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

2019 DOE Cross-Cutting Conference, April 9, 2019

DOE Project DE-FE0031559, Innovative Technology Development to Enable and Enhance Highly Efficient Power Systems (DE-FOA-0001686)

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Outline

- Approach and its prior validation
- Project description
  - Goals
  - Tasks and Schedule
  - Progress
  - Plans
  - Team

Overall goal

Advance technology-readiness level of ultrasound method for real-time measurement of temperature profiles in solids. Validate a prototype multipoint measurement system in a coal-fired utility boiler.

Original Motivation: Noninvasive measurements in extreme environments

Even hardened sensors cannot withstand harsh environment of energy conversion processes for long time

Rosemount Sapphire TC

NETL, US DOE

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

US Temperature Measurements in Solids

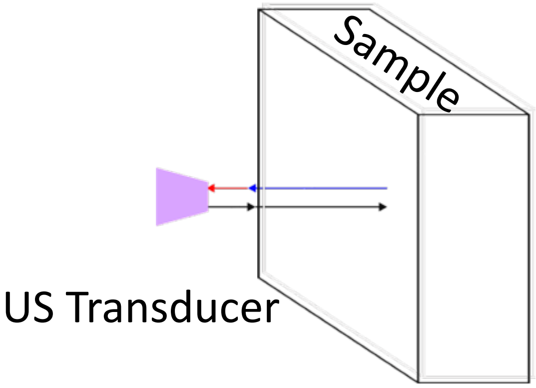
- Speed of sound (SOS) is temperature dependent in gases, liquids, and solids:

$$c=f(T)$$

- SOS can be obtained by measuring time of flight (TOF) of the test pulse:

$$SOS=\frac{2L}{TOF}$$

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



- **Key difficulty**: *When temperature changes*, the TOF depend on the entire temperature distribution in a complex way:

$$TOF=\int_{r_h}^{r_c}\frac{2}{f\left(T\left(t,r\right)\right)}dr$$

Going from ultrasonic TOF to *T*(*z*) is difficult

- Deconvolution of TOF measurements from integral model

$$t_{of} = \int_0^{L(T)} \frac{2}{f\left(T\left(t,z\right)\right)} dz$$ does not have a unique solution

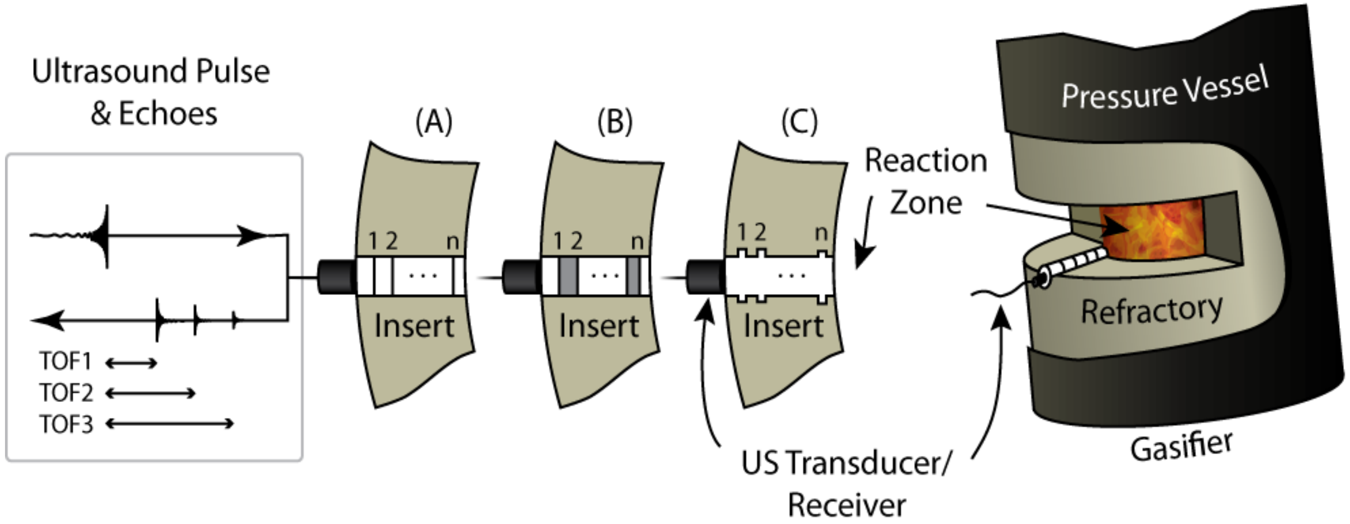
- What can we do:
  - Use more data
  - Constrain allowable temperature distribution
    - Possible parameterizations:
      - Assume constant temperature :

$$\int_0^L \frac{2}{f\left(T\left(z\right)\right)} dz = \frac{2L}{f(T_a)}$$

      - Linear temperature distribution
      - Heat transfer model

US Measurements of Segmental Temperature Distributions: US-MSTD Method

- Create multiple partial reflections that give information about temperature distribution in different segments of the propagation path

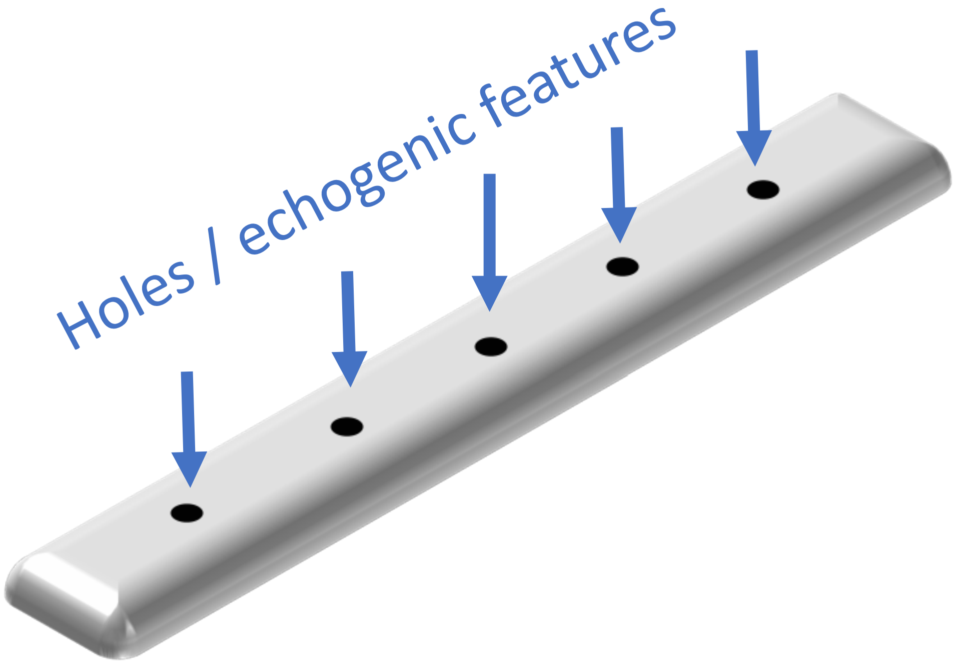


- Methods to create partial reflections:
  - Change in US impedance
  - Scatterers
  - Change in geometry

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

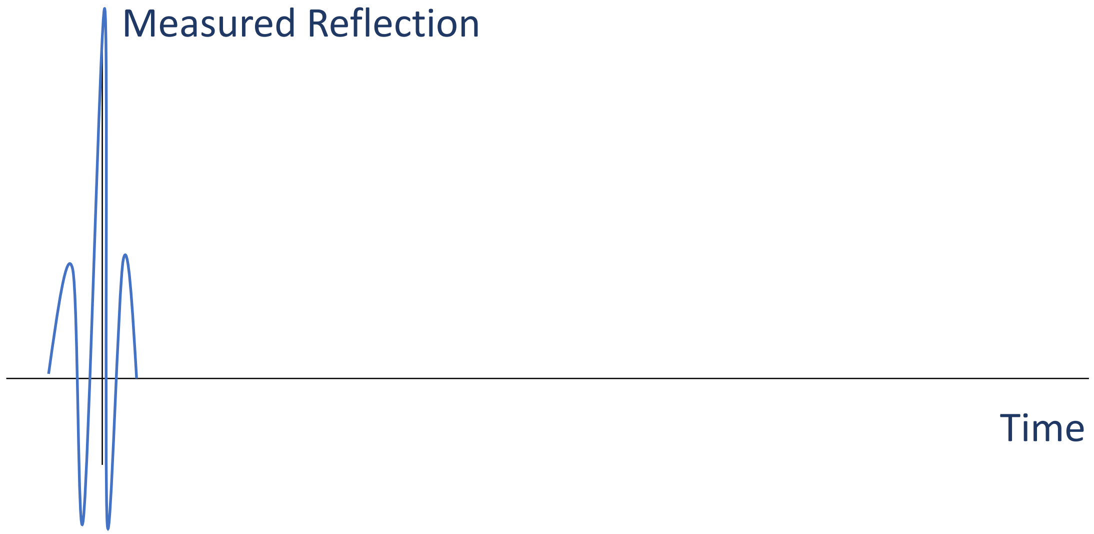
Design of Echogenic Features: A simple solution

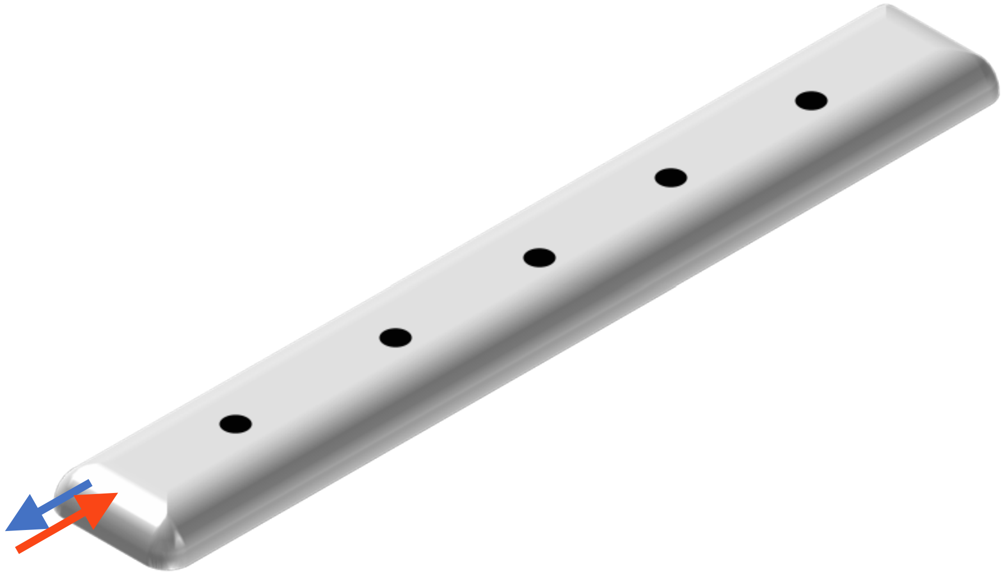
- Design a waveguide with ”geometric” features creating ultrasound reflections



Train of Echoes Provides Segment-Specific Data

- TOF between echoes encodes temperature information for the corresponding segment





