2015 Crosscutting Research Review Meeting

Harsh Environment SAW Wireless Sensor Array for Power Plant Applications

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2. HT Electrode Materials for Operation up to 1100°C
3. Investigation of Sensor Stability: Multiple Cycling 350°C to 1000°C
4. Power Plant (PERC) Wireless Sensor Array Tests

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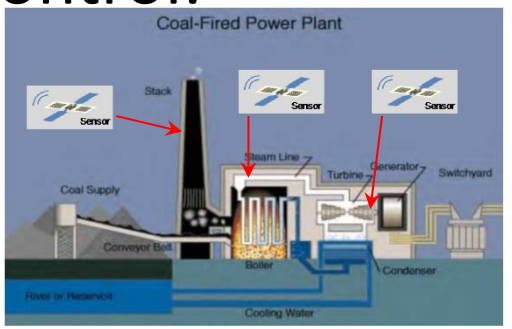
I. INTRODUCTION

Review of Project Concerns & Scope

- Power plant need to better monitor & control:
  - ✓ Fuel burning **efficiency**
  - ✓ Process dynamics & gases concentration
  - ✓ Health of the power plant structures

AVAILABILITY ↑ NO OUTAGES



- Dependable HARSH ENVIRONMENT **sensors** needed: temperature/pressure/vibration/stress/torque/gas
- Wireless → a MUST → High temperatures; movable parts; easier installation; improved reliability
- Battery-free → another MUST → Temperature; Harsh Environment; Maintenance-free; ↓ complexity / ↑ reliability; ↓ Weight

Review of Project Concerns & Scope

- Surface Acoustic Wave (SAW) HE Technology capable of:
  - ✓ Operation in High Temperature & Harsh Environments
  - ✓ Wireless operation
  - ✓ Battery-free, passive radar interrogation
  - ✓ ID tag function by addressing multiple sensors (frequency, time, or code separation)
  - ✓ Capable of delivering multi-measurand functions: temperature/pressure/vibration/stress/torque/gas
  - ✓ Operation on static & rotating part EVEN TURBINE ENGINES

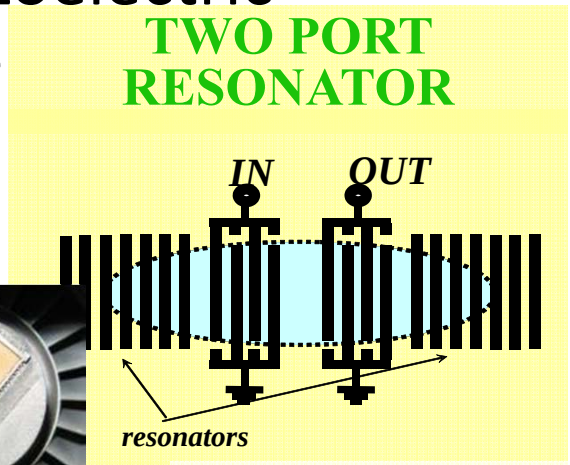
- Project goal: R&D and technology transition of a

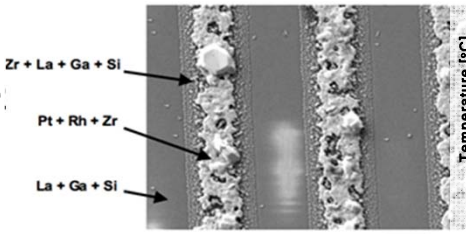
WIRELESS SAW SENSOR ARRAY FOR POWER PLANTHARSH ENVIRONMENT OPERATION

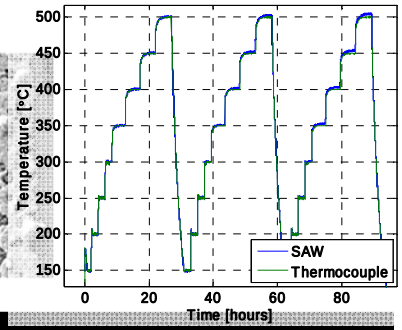
II. BACKGROUND

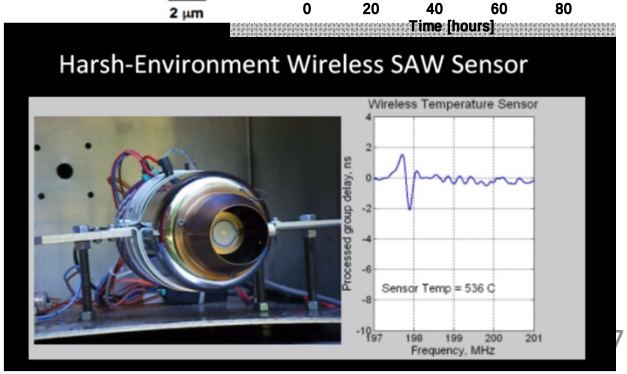
Prior Achievement & Impact

- SAW HE Technology: LGS crystal → Piezoelectric
  - ✓ Interdigital transducer couples electric to mech. wave
  - ✓ Responds to temp., surface pert., gas, vibr., pressure
  - ✓ Material operates up to 1470°C
  - ✓ Takes shock in temperature
  - ✓ Low profile package possible
- Electrode stability at HT: essential
- Reported last year:
  - ✓ Interfacial Layer at High Temperature
  - ✓ Capping Layer at High Temperatures
  - ✓ Capacitive Coupling
  - ✓ HT Devices & Wireless Temp Profile Furnace
  - ✓ Multiples Tests in Turbine Engines & Power Plant Environments



