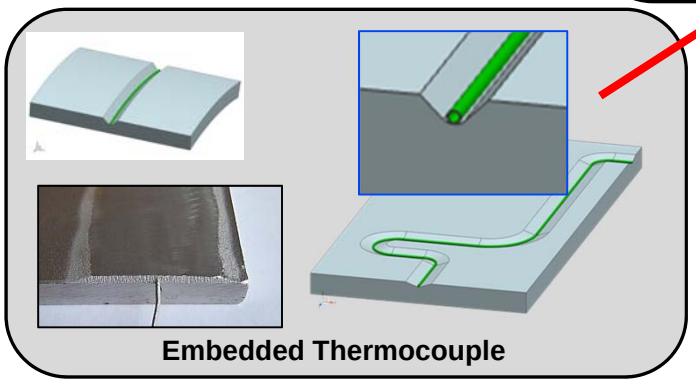


Additive Topology Optimized Manufacturing

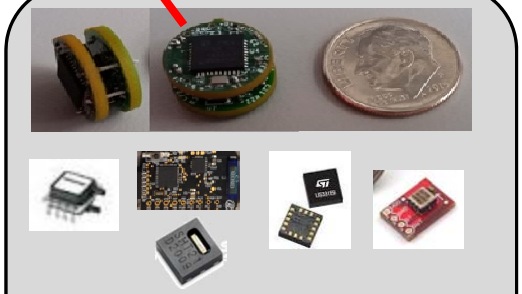


HUMS Diagnostics

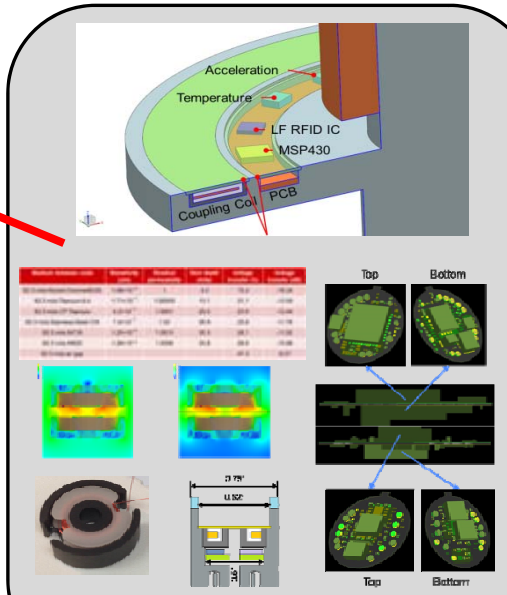




Embedded Thermocouple



COTS (TRL9) RF Components and Sensors



EM Modeling, Component Integration and Testing

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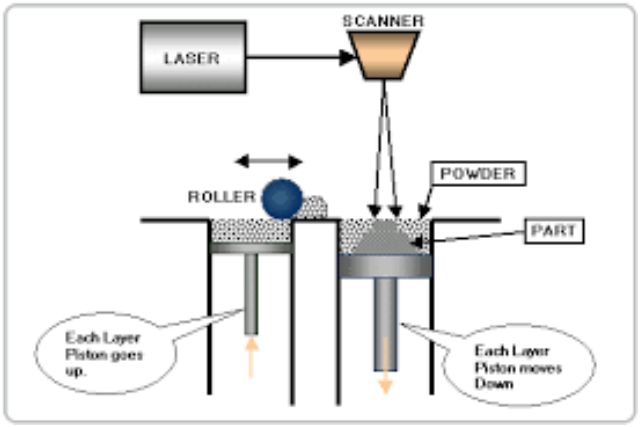
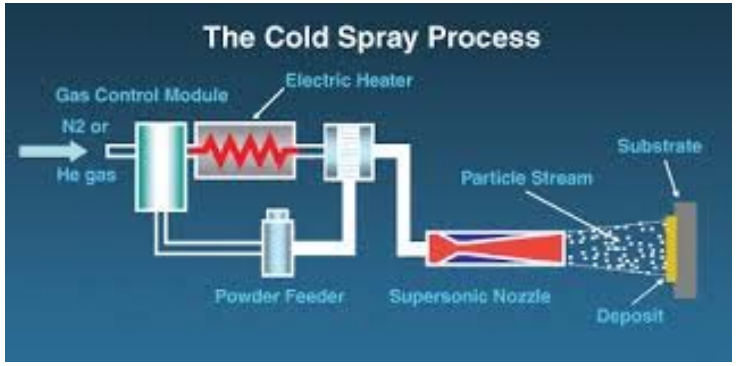
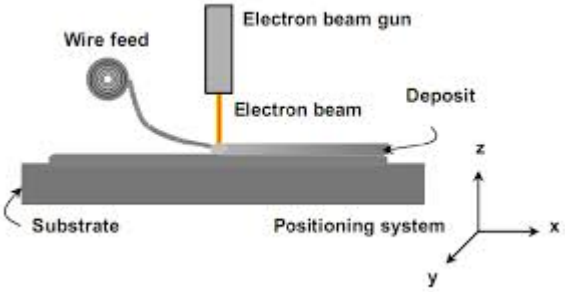
Additive Manufacturing Palette



