DE-FE0031765

Test and Validate Distributed Coaxial Cable Sensors for in situ Condition Monitoring of Coal-Fired Boiler Tubes

Project Team:

Clemson University: Yongji Wu, Xinyu Jiao, Yizheng Chen, Mahabubur Rahman, Tanuj Gupta, Huijuan (Jane) Zhao (co-PI), Dock Houston (Co-PI), Hai Xiao (PI)

University of Cincinnati: Junhang Dong (co-PI)

Electric Power Research Institute: Susan Maley (co-PI), Steve Seachman, Kent Coleman, Dan Purdy

Southern Company Services: Chethan K. Acharya (co-PI)

Project Managers:

Richard Dunst, Project Manager, DOE/NETL

Sydni Credle, Technical Manager, DOE/NETL

Sheldon Funk, Contract Specialist, DOE/NETL

Project Objective and Background

A novel sensing technology for *in situ* monitoring in harsh conditions

Objective

To test, validate, and advance the TRL of a novel distributed coaxial cable sensing (CCS) technology for in situ monitoring of the boiler tube temperature in coal-fired power plants.

Background

- **Boiler tube failures**: extremely costly with significant economic impacts
  - A single tube failure in a 500 MW boiler requires an average of 3.6 days of repair work and results in a loss of more than 1 million dollars per day
- **Tube failures**: complicated mechanism & difficult to predict
  - Harsh operation conditions (subcritical units): steam pressure: 2,400 psi and higher; steam temperature: 540-600°C; flame temperature: 1500°C
  - Various failure reasons: Overheating, corrosion, erosion, fatigue, welding flaws, etc.
- Current high-temperature sensors for coal-fired boiler tube monitoring
  - **Electronic sensors**: points sensors. **Issue:** limited lifetime and installation difficulties
  - **Optical fiber sensors**: used for high temperature environment. **Issue:** Fragile to handle

Project Overview

Needs and Challenges

- Condition-based monitoring (CBM) is needed to handle frequent load changes due to the increasing contributions of renewable energy sources.
- Currently available sensors have low survival rate under harsh environment and too expensive to be widely deployed in existing boilers

Monitoring sensors and instrumentation are needed for in situ distributed temperature monitoring of the boiler tubes

Technology Gaps

- **Gap #1**: Need for low-cost **robust distributed temperature sensors** that can survive and operate in high temperatures
- **Gap #2**: Need for practical methods to **install/deploy sensors** into existing coal-fired boilers at a low cost for reliable measurements
- **Gap #3**: Need for validated **models** to integrate the distributed temperature information into the existing boiler control, operation and maintenance programs to realize CBM

Current Status of Project

Budget Period I (09/2019-03/2021)

Scope of Work in Budget Period I

- Engineer the sensors, test the welding-based sensor installation methods in high temperatures, and optimize the instrumentation.

Update on Project Team

- Six month no-cost extension has been applied due to the Covid-19 pandemic and unexpected temporary closure of University labs

Progress of the project

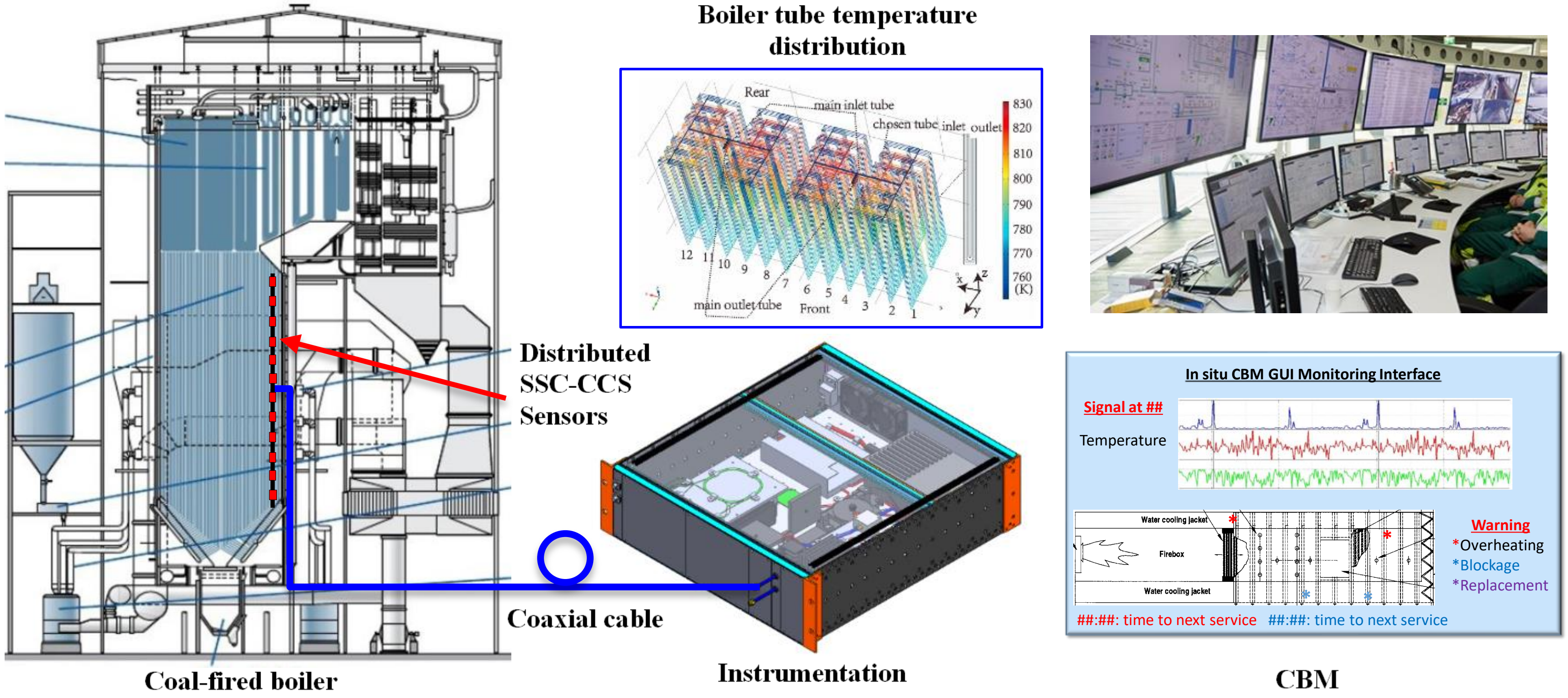
- The technical progress of the project is on track. All the milestones have been met.
- Progresses have been made in sensor design, fabrication, testing, boiler simulations, and installation.
- Continuation application submitted

Proposed Solution

A boiler tube monitoring system with distributed coaxial cable temperature sensors

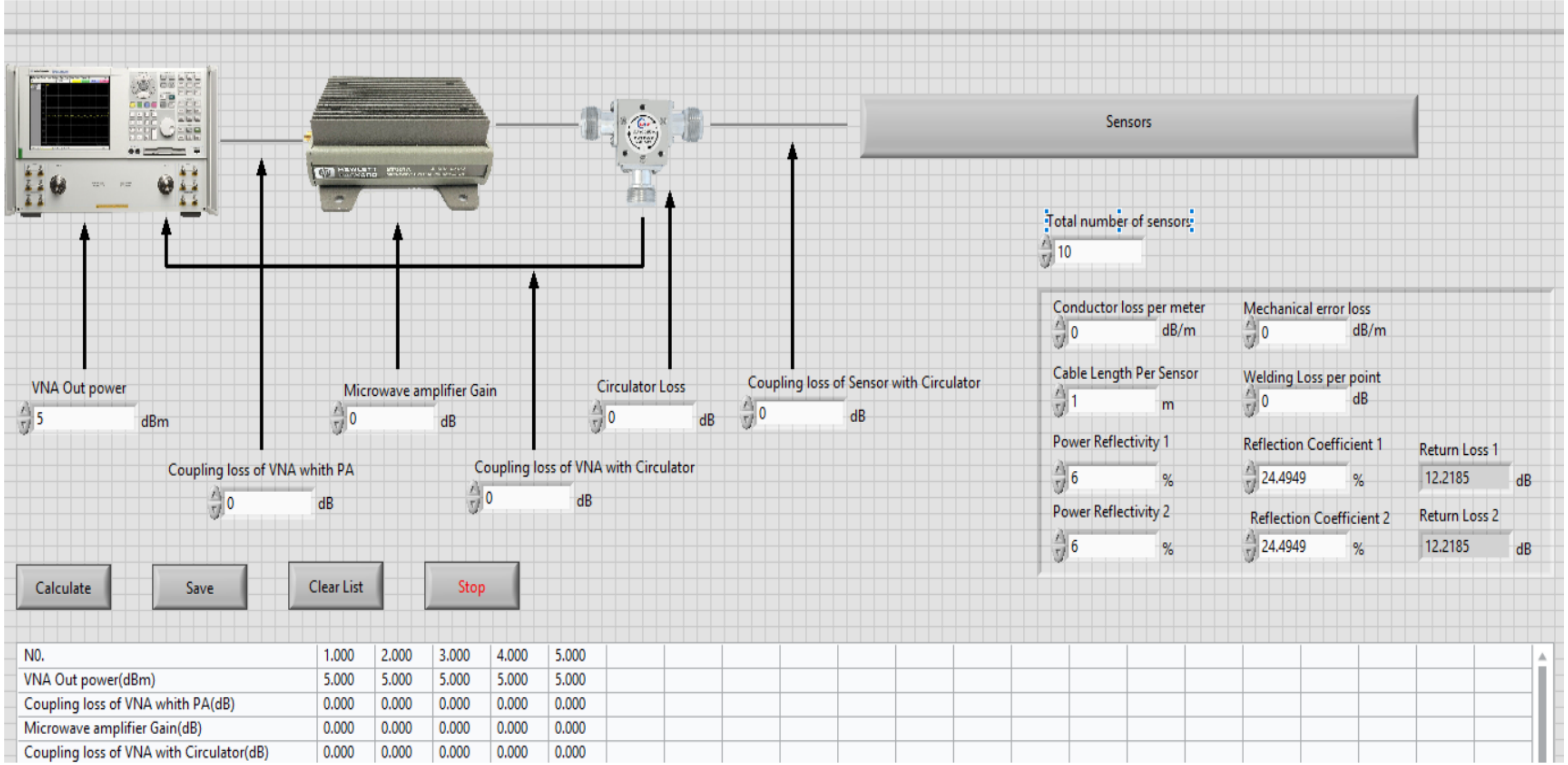
The system includes four parts:

- ❑ High-T distributed stainless-steel/ceramic coaxial cable sensors (**SSC-CCS**)
- ❑ **Instrumentation** system to interrogate SSC-CCS
- ❑ **Models** to optimize the sensor design/installation and understand the measurement results
- ❑ Condition-based monitoring (**CBM**) system



Project Update – Sensors

Power budget, Signal-to-Noise Ratio and System Design



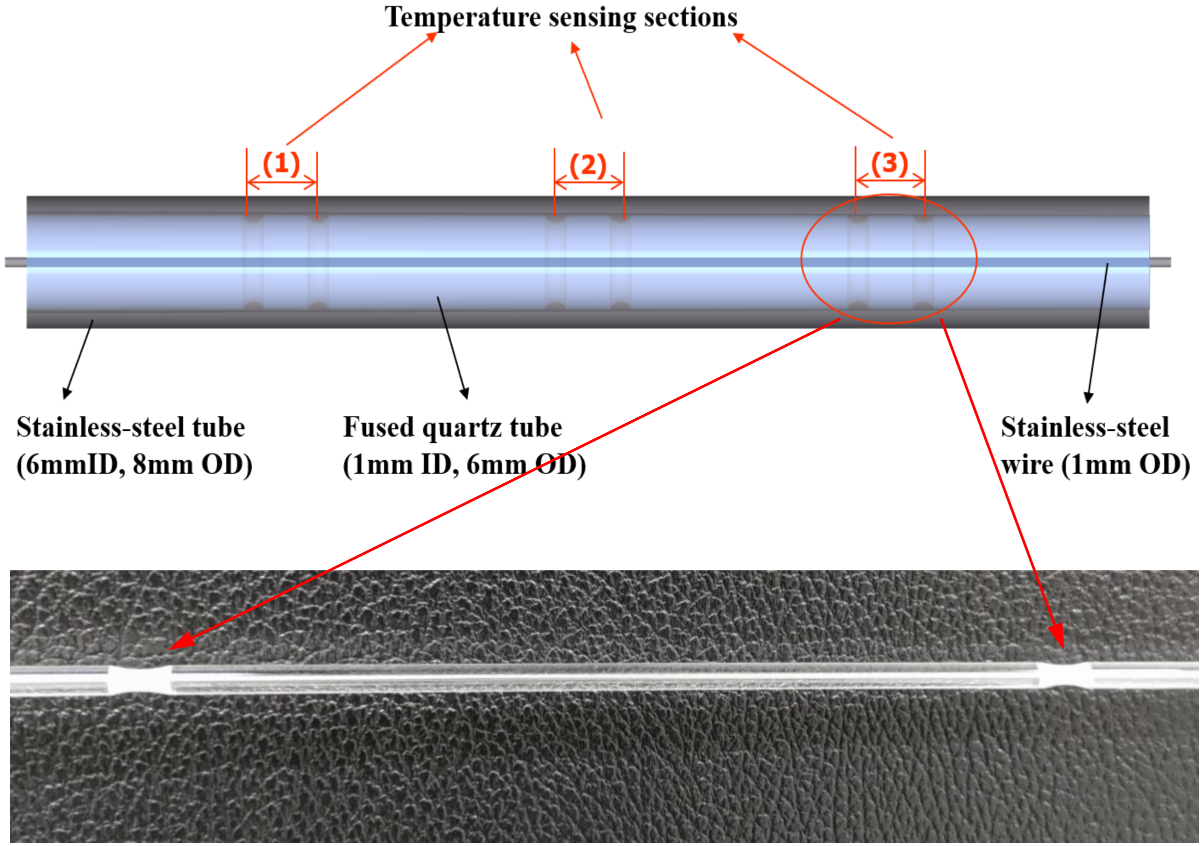
- Simulation software is developed to study the power budget and signal-to-noise ratio of the sensors and sensing system.

