TECHNOLOGY MATURATION OF WIRELESS HARSH-ENVIRONMENT SENSORS FOR IMPROVED CONDITION-BASED MONITORING OF COAL-FIRED POWER GENERATION

Project DE-FE0031550: Kick-off Meeting

DOE / NETL Program DE-FOA-0001728:
Advanced Combustion Systems (ACS): Existing Plant Improvements and Transformational Technologies

PI: Mauricio Pereira da Cunha **Co-PI: Robert Lad**
Presenter/Contact: mdacunha@maine.edu

Conference Call, Orono, ME / Morgantown, WV, February 22, 2018

OUTLINE

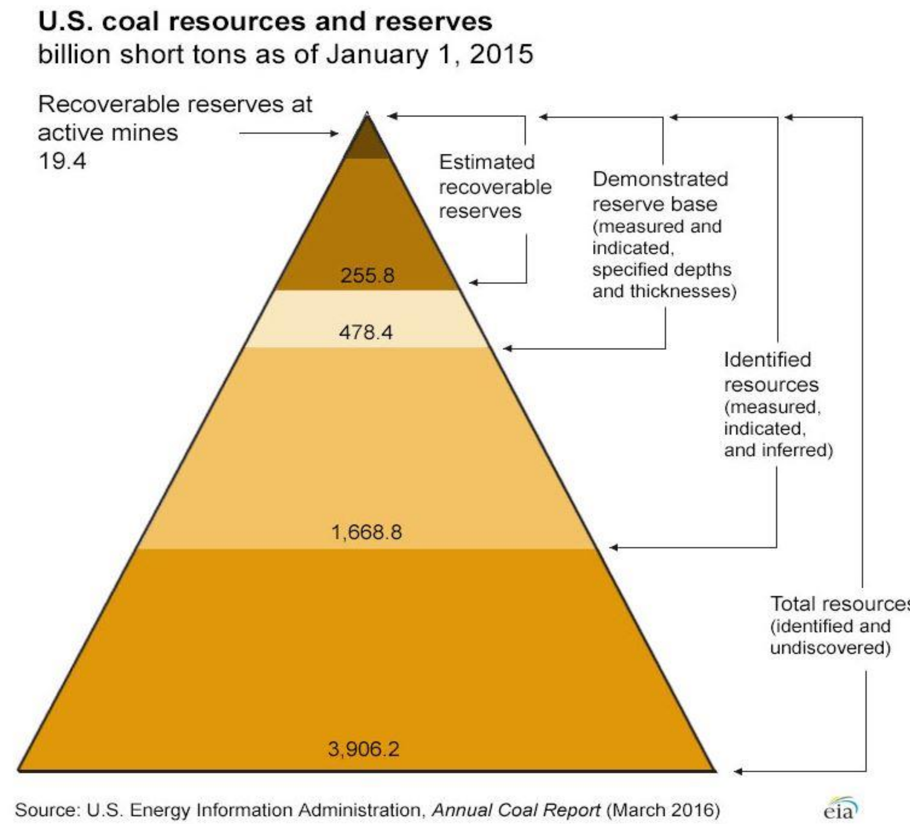
1. Project Background
   - Motivation
   - Statement of Goals & Objectives
2. Technical Approach:
   - Technology & Applications
   - Achievements under other projects
3. Project Structure
   - Participants (UMaine, Environetix, Duke, PERC)
   - Project Management Plan:
     - ✓ Tasks, Schedule, Milestones, Budget
     - ✓ Risk Management & Current Activities
4. Summary Statement

1. Project Background

- Motivation
- Statement of Goals & Objectives

Motivation (1)

- **USA → COAL** U.S. Energy Information Administration (EIA)
  - 21% of the world's *proven recoverable reserves* of coal (255.8 billion short tons)
  - This is only 6.5% of the potential total coal resources (identified and undiscovered)
  - **THUS: HUGE SOURCE OF ENERGY FOR THIS COUNTRY!**

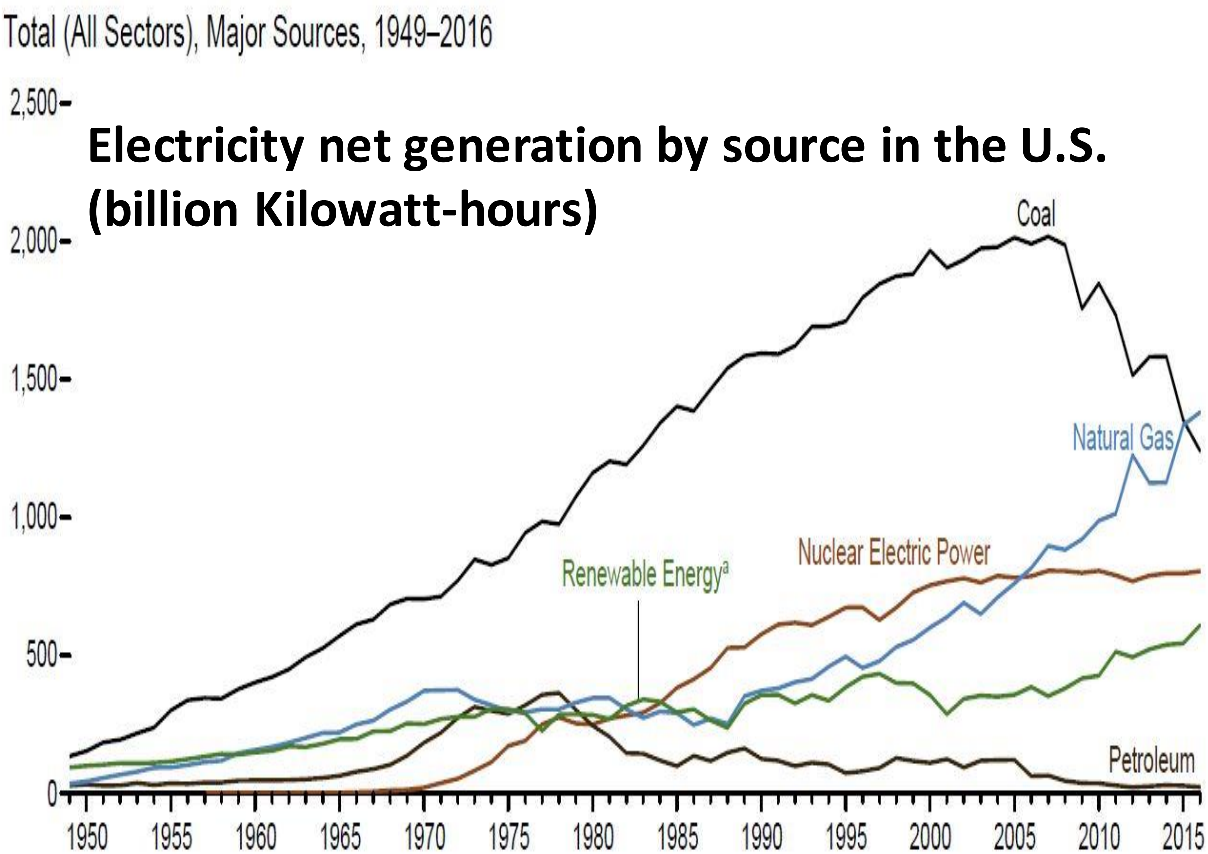


U.S. coal resources and reserves

Motivation (2)

- **Electricity Source in the USA (See Figure)**
  - **coal usage → diminishing since the mid-2000s**

- **Mostly due to:**
  - **Operation costs**
  - **Maintenance**
  - **Emissions**

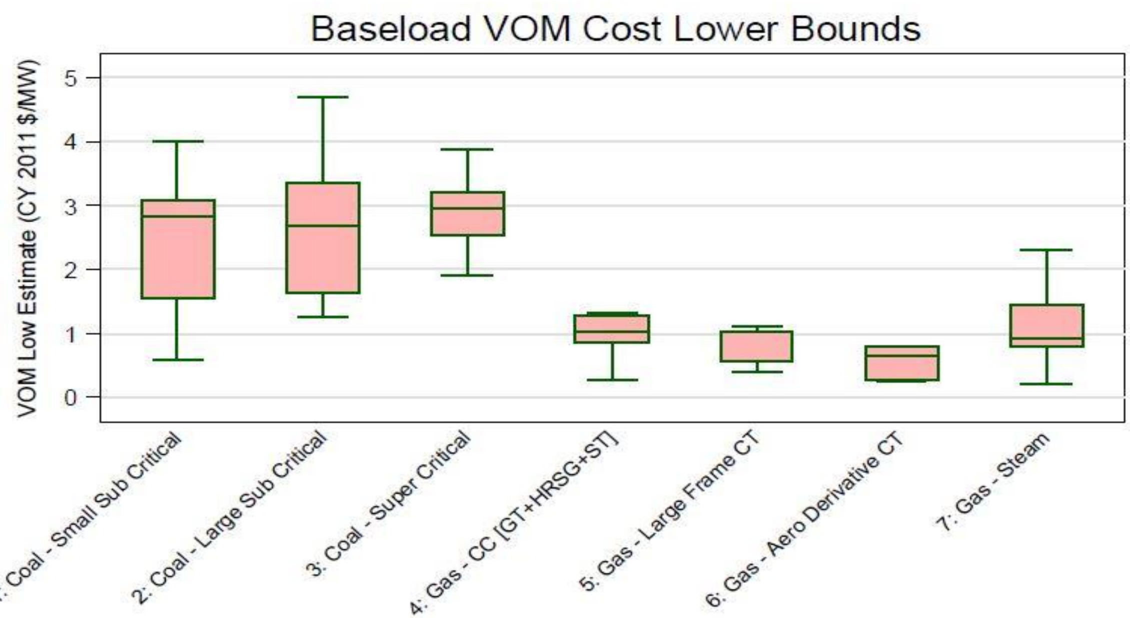


Electricity net generation by source in the U.S. (billion Kilowatt-hours)

June 2017 Monthly Energy Review, U.S. Energy Information Administration (EIA), DOE/EIA-0035(2017/6)

Motivation (3)

- **Comparison: Coal-Fired vs. Natural Gas generation**
  - Variable Operations and Maintenance (VOM) Cost
  - Coal-fired VOM consistently HIGHER than Natural Gas
  - Reasoning for the ↓ in Coal usage wrt Gas
- **Coal power plants → built before the 1990's**
  - Hampered by ↑ costs of operation & maintenance
- **High COAL availability in the U.S. calls for:**
  - New advanced Tech
  - Advanced Sensors
- **Target:**
  - ↑ power plant efficiency
  - ↓ maintenance costs
  - ↓ emissions



N. Kumar, et al, "Power Plant Cycling Costs," National Renewable Energy Laboratory (NREL), Report NREL/SR-5500-55433, July 2012

Goals

Major Goals of the current project can be listed as:

- **Usage of Harsh-Environment (HE) High-Temperature (HT) Wireless Surface Acoustic Wave (SAW) Sensor Technology to**
  - Promote reliable maintenance through Condition Based Maintenance (CBM) of critical coal-based power plant equipment
  - Promote cost-effective efficiency of power plant operations
- **Increase the HE HT Wireless SAW Sensor Technology Readiness Level (TRL) via test and implementation in Coal-based power plants:**
  - From current TRL-5 (Technology validated in relevant environment) to
  - TRL-7 (System prototyped validated in an operational system)

  or possibly
  - TRL-8 (Actual technology successfully commissioned in an operational system)
- **Area of Interest 1:**

  Advanced Combustion Coal Power Plant Improvement Technologies

  Subtopic 1A: Condition Based Monitoring of Coal-Based Power Generation Boilers

Objectives

To achieve last slide project Goals, targeted OBJECTIVES are:

- **HE HT Wireless SAW Temperature Sensors → CBM in Coal-Based Power Plant**
  - Boiler tube heat flux for optimized soot blower operation
  - Boiler tube fire side fouling, slagging, corrosion, and corrosion fatigue cracking, boiler acoustic/vibration characteristics, fatigue on tubes, headers, and piping, and boiler gas temperature profiles
- **Advancements in the packaging of SAW temperature sensors & antennas →**
  - Long-term robust operation up to 1000°C in coal-fired environment
- **Wireless communication protocols & signal processing refinements**
  - More user-friendly operation in industrial settings
- **Technology development to provide**
  - Diversification of sensor type to include Temperature & static/dynamic Strain diagnosis for CBM of boiler components
  - Improved thin films for SAW sensor manufacturing (piezo thin film & protective coating)
  - Improved non-destructive CBM supervision & process temperature monitoring
- **Technology validation and transition to coal-based power plants**

OUTLINE

1. Project Background
   - Motivation
   - Statement of Goals & Objectives
2. **Technical Approach:**
   - **Technology & Applications**
   - Achievements under other projects
3. Project Structure
   - Participants (UMaine, Environetix, Duke, PERC)
   - Project Management Plan:
     - ✓ Tasks, Schedule, Milestones, Budget
     - ✓ Risk Management & Current Activities
4. Summary Statement

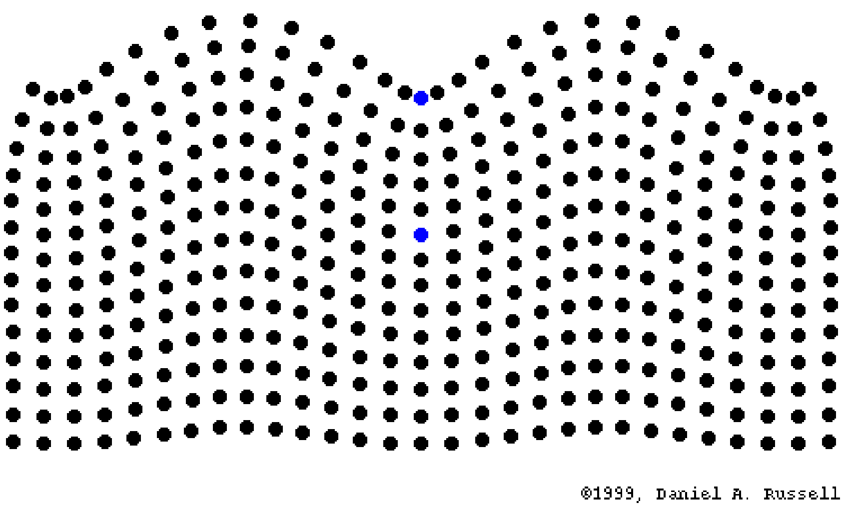
2. Technical Approach

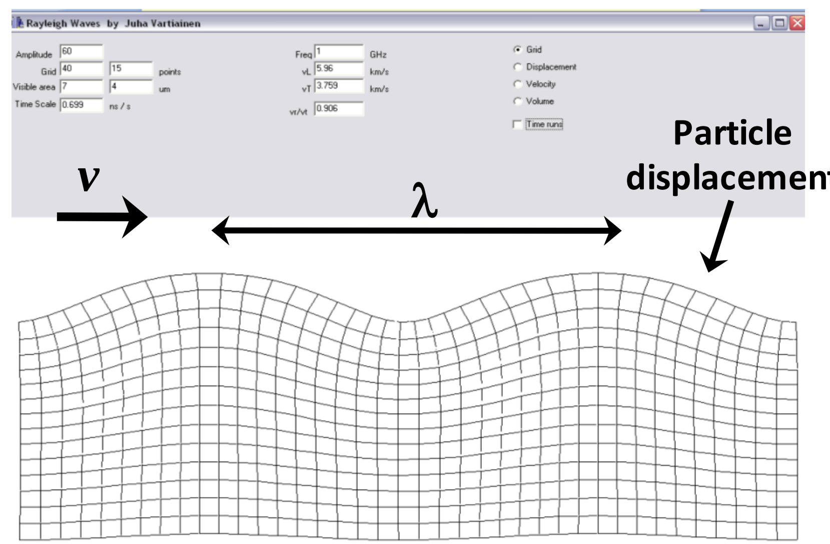
- Technology & Applications
- Achievements under other projects

Technology Fundamentals

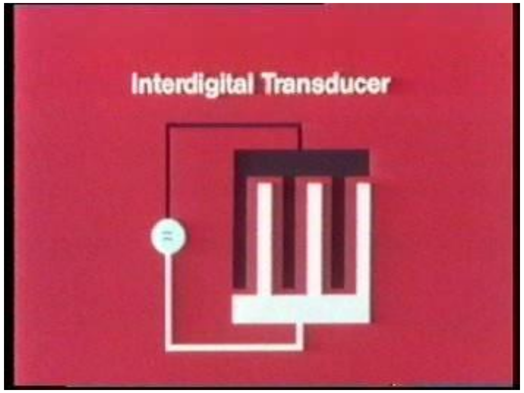
Surface Acoustic Wave (SAWs)

- SAW → guided wave → prop. @ the surface
  - Fields decay exponentially inside the material
  - Energy: ~ 90% in 1 λ_{SAW}
  - Ex: Rayleigh mode (elliptical particle trajectory)





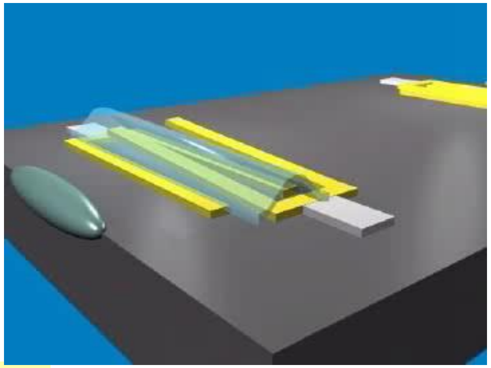
SENSORS



- Phase vel.: 1 to 6 Km/s ⇒ 10^5 x < than EM waves

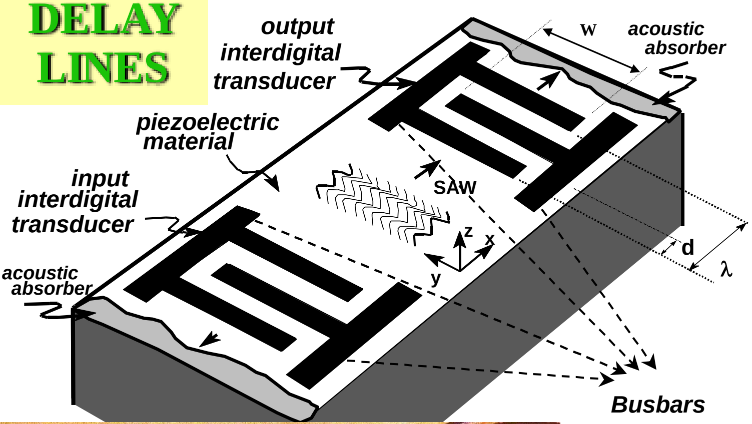
COMPACT DEVICES

- **Piezoelectric material:** electrical signal ⇒ acoustic wave

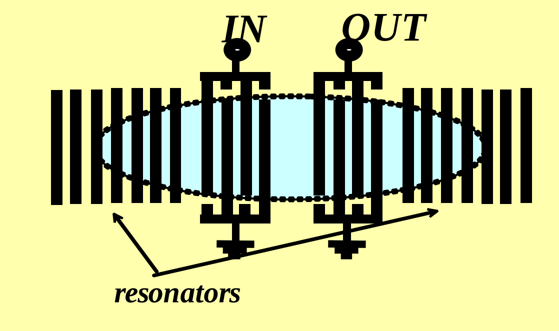


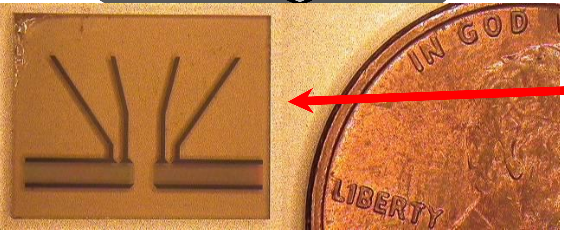
Sensing: device response (delay, freq.) ⇒ depend on crystal orientation, surface perturbation (thin film, temperature, pressure, strain, corrosion, gases, vibration)

