Ultrasonic Measurements of Temperature Profile and Heat Fluxes in Coal-Fired Power Plants

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Acknowledgment and Disclaimer

Acknowledgment

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Project objective

- Advance technology-readiness level of ultrasound method for real-time measurement of temperature profiles in solids
- Test a prototype implementation of the technology at a utility power plant

Strategic alignment with Fossil Energy objectives

Reliably characterize extreme environments of energy conversion

- Even the most hardened sensors cannot withstand certain harsh environments of energy conversion processes for long
  - Extremely high temperatures and pressures
  - Chemical aggressiveness
  - Abrasion
  - Radioactivity

Rosemount Sapphire TC

Prof. Zhang Jiansheng (China): “Domestic TC survive ~1-2 weeks; Rosemount sapphire TC: ~4-6 weeks”

NETL, US DOE

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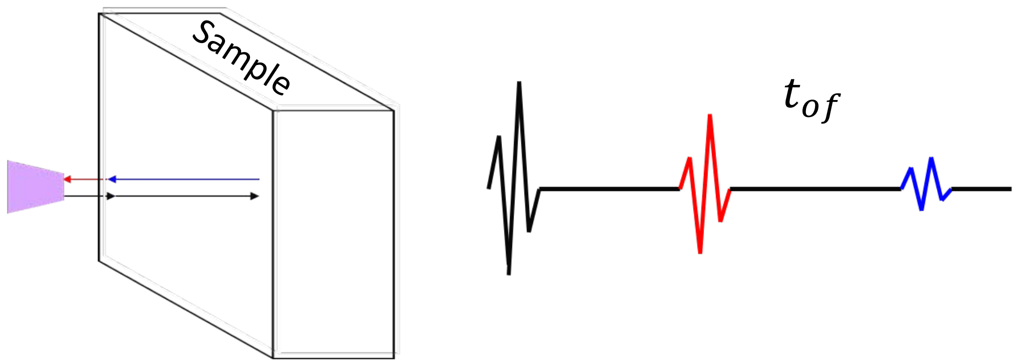
Technology status at the start of the project

Concept of US thermometry

- Speed of sound (SOS) is temperature dependent in gases, liquids, and solids: $c = f(T)$
- In *isothermal* case, in pulse-echo mode,

$$c = \frac{2L}{t_{of}} \rightarrow T = f^{-1}\left(\frac{2L}{t_{of}}\right)$$



- In *non-isothermal* case,

$$t_{of} = \int_0^{L(T)} \frac{2}{f(T(t,z))} \mathrm{d}z$$

- An unknown *temperature distribution*, $T(t,z)$, must now be found.

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Technology status at the start of the project

US thermometry of *temperature distributions*

- Deconvolution of $T(t,z)$ from TOF measurements,

$$t_{of} = \int_0^{L(T)} \frac{2}{f(T(t,z))} \mathrm{d}z$$

  is an ill-posed problem without a unique solution.

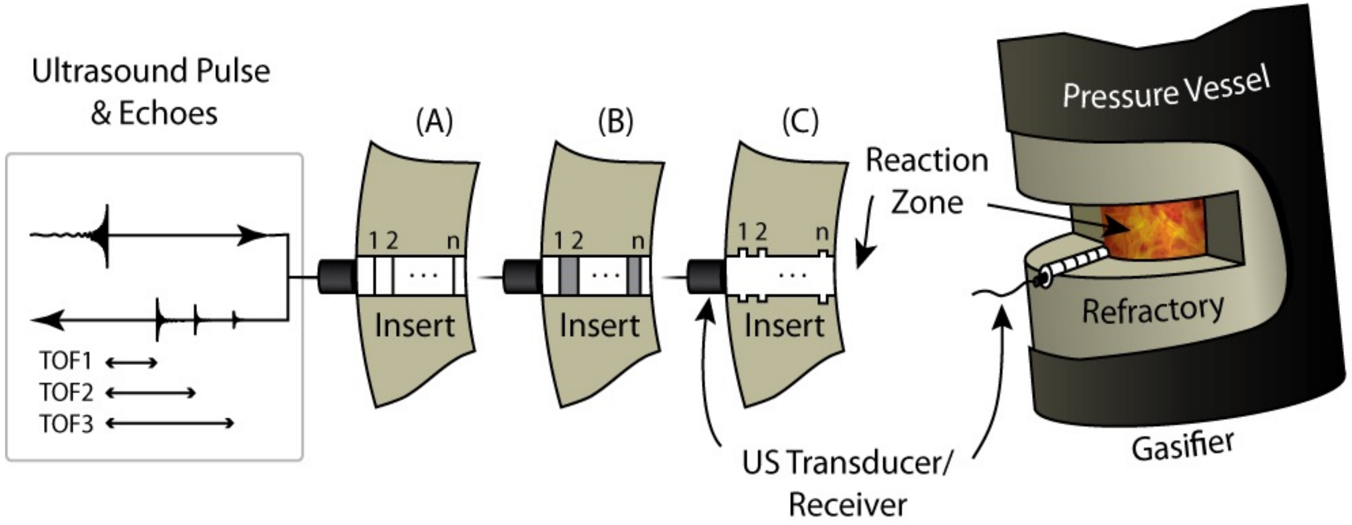
- Traditionally, the problem is resolved by:
  - Additional data from multiple transducers-receiver followed by tomographic reconstruction.
  - Imposition of constraints on allowable temperature distributions.

Technology status at the start of the project

US-MSTD Method

- **US M**easurements of **S**egmental **T**emperature **D**istributions: **US-MSTD** Method.
  - Design US propagation path to create multiple US echoes that encode information about temperature distribution in different segments

- Methods to create echogenic features:
  - Introduces change in US impedance
  - Embed scatterers
  - Change geometry
  - Use AM

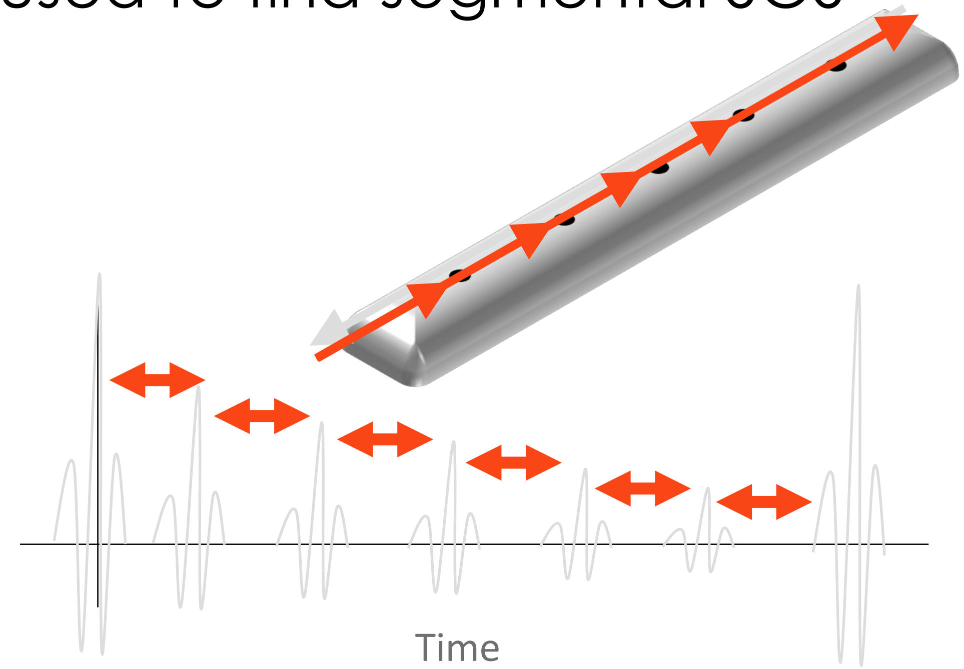


M. Skliar, K. Whitty, and A. Butterfield, Ultrasonic temperature measurement device, US Patent 8,801,277 B2, 2014; US Patent 9,212,956, 2015.

Technology status at the start of the project

Implementation of MSTD method

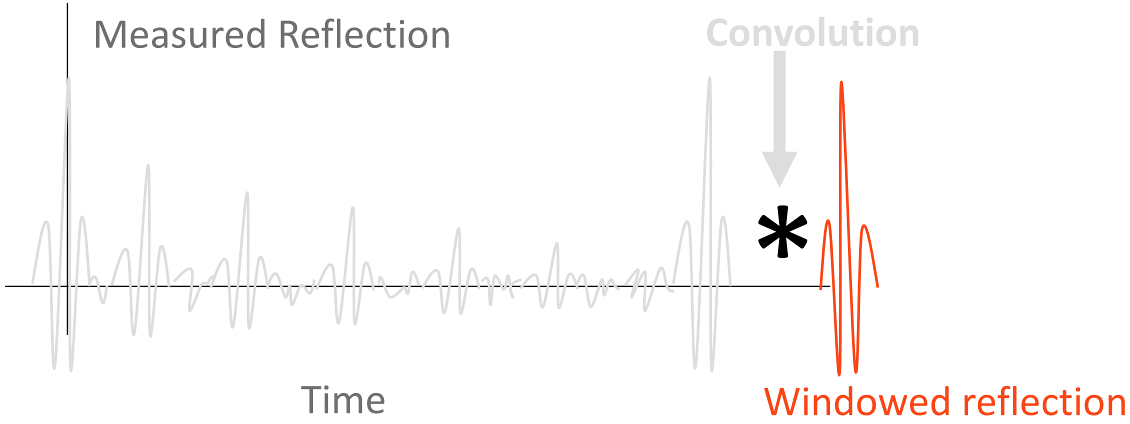
- Segmental velocity of ultrasound propagation is correlated to the segmental temperature
- Time of flight estimation algorithms are used to find segmental SOS



Interface layer

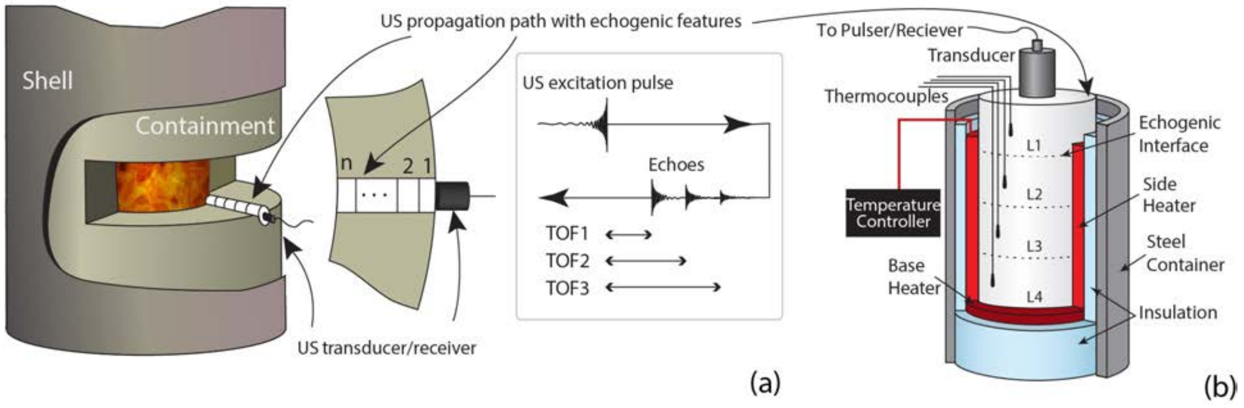
Computational Algorithms

- Choose Window
- Cross-correlation of windowed waveforms
- Compute TOFs
- Calculate Segmental SOS

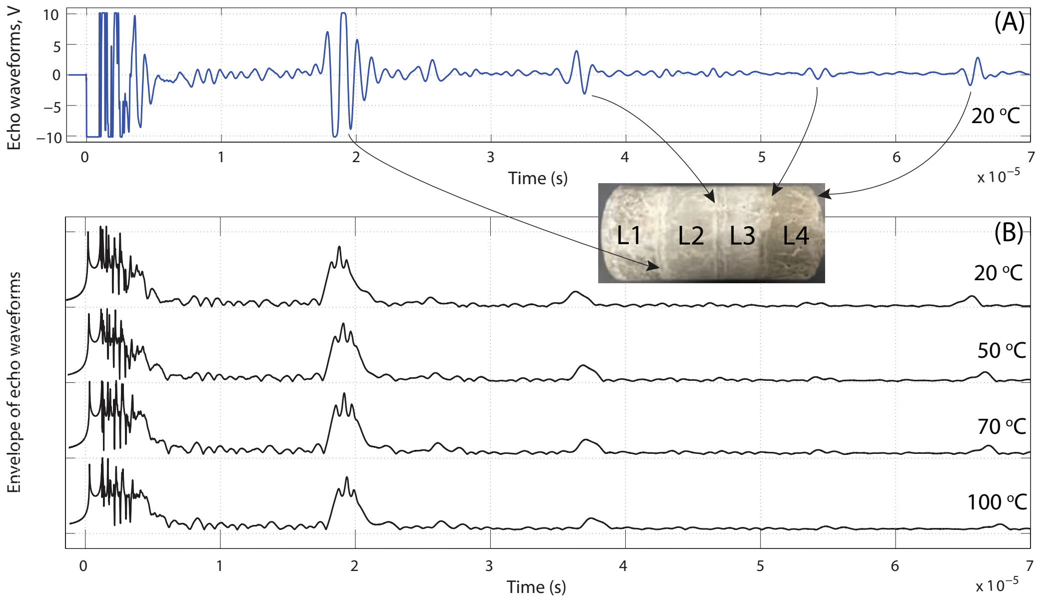


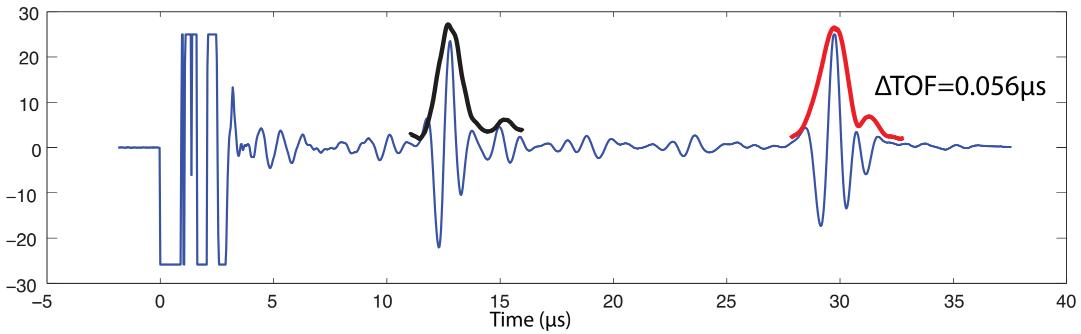
Technology status at the start of the project

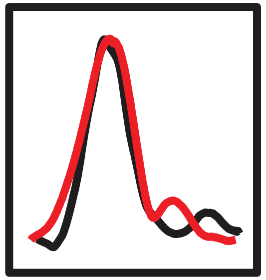
Demonstration of MSTD method in cementitious samples



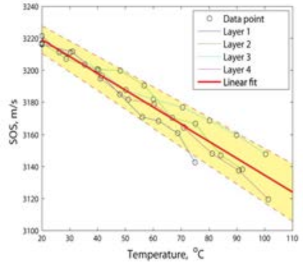
- 4” cementitious sample with four layers
- Surface temperature measured by TCs attached in the middle of each layer







TOF → **SOS** →



→ $T(z)$

Technology status at the start of the project

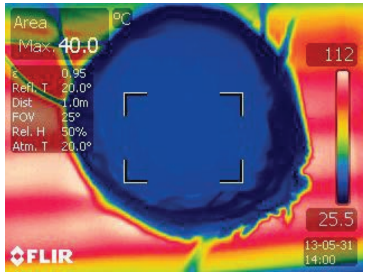
3D temperature measurements in a cementitious sample

- Volumetric temperature was reconstructed to match the model-predicted and measured TOF:

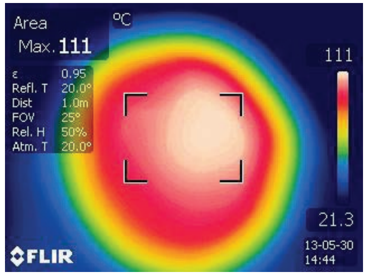
$$t_{of} = \int_0^L \frac{2}{f(T(t,z))} \mathrm{d}z$$

and to satisfy the heat transfer model:

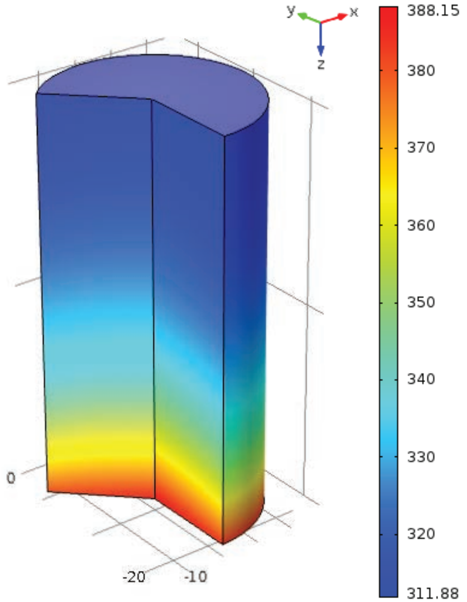
$$\rho C_p \frac{\partial T}{\partial t} = k \left(\frac{1}{r} \frac{\partial}{\partial r} r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial z^2}$$



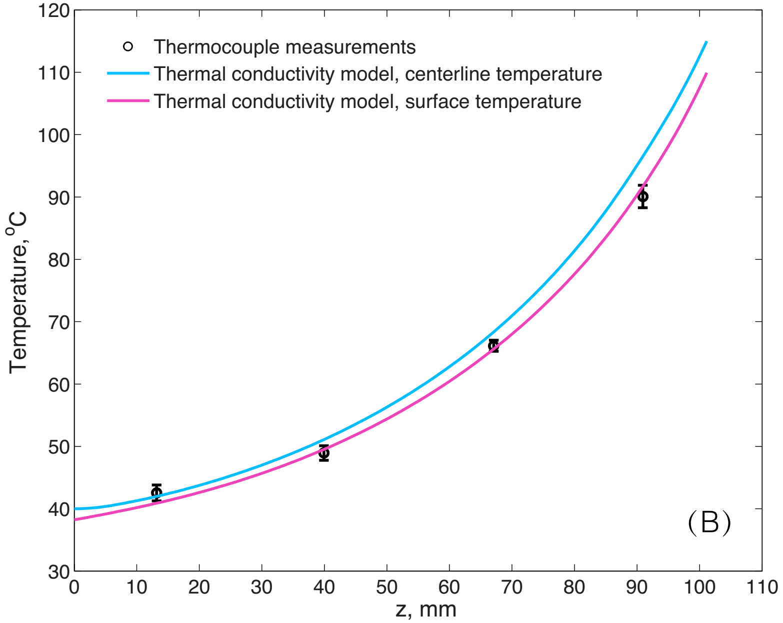
(A)



(B)



(C) Temperature (K)

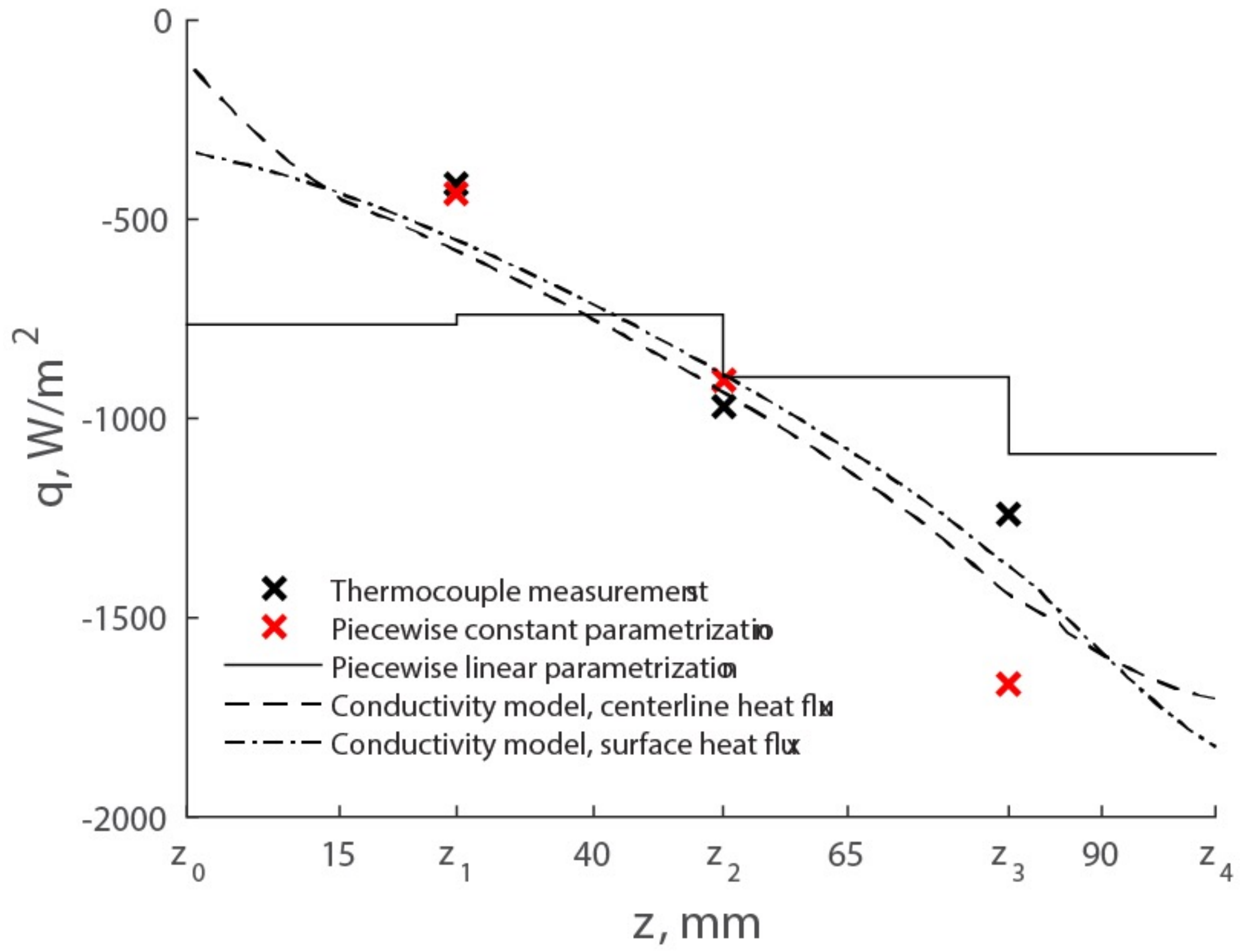


Jia, Y. and M. Skliar, Noninvasive Ultrasound Measurements of Temperature Distribution and Heat Fluxes in Solids, Energy & Fuels, 30:4363–4371, 2016.

Technology status at the start of the project

MSTD method allows us to find surface and internal heat fluxes

- Surface and internal heat fluxes in axial direction in the cementitious sample
- Results for different parametrizations – piecewise constant, piecewise linear, and model-based parametrization – are compared with thermocouple-bases heat flux measurements.

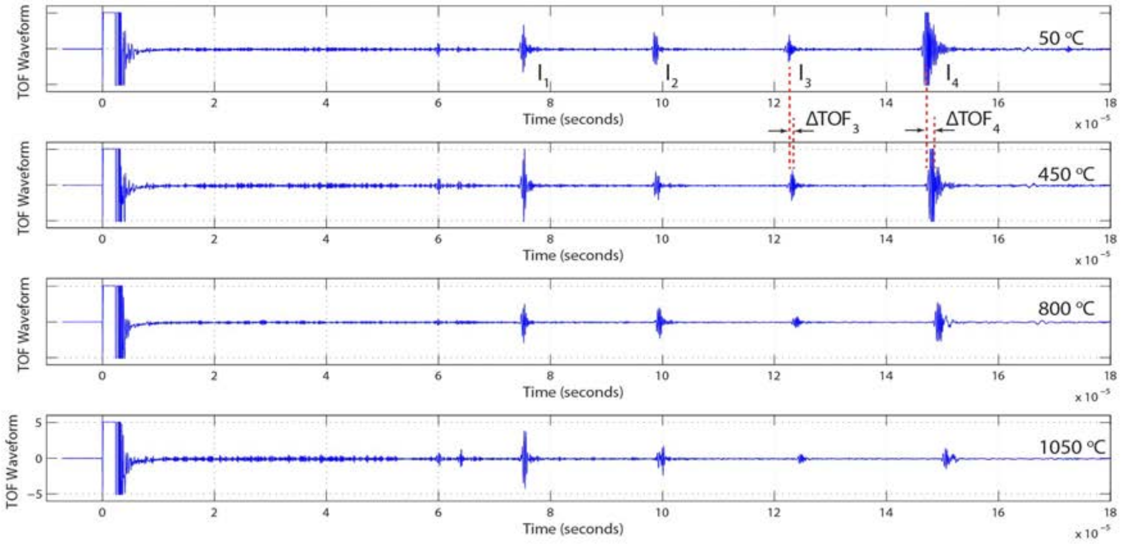


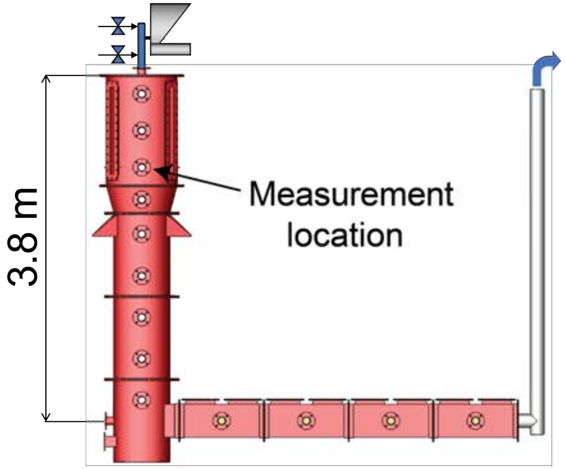
Jia, Y. and M. Skliar, Noninvasive Ultrasound Measurements of Temperature Distribution and Heat Fluxes in Solids, Energy & Fuels, 30:4363–4371, 2016.

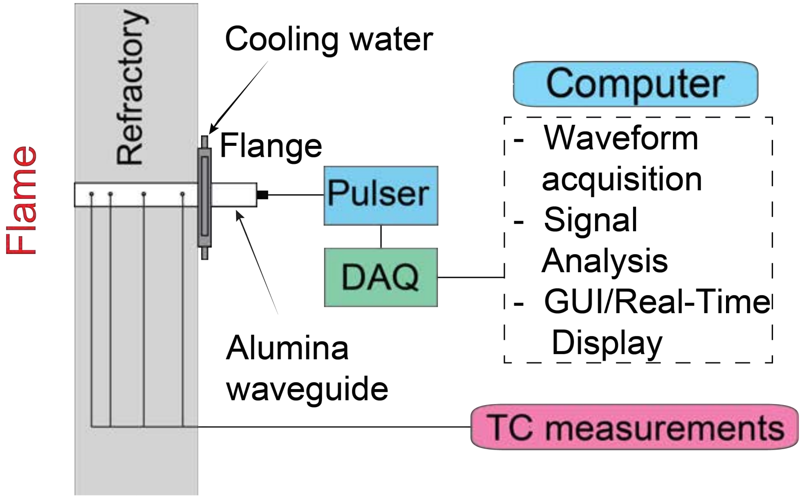
Technology status at the start of the project

Pilot-scale oxy-fuel combustor testing

- Ceramic (alumina and zirconia) waveguides were used.
- Echogenic segmentation was performed changes in geometry.





