Technology Maturation of Wireless Harsh-Environment Sensors for Improved Condition-Based Monitoring of Coal-Fired Power Generation

NATIONAL ENERGY TECHNOLOGY LABORATORY

2020 Transformative Power Generation Project Review Meeting

Project: DE-FE0031550

VIRTUAL MEETING, September 30, 2020

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September 30, 2020, 12:00PM

U.S. DEPARTMENT OF ENERGY

1865 THE UNIVERSITY OF MAINE

ELECTRICAL & COMPUTER ENGINEERING Orono, Maine

FIRST Frontier Institute for Research in Sensor Technologies

ENVIRONETIX TECHNOLOGIES CORPORATION

Outline

I. Program & Project Motivation, Goals, and Objectives

a) Project Motivation & Purpose
b) Project Goals & Strategic Alignment to Fossil Energy Programmatic Objectives
c) How the Project has been Achieving the Goals Established by DOE HQ

II. Project Description & Recent Achievements

a) Verification of surface preparation for antennas & connections
b) Verification of SAW temp. sensor unit stability and consistency in power plant operation
c) Design, Implementation, Testing: Wireless SAW Sensor Syst. for Boiler Tube Monitoring
d) Design & Implementation of Wireless Signal extraction system for remote data gathering & compilation

III. Current Progresses & Next Steps

a) Newly identified power plant problem and solution
b) New technologies validation and planning for insertion in multiple power plants
c) Identified Challenges and Mitigation alternatives

IV. Concluding Remarks

I.

Program & Project Motivation, Goals, and Objectives

I. Program & Project Motivation, Goals, and Objectives

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a) Project Motivation & Purpose

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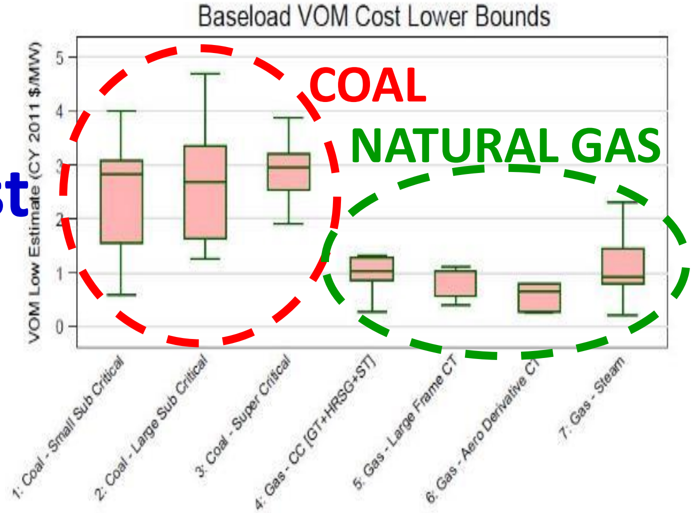
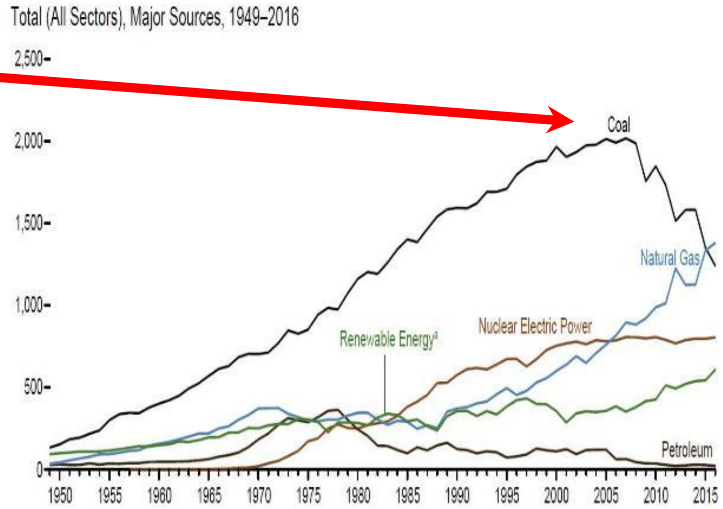
- ➢ **Consistent with original proposed project**
  - ✓ **Contribute to improve performance of COAL based power plants:**
    - ↑ Efficiency & ↓ emissions → Monitoring processes (boiler, plant chambers)
    - ↓ operation & maintenance costs → Monitoring plant (Cond. Based Maint.,CBM)
- ➢ **Coal power plants (aging) → coal usage**
  - ✓ ↓ since mid-2000s
- ➢ **Variable Op. Maint (VOM) cost**
  - ✓ Higher than Natural Gas





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

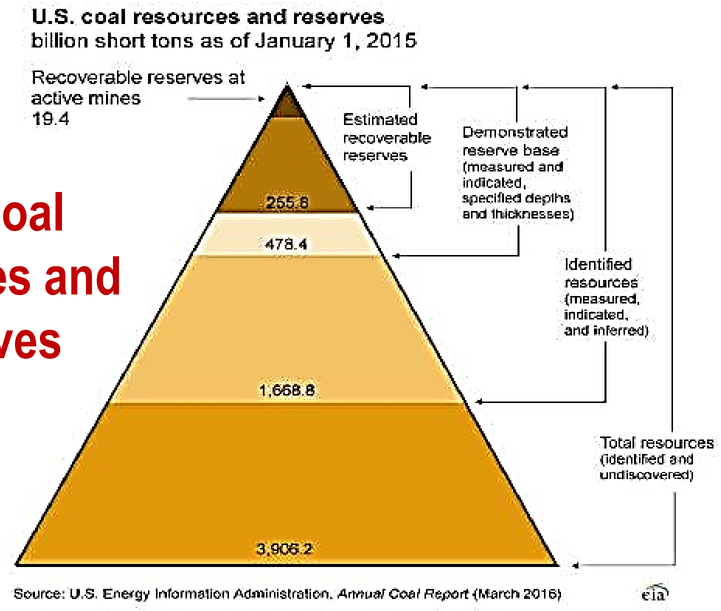
June 2017 Monthly Energy Review, U.S. Energy Information Administration (EIA), DOE/EIA-0035(2017/6)

I. Program & Project Motivation, Goals, and Objectives

a) Project Motivation & Purpose

- **Why insist on COAL?**
- **USA → SIGNIFICANT SOURCE OF ENERGY FOR THE U.S.A. !**
  - ✓ 255.8 billion short tons: 21% of the world's *proven recoverable reserves* of coal
  - ✓ Above #: ONLY 6.5% of the potential total coal resources (identified & undiscovered)
- **So what is missing?**
  - **New advanced Technologies & Sensors ⇒ ↑ PP efficiency; ↓ maint. Costs; ↓ emissions**

U.S. coal resources and reserves



Alignment with FOSSIL ENERGY PROGRAMMATIC OBJECTIVE:

- **Develop cost-effective, reliable technologies to improve the efficiency of new and existing coal-fired power plants.**

I. Program & Project Motivation, Goals, and Objectives

b) Project Goals & Strategic Alignment → Fossil Energy Program

- **Usage of Harsh-Environment (HE) High-Temperature (HT) Wireless Sensor Technology Systems 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 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 tech. successfully commissioned in an operational system)

I. Program & Project Motivation, Goals, and Objectives

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c) How the project has been achieving the goals established by DOE HQ

➢ **Univ. of Maine in partnership with Environetix Technologies Corp.:**

- ✓ Collaboration with Power Plants: Testbed Identification & Target Locations within power plants
- ✓ Investigation of Materials: Sensor Packaging & Antenna Fab. in Coal Power Plants
- ✓ Implementation of Wireless Communication Systems in Power Plant Environment

I. Program & Project Motivation, Goals, and Objectives

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c) How the project has been achieving the goals established by DOE HQ

- ✓ Fabrication and Test of Harsh Environment Sensors & Antennas in Power Plants
- ✓ Deployment of Embedded Wireless Temperature Sensors Arrays and Interrogators into Power Plants
- ✓ Investigation of Alternative Materials & Sensors for Integration into Developed Systems
- ✓ Consideration of Power Plant feedback and adjustment of sensor solution to power plant indicated needs

