RESEARCH & DEVELOPMENT

Creare®

Wireless Temperature Sensor for Rotating Turbine Blades

STTR Phase I Grant DE-SC0020908

Phase I Final Results Meeting

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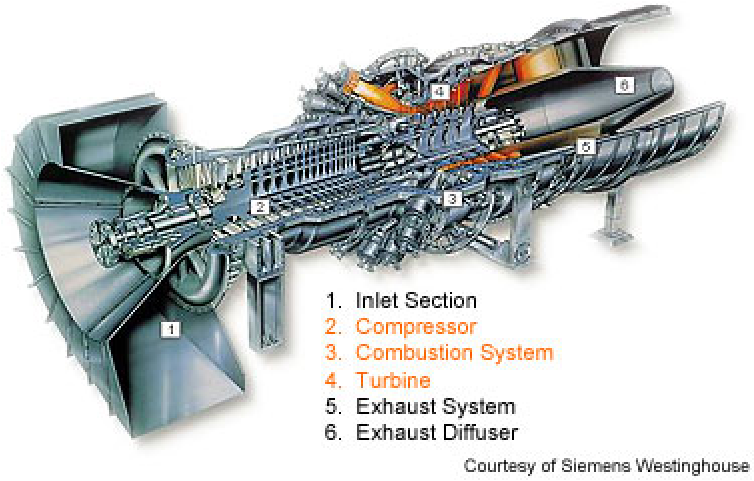
Outline

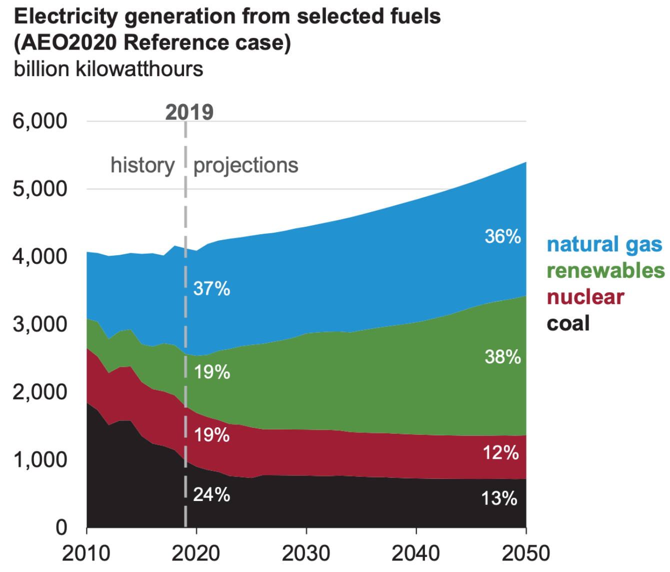
- Wireless Temperature Sensor Overview
- Phase I Overview
- Sensor Head Design and Fabrication
- Sensor Testing
- Turbine Engine Integration Plan
- Conclusions

Wireless Sensor Overview

Need for Turbine Temperature Sensor

- **Natural gas turbines are largest source of electricity in the US**
  - **Projected to remain #1 for the next 2 decades+**
- **The turbine metal temperature limits the machine efficiency and durability**
  - **Measurement of turbine temperature would allow optimized operation for higher efficiency and/or lower maintenance**
- **Existing measurement of rotating turbine blade temperature**
  - **Infrared thermometry: Requires optical access and is impacted by emissivity variation**
  - **Phosphor thermometry: Newer technique optical access required, signal weakening at high temperatures**

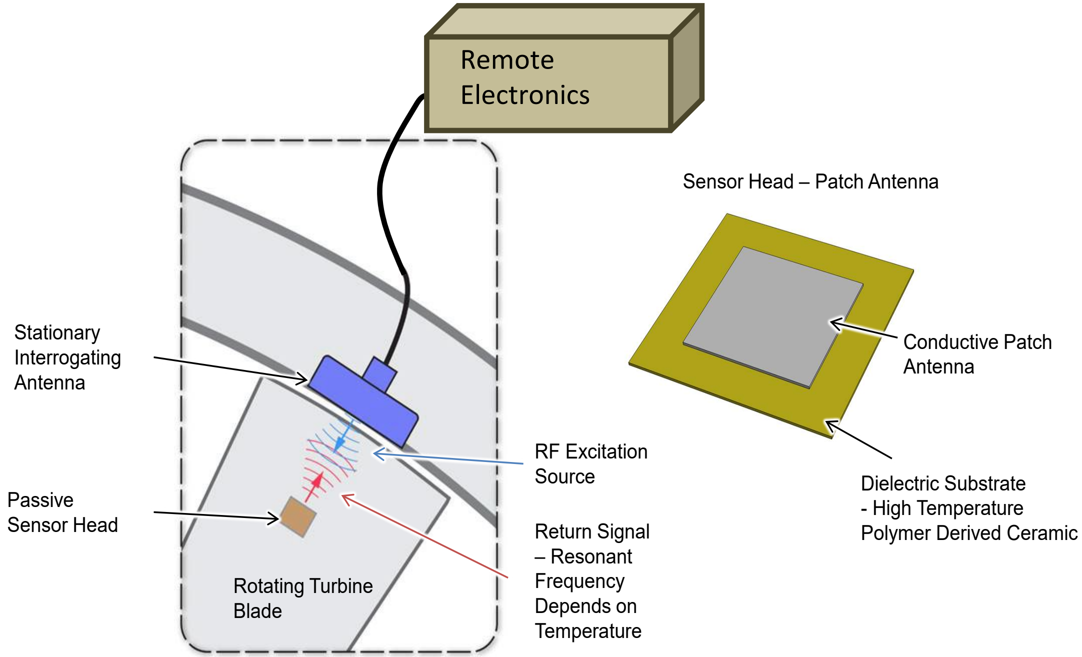


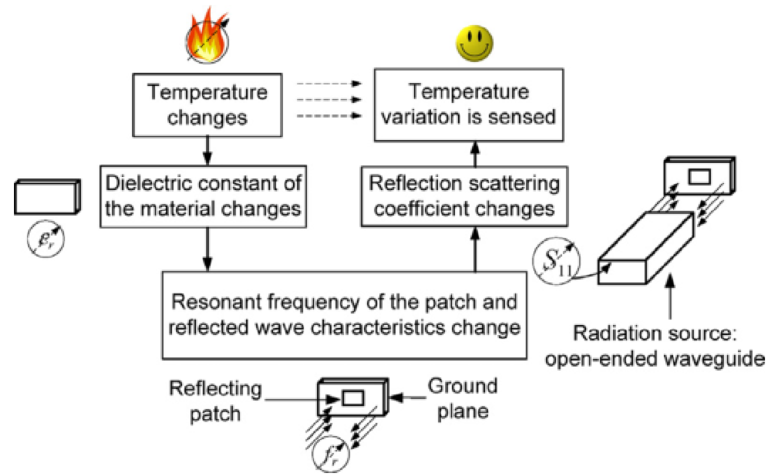


EIA US Electricity Generation Forecast

UCF/Creare Turbine Temperature Concept

- **Passive sensor head (patch antenna) attached to turbine blade**
- **High temperature sensor head is an antenna with a resonant frequency that is temperature dependent**
- **Temperature is measured by RF transceiver mounted in the turbine case**