DMLS: Direct Laser Metal Sintering



Cold Spray



WASP:
Wire Arc Sintering Processing

LENS: Laser Engineered Net Shaping

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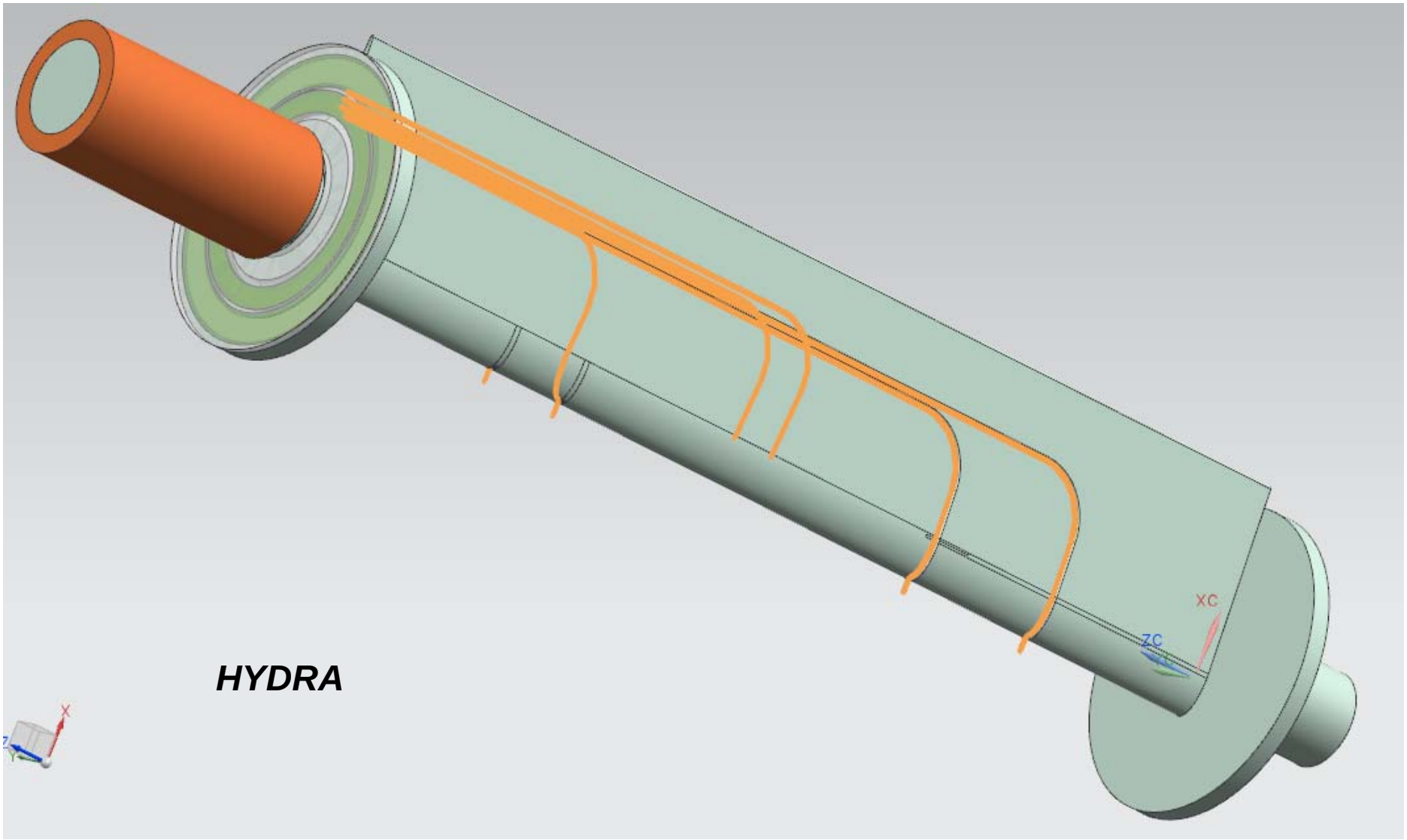
Integrated Inlet Guide Vane with Embedded Sensing



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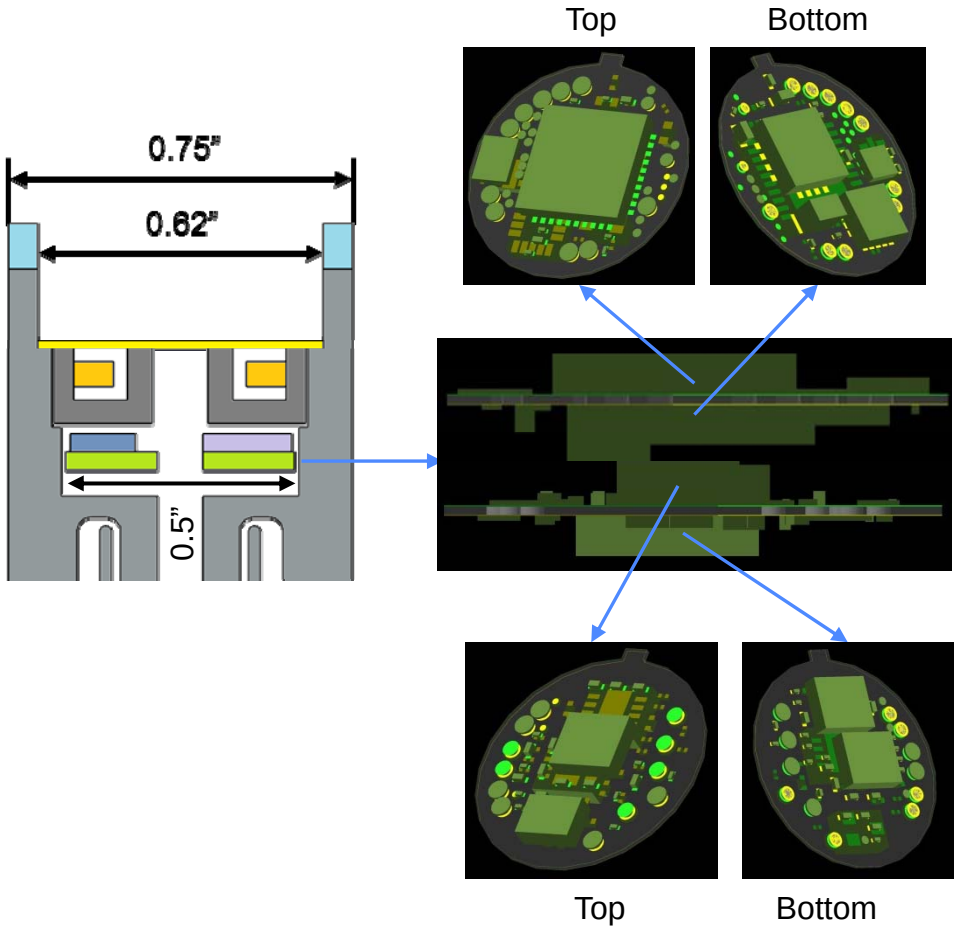
Tag Board Layout and COTS BOM



Design Philosophy: Use Non-Proprietary COTS Components to Allow User Community Access

