2014 Crosscutting Research Review Meeting

Wireless Battery-free Harsh Environment Sensor System for Energy Sector Applications

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Preliminary Notes

Thank NETL / DOE for:

- The support received to successfully transition this technology to power plant and industrial applications.
- The opportunity to share the current results of our work.
- The opportunity to learn from NETL & others about:
  - The most current sensor and monitoring needs.
  - How we can contribute to respond to those needs.

- Work involves a large group of people: Profs. , scientists, supporting tech. staff, grad &undergraduate students, and industry:

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Outline

I. Introduction: Wireless AW in Hostile Environment (HE)

II. Background & Prior Art

   A. Materials for HE: substrates, films, electrodes

   B. Packaging & Sensors in HE

III. Recent Progress in Wireless SAW Sensors for HE

   A. Electrodes for 1000°C and higher

   B. Interfacial Layer at High Temperatures

   C. Capping Layer & Capacitive Coupling at High Temperatures

   D. Recent Tests: HT Devices & Wireless Temp Profile Furnace

   E. Recent Tests in Turbine Engines & Power Plant Environments

IV. Conclusion & Acknowledgements

I. INTRODUCTION

SENSORS IN HOSTILE ENVIRONENTS

- Current **APPLICATIONS** → Need enabling technology
- Monitoring desired → **Diagnostics & Prognostics Sensors**
- Sensors: temperature/pressure/vibration/stress/torque/gas
- Reliable sensors for these environments: **already @ premium**

Structural Health Monitoring

POWER PLANTS

COMBUSTION ENGINES

GAS/OIL EXTRACTION

Improve Fuel Burning Efficiency

Reduction of Environmental Impact

OIL REFINERIES

HIGH TEMP PROCESSING

INDUSTRIAL COMPRESSORS

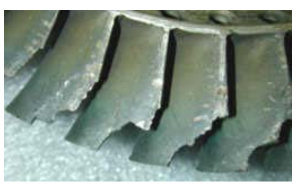
Improve Process Control

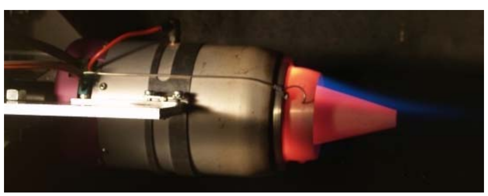
WIRELESS: highly desired ... WHY?

- Wired sensors:
  - Reliability problems $\rightarrow$ degradation and breakage of physical connections over time
  - Weight $\rightarrow$ of all the wires and connections
  - Complicated and costly sensor installation and maintenance
  - Limited overall # of sensors due to complexity of the wiring.
- Wireless :
  - Freedom to place sensors in more versatile independent locations
  - Capability to request information from MULTIPLE sensor devices with the same interrogator
  - reduction in sensor system size and weight
  - Static and also ROTATING parts

What about wireless sensing in hostile environment?

- ➢ Very different from consumer day to day wireless experience
- ➢ Wireless **sensor** operation expected to:
  - Perform accurately from room temperature up to 1400°C
  - Operate reliably:
    - ✓ Thousands of hours, if not for the entire life of the equipment
    - ✓ Meet application oriented precision and stability
    - ✓ Pressures ranging from atmospheric to thousands of psi;
  - Endurance to abrupt and sudden pressure and temperature variations (pressure and thermal shock);
  - Operation under physically or chemically aggressive environments, including vibration, corrosive gases, and/or high energy particulate bombardment





Battery???

- Wireless operation needs a source of energy
- For sensing in HE → battery is inadequate
  - Temperature limited to a few hundreds °C (<500°C)
  - Maintenance and replacement required
  - Add significant weight to the system
- Energy scavenging → viable approach, but
  - Can quickly increase system complexity / reliability, weight, and cost
  - Challenge to provide enough energy for wireless communication in hostile environments

What then?

- Thus $\rightarrow$ desirable sensor system:
  - Wireless operation
  - Battery-free
  - Address multiple sensors (ID tag function)
  - Of course $\rightarrow$ operate in HOSTILE ENVIRONMENTS
- MICROWAVE ACOUSTICS: Surface Acoustic Wave tech.

WIRELESS SAW HARSH ENVIRONMENT SENSORS

- Other technologies partially fulfill some of the requests:
  - Optical interrogation
  - Semiconductor
  - MEM's

Beyond the scope of this presentation

II. Background & Prior Art

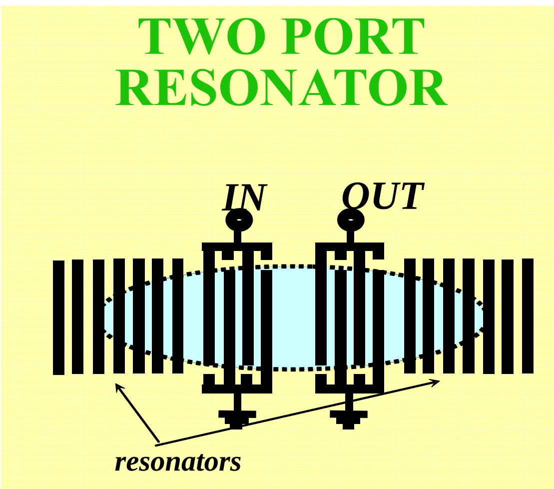
A. Microwave Acoustic Sensor Technology for HE

SENSING MECHANISM:

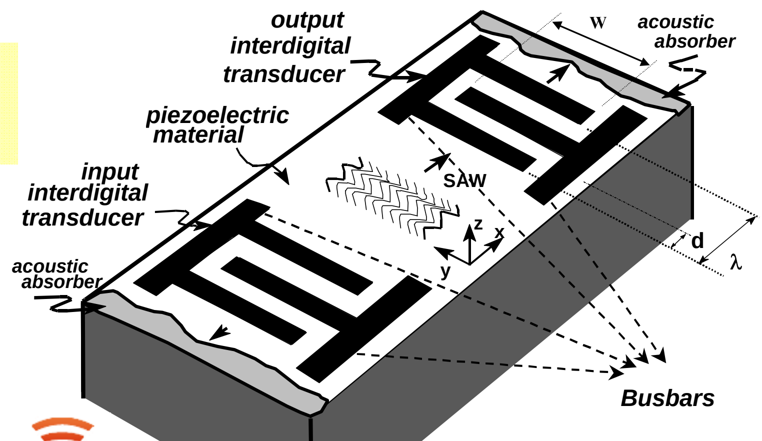
The wireless RF signal → sent to interdigital transducer electrodes on top of a piezoelectric crystal, which causes propagation of surface and bulk acoustic waves that are sensitive to the harsh environment.

Surface Acoustic Wave → guided waves → prop. @ the surface

- **Ex: Rayleigh mode (elliptical particle trajectory)**
- **Fields decay exponentially inside the material**
- **Phase velocity: 1 to 6 Km/s ⇒ 10^5 x smaller than EM waves**
- **Piezoelectric material: electrical signal ⇒ acoustic wave**
- **Sensing: device response (delay, freq.) ⇒ depends on crystal orientation, surface perturbation**
- **SAW Propagation ⇒ Measures temperature, pressure, strain, corrosion, gases, vibration, thin film**



DELAY LINES



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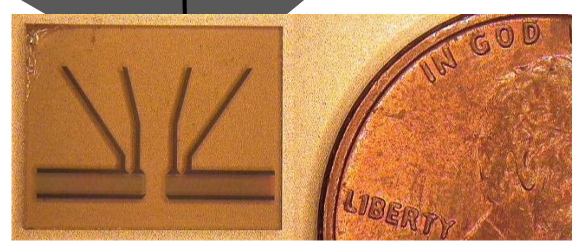


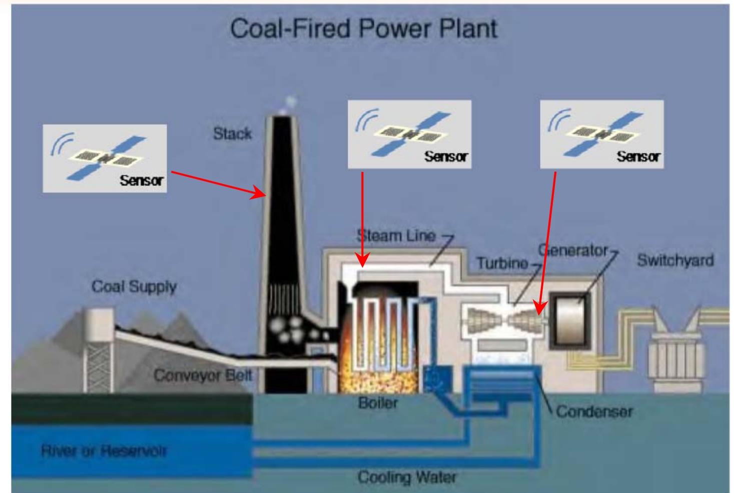
HE Wireless Temperature Sensor System

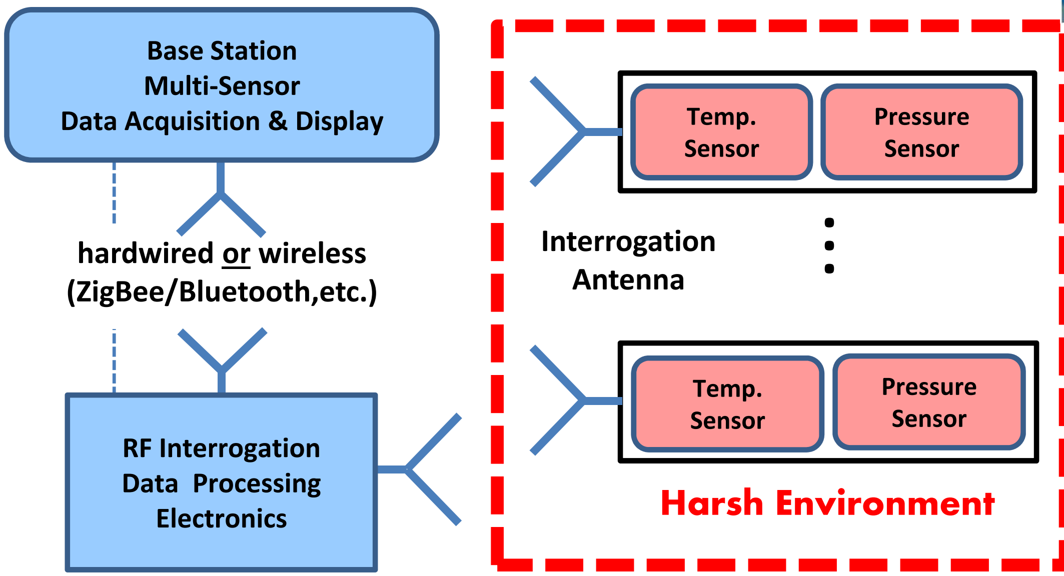
LANGASITE $La_3Ga_5SiO_{14}$
PIEZOELECTRIC CRYSTAL