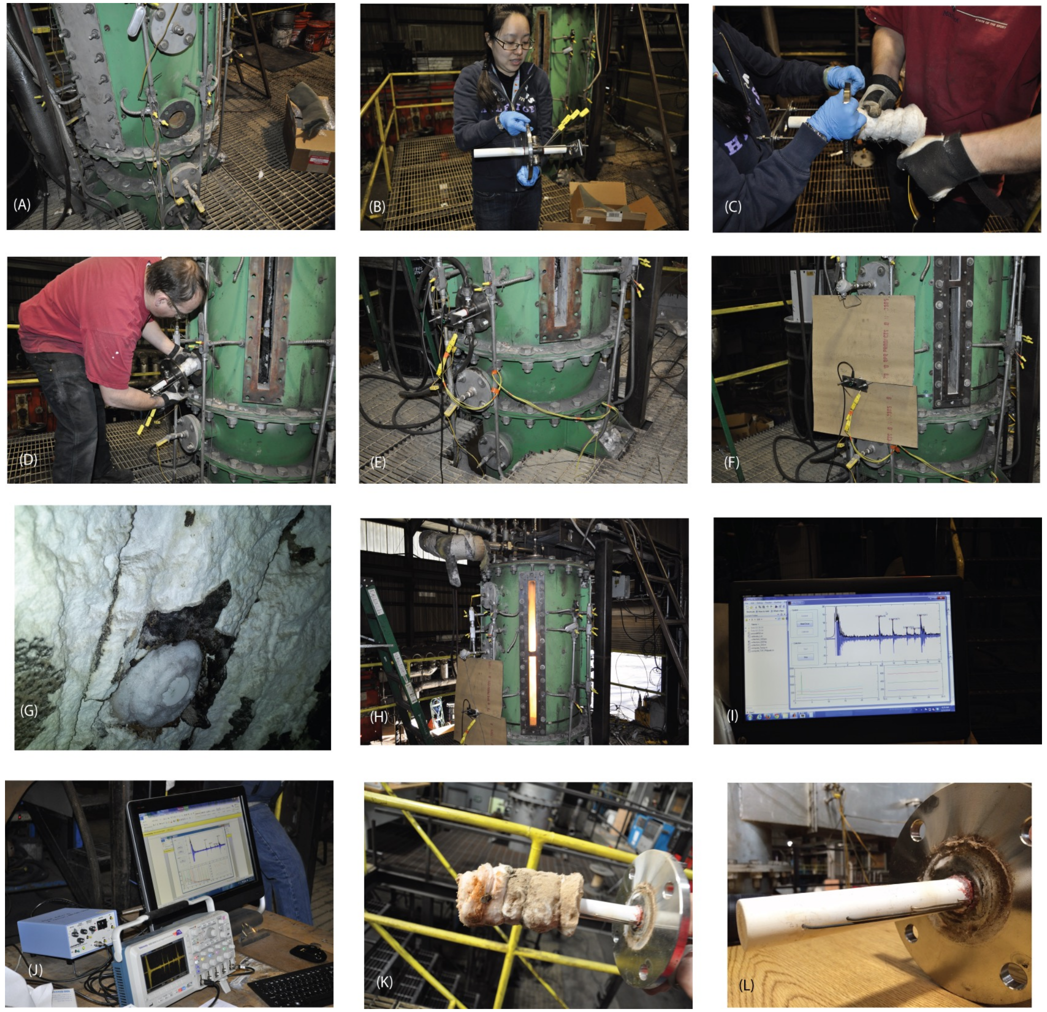


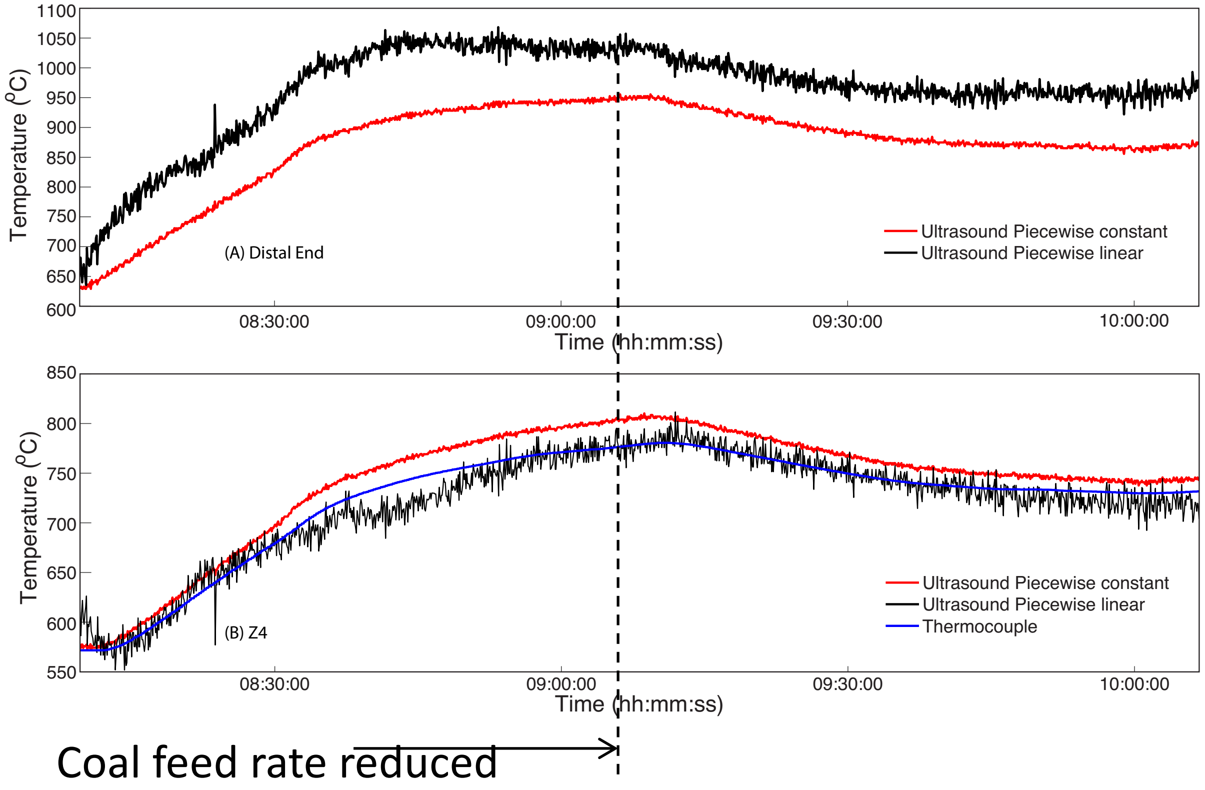
1. Maximum capacity 100 kW
2. Representative of full-scale units: (a) Self sustaining combustion; (b) Similar residence times and temperatures; (c) Similar particle and flue gas species concentrations
3. Allows systematic variation of operational parameters

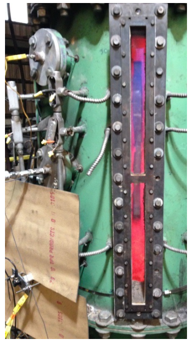
Jia, Y., V. Chernyshev, and M. Skliar, Ultrasound measurements of segmental temperature distribution in solids: Method and its high-temperature validation, Ultrasonics, 66:91-102, 2016.

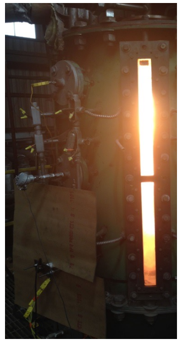
Technology status at the start of the project

Installation performance of MSTD system during pilot testing









Jia, Y. and M. Skliar, Ultrasonic Measurements of Temperature Distribution and Heat Fluxes Across Containments of Extreme Environments, Proceedings of 2019 IEEE International Ultrasonics Symposium, Glasgow, Scotland.

Current status of the project

Task	Tasks, Schedule, Milestones	Completion
PHASE I		
Task 2	The multipoint US-MSTD method is developed	Month 12
Task 3	Multipoint US-MSTD prototype is tested in laboratory	Month 12
PHASE II		
Task 2	Software integration of the TRL 6 prototype is completed	Month 24
Task 3	1. Pilot scale testing of the capability to simultaneous measure the temperature profile and heat fluxes at multiple locations. 2. Test on the pilot scale the sensitivity of the US-MSTD method to simulated soot deposits.	Month 24
PHASE III		
Task 2	Continues iterative refinement of the prototype	Month 36
Task 3	1. Test on the pilot scale the US-MSTD capability to measure the temperature distribution across the entire combustion zone. 2. Test single-point US-MSTD system at the power plant. 3. Power plant testing of the capability to simultaneous measure the temperature profile and heat fluxes at multiple locations. 4. Repeat utility boiler testing after soot blowing.	Month 36
PHASE IV		
Task 2	Develop low-cost instrumentation package and Python software to run and integrate it into a stand-alone and modular system for measuring temperature distributions and heat fluxes	Month 48
Task 3	Perform power-plant trials of developed MVP. Compare with the industry-standard heat flux sensor commercially available from Diamond Power, a subsidiary of Babcock & Wilcox -- our OEM partner	Month 48

Project Update

Technology status

- Method is proven to provide accurate continuous noninvasive real-time measurements of temperature distributions in solids
- Demonstrated in laboratory, a pilot process, and **first power plant test** (August 2019)
- Heat fluxes deep inside structures can be measured
- Measurements in multiple locations are possible and demonstrated
- System integrated in Python
- Can be used with existing and integrated into new energy conversion units
- The temperature and heat flux measurements in multiple locations on the boiler waterwall: **Second power plant** (April 2021)
- Custom instrumentation is in early stages of development
- New method for measuring flow rates in extreme environments is disclosed

Project Update

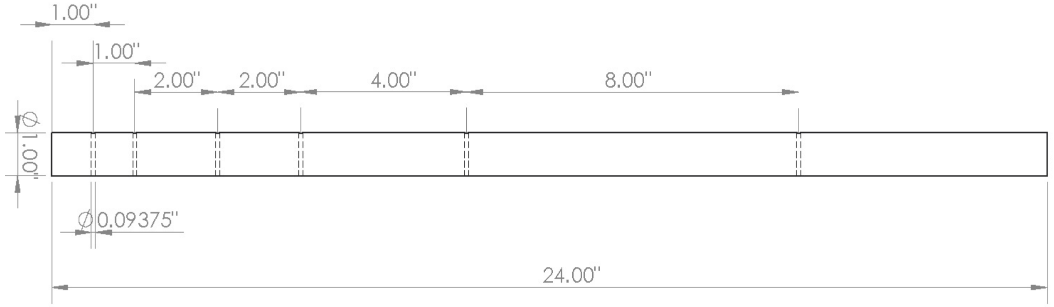
Utilization of metal waveguides

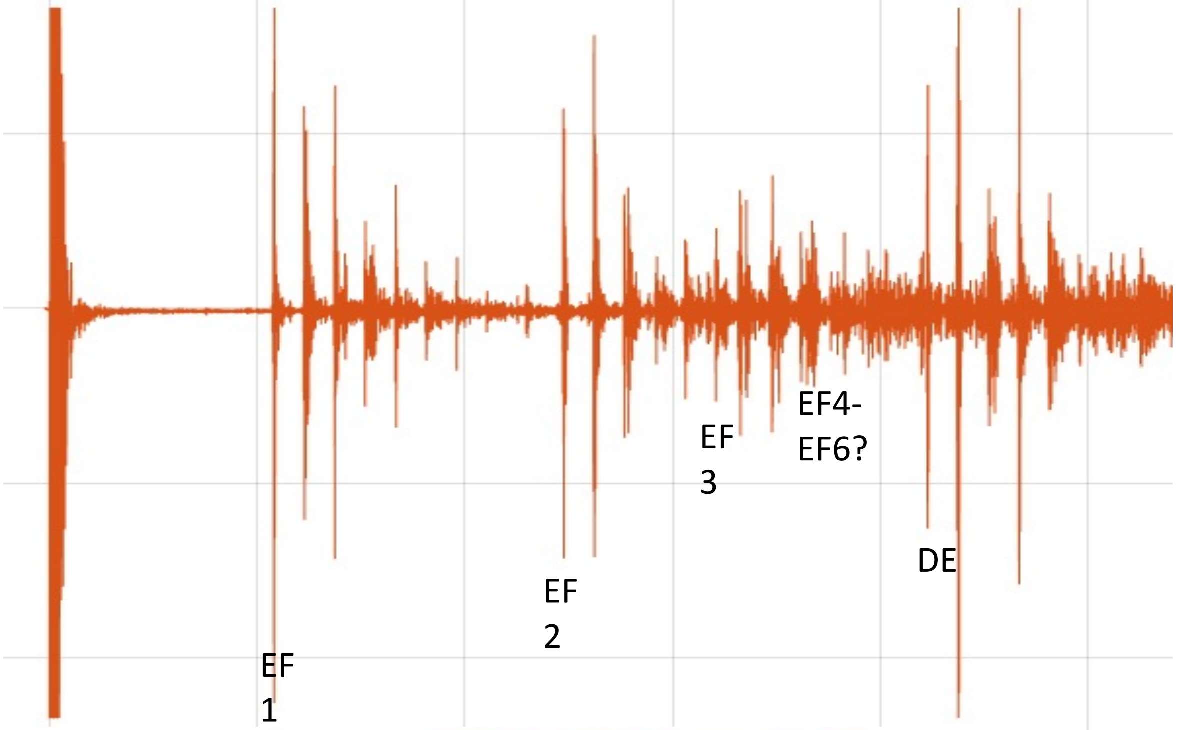
- Can be incorporated into the structure by original design or retrofit, such as welding.
- Metal structures as waveguides
- Factors to consider:
  - Range of admissible temperatures, chemical environment, mechanical abrasion,…
  - Ultrasonic attenuation
  - Toughness/resistance to fracture
  - Thermal conductivity and expansion
  - Design of echogenic features

Project Update

Evolution of waveguide designs

Inconel 625 waveguide with six echogenic features

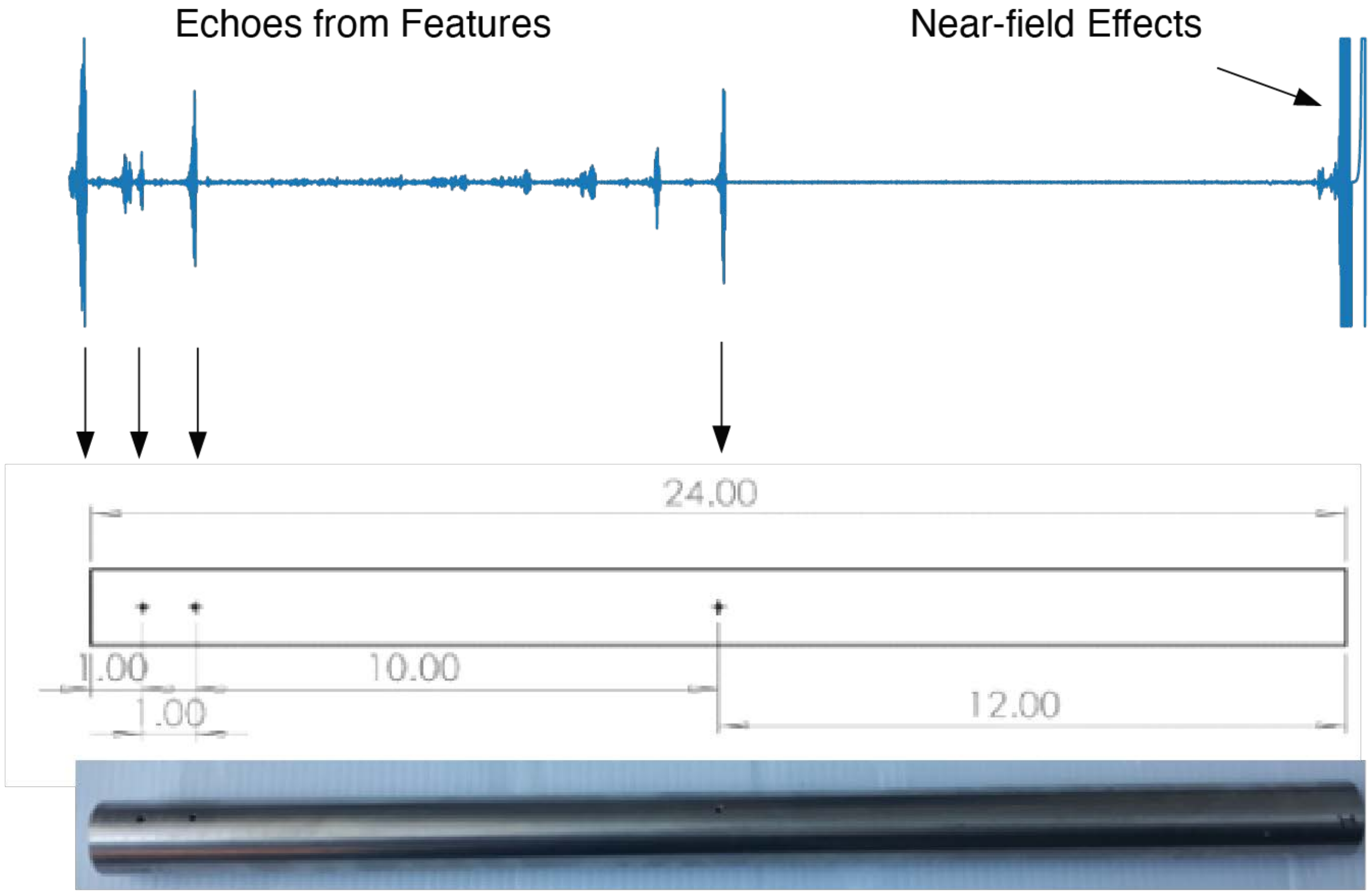


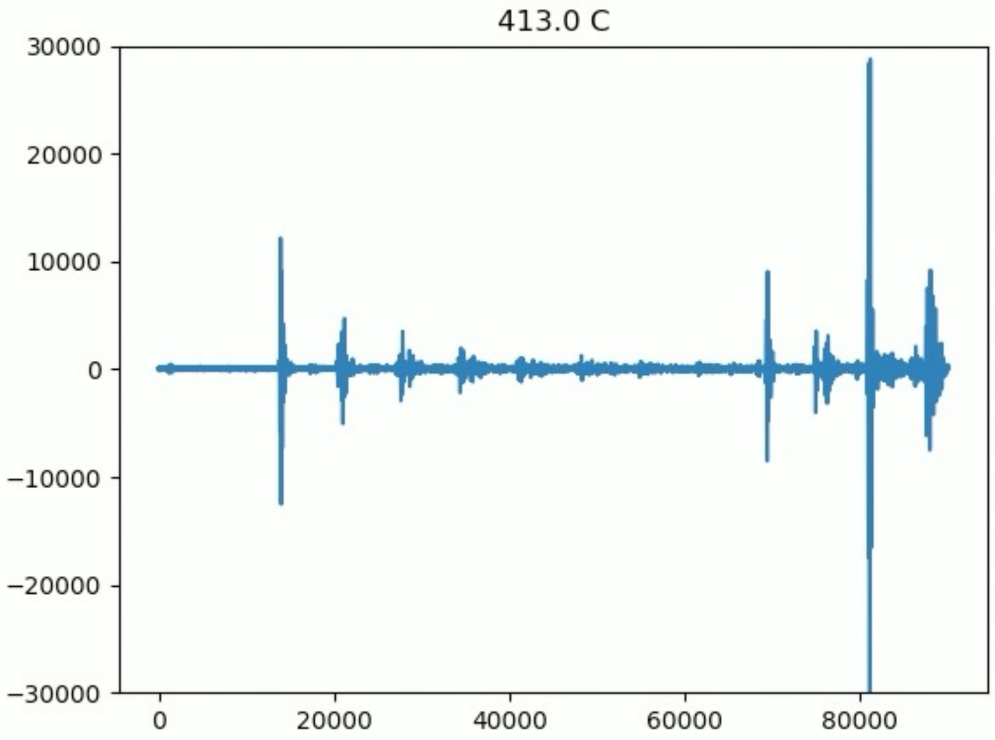


- Ultrasonic response is complex
  - Each echogenic feature produces a train of trailing echoes
  - Trailing echoes can overlap with echoes produced by EFs
  - The overlap is impacted by the temperature
- Signal processing becomes difficult
- Need to redesign the WG to simplify the response