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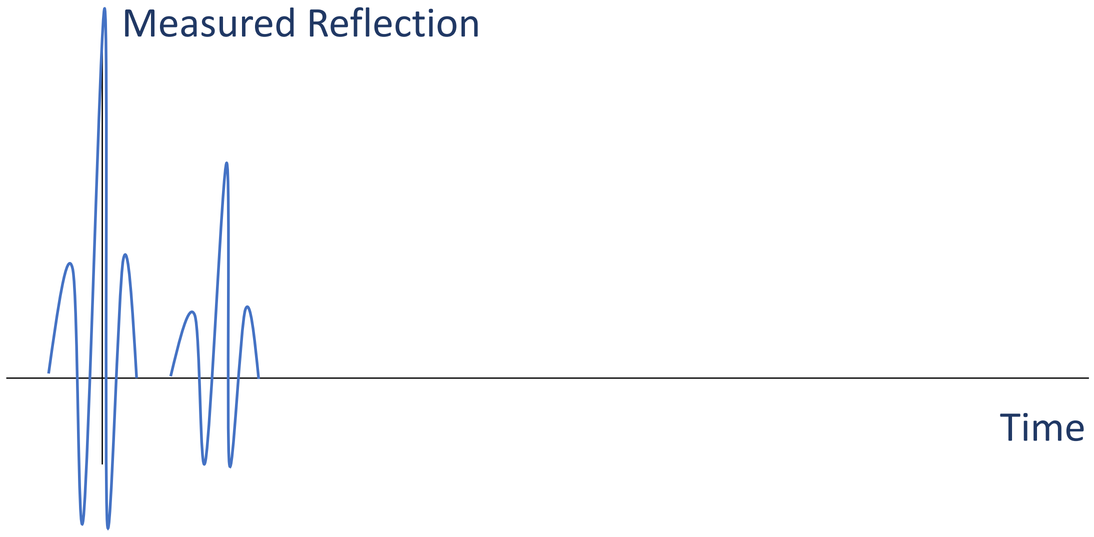

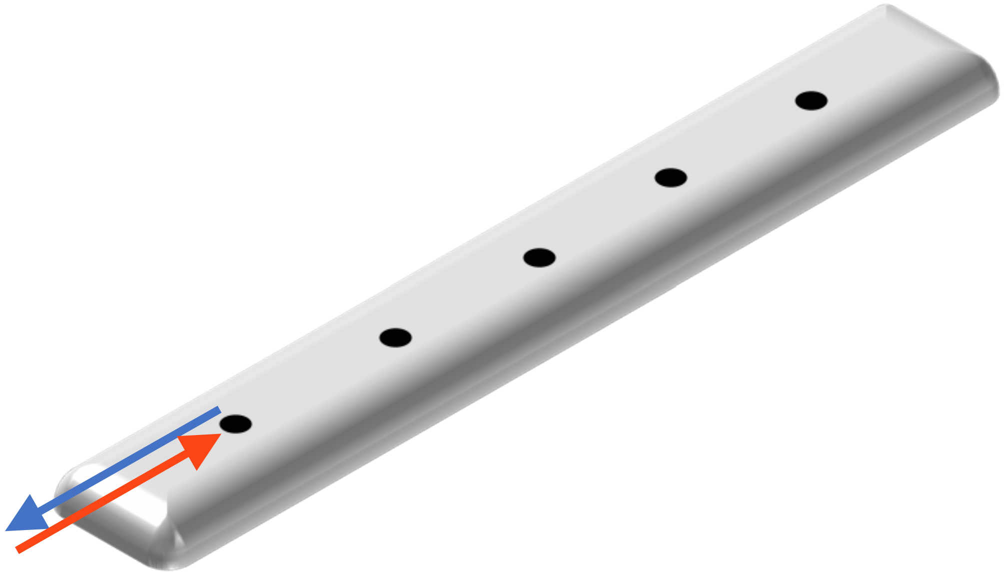

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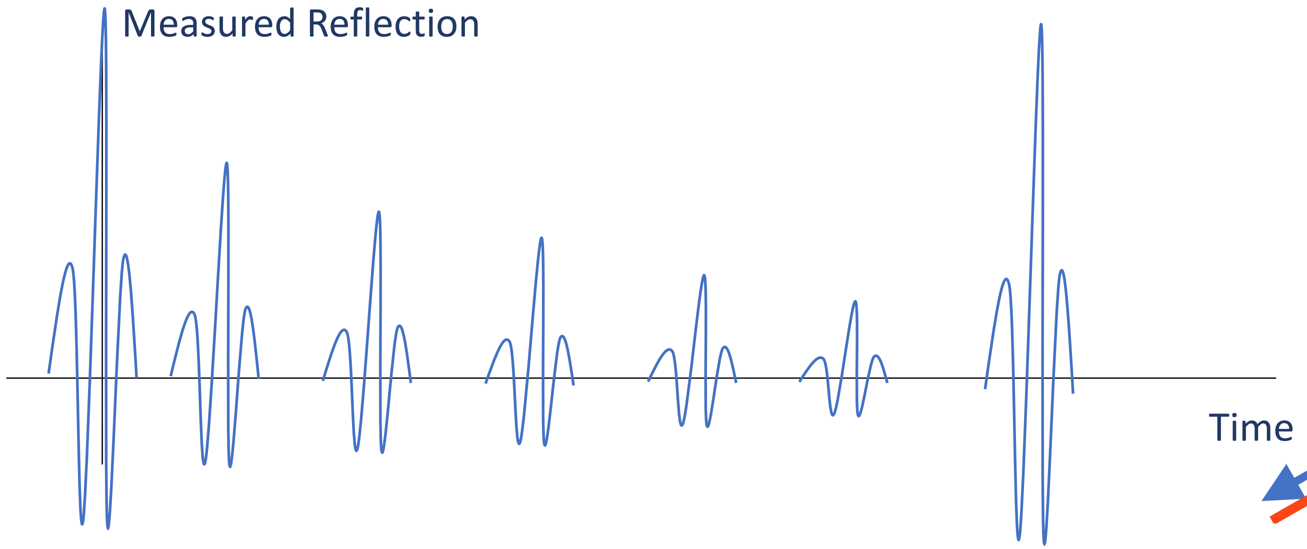
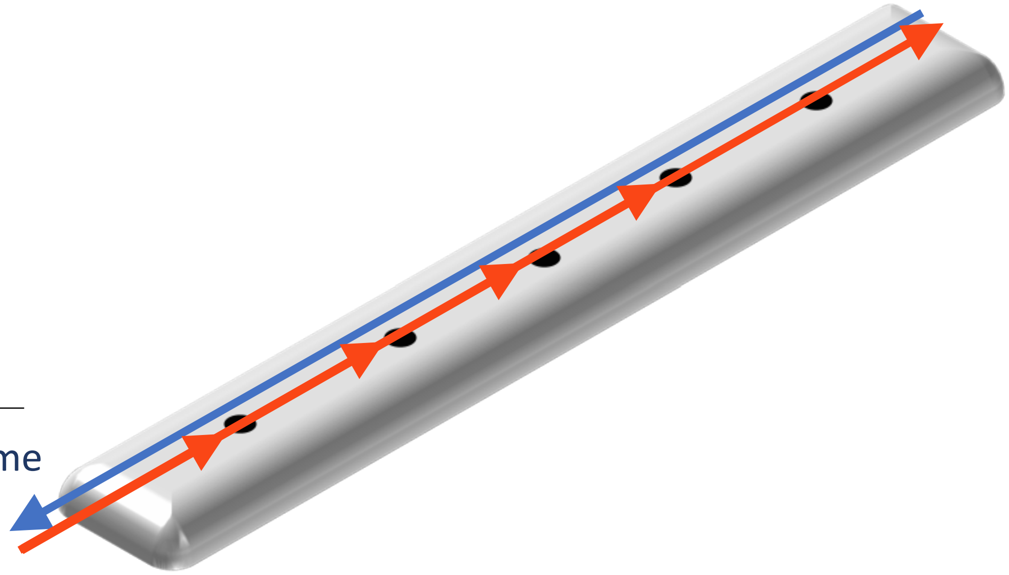
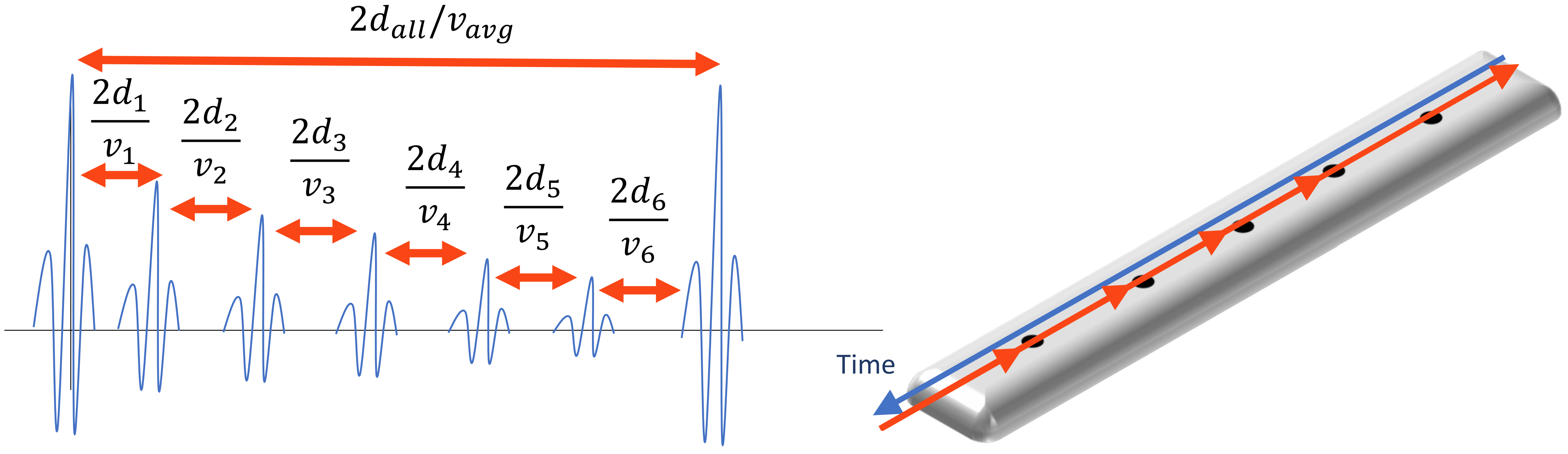