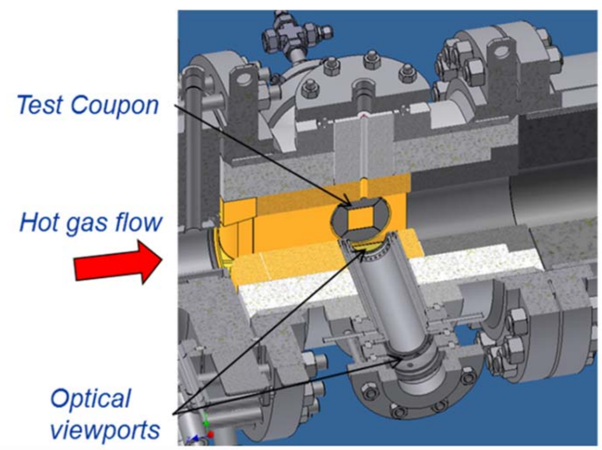
✓ Stable up to 1400°C
✓ Thermal shock resistant

SAW SENSOR & ANTENNA

Low profile package







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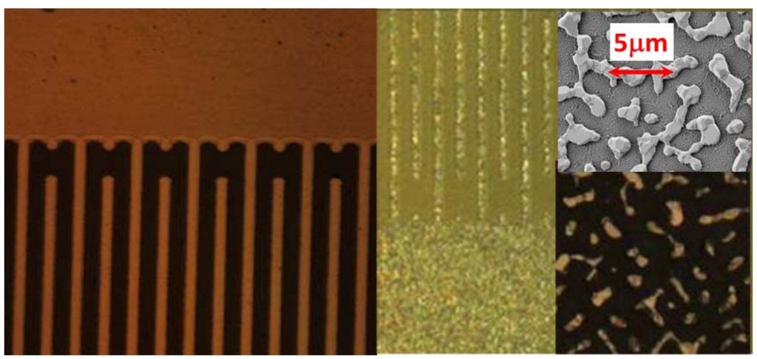
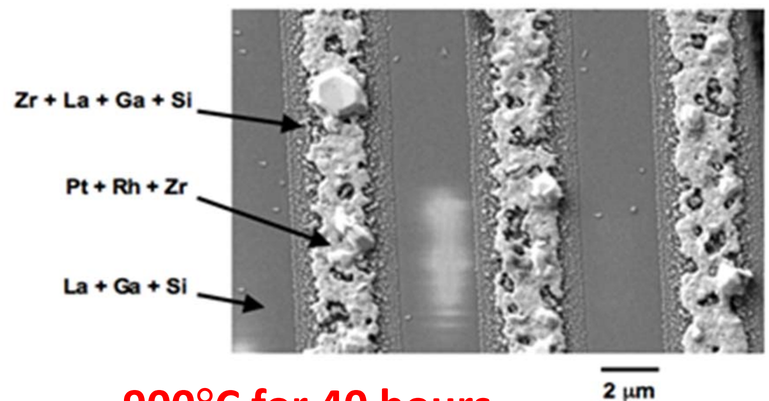
Thin Film Electrodes

- Interdigital Transducer (IDT) → electrode → Pt stable @ HT → no significant mass loss btwn 850°C and 1100°C
- **BUT** → Pt thin film dewets → around 700°C



1000°C for 40 hours



900°C for 40 hours

- UMaine→ PtRh/ZrO_2→ stable 850°C

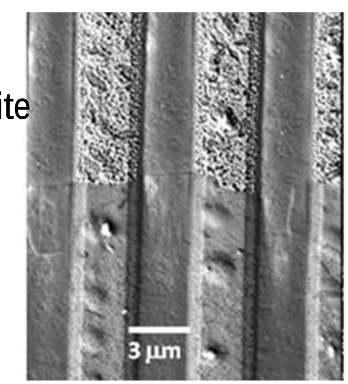
  Later in this presentation →

  other films & techniques

  1000°C & above

conductive nanocomposite alloy film

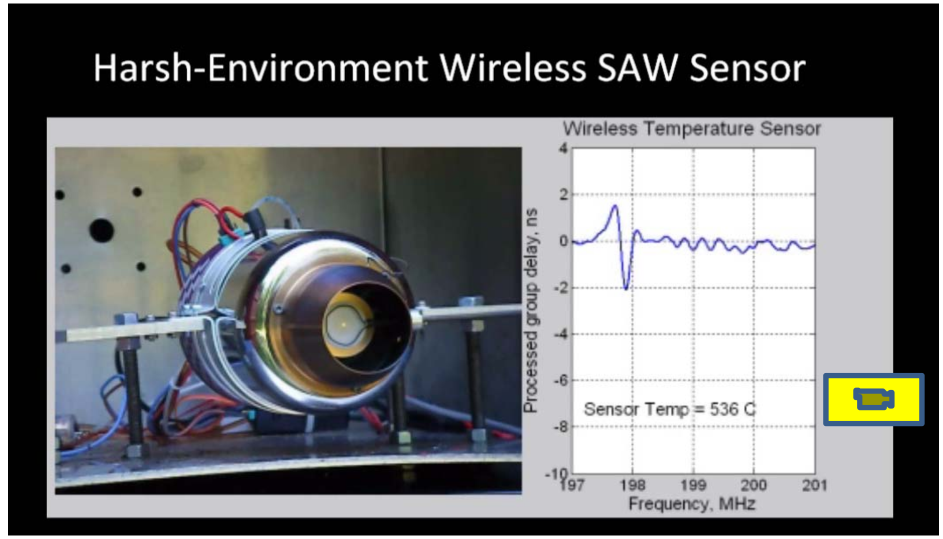
with passivation coating



Wireless Temperature Sensors

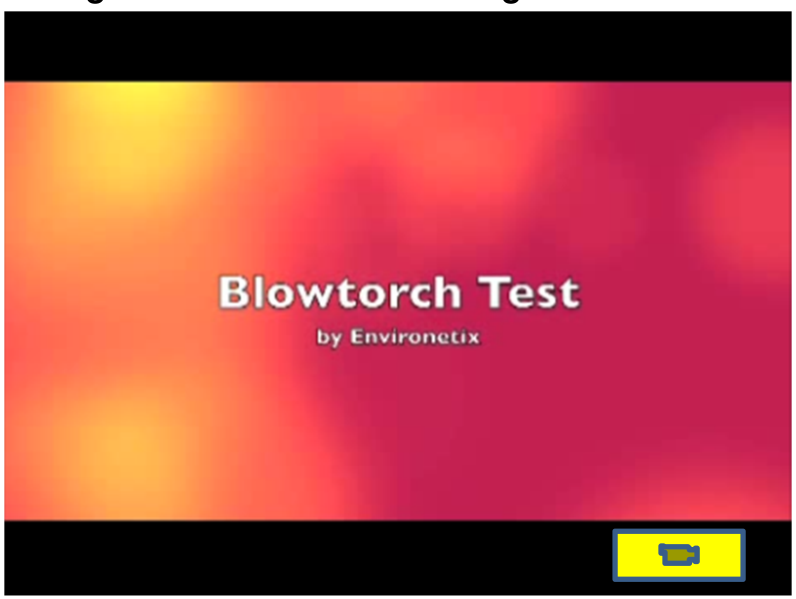
Static & Rotating Applications

Demonstration of Wireless SAW Sensor Interrogation on an Integrally Bladed Rotor (IBR) within a JetCat P-70 Turbine Engine



Real Time Wireless SAW Sensor Response

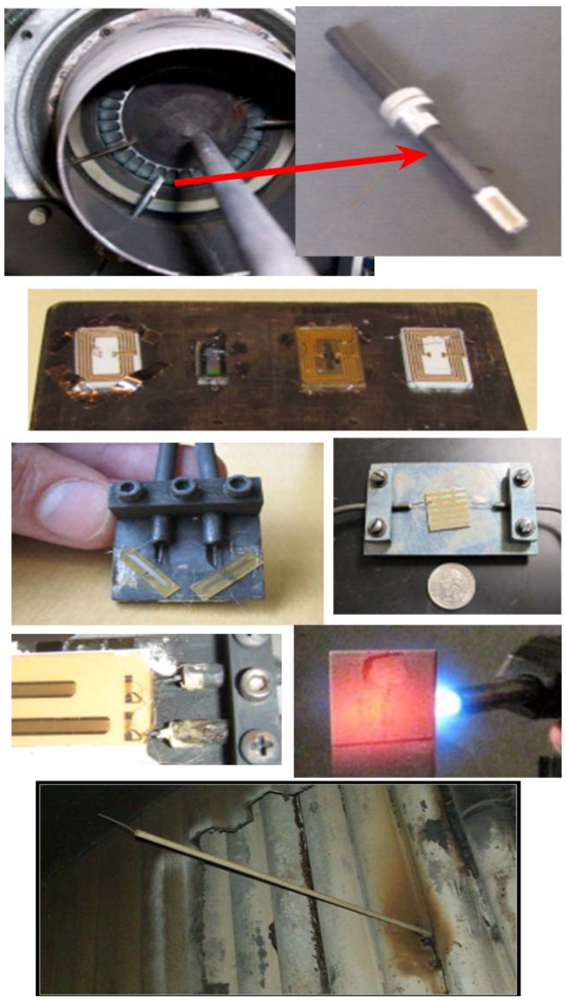
during Thermal Shock Testing with Blow Torch



B. Packaging & Sensors in HE

Multiple Attachment Techniques to Meet Application Requirements

Static Parts



Rotating Parts

SAW Sensors Attached to Inconel Blades

VEXTEC

Integrated 22" radius bladed turbine rotor

Packaging Adhesion Verification

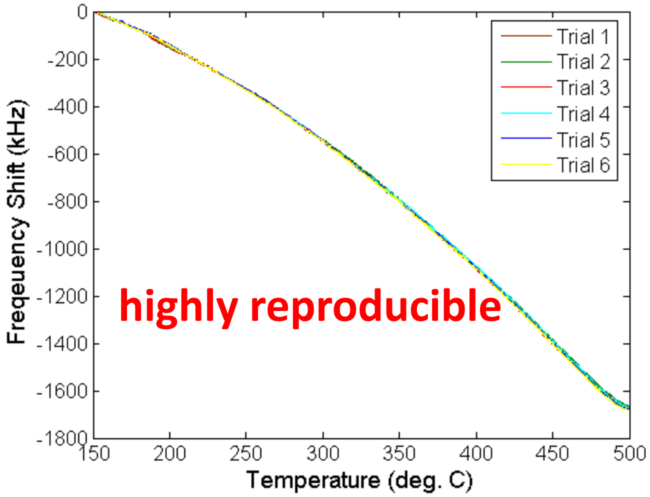
→ g Levels = 14k, 26k, 40k, 58k @ 800°F (425°C) & 1200°F (650°C)