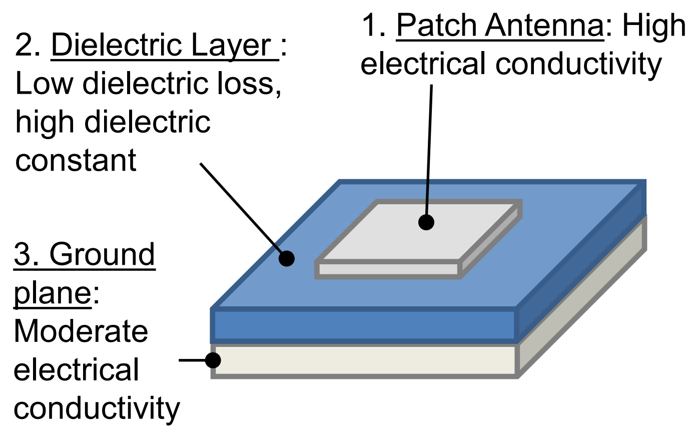


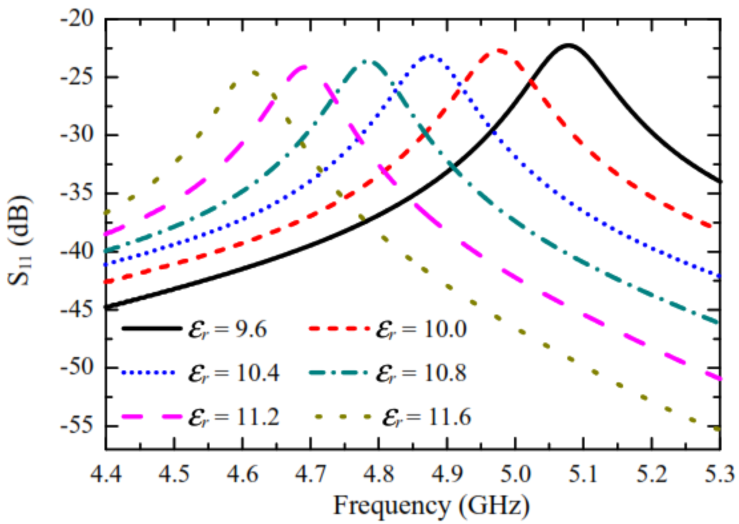


Wireless Sensor Head

- **Layers of conductors separated by dielectric**
- **Material properties of dielectric are key**
  - **Low dielectric loss**
    - **Required for high quality factor**
    - **Increases signal peak, sensing distance, and accuracy**
  - **Dielectric constant**
    - **Must vary with temperature**
    - **Higher value allows smaller sensor for same operating frequency**
- **Patch antenna size based on dielectric properties and desired operating frequency**

$$f_r = \frac{c_0}{2L_{eff}\sqrt{\varepsilon_{eff}}}$$

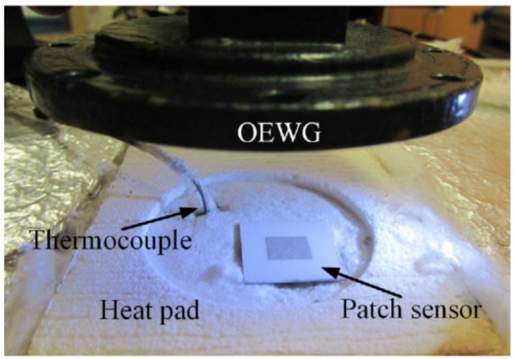


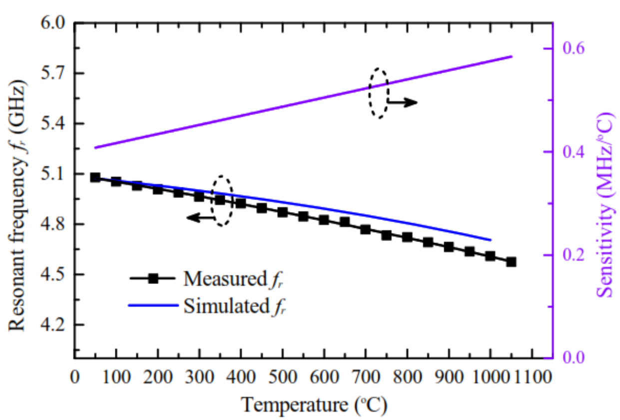


Previous Related Work at UCF

Wireless Temperature Sensor

- **Prof. Xun Gong of UCF developed and tested a wireless temperature sensor based on patch antenna**
- **Basis for current work – needs further development for gas turbine application**

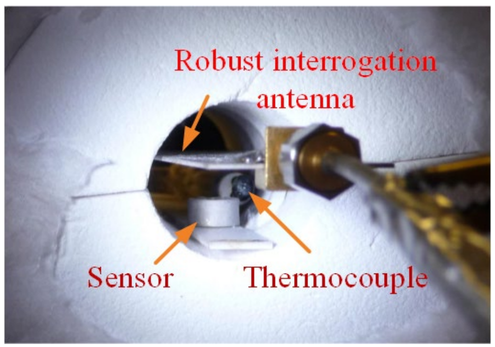


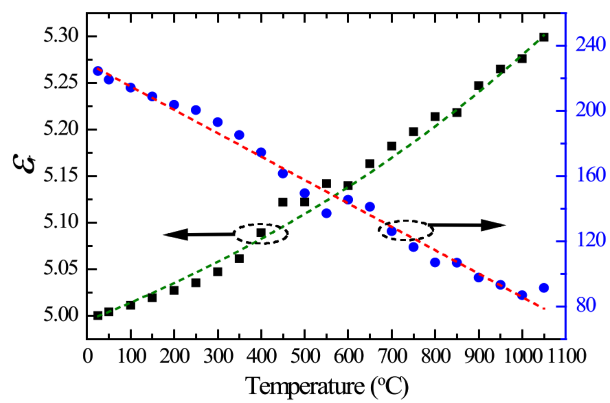


Cheng et al. 2015a, http://dx.doi.org/10.1016/j.sna.2014.11.010

Novel High Temperature Materials

- **UCF has developed novel polymer derived ceramic materials with desirable properties for the sensor dielectric: SiBCN, SiCN**
- **Excellent stability in high temperature combustion products**
- **Low dielectric loss**
- **Dielectric constant varies with temperature**
- **Microfabrication capability**