Project Update – Sensors

Sensor Design: Quartz as the insulator

Principle

- **Microwave reflections** are generated by polished notches along a quartz tube.
- The quartz tube **changes its length and dielectric constant** as a function of temperature.
- The change is measured accurately by **microwave interference**.



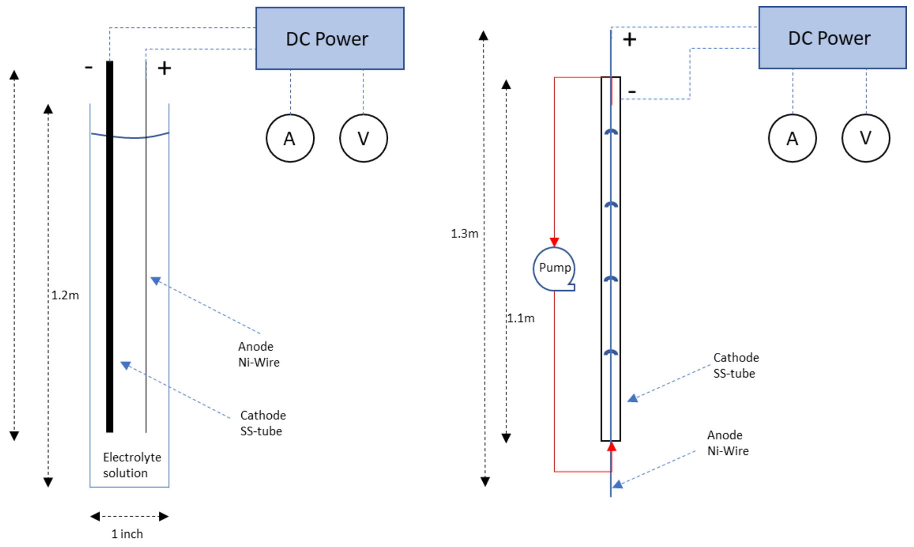
Advantages

- Sensing element is well protected.
- Quartz is stable (material and structure) at high temperatures.

Project Update - Sensors

Nickel Coating Development

- ❑ Development of surface coated conductors for enhancing the metal ceramic coaxial cable sensor performance
  - Establishment of lab apparatus for electroplating of Ni thin films on inner surface of the stainless steel (SS) tube and outer surface of SS wire for surface electric conductivity enhancement
  - The Ni coating thickness is varied between 10 – 40 μm for performance evaluation in the CCS.

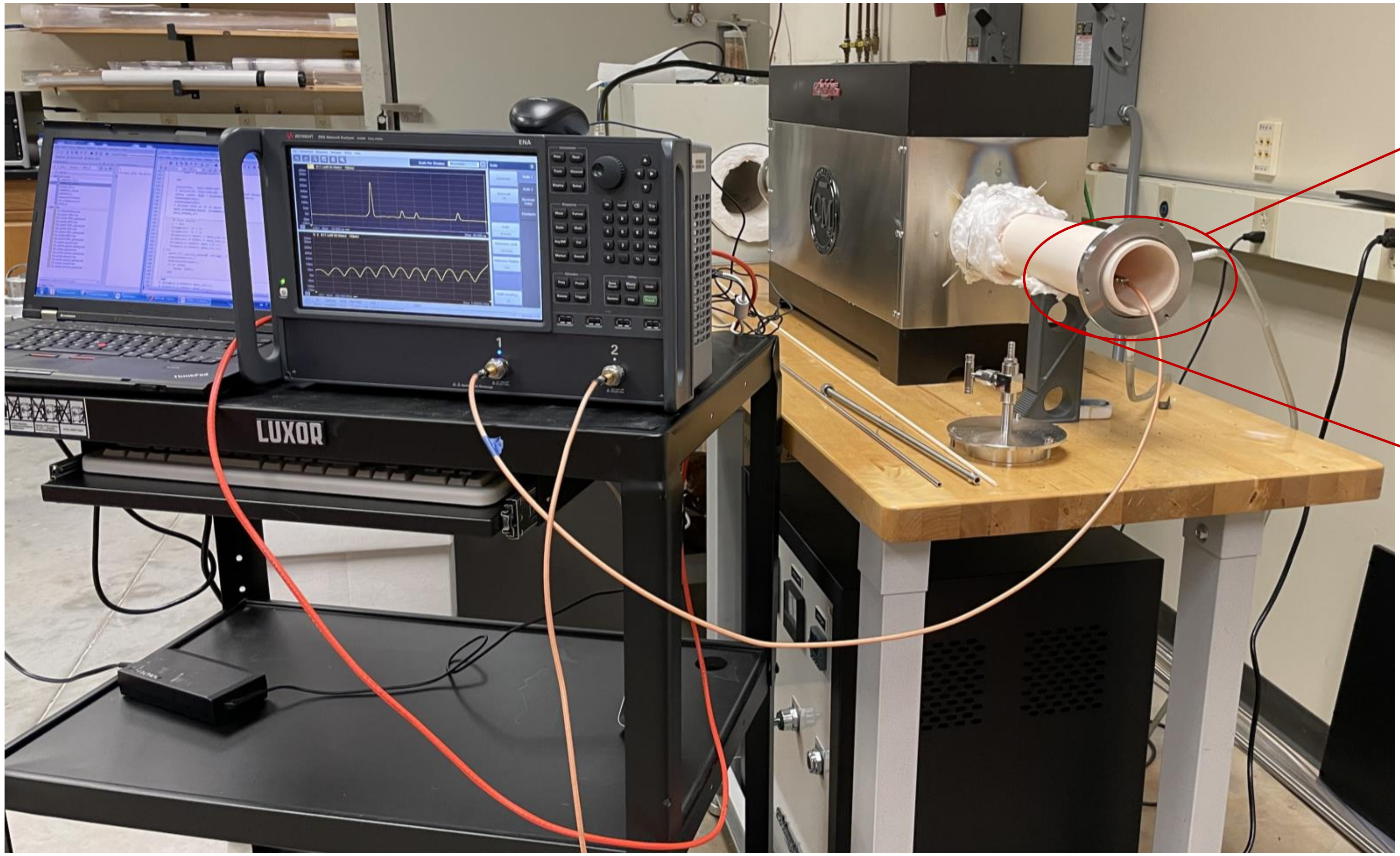


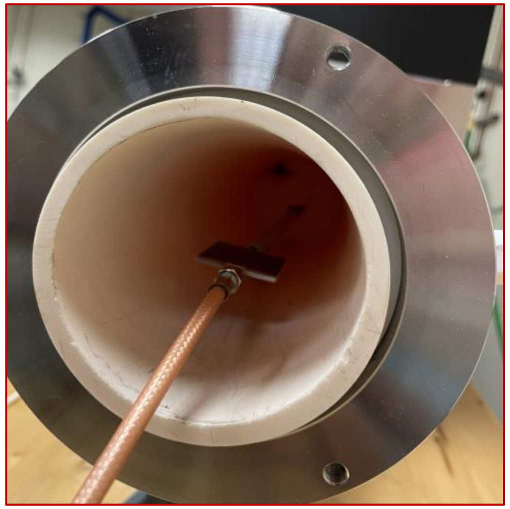
❑ Schematic showing the apparatus arrangements for electroplating (left) on outer surface of small SS tube or wire, and (right) on inner surface of large SS tube.

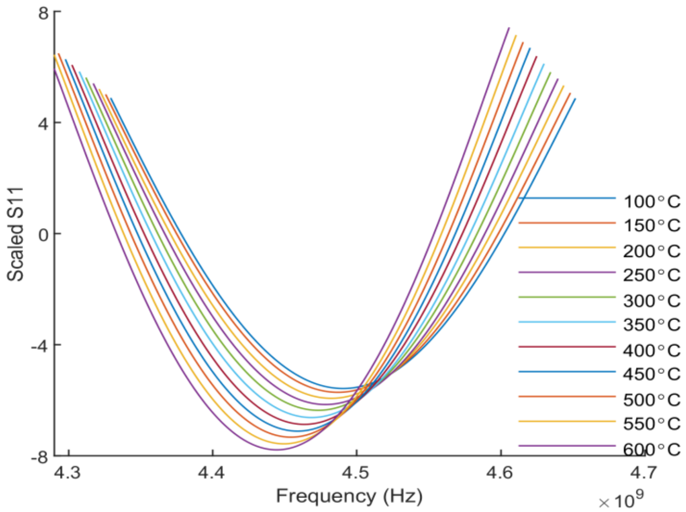
Sample dimensions	Quantity	electroplating duration, h	Voltage, V	Ave. current, A	Thickness, μm
Tube: OD = ¼"; L = 1.10 m	4	2	1.5	1.4	20±2
Tube: OD = ¼"; L = 1.10 m	2	2	1.3	0.7	10±1
Tube: OD = 3/8"; L = 1.10 m	4	4	1.3	0.6	40±3
Tube: OD = 3/8"; L = 1.10 m	2	2	1.3	0.7	20±2
Wire: φ = 1/16"; L = 1.10 m	4	2	1.5	1.3	20±2
Wire: φ = 1/16"; L = 1.10 m	2	2	1.3	0.5	10±1
Tube: OD = 1/8"; L = 1.10 m	4	4	1.3	0.5	40±3
Tube: OD = 1/8"; L = 1.10 m	4	2	1.3	0.4	20±2