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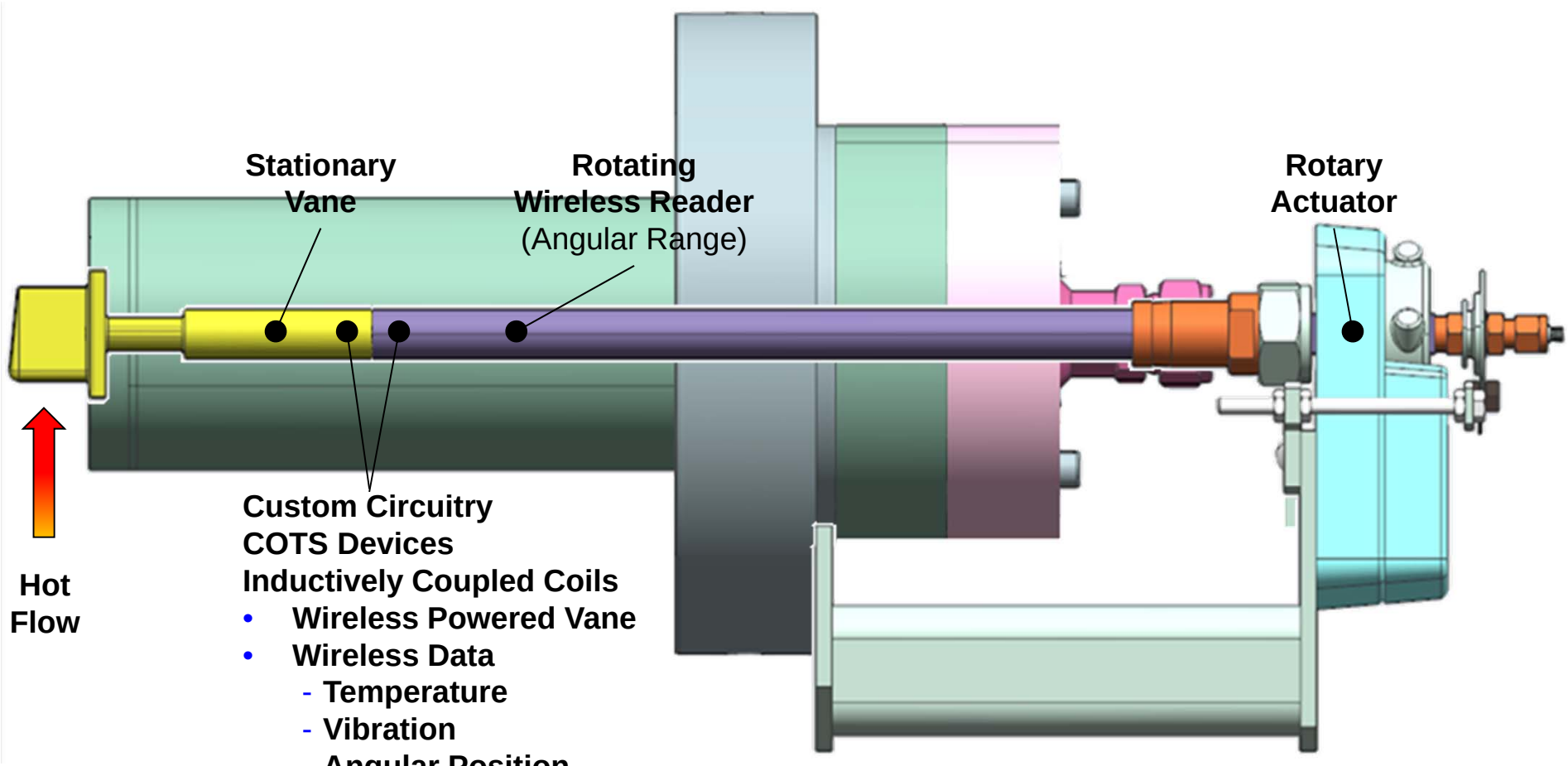
NETL Aero-thermal Test Platform



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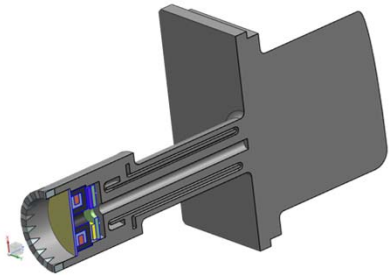
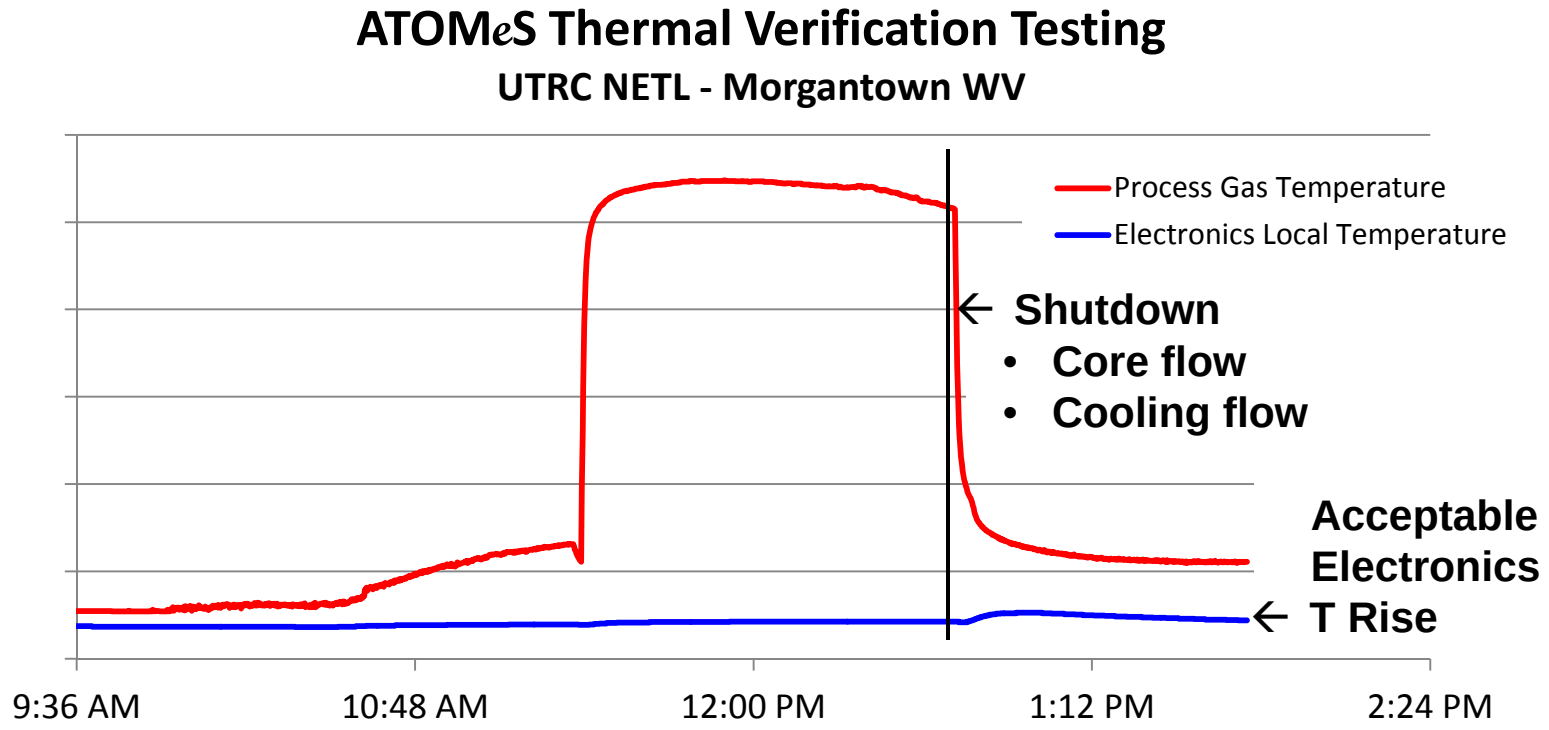
Successful Thermal Testing at NETL Morgantown WV