→ up to 60min dwell at 1200°F (650°C) and 58 k g's

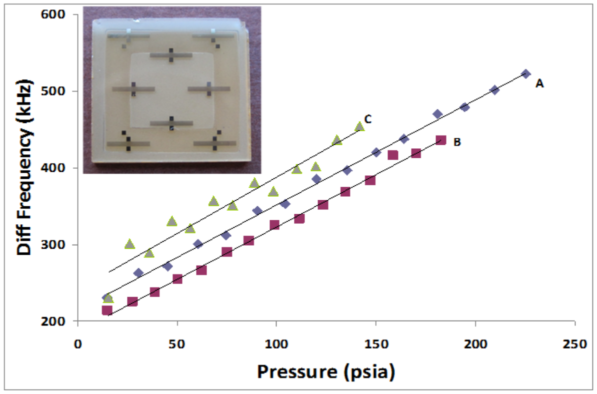
→ temperature snap action tests

Hostile Environment Sensor Performance

LGS SAW temperature sensor cycling over a period of 2 weeks

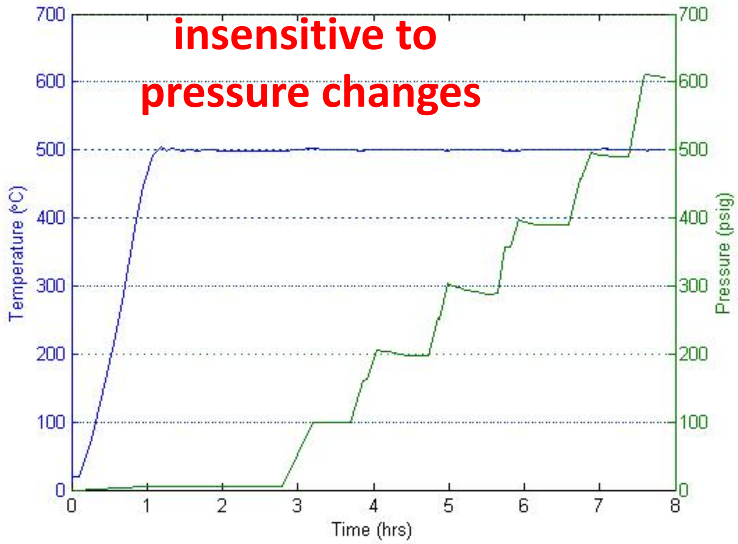


Pressure Sensor: RT to 515°C / 225 psia



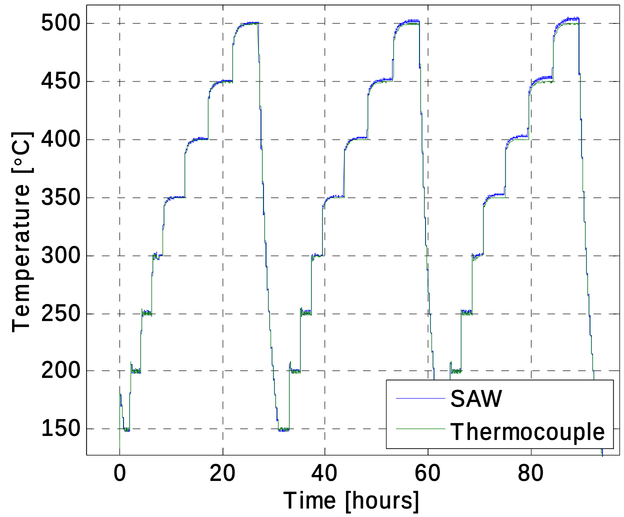
(A) 17°C - 26°C
(B) 234°C - 258°C
(C) 488°C - 516°C

Temperature & pressure profile



SAW & thermocouple temperature measured during temperature ramp cycles

Accuracy and drift at least as good as thermocouple



High T / High P Furnace

Up to 1500°C / 750 psi

III. Recent Progress: Wireless SAW Sensors for HE

A. Electrodes for 1000°C and higher

- LGX crystal operates up to 1300°C
- Major recent target: wireless sensor for operation @ 1000°C and higher
- THIN FILM ELECTRODE → current roadblock
- Previous film →

  co-deposited PtRh/ZrO_2 → short term @ 1000°C
- Series of new multilayer & co-deposited films studied:

  PtCo, Pt-Rh/CoO, PtNi, Pt-RhNiO, PtCr, Pt-Al, Pt-Al/Pt/ZrO_2, Pt-Al/Pt/Nb, Pt-Al/Pt/Cr, Pt-Al/Pt/ZrO_2, Pt/Al_2O_3, Pt-Rh/HfO_2, among others …
- Best films from the above → **Pt/Al_2O_3 and Pt-Rh/HfO_2**.

B. Interfacial Layer at High Temperatures

- Previous verification $\rightarrow$ XPS results / heating at 800°C
  Stoichiometry of **BARE** LGS SAW sensor surface becomes
  - Depleted of Ga in a reducing (vacuum) environment
  - Remains close to the bulk composition when heated in an oxidizing (air) environment
- However at higher temperatures (1000°C): LGS/air interface needs protection
  - Capping layer (SiAlON and ALD Al_2O_3) **protect the surface of the LGS** & **prevent dewetting**
  - In addition @ the interface between LGS & electrode $\rightarrow$

  New issue: **INTERDIFUSION** between LGS & electrode
- Therefore, electrode development alone is not enough $\rightarrow$

  Electrode architecture is necessary
- Solution for interdifusion:

  Use of an **INTERFACIAL** layer to mitigate diffusion

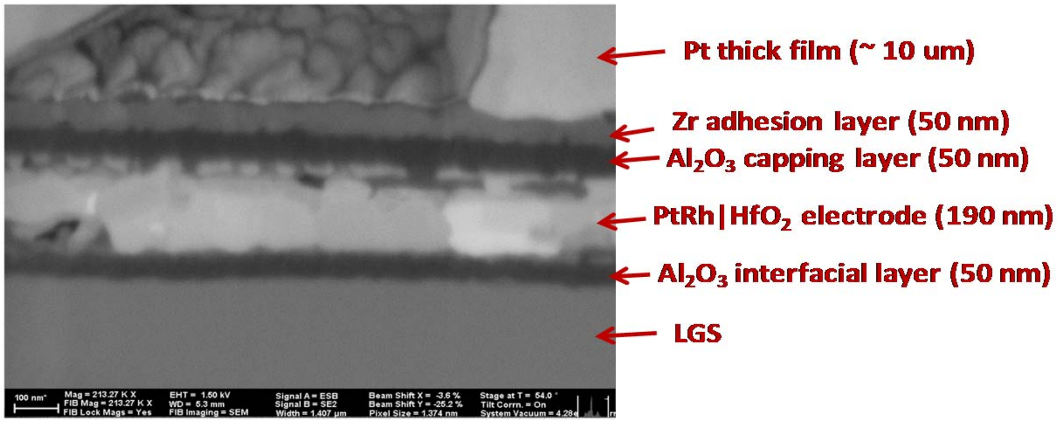
Depos. of conformal ALD Al_2O_3 monolayers with atomic layer precision

Interfacial Layer between LGS & Electrode

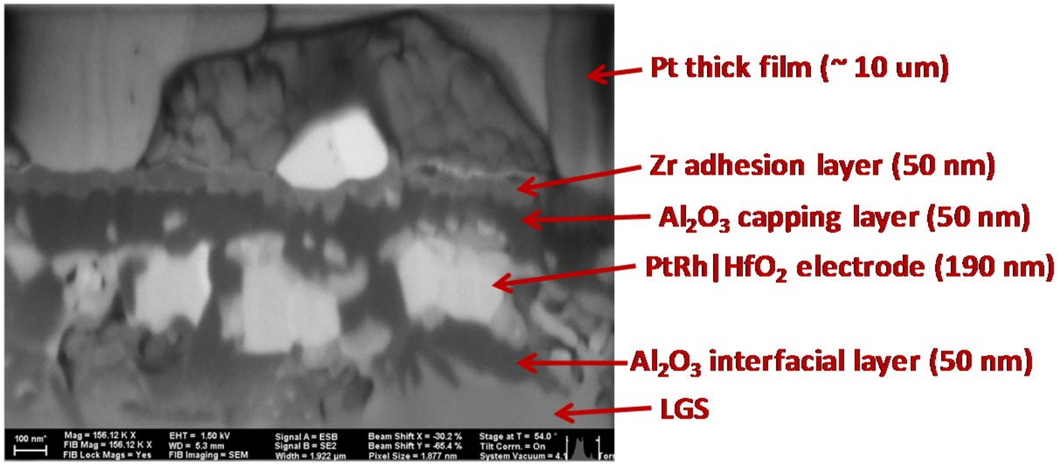
- **Interfacial layer** btwn LGS & electrode → ALD Al_2O_3

Mitigates interdiffusion → extends electrode life / temp. oper.

- SEM/FIB **CROSS SECTION** of LGS SAW PtRh|HfO_2 electrode



- 850°C for 4 hrs
- Well separated layers



- 1000°C for 4 hrs
- Interdiffusion → significant difference wrt 850°C

C. Capping Layer & Cap. Coupl. @ High Temp.

- Capping or protective layer → electrically insulating
- How to access the bond pads?

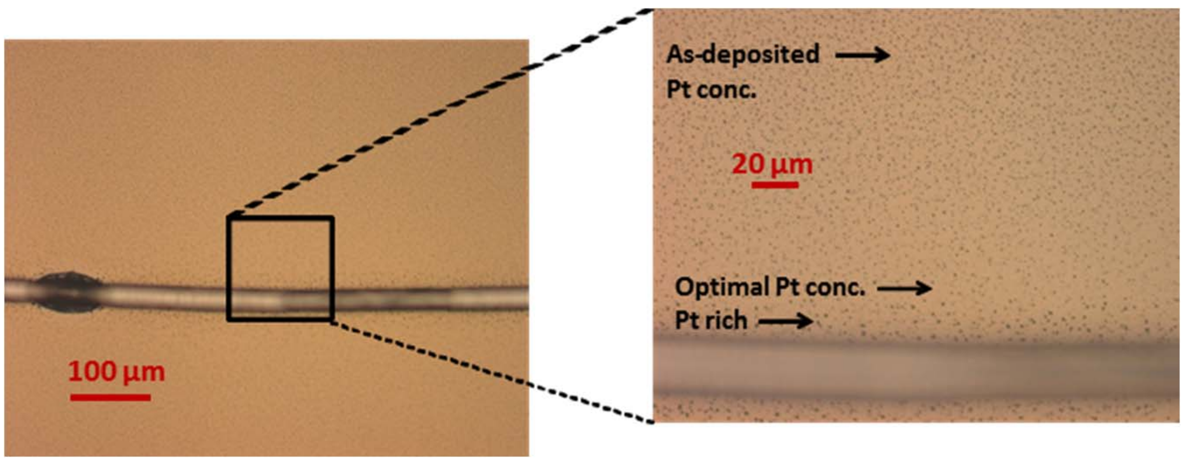
  i. Break through the hard insulating (SiAlON, ALD Al_2O_3)