Project Update – Sensors

Test at high temperatures – resolution and stability

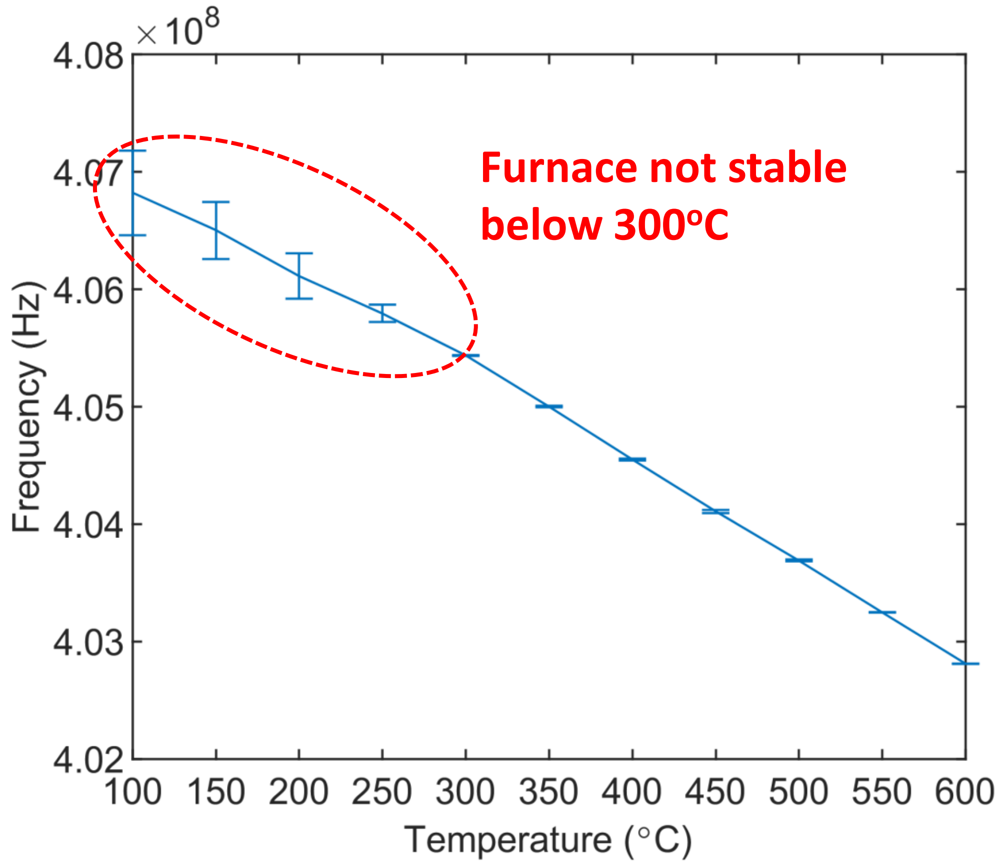


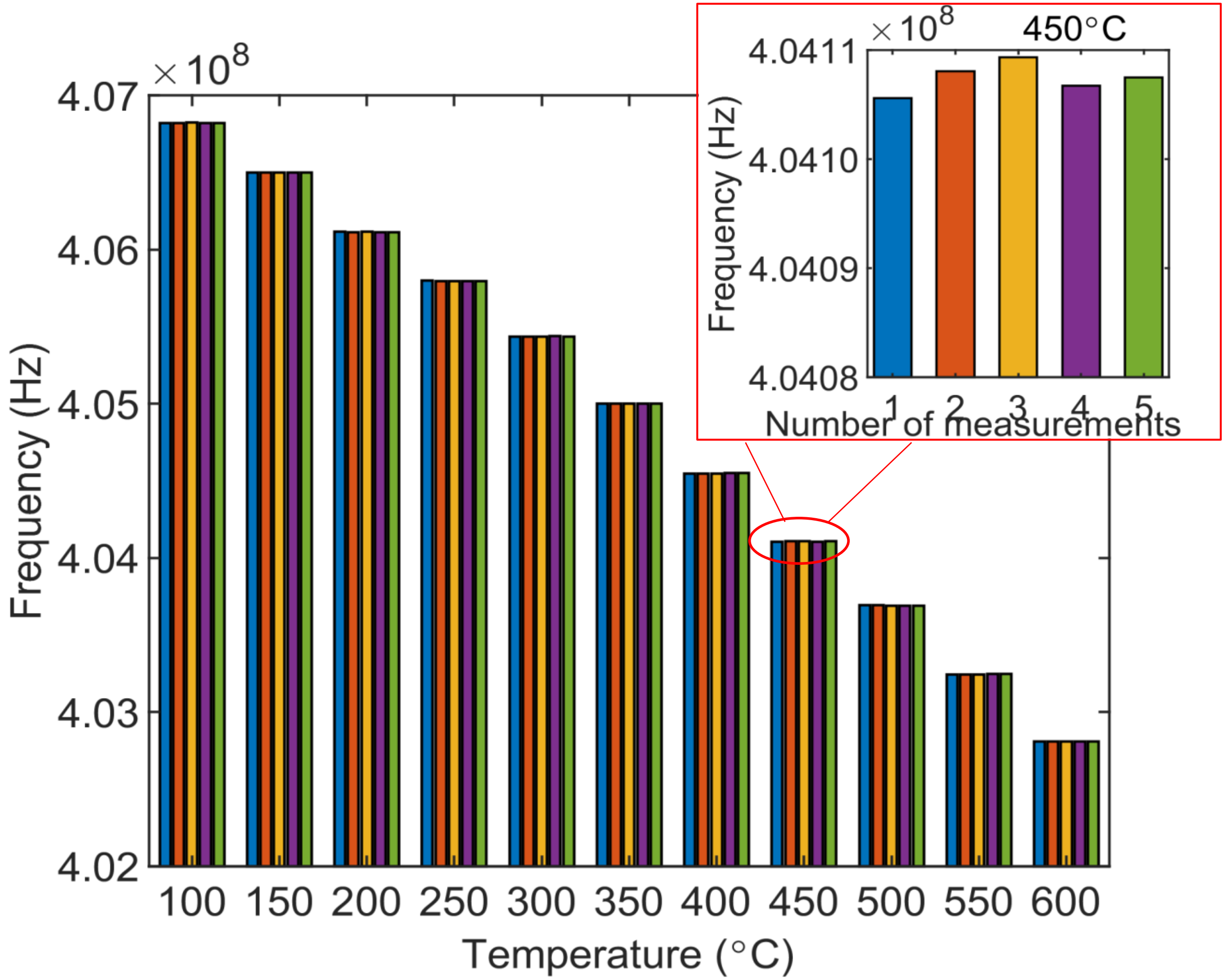




Project Update – Sensors

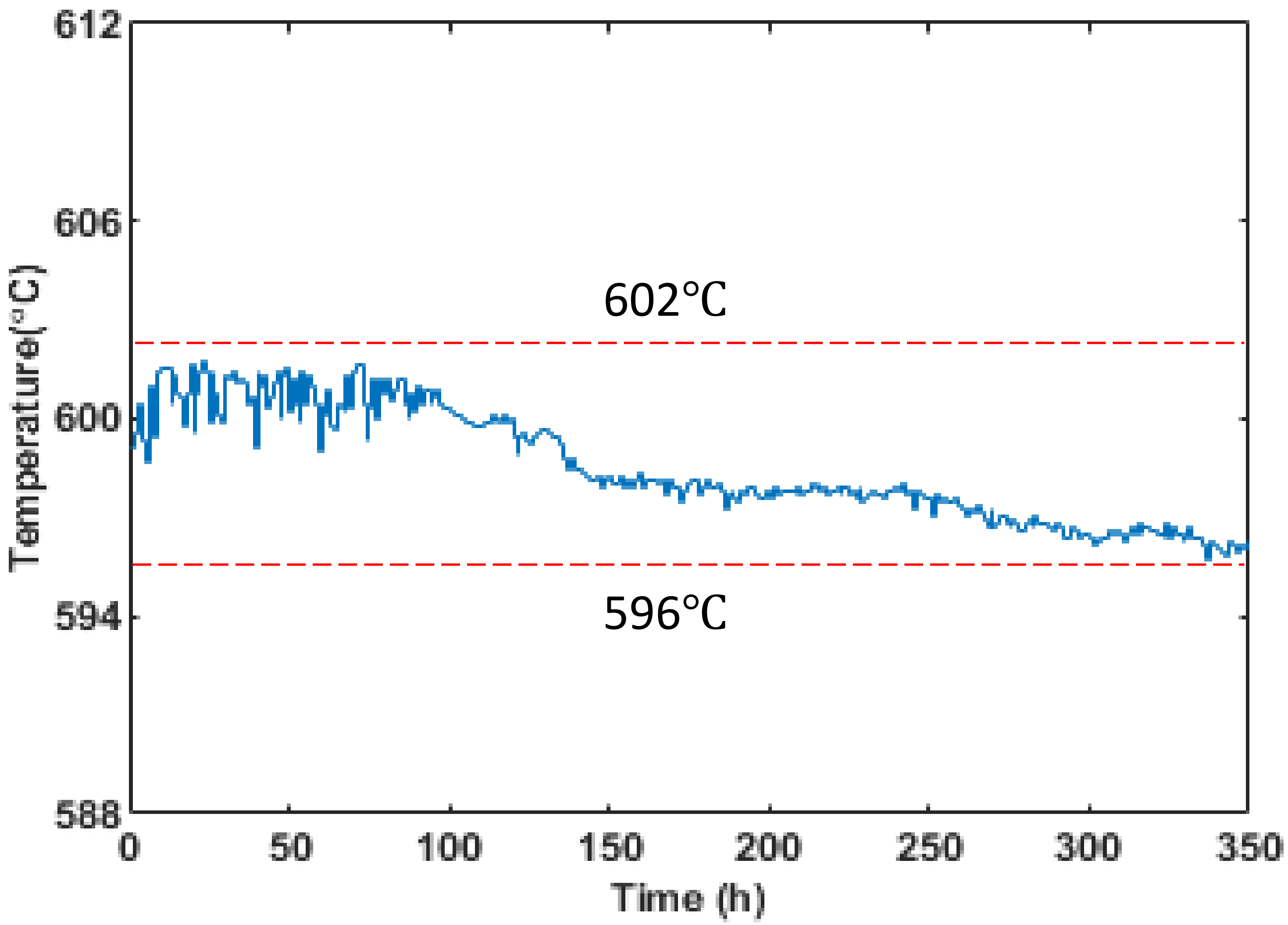
Sensor test results – Temperature resolution about 0.5°C





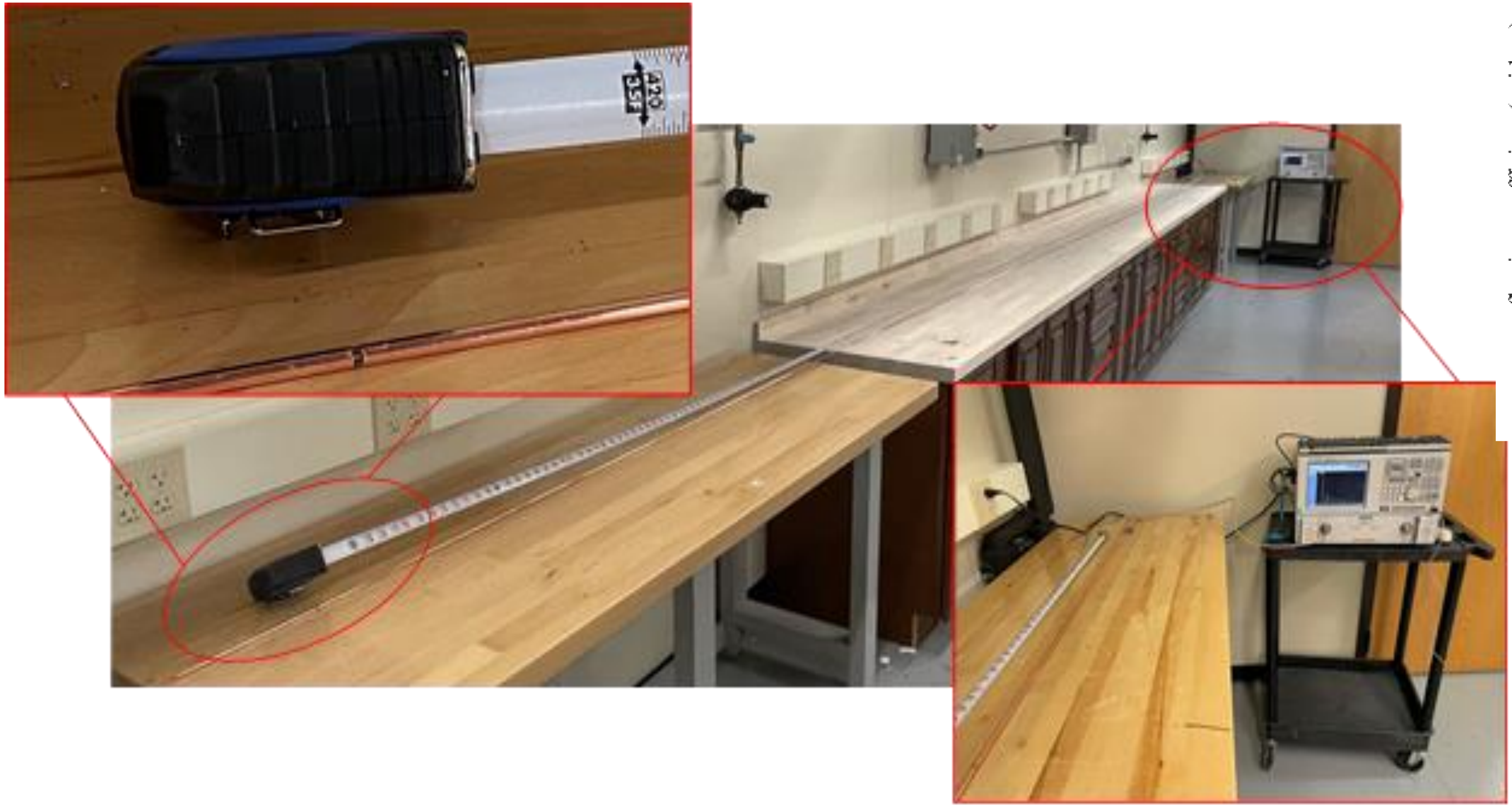
Project Update – Sensors

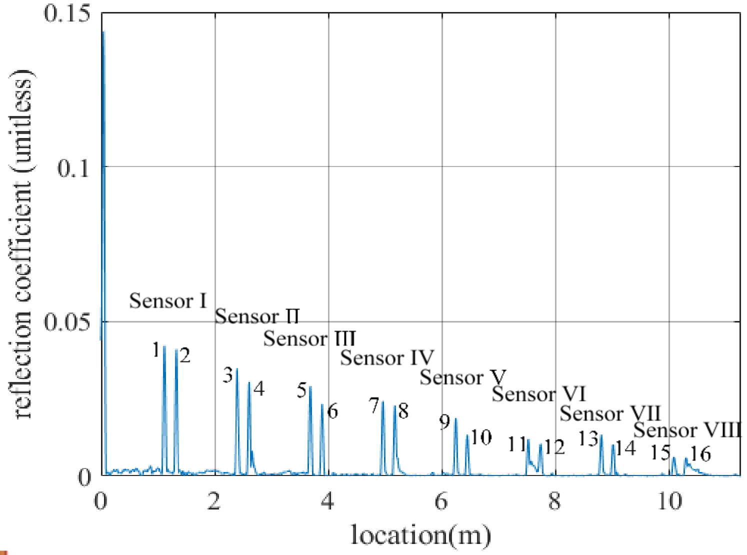
Sensor test results – 350 hours stability at 600°C, Less than 6°C peak-to-peak including furnace drift