DELAY LINES



TWO PORT RESONATOR

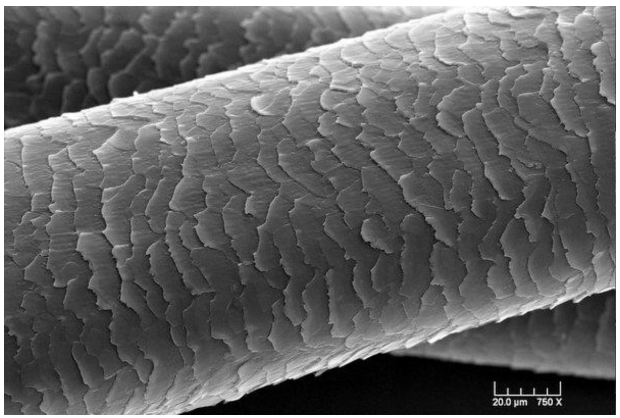




Delay line and two-port resonator fab @ UMaine

Critical Dimension $\rightarrow$ Fab. Challenge

- Ex: v quartz ST-X = 3,158 Km/s $\Rightarrow$ λsaw = 3,158 μm (@ 1 GHz)
  $\Rightarrow$ λsaw /4 fingerwidth

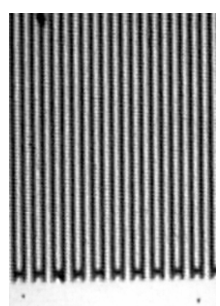


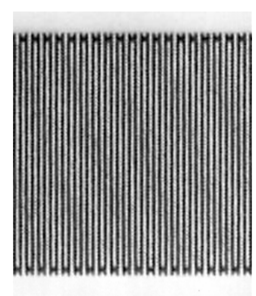
human hair: 60 to 80 μm thick

100 MHz: fingerwidth 8 μm

250 MHz: fingerwidth 3 μm

900 MHz fingerwidth 1 μm (GSM band)

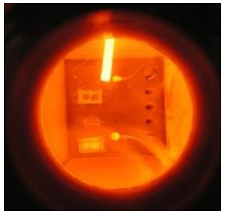




1800 MHz fingerwidth 0.5 μm (PCS, PCN band)

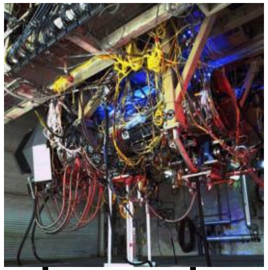
High Temp. (HT) / Harsh Environment

➢ **Surface Acoustic Wave** technology →

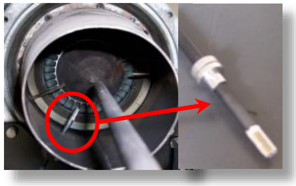


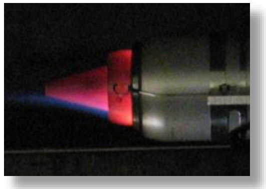
Very attractive for HT / HE sensor applications:

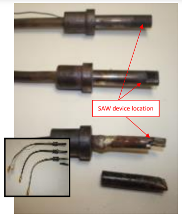
- **Sensitive** & **stable** crystal based platform
- Capable of **Wireless** Operation in harsh environment
- **Battery-free** in Harsh Environment



- **Robust** device: take extreme shocks in temperature (hundreds of °C in a few seconds)
- **Simple** device: thin film electr. & protective layers on top of a crystal
- **Easy installation** (the closest to the concept of "lick & stick")
- **Reduced** ↓ (or no) **maintenance**
- **Reduced** ↓ (or no) **safety concern**







2. Technical Approach

- Technology & Applications
- Achievements under other projects

List of Accomplishments for UMaine/Environetix SAW Sensor Technology

(See also "Supplementary Information" at the end of this presentation)

1) NASA – High temperature hydrocarbon and hydrogen SAW sensor
2) Air Force, NSF – Stable high temperature electrodes and SAW devices
3) Air Force – Sensor packaging and thermal shock resistance
4) Air Force - Adhesion tests on a bladed turbine rotor at high g-force
5) Air Force / Army – Long term furnace tests of T sensor reliability & accuracy
6) Air Force - Wireless multiple sensors & alternative interrogation schemes
7) Air Force – Sensor testing on static & rotating parts of turbine engines
8) Air Force - *In situ* wireless T sensor on rotating parts in JetCat P-70 turbine Engines
9) Army – SAW sensor inside compressor section of GE CT7 helicopter turbine engine
9) Customer – Wireless T sensors on steel pipe interrogated up to 45 feet
10) Air Force - Wireless test on Rolls-Royce Viper engine
11) DOE-NETL - Tests at NETL Aerothermal Facility
12) DOE-NETL – SAW gas sensor to detect hydrogen/oxygen at high T
13) Air Force – Test in hot spin rig with Pratt & Whitney
14) Customers – Sensors in High T commercial processes
15) DOE-NETL – Tests at Penobscot Energy Recovery Company (PERC) power plant

Power Plant Tests: PERC

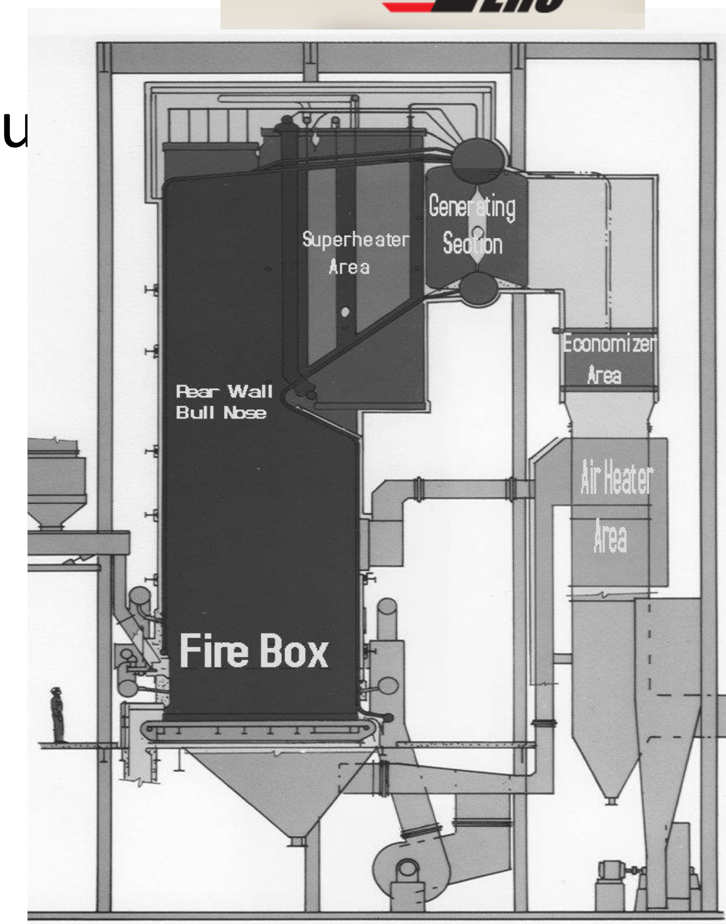
6. Penobscot Energy Recovery Company (PERC)

(Orrington,ME)

ERC

Municipal Solid Waste (MSW) Power Plant

Garbage is burned to release energy



- Environetix,UMaine,&PERC teamed u

Goal: Implement a Wireless Temperature Monitoring System(s) at the MSW power plant

ENVIRONETIX TECHNOLOGIES CORPORATION

1865 THE UNIVERSITY OF MAINE

Power Plant Tests: PERC

- Power plant conditions:
  - Temps ↑ 900°C (1650°F)
  - Highly erosive/corrosive exhaust gases

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

- **Technology transfer steps followed during the project:**

6.1 Material Tests

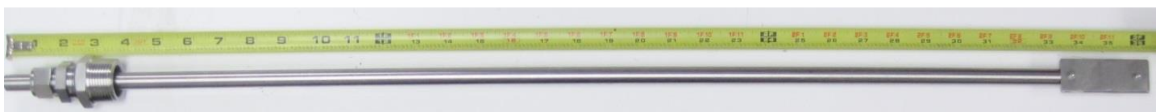
6.2 Wireless HE Sensor Array tested at Economizer

6.3 Wireless Sensor testing at Boiler tubes

Power Plant Tests: PERC

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

BEFORE



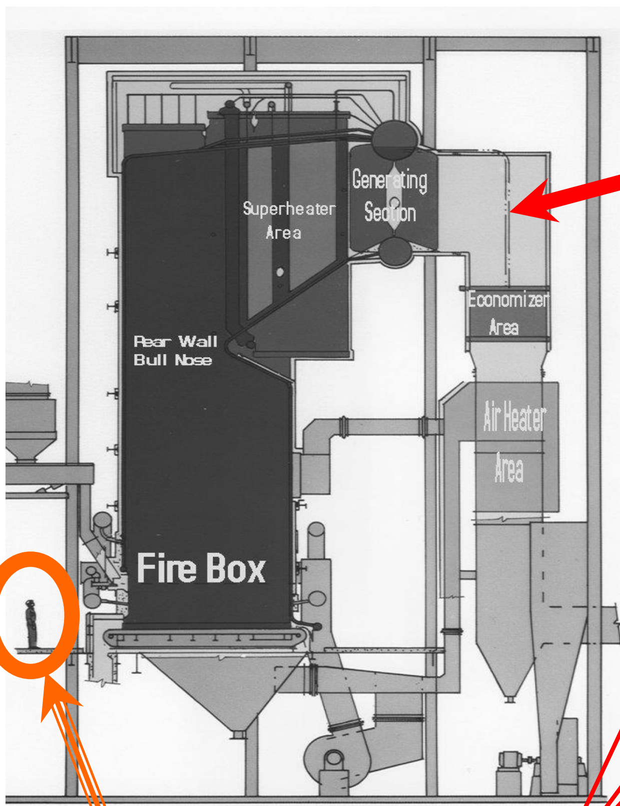
AFTER 10 DAYS IN THE ENVIRONMENT

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

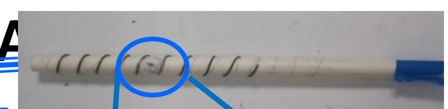
Power Plant Tests: PERC

➢ 6.2 Wireless HE Sensor Array tested at Economizer

Array ⇒ Sensors & Antennas Design, Implementation, Installation



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



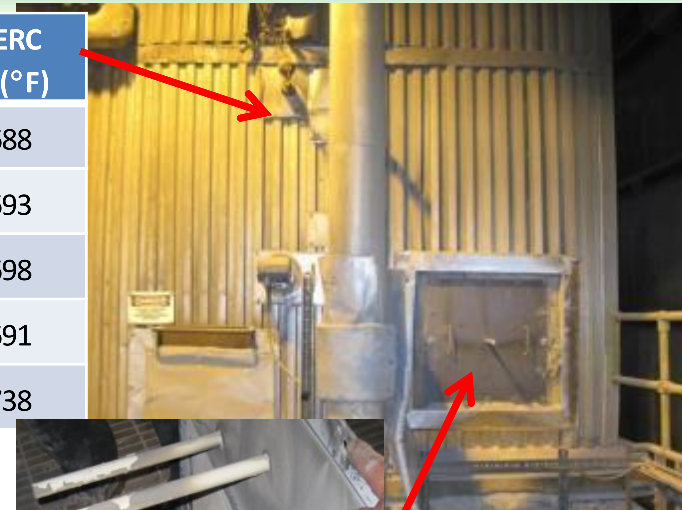
Relative dimension

6 dipoles + SAW sensors

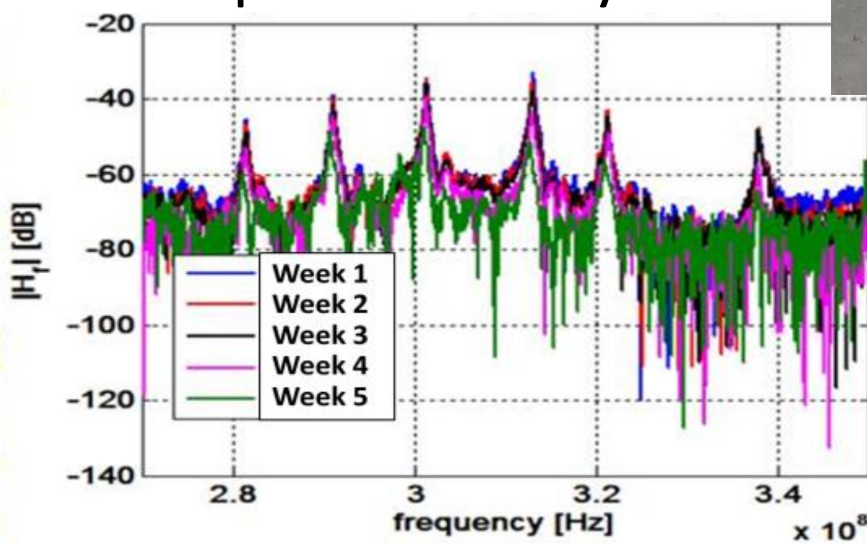
monopole interrog. ant.

Power Plant Tests: PERC

Date	Sensor 1 (°F)	Sensor 2 (°F)	Sensor 3 (°F)	Sensor 4 (°F)	Sensor 5 (°F)	Sensor 6 (°F)	PERC TC(°F)
Week 1	684	673	684	679	680	696	688
Week 2	694	684	695	670	688	706	693
Week 3	706	691	702	705	688	711	698
Week 4	712	689	701	702	671	711	691
Week 5	763	737	741	748	750	728	738



- First test: five weeks
  - Clear & consistent readings
- PERC thermocouple ~10’ away



ERC

THE UNIVERSITY OF MAINE

ENVIRONETIX TECHNOLOGIES CORPORATION

Power Plant Boiler Tests: PERC

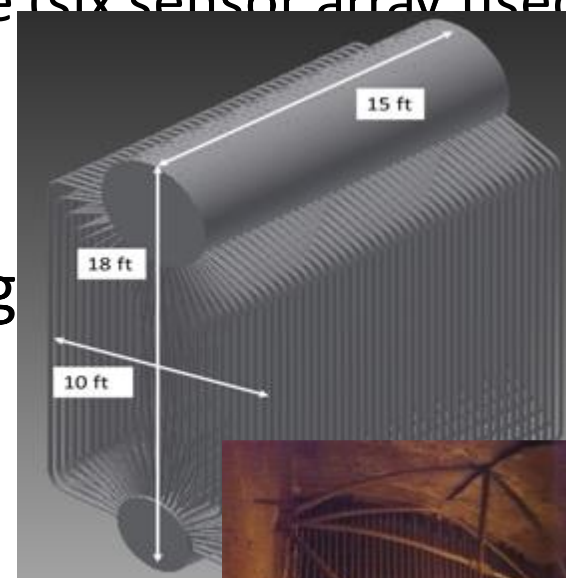
➢ 6.3 Instrumentation of Boiler Tubes

- ➢ Upon proof that Environetix/UMaine sensor array
  - Achieved successful operation in Power Plant Economizer
  - Wireless sensor array response: stable (six sensor array used)
  - Packaging stable in such environment
  - Tests performed throughout 2 years
- ➢ PERC was inquired $\rightarrow$ practical usag

  Wireless / Battery free / HE sensor array
- ➢ Indicated the need for:

  Placement of sensor array on

  Boiler tubes for condition based



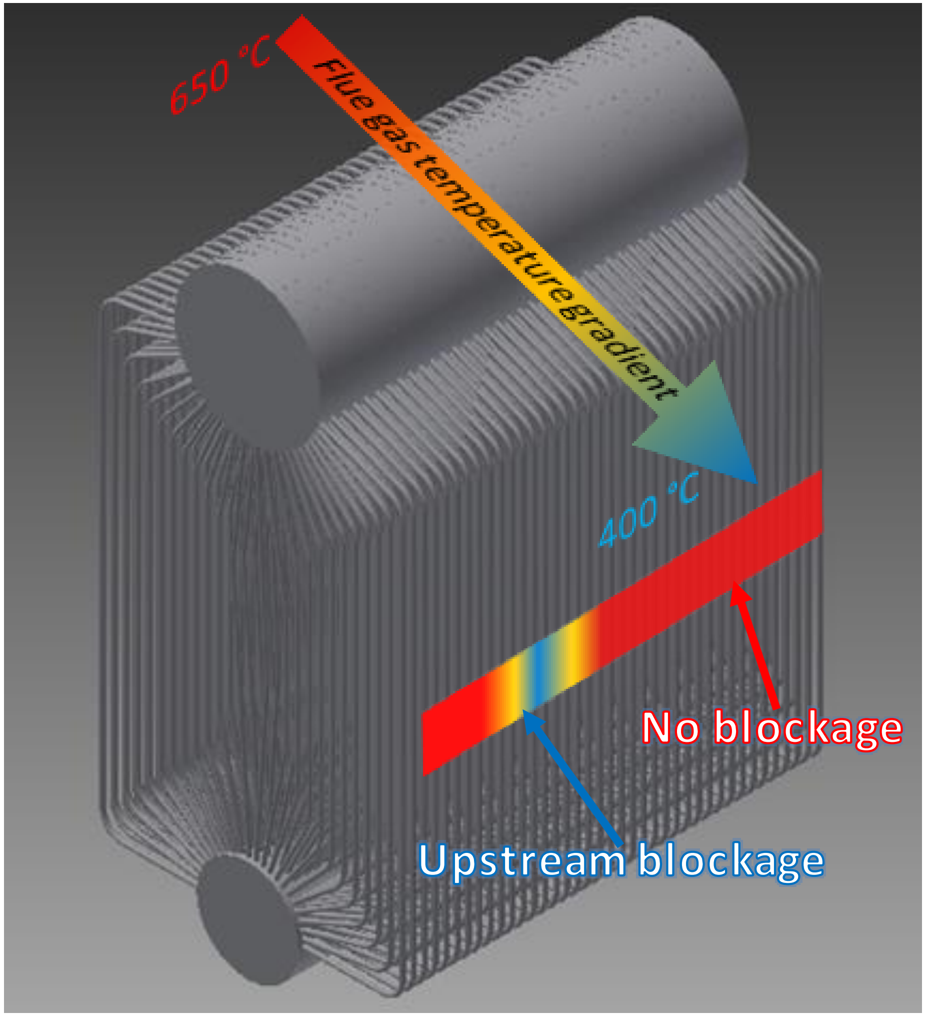
Identification of blockage

***Q*: How can we locate the blockage in order to optimally aim the steam/soot blowers?**

A: Wireless battery-free (maintenance free)

SAW Harsh environment temperature sensors positioned at the boiler tubes can be used to obtain a temperature profile.