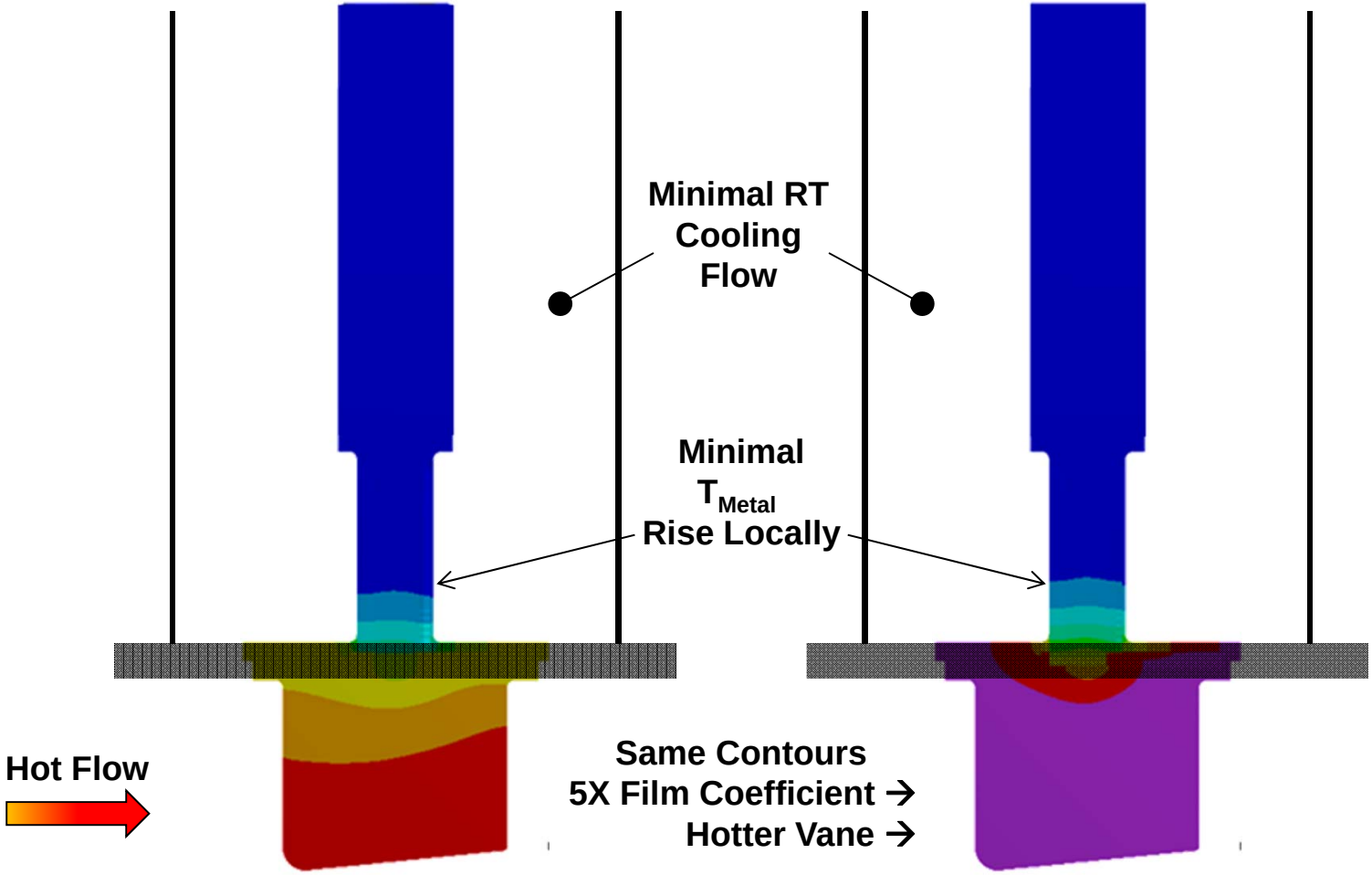
- Long duration steady conditions
- Rapid transients
- Moderate cooling flow
- Thermal stability on shutdown soak back





Sensitivity Study – Robust Cooling Protects Electronics

- Hot Side Convection Film Coefficient
- Metal Temps Acceptable



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Embedded Thermocouples – LENS Process Modelling

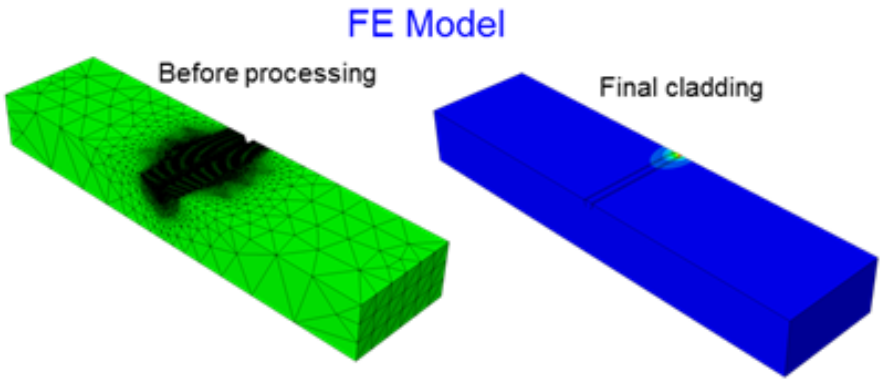
LENS: Laser Engineered Net Shaping

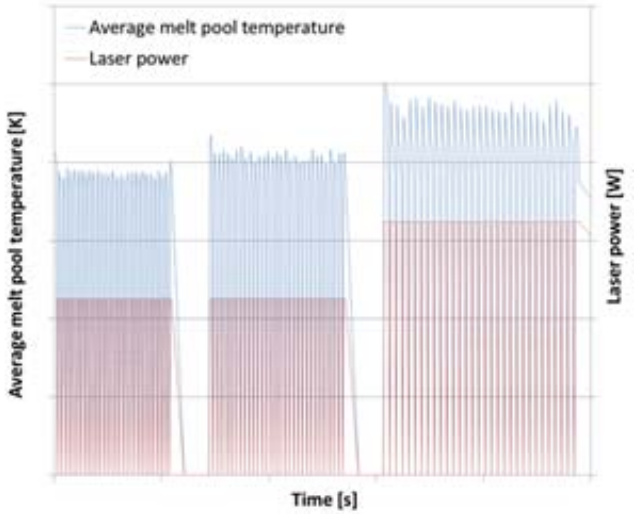
Transient temperature prediction

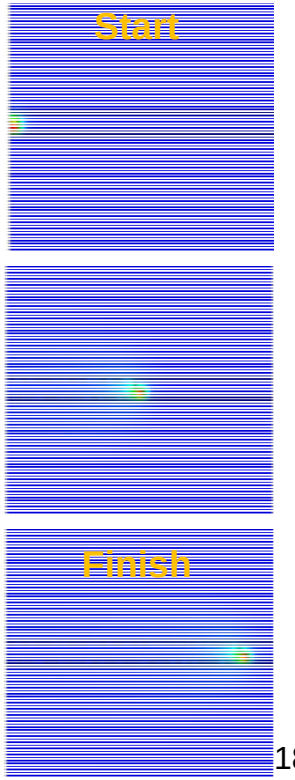
Multi-pass welding simulation

Process parameters

- Power, Direction, Speed
- Confirmed reduced residual stresses
- Impact on TC embedment







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Embedded Thermocouples – LENS Process Successfully Demonstrated

Successfully embedded TC's in development trial hardware

- Linear & planar
- Learned out power settings, feed rates and sequence

Transitioned to 3D LENS trial specimens

- DMLS is limited to 2.5D
  - X,Y and successive planar layers in Z direction
- LENS has no such limitation as metal powder delivery is concurrent.
- Observed TC reading during processing.
  - Reliably reading
- Not trivial but routinely successful
  - Continuous welds
  - TC's reading.
  - Micro's reasonable.
  - Testing will be next judgment on weld condition
    - Strength, Fatigue, Further sectioning.