Project Update

WG used during first power plant test





- Rational design procedures were developed to reduce interference from trailing echoes
- We continue improving the design and are developing signal processing techniques to deal with overlapping echoes

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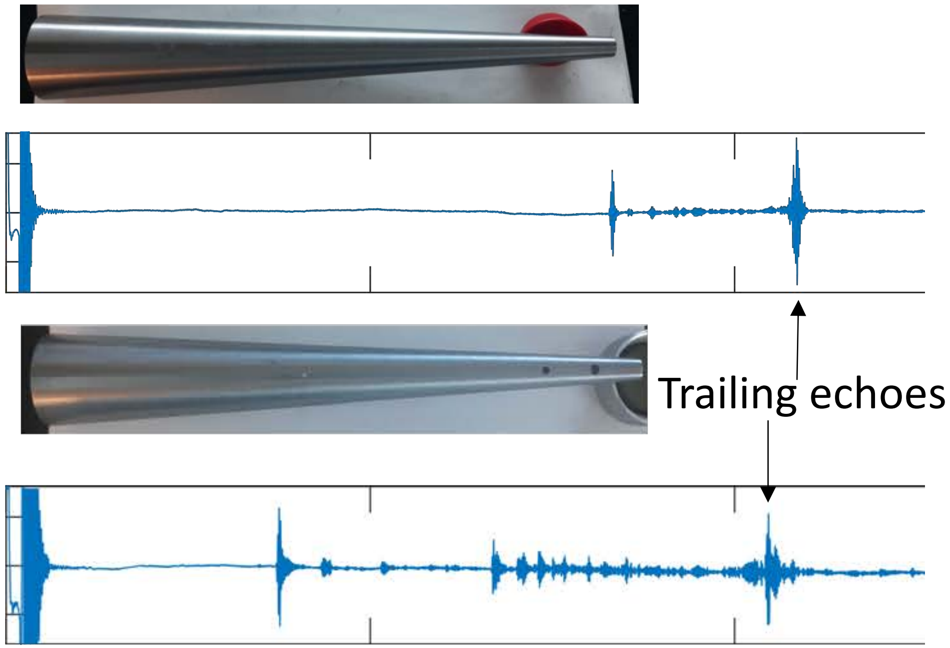
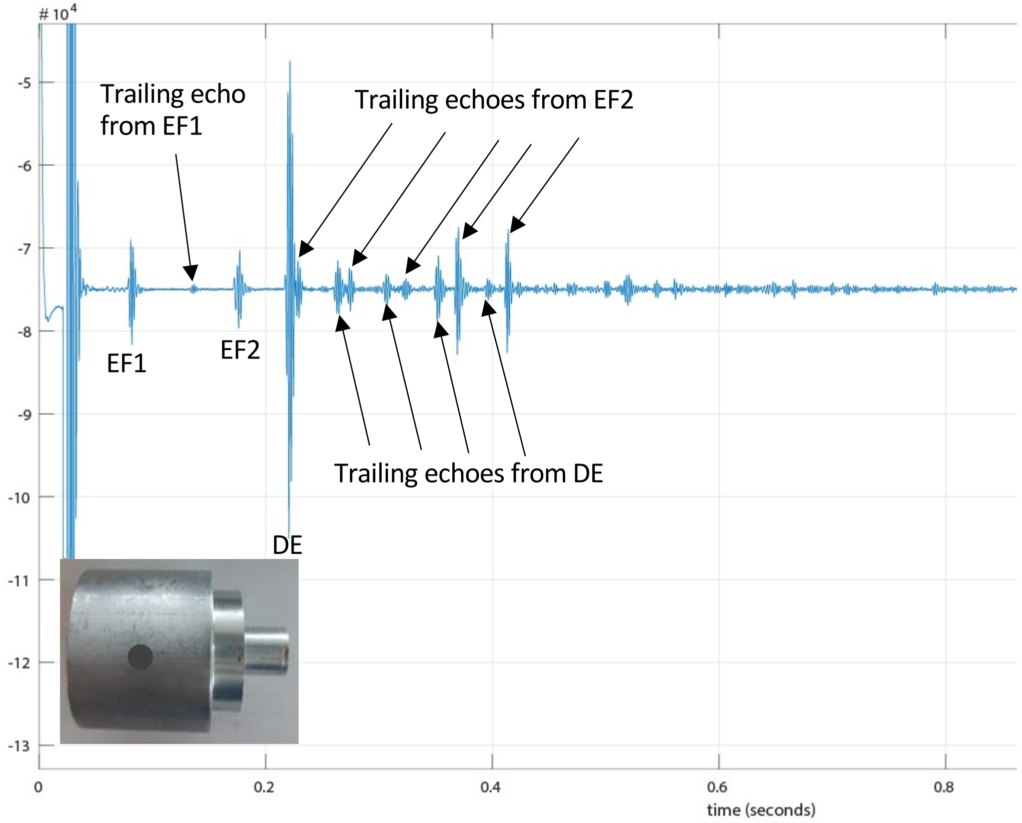
Project Update

WG design decisions

- Tapering waveguides significantly delays trailing echoes compared to WGs with uniform cross section

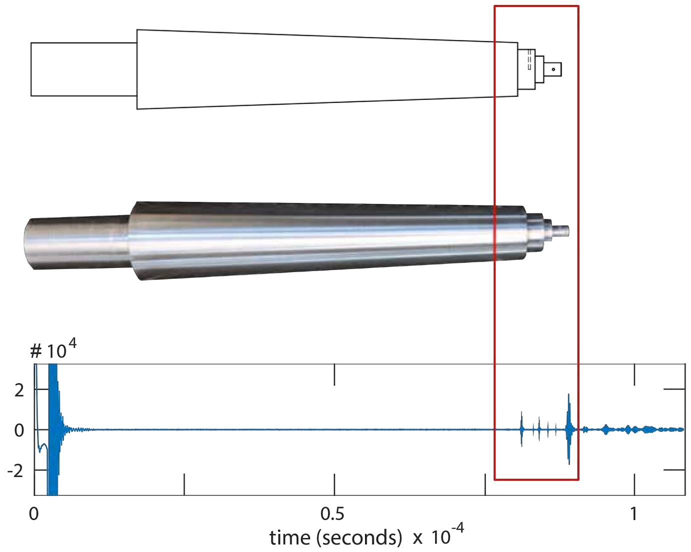


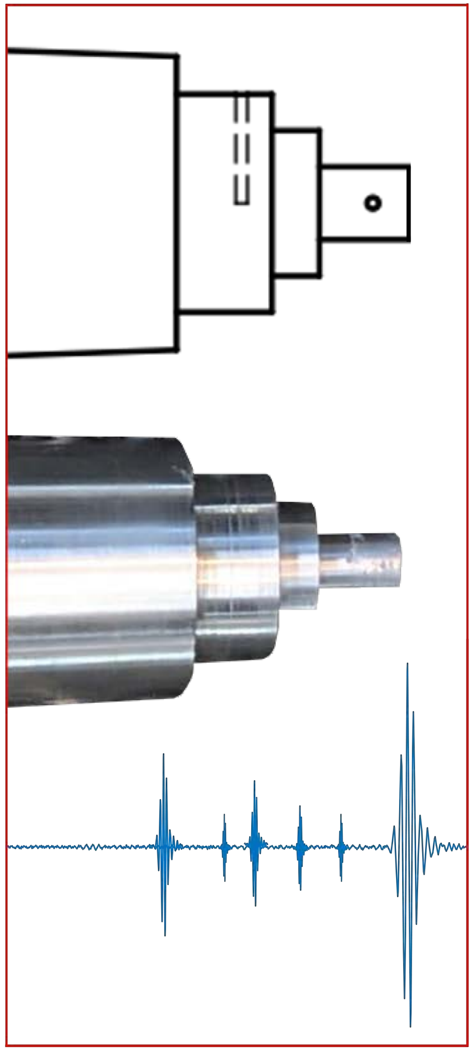
- Optimization of multiple factors (geometry, diameter, tempering, location of radial holes, etc.) impacting the overlap of echoes



Project Update

Achieved density of echogenic features without echo overlap



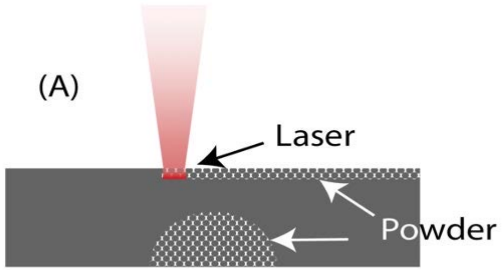


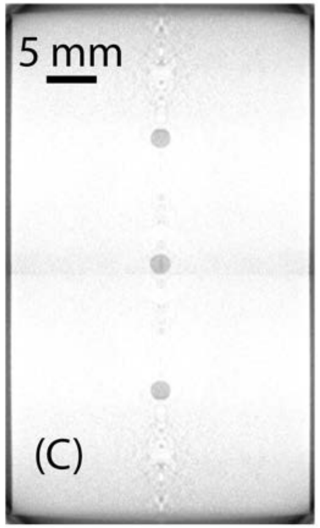
- In 1" O.D. 1018 steel waveguide we can now place 5 EFs within 0.8" axial distance without interference.
- Optimization of multiple factors (geometry, diameter, tempering, location of radial holes, etc.) impacting the overlap of echoes allows us to obtain an even larger density of EFs.
- Strategically placed EFs avoid interaction with each other and their trailing echoes. Further improvements will be achieved with signal processing.
- Densely segmented waveguides will allow us to measure temperature distribution and heat fluxes with high accuracy.

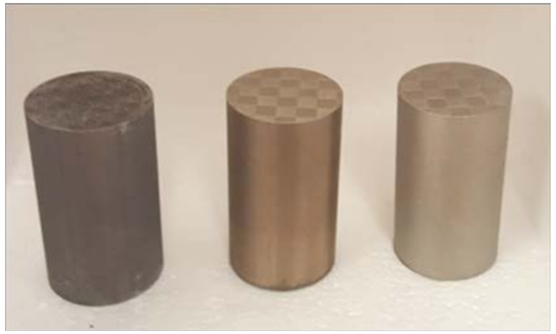
Project Update

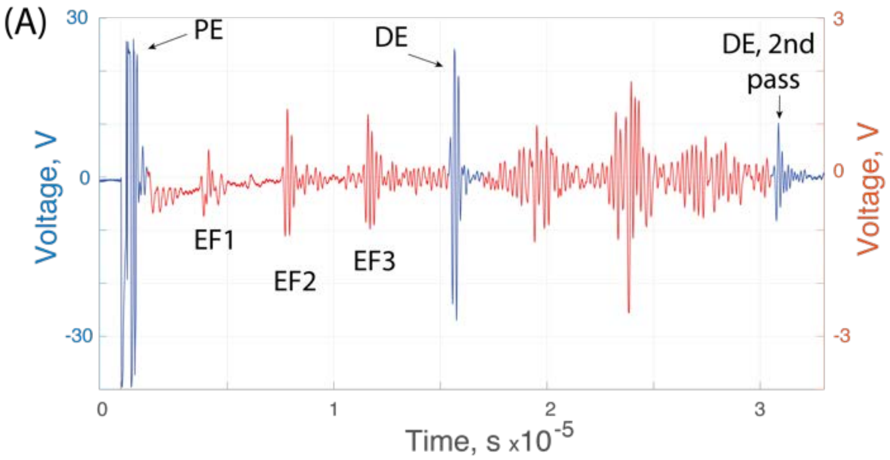
3D metal printing and other AM methods give us new options

AM will allow us to create multifunctional structures and components in which temperature distributions and heat fluxes can be measured by MSTD method.







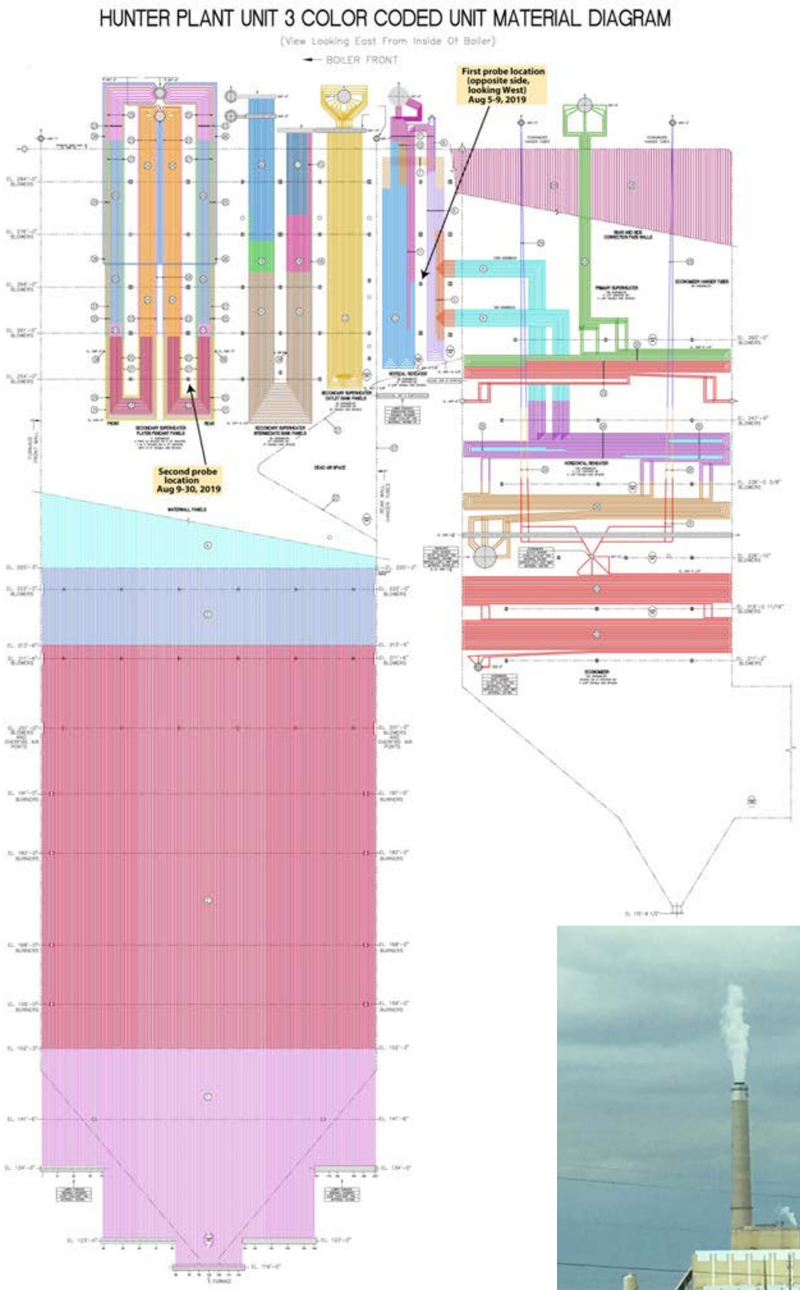


K. Walton and M. Skliar, "Ultrasonic Characterization of Spatially Varying Material Properties in Metal Components Fabricated by Additive Manufacturing," IEEE International Ultrasonics Symposium (IUS), Glasgow, United Kingdom, 2019.