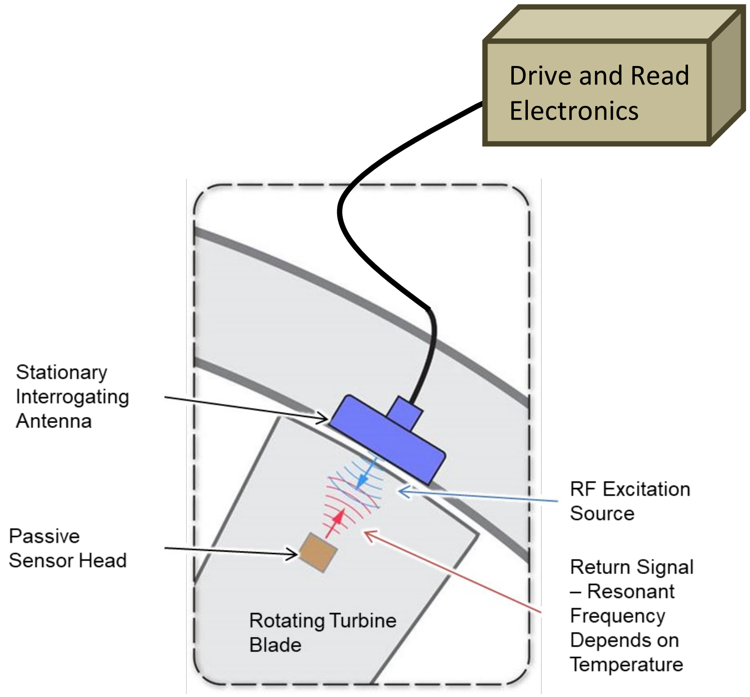


Cheng et al. 2015b, http://dx.doi.org/10.1109/JMEMS.2016.2642580

Integration with a Gas Turbine Engine

- **Wireless sensor head**
  - **Must be integrated with TBC coated turbine blade**
  - **Materials, size, manufacturing considerations**
- **Stationary antenna mounted in case**
  - **High temperature materials**
- **Drive and read electronics**
  - **Remote located in benign environment**
  - **Short time to read each passing blade (order 100 μs)**
  - **Distance to sensor, 10-100 mm**
  - **Need high energy RF pulse**

TBC coated turbine blade
Image source: GE



Phase I Overview

Project Team

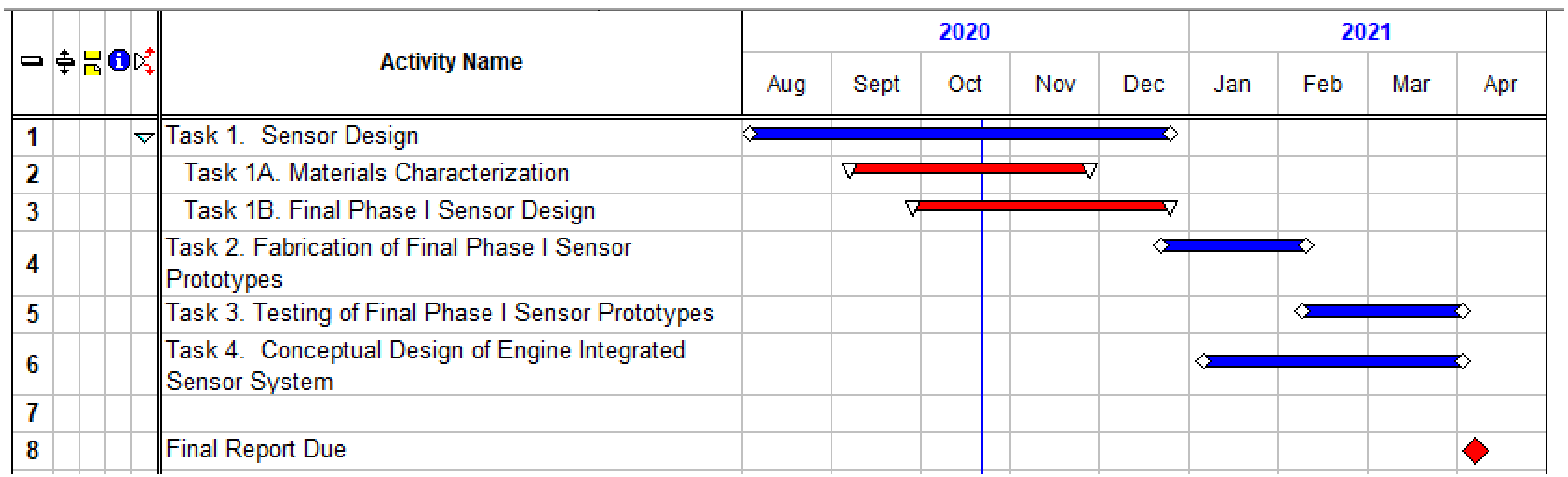
- Creare
  - Dr. Danny Micka, Principal Investigator
  - Greg Daines, Project Engineer
- University of Central Florida
  - Prof. Kareem Ahmed, UCF Lead and High Temperature Testing
  - Prof. Xun Gong, RF and Electronics Design and Testing
  - Prof. Seetha Raghavan, High Temperature Materials
  - Dr. Quentin Fouliard, High Temperature Materials
- Industrial Collaborator (Unfunded)
  - General Electric, Dr. Keith McManus

Phase I Technical Objectives

- **Overall Objective: Development and commercialization of an accurate, durable temperature sensor for rotating turbine blades**
- **Phase I: Prove feasibility of sensor concept for gas turbine engines**
  - **Design and build sensor head for turbine blade application**
  - **Build and test prototype sensor head**
  - **Conceptual design of a turbine engine integrated sensor system**
- **Key Questions to Address in Phase I**
  - **Sensor head size and materials**
  - **Sensor head integration with turbine blade**
  - **Sensor performance**
  - **System integration challenges**