II. Project Description & Recent Achievements

II. Project Description & Achievements

Project Description

➢ UMaine & Environetix → following up on Wireless SAW technology validated in relevant environment (boiler tubes @ economizer section):

- ✓ TRL 5: Penobscot Energy Recovery Co (PERC), Orrington, ME

Municipal Solid Waste (MSW) Power Plant

➢ Steps taken → Technology verification at Longview coal-based power plant:

1. Material Tests ⇒ verification of surface preparation for antennas & connections
2. Verification of temp. sensor unit stability and consistency in power plant operation
3. Design & Implementation: Wireless SAW Sensor Syst. for Boiler tube Monitoring
4. Design & Implementation of Wireless Signal extraction system for remote data gathering and compilation
5. Investigation towards power plant sensor needs → alternative locations, sensor types and materials

II. Project Description & Achievements

Material Test: metallic plate coatings for antenna use in HT Environment

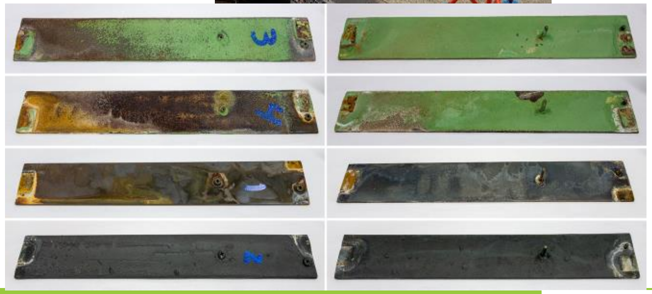
➢ **1. High Temperature (HT) coating of metallic surfaces to mitigate corrosion/erosion:**

✓ **Two sets of anti-corrosion & anti-erosion coatings tested in the NOx port in Selective Catalytic Reduction (SCR) inlet**

FIRST: Four coated low-carbon steel coupons installed

RF Test Setup

Second: Four antenna elements with ≠ sprayed ceramic coatings installed

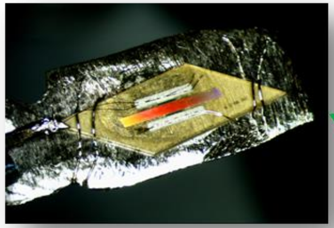


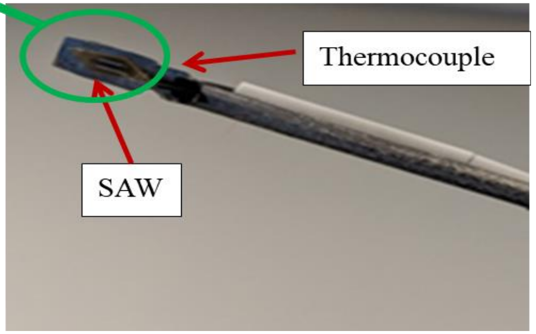
- **<u>Goal:</u>** confirm plate performance for antennas @ HT
- Inconel plates → ↑ $ ⇒ Steel cheaper & easier to work
- Commercial & proprietary coatings on low-carbon steel:
  - ✓ 1st Test: visual inspection → corrosion resistant; sealant removed due to erosion
  - ✓ 2nd Test: antenna plates → **DC & RF (PIFA antenna top plate) before & after tests** → performance maintained for all protective coatings; sealant still removed due to erosion
    - Tests shown performed at Longview Power
    - Similar test was also carried out at PERC
      - ➢ Comparable erosion / corrosion

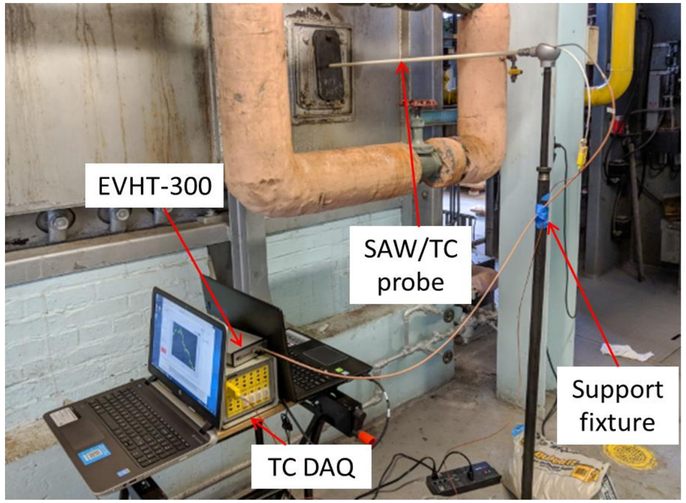
II. Project Description & Achievements

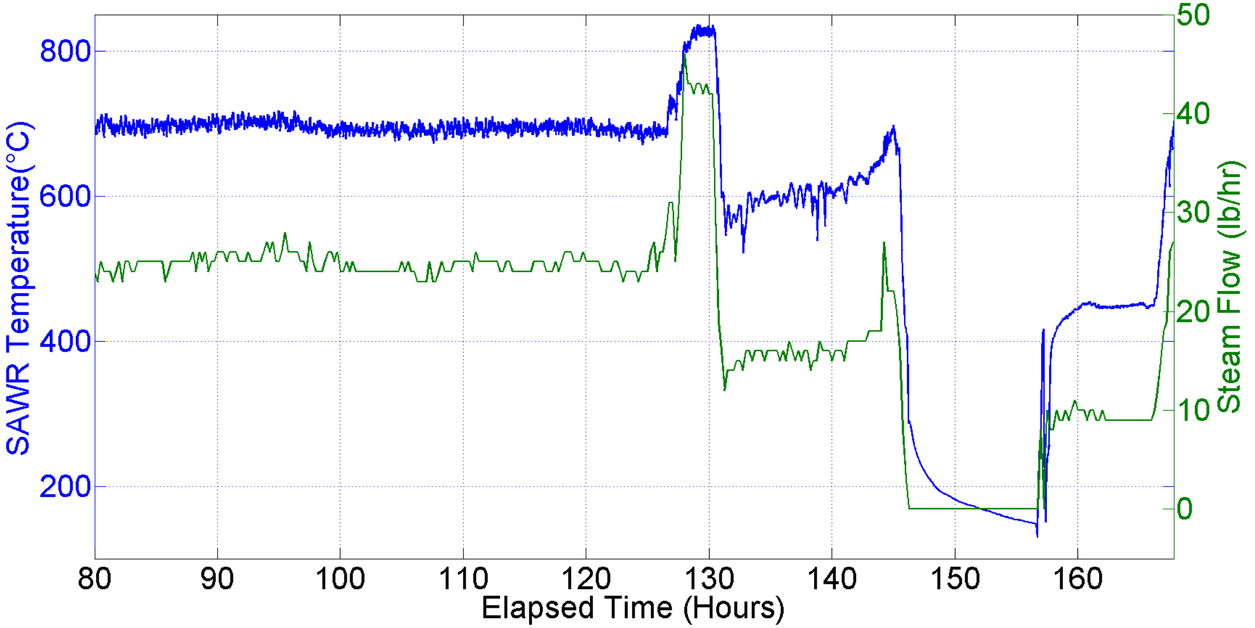
UMaine Steam Power Plant → SAW Sensor Probe in Natural Gas Fired Boiler

- 2. Verification of sensor unit stability & consistency →
  - Test of materials, signal propagation, sensor stability, data acquisition techniques, and resilience of packaging techniques → performed prior to and in preparation to the planned Longview Tests









Confirmed correlation between generated steam and measured SAW sensor temperature

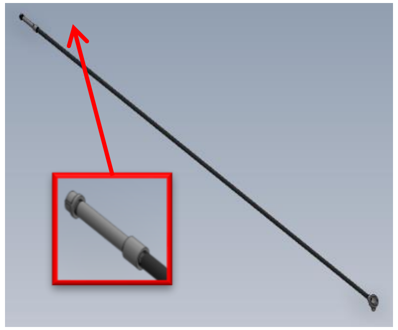
II. Project Description & Achievements

Longview: SAW Temp. Sensor Probes in Superheater Pass Damper Chamber

- 2. Verification of sensor unit stability & consistency →
  - Two SAW sensor probes with ref. thermocouples mounted in Superheater Pass Damper Chamber
  - Inserted in 138” long Longview probe through two access ports into superheater chamber