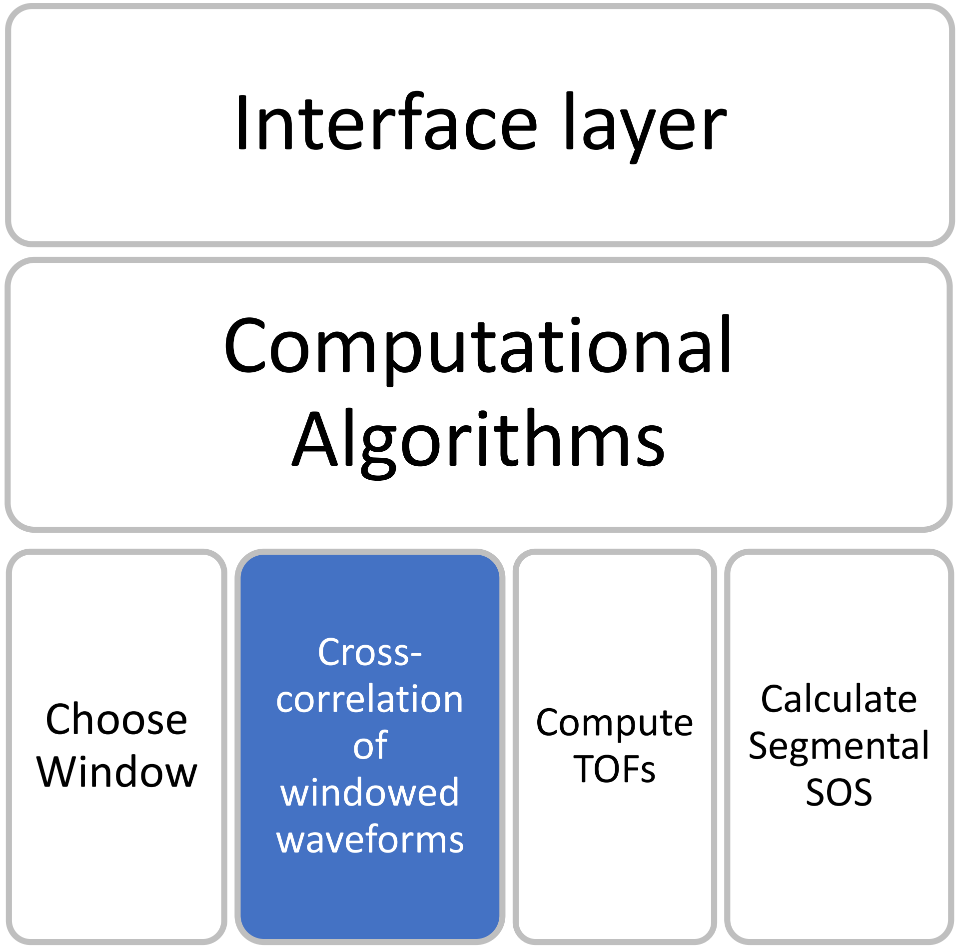
Train of Echoes Provides Segment-Specific Data

- Segmental velocity of ultrasound propagation is correlated to the segmental temperature



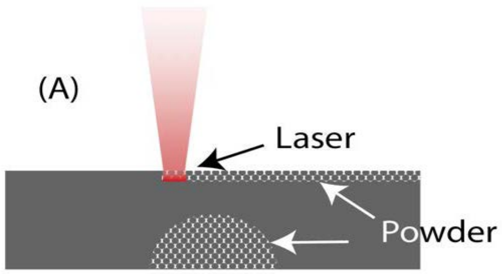
Algorithm and System Integration

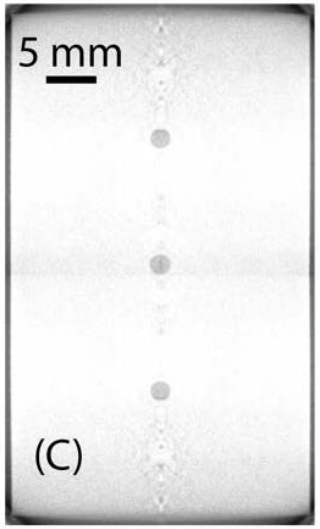
- Our time of flight estimation algorithms
  - Perform cross-correlation / pulse compression

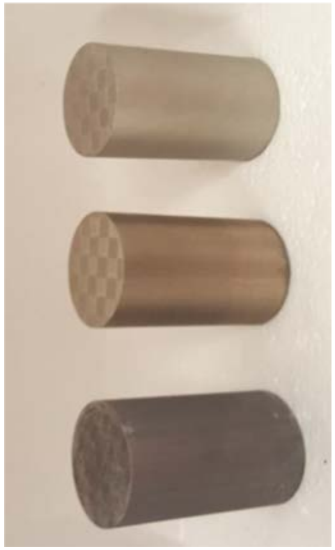


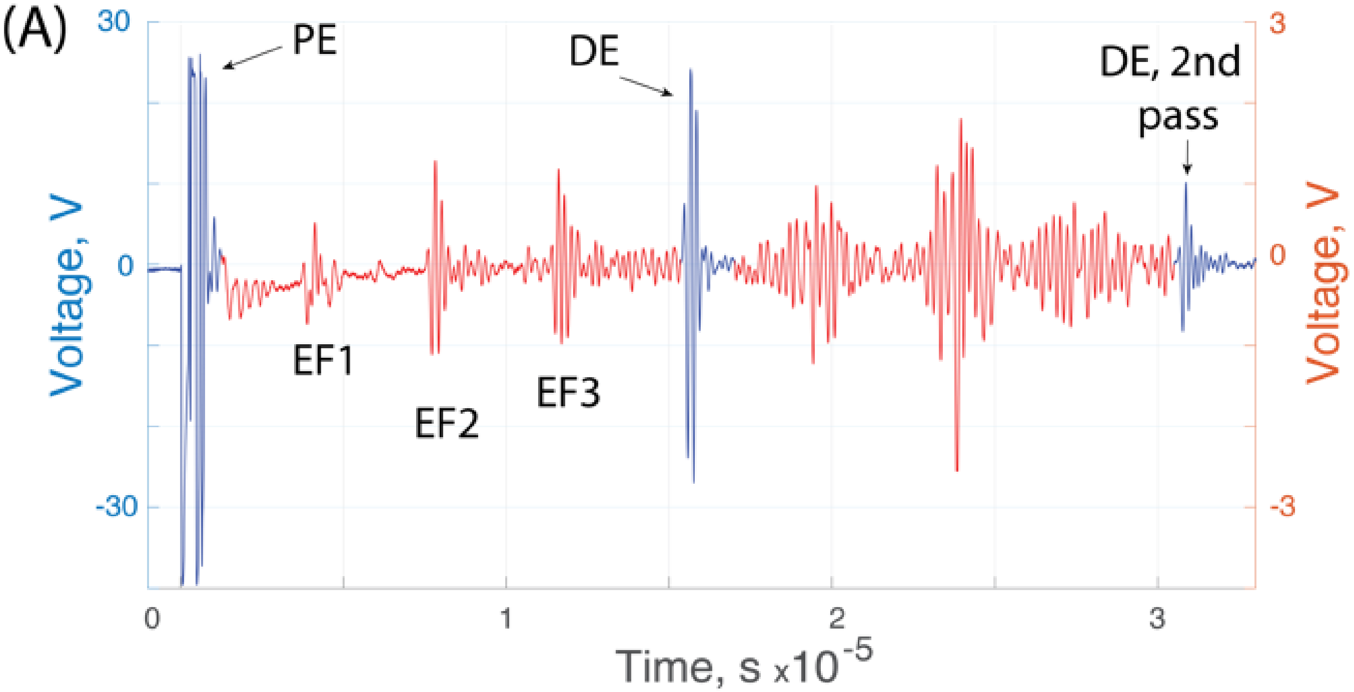
Additive manufacturing gives new ways to introduce echogenic features

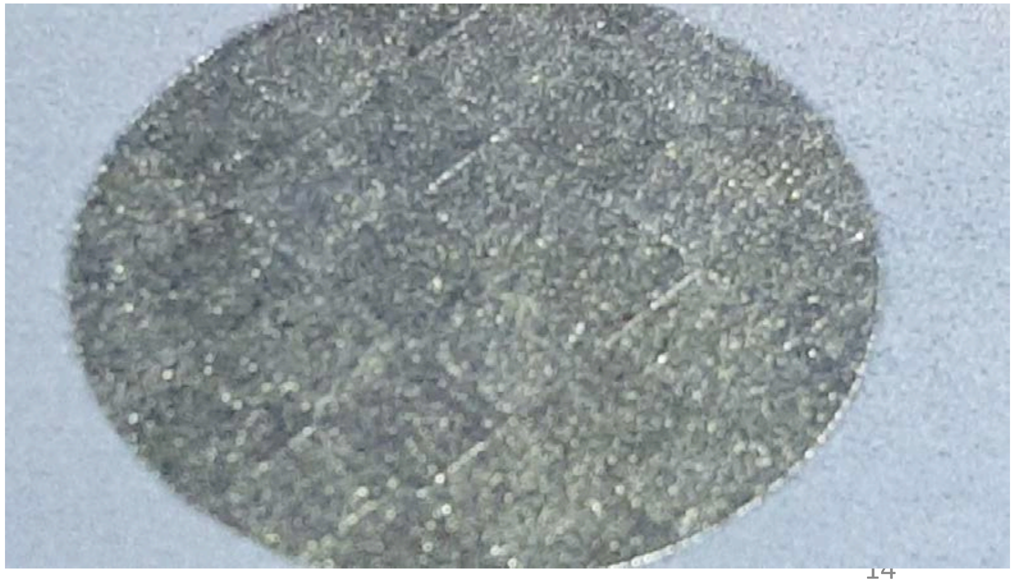
Additive manufacturing can be used to create structures and components through which we can measure temperature distribution using US-MSTD method.