Cooler zones **indicate airflow blockage**.

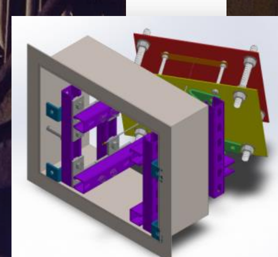


THE UNIVERSITY OF MAINE

ENVIRONETIX TECHNOLOGIES CORPORATION

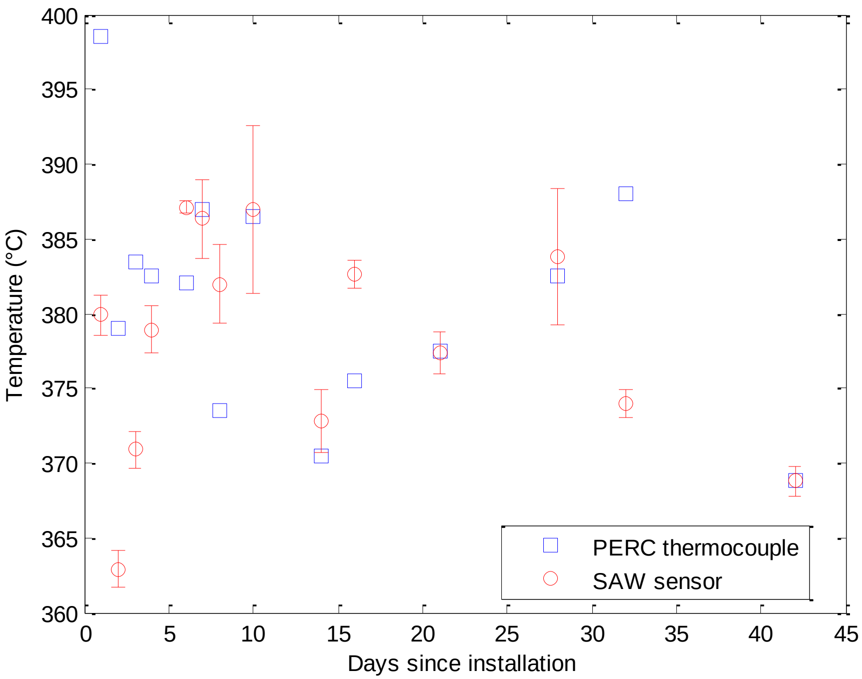
Sensor Array Deployed at PERC

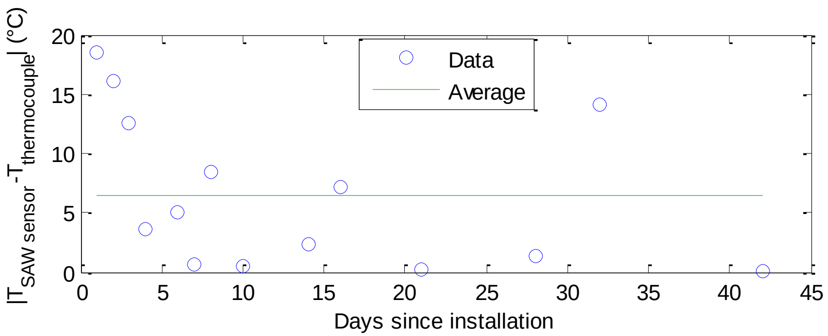
- Four sensor packages were assembled & installed at PERC 2016 shut down (view: boiler tube from economizer)
- Their relative placement is shown in the figure
- Preliminary Interrogation antenna (lower corner) used to test the installed sensors.

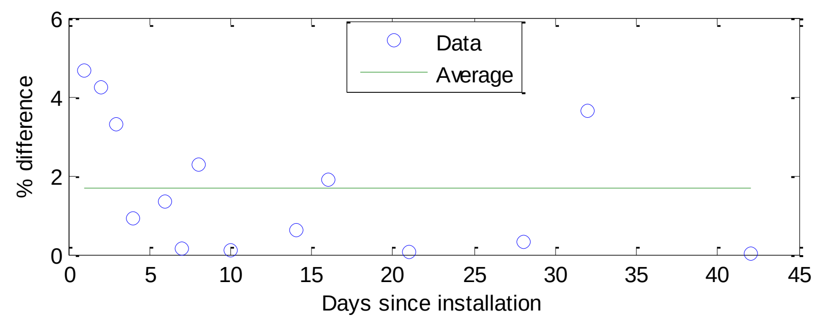


Wireless Interrogation vs. Time

- Again: measurement compared to economizer thermocouple
- Average differences between the daily temperatures measured: 1.7%
- Reading over 40 days







OUTLINE

1. Project Background
   - Motivation
   - Statement of Goals & Objectives
2. Technical Approach:
   - Technology & Applications
   - Achievements under other projects
3. **Project Structure**
   - Participants (UMaine, Environetix, Duke, PERC)
   - Project Management Plan:
     - ✓ Tasks, Schedule, Milestones, Budget
     - ✓ Risk Management & Current Activities
4. Summary Statement

3. Project Structure

- **Participants (UMaine, Environetix, Duke, PERC)**
- **Project Management Plan:**
  - ✓ Tasks, Schedule, Milestones, Budget
  - ✓ Risk Management & Current Activities

THE UNIVERSITY OF MAINE

Laboratory for Surface Science & Technology

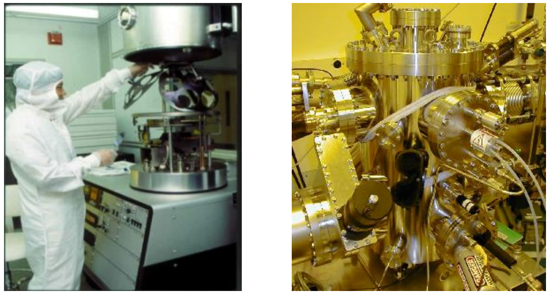
- Maine Team → working on HT μ~ technology since 1999
- Topics include:
  - Microwave acoustic material characterization & device design
  - Thin film R&D for HT applications
  - Wireless communication: in turbine engine & harsh environments
- Interdisciplinary Research Center
  - Physics, Chemistry, Electrical & Computer Engineering, Chemical & Biological Engineering
  - 2005 Research Building (18 M$) with 3500 ft^2 micro/nano fab clean room
  - Well instrumented for Materials Science and RF work
  - Over 70 people: faculty, tech staff, graduate /undergrad students

ENVIRONETIX TECHNOLOGIES CORPORATION

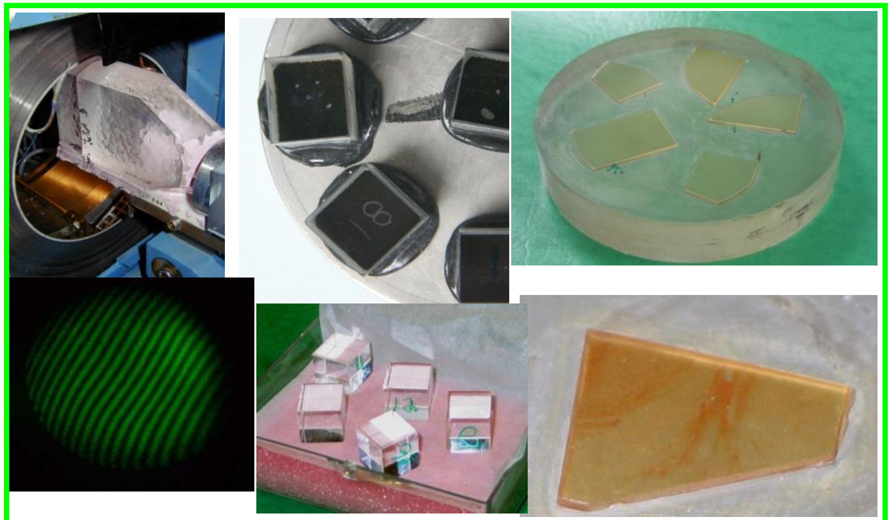
- UMaine spin-off high tech company (June 09)
  - Currently six employees + administrative support
  - Located Target Technology Center, Orono, ME
  - Funded by DoD SBIRs, Maine State, Customers
  - Wireless product/services for harsh environments

Device Fabrication &Test At UMaine Facilities

photolithography

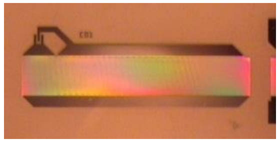


thin film deposition

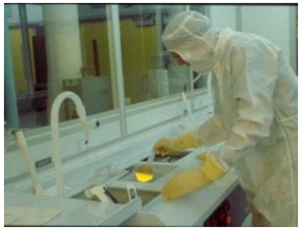


Cutting, grinding and polishing

device packaging



dry etch



wet etch

Film Characterization

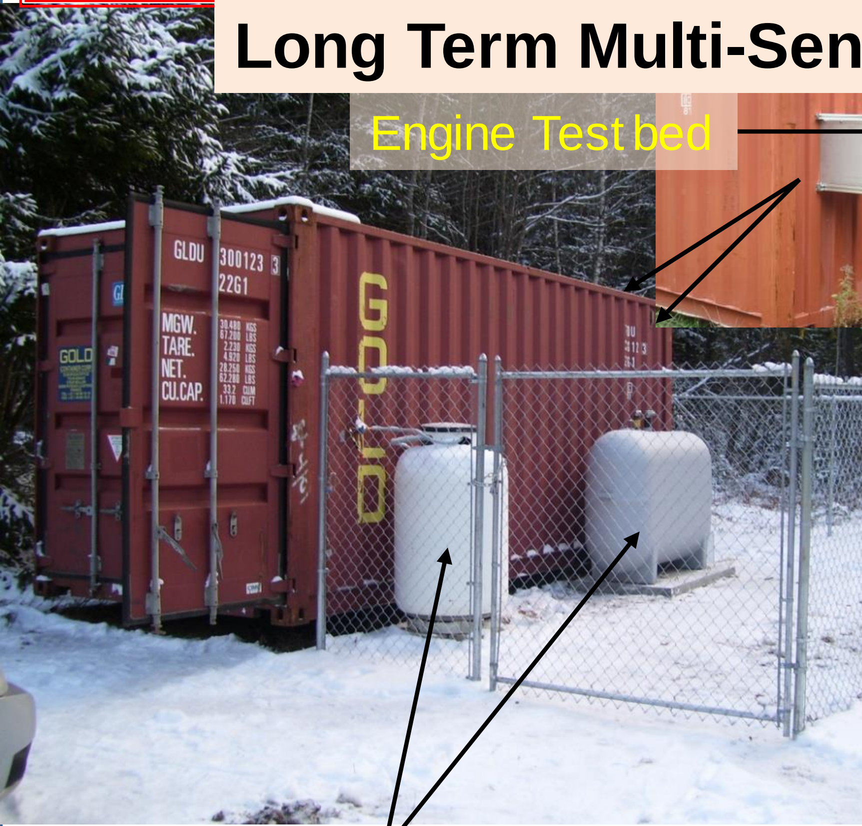
High Tech Testing Facility

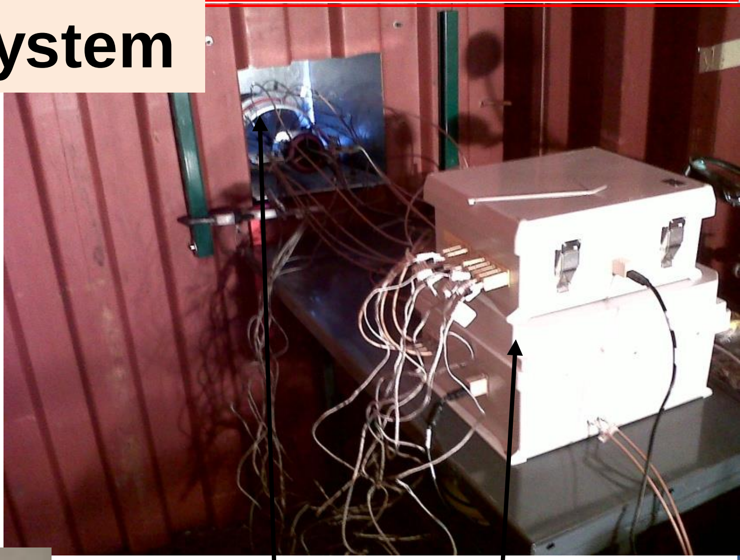
Device design, fabrication, and Test

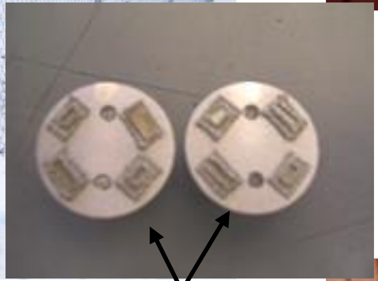
Field Testing: UMaine / Environetix Facilities

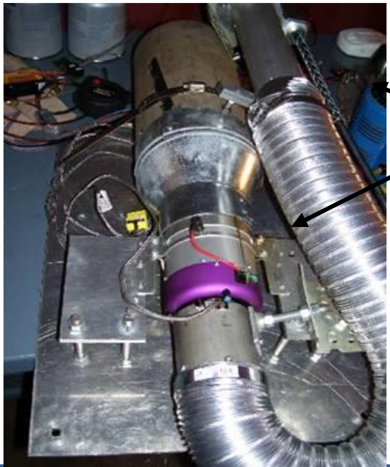
Long Term Multi-Sensor Test System

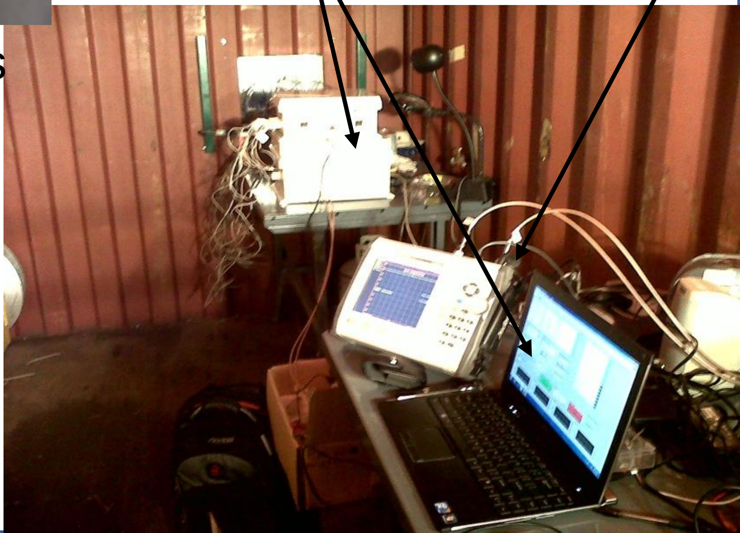
Engine Test bed











-Fixtures, support electronics for up to 8 devices, and Jetcat engine

VNA

Fuel Sources

-Rotating discs

-Facility can be operated year round.
-With K-1 fuel source an engine can be run Continuously for over 73 hours at 120,000 rpm

-Scaled Turbine Engine w/ duct heater

Penobscot Energy Recovery Company (PERC)

(Orrington,ME)

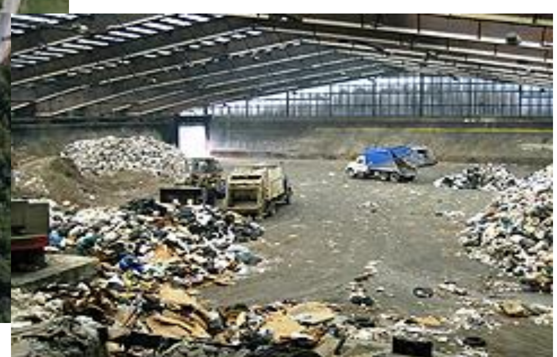
Municipal Solid Waste (MSW) Power Plant

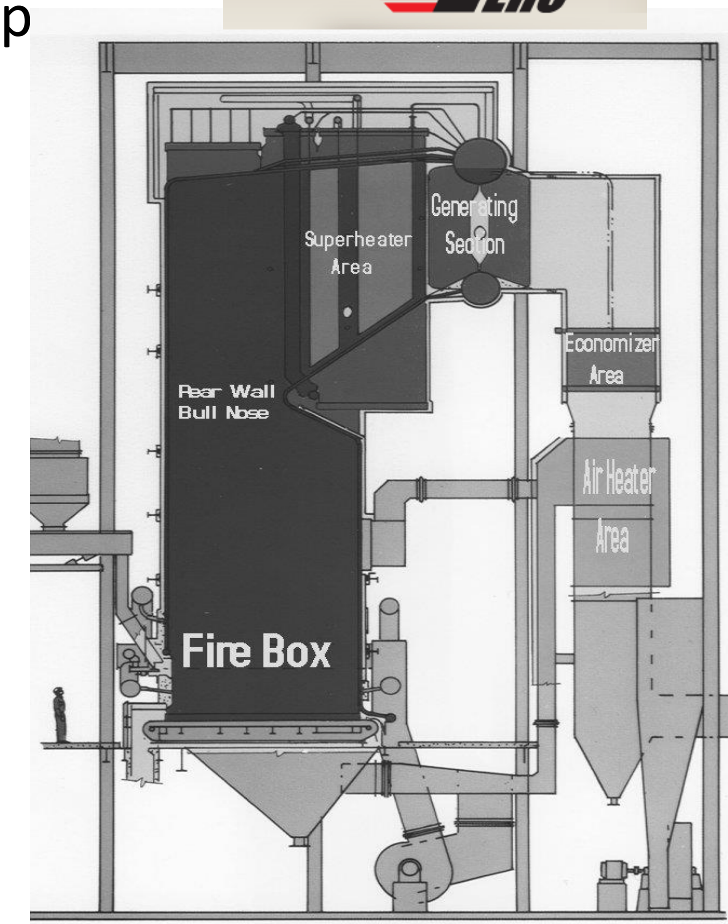
Garbage is burned to release energy

- Environetix, UMaine, & PERC teamed up

Goal: Implement a Wireless Temperature Monitoring System(s) at the MSW power plant

(previously described)





ENVIRONETIX TECHNOLOGIES CORPORATION

1865 THE UNIVERSITY OF MAINE

Duke Energy, Charlotte, NC

- **Coal-based power plants**
- Environetix/UMaine POCs:
  - Neil Kern (Technology Development Manager)
  - Stephen K. Storm (Boiler Performance Program Manager)
  - David Charles Julius (Director of Technology Development)
- First contacted through Barbara Carney & follow-up 2015 (EPRI)
- Expressed strong interest in
  - Wireless capabilities
  - Harsh to place locations to monitor boilers (not feasible with wired TCs)
  - Interested in reliable & distributed sensor diagnostics data acquisition
  - Their goals:
    - ✓ Improve efficiency
    - ✓ Increase economic benefit of coal-based power plants
    - ✓ Environmental Impact

PI's

- **Mauricio Pereira da Cunha**, *Professor of Electrical & Computer Engineering and Member of LASST (PhD in Electrical Engineering, McGill University, 1994).* Principal Investigator who is responsible for overseeing the entire project. Areas of expertise include microwave acoustic materials research and characterization, wave propagation, wireless communication, and sensor development.
- **Robert J. Lad**, *Professor of Physics and Member of LASST (PhD in Materials Science, Cornell University, 1986).* Co-Principal Investigator responsible for assisting in monitoring the project. His area of expertise includes ceramic and semiconductor thin film growth and characterization, electrical transport measurements, and high temperature materials.