Project Update

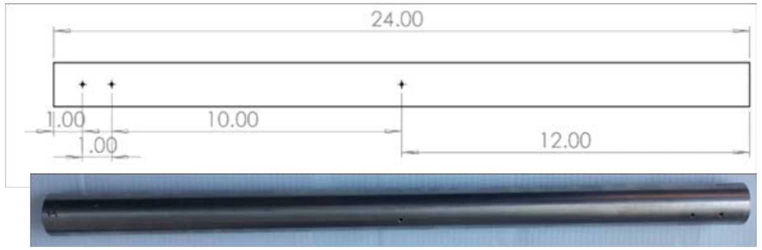
First Hunter Unit 3 power plant test, August 2019

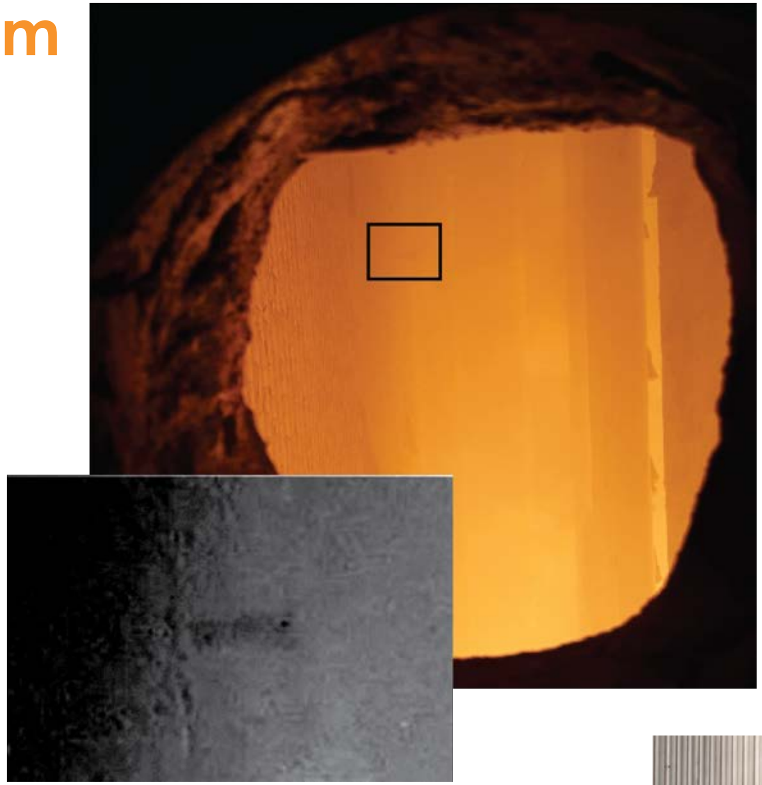
- Front and rear-wall fired, B&W design
- 2400 PSIG steam, 1,000° F superheat, and 1,000 °F reheat
- Burns local sub-bituminous coal
- Measurements in two locations
  - 4 days of continuous data acquisition in Location 1
  - 3-week installation in Location 2 and 1 day of data collection
- US and TC data every 15 sec
- ~10 GB of data acquired every 24 h
- 2/6 industry standard TCs failed in Location 2. MSTD system performed flawlessly.



Project Update

Installation of the MSTD system



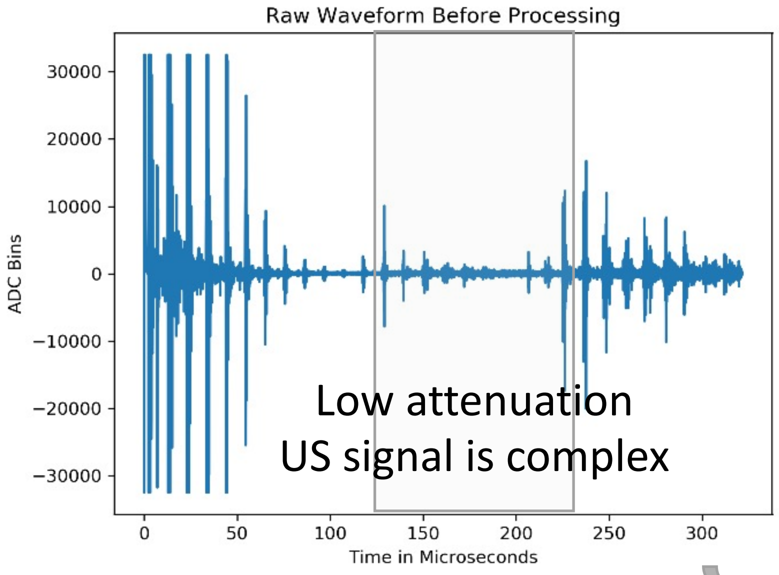


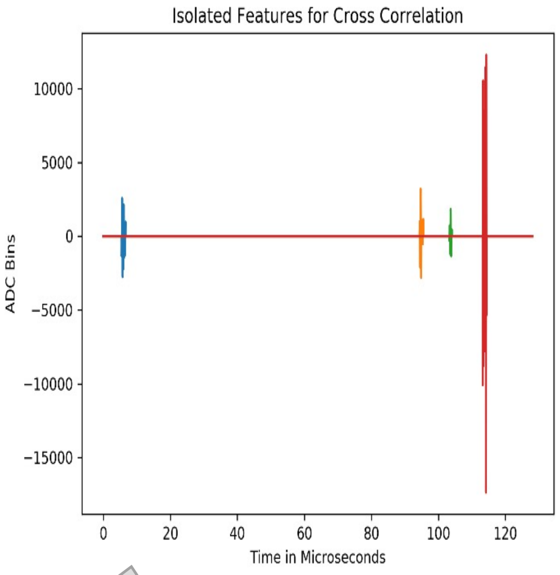
- Inconel 625 WG
- Mounted in access ports
- Independent TC data for validation

M. John, K. Walton, and M. Skliar, Ultrasonic Measurements of Temperature Distribution in Extreme Environments: Results of Power Plant Testing, IEEE International Ultrasonics Symposium (IUS), Las Vegas, NV, 2020.

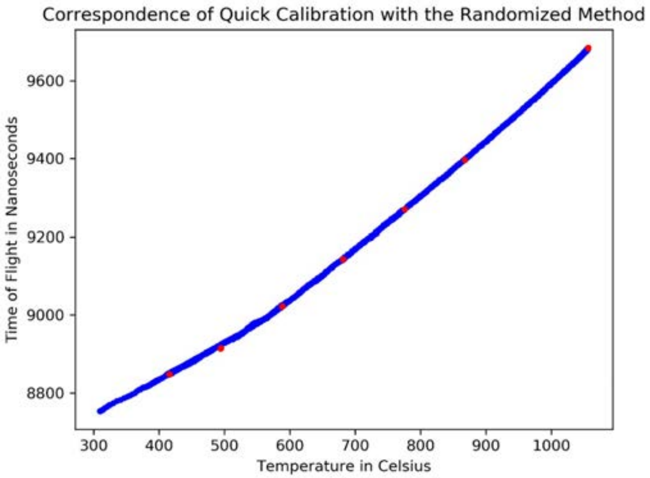
Project Update

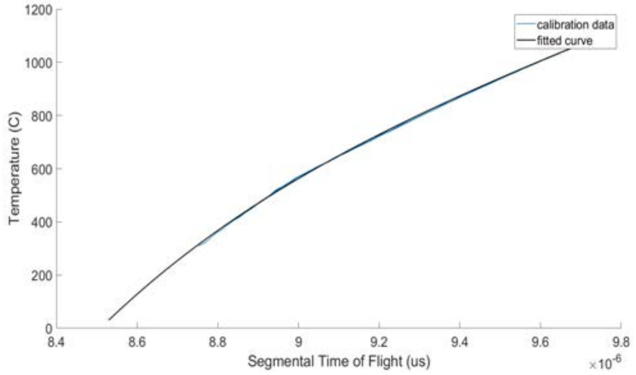
Power plant results – Data interpretation





Segmental TOF





- Low attenuation makes US response complex
- Rapid method for SOS/TOF vs. temperature calibration allow us to recalibrate the waveguide when needed.

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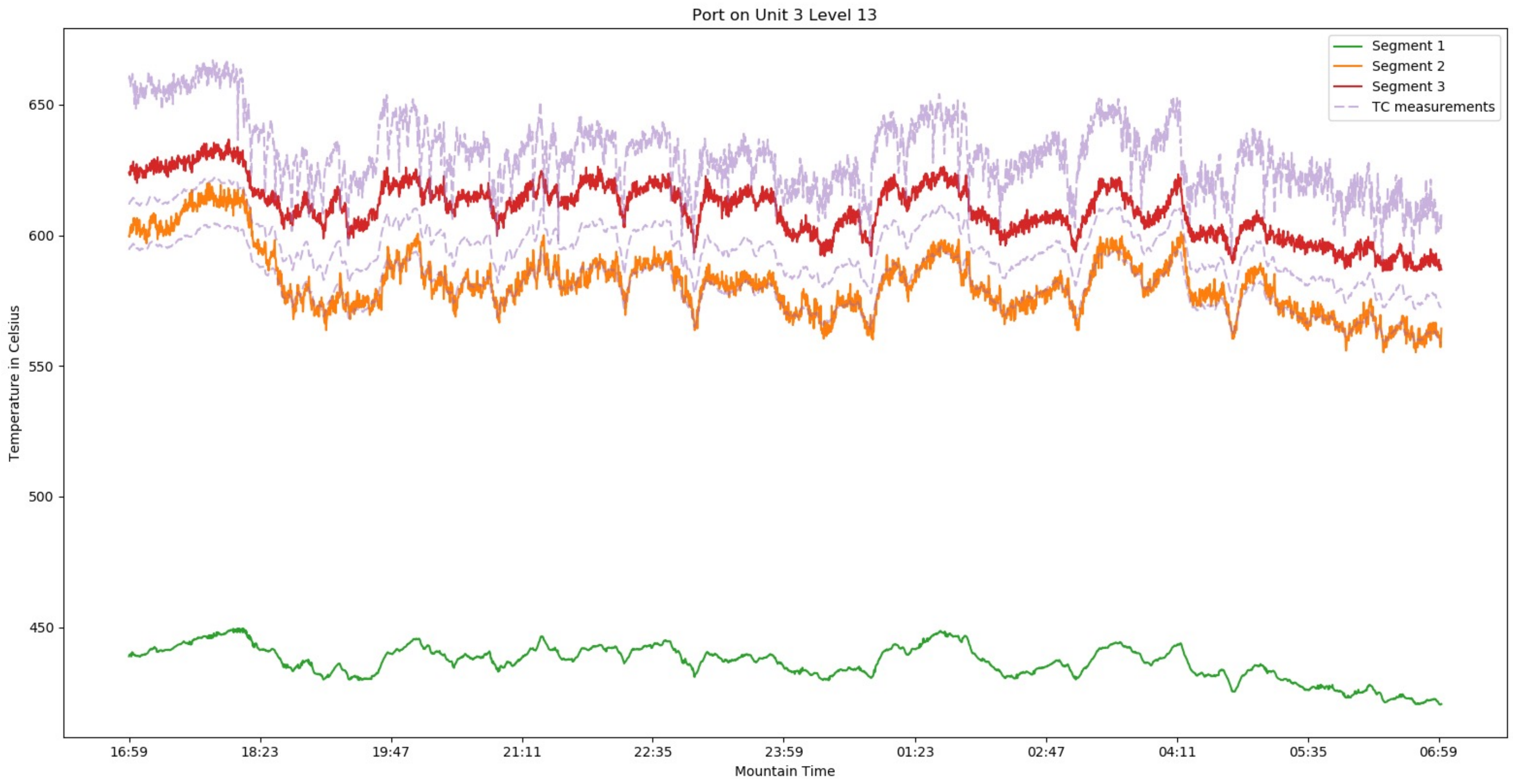
Project Update

Operator's view of segmental temperatures

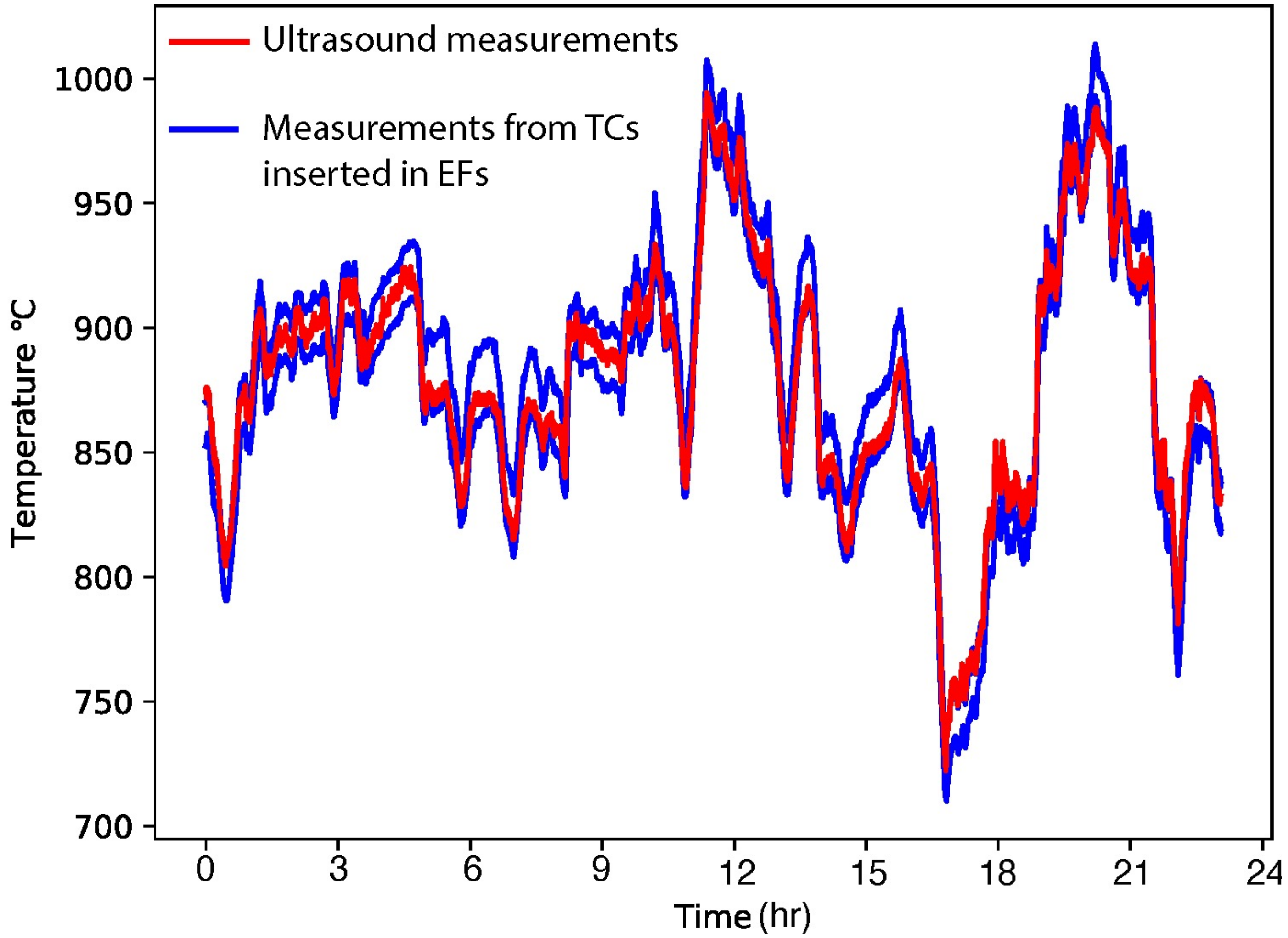
<u>First WG Location</u>: Monday 5 PM (August 5) to Tuesday 7 AM (August 6)