Mounted SAW sensor

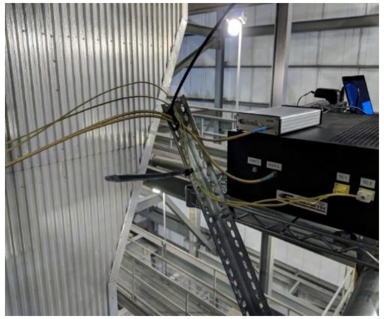
Sensor packaged in 6” long closed tube



Sensor probe integration with Longview fixture

Probe insertion

Access ports for the two probes



Environetix Measurement Systems for Wireless Remote Monitoring

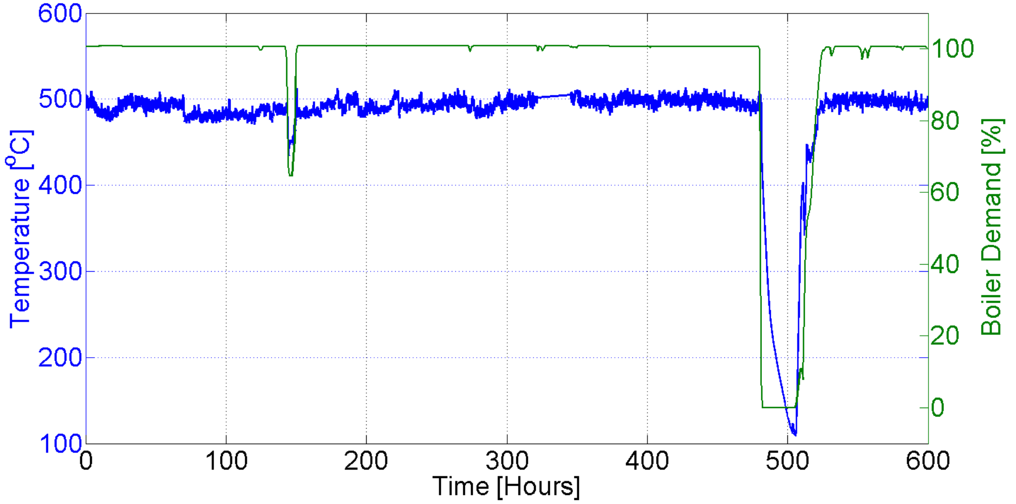
II. Project Description & Achievements

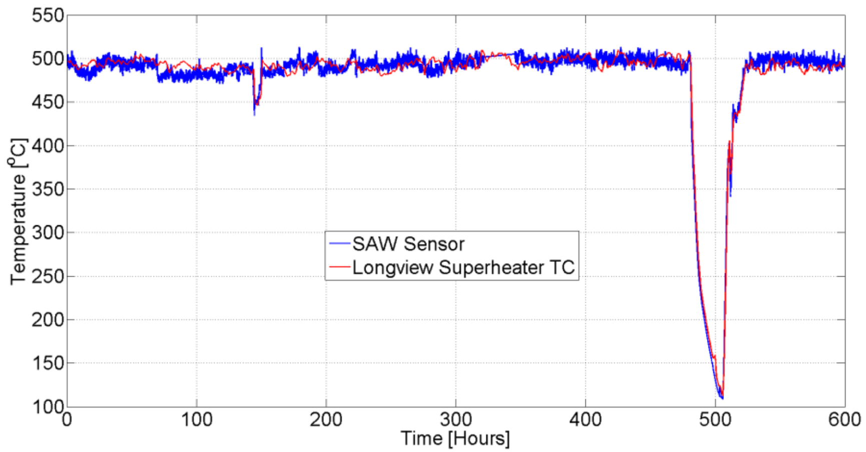
SAW Temperature Sensor Probes in Superheater Pass Damper Chamber

- **Ongoing test → Current status →**
  - **Both probes functional after 18 months of continued exposure to flue gases**
  - **Data being recorded remotely onto secure server ⇒ allows identification of power plant states:**
    - ✓ Base-loaded state
    - ✓ Demand fluctuation
    - ✓ Shutdown event

Verified temperature change with boiler demand

Consistent temperature readings between Env/UMaine SAW sensor & Longview Superheater TC

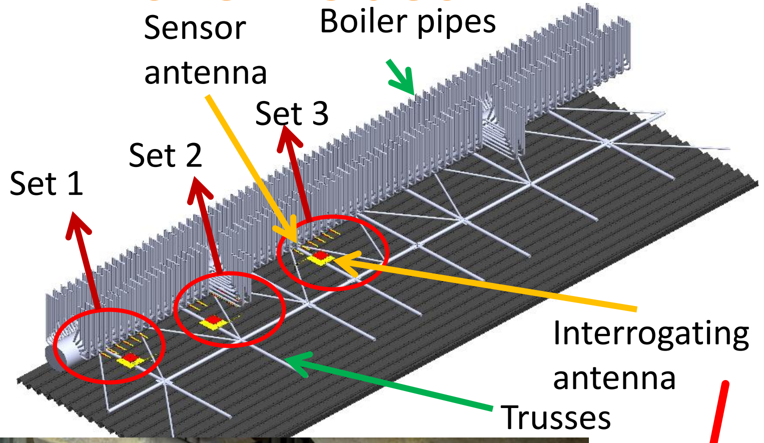


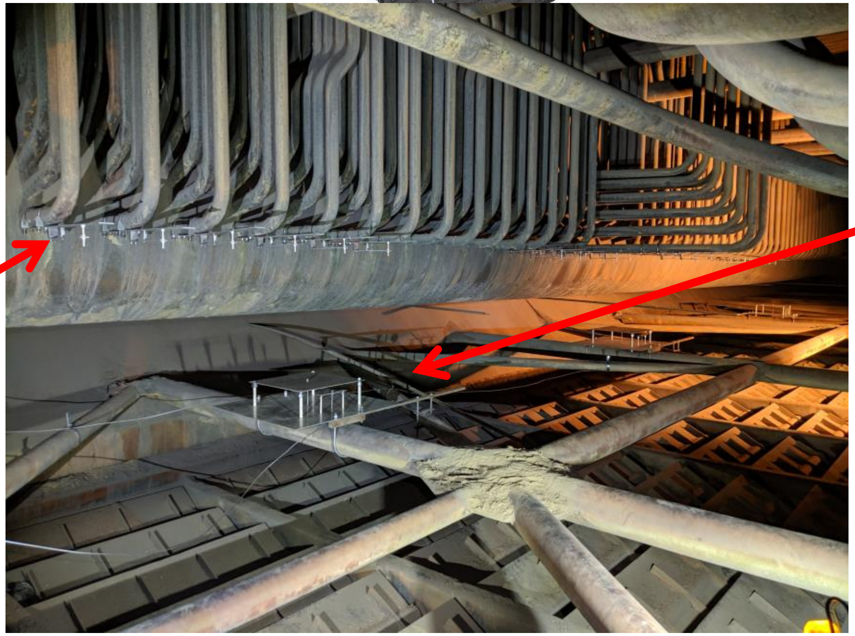


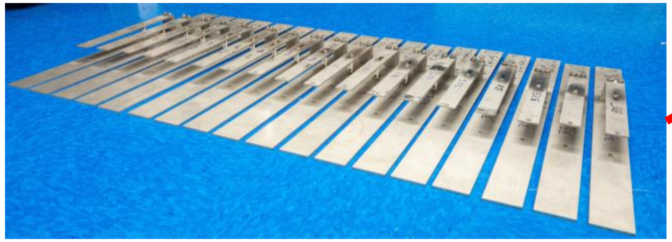
II. Project Description & Achievements

Deployment of Wireless SAW Temperature Sensor Array in Boiler Tubes

- 3. Design & Implementation: Wireless SAW Sensor Syst. for Boiler tube Monitoring
  - ✓ 18 wireless sensor units installed on Longview boiler tubes in the reheater pass damper chamber
  - ✓ 3 interrogating antennas mounted on trusses (3 sets)
    - 18 sensor units (sensor + sensor antenna) mounted directly on the boiler tubes
  - ✓ Sensor locations distributed to:
    - Maximize boiler coverage
    - Allow monitoring for half of the chamber