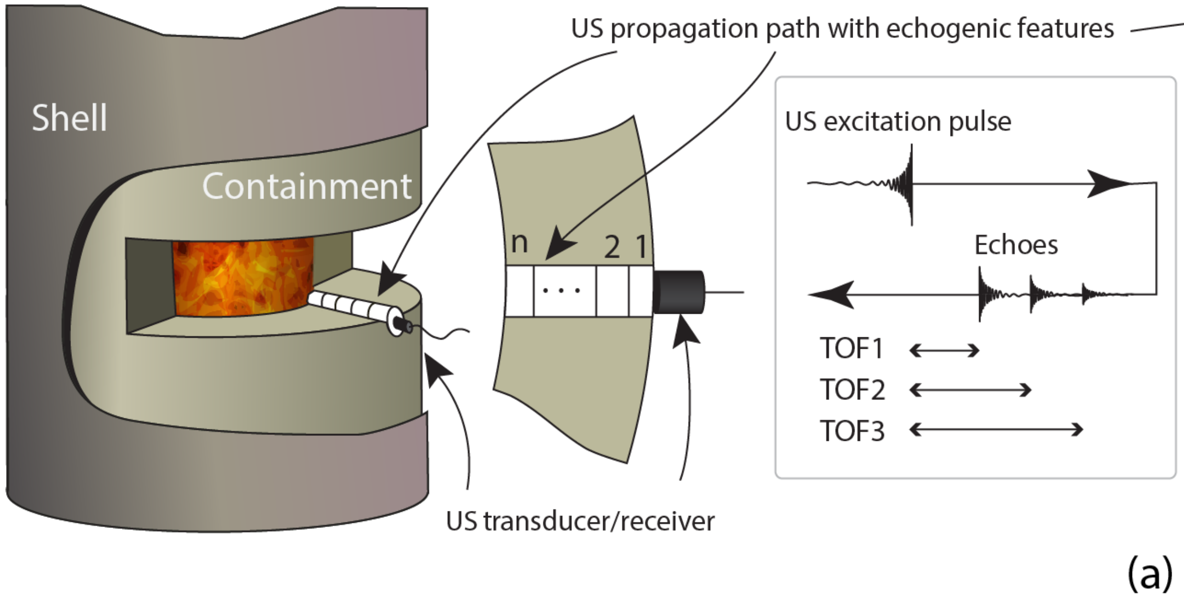




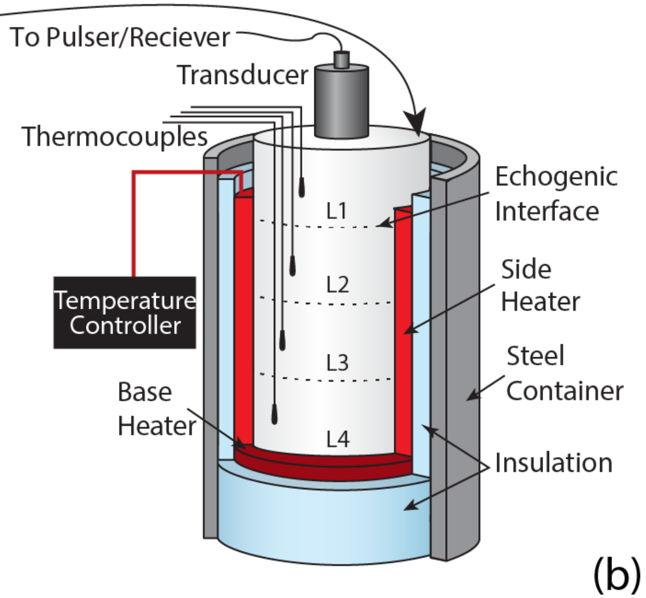




Demonstration of US-MSTD Method in Cementitious samples

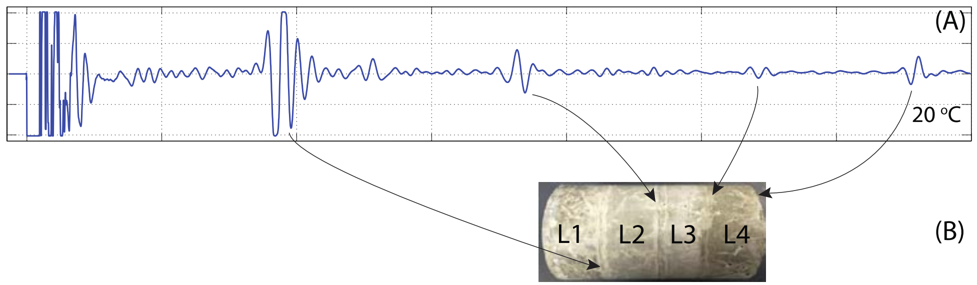


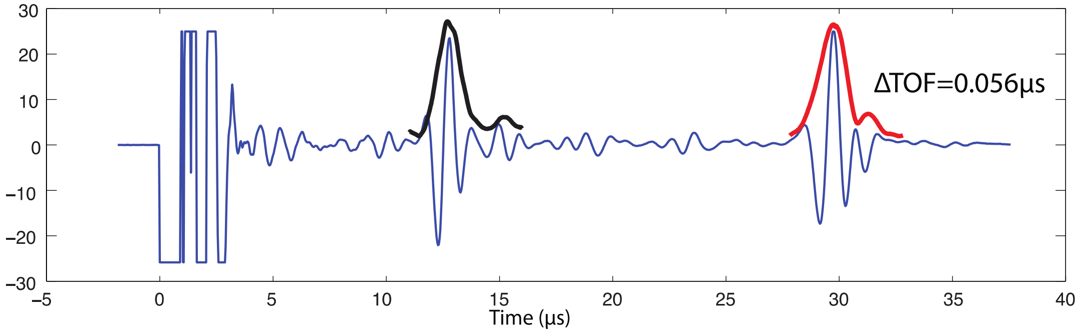
(a)

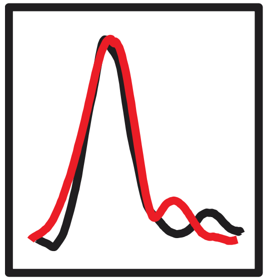


(b)

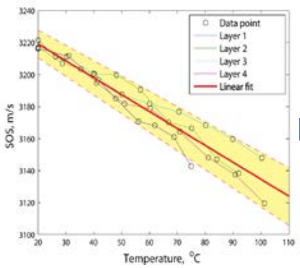
- 4” cementitious sample with four layers
- Surface temperature measured by TCs attached in the middle of each layer







→ **TOF** → **SOS** →



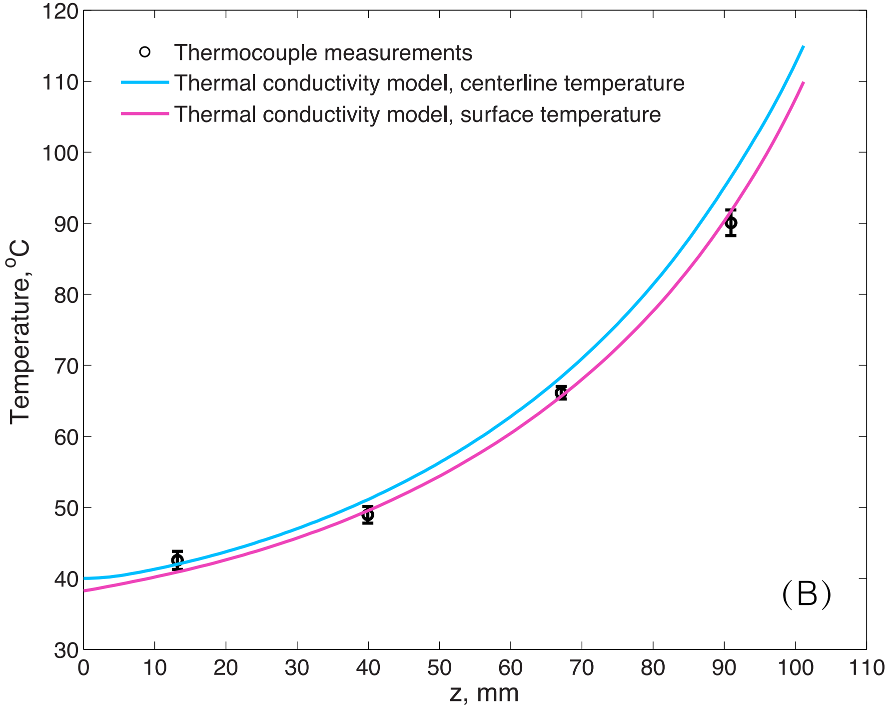
→ $T(z)$

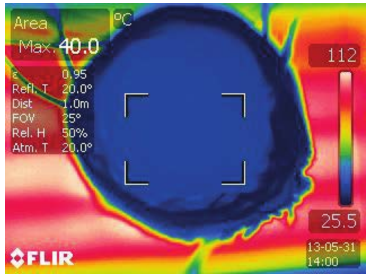
3D Reconstruction of Temperature Distribution

Temperature is reconstructed to satisfy measurements and heat transfer models:

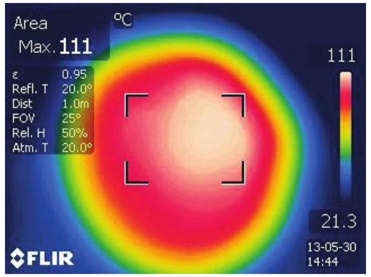
$$t_{of} = 2\int_0^L \frac{1}{f(T(z))}dz$$

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

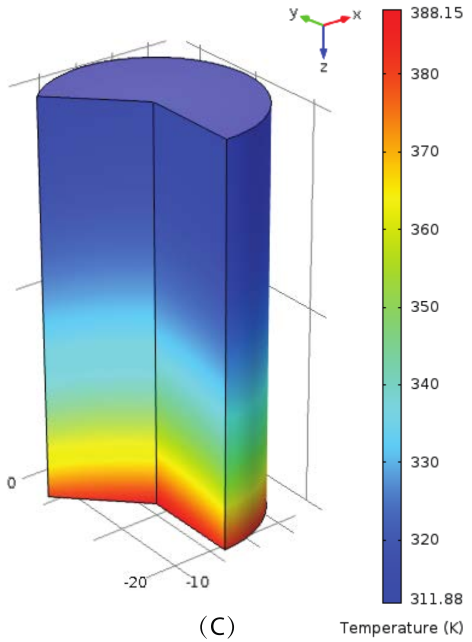




(A)



(B)

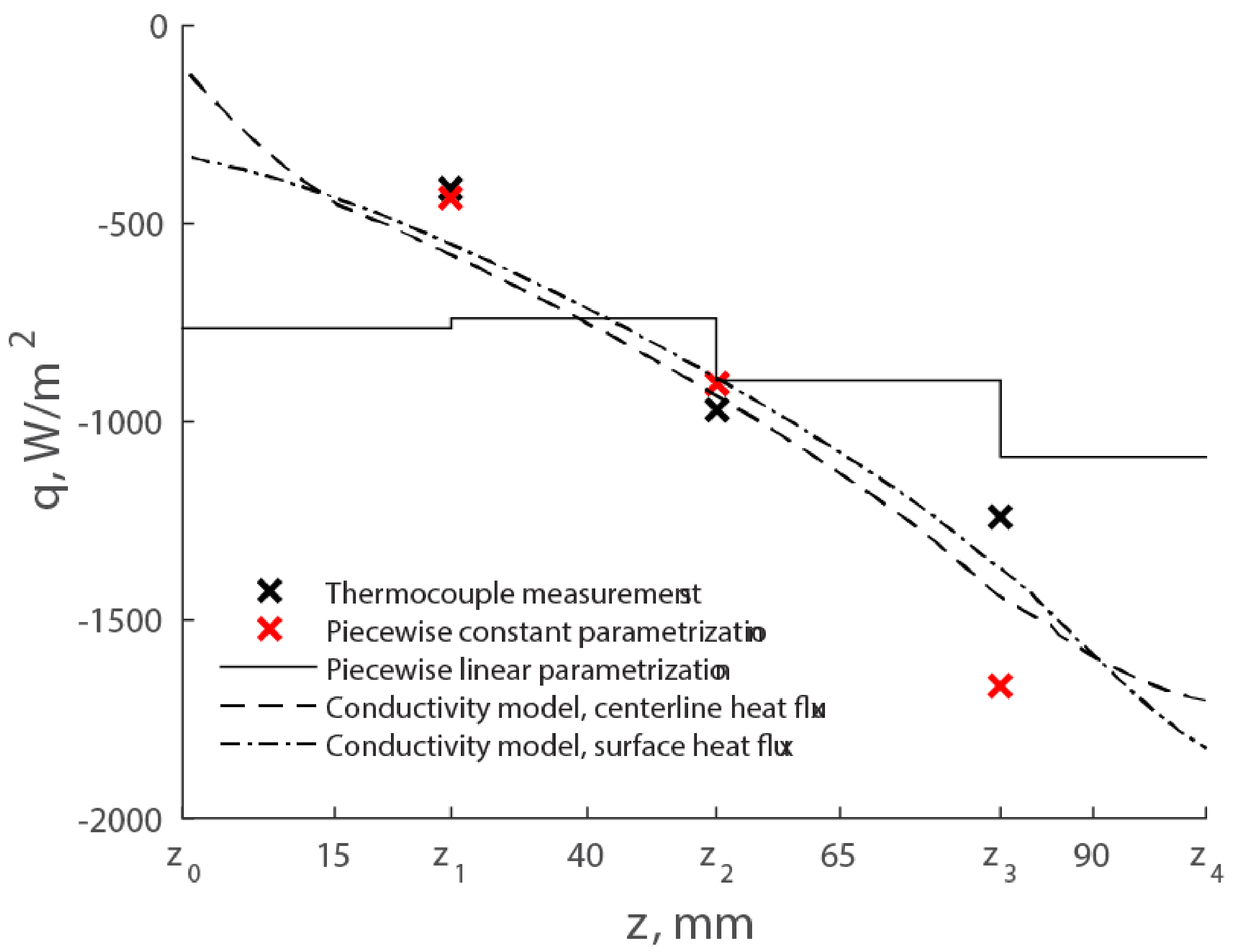


(C)