Embedded 3 out of 3 TC's in Final Test Article

- Verified working after

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Embedded Thermocouples - Produced Several Topologies

Depth and Draft Angle

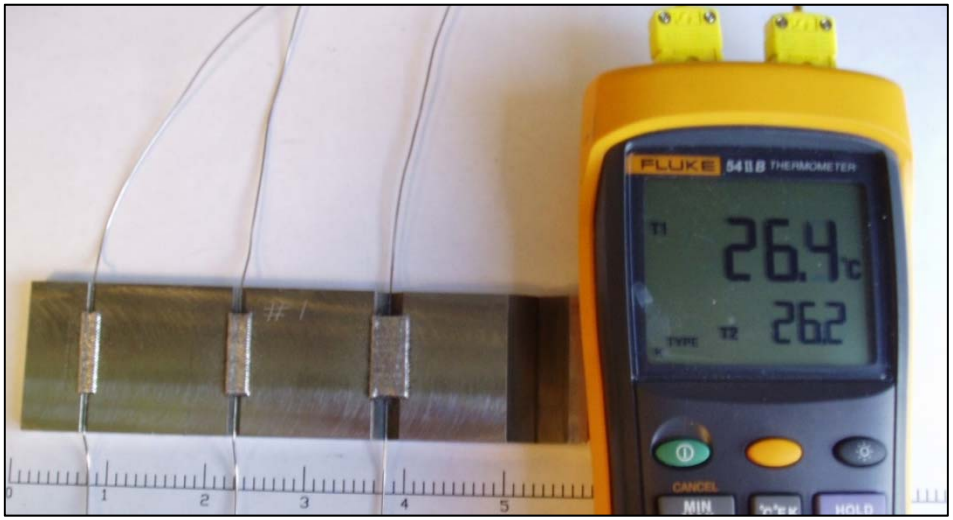
- Wider angles producing greater distortions
- Machined and DMLS

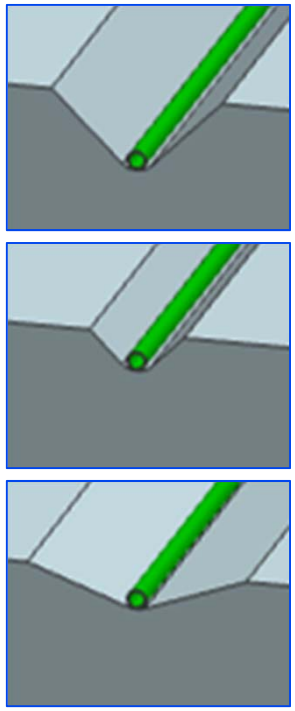
Residual stress strong function of processing temperatures

- Elevated initial temps put TC at greater risk

Literature references to coating prior to processing

- Produced coated TC's
- Haven't needed alternate





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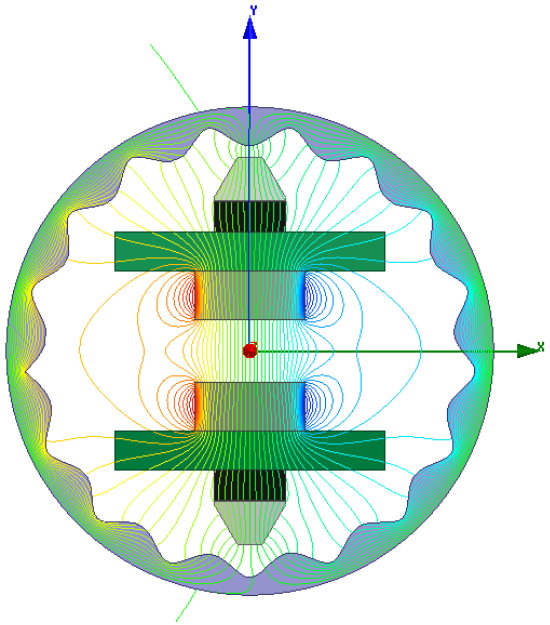
Electro-Magnetic Field Simulations

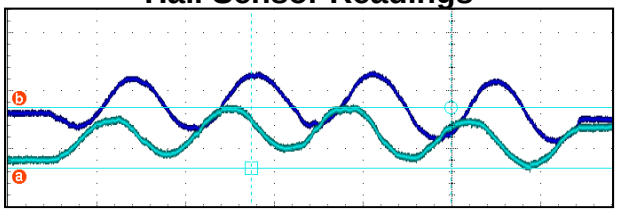
Multiple Configurations Studied

- Coil coupling
  - Sensitivity to air gaps and materials studied
- Variable Reluctance Sensor
  - Simulated baseline and contingency configurations
  - Prediction accuracy and bench test in reasonable agreement

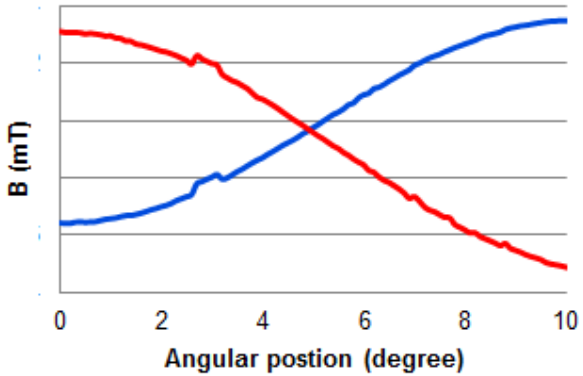


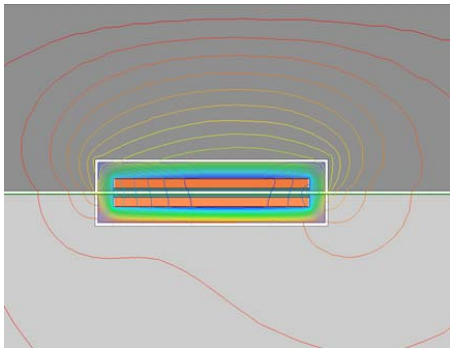
Flux lines of a VR sensing assembly

Hall Sensor Readings



Magnetic field density variation





Field Lines of Coupling Coils

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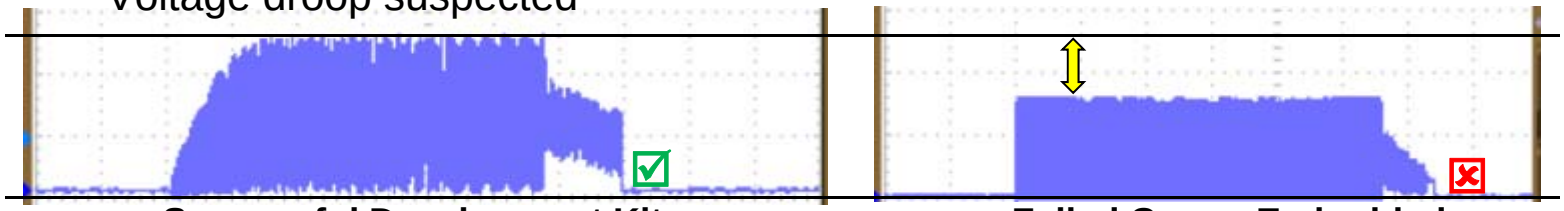
Current Firmware Challenge Working Towards Closure

Communication link has been a challenge in miniature hardware.