UMaine Technical & Support Staff

- **UMaine Staff Engineer**, *Search in progress*
- **George Bernhardt**, *LASST Research Scientist (PhD in Physics, U.Maine 1994).*
- **Armando Ayes**, *Ph.D. Student (BS in Electrical Engineering, U.Maine 2016).*
- **Morton Greenslit**, *Ph.D. Student (BS in Physics, U. of Minnesota 2016).*
- **Anin Maskay**, *Ph.D. Student (BS in Electrical Engineering, U.Maine 2013).*
- **Michael Call**, *LASST Research Technician (MS in Electrical Engineering, U. of Southern Maine, 2005).*
- **Tracy Richardson**, *LASST Administrative & Financial Officer*
- **Nicholas Aiken**, *Undergraduate Student ECE*

UMaine Students

- **Technical Staff and Ph. D. Students at UMaine***:*
- *Proficiency in microwave techniques and with thin film technology & characterization.*
- *Be involved in* $\rightarrow$
  - ✓ *Design, fabrication, and testing of HT SAW sensors for integration of thin sensing films*
  - ✓ *Research, Fabrication, Characterization, & Integration of the novel HT SAW sensor films into the* $\mu\sim$*acoustic (SAW) device,*
  - ✓ *Performing wireless interrogation experiments on temperature / strain sensor arrays in laboratory furnace environments*
  - ✓ *Performing embedding of prototype sensors into targeted power plant components*
  - ✓ *Transitioning the technology to power plant environments*

- **Undergraduate Students at UMaine.** *The selected candidates will also be trained in microwave technology, thin film deposition and sensor fabrication. It is expected that the undergraduate students will assist in:*
  - ✓ *Research and characterization of thin films for the targeted sensors at elevated temperatures (up to 1000 ℃).*
  - ✓ *Research and fabrication of prototype temperature and strain sensors for operation at elevated temperatures (up to 1000 ℃) and for the targeted gases species.*
  - ✓ *Performing wireless interrogation experiments on temperature / strain sensor arrays in laboratory furnace environments and participate in the field test experiments in operating power plant environments.*
  - ✓ *Field test experiments in operating power plant environments*

Environetix
Technical & Support Staff

ENVIRONETIX

- **Gregory Harkay,** *Project Engineer & Project Manager (MS in Physics, Penn State, 2013; BE in Engineering, Dartmouth's Thayer School of Engineering, 2008).*
- **Anin Maskay**, *Engineer Manager (B.S in Electrical Engineer, U. of Maine 2012, Ph.D. May 2018).*
- **Seth Braun**, *Project Engineer (B.S in Electrical Engineer, Georgia Tech, 2016).*
- **Timothy Coyle**, *Project Engineer (B.S in Electrical Engineer, U. of Maine, 2000).*
- **George Harris**, *Technical Engineer (BS in Engineering Physics, U. of Maine 1978).*
- **Suzanne Sharrow,** *Financial Administrator (BS in Education, U. of Maine, 1980; AS Health Information Technology, U.Maine 1986)*

Duke & PERC
Current Technical POCs for the Project

Duke Energy

- **Neil Kern** (Technology Development Manager)
- **Stephen K. Storm** (Boiler Performance Program Manager)
- **David Charles Julius** (Director of Technology Development)

- **PERC**
- **Richard Kelley**, *Plant Manager (Penobscot Energy Recovery Co.)*

3. Project Structure

- Participants

  (UMaine, Environetix, Duke, PERC)
- **Project Management Plan:**
  - ✓ Tasks, Schedule, Milestones, Budget
  - ✓ Risk Management & Current Activities

Tasks

Project contains 4 major tasks / subtasks, as follows:

1. **TASK 1 – Project Management & Planning**
2. **TASK 2 – ADVANCEMENT OF HIGH TEMPERATURE WIRELESS SAW SENSOR TECHNOLOGY FOR USE IN HARSH COAL-FIRED POWER PLANT ENVIRONMENTS**

2.1 Study and Definition of Target Power Plant Locations

2.2 Development of Interrogating and Sensor Antennas

2.3 Identification, Fabrication, and Testing of Sensor & Antenna Packaging Materials

2.4 Wireless Communication Planning and Testing

2.5 Integration of Technology Improvements Made in Task 4 and Task 5

Tasks (cont.)

3. **TASK 3 – IMPLEMENTATION AND TESTING OF MATURE PROTOTYPE WIRELESS SENSOR SYSTEM WITHIN POWER PLANT ENVIRONMENTS**

3.1 Fabrication of Specific Prototype Sensor System

3.2 Installation of Specific Prototype Sensor System in Identified Power Plant Locations

3.3 Testing of Specific Prototype Sensor System in Identified Power Plant Locations

3.4 Refinement of Sensor System Performance and Additional Testing

Tasks (cont.)

4. **TASK 4 – PROTECTIVE COATINGS AND PIEZOELECTRIC THIN FILMS FOR IMPROVED SENSOR PACKAGING & PERFORMANCE**

4.1 Development of Thin Film Dielectric Coatings for Packaging of Sensors in Harsh-Environments

4.2 Development of Piezoelectric Thin Film Materials for Enhanced Sensor Manufacturability and Integration with Sensor Antenna

5. **TASK 5 – DEVELOPMENT OF PROTOTYPE SAW-BASED STATIC / DYNAMIC STRAIN SENSOR**

5.1 Development and Demonstration of Dynamic Strain Sensor

5.2 Development and Demonstration Static+Dynamic Strain Sensor

Project Schedule (Timeline)

Task and subtasks Listed by Lead organization/Support team : UM = UMaine; E = Environetix In red: Milestones in accordance with Section D	Year 1				Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
Task 1 – Project Management and Planning	UM/E M1											
Task 2 – Synthesis and Processing of Novel SAW Sensor Nanocomposite Thin Film Materials for Harsh Environment Wireless Operation up to 1200°C												
Subtask 2.1 – Study and Definition of Target Power Plant Locations	UM/E	UM/E	UM/E	UM/E M2								
Subtask 2.2 – Development of Interrogating and Sensor Antennas		UM/E	UM/E	UM/E	UM/E							
Subtask 2.3 – Identification, Fabrication, and Test of Sensor & Antennas Packaging Materials		UM/E	UM/E	UM/E	UM/E							
Subtask 2.4 – Wireless Communication Planning and Testing		E/UM	E/UM	E/UM	E/UM M3							
Subtask 2.5 – Integration of Technology Improvements Made in Tasks 4 & 5						UM/E	UM/E	UM/E	UM/E	UM/E	UM/E	
Task 3 – Investigation of Materials and Techniques for Embedding Wireless Temperature Sensor Arrays and Sensor Interrogators into Power Plant Components												
Subtask 3.1 – Fabrication of Specific Prototype Sensor System					E/UM	E/UM	E/UM M4					
Subtask 3.2 – Installation of Specific Prototype Sensor System in Identified Power Plant Locations						E/UM	E/UM	E/UM M5				
Subtask 3.3 – Testing of Specific Prototype Sensor System in Identified Power Plant Locations							E/UM	E/UM	E/UM M6			
Subtask 3.4 – Refinement of Sensor System Performance and Additional Testing								E/UM	E/UM	E/UM	E/UM	E/UM M7 & M12
Task 4 – Protective Coatings and Piezoelectric Thin Films for Improved Sensor Packaging and Performance												
Subtask 4.1 – Develop of Thin Film Dielectric Coatings for Packaging of Sensor in Harsh-Environment	UM/E	UM/E	UM/E	UM/E	UM/E	UM/E	UM/E	UM/E	UM/E M8			
Subtask 4.2 – Development of Piezoelectric Thin Film Materials for Enhanced Sensor Manufacturability and Integration with Sensor Antenna		UM/E	UM/E	UM/E	UM/E	UM/E	UM/E	UM/E	UM/E	UM/E M9		
Task 5 – Development of Prototype SAW-based Static/Dynamic Strain Sensor												
Subtask 5.1 – Development and Demonstration of Dynamic Strain Sensor	UM/E	UM/E	UM/E	UM/E	UM/E	UM/E	UM/E	UM/E	UM/E	UM/E M10		
Subtask 5.2 – Development and Demonstration Static+Dynamic Strain Sensor		UM/E	UM/E	UM/E	UM/E	UM/E	UM/E	UM/E	UM/E	UM/E M11		

Project Milestones

Project Milestone	Planned Completion Date	Milestone Title
M1	Q1 (1st quarter of Year 1)	Kick-off Meeting with DOE / NETL Program Officer
M2	Q4 (4th quarter of Year 1)	Definition of Target Point to Install Prototype Wireless HE SAW Sensor System
M3	Q5 (1st quarter of Year 2)	Wireless Communication Planning and Testing
M4	Q7 (3rd quarter of Year 2)	Fabrication of Prototype Wireless HE SAW Sensor System
M5	Q8 (4th quarter of Year 2)	Installation of Specific Prototype Sensor System in Identified Power Plant Locations
M6	Q9 (1st quarter of Year 3)	Testing of Specific Prototype Sensor System in Identified Power Plant Locations
M7	Q12 (4th quarter of Year 3)	Refinement of Sensor System Performance and Additional Testing (including improvements from Tasks 4 & 5)
M8	Q9 (1st quarter of Year 3)	Identification of the Best Thin Film Dielectric Coatings for Packaging of Sensor in Harsh-Environment (*for integration in subtasks 2.5 and 3.4*)
M9	Q10 (2nd quarter of Year 3)	Identification of the Best Piezoelectric Thin Film Materials for Enhanced Sensor Manufacturability and Integration with Sensor Antenna (*for integration in subtasks 2.5 and 3.4*)
M10	Q10 (2nd quarter of Year 3)	Field Testing of Wireless Temperature Sensor Arrays in Selected Power Plant Locations (*for integration in subtasks 2.5 and 3.4*)
M11	Q10 (2nd quarter of Year 3)	Demonstration of Dynamic Strain Sensor (*for integration in subtasks 2.5 and 3.4*)
M12	Q12 (4th quarter of Year 3)	Final Demonstrations in Coal-fired Power Plants and Final Project Reporting Preparation to DOE / NETL

Budget of Category Costs

CATEGORY	Budget Period 1 Costs	Budget Period 2 Costs	Budget Period 3 Costs	Total Costs	Project Costs %
a. Personnel	$208,530	$268,957	$282,404	$759,891	**30.3%**
b. Fringe Benefits	$55,872	$87,295	$91,658	$234,824	**9.4%**
c. Travel	$12,000	$15,000	$18,000	$45,000	**1.8%**
d. Equipment	$0	$0	$0	$0	**0.0%**
e. Supplies	$42,000	$42,000	$42,000	$125,999	**5.0%**
f. Contractual					
Sub-recipient	$250,000	$250,000	$250,000	$750,000	*29.9%*
Vendor	$0	$0	$0	$0	*0.0%*
FFRDC	$0	$0	$0	$0	*0.0%*
Total Contractual	$250,000	$250,000	$250,000	$750,000	**29.9%**
g. Construction	$0	$0	$0	$0	**0.0%**
h. Other Direct Costs	$18,206	$19,116	$20,072	$57,394	**2.3%**
Total Direct Costs	$586,608	$682,368	$704,133	$1,973,109	
i. Indirect Charges	$153,445	$184,296	$193,575	$531,316	**21.2%**
Total Project Costs	$740,053	$866,664	$897,708	$2,504,425	**100.0%**

Risk Management

- Further details in the Project Management Plan

TECHNICAL RISK ANALYSIS	INITIAL RISK ANALYSIS ITEM PER TASK
Task 2	Confirmation of initial selection of boiler tube locations @ collaborating power plants
Task 3	Fabrication and installation of specific prototype sensor system in identified power plant locations
Task 4	Development of thin film dielectric coating for packaging of sensor in harsh-environment & piezoelectric thin film for enhancement manufacturability and integration with sensor antenna
Task 5	Development and demonstration of dynamic and static strain sensors

Current Activities

- Project Being Signed and Submitted by UMaine Week of February 20, 2018.
- Task 1 – Project Management & Planning
  - Review of Project Management Plan (PMP) with program officer & DOE Personnel
  - Kick-off meeting (This presentation)
  - Contact and Coordination with Duke Energy / PERC
  - Hiring staff for project support at UMaine
  - Engaging Grad and Undergrad students

OUTLINE

1. Project Background
   - Motivation
   - Statement of Goals & Objectives
2. Technical Approach:
   - Technology & Applications
   - Achievements under other projects
3. Project Structure
   - Participants (UMaine, Environetix, Duke, PERC)
   - Project Management Plan:
     - ✓ Tasks, Schedule, Milestones, Budget
     - ✓ Risk Management & Current Activities
4. **Summary Statement**

4. Summary Statement

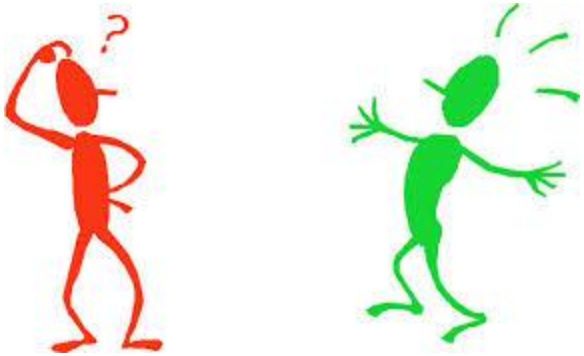
Summary

This presentation addressed:

1. **Project Background: Motivation, Goals, & Objectives**
2. **Technical Approach Overview →**
   - **Technology State-of-the-art**
   - **Prior Accomplishments**
3. **UMaine capabilities and Environetix/PERC/Duke**
   - **Expertise, Commitment, & Technical Support to the project**
4. **Project Implementation**
   - **Tasks, Schedule, Milestones, Budget**
   - **Risk Management & Current Activity Status**

END / QUESTIONS?

mdacunha@maine.edu



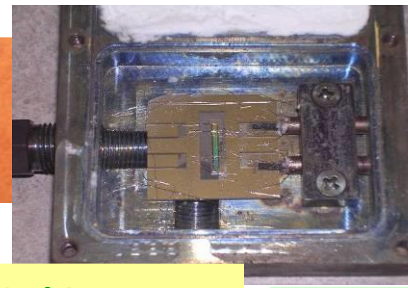
Supplementary Information

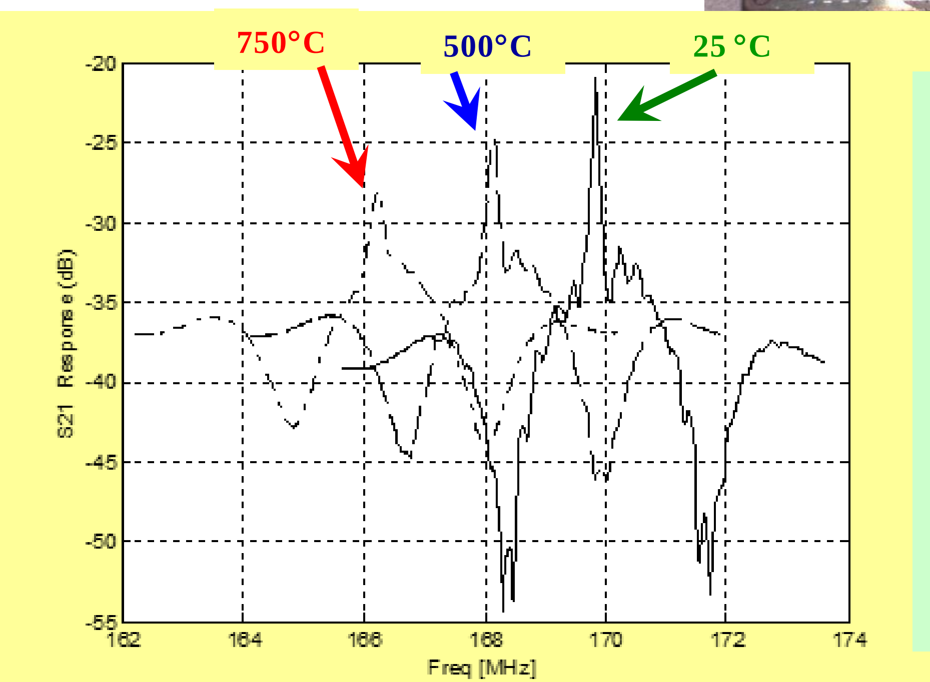
- **Details on:**

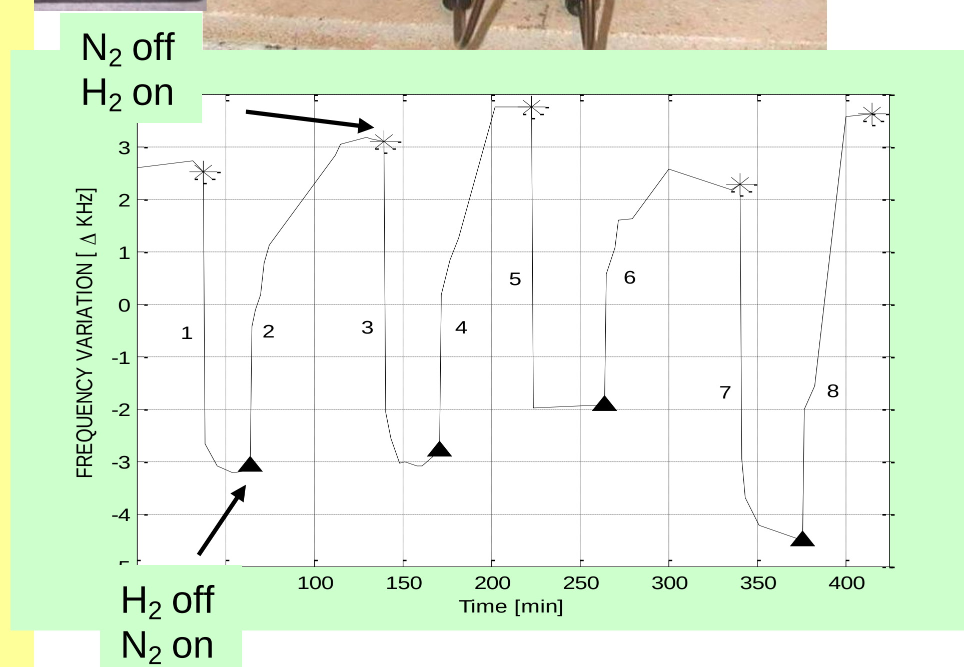
“Achievements under other projects”