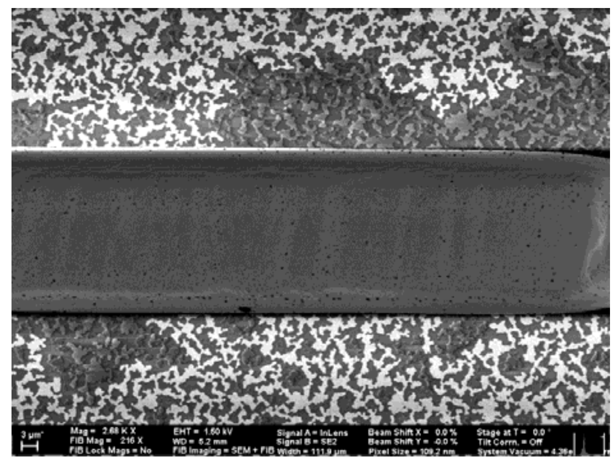
Not good: reduces bonding quality and performance (1000°C)

  ii. Mask a window

Not ideal: **bonding fails before film!**

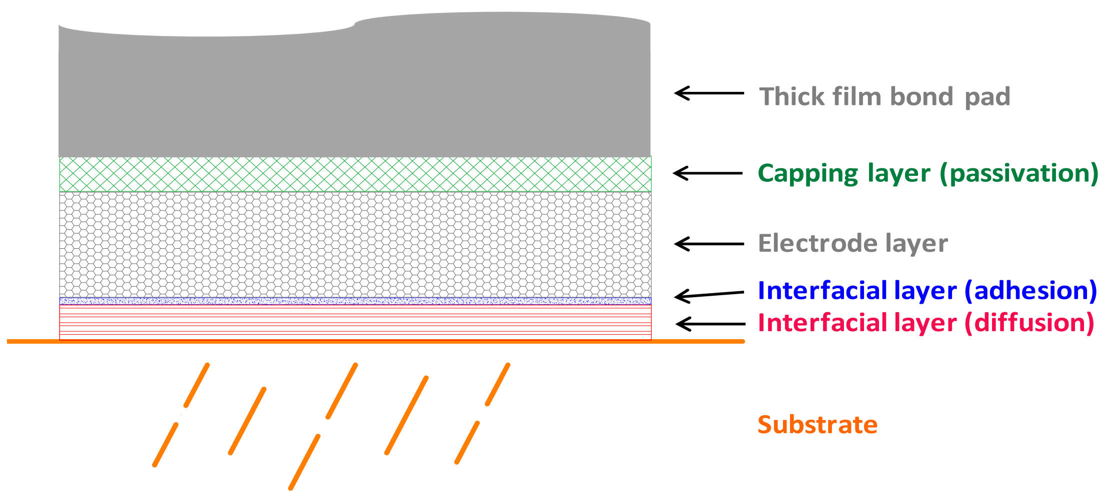
- agglomeration in the exposed area
- evidence → around bonding area → ↑ agglomeration → failure

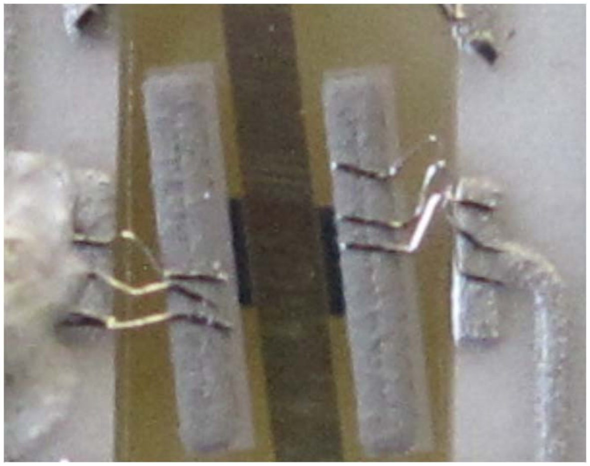




Capacitive Coupling

- Solution → capacitive coupling at high temperature
- Thick film Au or Pt paste used as the final layer
- Capacitive impedance low enough to allow proper signal transfer (couple Ω for the device in the Fig.)
- Devices operated at 1100°C back a few slides → used this technology





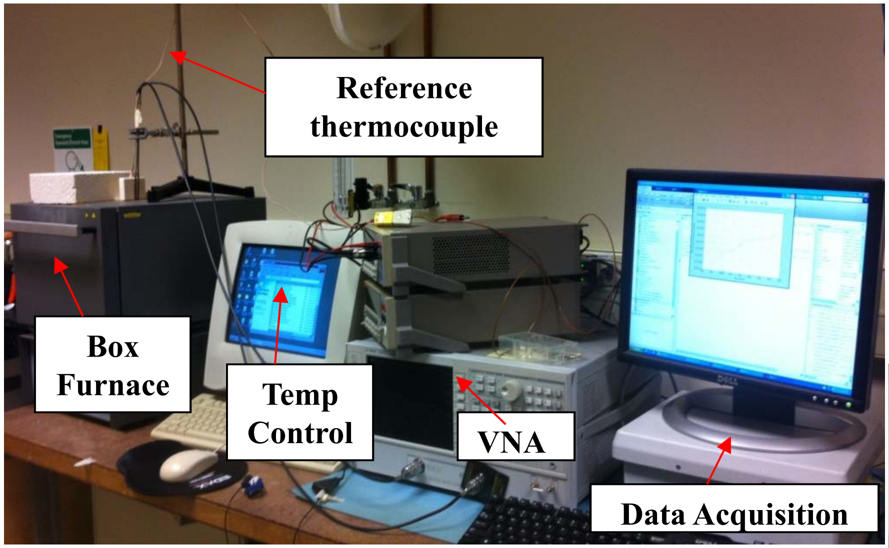
D. Recent Tests: HT Devices & Wireless Temp Profile Furnace

High Temperature Survivability Tests

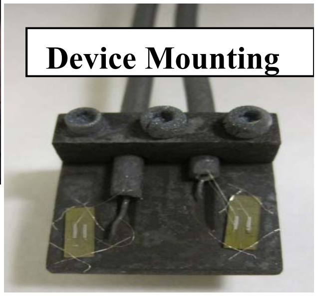
Tube Furnace (Before & After Test)

- Temperature gradient along the tube
- 800°C to 1200°C

BoxFurnace (Continuous time Test)



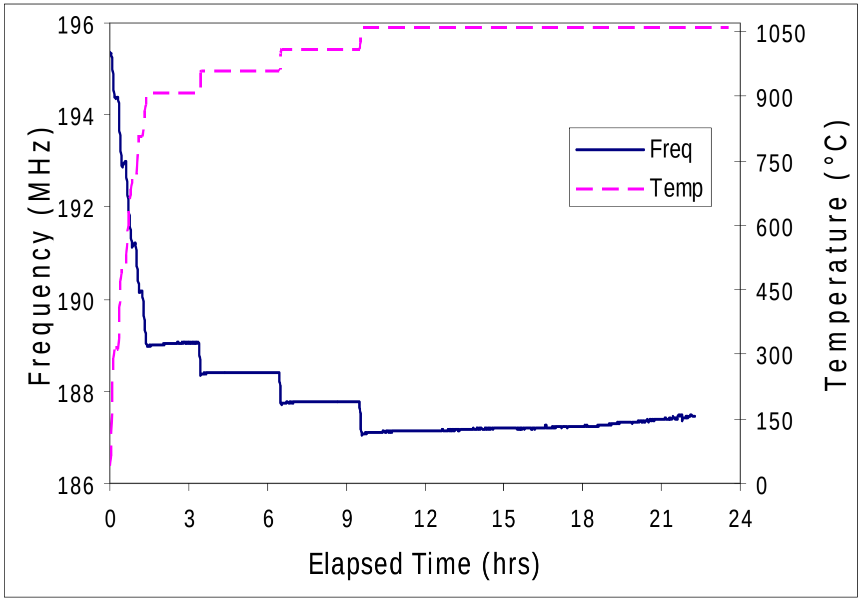
Temperature (°C)	Duration (hours)
350	0.15 (≈ 10 min)
550	0.15
750	0.15
800	0.15
900	2
950	3
1000	3
1050	3
1100	3



Resonator Response x Electrode Thickness

- Film used on langasite: $Al_2O_3|Zr|PtRh/HfO_2|Al_2O_3$
- Thicknesses explored from 100 nm to 300nm
- Film thickness $\rightarrow$ impact SAW resonator response

  Device design must be adjusted for optimum response
- Devices heated up to 1100°C (>2h) and 1050°C (12h)