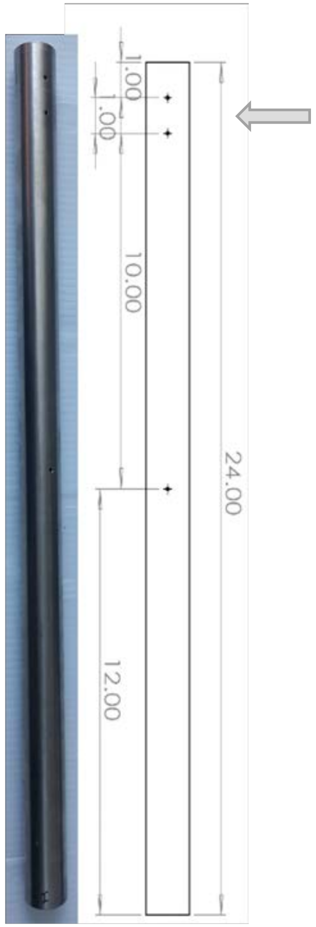


Project Update

Power plant results – Comparison of MSTD and TC measurements

Second WG Location



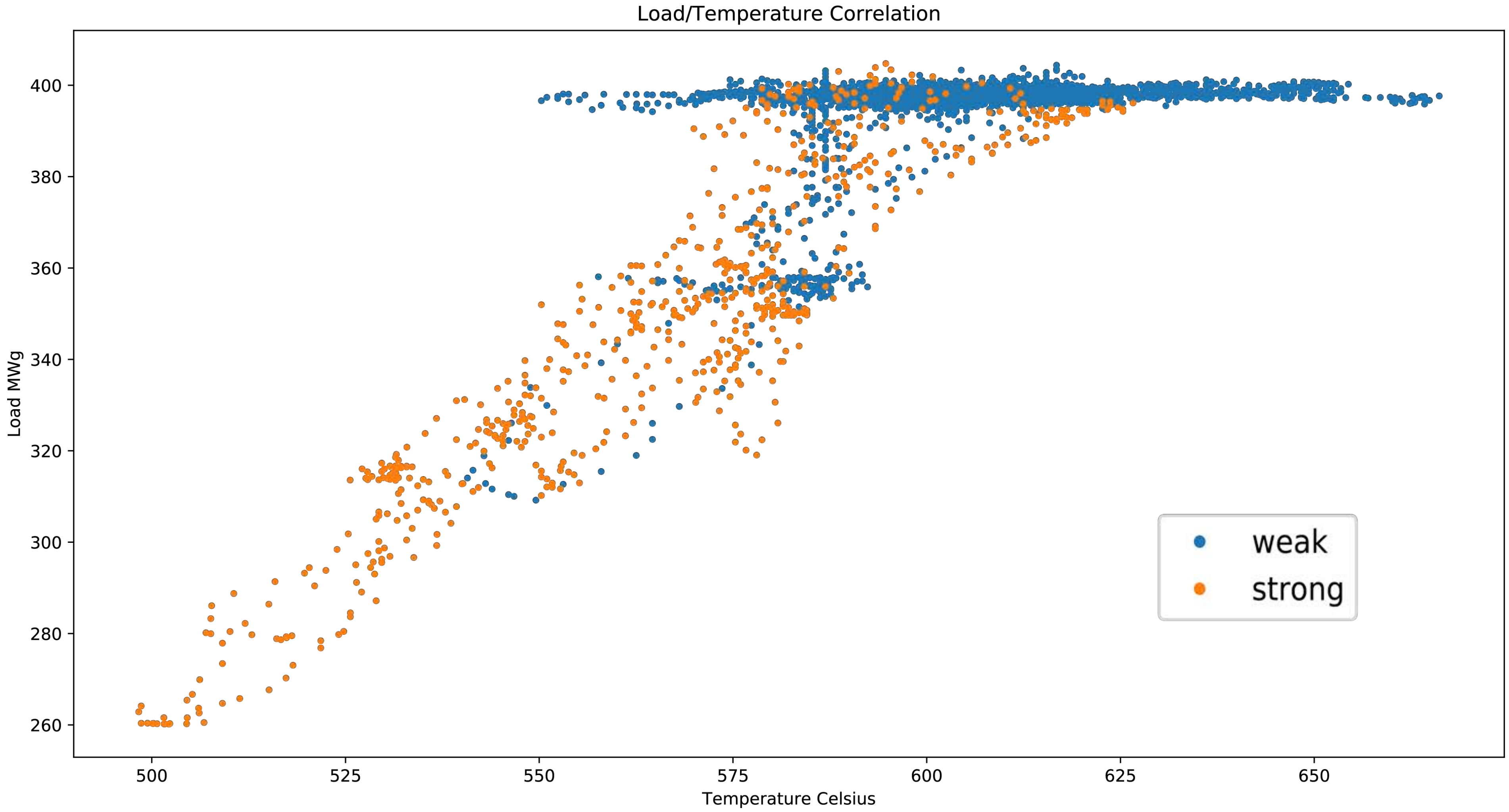


Thermocouples are inserted into EFs defining the indicated segment of the WG.

The shown ultrasound measurements assume piecewise constant segmental temperature.

Project Update

Power plant results – Correlation with changing load



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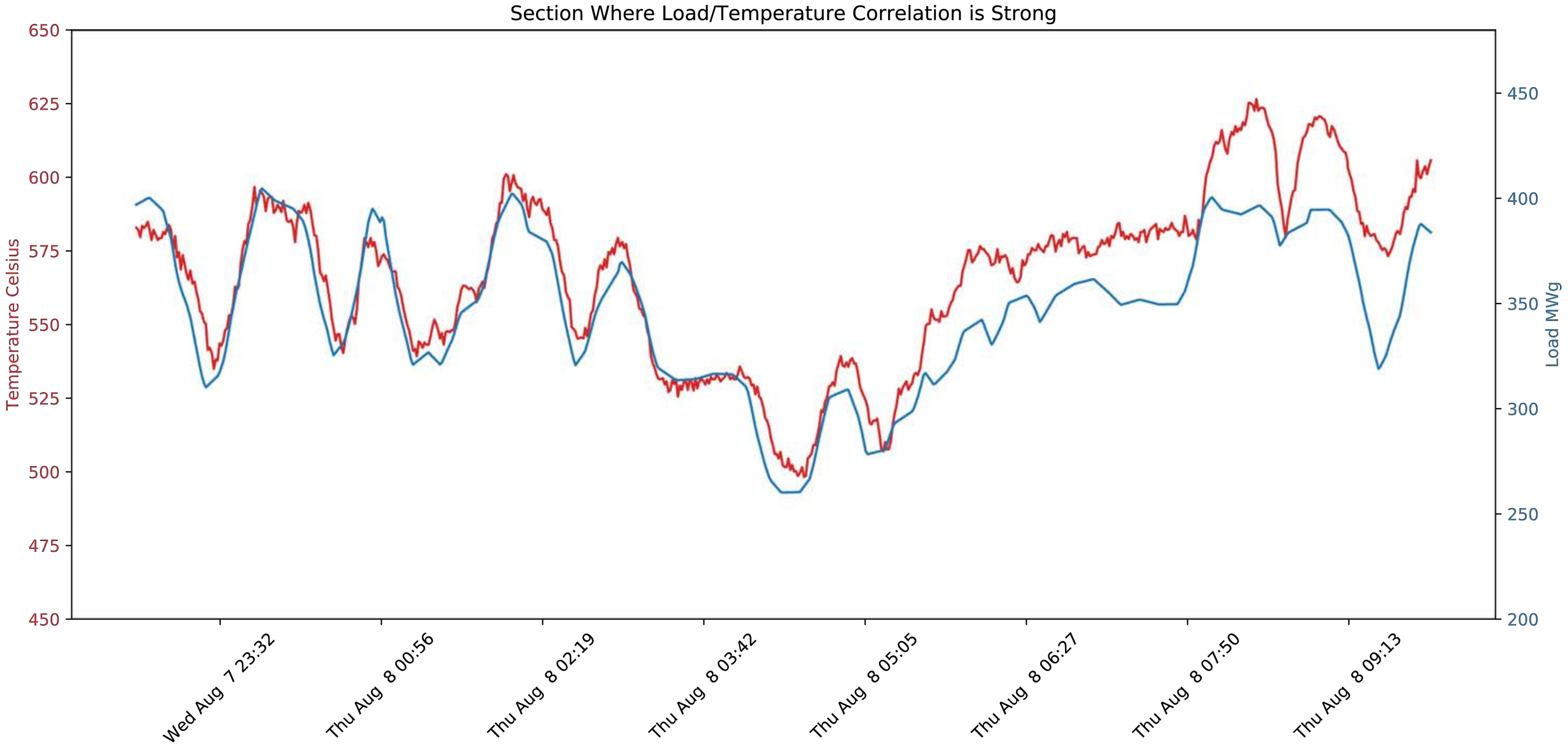
Project Update

Power plant results – Example of strong temp-load correlations



Correlation is strong when load is changing

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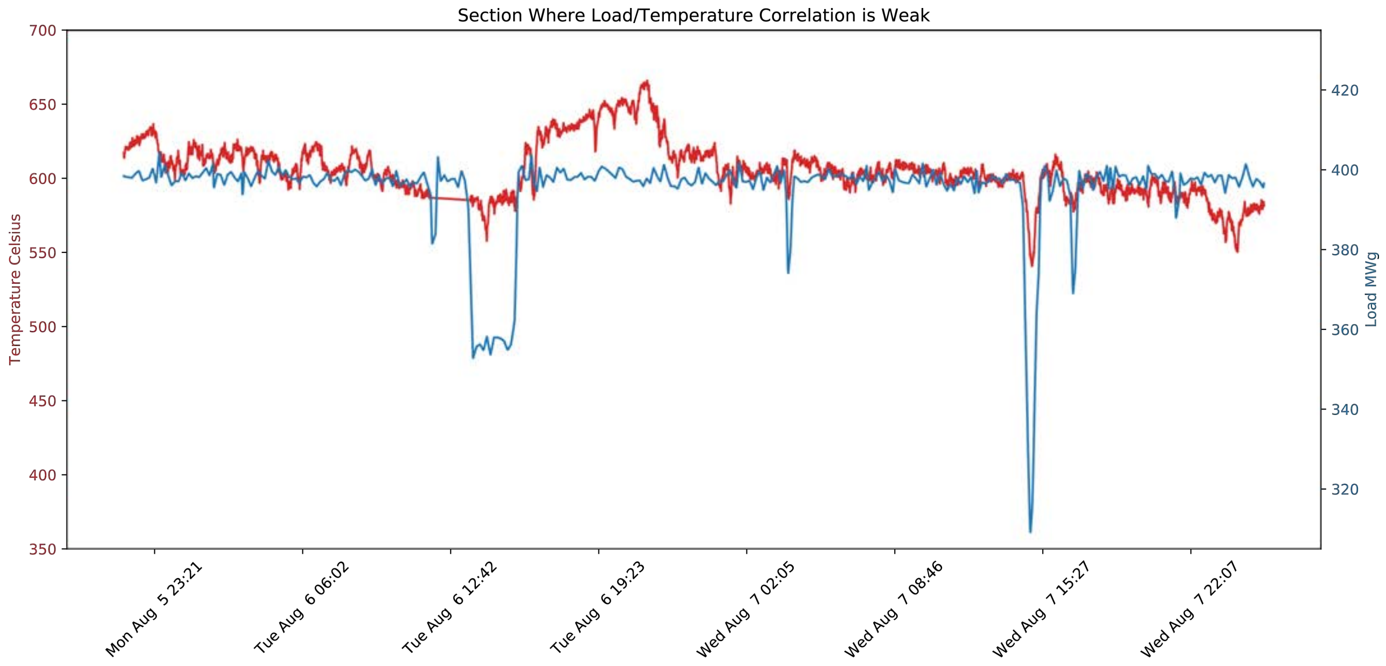
Project Update

Power plant results – Example of weak temp-load correlations

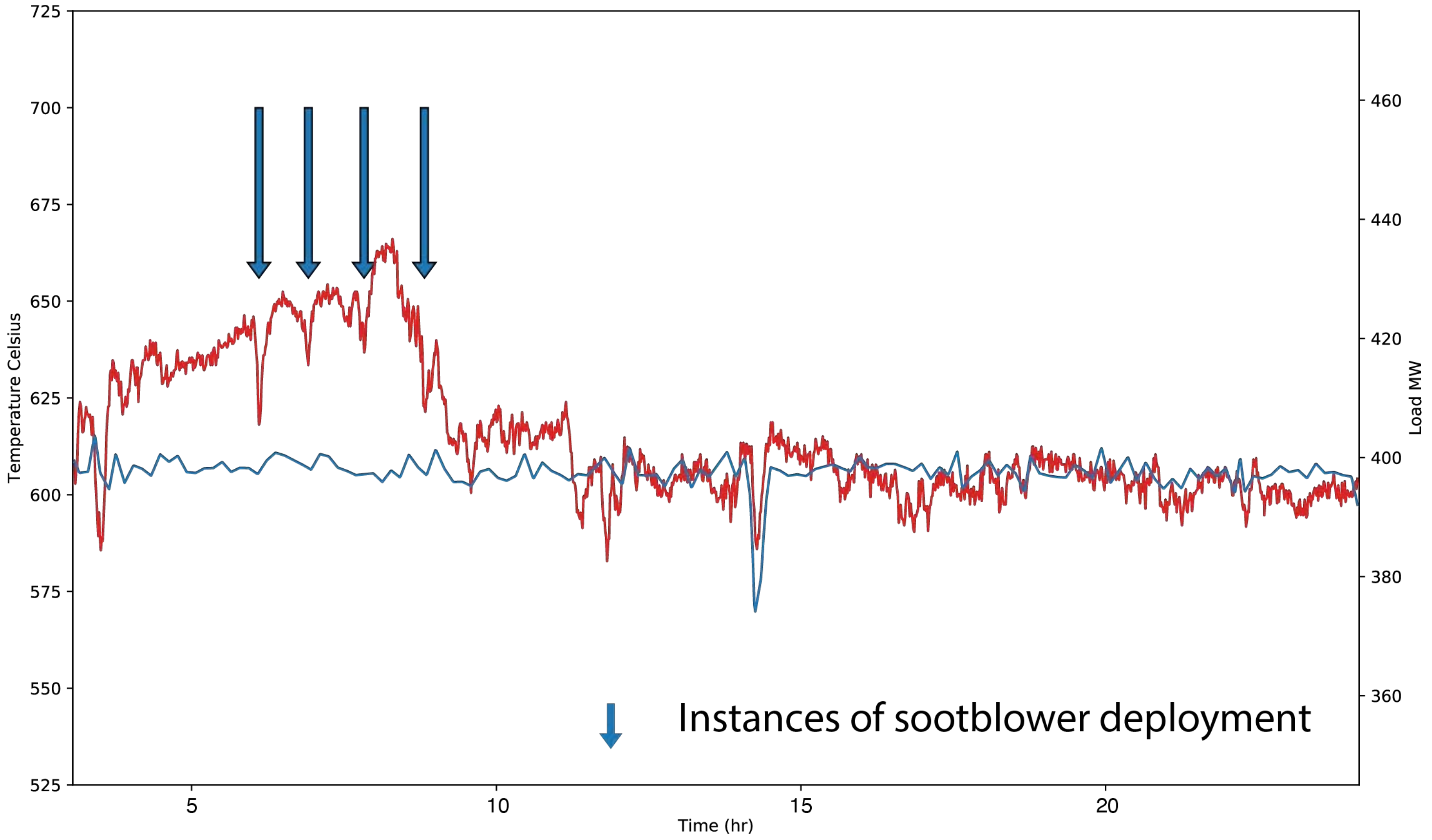


Correlation is weak when load is not changing

- "At a constant higher load with the slag insulating the tubes there is a possibility the ***sootblowers aren't keeping up*** or are not being ran as much as they should."
- "The weak correlation may have to do with temperature optimization/compensation of the unit…***When the unit settles enough for the temperature control to begin to work*** it effects the temperature vs load correlation. "

Project Update

Power plant results – Correlation with soot blowing



- Temperature drops sharply with the deployment of certain "up stream" soot blowers.
- The load is plotted to show it does not impact the temperature.