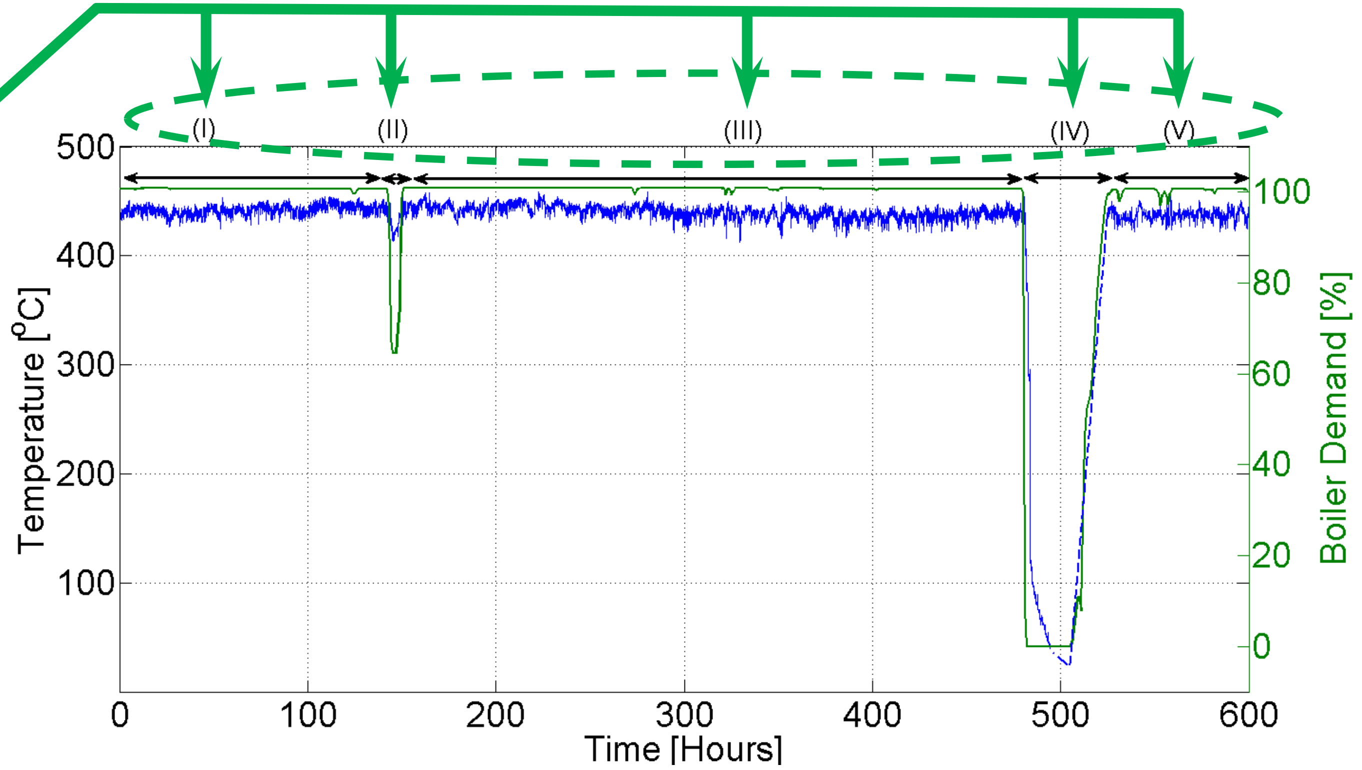




II. Project Description & Achievements

Deployment of Wireless SAW Temperature Sensor Array in Boiler Tubes

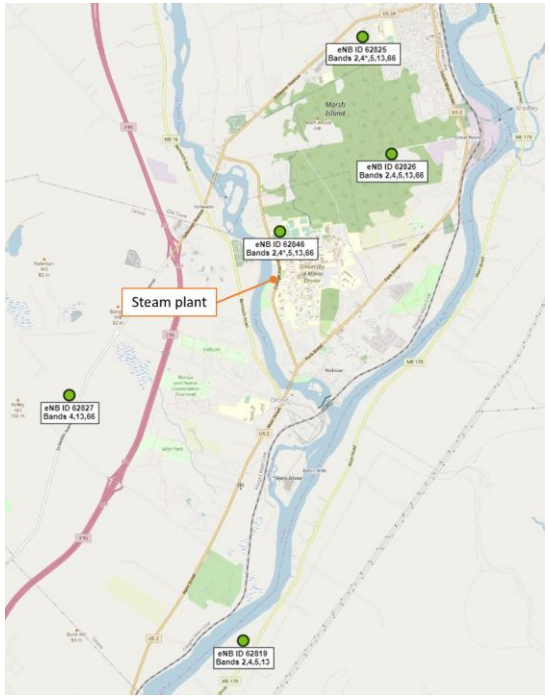
- 3. Design & Implementation: Wireless SAW Sensor Syst. for Boiler tube Monitoring
  - ✓ Temperature monitoring of boiler tubes → 400 °C ± 20 °C
  - ✓ Identification of power plant states:
    - Base-loaded state → (I), (III), (V)
    - Demand Fluctuation → (II)
    - Shutdown event → (IV)
  - ✓ Data being recorded remotely onto secure server
  - ✓ Sensors operational after 16 months of continued exposure to flue gases



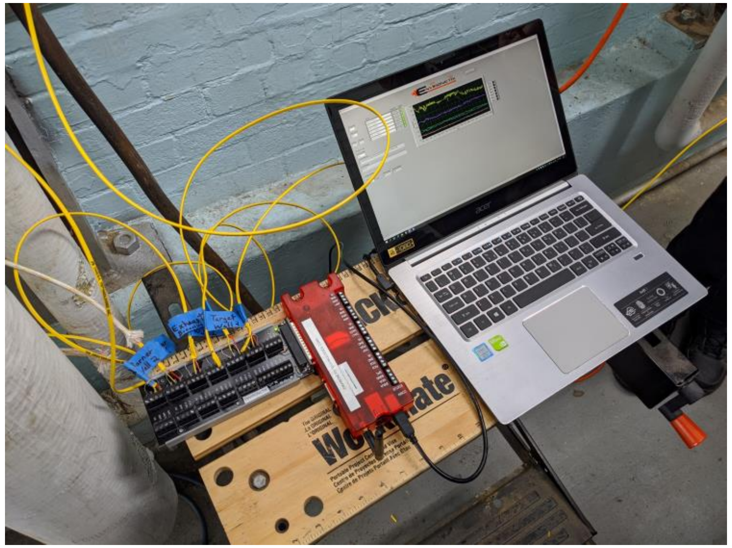
II. Project Description & Achievements

Steam Power Plant: Remote Wireless Data Acquisition System

- **4. Design & Impl. of Wireless Signal Extraction System for Remote Data Gathering & Compilation**
  - ✓ **Environetix established a wireless sensor network data acquisition system →**
    - **Capable of HT data acquisition & monitoring from anywhere in the world (local wireless, LAN, cel network)**



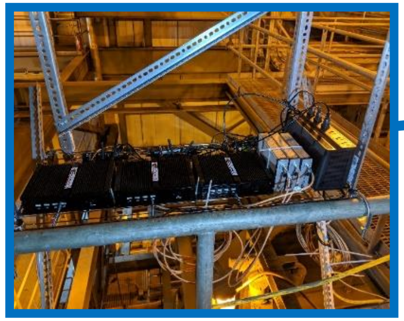
Location	Frequency (MHz)	Band	Bars (out of 5)	Signal strength (dBm)
West entrance	1700	4	4	-97
Building center	1700	4	4	-100
East wall	850	5	4	-95
East wall	700	13	3	-97
East window	850	5	3	-102
South wall	850	5	4	-101
North wall	700/850/1700	4/5/13	4	-96
Probe location	850	5	4	-101



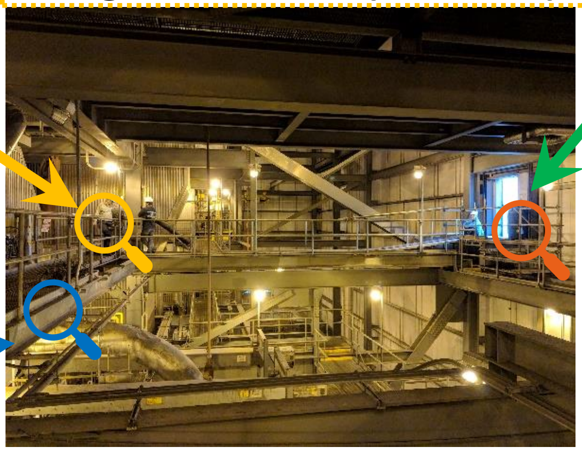
II. Project Description & Achievements

Longview: establishment of Remote Wireless Data Acquisition & Monitoring Syst.