- Development kit hardware for wireless power/data early success
- Demonstration on embedded hasn't passed data

Vane/Reader Power/Data Process

- Vane MSP Access command
  - Comes through RF field from the reader to the transponder in the vane
  - Wakes processor in vane up
  - Vane transponder receives data from processor
  - Vane transponder transmits data through RF field to Reader
  - Longer to execute
  - Voltage droop suspected



Successful Development Kit **Failed Comm Embedded**

Testing as Recent as 4/15

- Indicates power transfer issue close to resolution.

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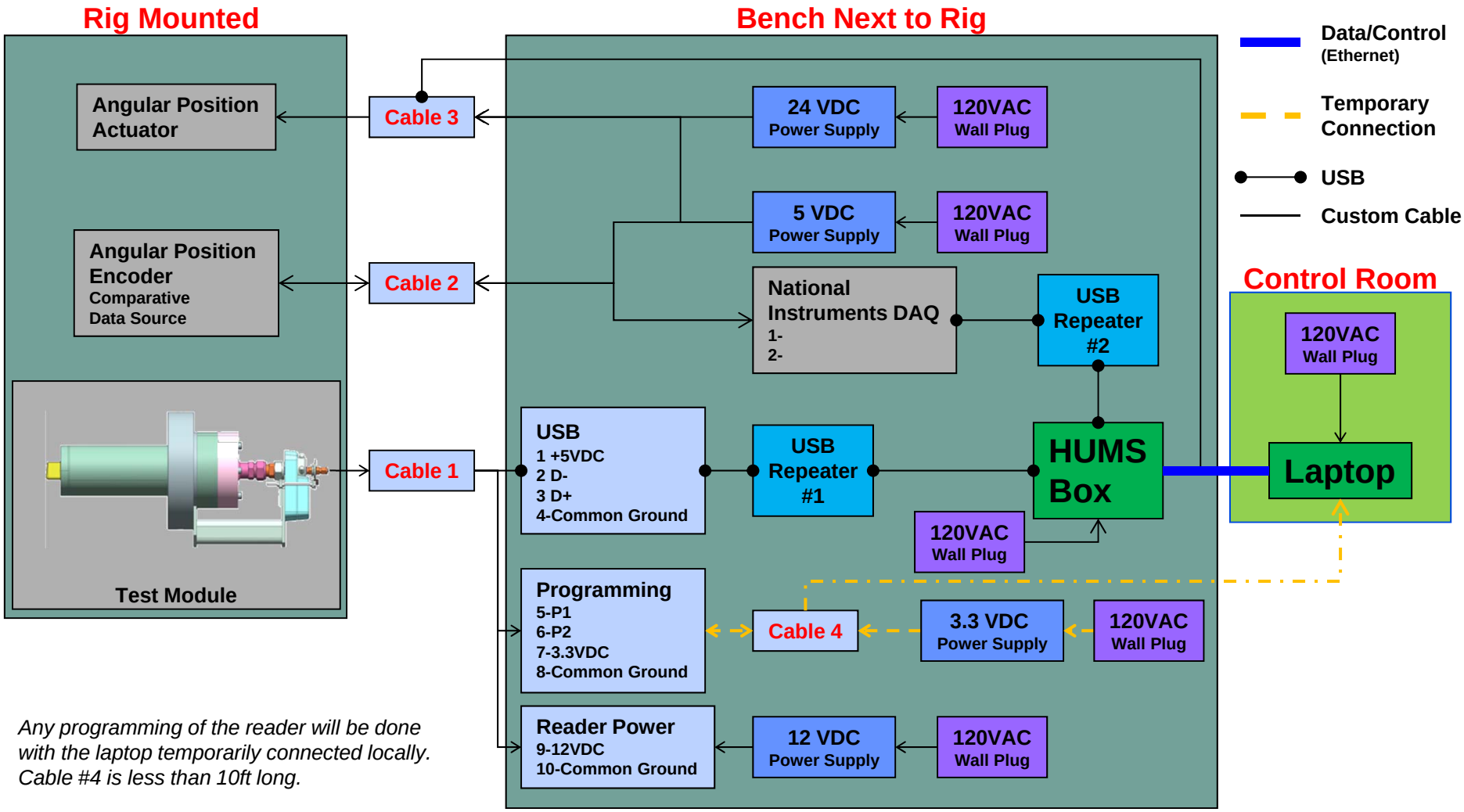
NETL Test Hardware Schematic Block Diagram



Any programming of the reader will be done with the laptop temporarily connected locally. Cable #4 is less than 10ft long.

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Firmware and Validation Test Plan

Firmware Requirements

Probe PCB

- Link with RF chip for power and communication channel
- Read three TC and PCB temperatures through ADC
- Read data from accelerometer

Reader PCB

- Link with RF chip for power and communication channel
- Read signals from angular position sensors through ADC
- Communicate data to lab data acquisition system through USB interface

Validation Test Plan

Performance Tests

- Start with Reader PCB firmware and validate proper USB communication, angular sensor data through ADC, and RF chip communication
- Demonstrate vane PCB firmware and validate proper TC and accelerometer data
- Test in lab before assembling in probe body