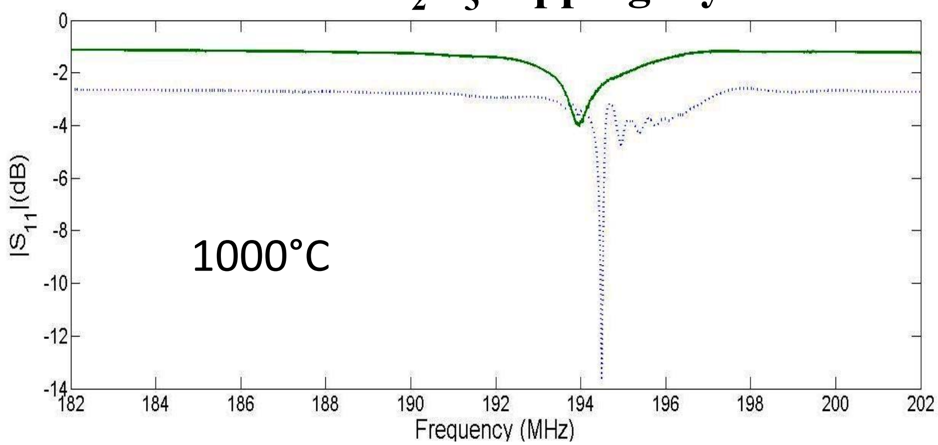


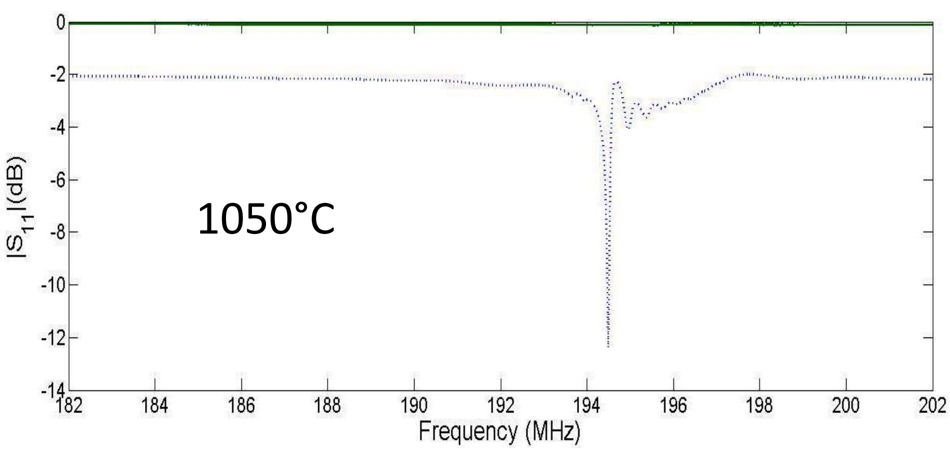
Impact of Capping Layer on Devices

- Currently: 50°C improvement in HT performance

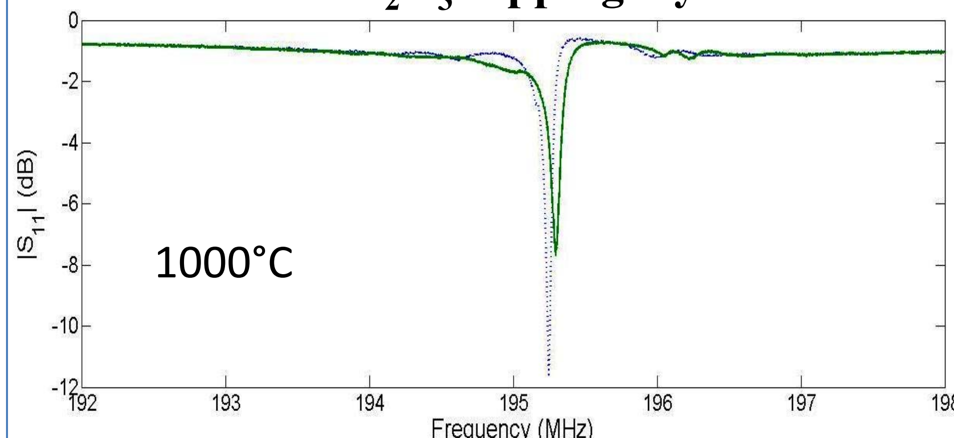
Before Heating
After Heating

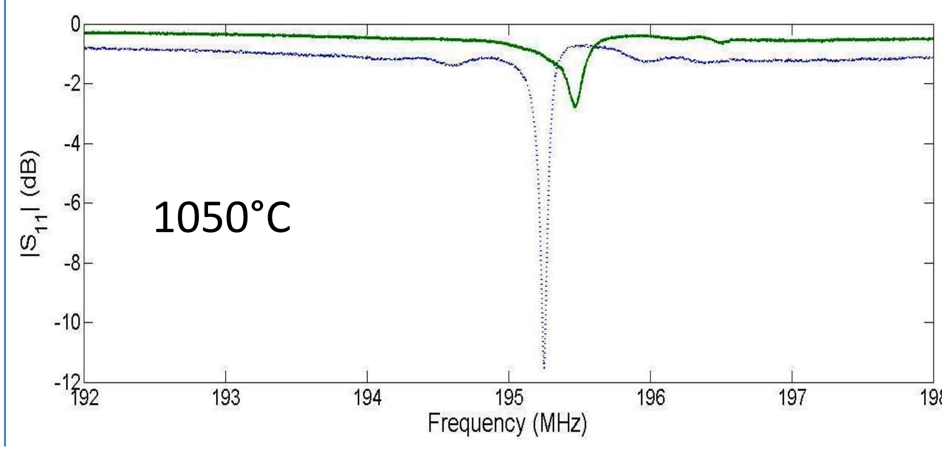
Without Al_2O_3 capping layer





With Al_2O_3 capping layer

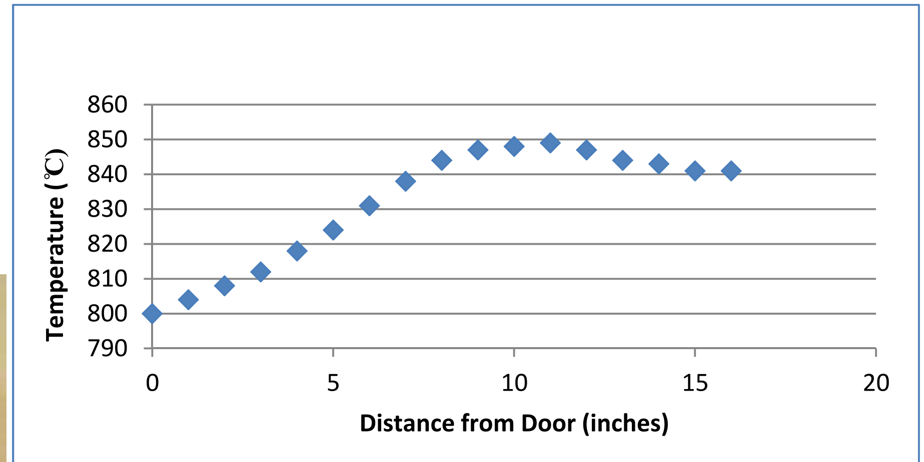




Temperature Profile Furnace: Wireless Tests

- ✓ Built using dielectric tiles:
  - ➢ Thermal Insulation
  - ➢ EM transmission

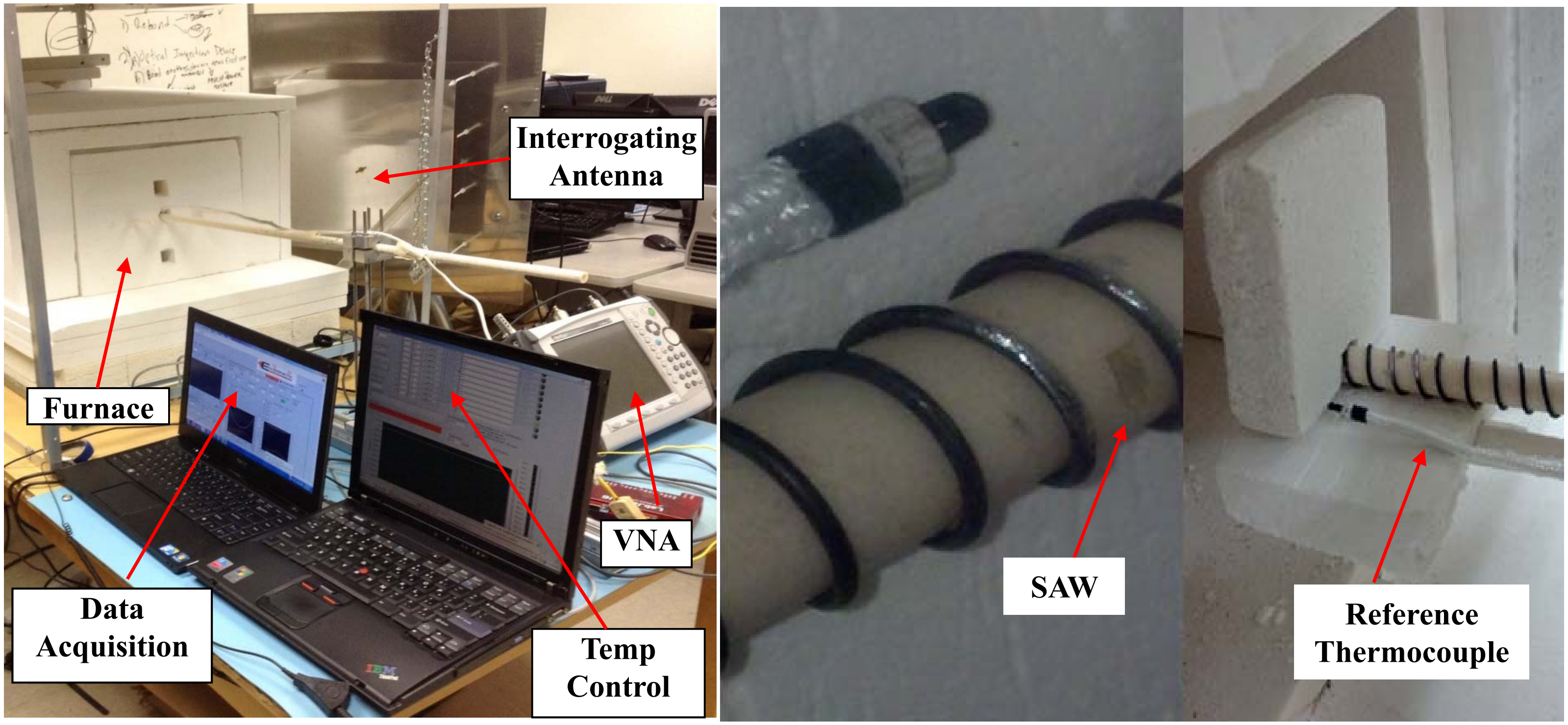
Temperature profile x distance



- ✓ Interrogating Antenna:
  - ➢ High-gain
  - ➢ Broadband
  - ➢ Suspended-plate antenna