1. NASA: Gas Sensor

- **High Temperature μ~ Sensors for NASA (2002-05)**
  - LGS H_2 and hydrocarbon HT gas sensors



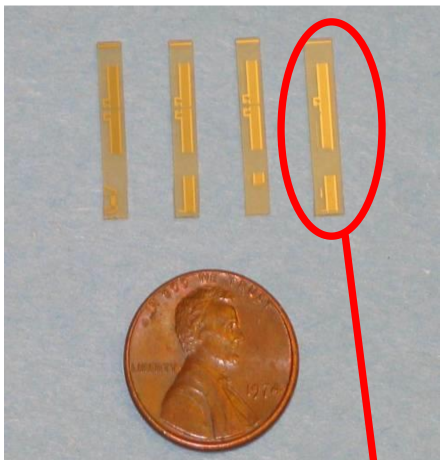




2a. Air Force: Thin Film

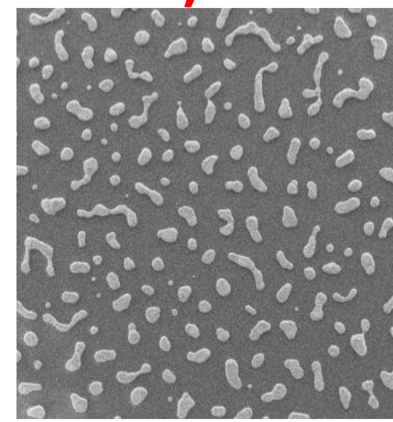
- High Temperature μ~ Sensors turbine engines applic.
- Major challenges overcome (state-of-the-art):

✓ Stable thin film electrode > 650°C (operation up to 950°C)



Rapid recrystallization & dewetting of Pt electrodes at ~ 700°C in air leading to loss of continuity

Critical problem that limited high T thin film technology

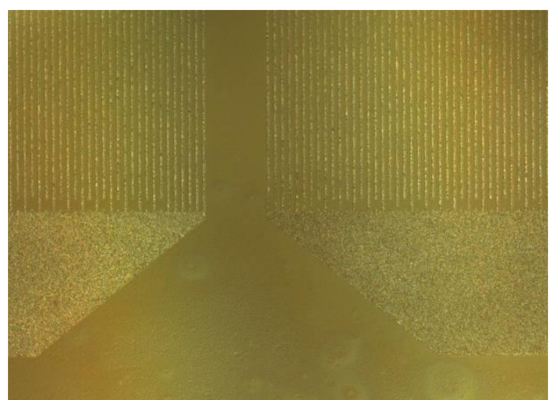


10 μm

SEM Image

As fabricated

⇒

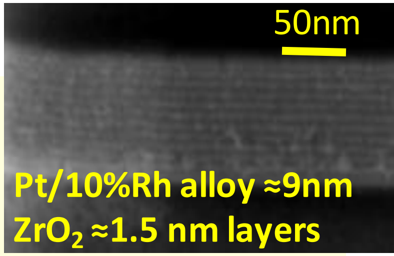


After heating to 1000 °C

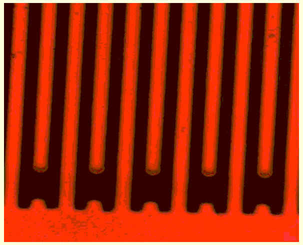
⇒

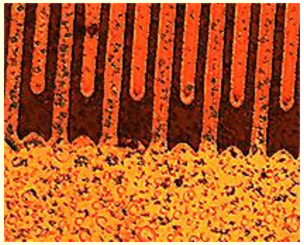
100x magnification

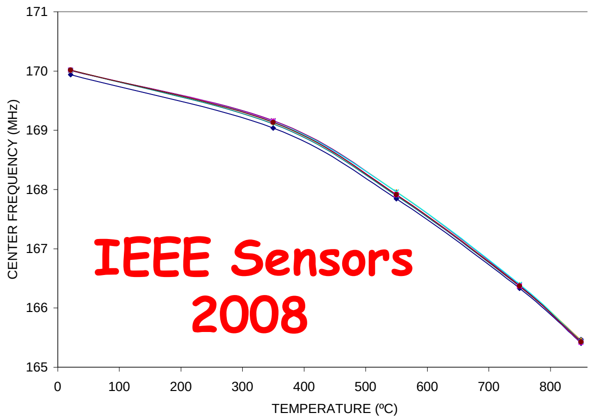
2b. Air Force Devices

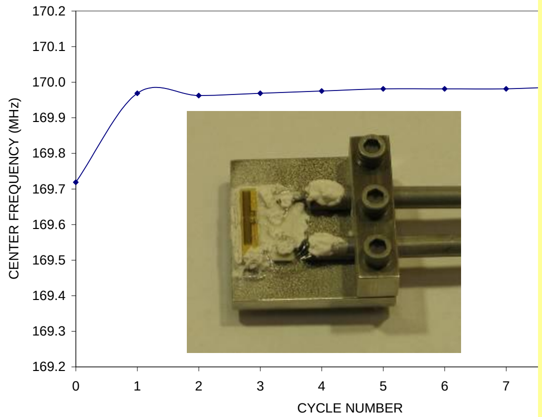


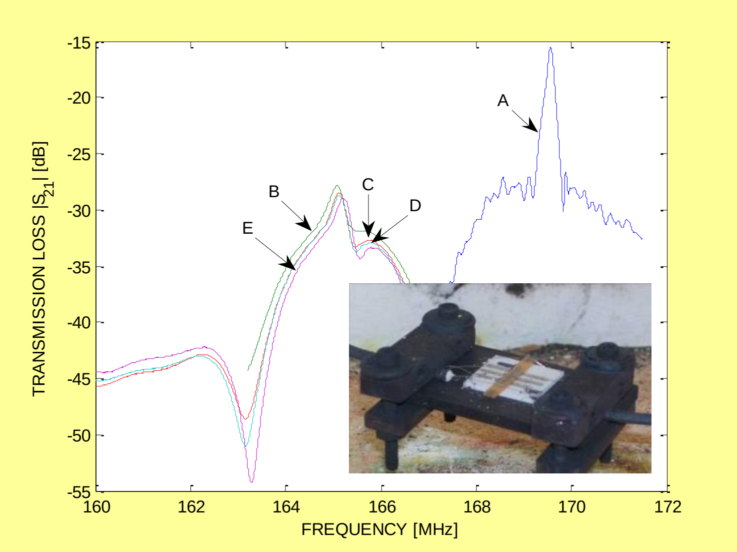
- Electrode and Protective Films Developed
  - Pt/Rh/ZrO_2 patented electrode technology
  - Ultra thin (up to 100nm) oxynitride passivating coatings
- Long Term HT Sensor Performance
  - **Tested @ 800°C for 5½ months**
- Thermal Cycling
  - **Multiple cycles (>8) reported btwn RT and 850 °C**
- Temperature Sensor Sensitivity
  - **9.1 KHz/°C around 800°C**











2c. Air Force: T Shock

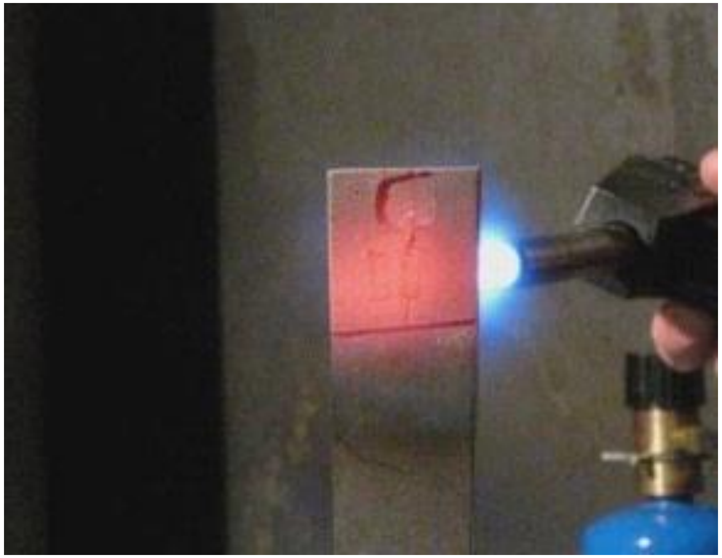
TEMPERATURE SHOCK TEST 1:

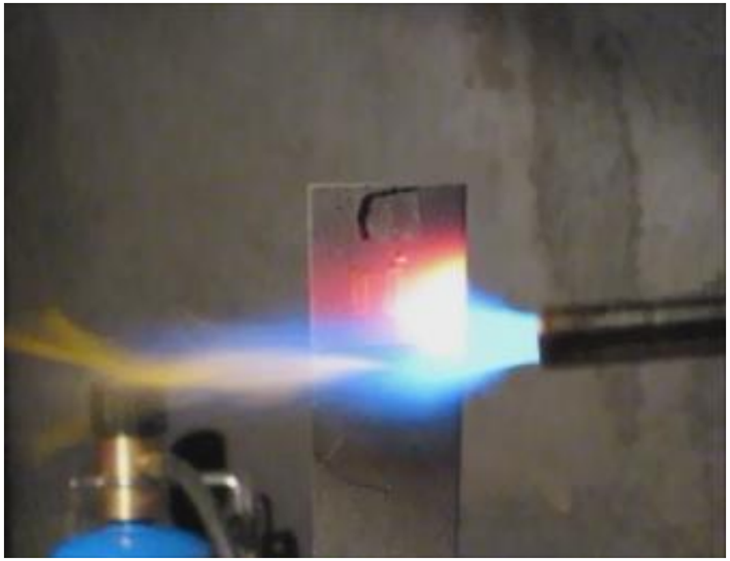
FURNACE TEMPERATURE SHOCK TEST

- Crystal 700°C pre-heated furnace & allowed to stabilize (≈8 min)
- Removed & cooled to RT (21°C) with an air gun
- No sign of device damage: tested repeated 3 times @ UMaine and HPI

TEMPERATURE SHOCK TEST 2

PROPANE TORCH & NITROGEN QUENCH



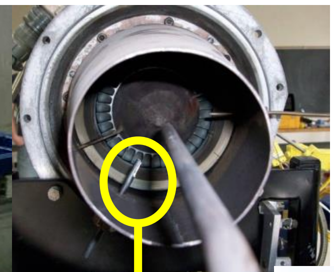


2d. Air Force: Packaging

Attachment to Parts of Jet Engine: Static & Rotating

- Rotation up to 90,000 rpm & tangential loads up to 53,000 g's

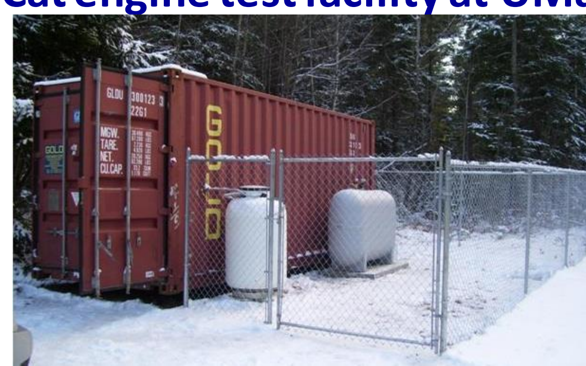
Armfield CM-4 turbine engine
at UMaine Mechanical Engineering



SAW sensors mounted on probes inserted into engine exhaust

TMC85-1 gas turbine engine
at Air National Guard, Bangor, Maine

JetCat engine test facility at UMaine



2e. Adhesion Tests on Bladed Turbine Rotor by VEXTEC (external)

Round 1: Two minute g level progression test

g Levels = 14k, 26k, 40k, and 58k

Performed at 800°F (425°C) and 1200°F (650°C)

Round 2: Operational dwell test

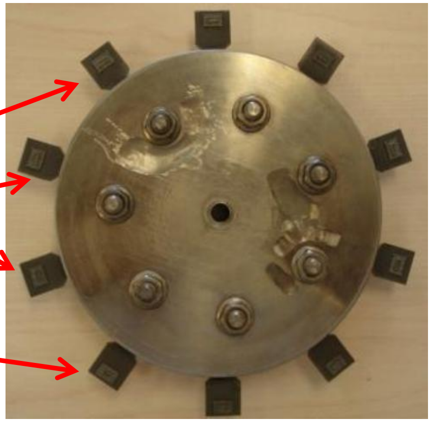
Durations = 10, 30, and 60 minutes

Operational Conditions → 1200°F at 24,300 rpm

Round 3: Snap action test

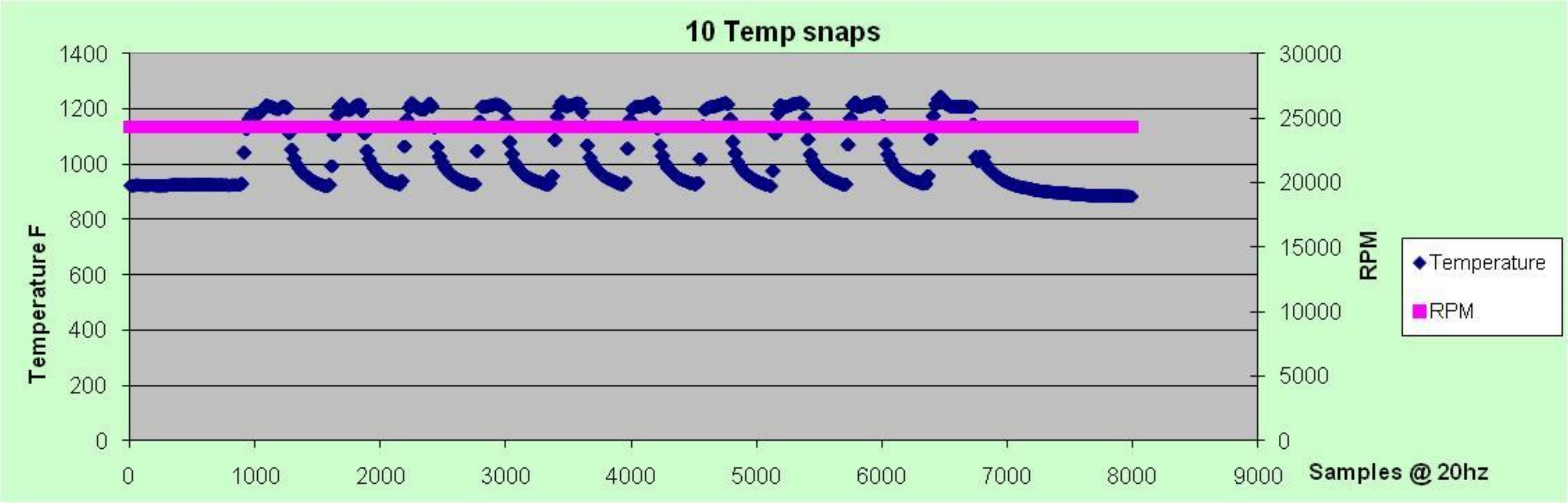
Temperature snap (10 snaps, inspect, then 16 snaps)