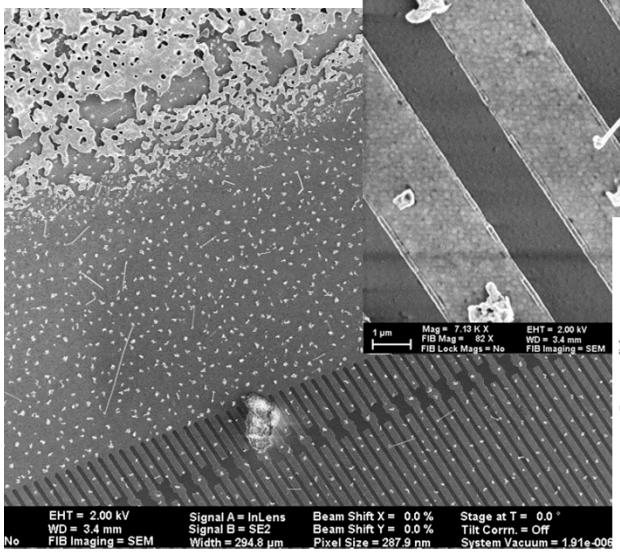


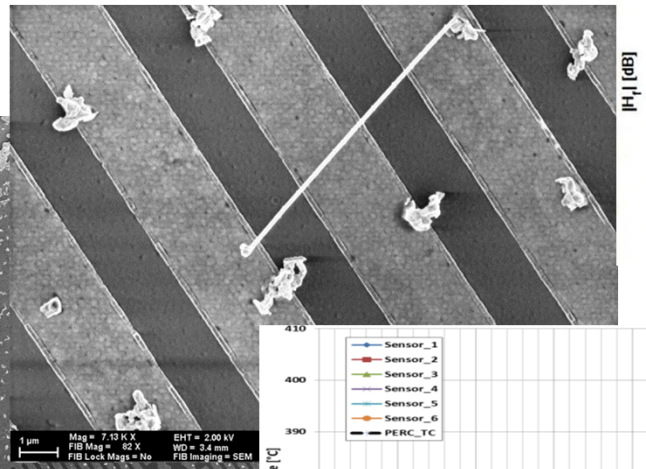


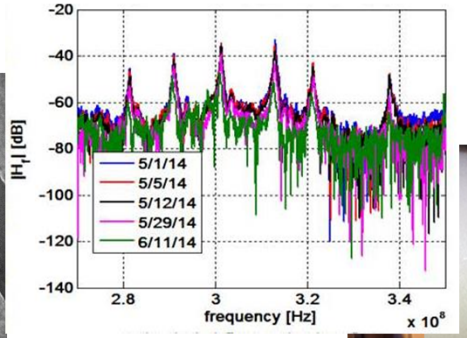


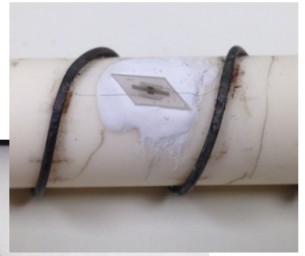
Key Contributions Discussed Next

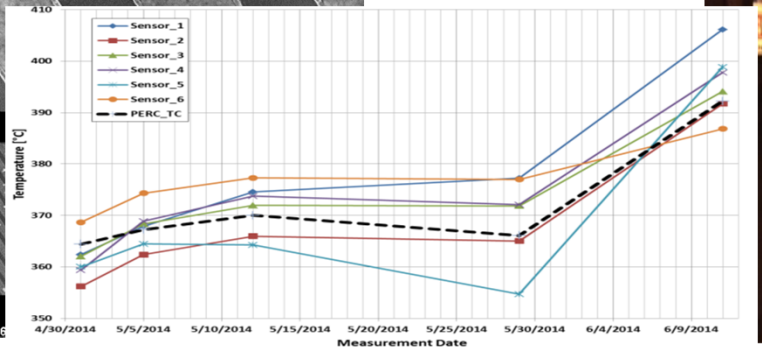
- New thin film structure findings & new electrode materials: operation up to 1100°C
- Sensor stability under cycling tests: sensor stability around ± 3°C after annealing phase (over 160h @ 1000°C in over 330h cycling test)
- Power plant measurements; Packaging & antenna material revisited & improved

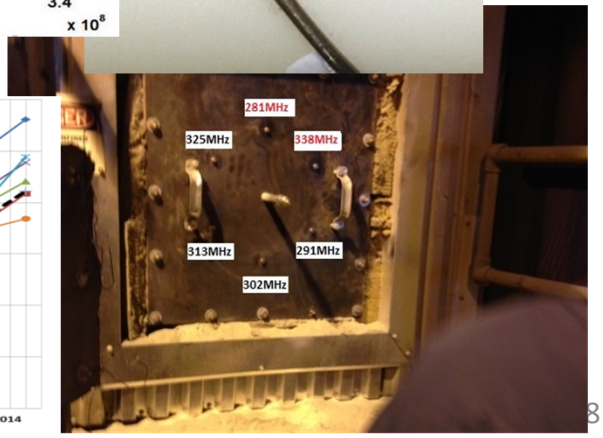








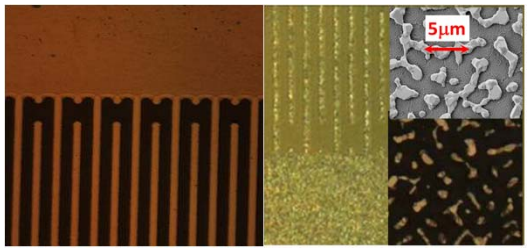




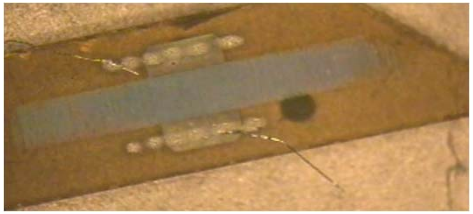
III. Transitioning Research Findings into HE Power Plant Environment Applications

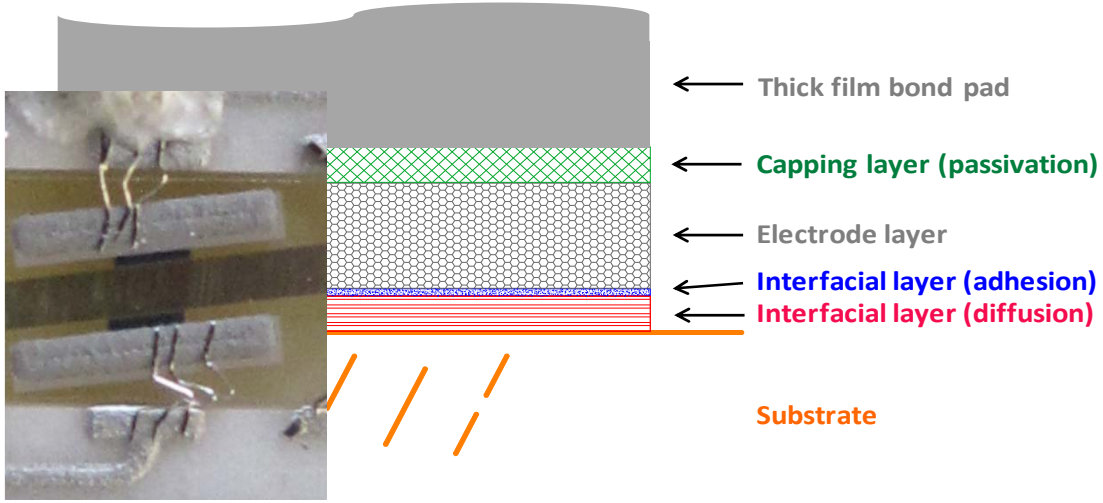
1. HT Thin film Structures for Stable Sensor Operation Beyond 1000°C