Schedule and Budget

- **DoE Phase I STTR**
- **Nominal 9 month schedule**
  - **PoP ended March 2021**



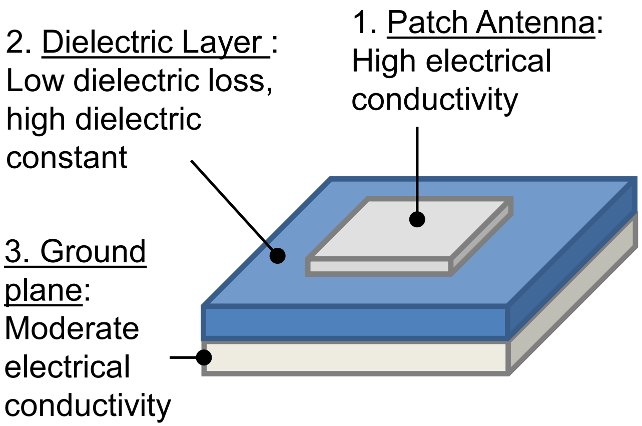
Overall Summary

- We focused on the development of the wireless sensor head in Phase I
- We designed built and tested several prototypes with different materials
- Some promising results, but experimental and schedule difficulties have slowed some key data
  - We requested and received permission to submit a Phase II proposal in 2022
- Temperature sensing performance
  - Measured good temperature response up to the maximum temperature measured (800 ºC) with alumina sensor
  - Have not yet been able to test at higher temperatures due to experimental difficulties
- Sensing distance
  - Up to 63 mm measured with high temperature sensor
  - Sufficient for turbine engine application
- Turbine engine integration
  - Conceptual design for buried sensor for long term durability
  - Requires verification of YSZ dielectric properties at high temperature (pending)

Sensor Head Design and Fabrication

Materials Selection: Sensor Head

- **Dielectric**
  - Requirements: dielectric properties, high temperature capability, turbine blade compatibility
  - SiBCN
    - » Great high temperature and dielectric properties demonstrated in previous laboratory studies
    - » Unique fabrication required – *Fabrication not feasible for Phase I sensor*
  - Al_2O_3
    - » Good high temperature and dielectric properties, widely available
    - » Issues with long term chemical compatibility with high temperature combustion products
    - » We built and tested several prototypes
  - YSZ
    - » Existing material on turbine – engine integration simplified
    - » Dielectric properties uncertain
    - » We built and tested several prototypes
- **Conductor**
  - Requirements: Electrical conductivity, high temperature capability, turbine blade compatibility
  - Platinum
    - » Very high melting temperature and good oxidation resistance at temperature
  - NiCrAlY
    - » Existing material on turbine – engine integration simplified



$$f_r = \frac{c_0}{2L_{eff}\sqrt{\varepsilon_{eff}}}$$

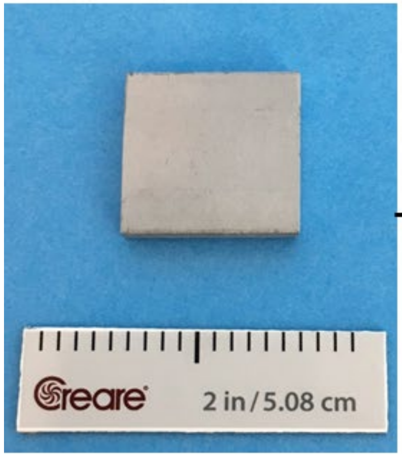
Phase I Prototypes

Table 1. Alumina (Al2O3) Based Sensors Built in Phase I				
Sensor Series	Description	Dielectric	Substrate/Ground Plane	Patch Antenna
A0	Low Temperature Pathfinder on Aluminum Substrate	Thermal Sprayed Alumina	Aluminum	Silver Paste / Copper Tape
A1		Thermal Sprayed Alumina	Aluminum with NiCrAlY Bond Coat	Silver Paste / Copper Tape
A2	High Temperature Sensors	Thermal Sprayed Alumina	Inconel 718 with NiCrAlY Bond Coat	NiCrAlY
A3	High Temperature Sensors	Prefabricated Alumina Substrate	Platinum Foil	Platinum Foil

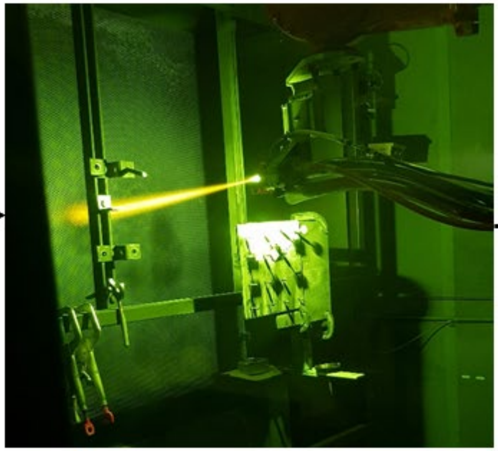
Table 2. YSZ Based Sensors Built in Phase I				
Sensor Series	Description	Dielectric	Substrate/Ground Plane	Patch Antenna
Y0	Low Temperature Pathfinder on Aluminum Substrate	Thermal Sprayed YSZ	Aluminum	Silver Paste / Copper Tape
Y1		Thermal Sprayed YSZ	Aluminum with NiCrAlY Bond Coat	Silver Paste / Copper Tape
Y2	High Temperature Sensors	Thermal Sprayed YSZ	Hastelloy with NiCrAlY Bond Coat	Platinum Paste
YER	High Temperature Sensors	Thermal Sprayed YSZ with Rare Earth Doping	Hastelloy with NiCrAlY Bond Coat	Platinum Paste