Project Update

Power plant results – Summary of observations

- Measurements are:
  - Accurate
  - Sensitive to load changes
  - Sensitive to soot blowing
  - Sensitive to location of soot blowing
  - Sensitive to soot deposits

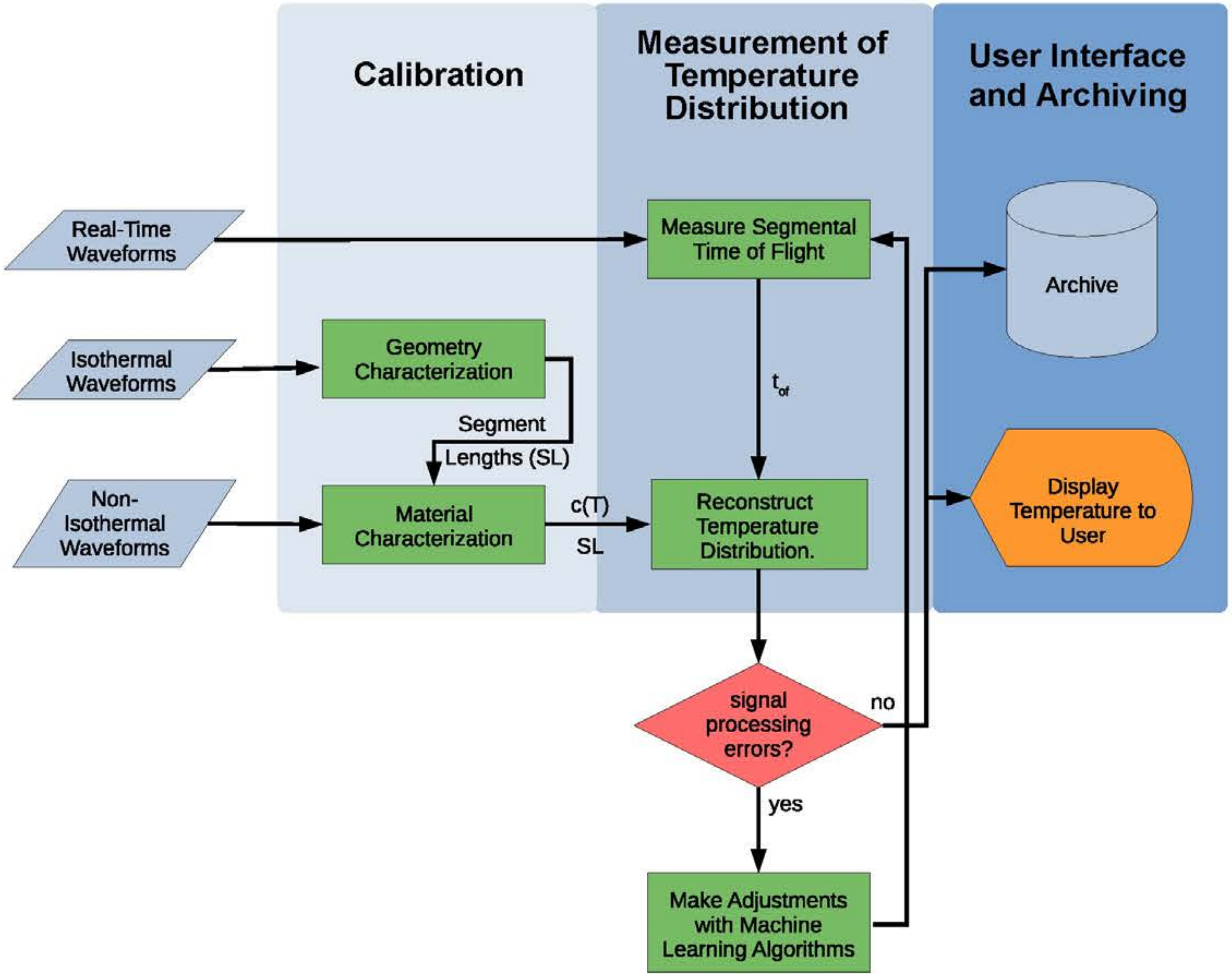
Preparing Project for Next Steps

- Power plant tests
  - ~~Repeat first test for B&W collaborators and Rocky Mountain Engineers from other plants~~
  - Measurements of heat fluxes to heat transfer surfaces, First test in April 2021
  - Compare performance to industry standard solution (B&W sensors were removed during the retrofit)
- Develop a minimum viable prototype consisting of a low-cost instrumentation and Python software to run and integrate it into a stand-alone and modular system for measuring temperature distributions and heat fluxes

Preparing Project for Next Steps

System integration of MVP

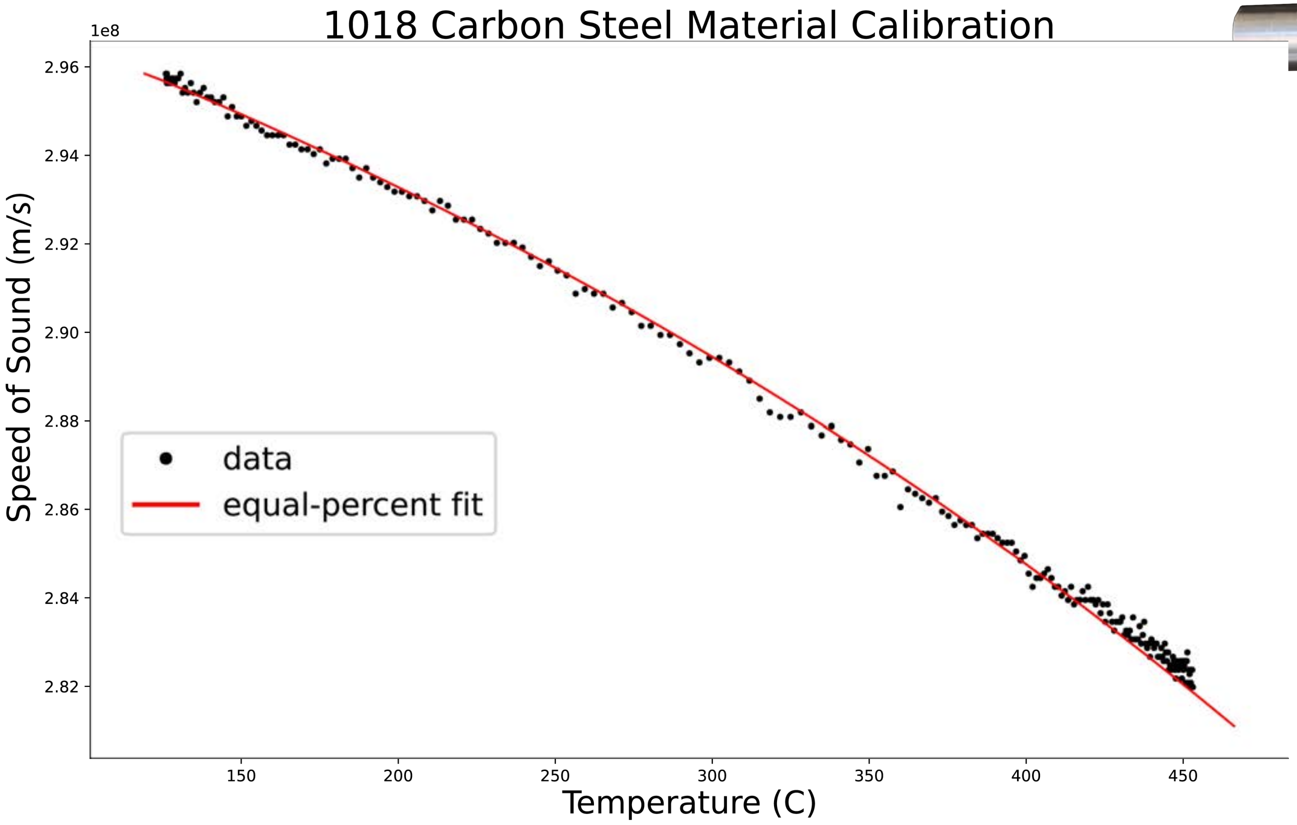
- Standardized workflow
- Rapid WG calibration
- Adaptive signal processing to handle exemptions and recalibration
- Python implementation



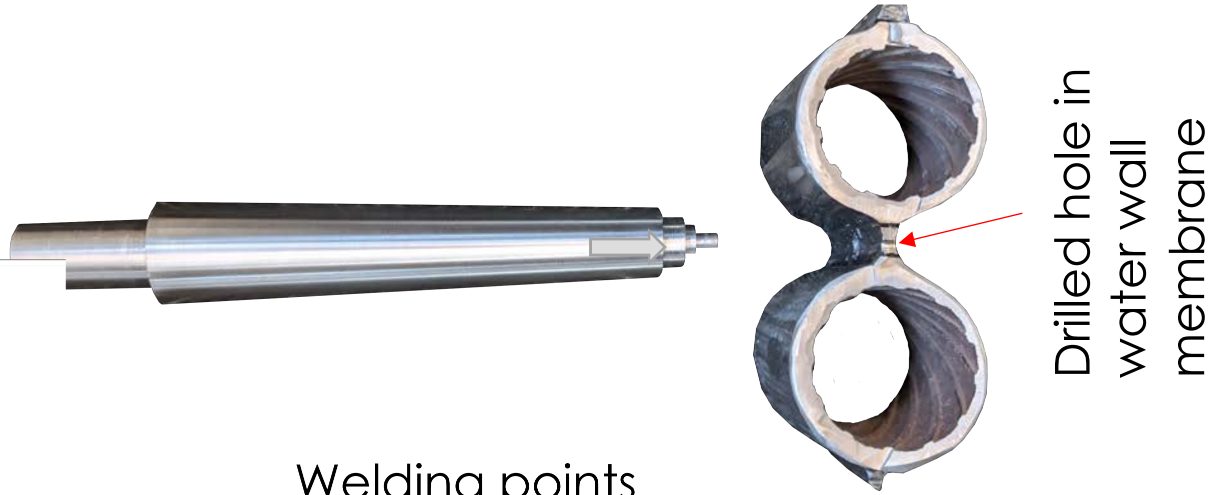
Preparing Project for Next Steps

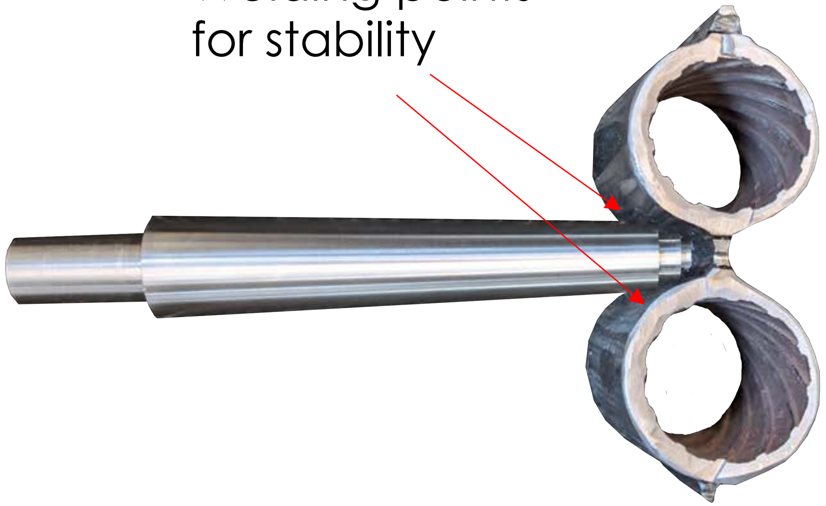
Measurements of heat fluxes to the waterwall

- WG flush with waterwall membrane on fireside and stabilized by welding



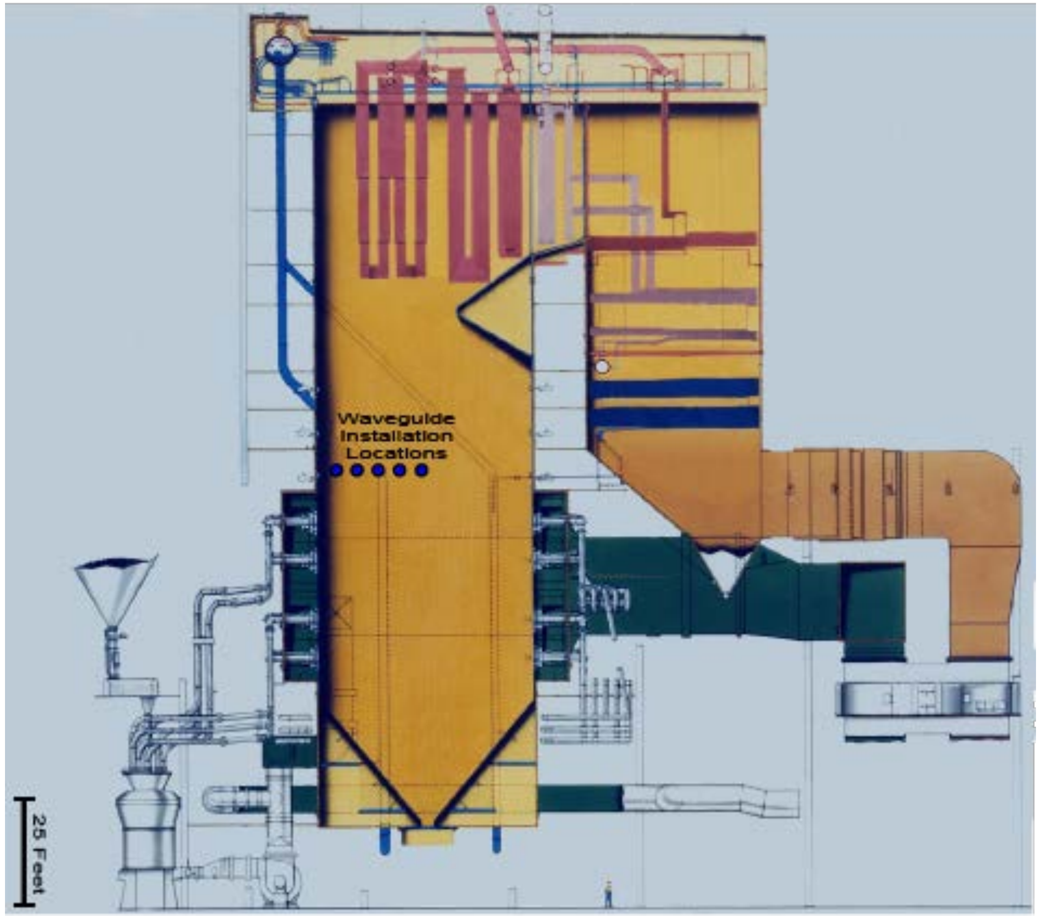
Waterwall membrane installation





Preparing Project for Next Steps

Measurements of heat fluxes to the waterwall – Original plan



Six WGs were to be installed just above the weld line on floor 9.5 and were placed to span half the width of the boiler

Preparing Project for Next Steps

Installation of waveguides at multiple waterwall locations

Waveguide welded to waterwall’s membrane; shown after the waterwall was covered with insolation

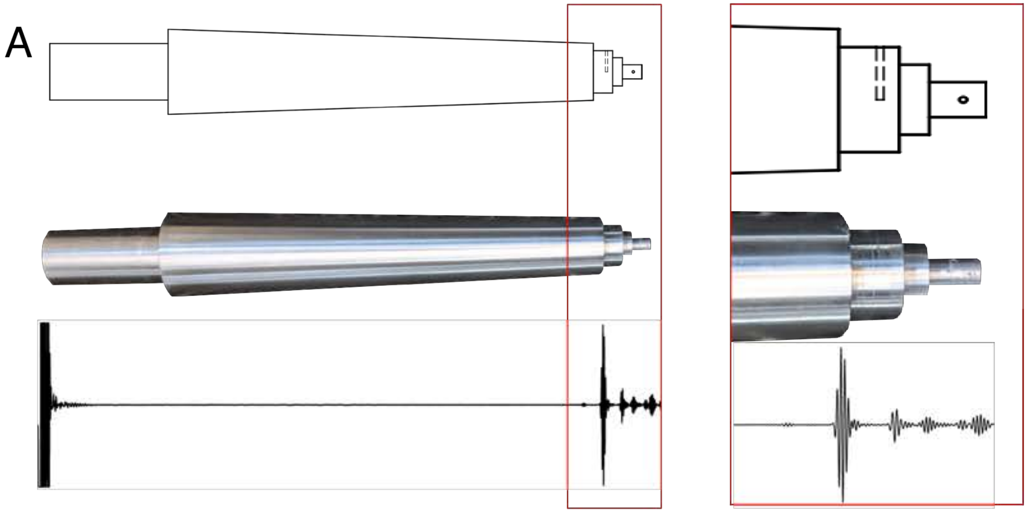
A wider view shows two of five installed waveguides