- UMaine/Environetix has been exploring several techniques (discussed last year):



- ✓ Interfacial layer
- ✓ Capping layers
  - Al_2O_3 ALD (atomic layer deposited) & sputtered
  - SiAlON;
- ✓ Capacitive coupling
- ✓ Thick Paste contact





Sensor Stability @ HT under Cycling

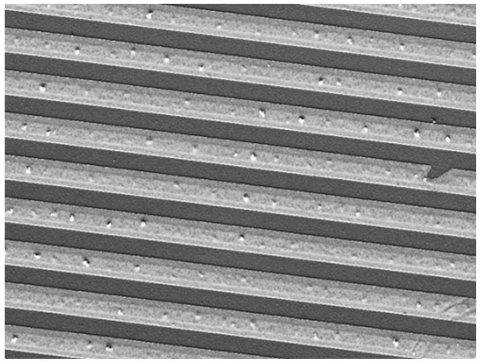
- Recent findings on LGS SAW resonators

2µm & 3.5µm wide, 190nm thick PtRh/HfO_2 electrodes

50 nm Al_2O_3 capping layer

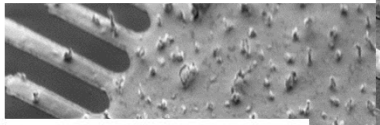
- Formation grains on the electrodes under T **cycling**

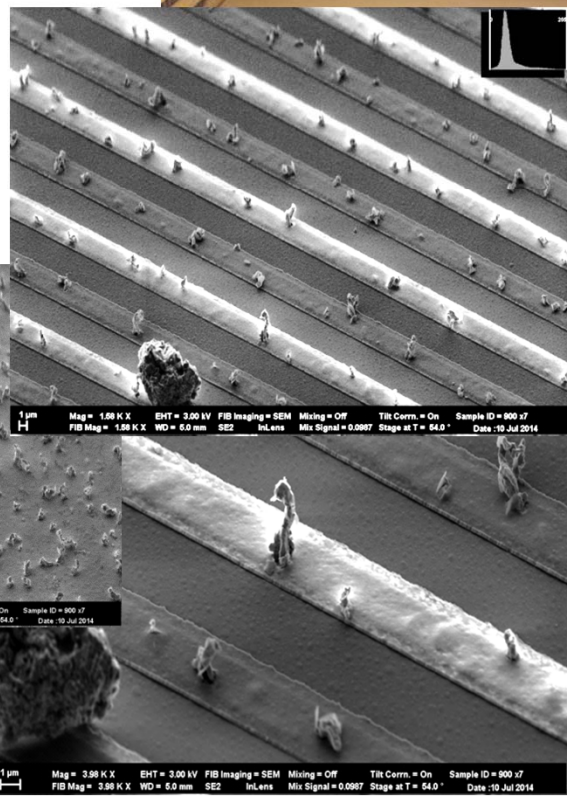
Related to types of film & film stresses → Affect dev. oper.