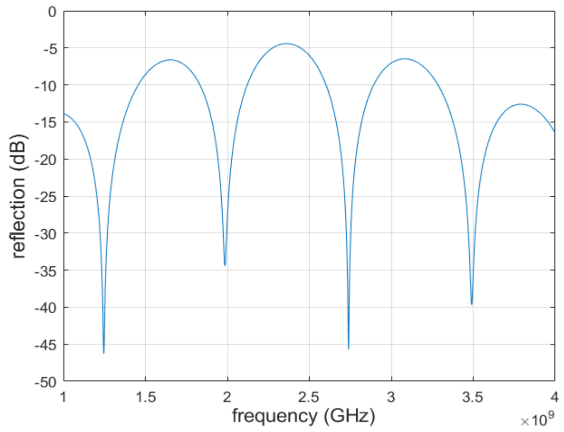


Project Update - Sensors

Distributed sensing – 10 meters with 9 sensors multiplexed

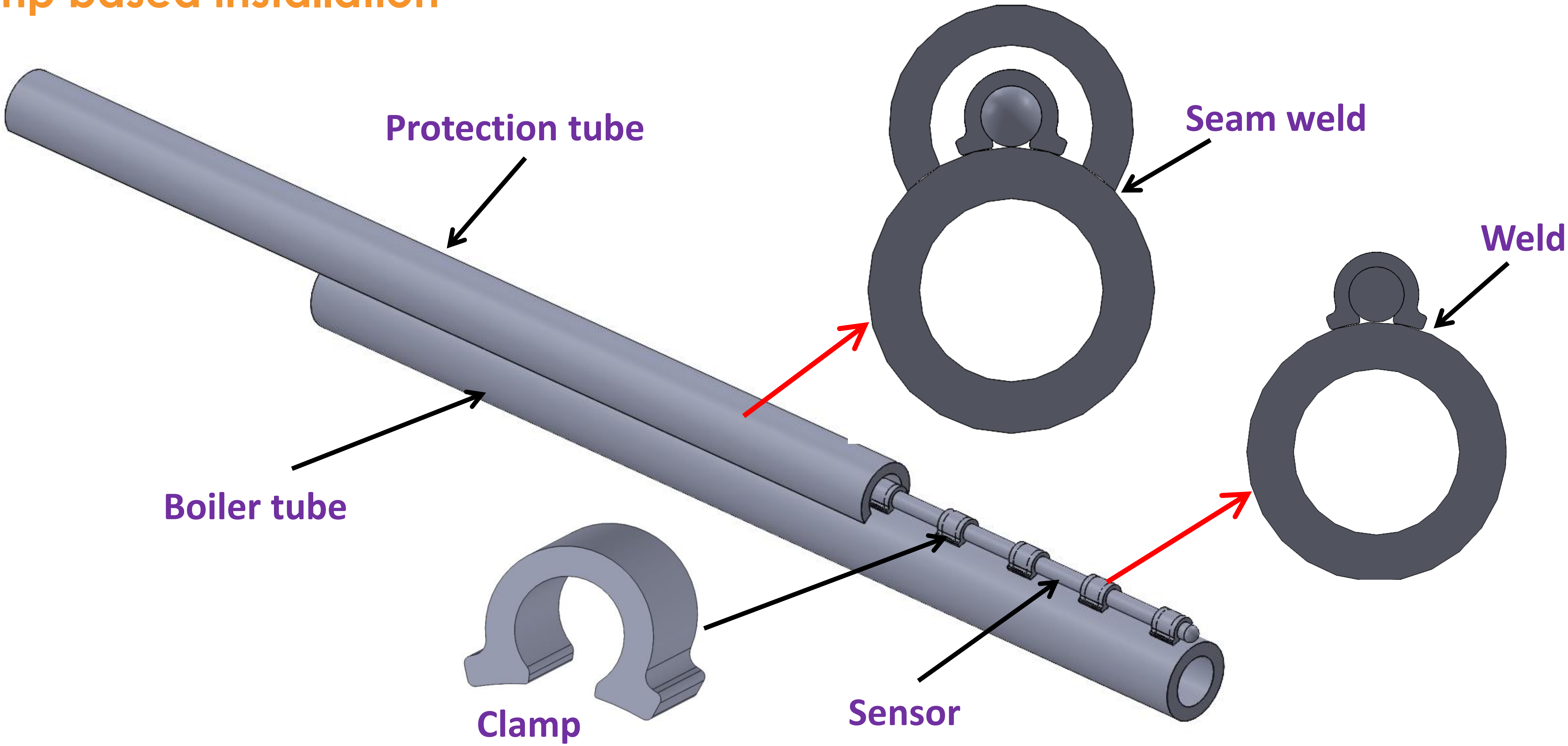






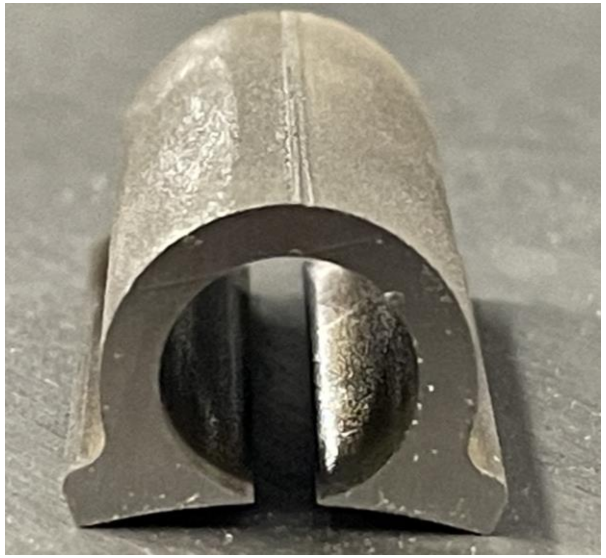
Project Update – Installation

Clamp based installation



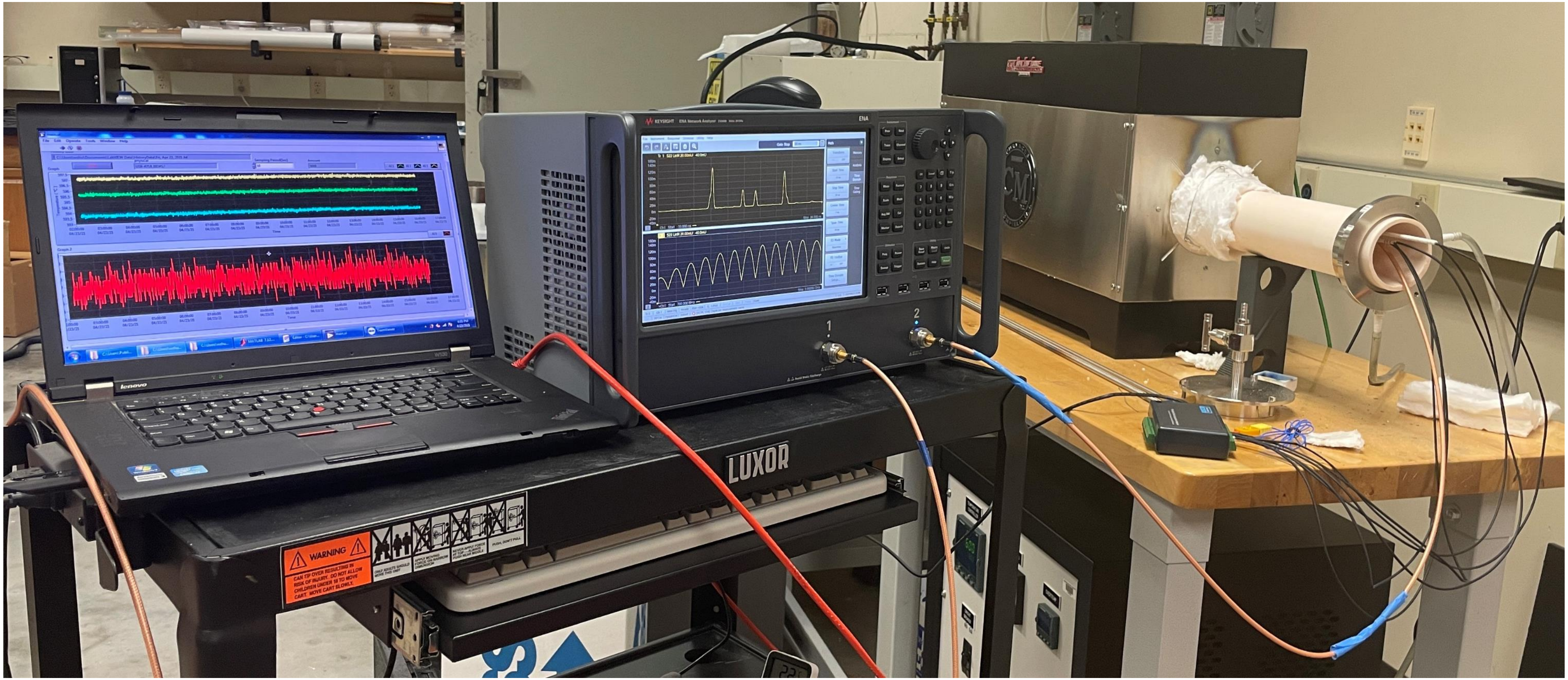
Project Update – Installation

Clamp based installation



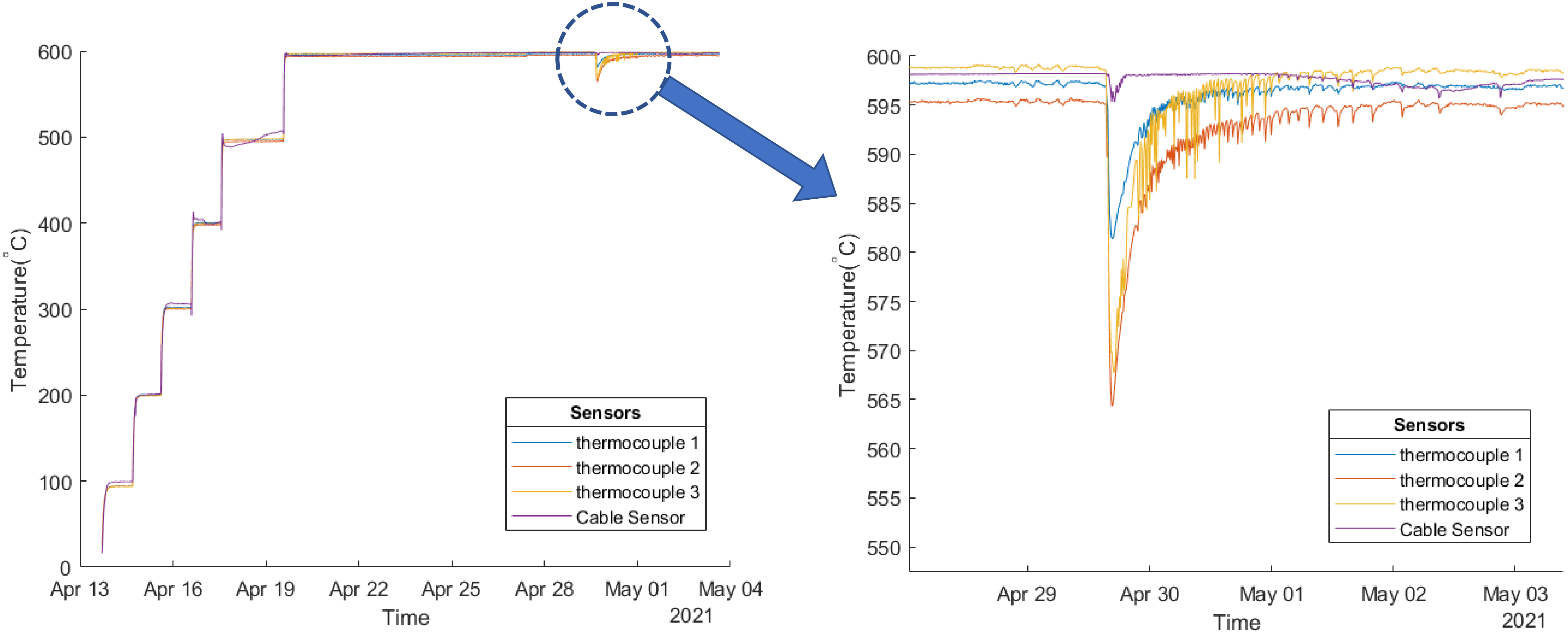
Project Update – Installation

Test the sensor welded boiler tube



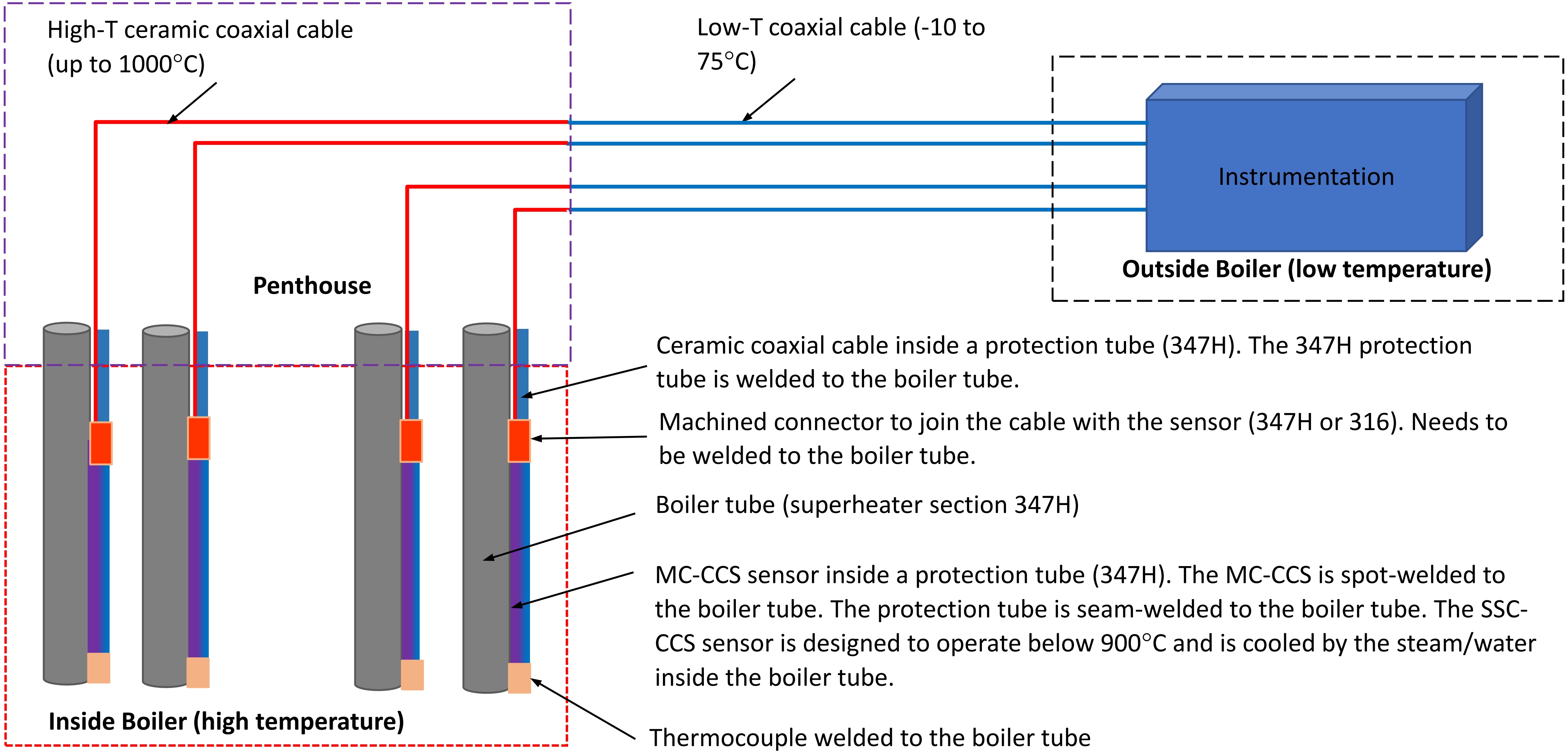
Project Update – Test results

Test results of Clamp based installation



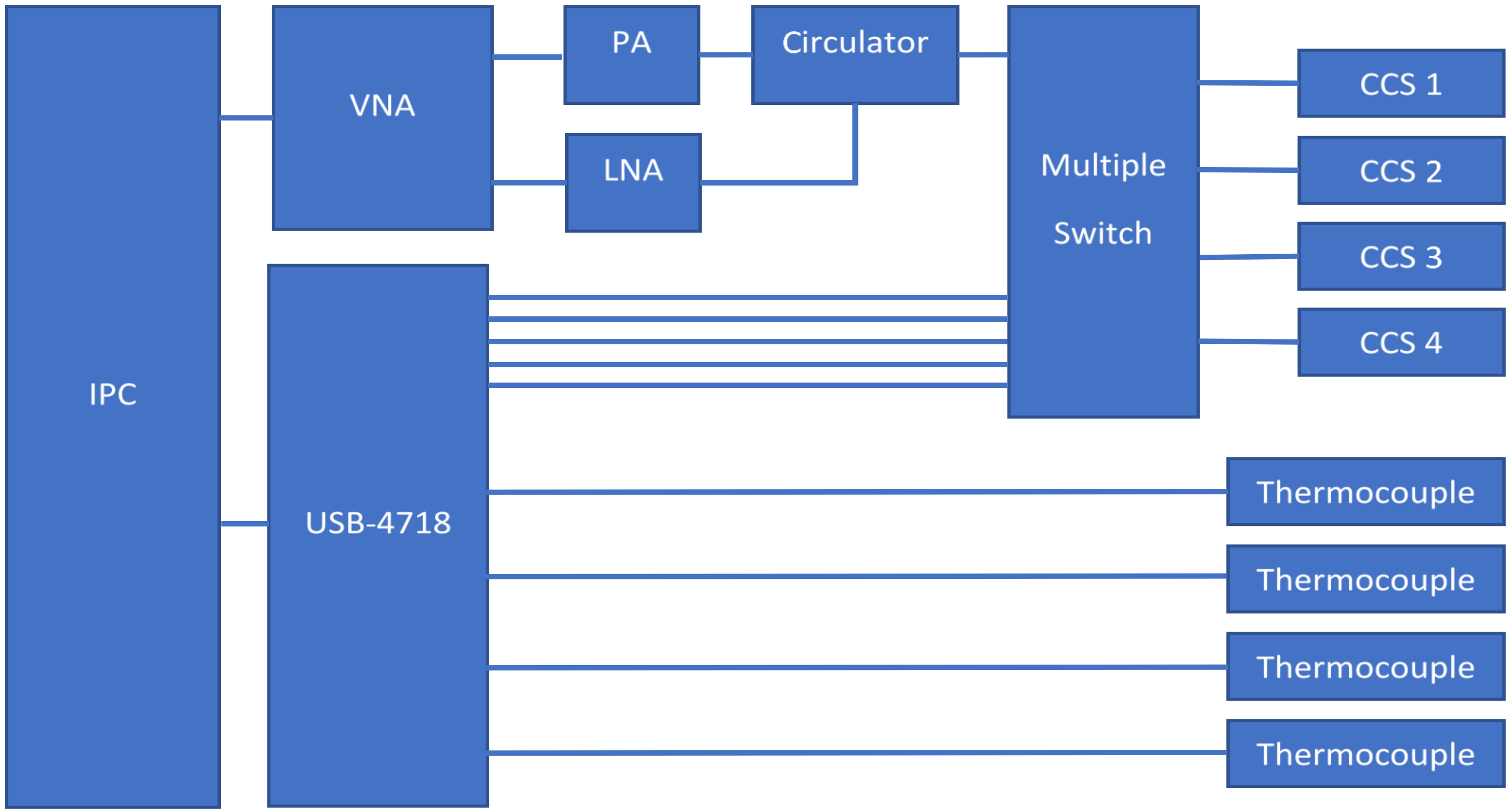
Project Update – Installation

Sensor attachment and connections



Project Update – Instrumentation

Data acquisition system and on-site instrumentation



Software:

- **Window 10**
- **LabView**
- **Microsoft Office**

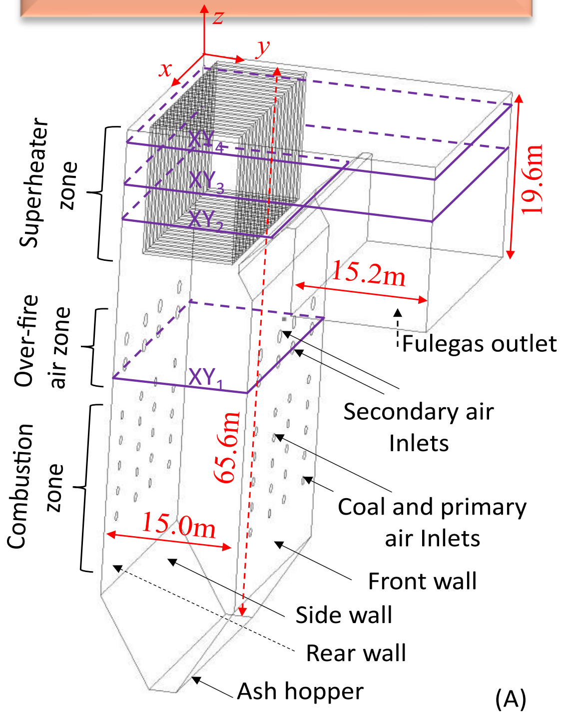