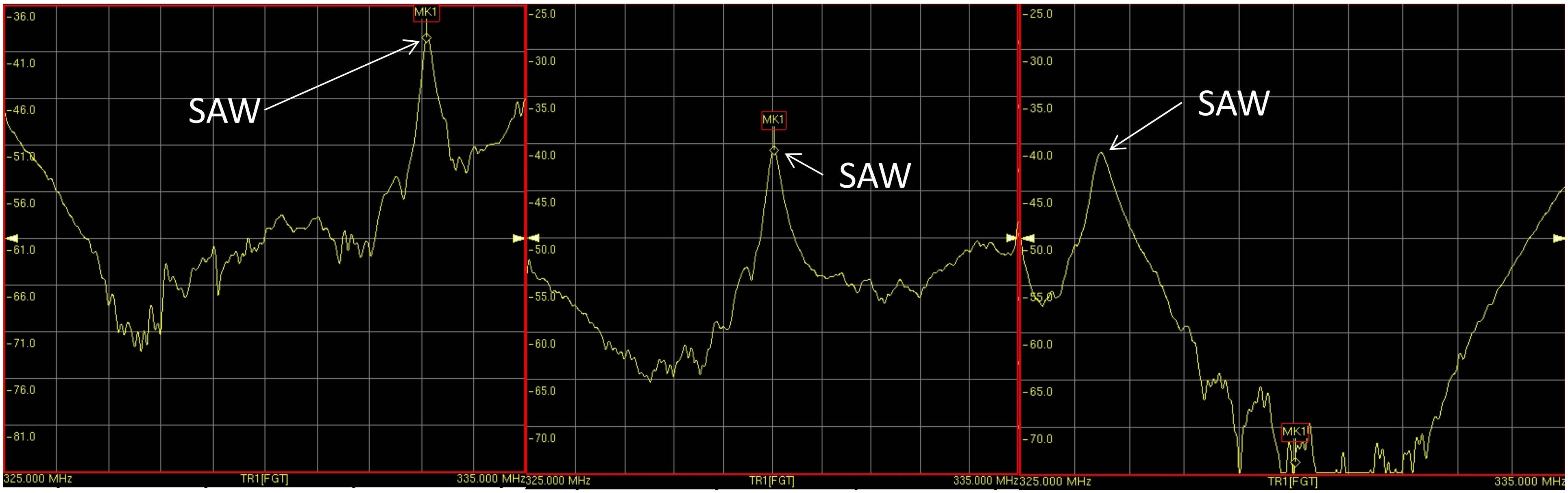
High Temperature Wireless

- ✓ Helical Antenna:
  - ➢ 50 cm of Nichrome Wire
  - ➢ 0.5 cm Alumina Tube

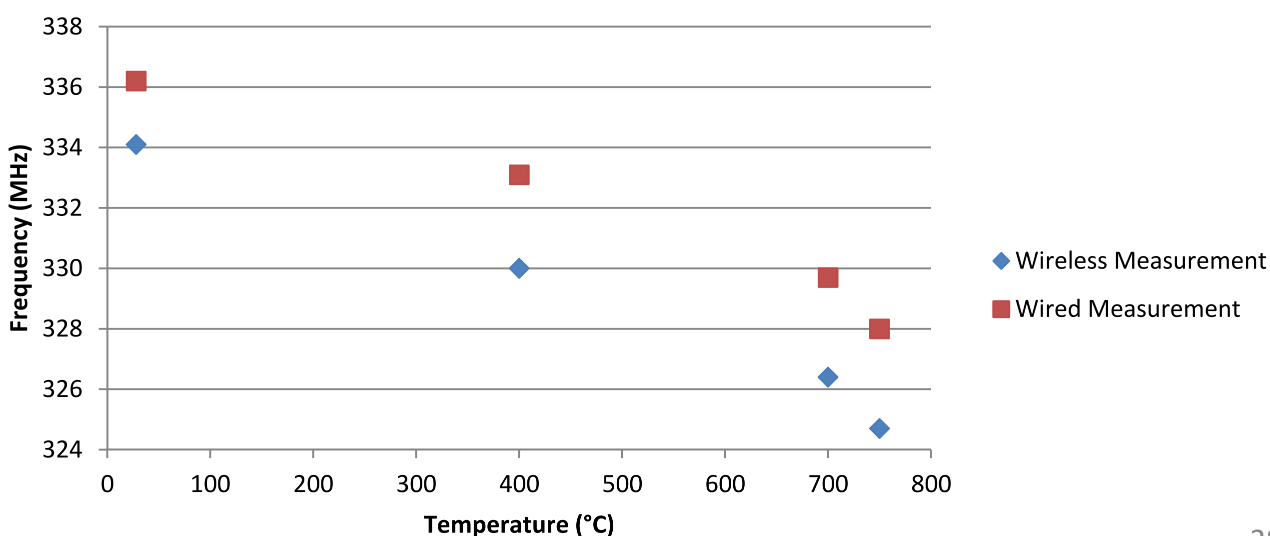


Temp Profile Furnace Measurements

Room Temperature | **400°C** | **700°C**

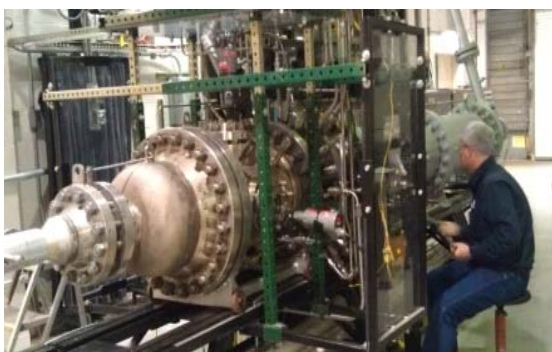
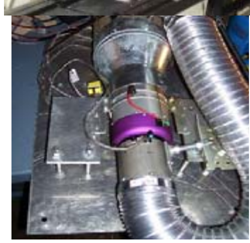


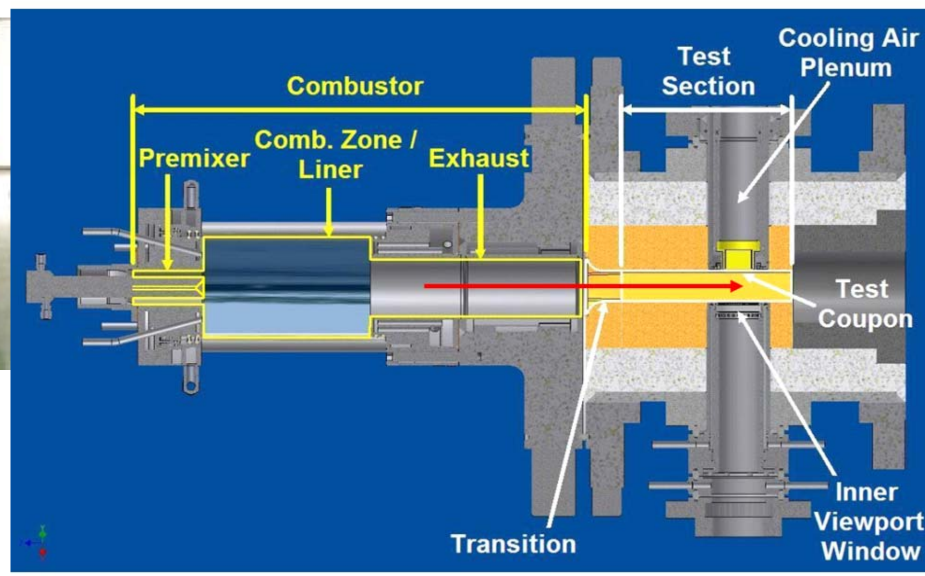
- Wired & Wireless
- 2 different SAW devices measured
- Further wireless characterization is under way.



E. Recent Tests: Turbine Engines & Power Plant Environments

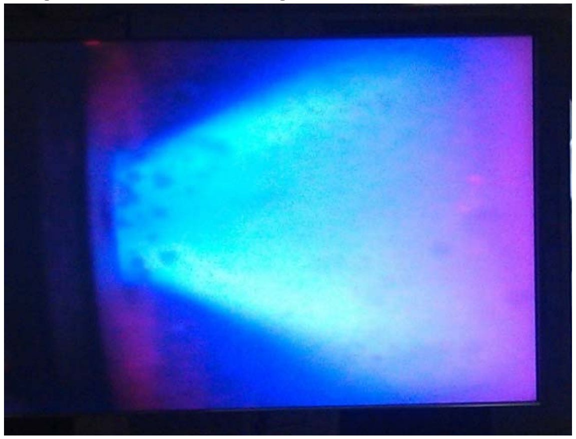
- Aerothermal Facility → natural gas combustor
  National Energy Technology Laboratory, NETL/DOE, USA
- Gas temperatures → up to 1100°C; pressure up to 60psi
- Wall temperatures → Up to 850°C
- Sudden pressure bursts; ceramic particulates; several hundred °C gradient with mm of the wall

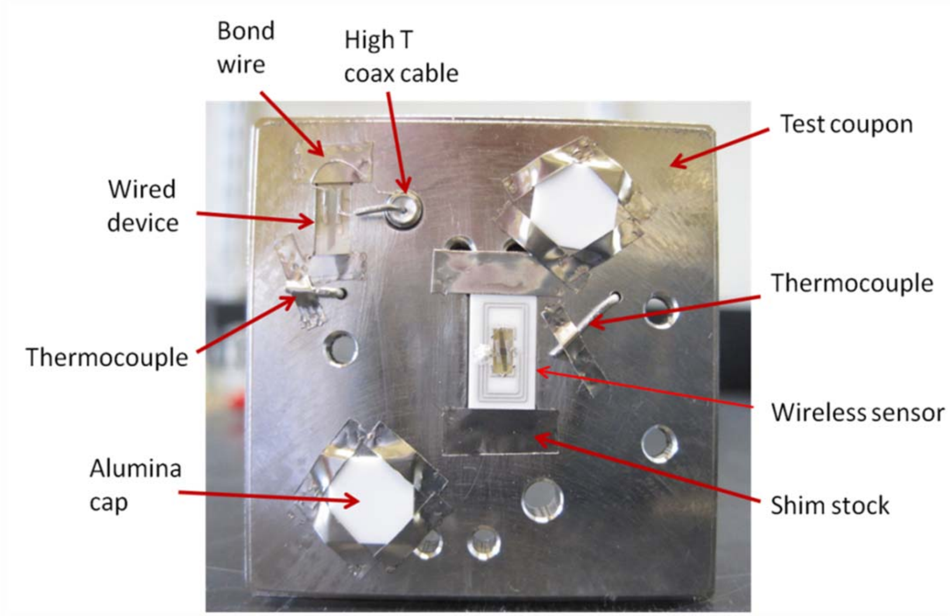



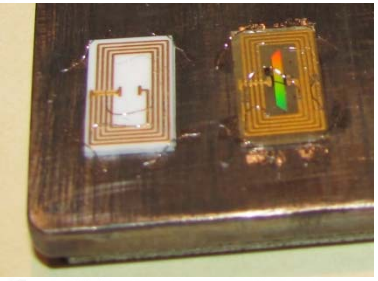


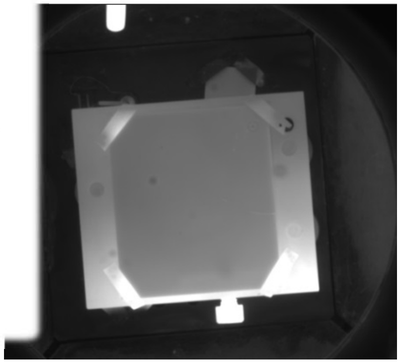

E.1 NETL Aerothermal Facility Tests

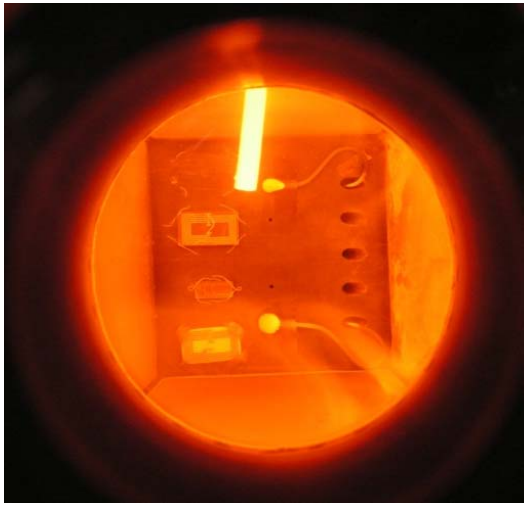
- Coupon installed directly in the gas flow (1100°C)
- Integrated antenna exposed to 1100°C
- Sensors exposed to environment & also embedded in the coupon
- Eight devices packaged in two coupons





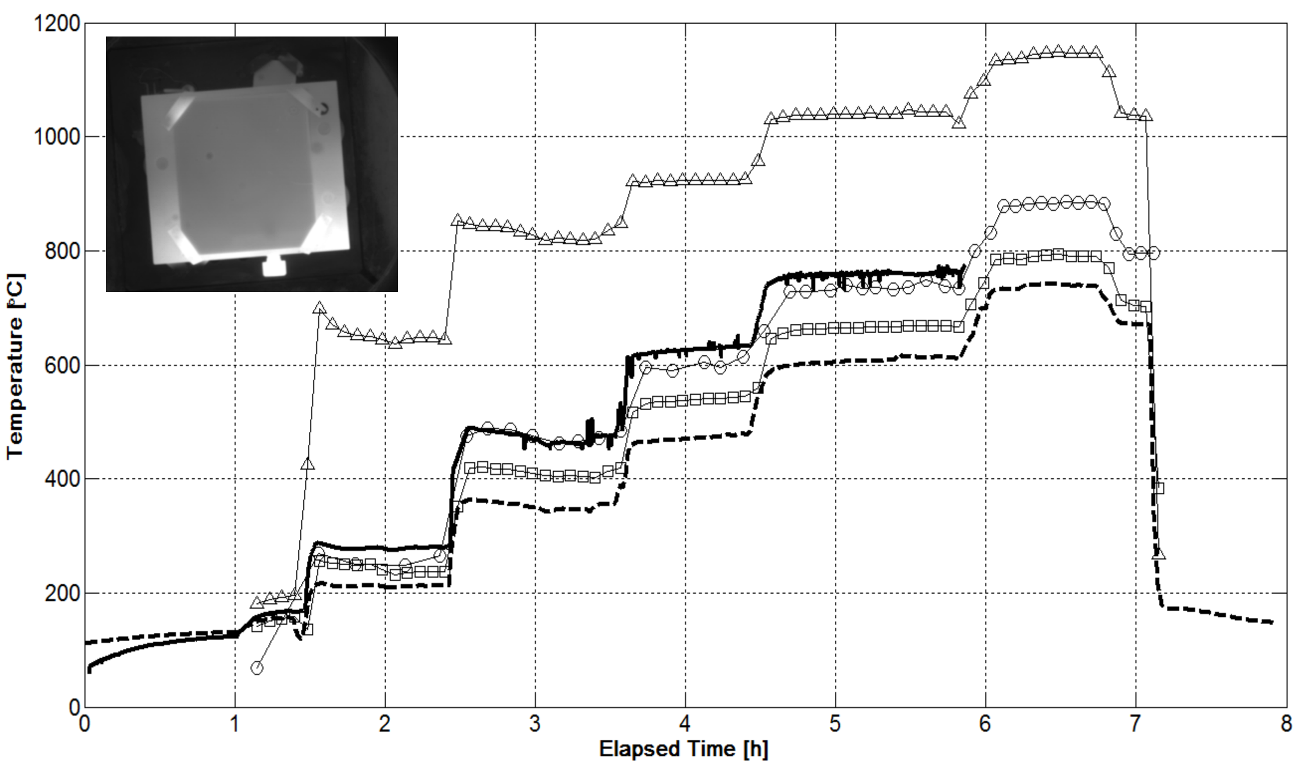






NETL Aerothermal Facility Tests

- Test results for a wireless and a wired LGS SAW sensors in the coupon fixtures.
- Two days tests (7 hours each day): Sensors & Packaging responded as expected to the variations in Temp. & Pressure