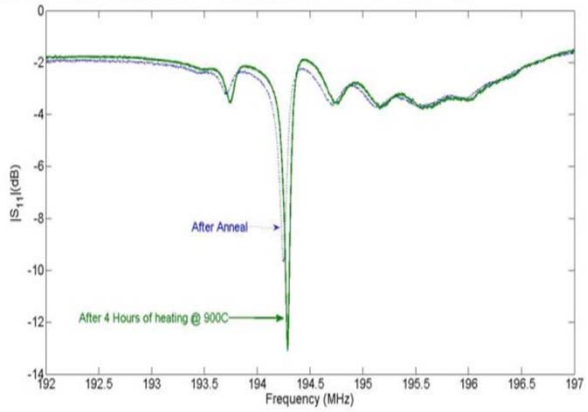


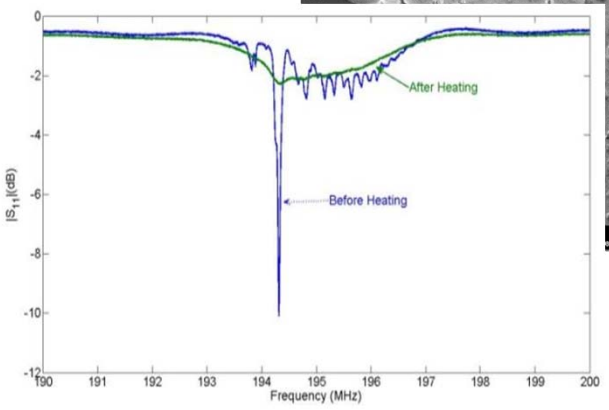
Device @ 900°C / 4h soaking

Devices CYCLED 7 x to 900°C



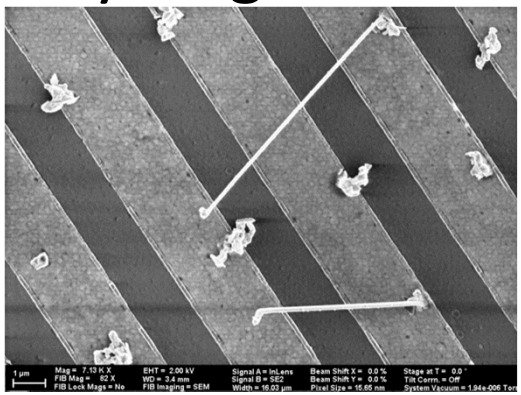




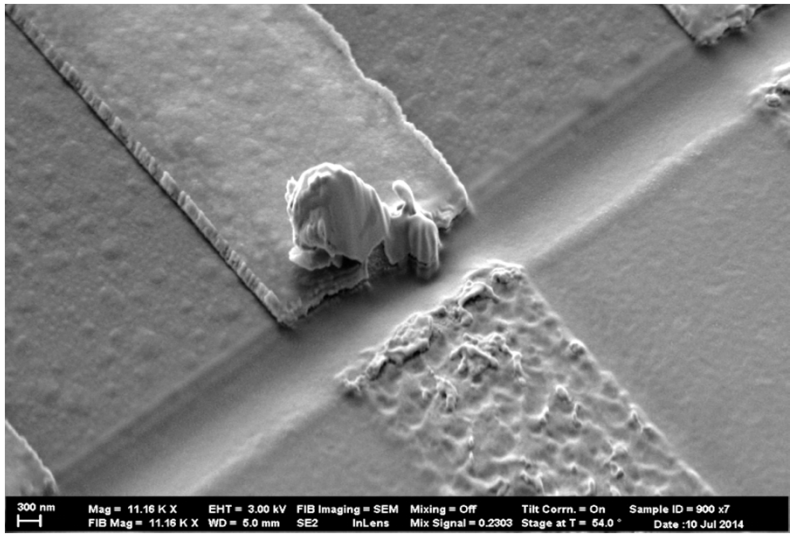


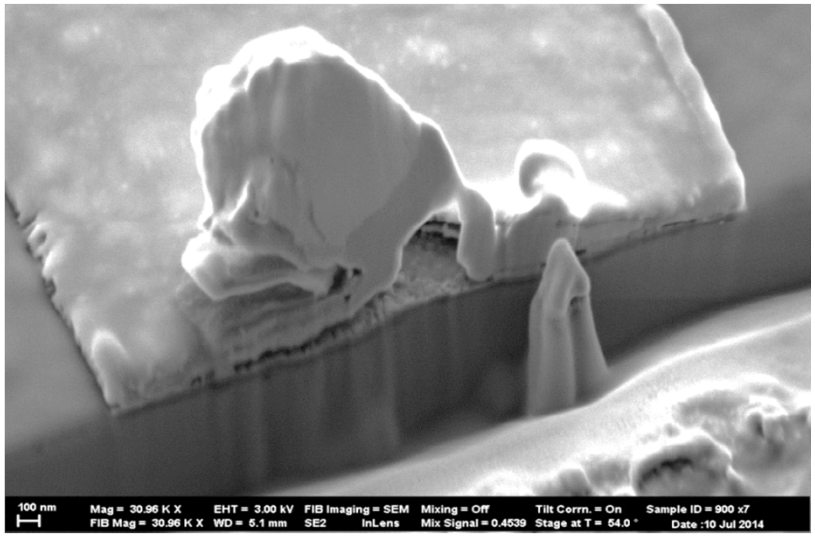
Sensor Stability @ HT under Cycling

- Grain formation on the electrodes under T cycling
  - ✓ Capping layer essential to mitigate effect
  - ✓ Related to types of film & film stresses
  - ✓ Delamination → compromise the electrode performance:
    - ☞ As transducer
    - ☞ As reflector



Devices cycled 7 x to 900°C

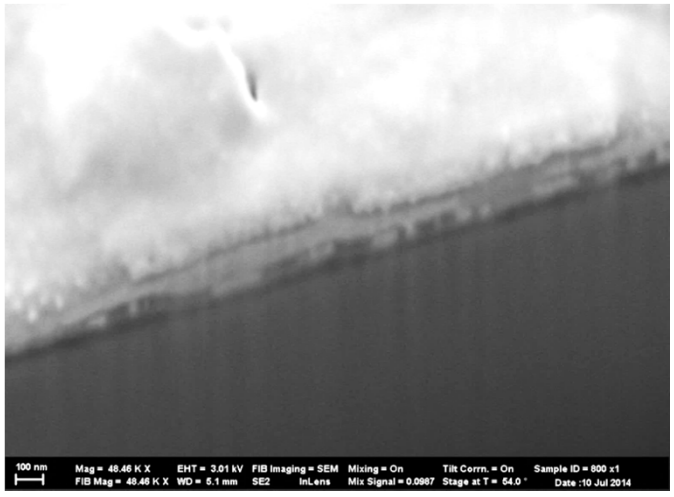




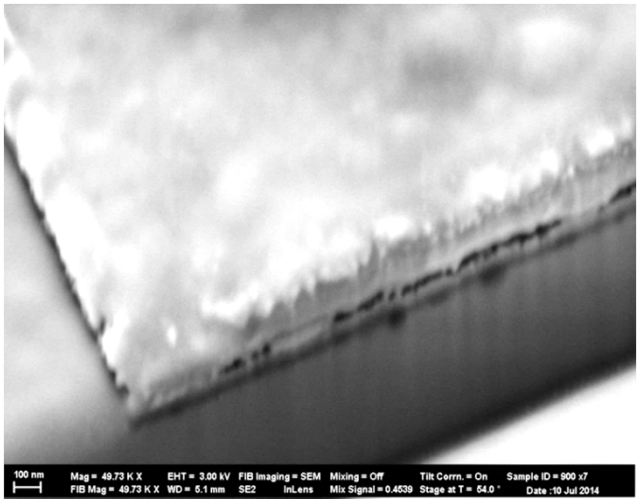
Interfacial Layer

- The delamination under CYCLING → takes place between the interfacial layer and the LGS
  - ✓ Interfacial layer → Important in extending Max T
  - ✓ Evidence that
    - Under cycling & for the PtRh/HfO_2 on ALD interfacial
    - Compromise device performance due to delamination

Device @ 900°C / 4h soaking



Devices CYCLED 7 x to 900°C



2. HT Electrode Materials for Operation up to 1100°C

- Continuous investigation for electrode improvement → Operation at and beyond 1000°C
- Power plant environment:

  Combustion gases →

Stable thin film electrode for long-term operation & cycles

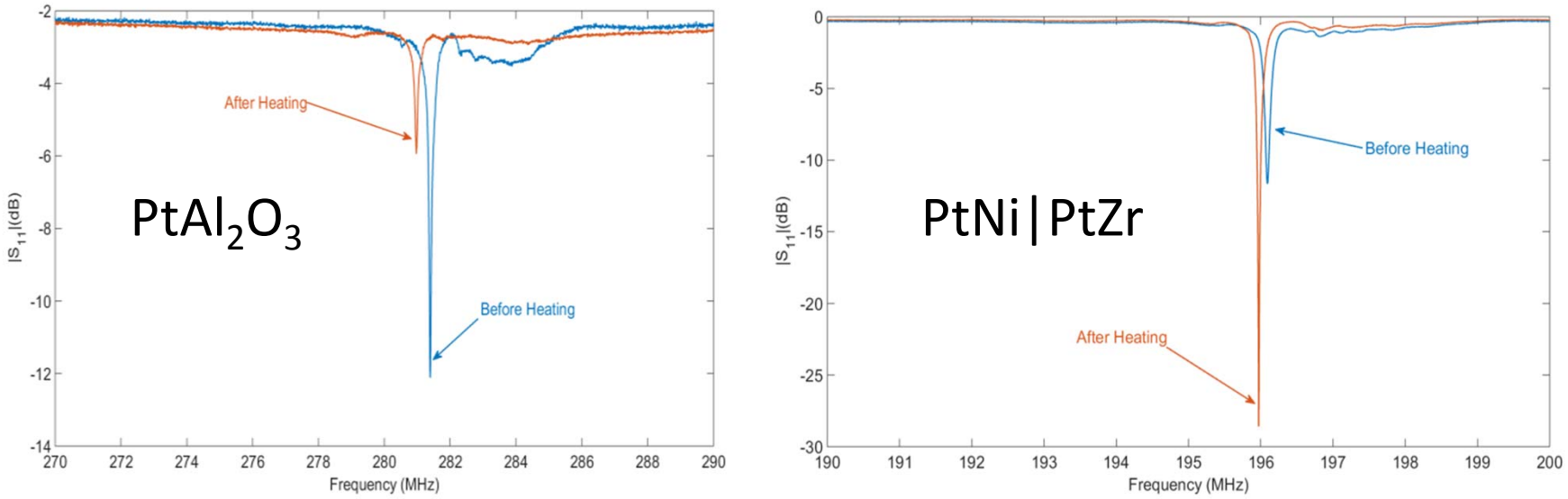
- UMaine/Environetix explored several films:

  $PtRh/ZrO_2$, PtCo, PtRh/CoO, PtNi, PtRhNiO, PtCr, PtAl, $Pt\text{-}Al/Pt/ZrO_2$, PtAl/Pt/Nb, $Pt\text{-}Al/Pt/Cr$, $PtAl/Pt/ZrO_2$, Pt/Al_2O_3, $PtRh/HfO_2$

- Currently most promising films → $PtRh/ZrO_2$, $PtRh/HfO_2$, Pt/Al_2O_3 and PtNi|PtZr.

Film Development

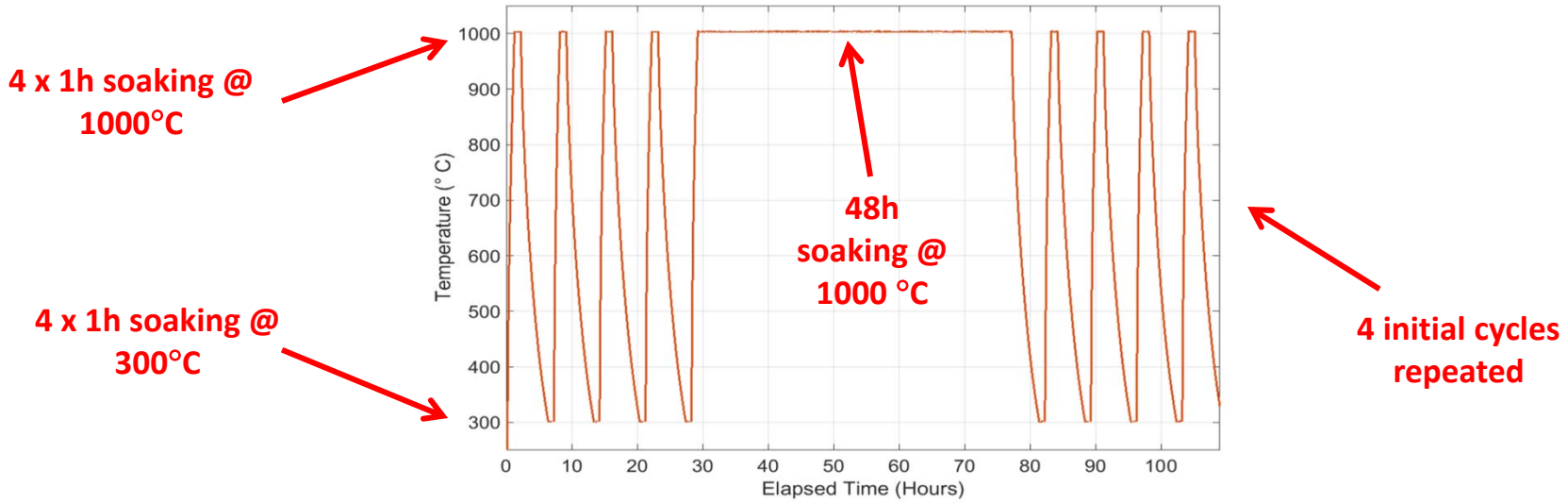
- Operation for 4 hours at 1100°C



- Operation beyond 12h achieved with PtNi|PtZr for 3.5μm wide / 196 MHz SAW devices

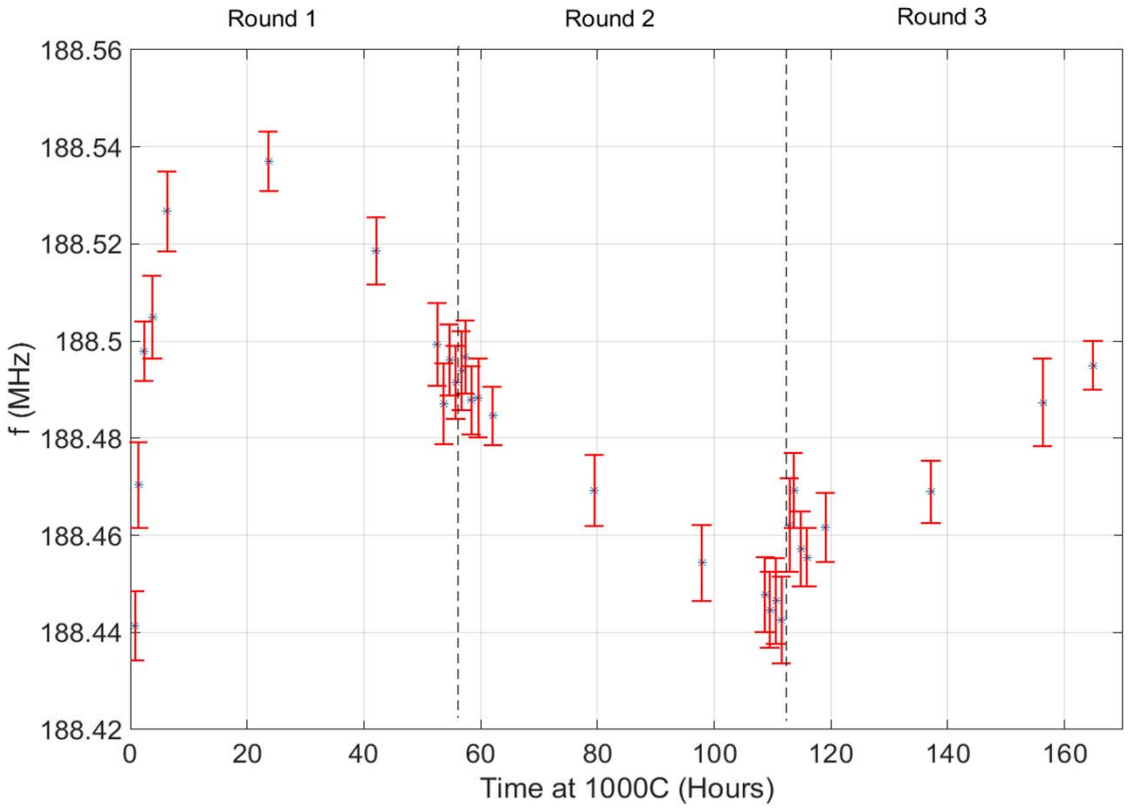
3. Investigation of Sensor Stability under Multiple Cycling up to 1000°C