Typical Sensor Head Fabrication

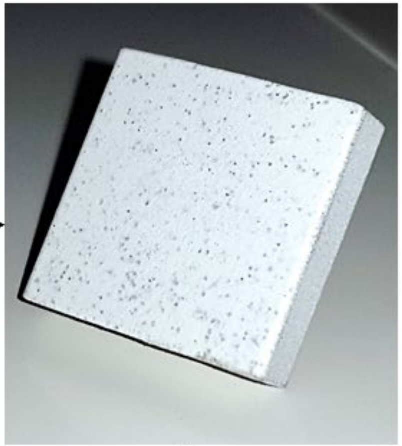
Metal Substrate

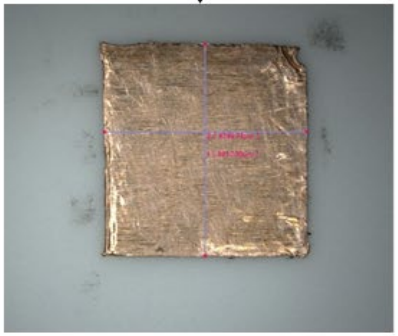


Apply NiCrAlY Bond Coat (if applicable) and Alumina or YSZ Top Coat

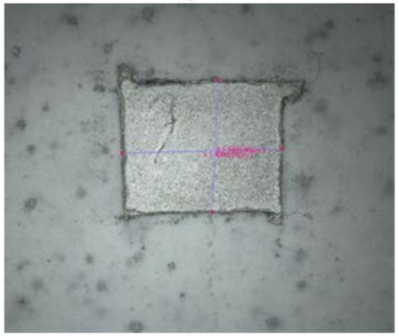


Dielectric Coated Sample

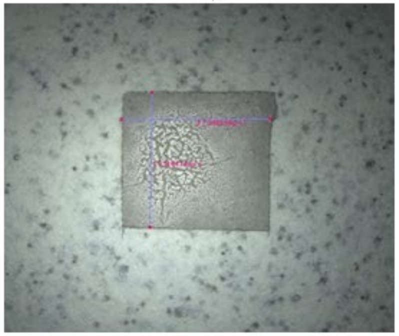




Copper Patch Antenna



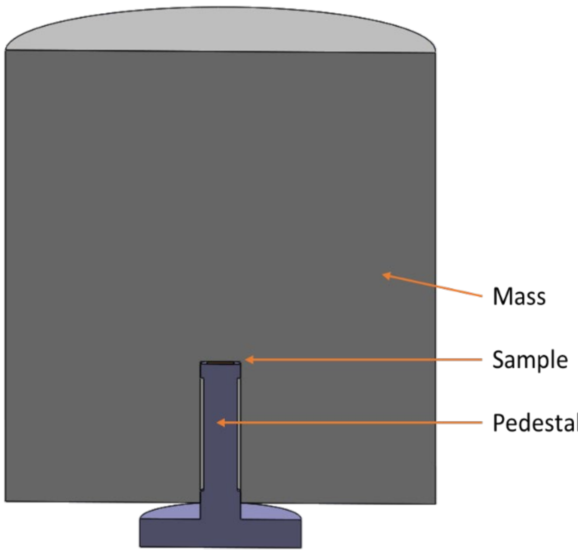
Silver Paste Patch Antenna

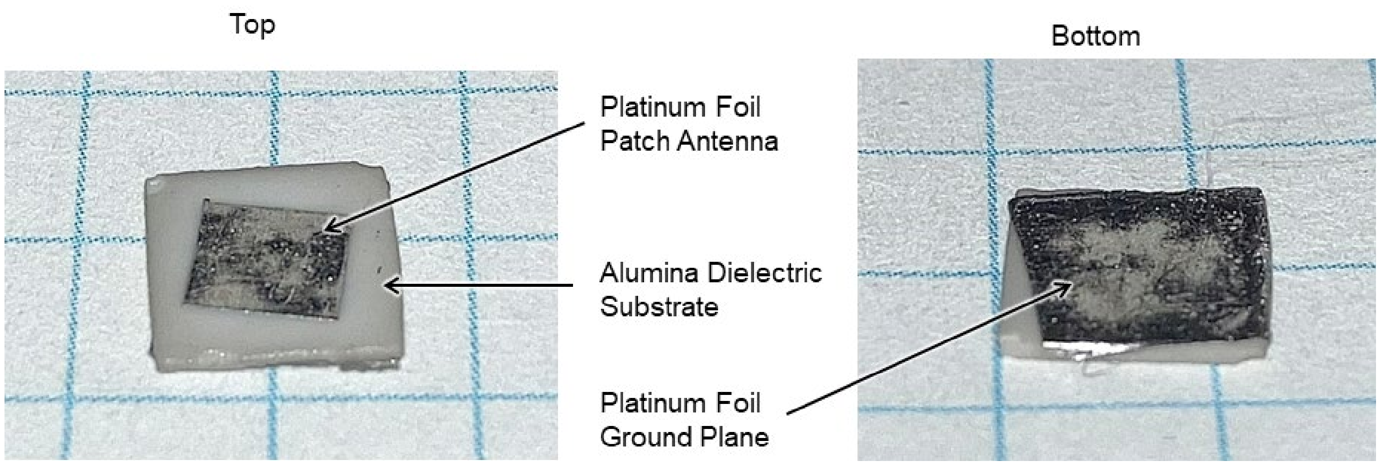


Platinum Paste Patch Antenna

Reaction Bonded Sensor

- **Reaction bonded alumina / platinum sensor (A3) developed for consistent materials and high temperature bond**
- **Size**
  - **6.35 x 6.36 x 0.5 mm alumina wafer**
  - **3.5 x 4.0 x 0.025 mm platinum foil**
- **Bonding at 1150 ºC and 2 MPa**