No Failures



VEXTEC

Integrated 4" radius bladed turbine rotor

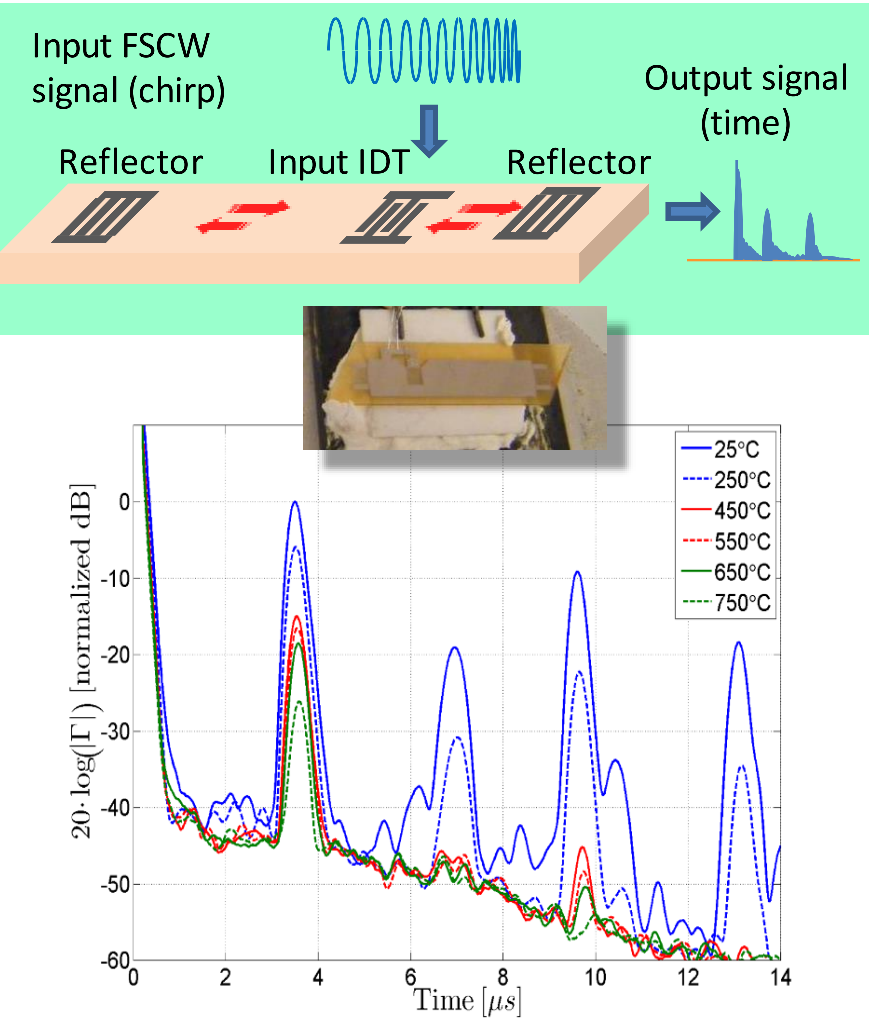


2f. Wireless Systems for Harsh Environment SAW Sensors

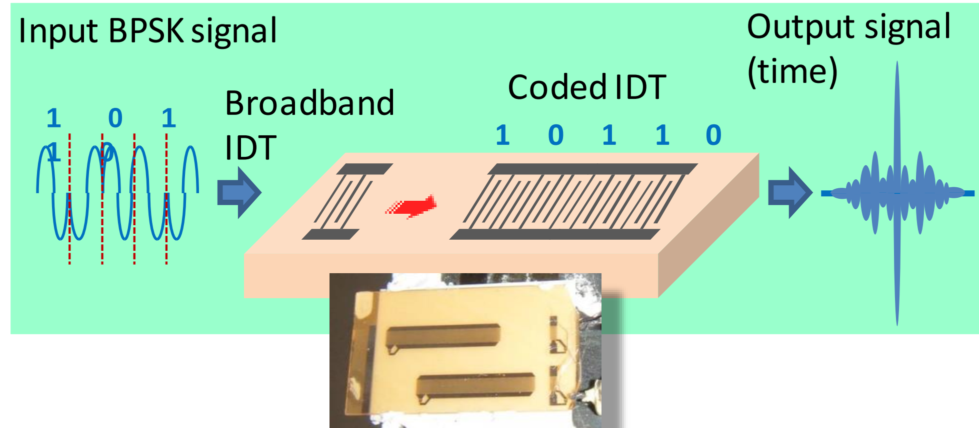
THE UNIVERSITY OF MAINE 1865

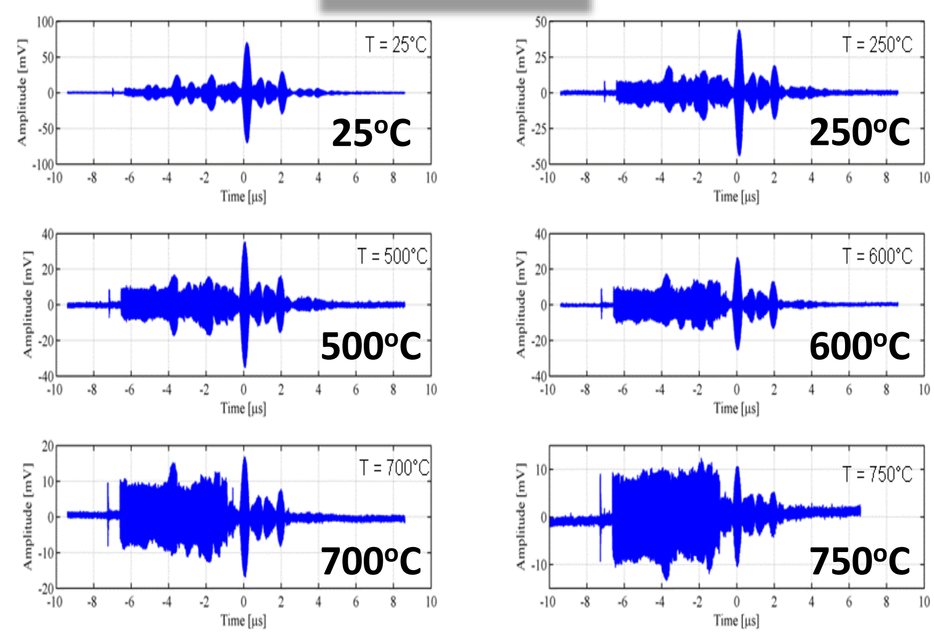
Multiple Sensor Interrogation or Multi-Sensing

1) Time Domain Frequency Scanning Continuous Wave (FSCW)



2) Code Division Multiple Access (CDMA)

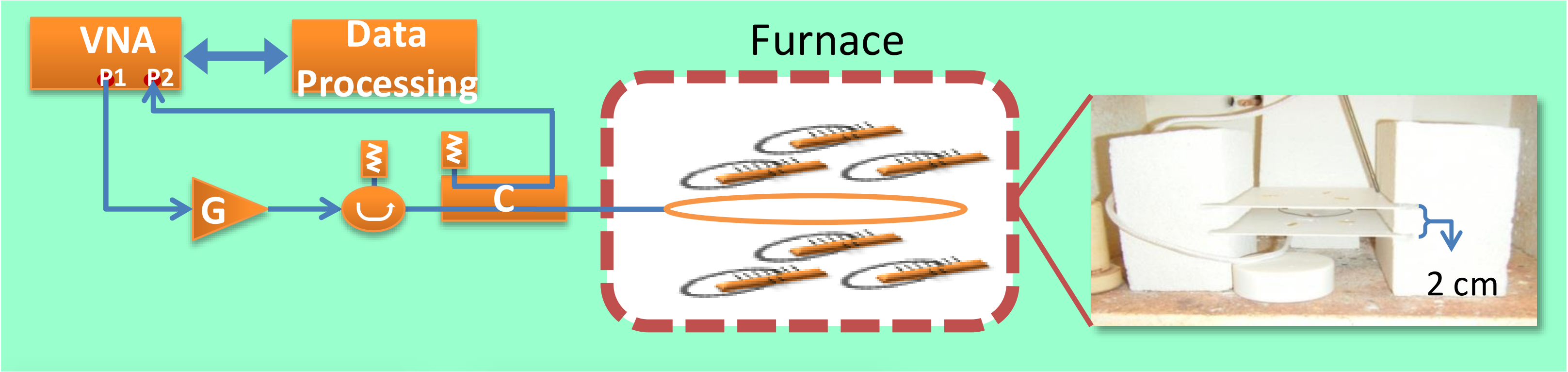


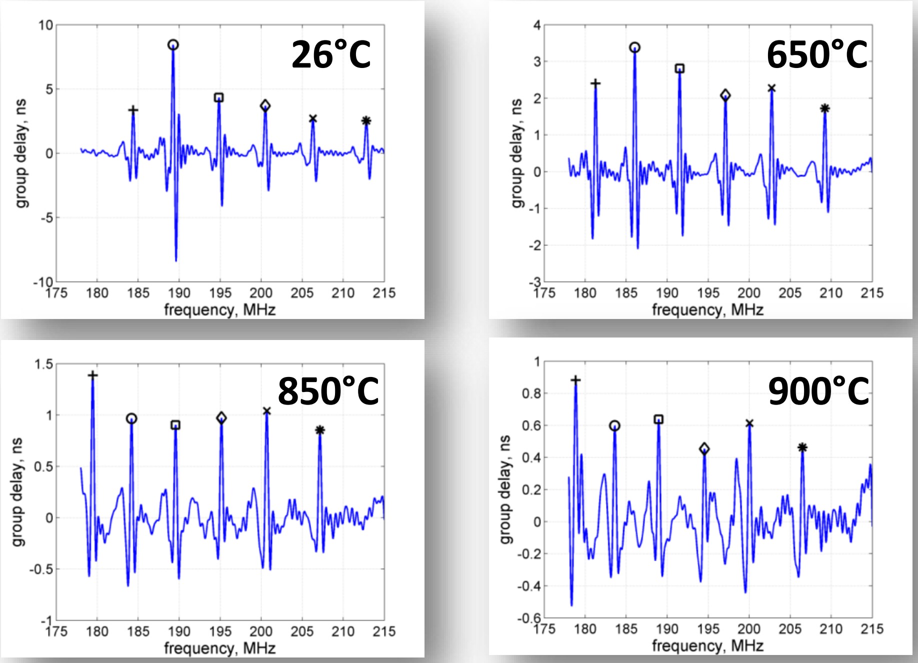


2f. Wireless Systems for Harsh Environment SAW Sensors

Multiple Sensor Interrogation or Multi-Sensing

3) Frequency Domain Multiplex (FDM)



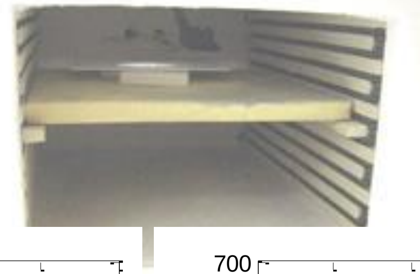


Allows sensing at different locations using a single interrogating antenna

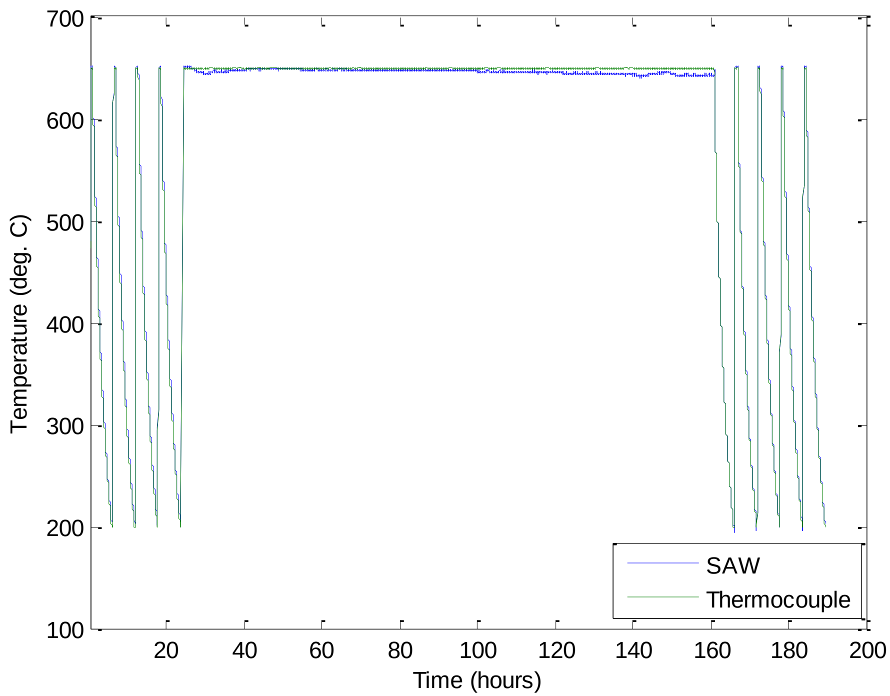
Multiple sensors with integrated antennas

Interrogation in frequency, time, or code domains

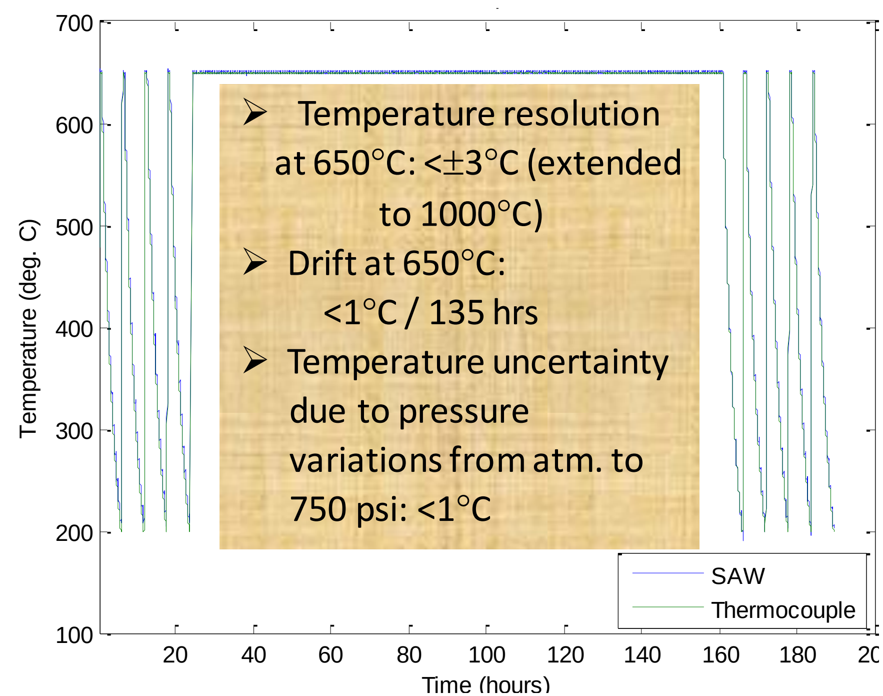
2g. Reliability, Resolution, & Accuracy of T Sensor



Temperature measured by thermocouple and Wired sensor



Temperature measured by thermocouple and Wireless sensor

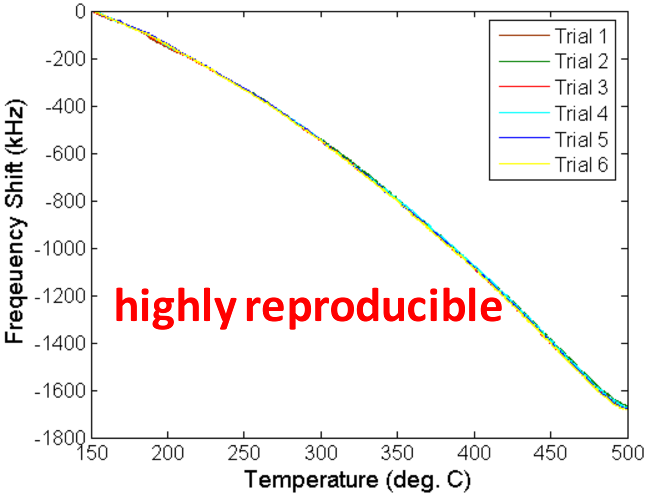


No sign of degradation or aging for Wired or Wireless Sensors

- **Wireless sensor measures true metal temperature (rotor, blade, casing, etc.)**
- **Thermocouple measures temperature in the heat path of surrounding environment**