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

Internal Heat Fluxes Vectors can be Estimated

Axial heat fluxes in the cementitious sample



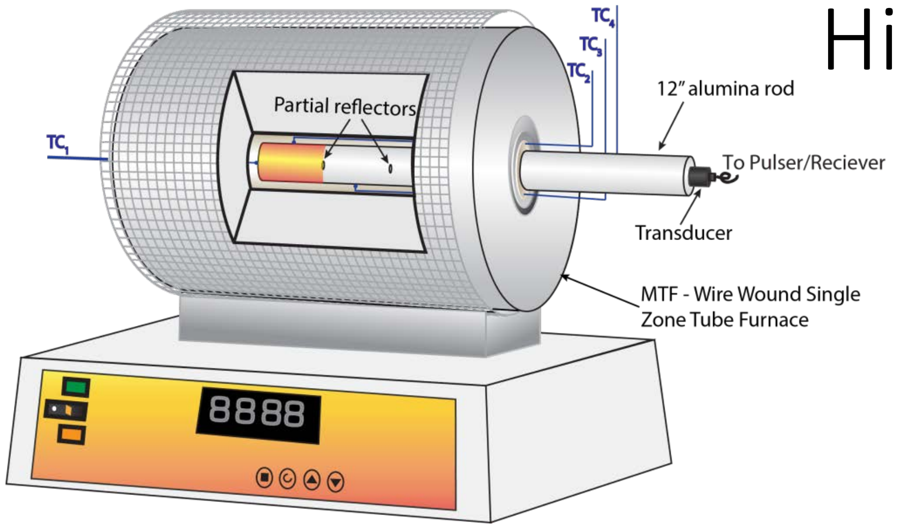
When T=const, segmental elasticity, density, and other material properties can be measured

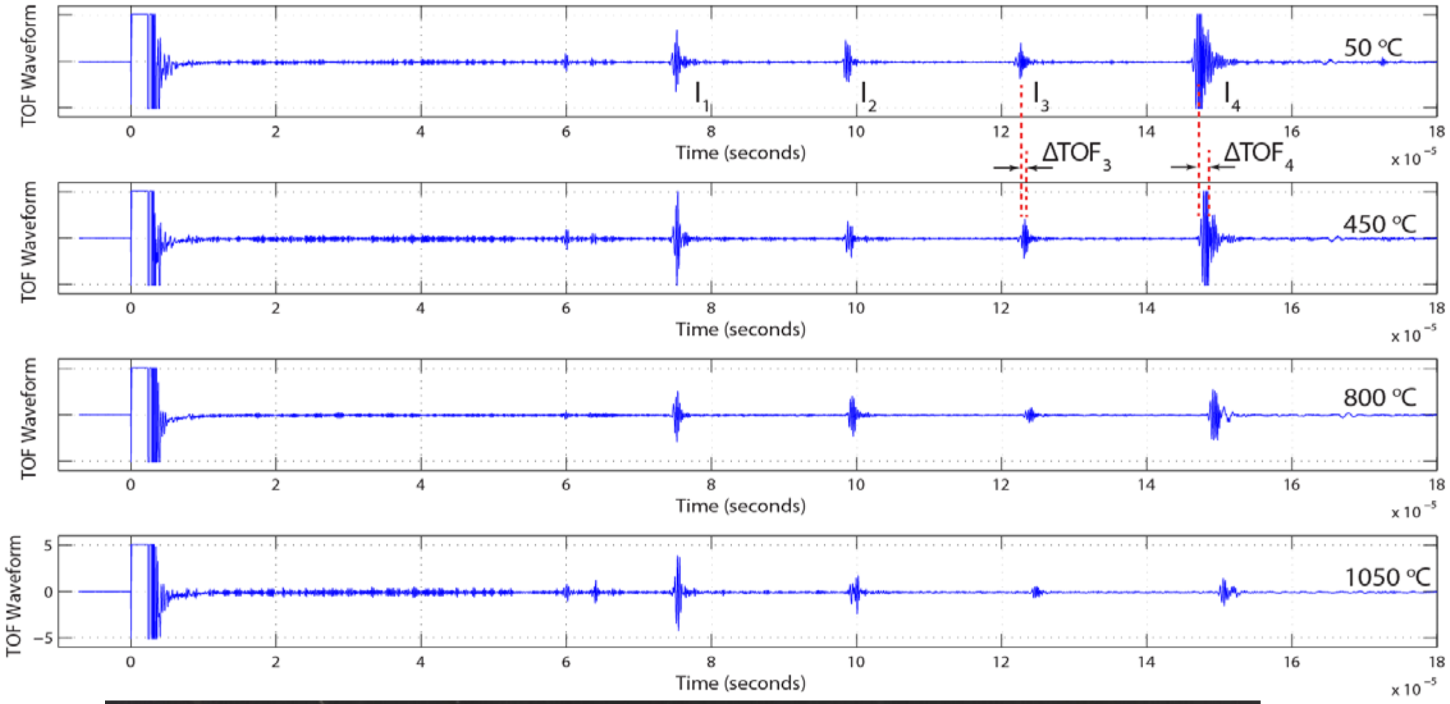
- In the simplest case of a “thin” waveguide

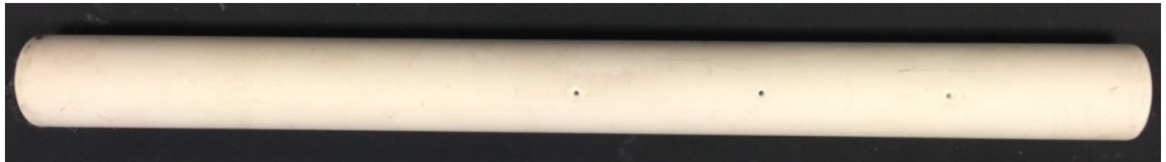
$$c_i = \sqrt{\frac{E_i}{\rho_i}}$$

- In more general case, the estimation of segmental elastic properties (Bulk, Young's, Shear moduli, Poisson's ratio) measurements with p- and s-waves are needed

High-Temperature Demonstration

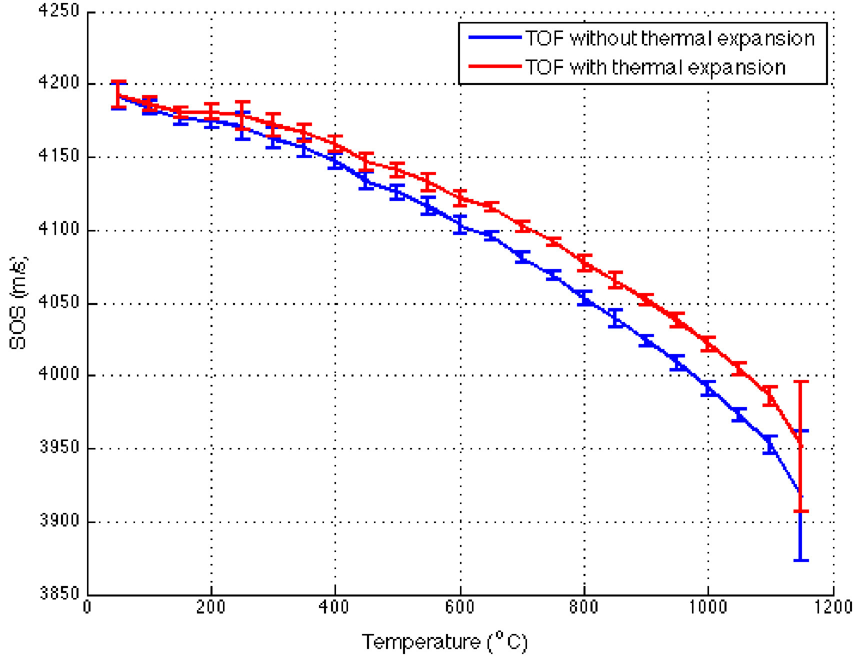






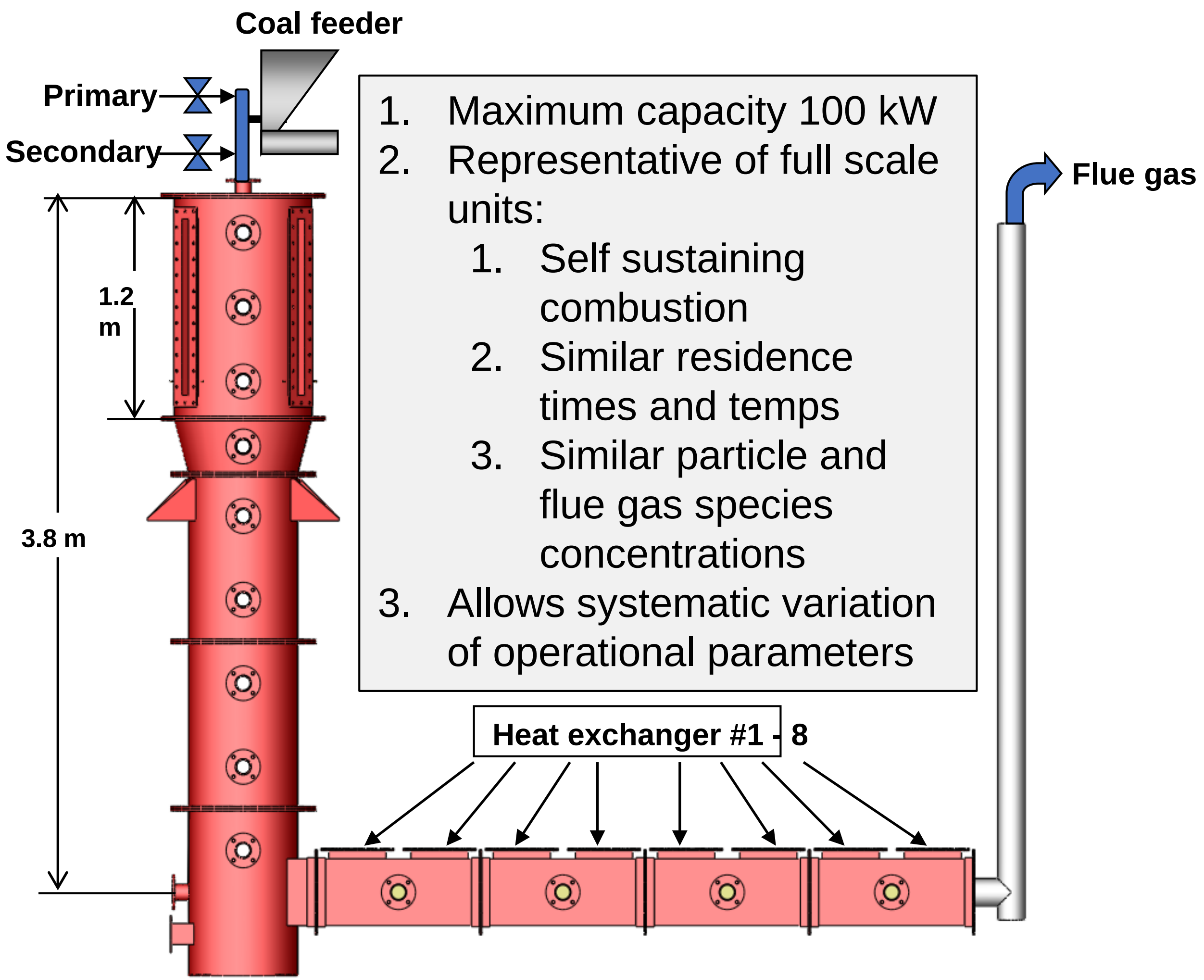
- Surface temperature independently measured by TCs