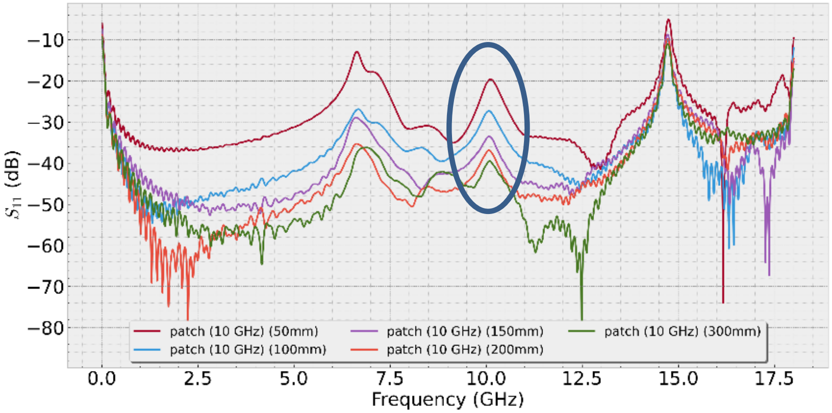




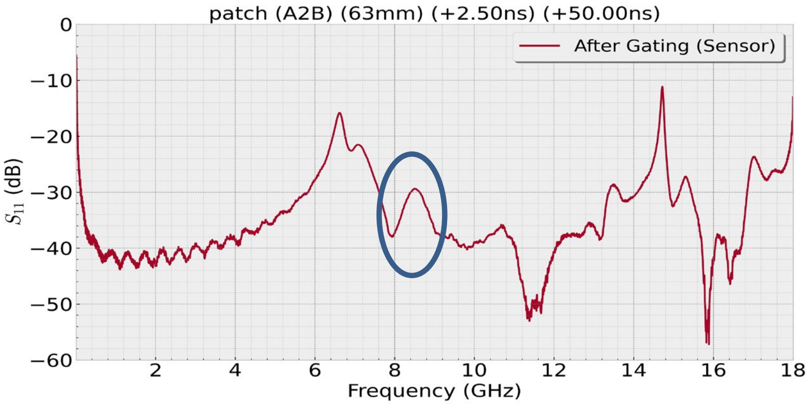
Sensor Testing

Sensing Distance

- **Commercial Network Analyzer (Agilent N5230A) and COTS Antenna were used to probe sensor response over critical frequency range**
- **Key measurement is sensor resonant frequency**
- **Sensing distance measurements at ambient temperature**
  - **Successful measurement at ~60 mm with A2 and A3 sensors**



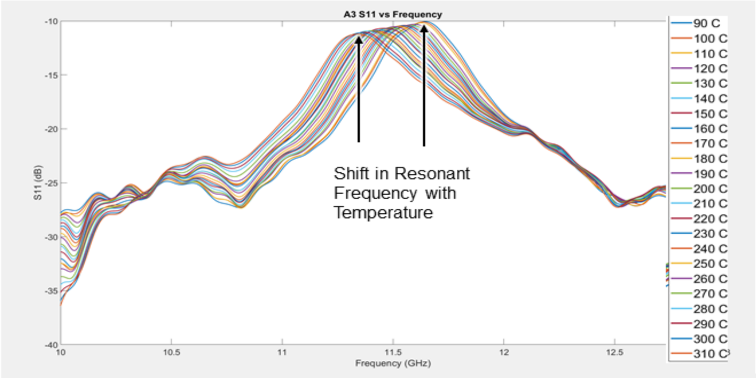
Low Loss Dielectric Sensor Measurement up to 300 mm

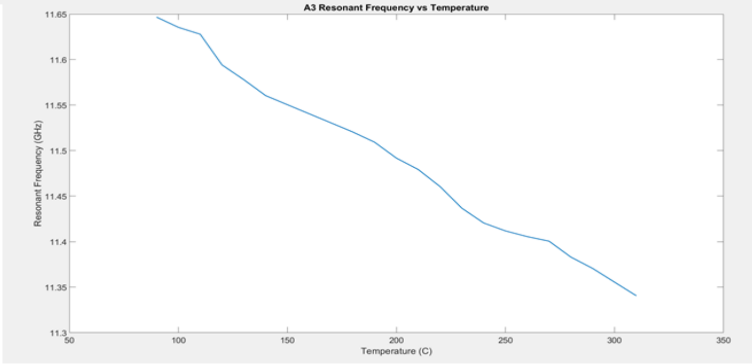


Alumina Sensor (A2) Measurement Successful at 63 mm

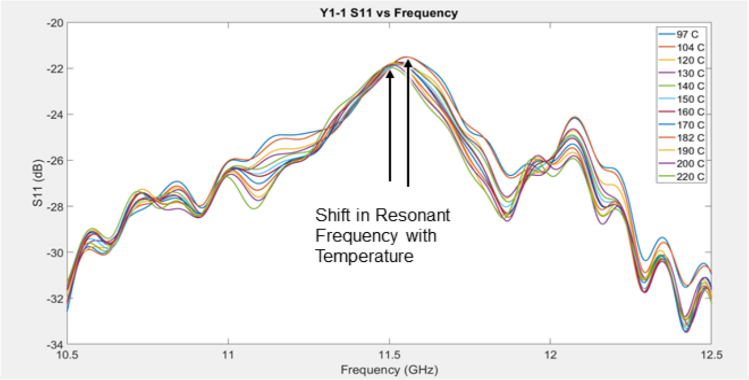
Low Temperature Hot Plate Testing

- **Alumina Sensor (A3) Performs well**
  - **10 C change in temperature clearly distinguished**
  - **Sensitivity ~1.4 MHz/ºC**
- **YSZ sensor also works**
  - **Demonstrates appropriate dielectric properties (at temperatures measured)**
  - **Sensitivity ~ 1/3 of alumina sensor**





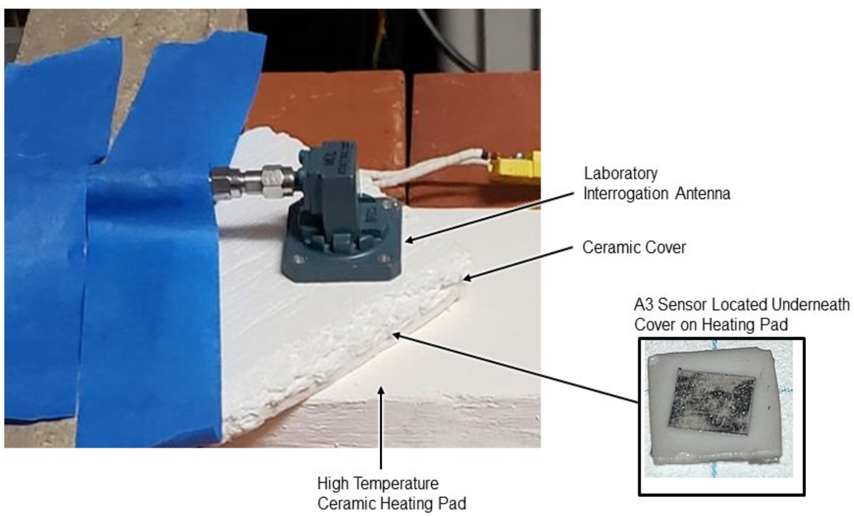
Alumina Sensor (A3)