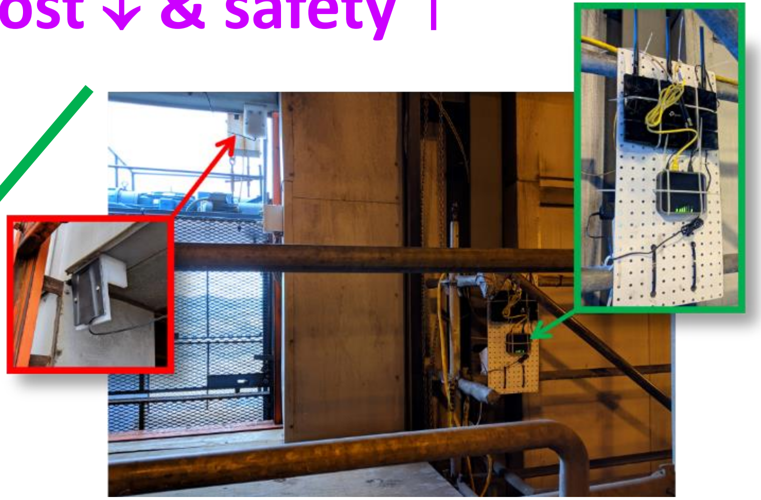
- 4. Design & Impl. of Wireless Signal Extraction System for Remote Data Gathering & Compilation
  - ✓ Local Area Network (inside plant) & Wireless Network → Remote Wireless data collection
    - TX from WV to ME/Environetix (data can ALSO be transmitted & monitored locally/control room)
  - ✓ Two data acquisition (DAQ) stations → SAW probes, SAW boiler wireless, witness TCs
- NO EXTRA WIRES IN THE PLANT → cost ↓ & safety ↑



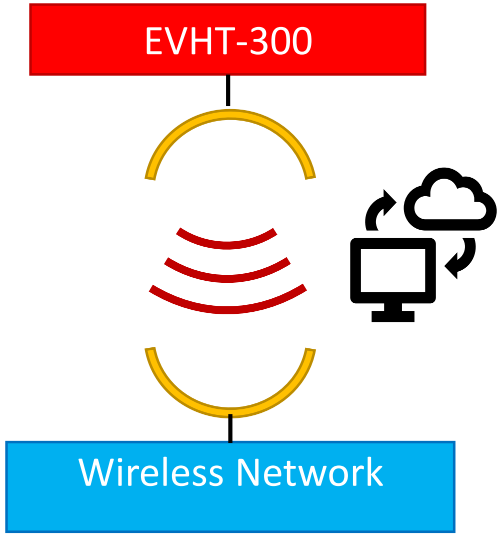
Longview Power (9th Floor)



Wireless SAW sensor station (reheater side)



Window location for cellular signal access



III. Current Progresses and Next Steps

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Burner Temperature & Fire monitoring

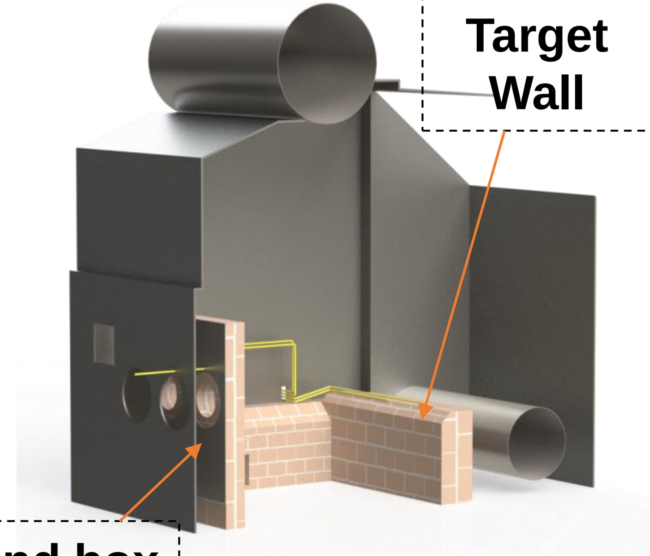
- 5. Power plant sensor needs → alternative locations, sensor types & materials
- Burner temperature & fire monitoring → currently have no instrumentation
  - ✓ Longview → emphasized → need for temperature instrumentation @ burner locations
  - ✓ Coal dust / HT / air flow → localized fire →
    - ✓ Equipment damage
    - ✓ Dow time
    - ✓ Maintenance cost ↑
  - ✓ Instrumentation under development → preventive
    - ✓ Structural health monitoring (SHM)
    - ✓ Condition-based maintenance (CBM)
  - ✓ Environetix/UMaine system under development→ wireless data collection → control room

III. Current Progresses and Next Steps

NATIONAL ENERGY TECHNOLOGY LABORATORY

UMaine Steam Power Plant → Prep. For Longview

- **5. Power plant sensor needs → alternative locations, sensor types & materials**
- **UMaine Steam Power Plant Testbed →**
  - ✓ **Furnace instrumentation for Wireless monitoring prior to working on Longview burner**
  - ✓ **Testbed → oil fired boiler → current NO instrumentation**



Target Wall

Wind box

Burner Wall

Target Wall

Wind box

Exhaust Breaching

DAQ station

III. Current Progresses and Next Steps

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UMaine Steam Power Plant → Prep. For Longview

- 5. Power plant sensor needs → alternative locations, sensor types & materials
- UMaine Steam Power Plant Testbed → oil fired boiler → current NO instrumentation

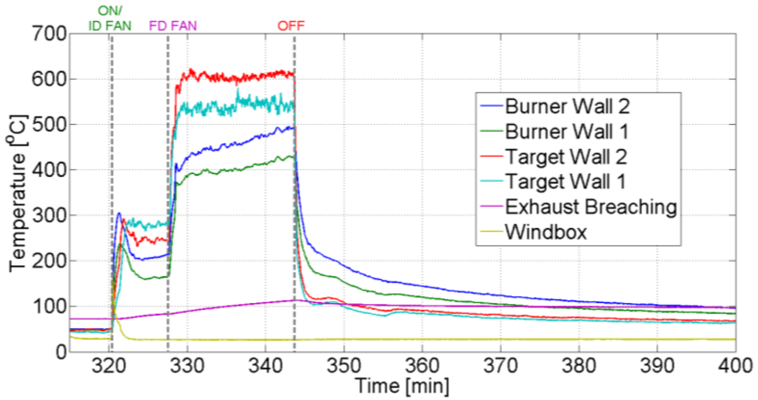
✓ Goal: furnace instrumentation for Wireless monitoring prior to working on Longview burner

✓ Tested TCs: data recorded logged wirelessly

✓ Events:

- Burner lit up (ON) & induced draft (ID) fan turned on → 320 mins
- Forced draft (FD) fan turned on → 327 mins
- Burner turned off (OFF) → 344 mins

✓ Boiler is scheduled to be online for normal operation in October 2020



III. Current Progresses and Next Steps

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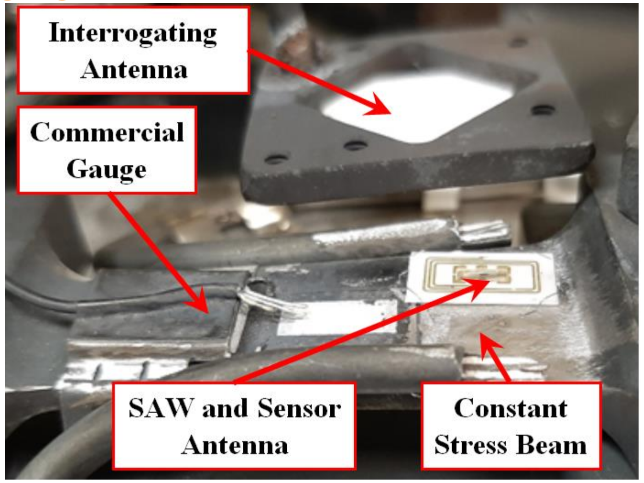
Alternative Sensor Types → Static and Dynamic Strain Sensors