SOS vs. T in Al_2O_3

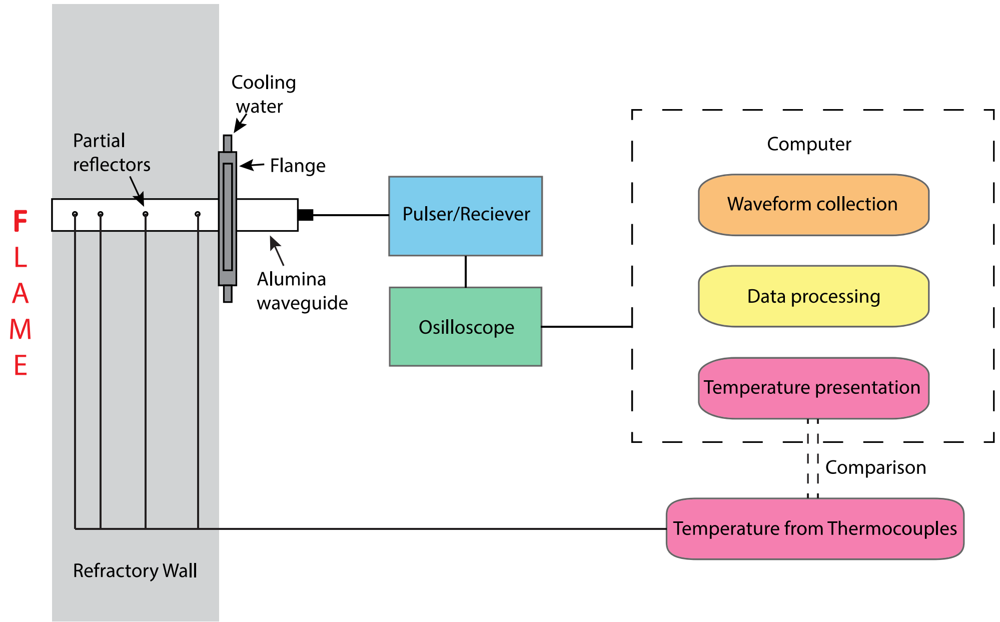


Jia, Y., V. Chernyshev, and M. Skliar, Ultrasound measurements of segmental temperature distribution in solids: Method and its high-temperature validation, Ultrasonics, 66, pp. 91-102, 2016.

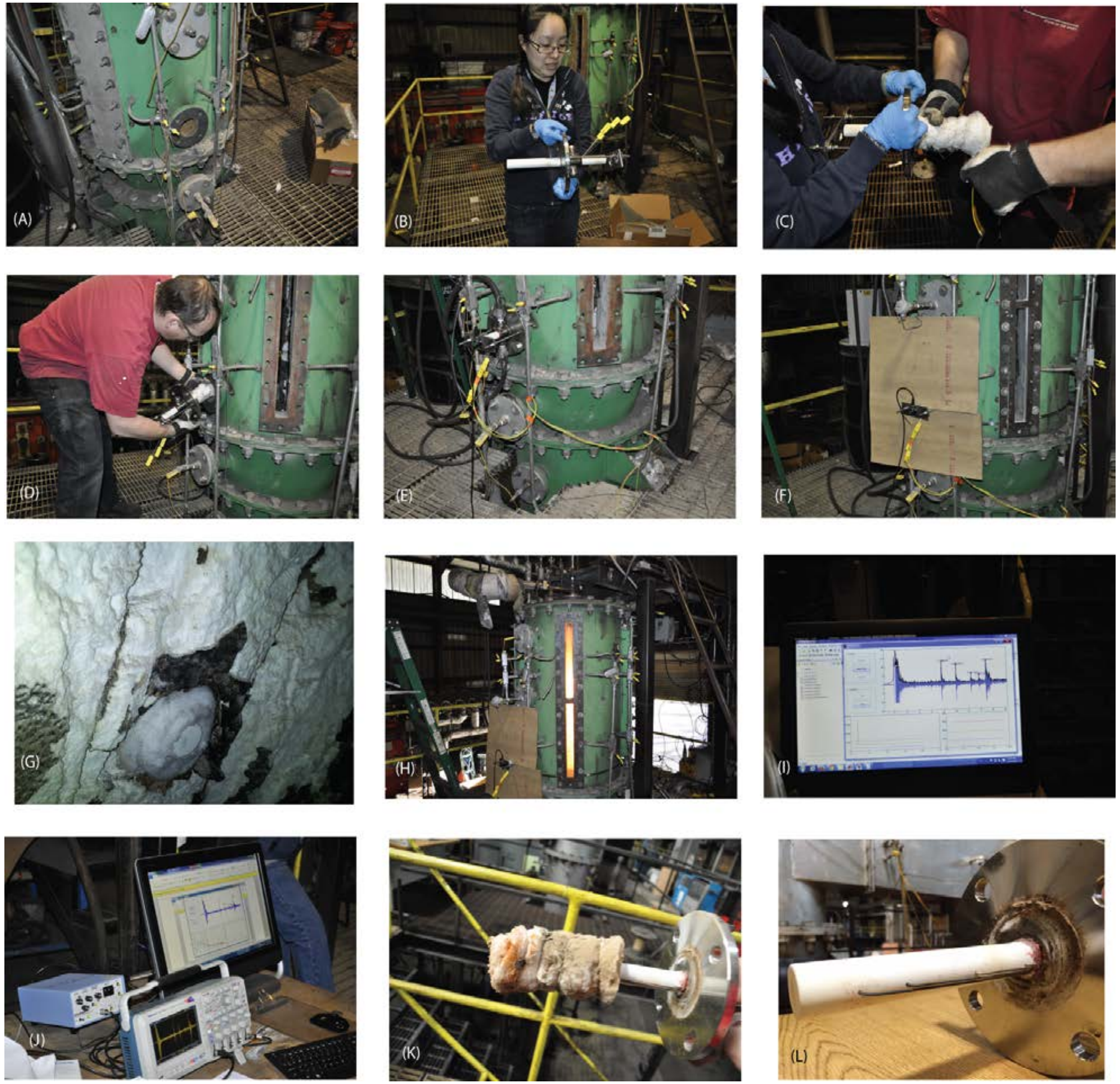
Pilot Validation: Down-flow Oxy-fuel Combustor



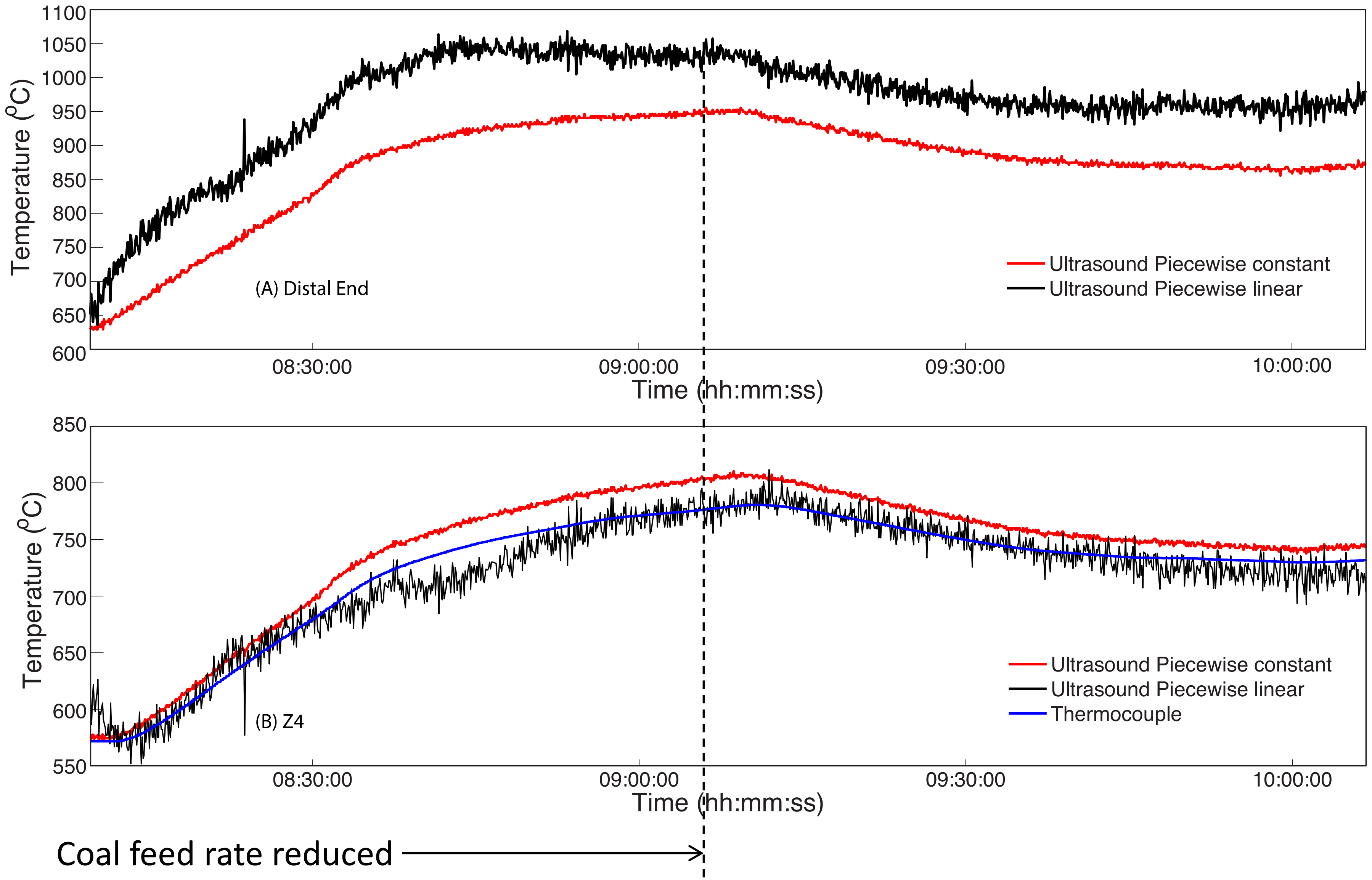
1. Maximum capacity 100 kW
2. Representative of full scale units:
    1. Self sustaining combustion
    2. Similar residence times and temps
    3. Similar particle and flue gas species concentrations
3. Allows systematic variation of operational parameters