ATOMeS

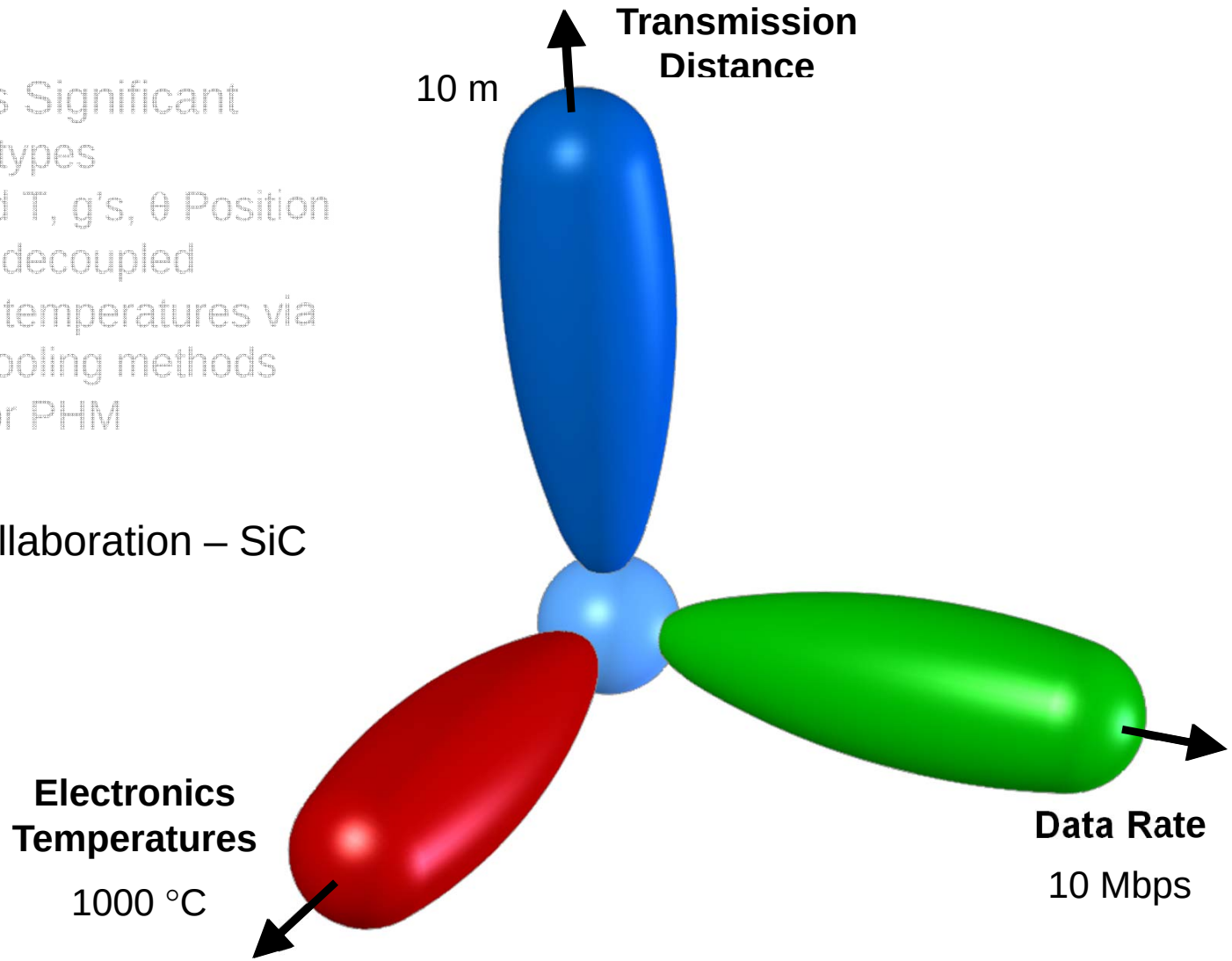
Wireless Power & Data – Expanding the Envelope For Broader Applications

Current Space is Significant

- Flexible data types
- Demonstrated T, g's, θ Position
- Mechanically decoupled
- High process temperatures via established cooling methods
- Rates ideal for PHM

Expanding

- ⇧T NASA Collaboration – SiC



HEAT

High Temperature RF Wireless Interface

National Aeronautics and Space Administration

Approach: More Complex Systems Moving Toward Engine Applications Smart Se…tems

Milestone: Demonstrate High Temperature Sensing, Wireless Communication, and Power Scavenging for Propulsion Health Management

Date: 6/30/2012

Metric: Demonstrate integrated self powered wireless sensor system at 500 °C with data transmission with operational life of at least 1 hr

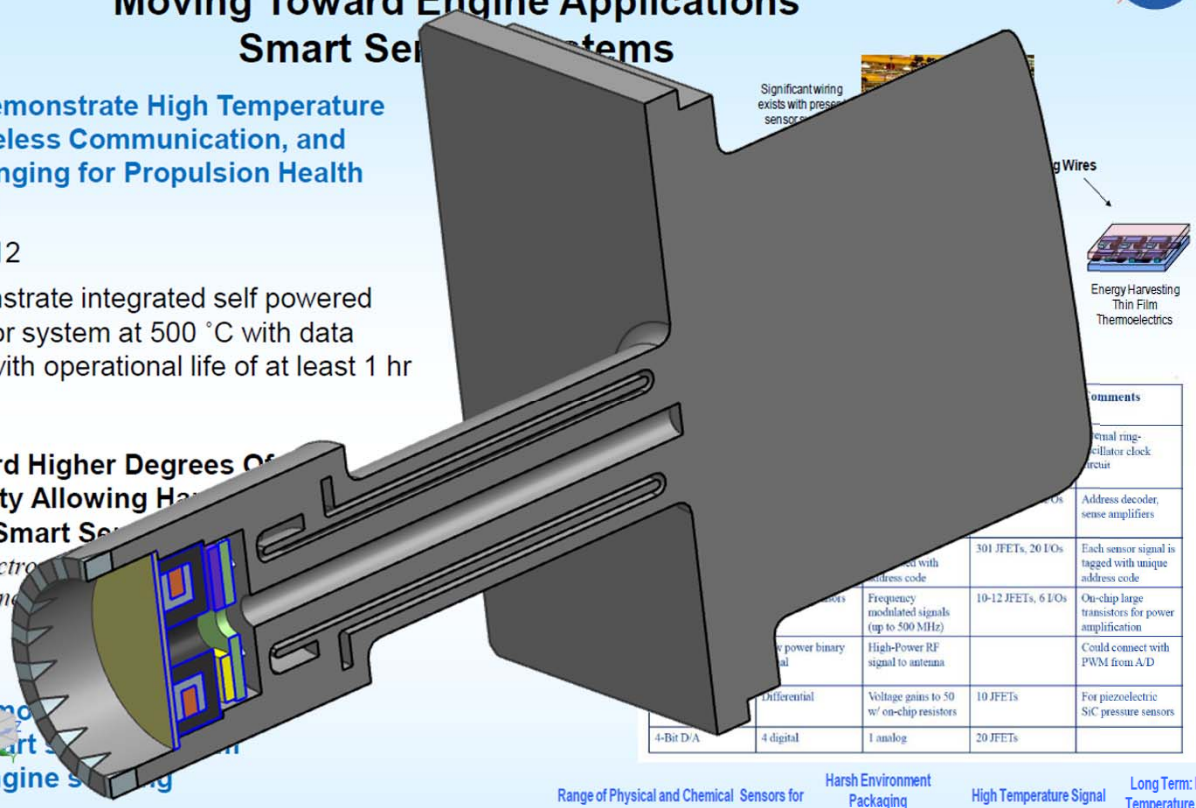
Move Toward Higher Degrees Of… Complexity Allowing Ha… Environment Smart Se…

High Temp Electro… plann…

Milestone: Demo… generation s…rt … off-nominal engine s…g

Date: 8/30/2016

Metric: Show first demonstration of a limited smart high temperature wireless data sensor system to detect engine faults