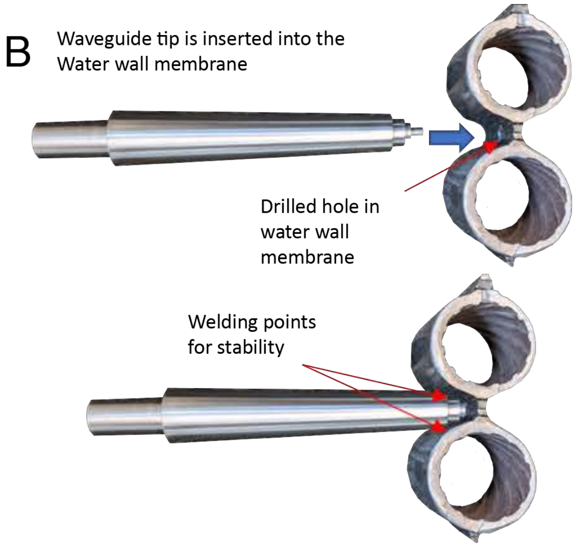
Preparing Project for Next Steps

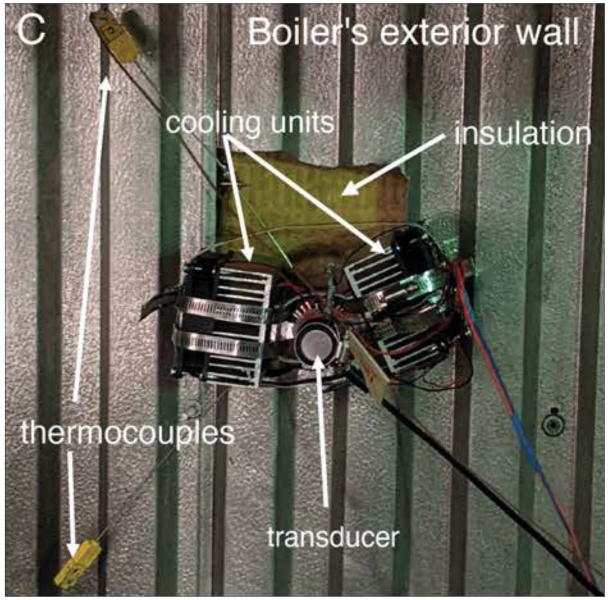
Conventional US sensors required cooling during waterwall installation

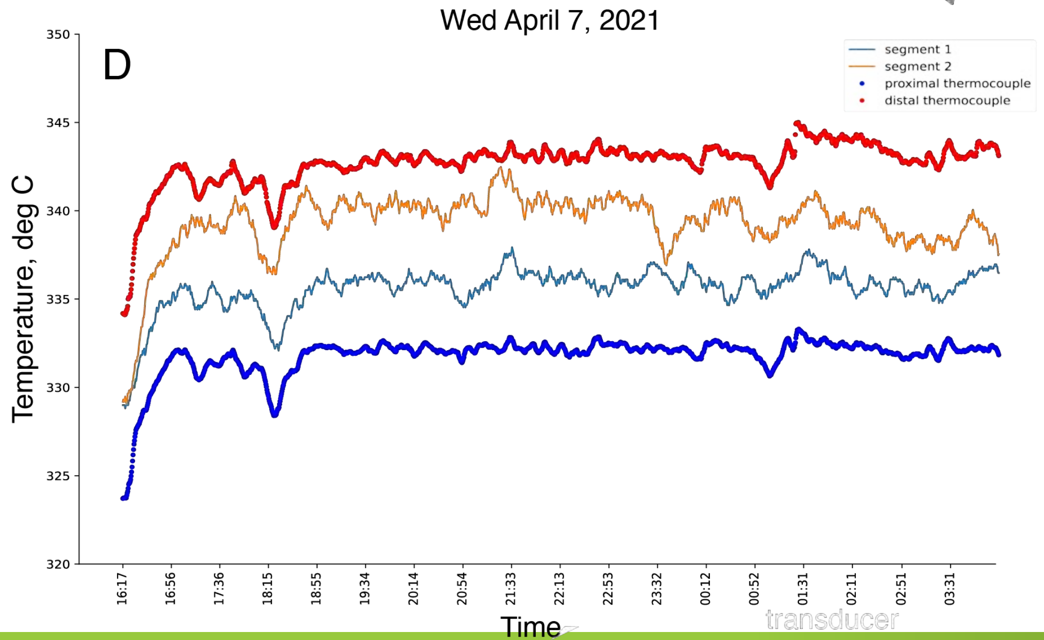
Preparing Project for Next Steps

Power Plant Test 2 – Preliminary results





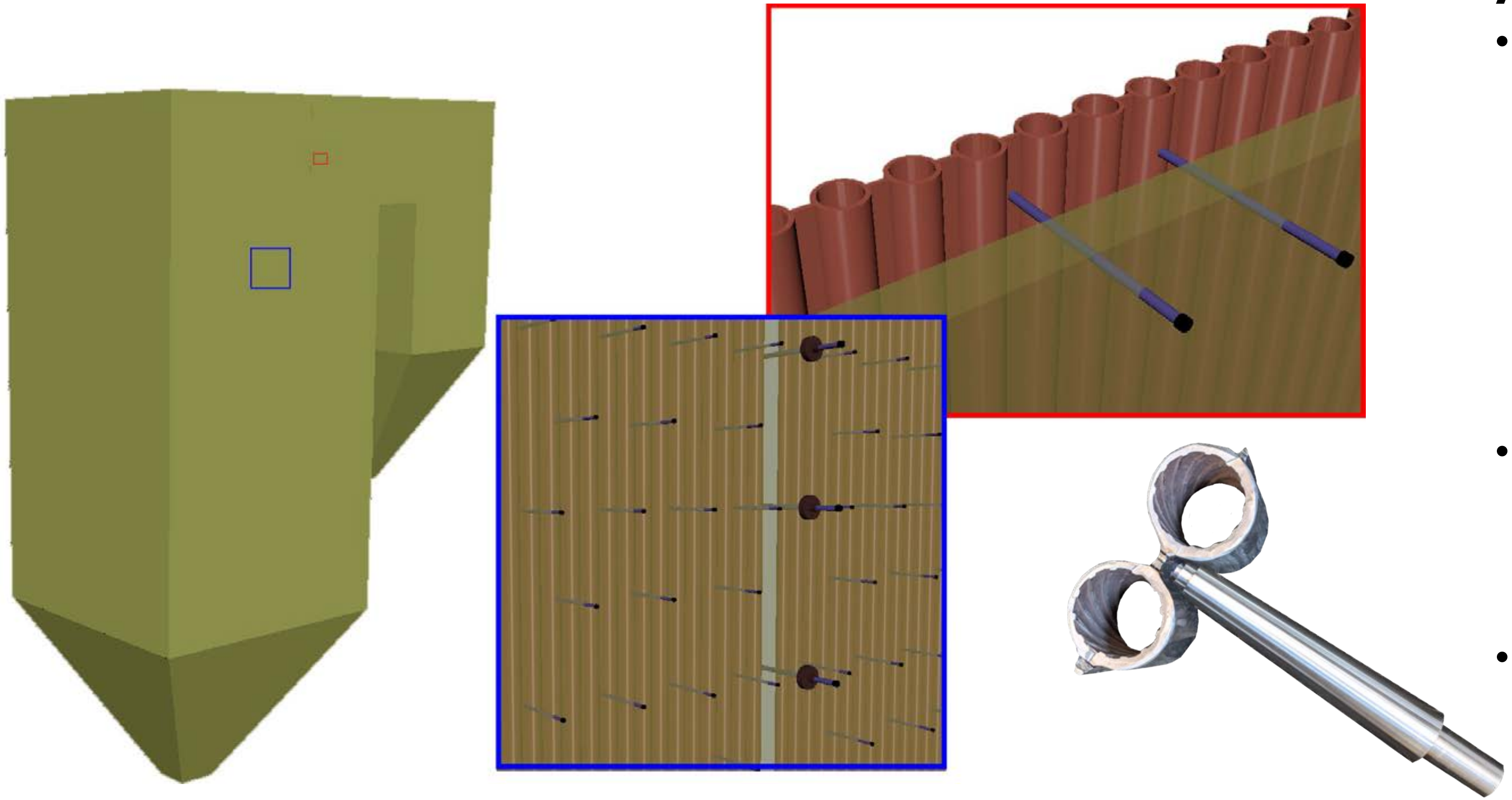




Preparing Project for Next Steps

Densely instrumented energy conversion processes

Example: Utility boilers



Market Benefits/ Assessment

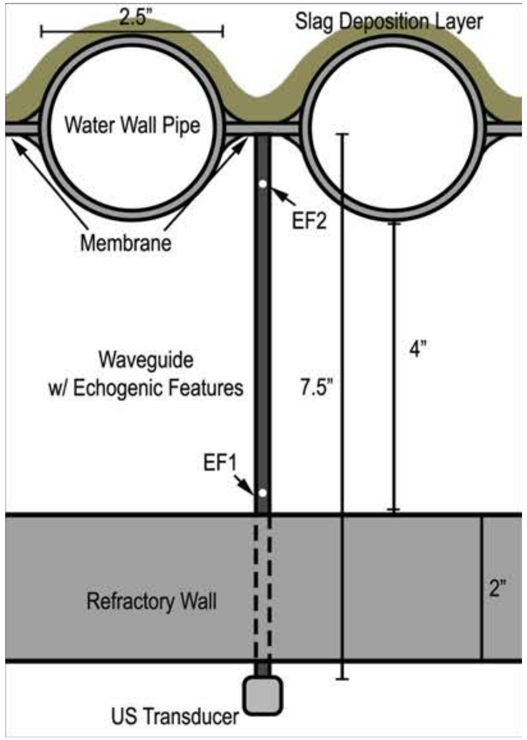
- Comprehensively characterize energy conversion processes with temperature and heat transfer MSTD sensors installed with required/high density.
- Use these data in control, optimization, and predictive maintenance.
- Build a demonstration unit.

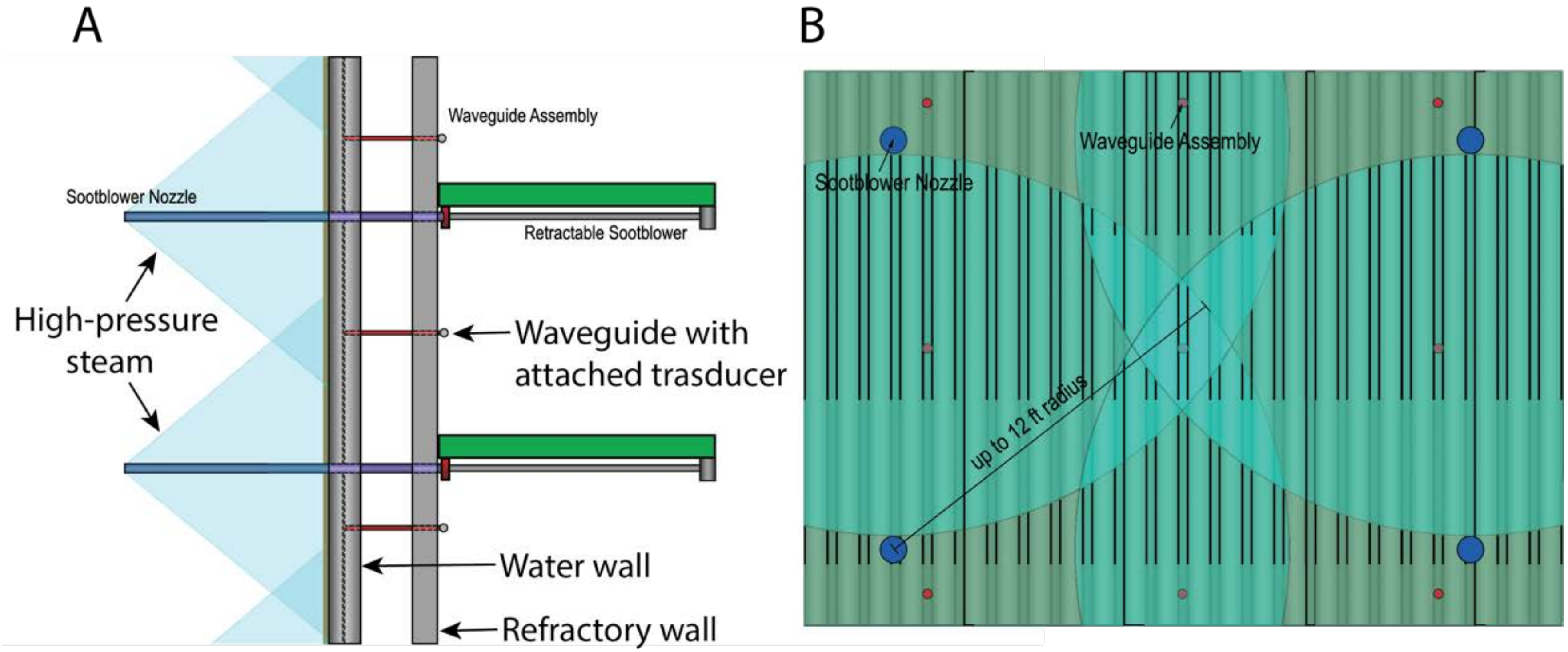
Technology-to-Market Path

Predictive & condition-based maintenance of HX surfaces

Weld WGs to membrane and steam tubes

Use data in predictive and condition-based maintenance

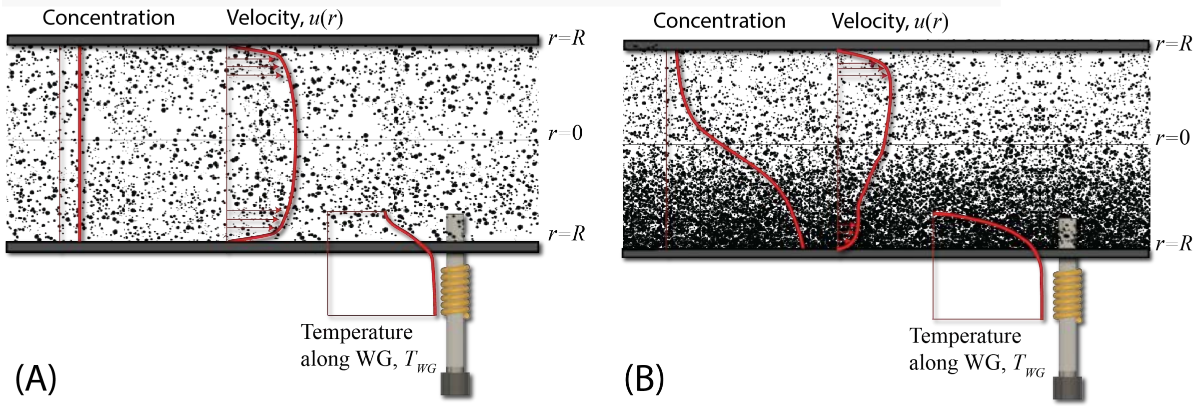




Concluding Remarks

Technology capabilities: Current and future

- Measurements of temperature distributions on lines, surfaces, and in volumes demonstrated
- Heat flux can be measured in any internal or external location
- Noninvasive characterization of thermal stresses is possible
- Extreme environments and inaccessible locations can be characterized
- *Ultrasonic Hot-Waveguide anemometry in flow characterization*



- On-board data processing
- Wireless communication
- Energy harvesting
- Dense instrumentation of heat transfer surfaces
- Digital twins in control, optimization, and predictive maintenance
- Measurements of heat flux vectors
- Structure integration with additively manufactured components
- Monitoring of turbines (*RMP demonstration*)
- Measurements of flow rates -- pulverized coal, molten salt, gas-particle flows (*RMP demonstration*)
- Miniaturization

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Questions