- Operation @ High Temperature:
  - ✓ Operate up and beyond 1000°C for a targeted period of time
  - ✓ Survive the harsh-environment condition
  - ✓ Provide STABLE OPERATION → with time and under cycling
- New devices → exposed to Temperature Profile



Multiple Cycling to 1000°C

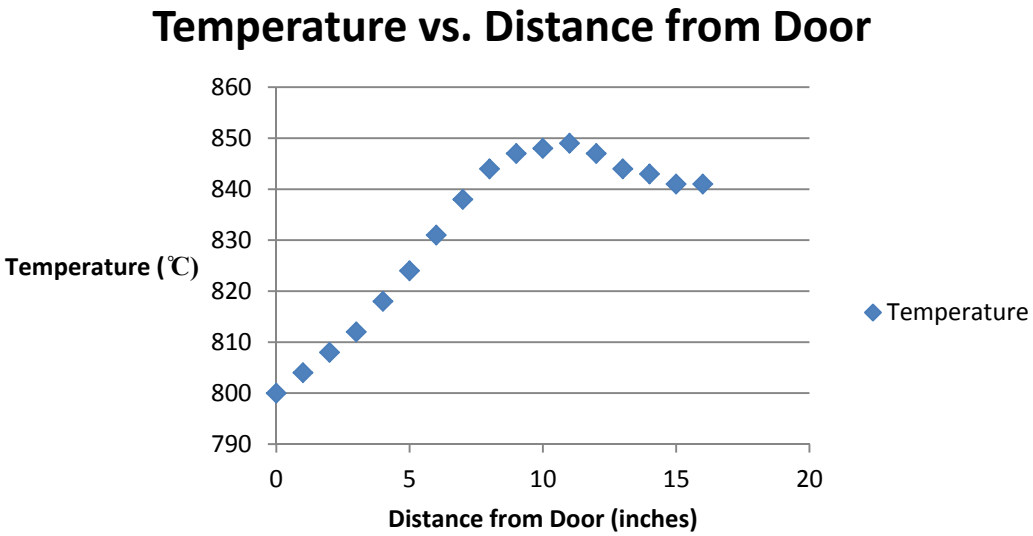
- Cycle shown in the previous slide was repeated 3 times
- Plot below → total time / cycle @ 1000°C
- Neglecting first 40h (annealing)→ 60KHz fluctuation → ± 3°C



4. Wireless Position Furnace

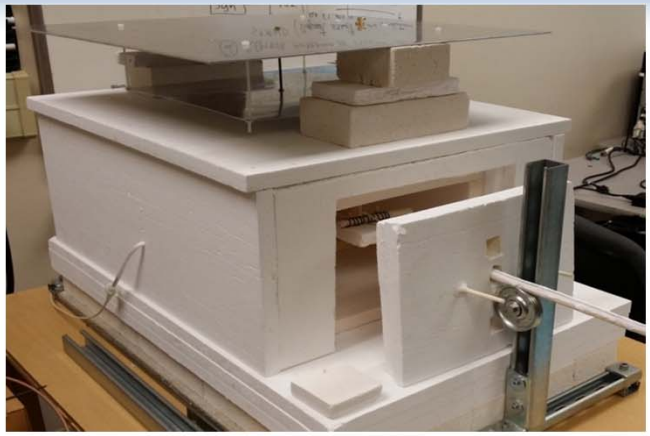
- Wireless Passive Sensor Interrogation on Movable sliding part
- Furnace designed at UMaine:

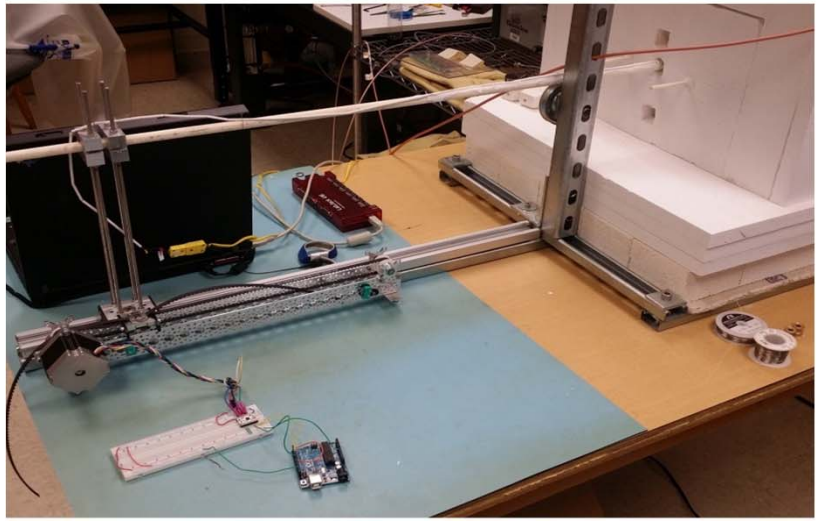
  Temperature Profile
- Moving rod: position @ ≠ Temps.