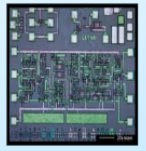
				omments
				ernal ring-cillator clock ircuit
				Address decoder, sense amplifiers
			301 JFETs, 20 I/Os	Each sensor signal is tagged with unique address code
		Frequency modulated signals (up to 500 MHz)	10-12 JFETs, 6 I/Os	On-chip large transistors for power amplification
		High-Power RF signal to antenna		Could connect with PWM from A/D
	Differential	Voltage gains to 50 w/ on-chip resistors	10 JFETs	For piezoelectric SiC pressure sensors
4-Bit D/A	4 digital	1 analog	20 JFETs	

Integration of a range of technologies is needed for Smart Sensor Systems

Range of Physical and Chemical Sensors for Harsh Environments

Harsh Environment Packaging (10,000 hours at 500°C)

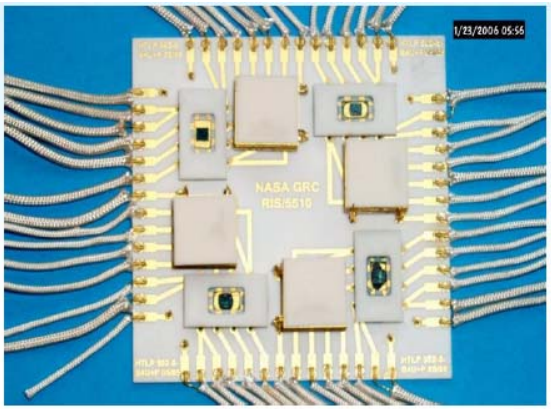
High Temperature Signal Processing and Wireless



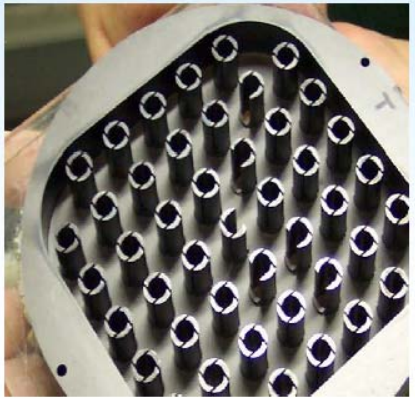
Long Term: High Temperature "Lick and Stick" Systems

www.nasa.gov

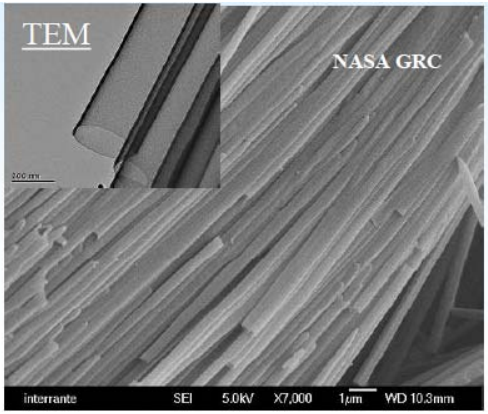
Sensors and Electronics Work at NASA



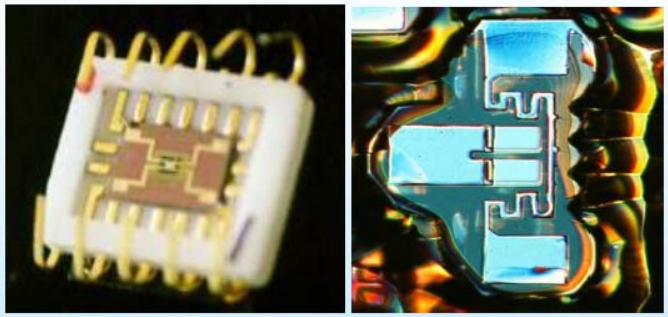
High Temperature SiC Electronics



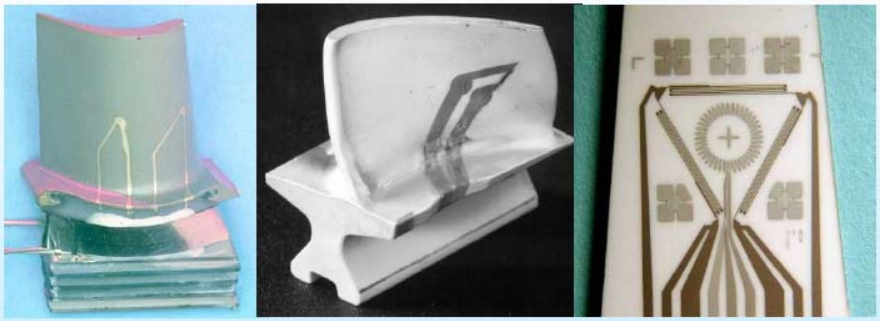
Micro-Electro-Mechanical Systems (MEMS)



Nanotechnology SiC Nanotubes



Chemical Sensors



Thin Film Sensors

ATOMeS

Next Steps

Complete Firmware and Validation Test Plan

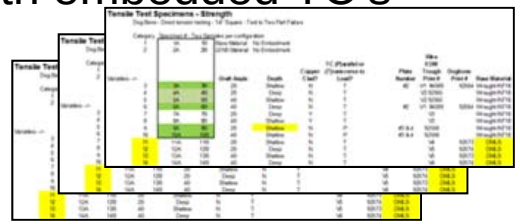
- Must demonstrate reliable power/data transfer in test article

Complete Assembly → NETL Aero-thermal Test Platform (Morgantown, WV)

- Run through steady and cycling thermal test
- Cycle angular position sensing and compare to encoder truth data

Mechanical Test on Hold Pending Completion of Firmware Checkout

- Strength and fatigue of LENS welded specimens with embedded TC's



Longer View

- United Technologies Research Center is:
  - pursuing the deployment of the current developed technology w/in UTC business units.
  - continuing to do research to grow envelope and expand the usage case
- Value to the customer is driven by technology transition
  - As we close on open concerns we continue to be interested in greater ties to customer driven requirements

ATOMeS

Creating Value - Several Patents Filed Under This Program

- Invention Disclosure File Number ID-0033072-US, Design Methodology and Tuning Procedure for Embedded Sensor Systems:
  - PW Filed
- Invention Disclosure File Number ID-0034155-US, Additional Capability for Magnetic Sensing
  - UTAS Filed
- Invention Disclosure File Number ID-0032806-US, Embedded Sensor System with Coupling Enhancement Using High Permeability Structures
  - PW Filed
- Invention Disclosure File Number ID-0034286-US, Electromagnetic Coupling and System Design for Metallic Part-Embedded Digital Sensors
  - PW Filed
- Invention Disclosure File Number ID-0034281-US, Embedded Magnetic Structures for Position Sensing Using Additive Manufacturing
  - PW Filed
- Invention Disclosure File Number ID-82373965, Additive Manufacturing Process for Embedded Thermocouple Probe tip Integrity Enhancement
  - In review with PW
- Invention Disclosure File Number ID-83797344, Variable Reluctance Sensing Using Additive Manufacturing
  - In review with PW

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