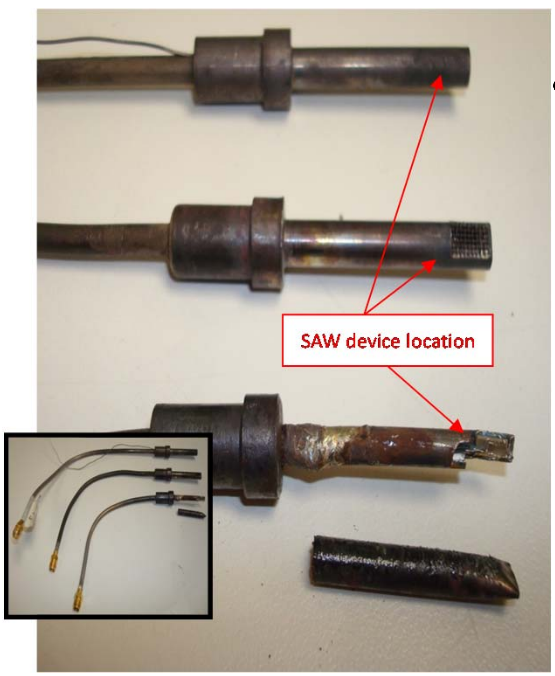


- Δ : gas thermocouple;
- Solid line: wireless SAW sensor;
- dashed line: wired 3.5µm SAW sensor;
- ○ : thermocouple near wireless SAW sensor;
- □ : Thermocouple near wired 3.5µm SAW sensor.

E.2 Tests at GE Research Center

- Tests inside a helicopter GE CT7 turbine Engine
- Location: last compressor section
- Packaging developed:

  Wireless sensor probes sealed & exposed to environment
- Temperature sensors (insensitive to pressure: $\leq$ 1°C for full range of pressure variation)



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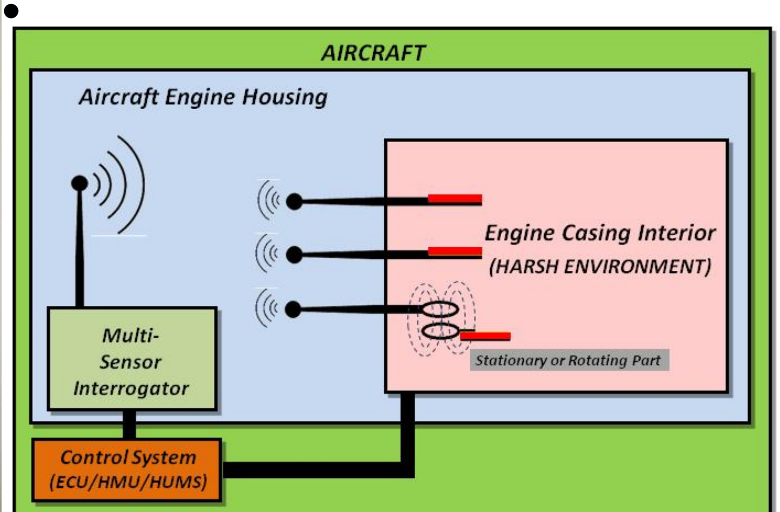
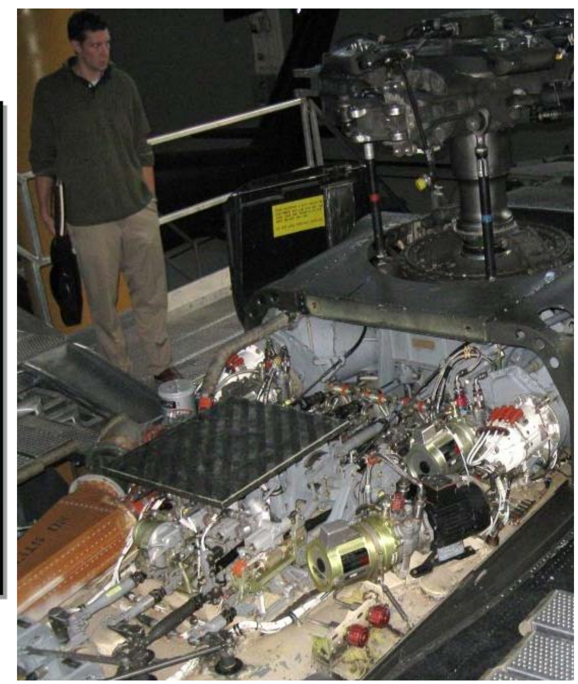




Tests at GE Research Center

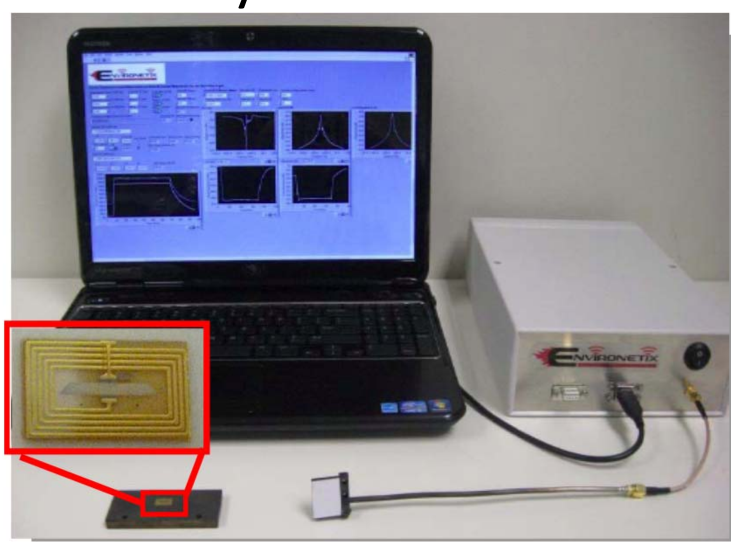
- Environetix: EVHT-100 interrogator system

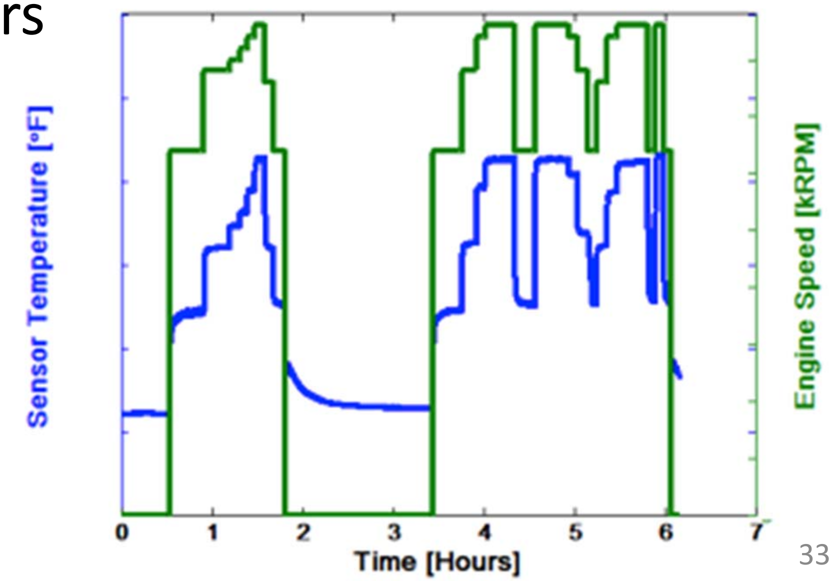
Dedicated Wireless Interrogator & Data Acquisition Software

- Capabilities of interrogating STATIC and ROTATING sensors

RF 100MHz to 1GHz & sampling rates from 1 Hz to 100 KHz

- Test results for wireless sensors (330 MHz) comparing variations in engine rotation with variations in engine temperature measured by the wireless SAW sensors

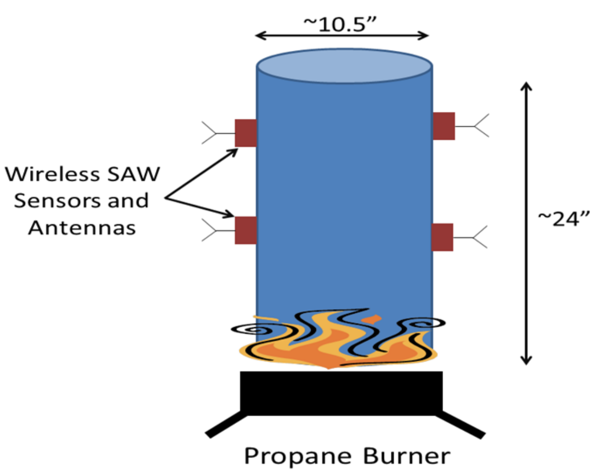




E.3 Prototype Pipe Structure: Industrial Settings

- Six sensors mounted on a steel pipe (power application)
- Temperatures up to 700°C
- Environetix EVHT-100 interrogator system used

SAW sensors: interrogation up to 45 feet



E.4 Penobscot Energy Recovery Company (PERC)

- Power plant: burns municipal **SOLID WASTE**
- Boiler conditions:

Temps ↑ 900°C (1650°F)

Highly erosive/corrosive exhaust gases

⇐ **¾" Schedule 40 Hastelloy thermocouple tube after ~6 mo**

- **GOAL:** **Demonstrate an array of wireless harsh environment temperature sensors in operational power plant**
- Steps:
  - Material tests
  - Array ⇒ sensors & antennas design, implementation, installation
  - Test in the power plant

Penobscot Energy Recovery Company

Material tests

- Sapphire, YSZ, alumina, pyrolitic graphite
  - mounted on an Inconel plate
  - Inserted into boiler thermocouple port