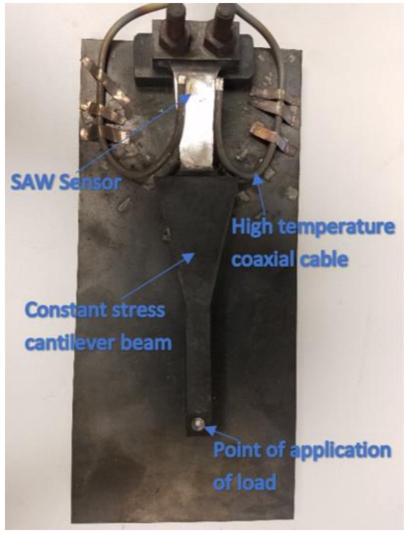
- 5. Power plant sensor needs → alternative locations, sensor types & materials
- Static and Dynamic strain sensors → Need for HT HE strain sensors to allow
  - ✓ Allow planned maintenance → ↓ in maintenance & repair costs → SHM & CBM in power plants
  - ✓ ↑ in process efficiency
  - ✓ ↑ in safety
- Static Strain
  - ✓ Monitor structure deformation
  - ✓ Identify weakening in structures due to corrosion, excessive stress, improper operation, etc.
- Dynamic Strain
  - ✓ Monitor structural health for equipment, machinery and structures subject to vibrations
  - ✓ Monitor loads on vibrating structures.

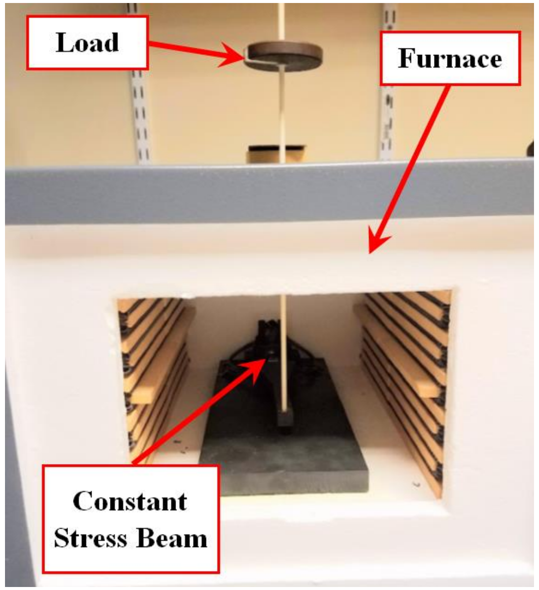
III. Current Progresses and Next Steps

Alternative Sensor Types → Static and Dynamic Strain Sensors

- **5. Power plant sensor needs → alternative locations, sensor types & materials**
- **UMaine/Environetix → Successful proof-of-concept →**
  - ✓ Static & Dynamic HT strain sensors
  - ✓ Laboratory work → performed up to 400°C
  - ✓ Wireless interrogation of strain sensors successfully achieved
- **Static Strain**
  - ✓ SAW sensor mounted on a constant stress beam
  - ✓ Calibration performed
    - i. Abaqus finite element analysis model
    - ii. Commercial HT strain gauge (temp. range for calibration identified)





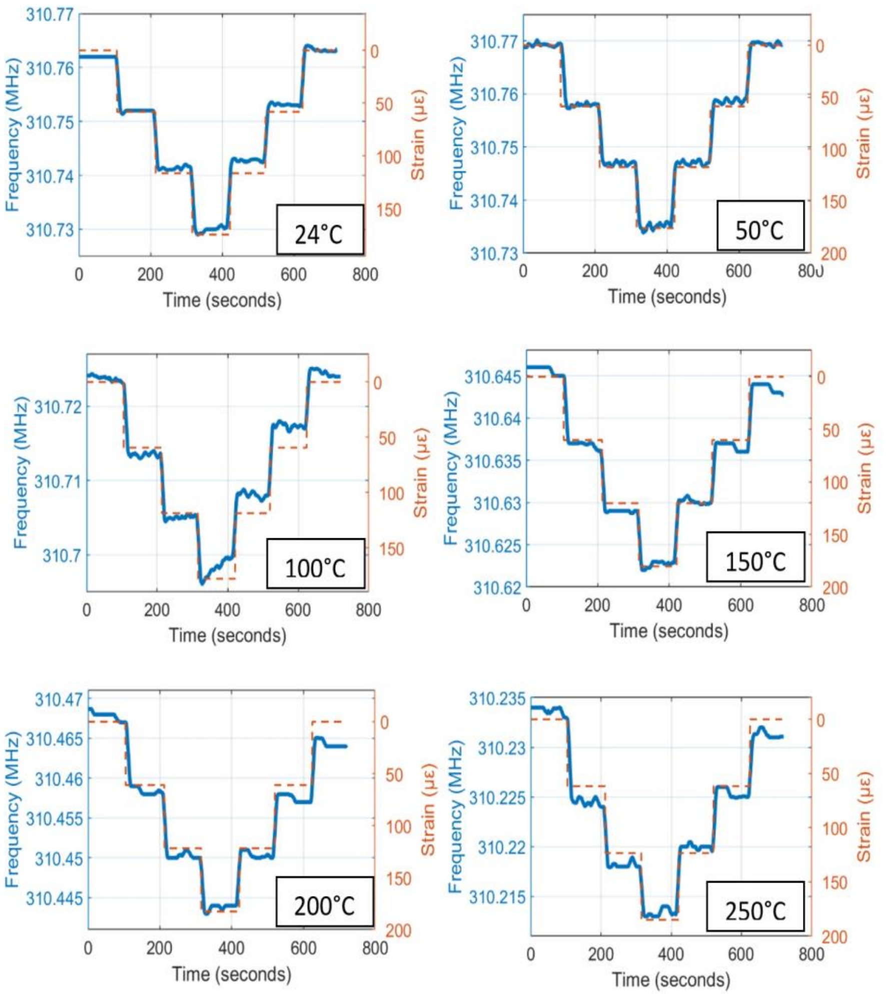


III. Current Progresses and Next Steps

NATIONAL ENERGY TECHNOLOGY LABORATORY

Alternative Sensor Types → Static Strain Sensors

- 5. Power plant sensor needs → alternative locations, sensor types & materials
- Wireless static strain measurements lab results
  - ✓ Wireless SAW sensor tested to 180με and 250°C ➔ ➔ ➔
  - ✓ Abaqus used for calibration in this temperature range
  - ✓ Packaging & mounting →
    - Sensitivity vs. max temp. of operation compromise identified
  - ✓ Identified sensitivities at 24°C, 100°C and 200°C
    - -182 Hz/με, -146 Hz/με, and -133 Hz/με, respectively.
  - ✓ Temperature compensation should be included
  - ✓ Packaging for technology application in power plant under design.