2h. UMaine/Environetix Extensive Tests

LGS SAW temperature sensor cycling over a period of 2 weeks



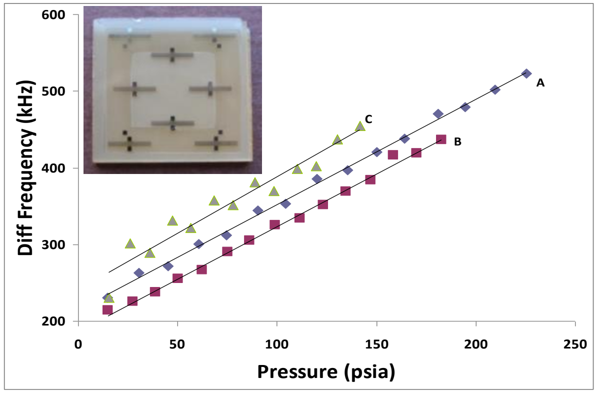
highly reproducible

Pressure Sensor: RT to 515°C / 225 psia

THE UNIVERSITY OF MAINE

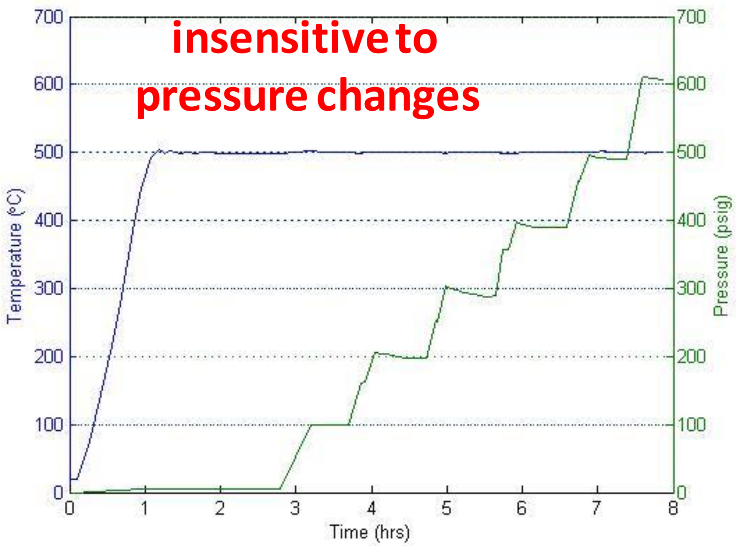
ENVIRONETIX TECHNOLOGIES CORPORATION

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



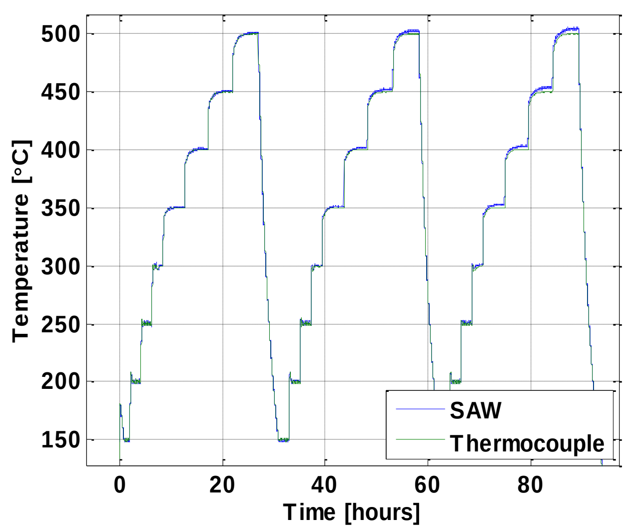
Temperature & pressure profile

insensitive to pressure changes



SAW & thermocouple temperature measured during temperature ramp cycles

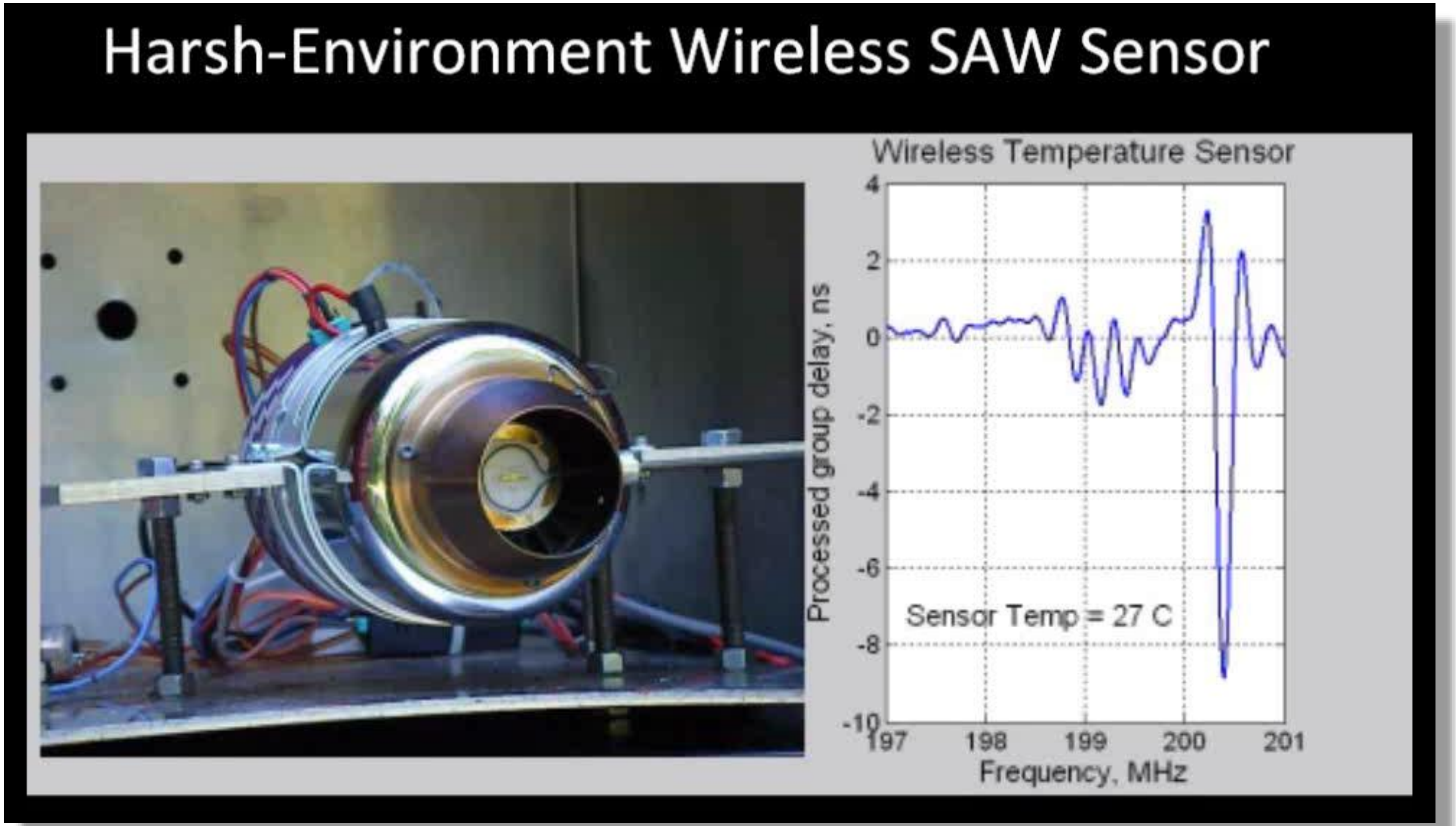
Accuracy and drift at least as good as thermocouple



HIGH T / HIGH P FURNACE
Up to 1500°C / 750 psi

2i. *In Situ* Wireless Temperature Sensor on Rotating Parts in JetCat Engine

First demonstration of a wireless SAW sensor interrogation on the integrally bladed rotor (IBR) of an operating turbine engine



3. UMaine/Environetix JetCat & Blowtorch

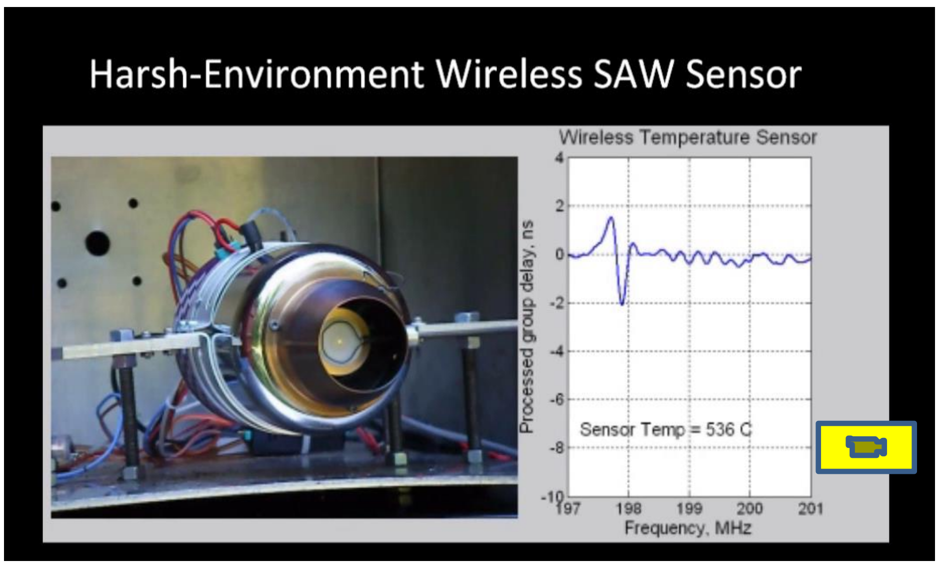
THE UNIVERSITY OF MAINE 1865

Static & Rotating Applications

ENVIRONETIX TECHNOLOGIES CORPORATION

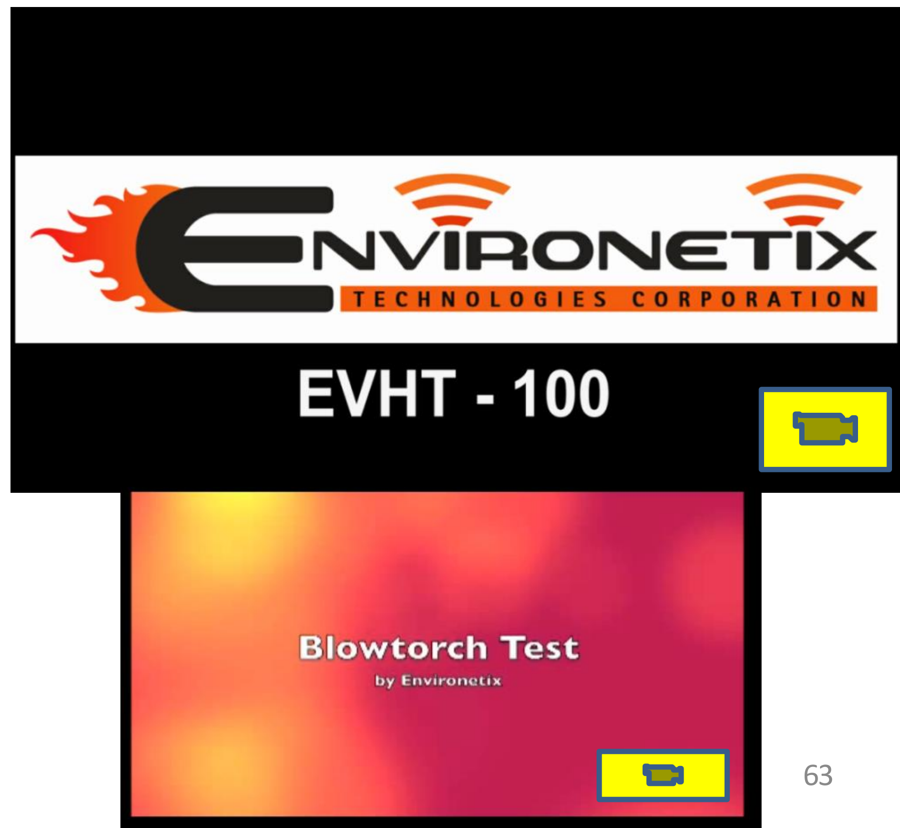
JETCAT P-70 TURBINE ENGINE TEST

Demonstration of Wireless SAW Temperature Sensor Interrogation on an Integrally Bladed Rotor (IBR)



BLOWTORCH DEMONSTRATIONS

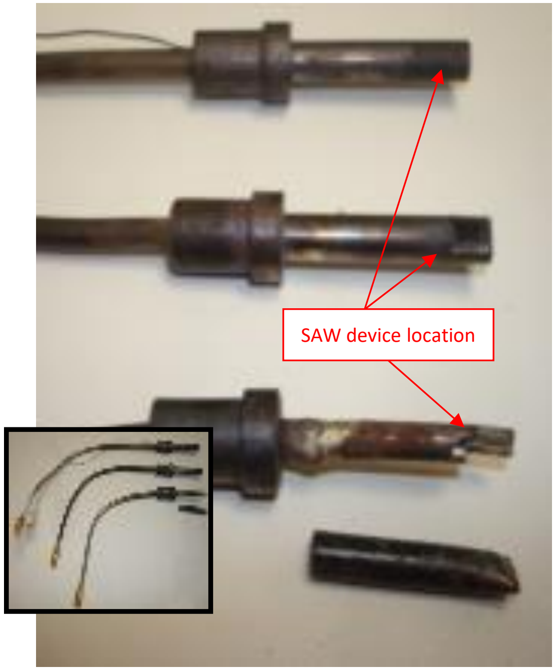
Real time temperature measurement employing a Wireless SAW Sensor under exposure to a blowtorch

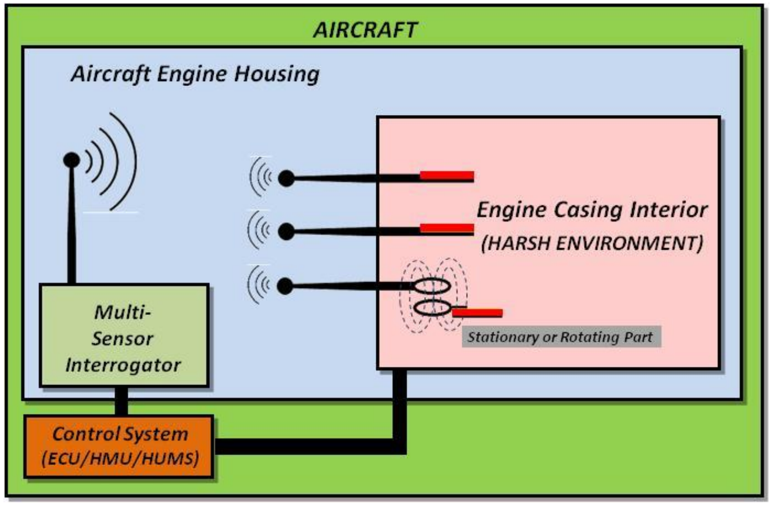


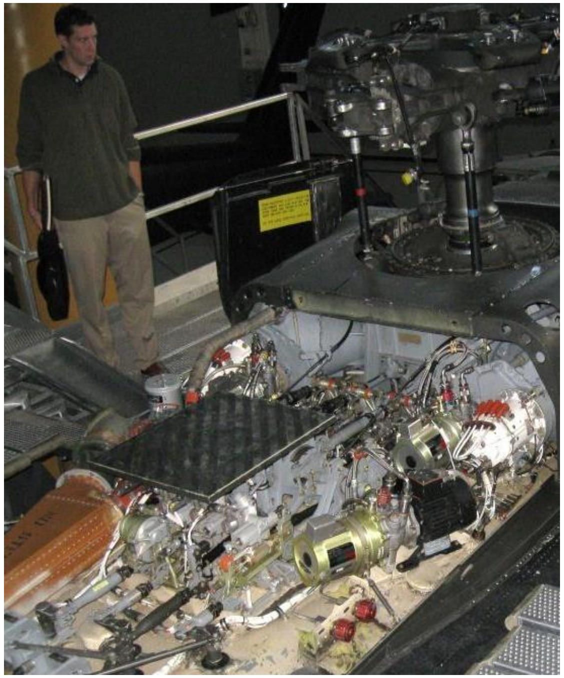
4. Tests at GE Research Center

- 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: ≤ 1°C for full range of pressure variation)





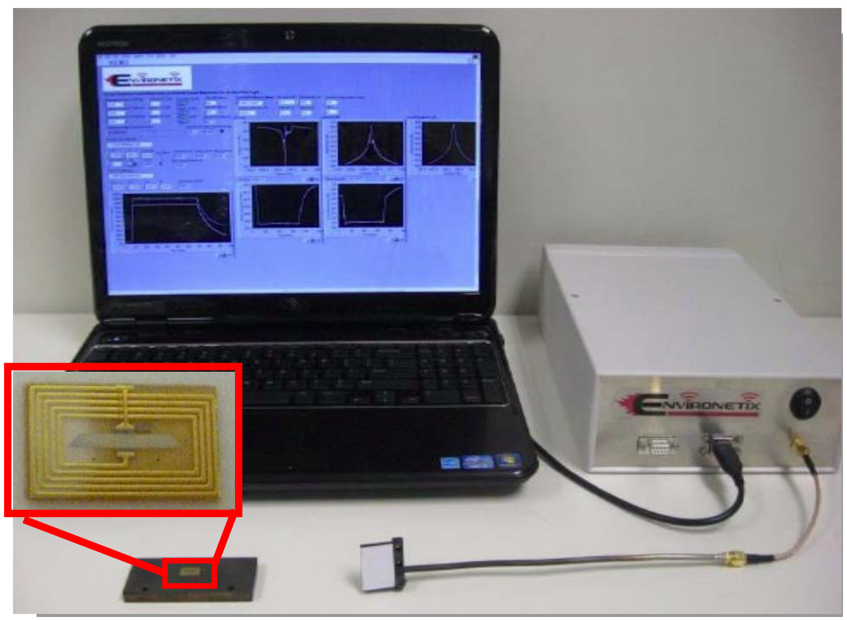


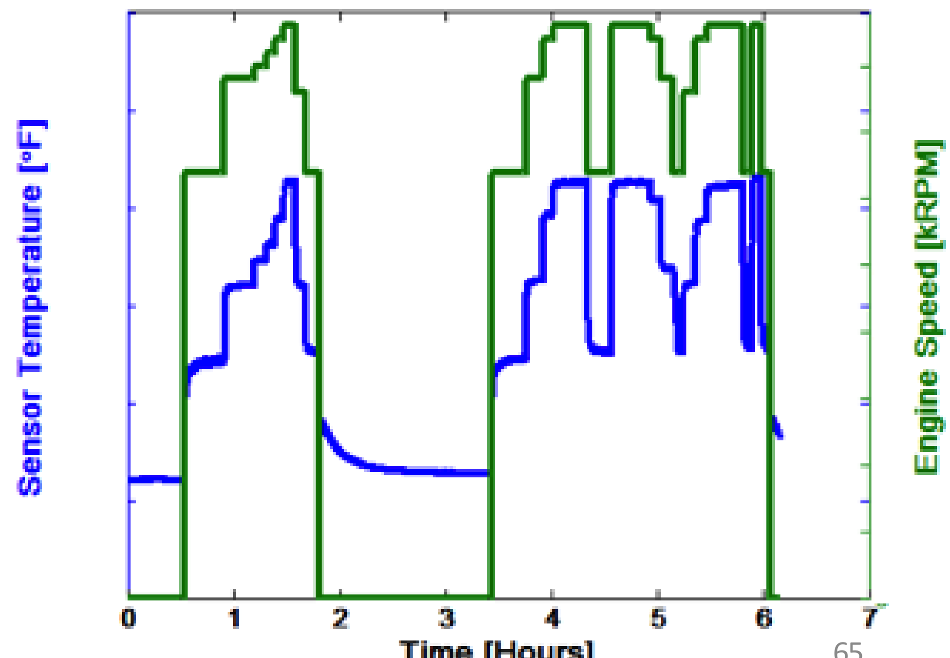
Tests at GE Research Center (cont.)