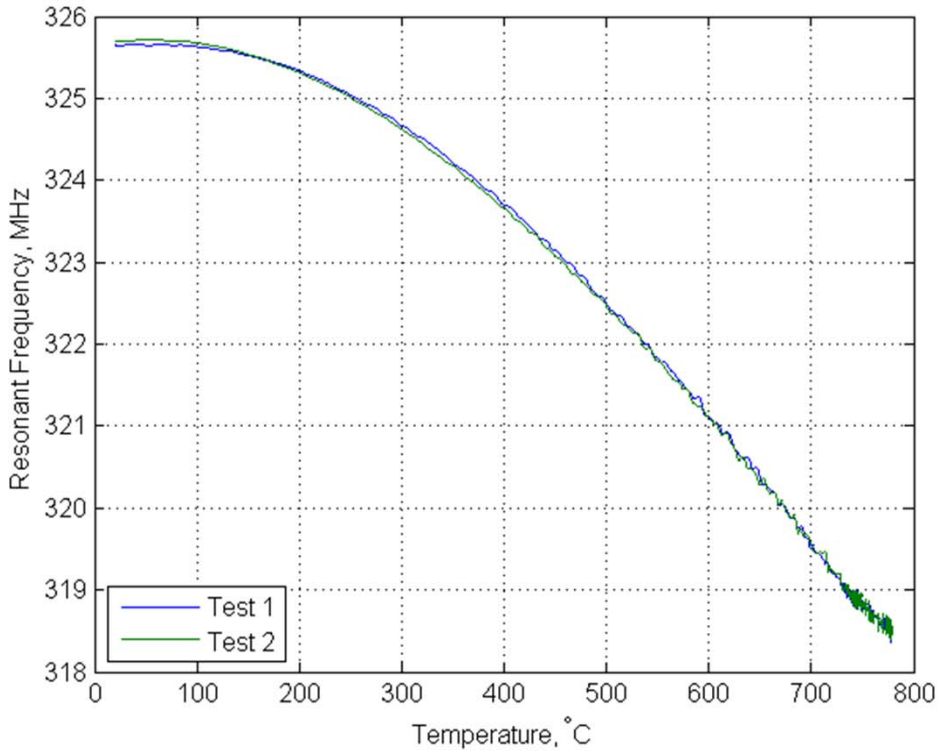


Position Furnace

- Automated / temp. profile /
- Wireless sensor charac. x time







5. Power Plant Tests: PERC

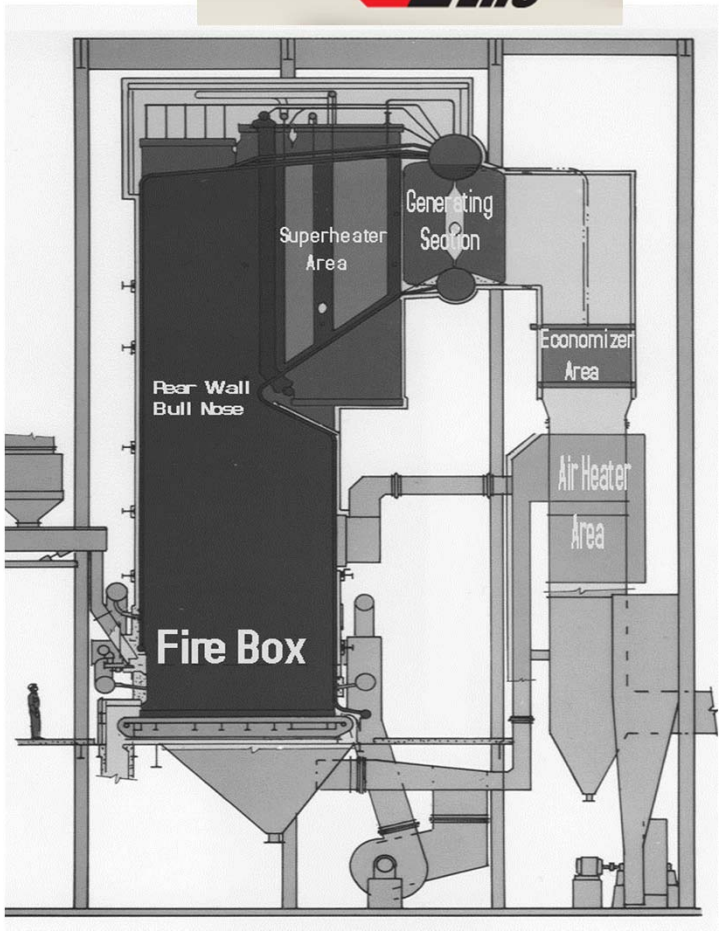
- Penobscot Energy Recovery Company (PERC)
  (Orrington,ME)

Municipal Solid Waste (MSW) Power Plant

Garbage is burnt to release energy

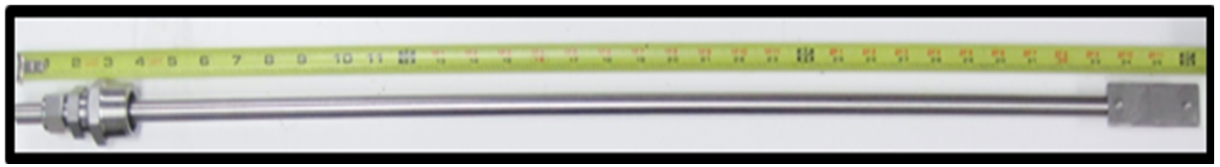
- Environetix, UMaine, &PERC teamed up

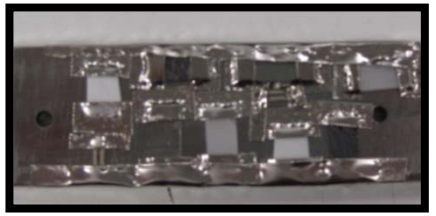
Goal: Implement a Wireless Temperature Monitoring System at the MSW power plant



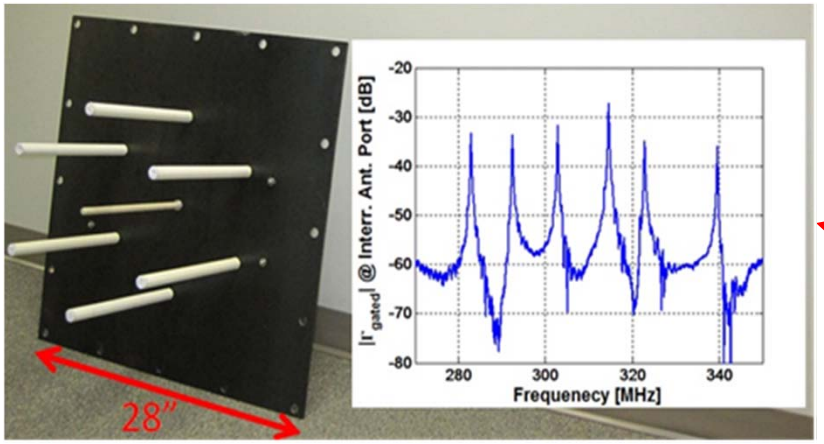
Reported last year

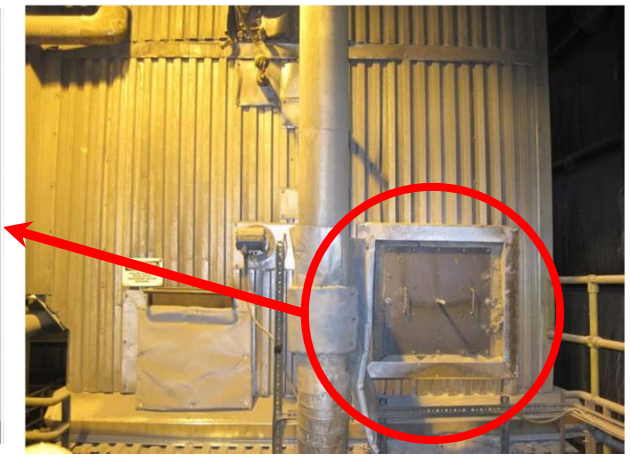
- After material testing for packaging at beginning 2014