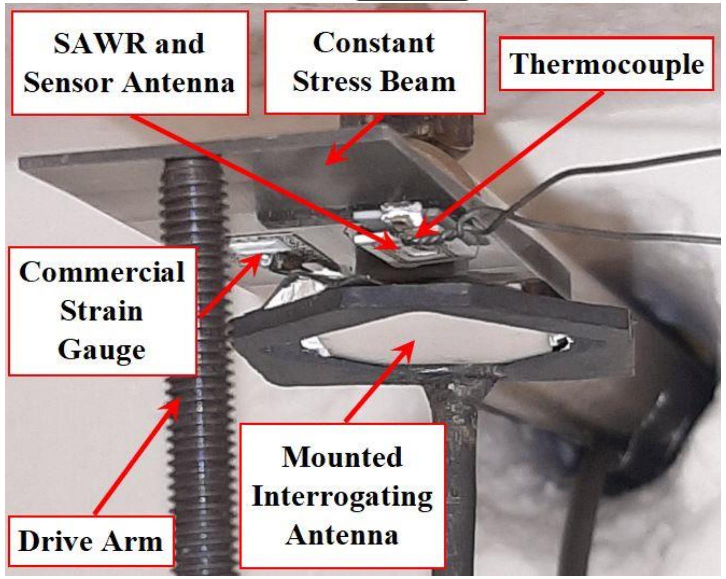
Fizzah et al, IEEE Int. Ultr. Symposium (Virtual Conference), Sept. 2020

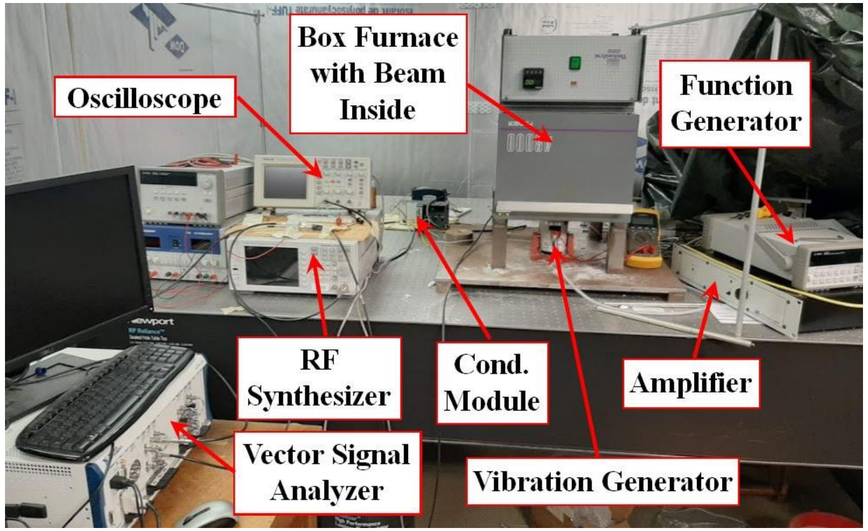
III. Current Progresses and Next Steps

Alternative Sensor Types → Dynamic Strain Sensors

- **5. Power plant sensor needs → alternative locations, sensor types & materials**

- **Wireless dynamic strain → laboratory tests**
  - ✓ Wired and wireless tests → up to 400°C in box furnace
  - ✓ Tapered-edge constant stress beam employed
    - Attached by steel rod clamped at the back of the furnace → thus suspended freely in the furnace
    - Excited by a vibration generator that was mounted outside of the furnace using a stainless-steel drive arm
  - ✓ SAW sensor, witness TC & commercial strain gauge mounted
  - ✓ Vibration generator provides dynamic strain signal up to several hundred Hz.

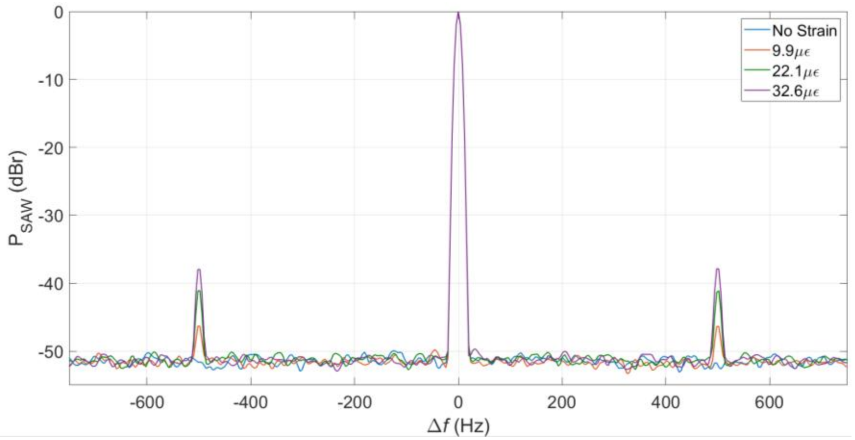




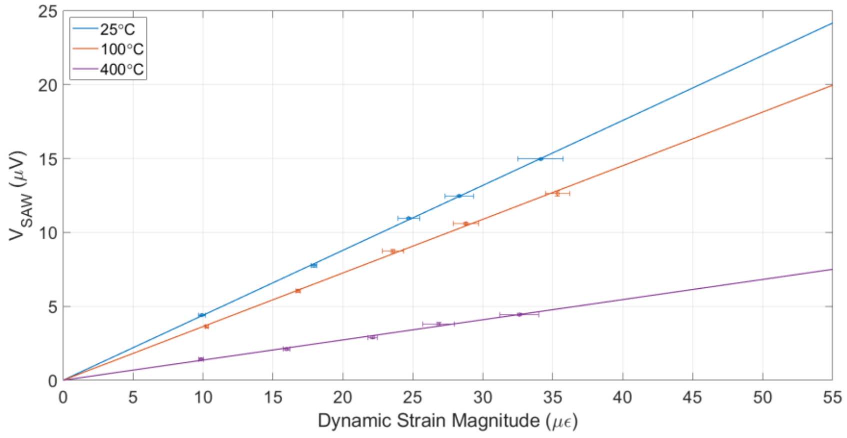
III. Current Progresses and Next Steps

Alternative Sensor Types → Dynamic Strain Sensors

- **5. Power plant sensor needs → alternative locations, sensor types & materials**
- **Wireless dynamic strain measurements lab results**
  - ✓ Wireless SAW sensor data obtained from 25°C to 400°C
    - Calibration performed with commercial gauge
    - Dynamic strain signal at 500Hz from about 9με to 33 με
    - From relative sidelobe power to main SAW resonant peak power, $\Delta P_{SAW} \rightarrow$ equivalent sidelobe voltage, V_{SAWR}^{Sb}
  - ✓ Sensitivity found to be temperature dependent
  - ✓ Temperature compensation must be included
  - ✓ Packaging for technology application in power plant under design.



$\Delta P_{SAW} \rightarrow V_{SAW}$

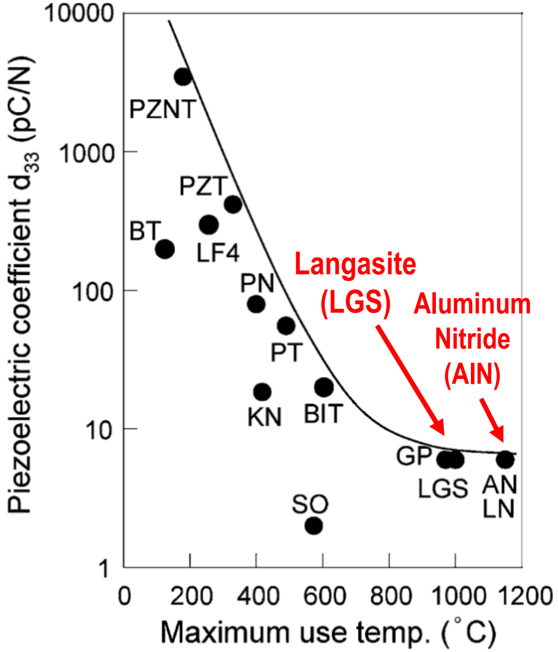


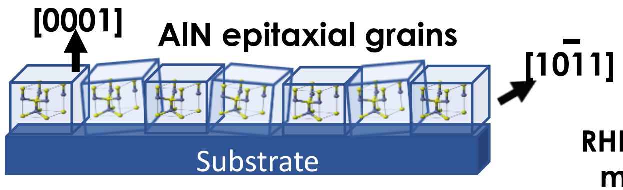
Leff et al, IEEE Int. Ultr. Symposium (Virtual Conference), Sept. 2020

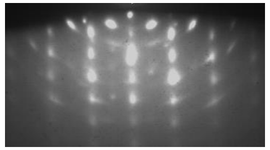
III. Current Progresses and Next Steps

Alternative Materials for Sensors → AlN-based Piezoelectric Thin Films

- **5. Power plant sensor needs → alternative locations, sensor types & materials**
- **Few materials remain piezoelectrically active above 600°C**
  - ✓ Langasite ($La_5Ga_{0.5}SiO_{14}$) SAW sensors operate up to 1000°C → fab from single crystals
- **Thin film AlN piezoelectric material**
  - ✓ Piezoelectric at HT & can be made as conformal thin films
  - ✓ Higher phase velocity than LGS → higher frequency of operation
  - ✓ Temperatures up to 800°C or above depending on operation and fabrication
- **UMaine/Environetix**
  - ✓ Have been investigating AlN for HT power plant applications
    - commercially available & in house fabricated