IPC: Industrial Personal Computer
VNA: Vector Network Analyzer
PA: Microwave Power Amplify
LNA: Low Noise Amplify
Multiple switch: Microwave Multiple Switch
CCS x: Coaxial cable sensor
USB-4718: 4 DIO ports to control Multiple Switch; 4 analog interfaces for thermocouple data acquisition

Project Update – Modeling

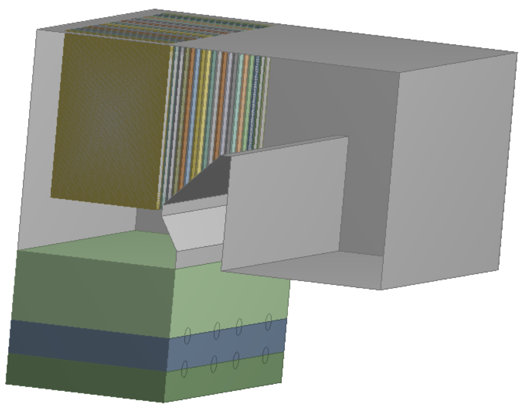
Multi-physics Modeling on Reference Boilers

- ❑ **Establish 3-D computational fluid dynamics and heat transfer model for coal fired boiler**
- ❑ **Evaluate Temperature/ thermal stress/deformation profile of the sensor and steam pipes**
- ❑ **Failure mechanisms**

Coal Fired Boiler Model

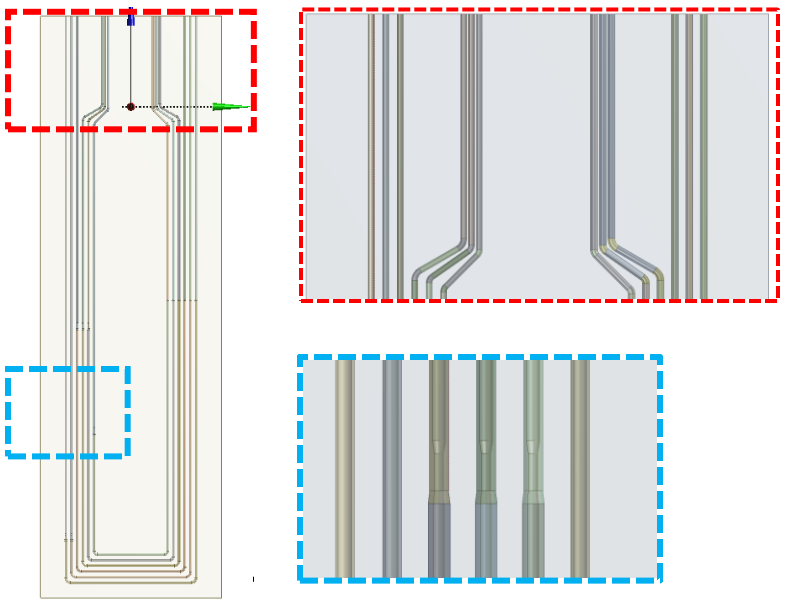


Steam Pipe Panel Model (Simplified)



Simplify the superheater boiler tube session with plate shape boiler tube panels (10m×15m×1m)

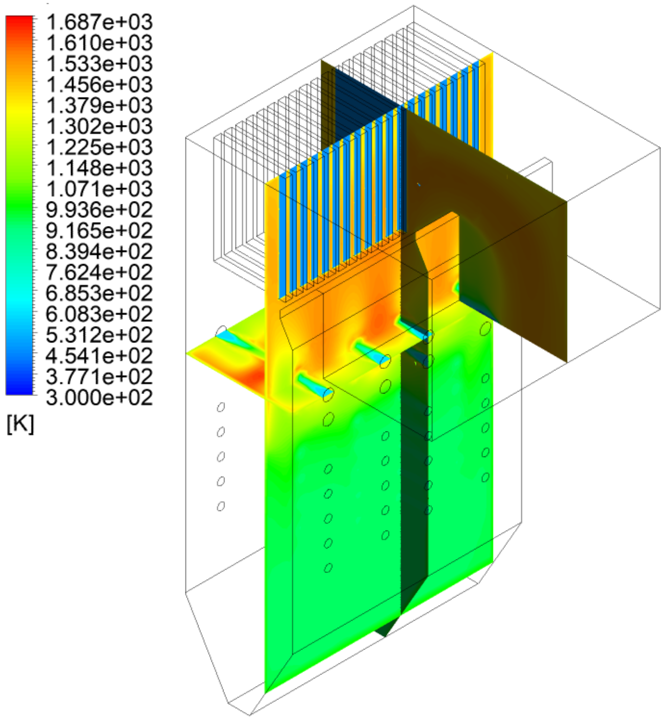
Steam Pipe Model (Full scale)