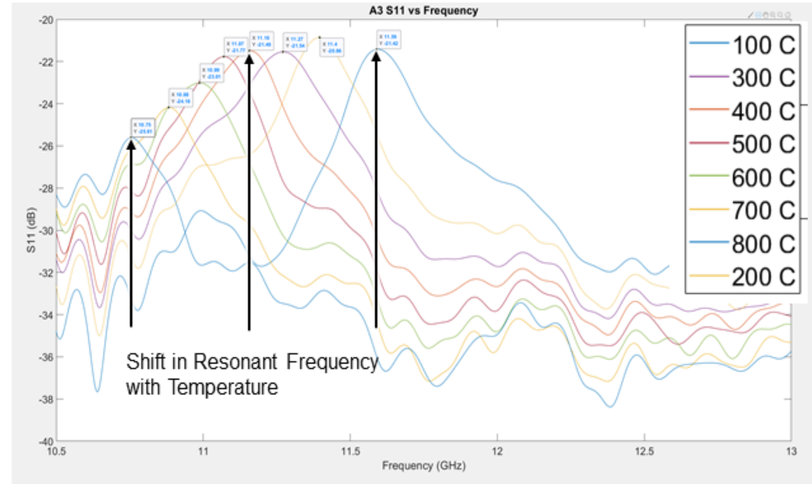


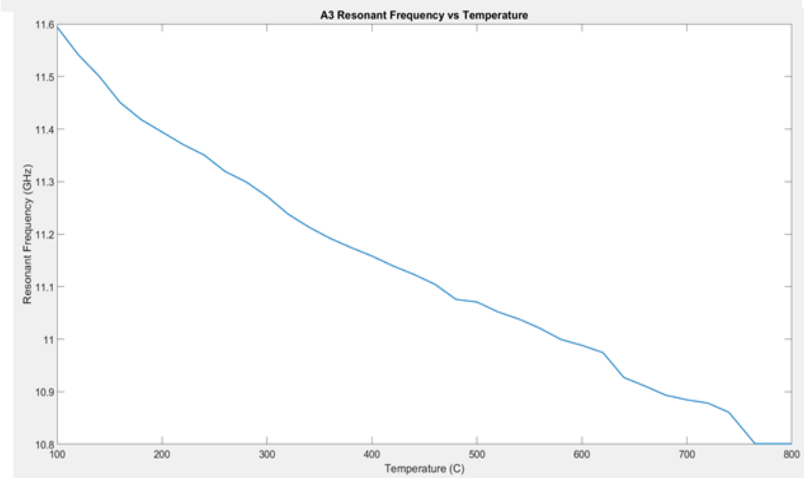
YSZ Sensor (Y1)

High Temperature Heating Pad Testing

- Only A3 tested due to size constraints
- Max temperature of pad is 800 ºC
- Sensor performs well up to maximum temperature measured
- Don’t have a good secondary measurement of sensor dielectric

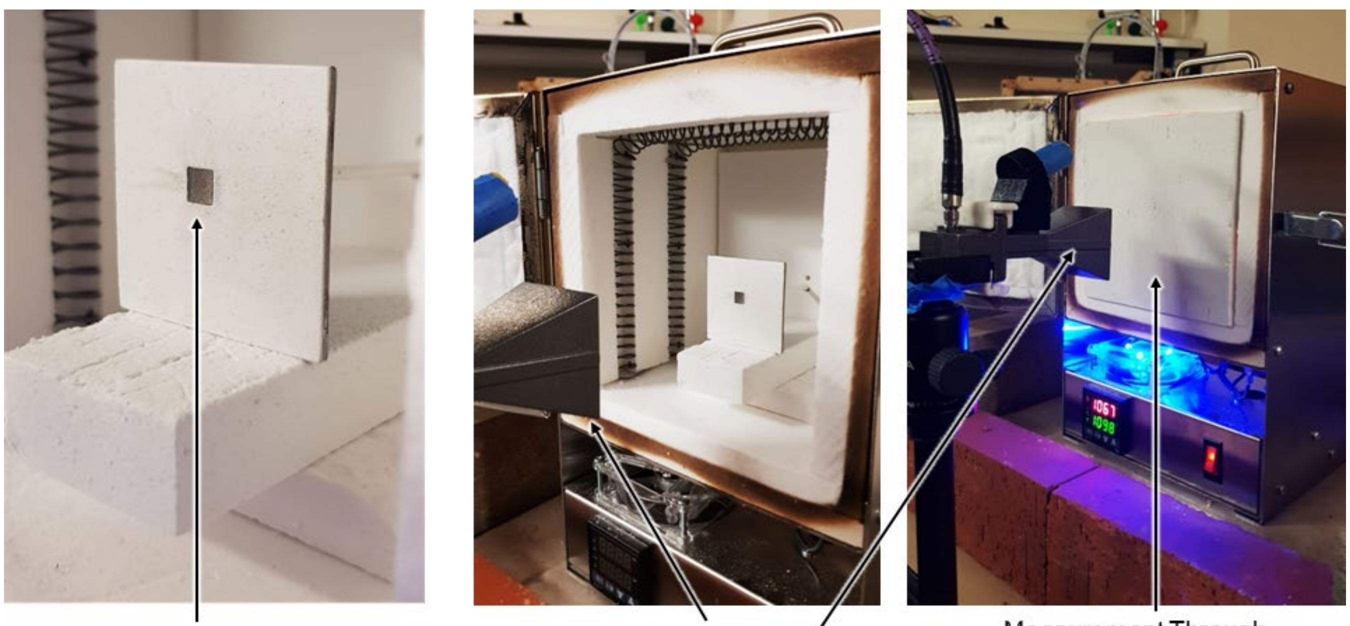






High Temperature Oven Testingc

- **Attempted measurements up to 1000 ºC in a high temperature oven**
- **Measurements failed, sensor resonant frequency cannot be reliably detected**
  - **Possible that reflections from metal walls cause issue with the measurement**
  - **Requires further investigation**