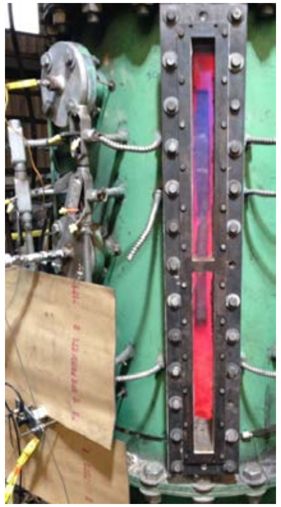


US Measurement System: Installation



Coal Combustion with Changing Coal Feed Rate

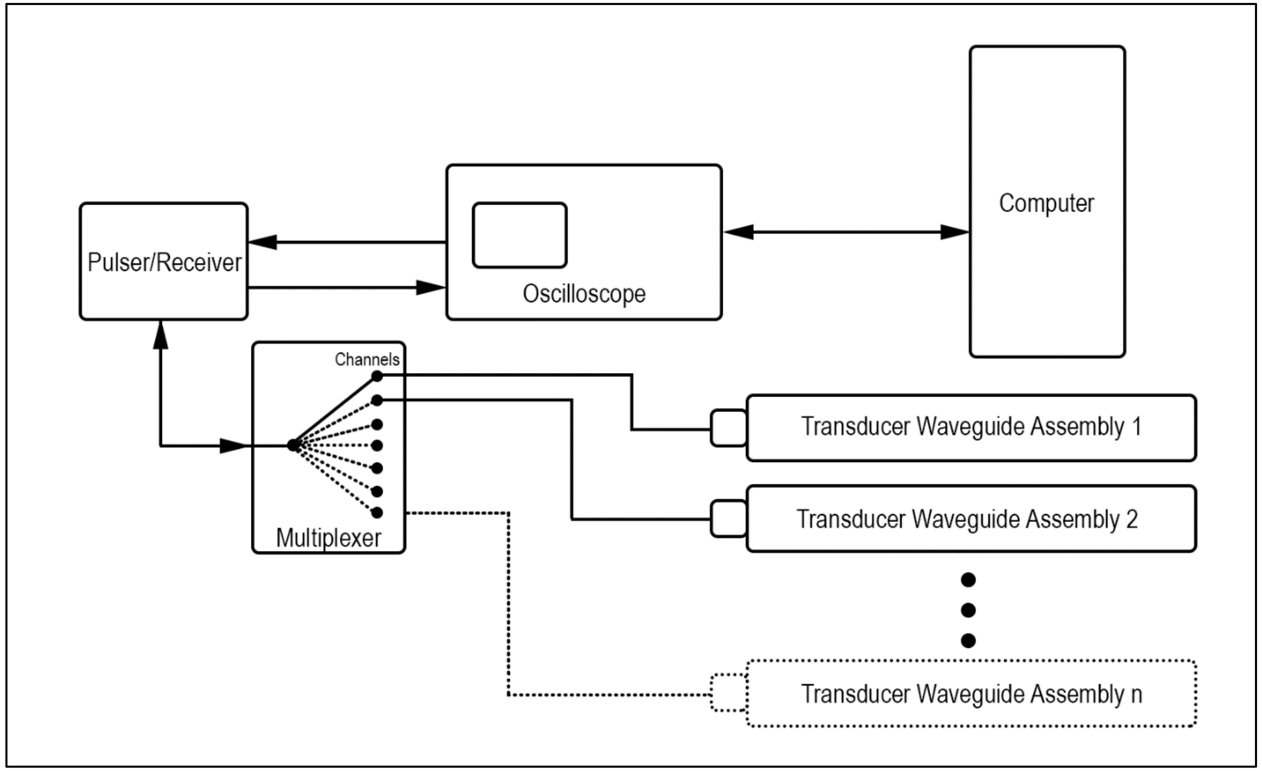




Task	Tasks, Schedule, Milestones	Completion
PHASE I		
Task 2	The multipoint US-MSTD method is developed	Month 12
Task 3	Multipoint US-MSTD prototype is tested in laboratory	Month 12
PHASE II		
Task 2	Software integration of the TRL 6 prototype is completed	Month 24
Task 3	1. Pilot scale testing of the 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

Technology status

- Method can provide accurate continuous noninvasive real-time measurements of temperature distributions in solids
- Demonstrated in laboratory and a small-scale process
- Heat fluxes deep inside structures can be measured
- Measurements in multiple locations are possible
- Can be used with existing and integrated into new energy conversion units
- Multipoint capability implemented
- System integration in Python
- Plant testing planned for this summer



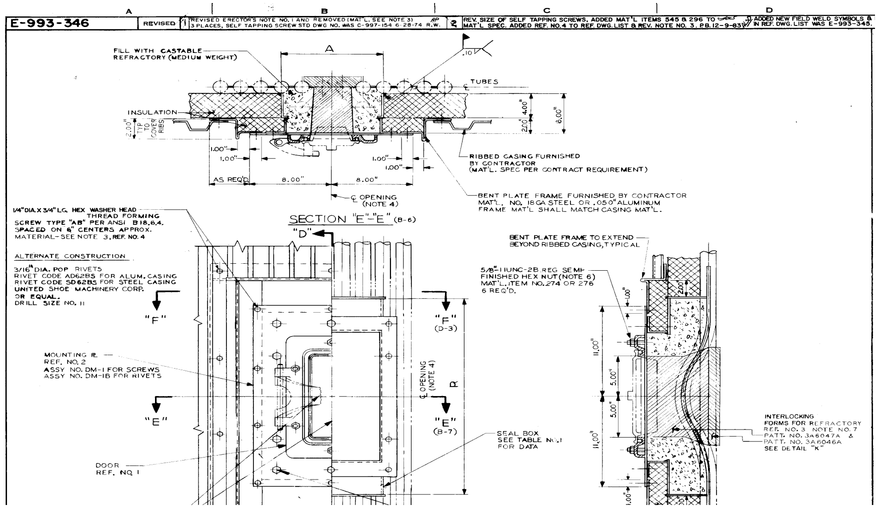
Rocky Mountain Power Hunter plant testing

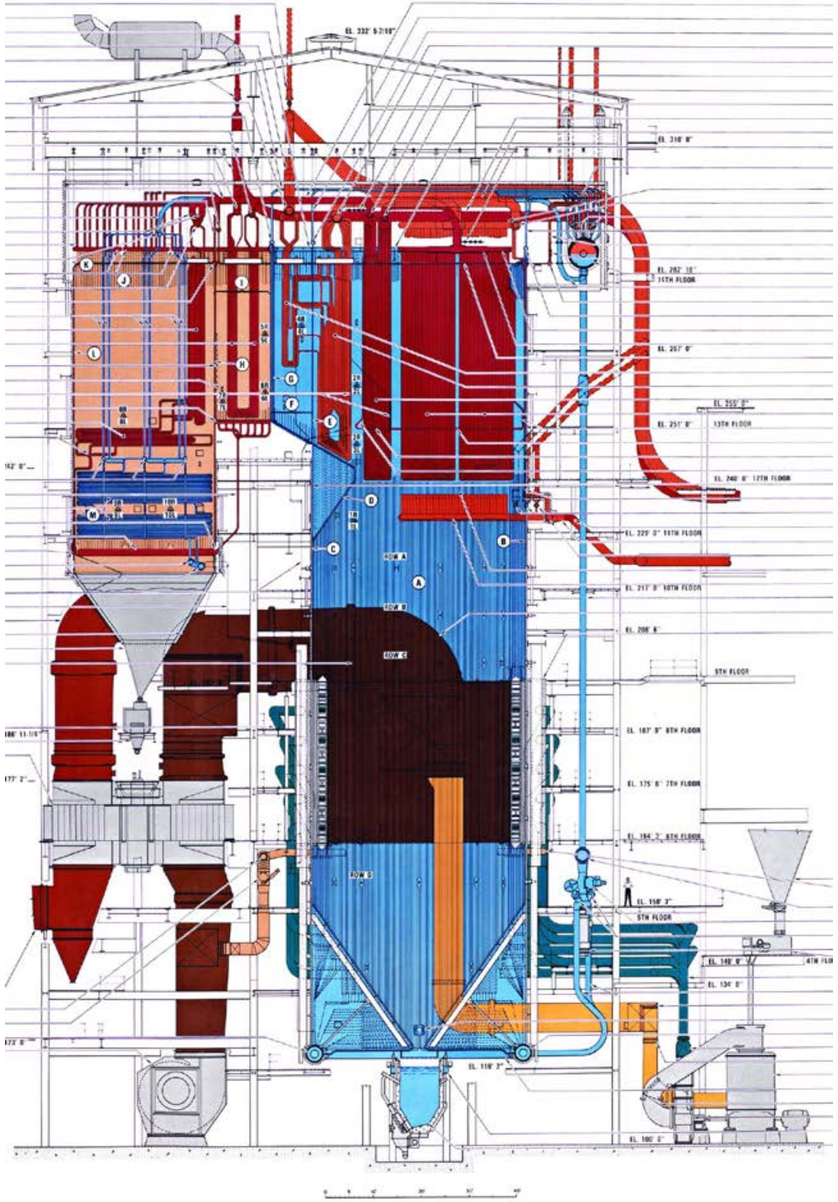
~~Year 3~~ Year 2

- Test single-point US-MSTD system. Temperature at the selected location may be as high as 1,500° C.

Year 3

- Measurements of temperature and heat fluxes at multiple locations.
- Repeat testing after soot blowing, if scheduling allows it.