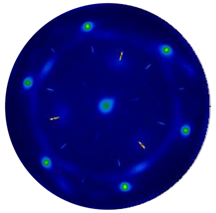






RHEED pattern from AlN film measured during growth

XRD (1011) pole figure



III. Current Progresses and Next Steps

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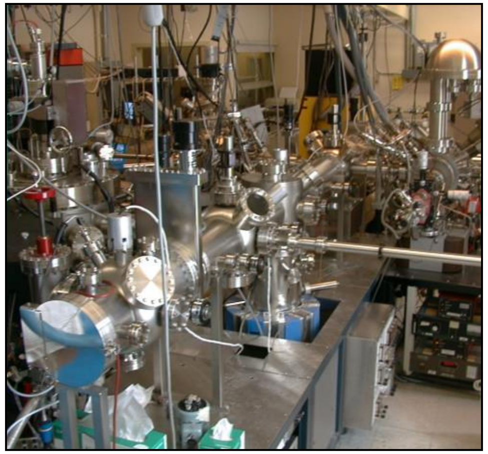
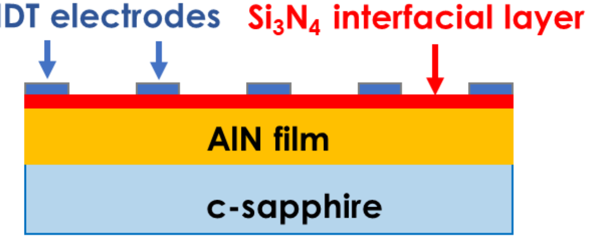
Alternative Materials for Sensors → AlN-based Piezoelectric Thin Films

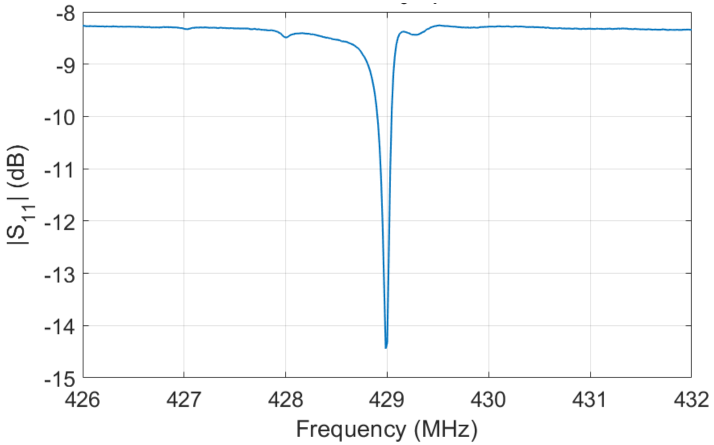
- **5. Power plant sensor needs → alternative locations, sensor types & materials**
- **Thin film AlN Plasma assisted MBA are being optimized**
  - ✓ Seed layer; O_2 in the chamber; T of growth; N_2 flux; etc.
- **SAW resonator have been fabricated & tested up to 900°C**
  - ✓ Si_3N_4 interfacial layer → developed to enable photolithography of SAWR devices without etch damage to AlN thin film
  - ✓ IDT HT electrodes under investigation

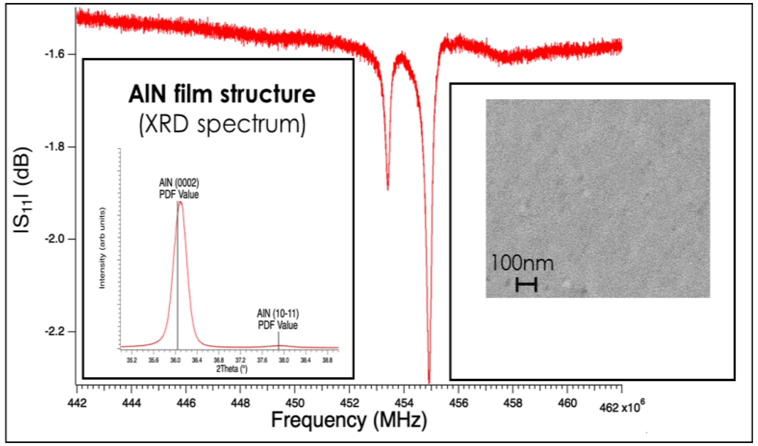


Plasma-Assisted Molecular Beam Epitaxy (PA-MBE) deposition chamber



SAW AlN tested at 800°C





III. Current Progresses and Next Steps

Current and next steps → General challenges HT HE tech transfer

- **Challenging aspects of current and next steps in currently tech. transition TRL5 → TRL7/8**

IDENTIFIED GENERAL CHALLENGES FOR HT HE SENSOR DEPLOYMENT IN POWER PLANTS

- **Test possibilities & availability window is very limited to access HT environments:**
  - ✓ Once a year and sometimes rescheduled based on maintenance events & urgencies
  - ✓ Difficulty in planning ⇒ very short notice (when such notice takes place)
  - ✓ Mitigation: alternative power plants
- **Regular HT HE conditions → RF signals → affected by different HE conditions**
  - ✓ Engineering solution still quite dependent on case by case engineering design input
  - ✓ Shock in temp.; extreme variation of pressure/temp.; mismatch in TCE between parts
  - ✓ Mitigation: proper coating, surface prep., packaging → address most erosive/corrosive situations
- **Engage more power plants into TRL advancement to capitalize on new sensor technologies:**
  - ✓ Additional participation of power plants to gain access to the technology made available

III. Current Progresses and Next Steps

NATIONAL ENERGY TECHNOLOGY LABORATORY

Current and next steps → Challenges for current activities & next steps

- **Challenging aspects of current and next steps in currently tech. transition TRL5 → TRL7/8**
- **Overcome current investment/cost/travel restrictions during the pandemic situation**
  - ✓ Interactions & tech transfer depend on visits and in-situ exchange of information

SPECIFIC UMaine/Environetix's PROJECT CHALLENGES AND NEXT STEPS

- **Additional resources needed to extend HE solutions to Longview burner application:**
  - ✓ Learning curve from successful initial experiments at UMaine Steam Power plant needs to be adapted to coal-based Longview Power plant
- **Further investment required for transitioning high impact newly identified HE technologies into power plants:**
  - ✓ Successful wireless strain sensor proof in laboratory → adaptation to power plant locations
  - ✓ Thin film AlN commercial & in-house fab. → adaptation to power plant environment & applications

IV. Concluding Remarks

IV. Concluding Remarks

Summary

- **Program & Project Motivation, Goals, and Objective reviewed ⇒**
  - ✓ **Strategic Alignment to Fossil Programmatic Objective highlighted**
  - ✓ **Path & strategy to achieve goals of ↑ TRL from 5 to 7 discussed**
- **Project status & recent achievements presented ⇒**
  - ✓ **Protecting materials for antennas and verification tests;**
  - ✓ **Verification of sensor stability in coal power plant for 18 months;**
  - ✓ **Wireless SAW Sensor System installation & operation in Longview Boilers (16 months)**
  - ✓ **Design and implementation of wireless signal extraction system for remote data gathering and compilation presented and discussed**

IV. Concluding Remarks

Summary

- **Current progresses and next steps ⇒ reviewed & discussed**
  - ✓ Identified Longview burner (fire/CBM) opportunity ⇒
  - ✓ System under development & test at UMaine Steam Power Plant
  - ✓ Static and dynamic strain sensors developed & wireless operation confirmed in lab.
  - ✓ Thin film AlN commercial and in-house tested for SAW sensor HE HT applications
- **General HE & project specific challenges presented ⇒**
  - ✓ Limited test windows;
  - ✓ HT HE challenges (specific boundaries; shock in temp./pressure; TCE);
  - ✓ Increase the number of stakeholders on the user side
  - ✓ Investment required for implementation of newly identified activities burner, strain, and thin film solutions.

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  [1] Frontier Institute for Research in Sensor Technologies, University of Maine, Orono, ME, U.S.A.

  [2] Environetix Technologies Corporation, Orono, ME, U.S.A.
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