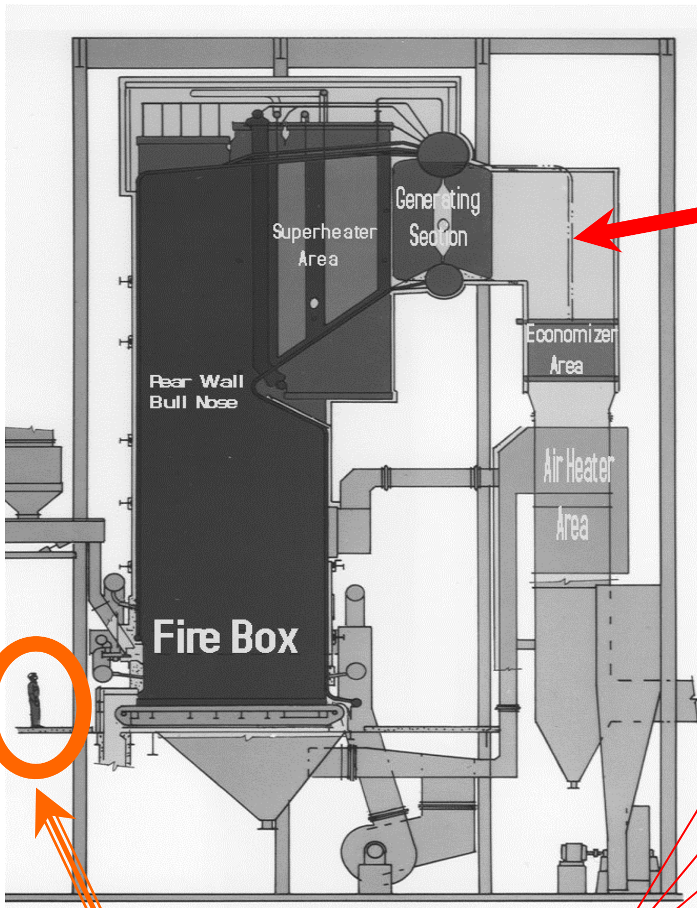
BEFORE

AFTER 10 DAYS IN THE ENVIRONMENT

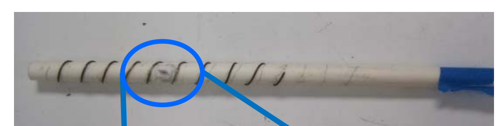
- **Materials selected displayed acceptable wear**
- **Alumina selected: due to $ & availability**

Penobscot Energy Recovery Company (PERC)

Array ⇒ Sensors & Antennas Design, Implementation, Installation



- Economizer area: easy access → Power plant in operation
- **6 tuned helical dipole antennas + SAW sensors + external sealing package**



Relative dimension

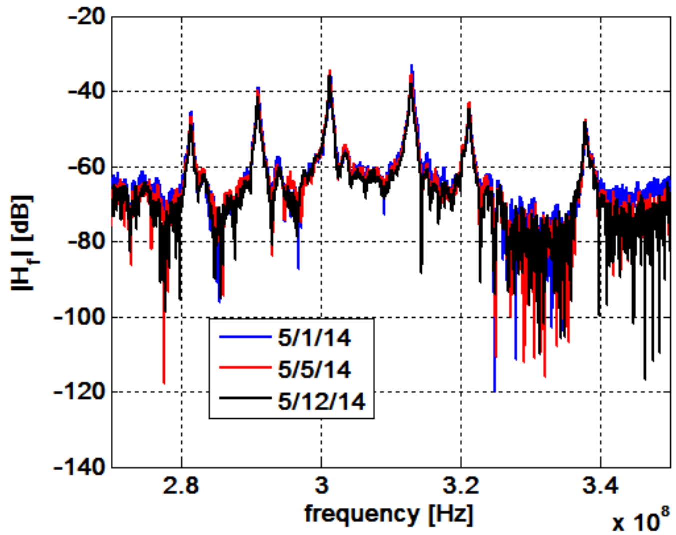
6 dipoles + SAW sensors

monopole interrog. ant.

Penobscot Energy Recovery Company (PERC)

Test in the power plant

- Sensors installed on May 1, 2014
  - Measurements being performed periodically
  - All sensors fully operational after 3+weeks
  - PERC reference thermocouple ~10' from array



Date	PERC TC (°F)
5/1/14	688
5/5/14	693
5/12/14	698

Date	Sensor 1 (°F)	Sensor 2 (°F)	Sensor 3 (°F)	Sensor 4 (°F)	Sensor 5 (°F)	Sensor 6 (°F)
5/1/14	684.3	673.2	683.7	678.9	680.1	695.6
5/5/14	694.2	684.3	695.0	696.0	688.0	705.8
5/12/14	706.2	690.7	701.5	704.8	687.7	711.1

IV. Conclusions

Conclusions

- Presentation: motivation, background & recent contributions on:

WIRELESS μ~SENSORS FOR HOSTILE ENVIRONMENTS

- Major recent technology progresses and breakthroughs presented:
  - ✓ New HT thin-film electrodes, and device design
  - ✓ Novel packaging: capping &interfacial layered structure to operate in HT / HE
  - ✓ Capacitive coupling for HT operation
  - ✓ Sensor temperature of operation: Increased from 800 °C to 1100°C
  - ✓ Implementation of targeted wireless temperature sensor array / respective packaging / and interrogation system
  - ✓ Short term material screening tests and continuous time device characterization
  - ✓ Wireless profile furnace temperature characterization

Conclusions

WIRELESS μ~SENSORS FOR HOSTILE ENVIRONMENTS

- Technology transitioning to power plant & turbine engine applications:
  - ✓ Successful sensor & packaging test at NETL / DOE Aerothermal Facility, Morgantown, WV
  - ✓ Successful sensor & wireless system test at a GE CT7 turbine engine
  - ✓ Successful test of wireless sensor link for a power plant material storage (Industrial application)
  - ✓ Ongoing tests on municipal waste power plant (May 2014)
  - ✓ PERC: installation of wireless sensor array in power plant environments
- Happy to report that significant progress has been achieved:
  - ✓ TRL level transitioned from 3 to 4 or 6 (depending on the application)
- Progresses listed above grant the possibility of employing this technology for applications never considered before!
- Energy sector, aerospace, and harsh environment industrial processes
- Increasing # of applications & opportunities → technology evolving to respond to those requests and demands.

Current Project Publications

1. Scott C. Moulzolf, Roby Behanan, Robert J. Lad, and Mauricio Pereira da Cunha, "Langasite SAW Pressure Sensor for Harsh Environments," *IEEE International Ultrasonics Symposium Proceedings*, 2012, Dresden, Germany, pp.1224-1227.

2. P. Davulis and M. Pereira da Cunha, "Temperature-compensated BAW orientations over 500°C on LGT for frequency control and sensor applications," *Electronic Letters*, vol. 49, no. 3, pp. 170-171, Jan. 2013.

3. P. Davulis and M. Pereira da Cunha, "A Full Set of Langatate High-Temperature Acoustic Wave Constants: Elastic, Piezoelectric, Dielectric Constants up to 900°C," *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, Vol. 60, No. 04, April 2013, pp. 824-833.

4. Scott C. Moulzolf , David J. Frankel, Mauricio Pereira da Cunha, Robert J. Lad, "**Electrically conductive Pt-Rh/ZrO_2 and Pt-Rh/HfO_2 nanocomposite electrodes for high temperature harsh environment sensors", Submitted, Proceedings SPIE vol. 8763, 2013.**

5. S. C. Moulzolf, R. Behanan, R. J. Lad, and M. Pereira da Cunha, "Capacitively Coupled IDT for High Temperature SAW Devices," *2013 IEEE Joint UFFC, EFTF, and PFM Symposium*, in *Proceeding of the Ultrasonics Symp.- IUS*, *Prague, Czech Republic*, pp. 255-258.

6. R. Behanan, S. Moulzolf, M. Call, G. Bernhardt, D. Frankel, R. Lad, M. Pereira da Cunha, "Thin Films and Techniques for SAW Sensor Operation Above 1000°C," *2013 IEEE Joint UFFC, EFTF, and PFM Symposium*, in *Proceeding of the Ultrasonics Symp.- IUS*, Prague, Czech Republic, pp. 1013-1016.

7. P. Davulis, M. Pereira da Cunha, "Langatate Temperature-Compensated BAW Orientations Identified Using High-Temperature Constants," *2013 IEEE Joint UFFC, EFTF, and PFM Symposium*, in *Proceeding of the Frequency Control Symp.- IFCS/EFTS*, Prague, Czech Republic, pp. 996-999.

8. Mauricio Pereira da Cunha, "Wireless Sensing in Hostile Environments," *2013 IEEE Joint UFFC, EFTF, and PFM Symposium*, in *Proceeding of the Ultrasonics Symp.- IUS*, Prague, Czech Republic, pp. 1337-1346. (*INVITED PAPER*).

9. Scott C. Moulzolf, David J. Frankel, Mauricio Pereira da Cunha & Robert J. Lad, "High temperature stability of electrically conductive Pt–Rh/ZrO_2 and Pt–Rh/HfO_2 nanocomposite thin film electrodes," Microsystem Technologies, ISSN 0946-7076, DOI 10.1007/s00542-013-1974-x, November 12, 2013, Vol. 20, No. 4-5, April 2014, pp. 523-531.

Additional Dissemination

1. M. Pereira da Cunha, "*Wireless Microwave Acoustic Sensor System For Condition Monitoring In Power Plant Environments*," DOE / NETL Program: Advanced Fossil Energy Research: Novel Developments In Sensors And Controls For Fossil Energy Power Generation And Fuel Production Technologies, March 12-14, 2012.
2. M. Pereira da Cunha, "*Technology and Product Update: Wireless Sensors for Extreme Environments*," WEB Conference with ExxonMobil, Feb. 02, 2012.
3. M. Pereira da Cunha, "*High-temperature wireless sensor design solutions*," Invited to sit on the panel and motive discussion on the Wed. session of the Wireless workshop at the International Instrumentation Symposium (IIS), La Jolla, CA, June 6, 2012.
4. M. Pereira da Cunha, "*Industrial Insertion of Wireless Microwave Acoustic Sensors and Systems for Harsh Environments*," Strategic Advisory Board (SAB) of the Propulsion Instrumentation Working Group (PIWG), June 06, 2012.
5. M. Pereira da Cunha, "*Harsh Environment Wireless Microwave Acoustic Sensor Systems for Aerospace, Energy, and Industrial Applications,*" nationwide WebEx presentation for General Electric, June 14, 2012.
6. M. Pereira da Cunha, R.J. Lad, T.B. Pollard, D.F. McCann, E.L. McCarthy, D.J. Frankel, S.C. Moulzolf, R. Behanan, G. Bernhardt, M. Call, "Wireless Sensors and Interrogation System for Harsh Environment Static & Dynamic Monitoring of Turbine Engines and Industrial Machinery," *59th International Instrumentation Symposium*, May 13-17, Invited Presentation to the Propulsion Instrumentation Working Group (PIWG), May 16th, 2013.

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Harsh-Environment Wireless SAW Sensor