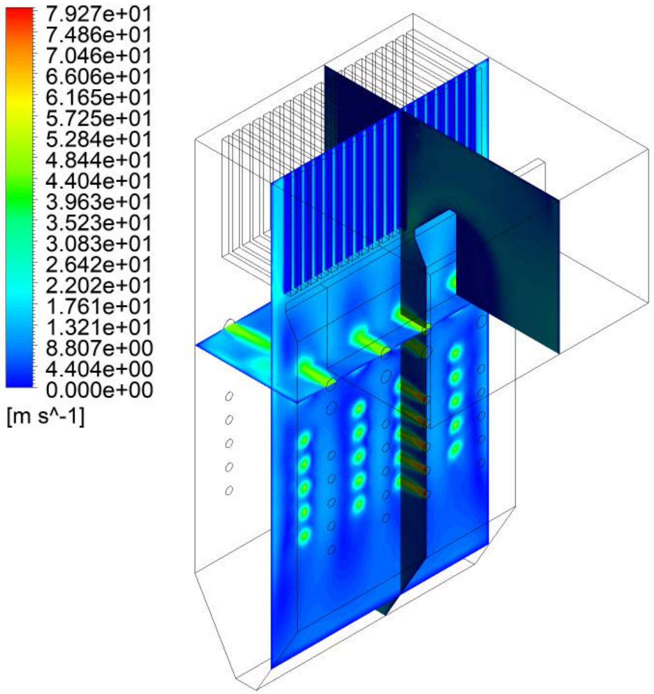
Project Update – Modeling

Multi-physics Modeling on Reference Boilers

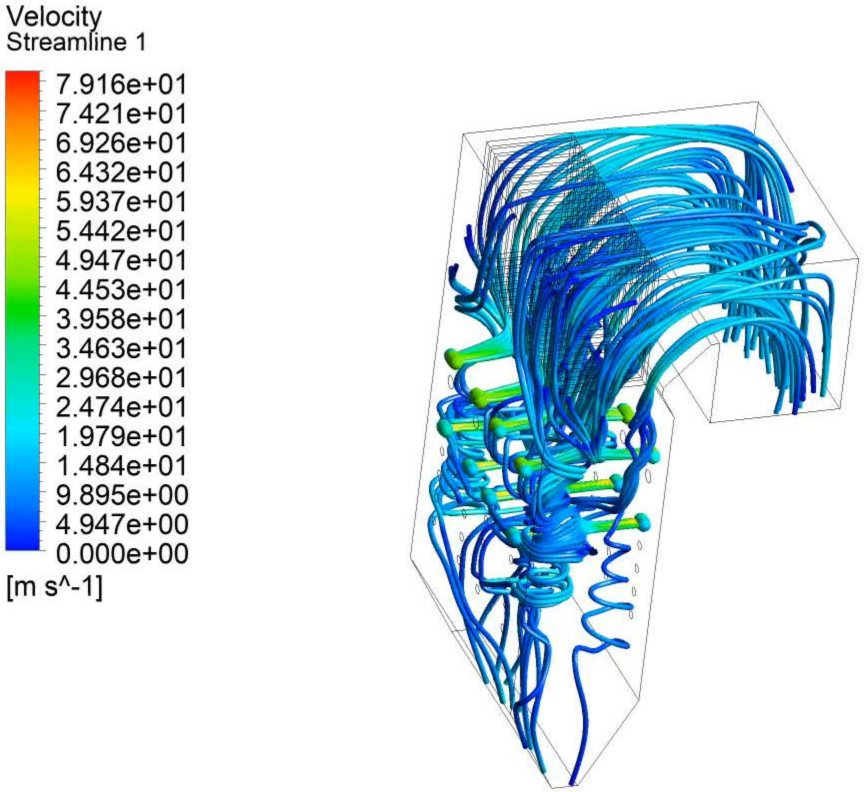
- ❑ **Predict the flue gas condition at the superheater/reheater region for sensor modeling and sensor installation guidance**



- Temperature Profile at the Steady State



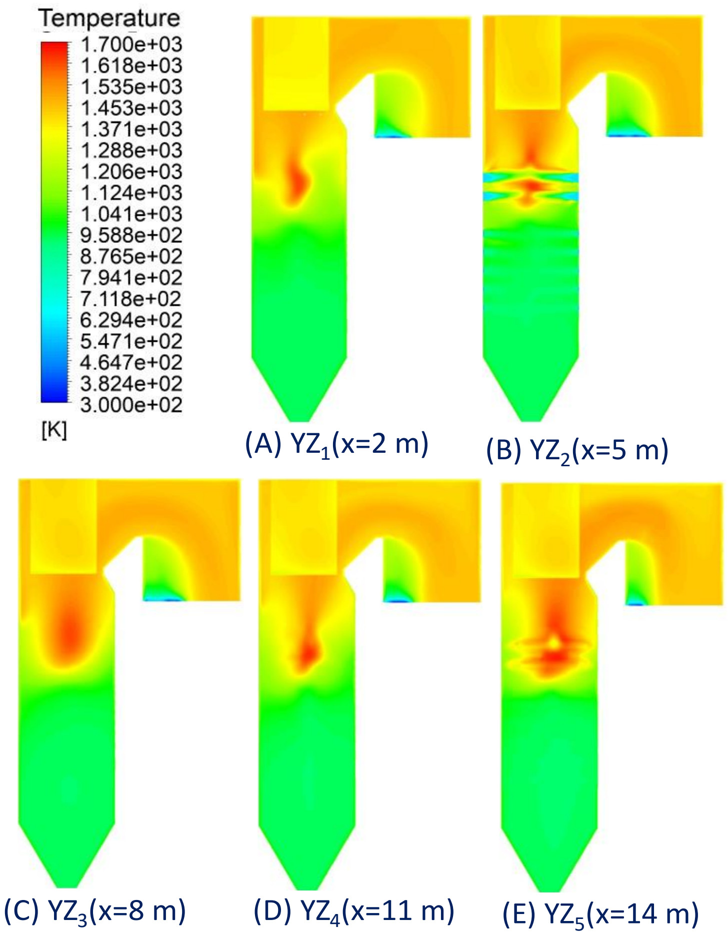
- Velocity Profile at the Steady State

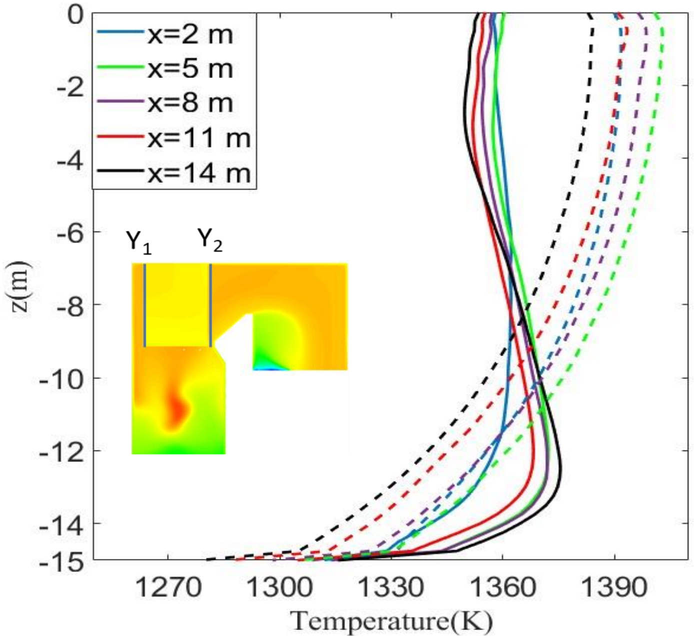


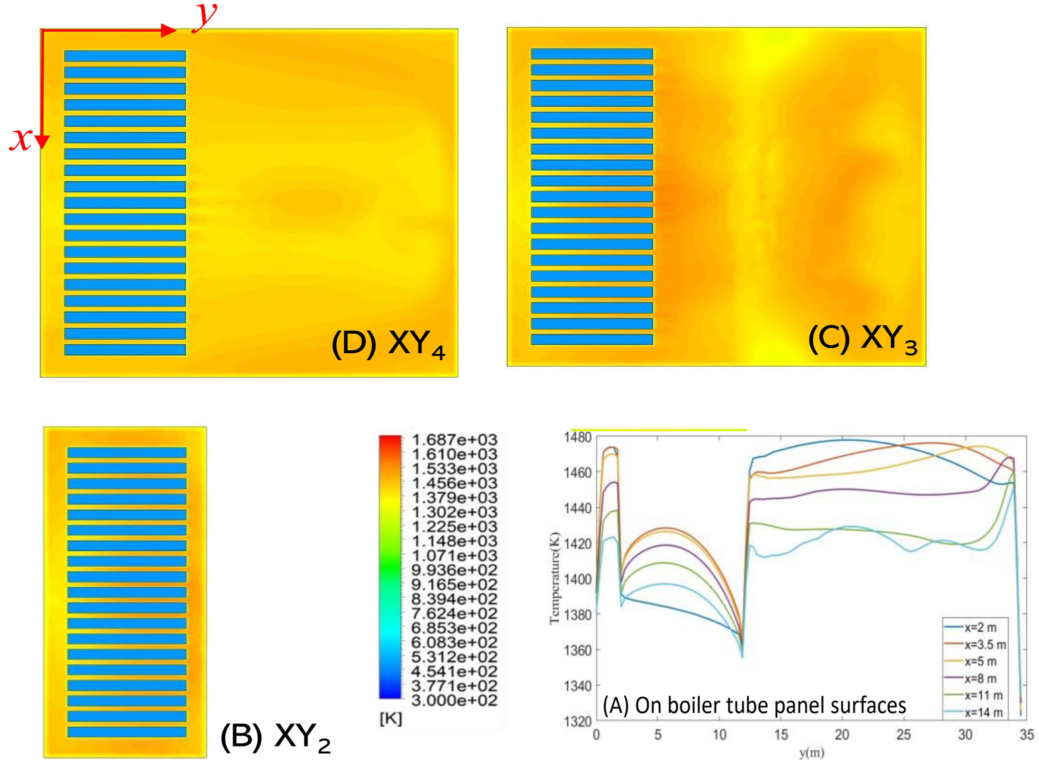
- Velocity Steamline starting from the coal inlets for air flow behavior

Project Update – Modeling

Criteria to Determine the Temperature Sensor Installation Location







- ❑ **Select the boiler tube panel away from the side walls**
- ❑ **Select the boiler tube section closer to the top wall of the boiler**
- ❑ **Select the boiler tube on the back of the boiler panel (not directly facing the flue gas flow).**

Project Update – Modeling

Boiler Tube Panel Modeling

- ❑ **Predict the temperature/stress distribution along the steam pipe for sensor installation plan and failure mechanism study**