A2 Sensor Mounted in Oven

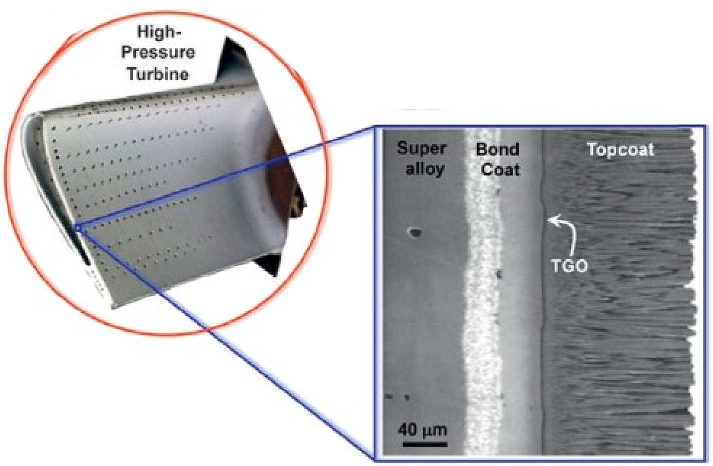
Horn Interrogation Antenna

Measurement Through Ceramic Oven Door

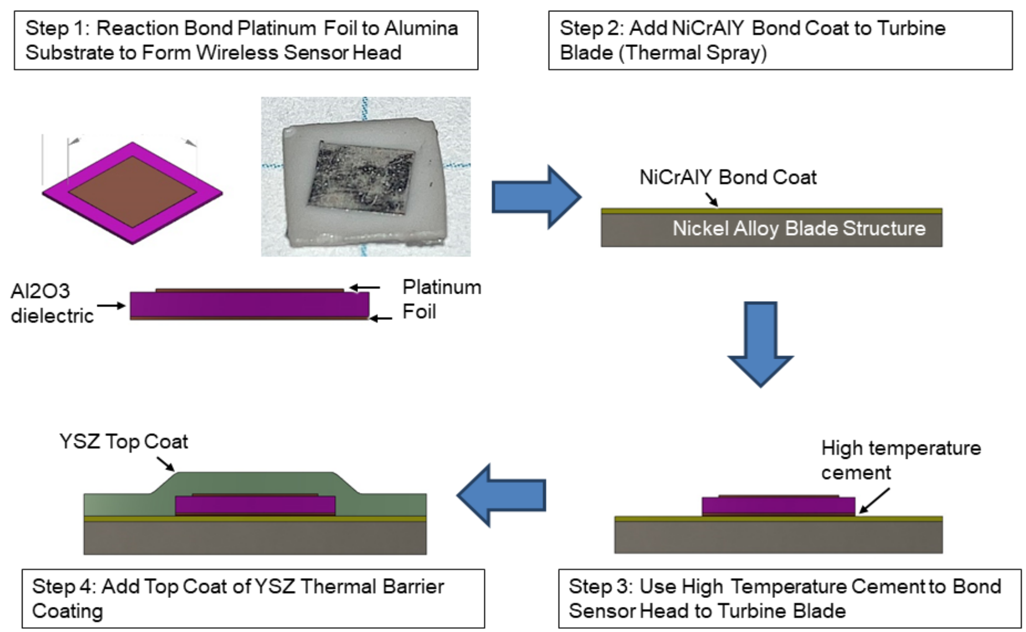
Turbine Engine Integration Plan

Sensor Head Integration with Turbine Blade

- **Key is long term durability (up to 24,000 hrs) and integration with existing blade materials and manufacturing**
- **We plan a buried sensor head (located under YSZ) for long term durability**
  - **Alumina and platinum both compatible with YSZ top coat**
- **Place in area with no cooling holes**

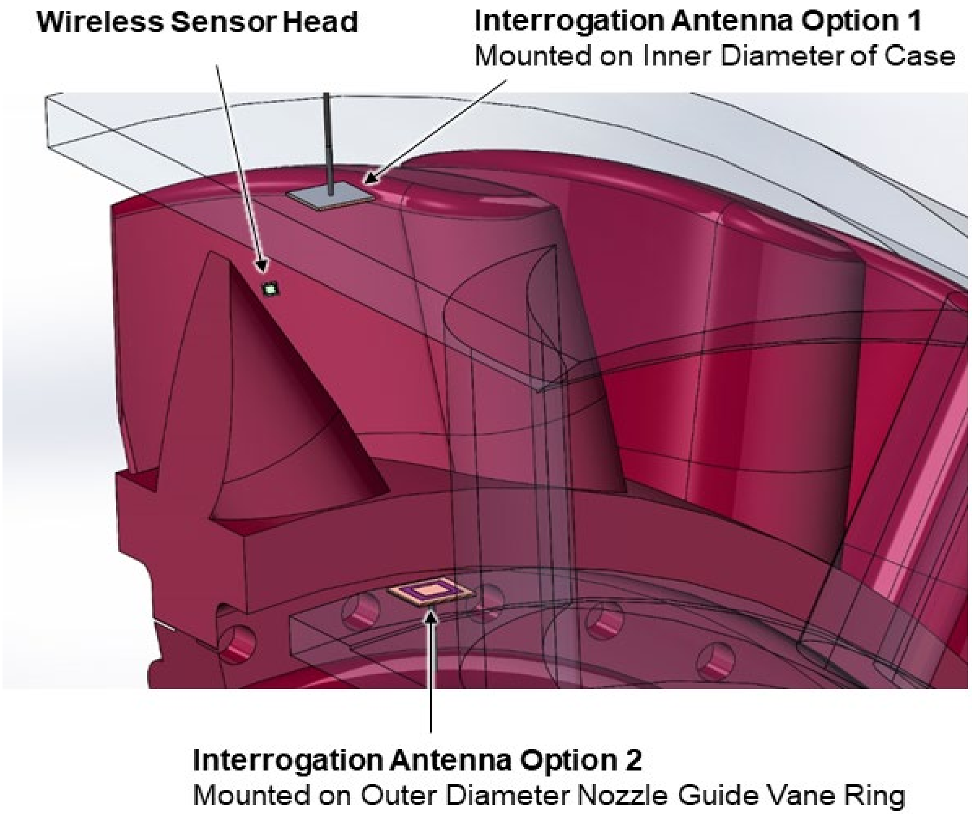


Clarke 2012
https://doi.org/10.1557/mrs.2012.232



System Integration Concept

- **Stationary interrogation antenna**
  - **Mounted on the case inner diameter or outer diameter of nozzle guide vane ring**
  - **Nominally made of same materials as the sensor head**
- **Remote electronics**
  - **Custom version of commercial network analyzer located outside engine in benign environment**
  - **High pulsed RF source for good signal to noise ratio with short measurement time on rotating blade**
- **Sensor heads**
  - **Single sensor head per blade**
  - **2-10 sensors per engine**



Conclusions

Conclusions

- Wireless temperature sensor has been proven to work with a variety of materials
- For the turbine engine application, we plan a buried sensor head for long life
- The high temperature sensor head can be made by reaction bonding platinum foil to an alumina substrate
- YSZ has appropriate dielectric properties for a top coat (or sensor dielectric) at low temperatures (up to 300 ºC). Further testing is required to verify these properties at high temperatures.
- Additional work needed:
  - Measurements of sensor operating at highest temperature needed for gas turbine application
  - Quantify temperature sensitivity / accuracy at high temperatures