- Wireless Array Temperature Monitoring

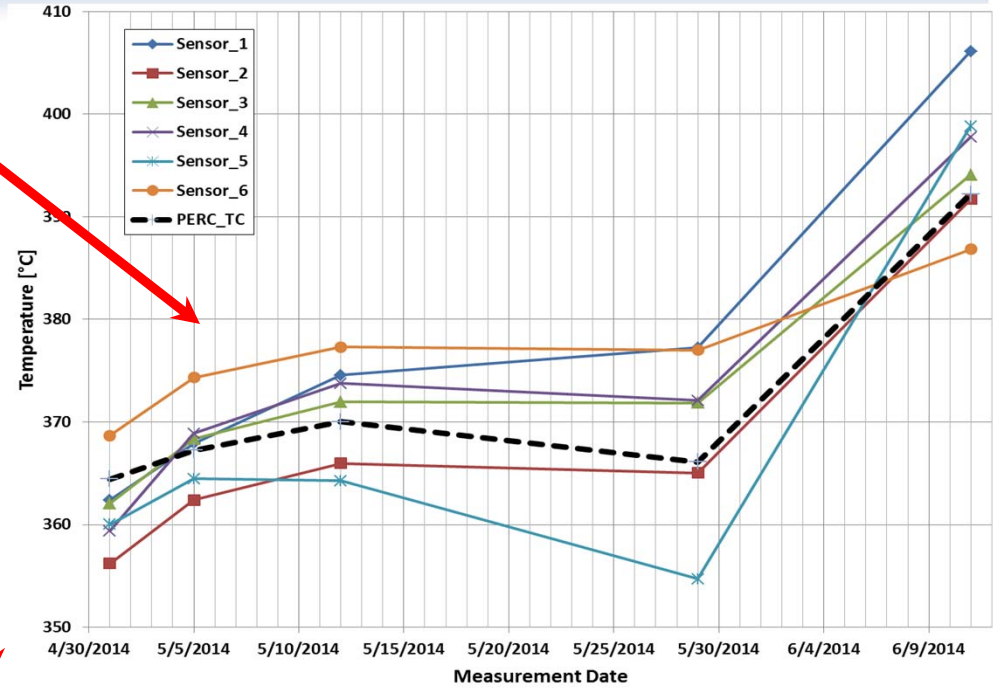


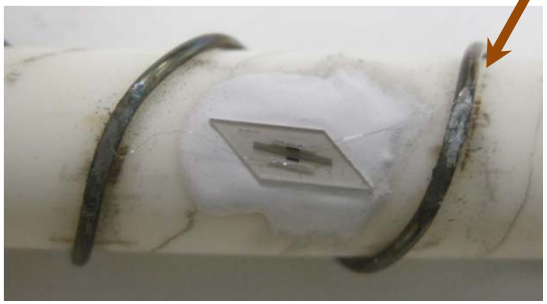


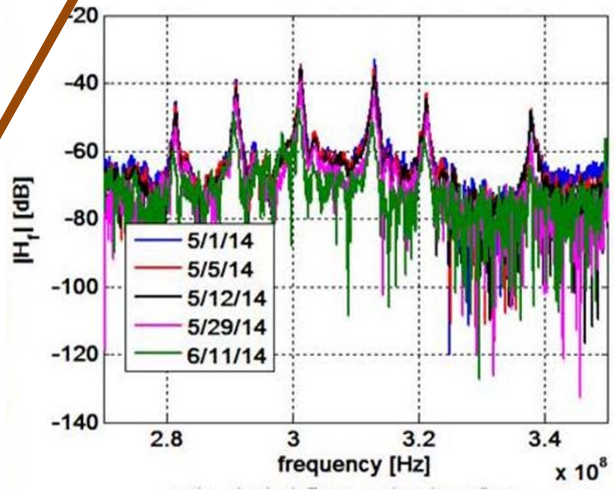
Measured Response

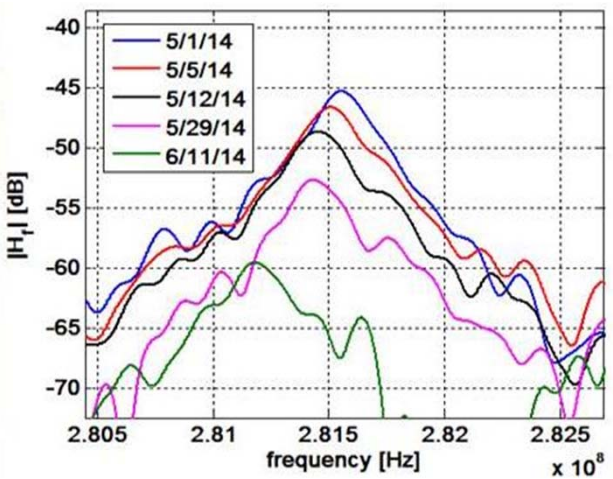
- T measurements consistent with witness thermocouple
- Sensor signal amplitude:

  → decaying with time
- Problem: NiCr wire used for the packaged antenna oxidized
- Device tested in probe station & re-bonded
- Amplitude recovered









PERC Wireless Array

- New array prepared: NiCr antenna replaced by Inconel
- Issues to bond and adjust antenna:

Solder flux used to measure the antenna & impedance match it remained in the wire and compromised bonding

- 3rd generation bonding / packaging:
  - Implemented & under test: Jan 2015 at PERC
  - No flux, no corrosion, mounting improved
- Plant shut-down 3rd week April:
  - Devices recovered and currently under analysis for packaging verification
  - Test will resume at the PERC power plant in mid-May (door replacement)

IV. CONCLUSIONS & ACKNOWLEDGMENTS

CONCLUSIONS

- Brief review: project scope, prior achievements & Impact
- Recent progresses presented & discussed regarding

Transitioning the R&D findings into HE Power Plant Environment

- In particular, details were given into the recent findings
  - ✓ Sensor stability under cycling
  - ✓ New electrode materials: operation to 1100°C
  - ✓ New successful cycling tests with sensor stability around ± 3°C after annealing phase
  - ✓ Power plant packaging & antenna material revisited & improved
- Technology ready for further power plant tests

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", 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.

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12. D.J. Frankel, S.C. Moulzolf, M. Pereira da Cunha, R.J. Lad, "Platinum-Based Nanocomposite Electrode Thin Films For High Temperature Operation," International Conference on Metallurgical Coatings and Thin Films, April 24, 2015.

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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Time for Questions?