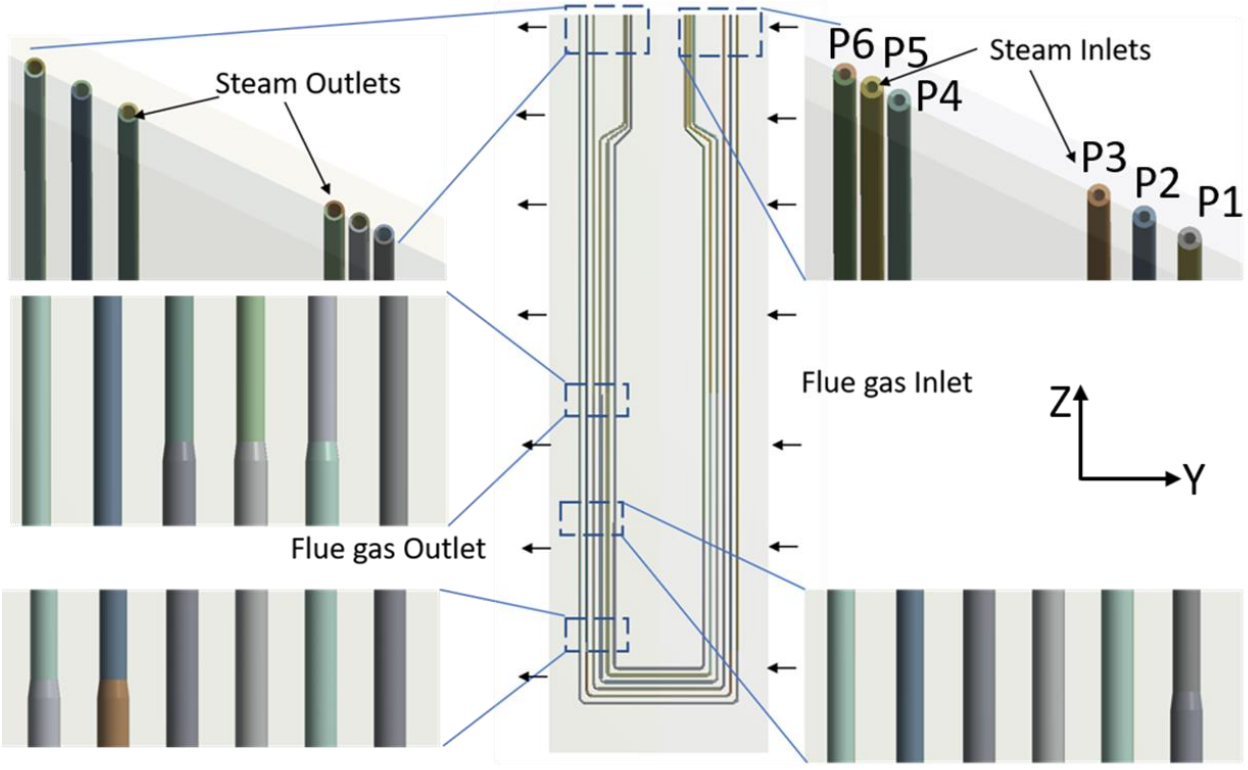
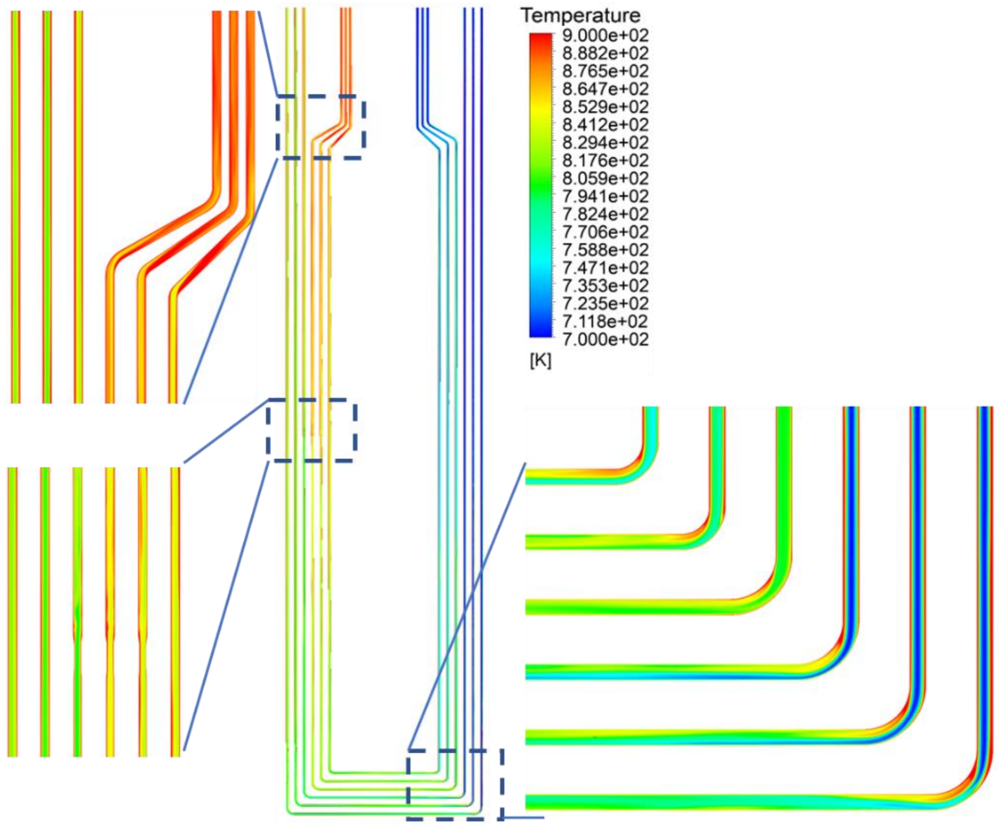


Figure 1: Steam panel with steam tubes

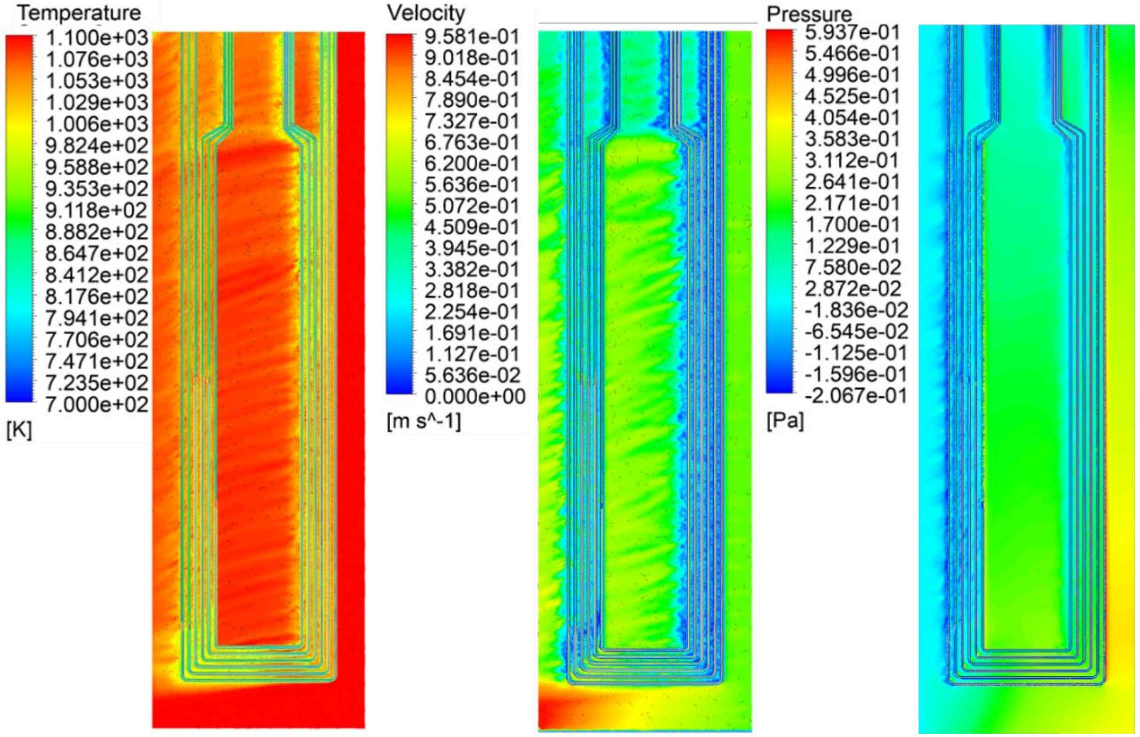


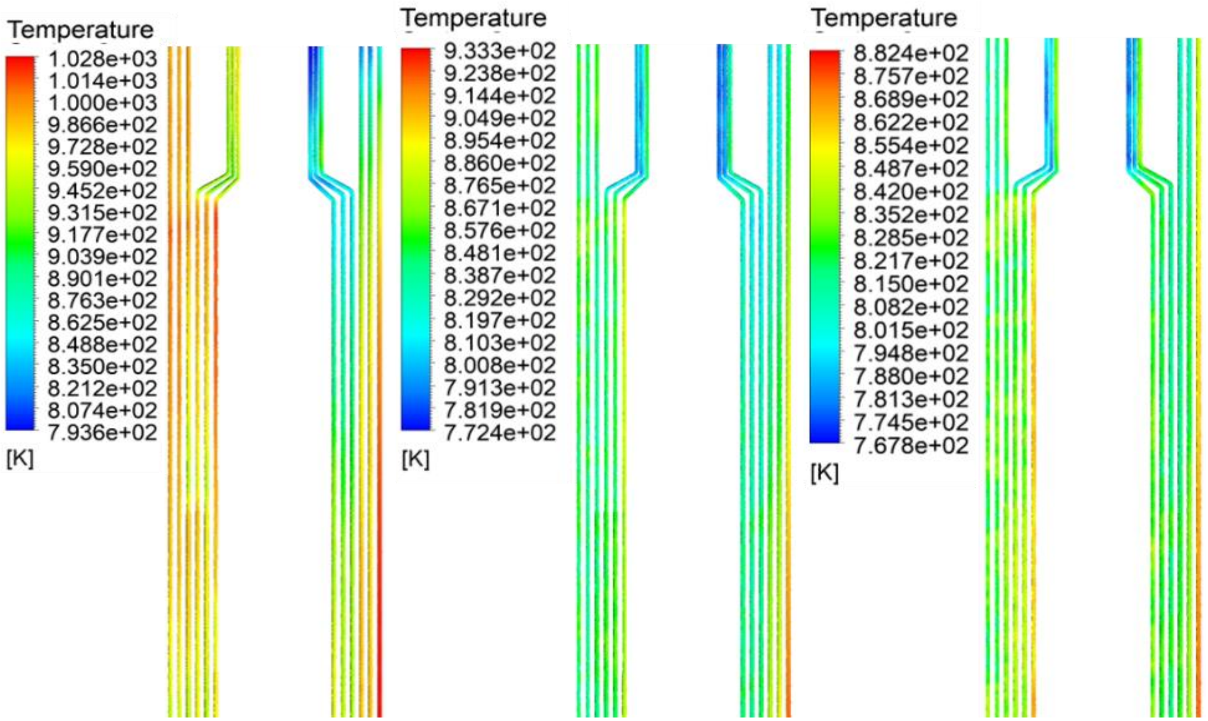
- More than 60 million of elements
- Temperature Profile of the steam

Project Update – Modeling

Boiler Tube Panel Modeling

- ❑ **Predict the temperature/stress distribution along the steam pipe for sensor installation plan and failure mechanism study**



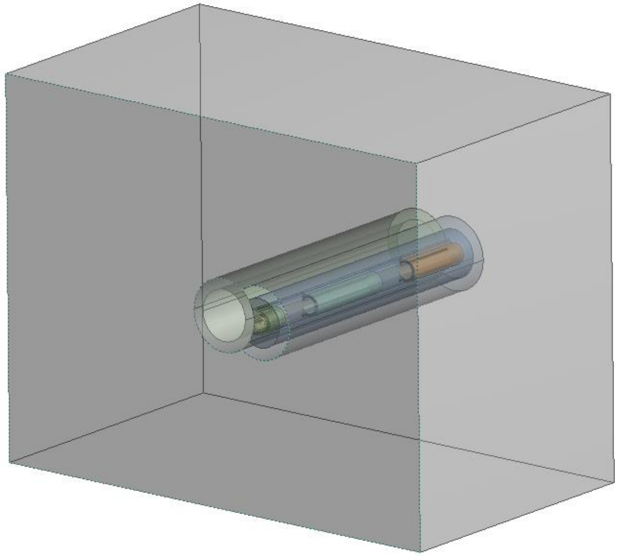


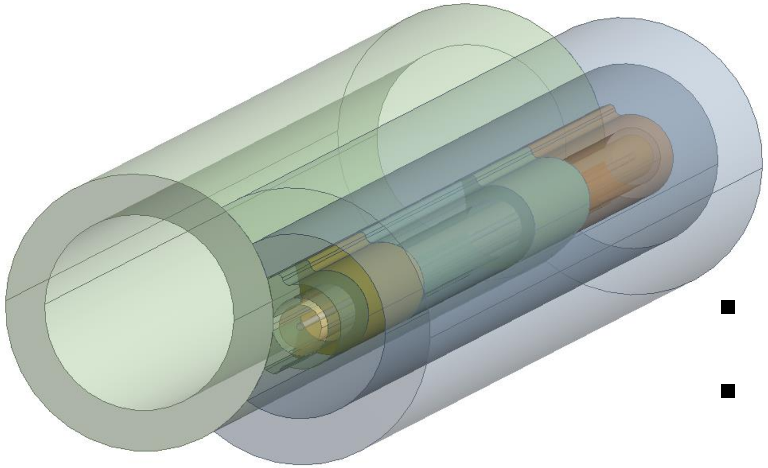
- Temperature, velocity and pressure profiles of the flue gas domain
- Boiler pipe temperature distribution is sensitive to the mass flow rate of the steam

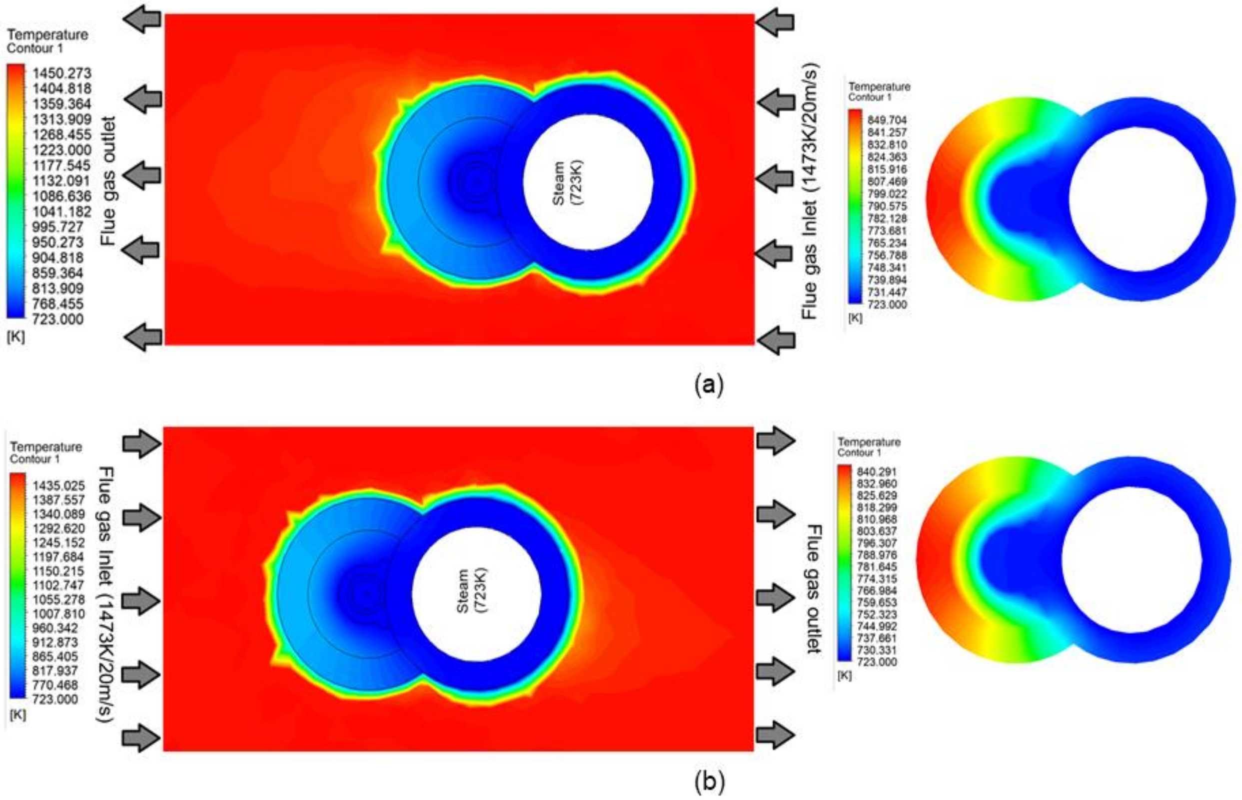
Project Update – Modeling

Multi-physics Modeling on Sensor Design and Optimization

- ❑ **Establish 3-D Computational Fluid Dynamics, Heat Transfer, and Structural Mechanics Model for Sensor Design and Optimization**