- Environetix: EVHT-100 interrogator system

Dedicated Wireless Interrogator & Data Acquisition Software

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

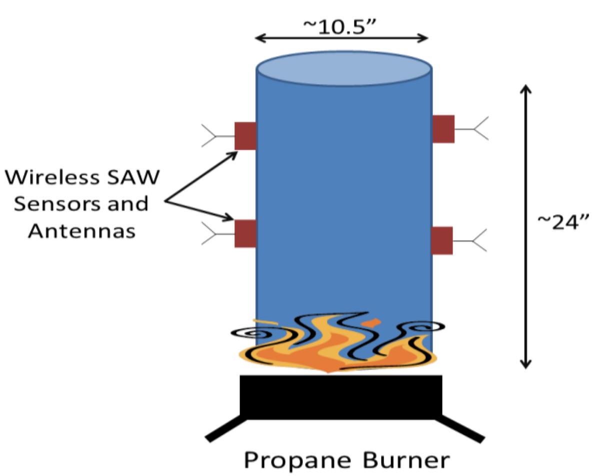




5. Prototype Pipe Structure: Industrial Settings

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

SAW sensors: interrogation up to 45 feet



6. Sensor Testing at Rolls-Royce

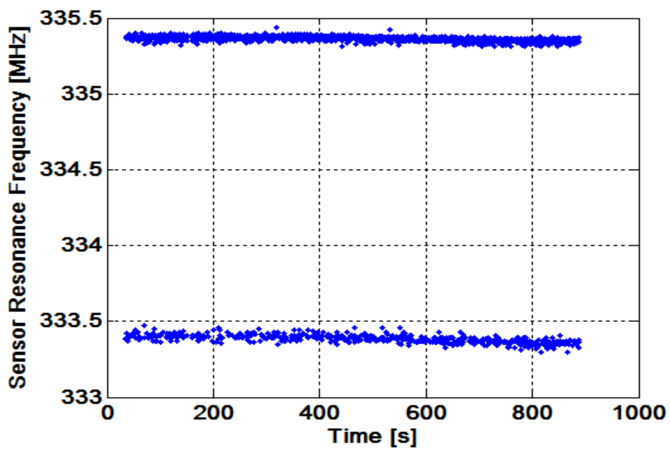
- Environetix's SBIR Air Force Research Laboratory project
- Tests performed in R&R, Derby, UK

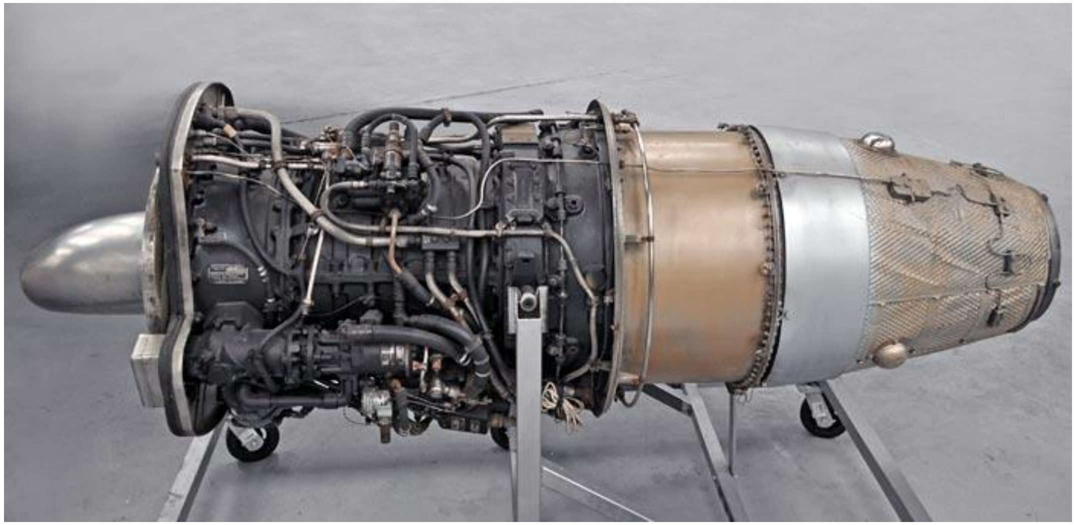
Laboratory Tests:

- ✓ SAW sensors monitored by thermocouples

Wireless test on Rolls-Royce Viper Engine

- ✓ "Cold test" → engine spun with compressed gas
- ✓ Spin rig disk tests



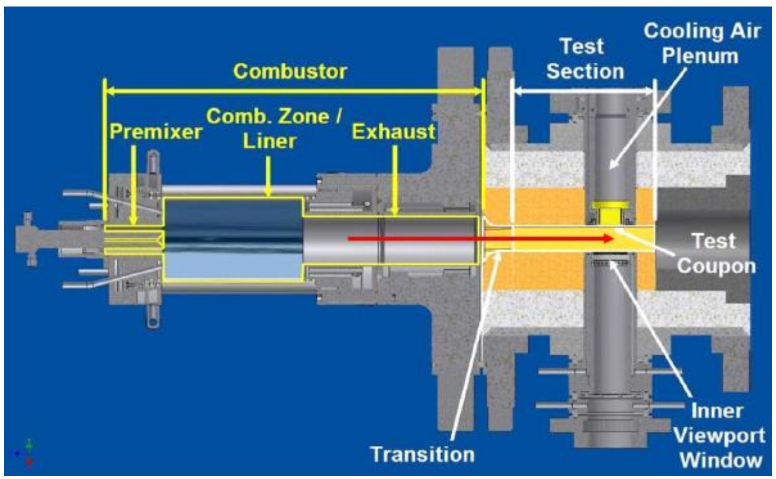


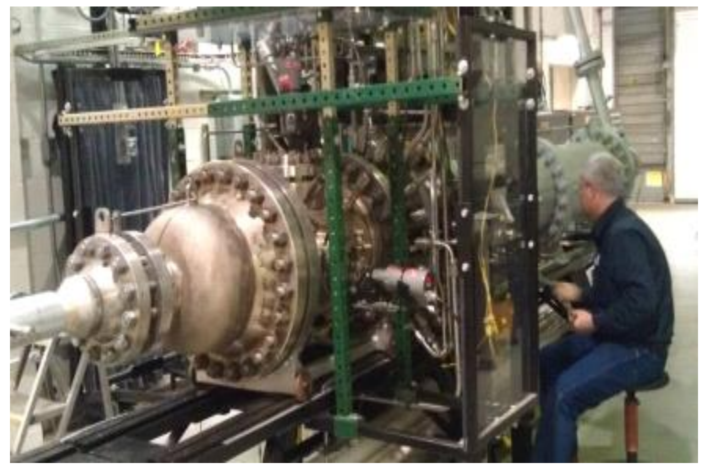
7. Tests at NETL Aerothermal Facility

Aerothermal Facility → natural gas combustor

National Energy Technology Laboratory, NETL/DOE, USA

- Gas temp. → up to 1100°C; Wall temperatures → Up to 850°C
- Pressure up to 60psi; Sudden pressure bursts (0, 30, 60 psi tested)





➢ Two test opportunities during project:

- First: tested materials & packaging for sensor and antenna in Harsh Env.
- Second tested wired & wireless sensors (compared with thermocouples)

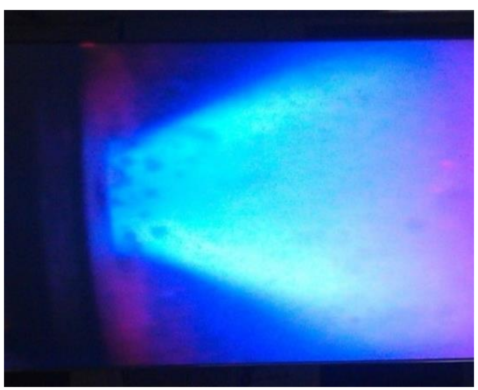
NATIONAL ENERGY TECHNOLOGY LABORATORY

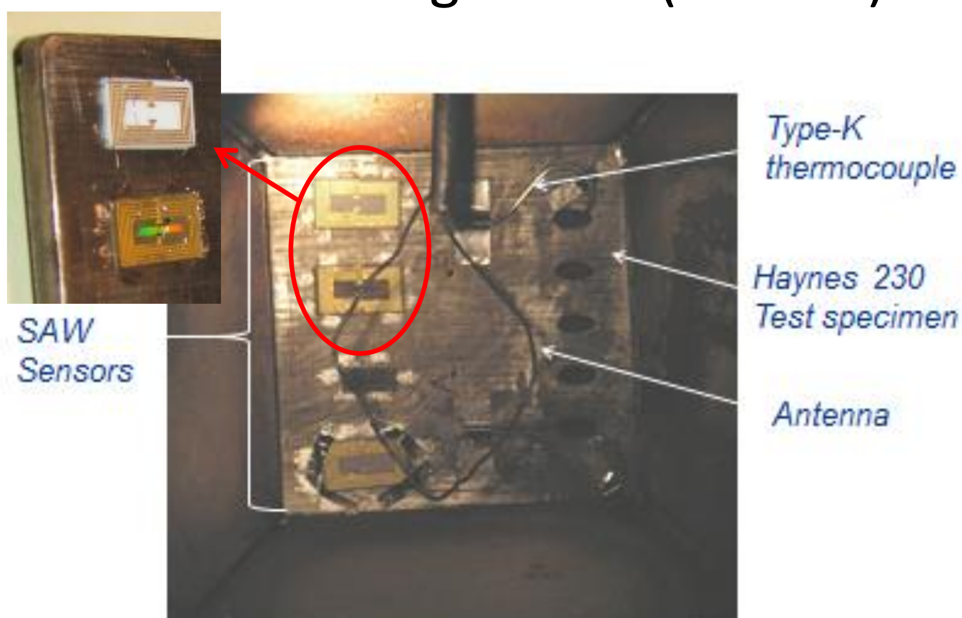
1865 THE UNIVERSITY OF MAINE

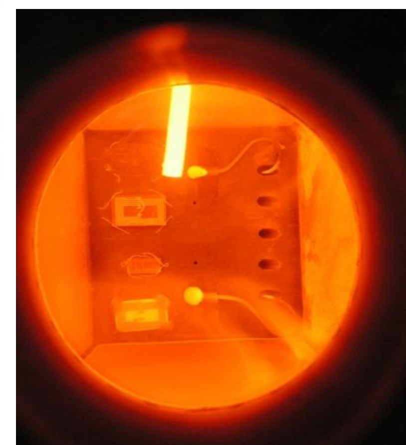
ENVIRONETIX TECHNOLOGIES CORPORATION

Tests at NETL Aerothermal Facility

- **First Test:** Materials Test →
  - LGS substrate with SAW resonators,
  - Gold plated antennas on LGS and on alumina,
  - Inconel loop antenna
  - Coupon mounted in the chamber wall (~800°C); integrated antenna in the gas flow (1100°C)







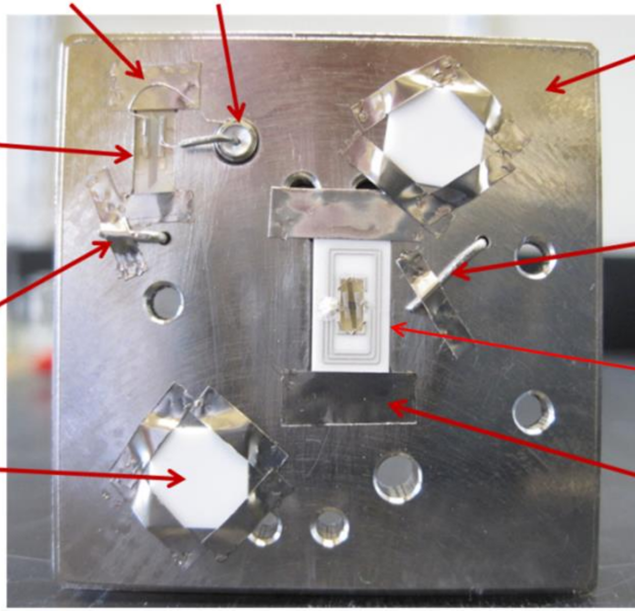
NATIONAL ENERGY TECHNOLOGY LABORATORY

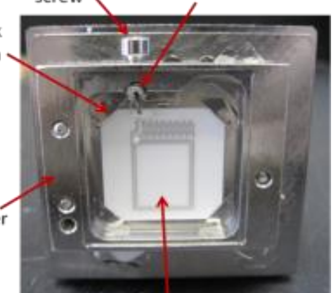
1865 THE UNIVERSITY OF MAINE

ENVIRONETIX TECHNOLOGIES CORPORATION

Tests at NETL Aerothermal Facility

- **Second Test:** Wireless and Wired Sensors Test / HE antenna test
- Coupon installed directly in the gas flow / antenna (1100°C)
- Eight sensors: in 2 coupons & exposed to environment





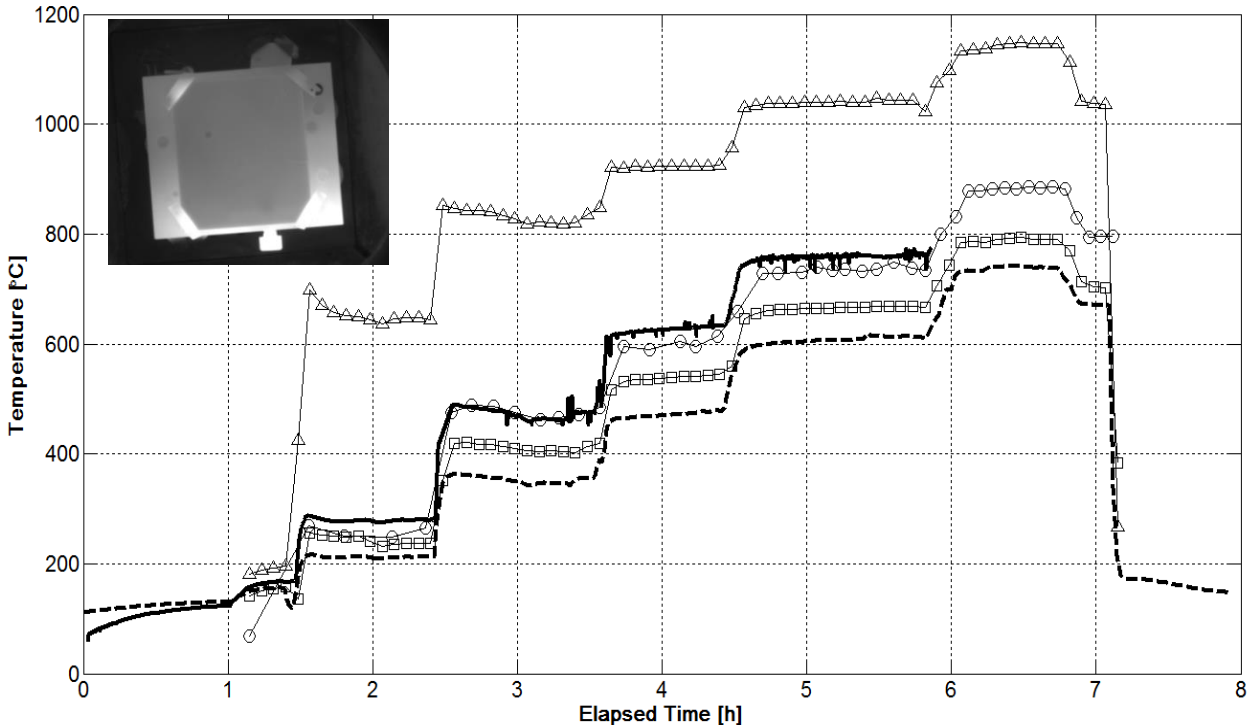
NATIONAL ENERGY TECHNOLOGY LABORATORY
1865 THE UNIVERSITY OF MAINE
ENVIRONETIX TECHNOLOGIES CORPORATION

Tests at NETL Aerothermal Facility

- **Second Test:** Wireless & Wired Sensors Test. **Objectives:**

1) Verify high-temperature wireless and wired sensor operation in the test rig;
2) Compare sensor responses with and without a protective Al_2O_3 capping layer;
3) Compare SAW temperature sensor measurements to witness thermocouples.

- **Two days tests (7 hours each day): Sensors & Packaging responded as expected to the variations in Temp. & Pressure**

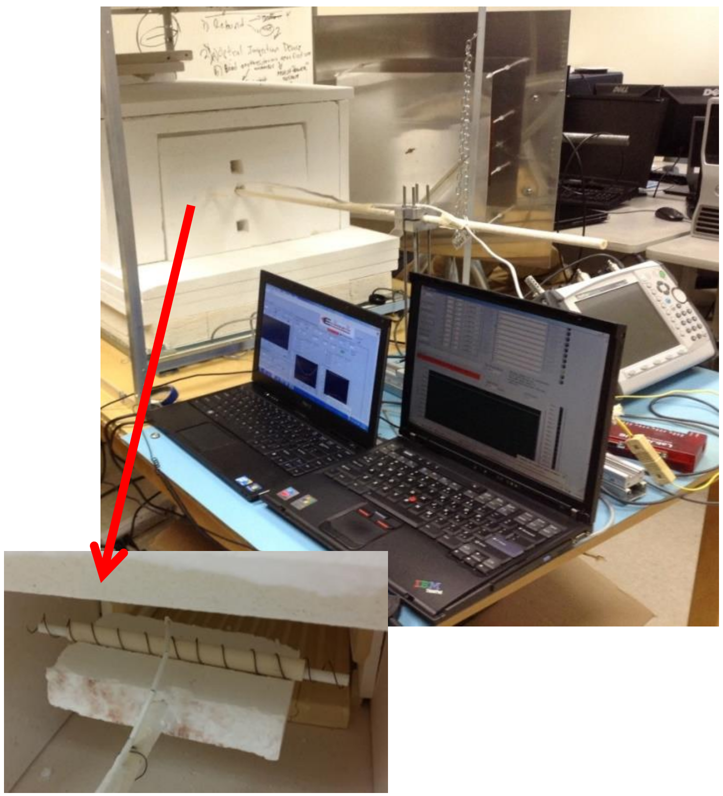


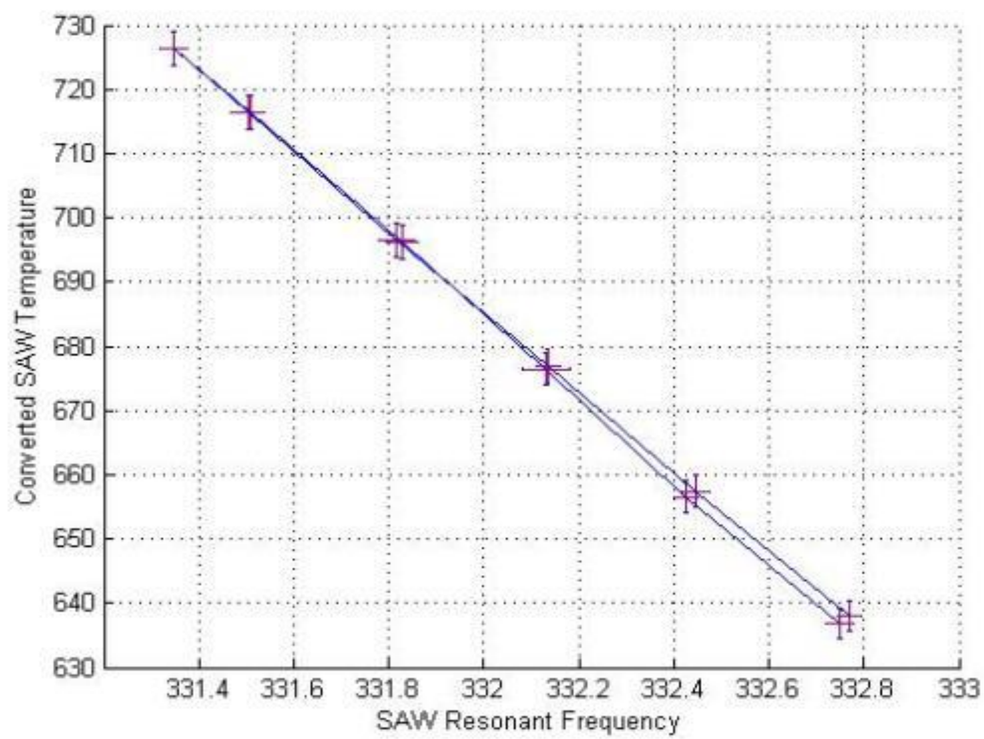
- Δ : gas thermocouple;
- Solid line: wireless SAW sensor;
- dashed line: wired 3.5µm SAW sensor;
- ○ : thermocouple near wireless SAW sensor;
- □ : Thermocouple near wired 3.5µm SAW sensor.

8. Wireless Position Furnace

Custom made furnace: Temperature variation (position)

- ➢ LGS SAW wireless interrogation
- ➢ Sensor calibrated by thermocouple response





Wireless Position Furnace

- Wireless interrogation: tracking temp. in the position furnace
- Temp. span of 25°C @ 700°C (fluctuation furnace control: ~1°C)
- Test repeated several times: repetitive