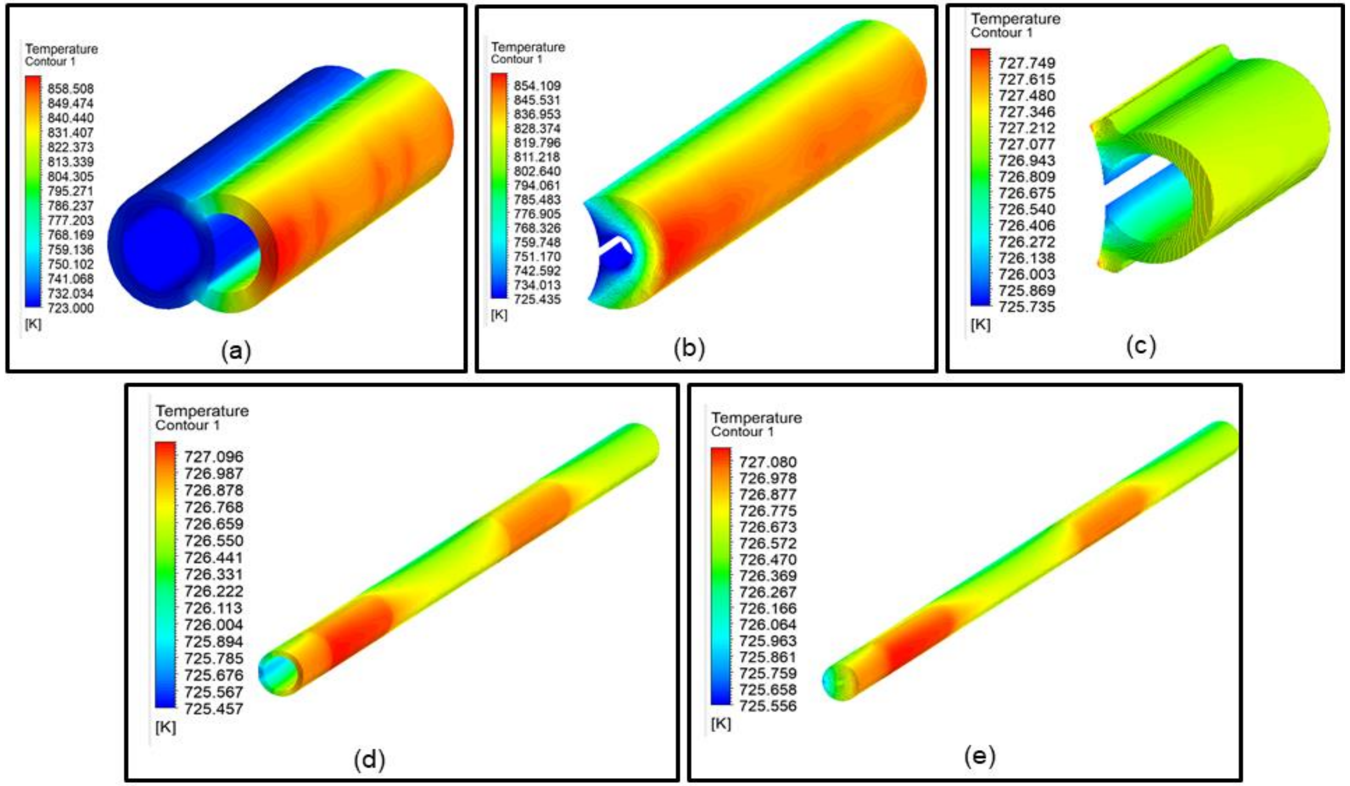


- Temperature dependent properties is considered in the simulation
- Fluegas direction is not an important factor to sensor performance

Project Update – Modeling

Multi-physics Modeling on Sensor Design and Optimization

- **Predict the sensor response with respect to various steam pipe/flue gas condition in order to guide the sensor design and optimization**

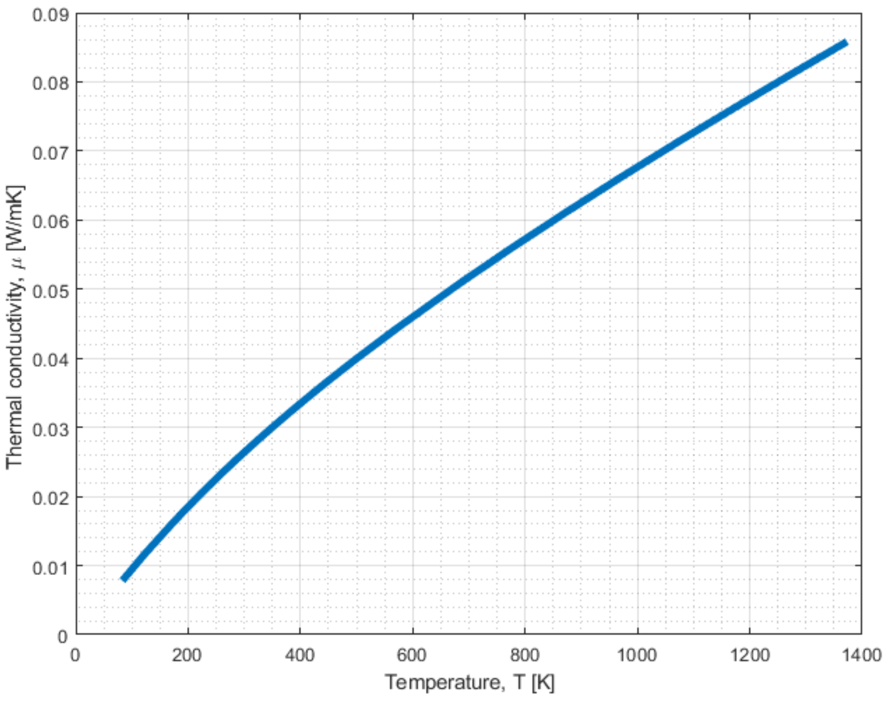


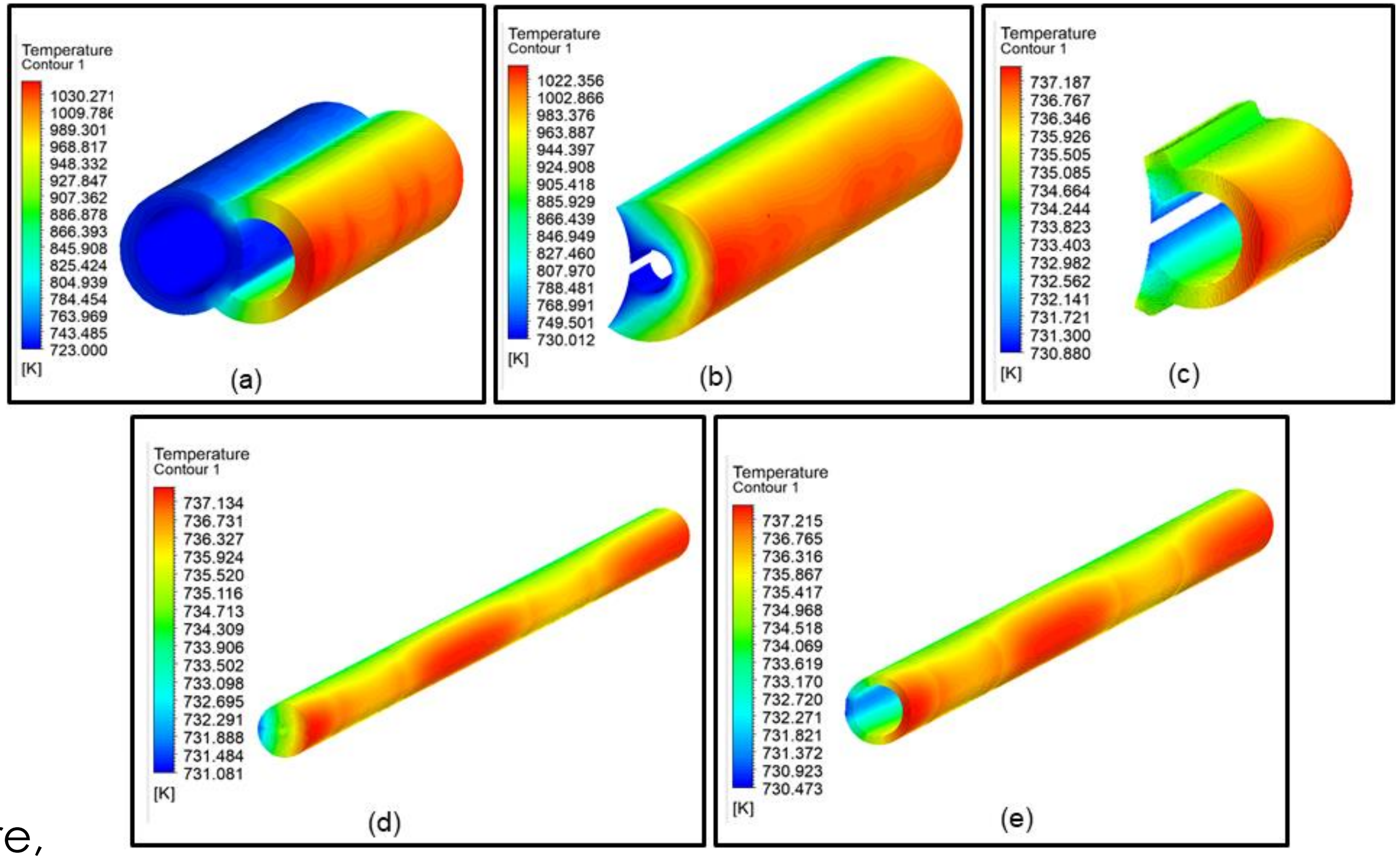
Cases [Steam /flue gas] (K)	Protective wall [Max/min]	Air domain [Max/min]	Clamps [Max/min]	Outer Conductor [Max/min]	Quartz [Max/min]
723 / 1423	858.5 / 723	854.5 / 725.4	727.8 / 725.7	727.1 / 725. 5	727.1 / 725. 5
723/1423 (opposite to flue gas)	845.9 / 723	842.1 / 725.3	727.5 / 725.6	726.8 / 725.4	726.8 / 725.3
723 / 1423 (Variable air property)	1030.3 / 723	1022.4 / 730	737.2 / 730.9	737.2 / 730.5	737.3 / 731.08
750 / 1100	813.6 / 750	811.5 / 751.1	752.2 / 751.3	751.9 / 751.1	751.9 / 751.2
923 / 1773	1061.7 / 923	1057.1 / 925.4	927.8/ 925.7	927.0 / 925.4	927.0 / 925.4

- Coaxial senor can capture the boiler pipe temperature with good consistency.

Project Update – Modeling

Multi-physics Modeling on Sensor Design and Optimization





- After consider the thermal conductivity variation of air with respect to temperature, the coaxial senor performance is satisfied.

Project Update – Test and Validation

Test and validate the technology in a real power plant

Plant A

- In collaboration with West Virginia University and EPRI because of the synergy of the two projects
- Sensor testing plan has been developed
- Two sets of 6-8 ft long coaxial cable sensors will be installed and tested in the superheater section
- Sample fabrication, installation and testing will be guided by engineers at EPRI and Southern Company Services

Areal picture of Plant A

Plan for Next Year

Sensor Fabrication, Installation and Testing

- ❑ Conduct the multi-physics simulations on boiler and coaxial cable sensor (CCS) for better sensibility and predict the sensor performance under various static/dynamic conditions.
- ❑ Optimize and finalize the CCS design and fabrication for best sensing performance, stability and robustness.
- ❑ Test boiler pipe with welded CCS.
- ❑ Sensor installation and field tests at Plant A.
- ❑ Develop the data analytics for the field testing.

Thank you!

Acknowledgment and Disclaimer

Acknowledgment: This material is based upon work supported by the Department of Energy Award Number DE-FE0031765.