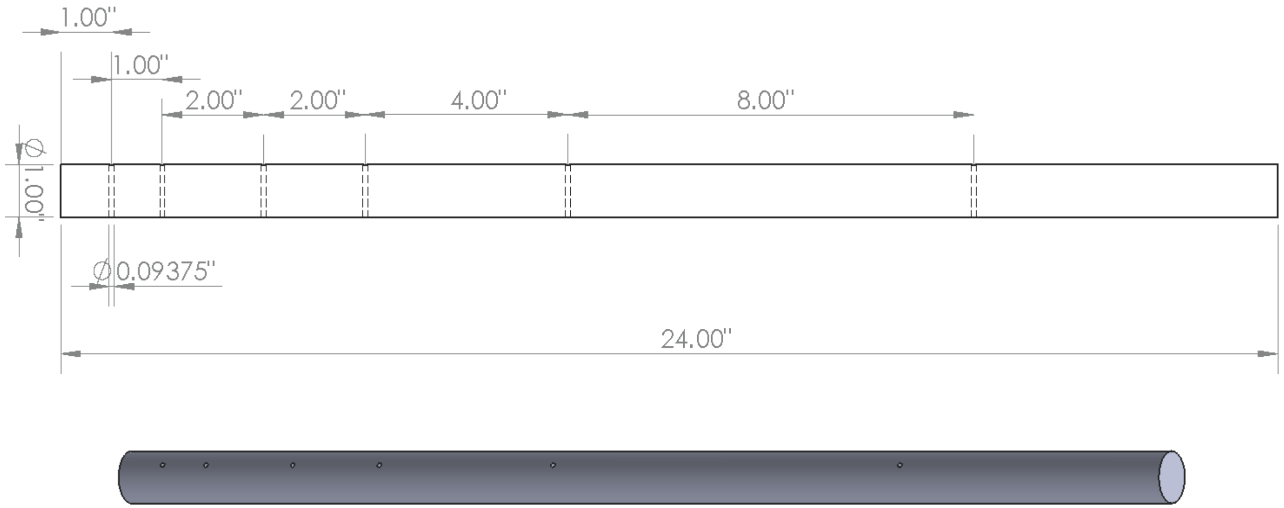


Transition to Metal Waveguides

Things to consider

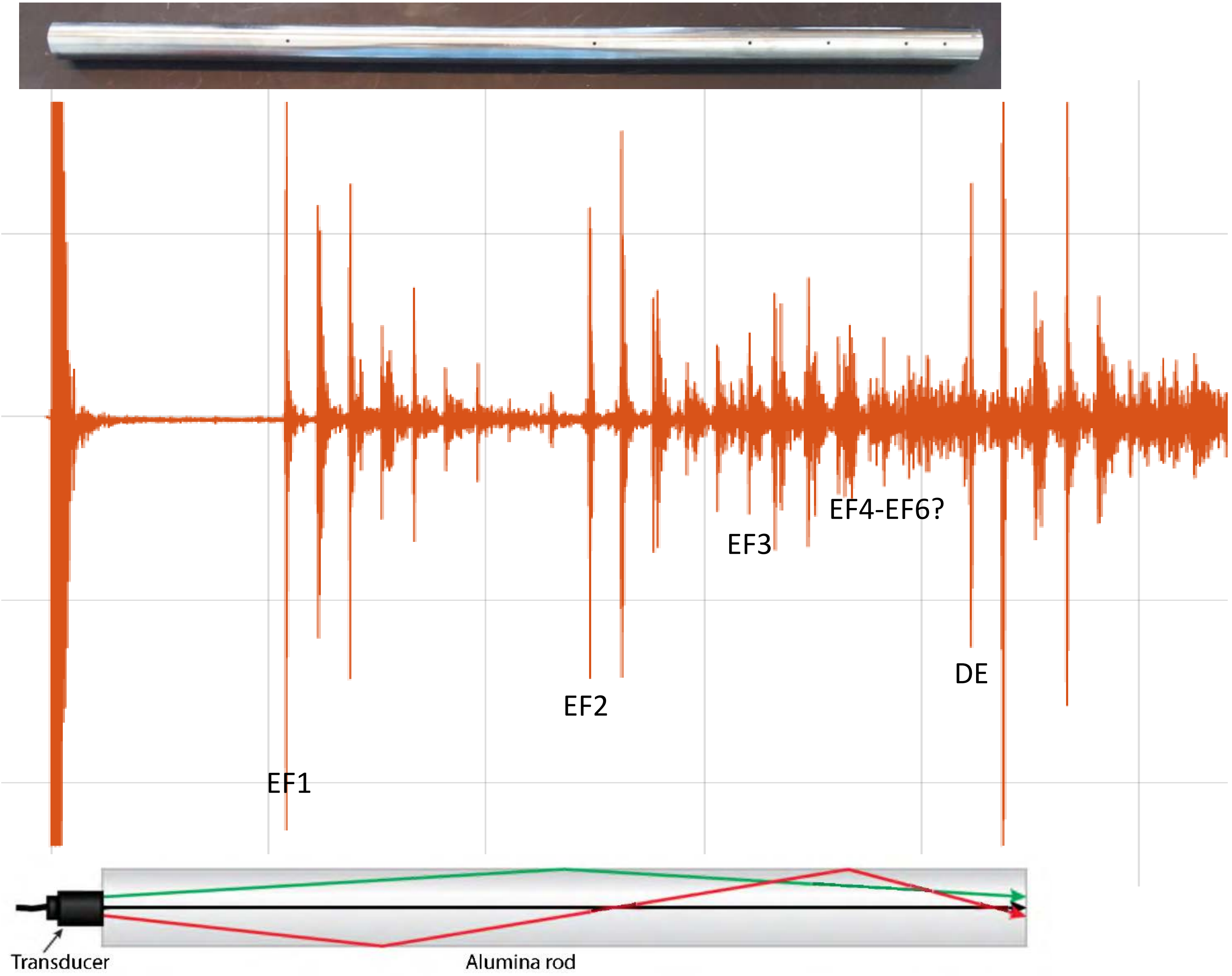
- Range of admissible temperatures
- Impact of high-temps (e.g., phases of materials)
- Ultrasonic attenuation
- Toughness/resistance to fracture
- Thermal conductivity and expansion
- Design and size of Echogenic Features
- Number, spacing, and orientation of Echogenic Features

Design of Inconel 625 waveguide with six echogenic features



Limitation of the original design

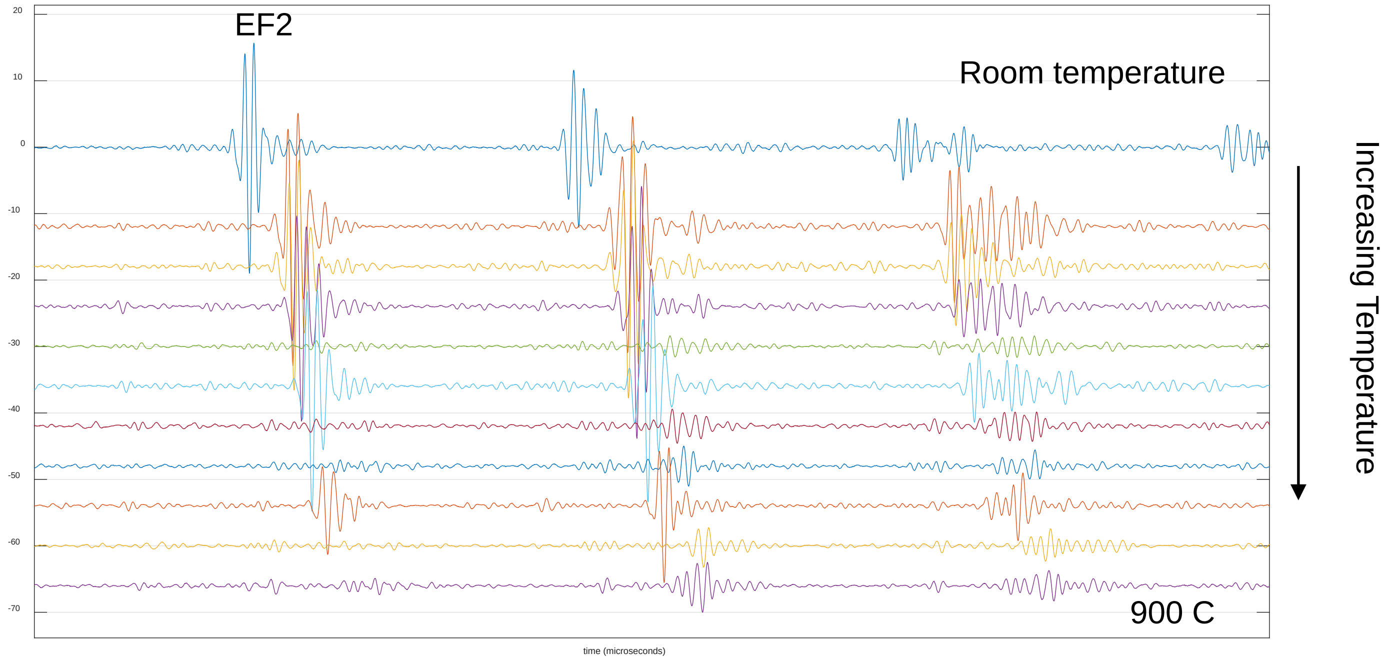
- Ultrasonic response is too complex
- Need to redesign waveguide to obtain simpler ultrasound response



Inconel 625 cannot be used at very high temperatures

Inconel WG before and after testing at 1,200° C

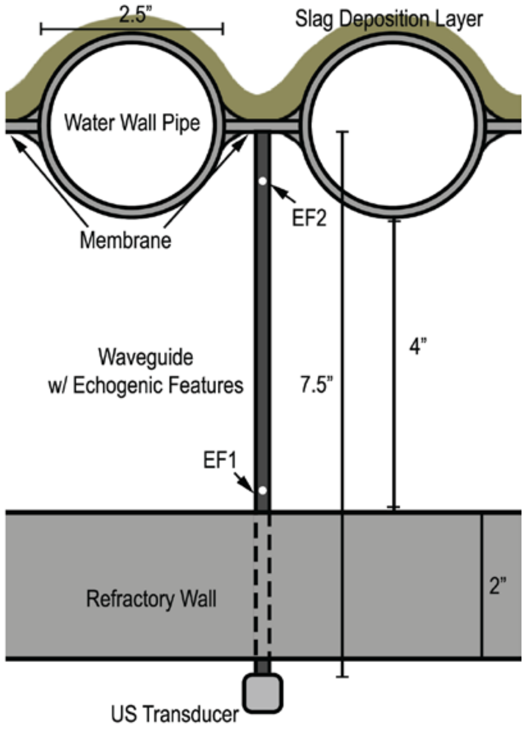
- We are considering refractory metals
- Perhaps, back to ceramics
- Locations with lower temperature

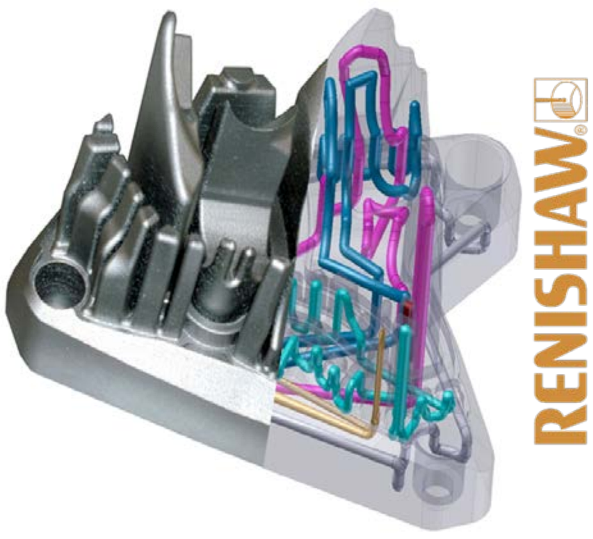


Overall goal of the current project

Advance technology-readiness level of ultrasound method for real-time measurement of temperature profiles in solids. Validate a prototype multipoint measurement system in a coal-fired utility boiler.

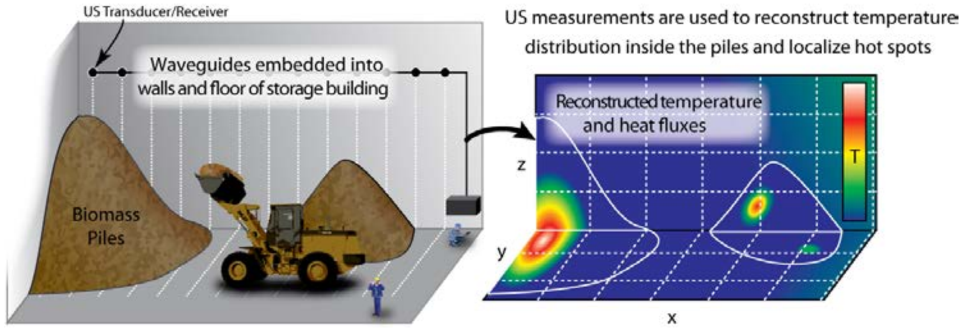
Call for collaborations





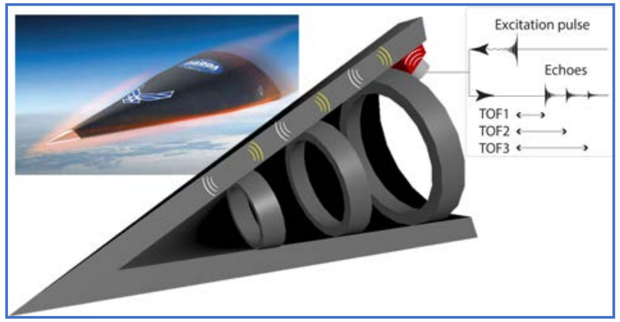
Technology Highlights

- Measure temperature distributions on lines/ surfaces/volumes. Heat fluxes inside structures measured.
- Use in extreme environments or when insertion sensors cannot be used. Works at macro-, micro- and nanoscales.
- Integration with structures by additive manufacturing.
- Measures changes in material properties.



Examples of Transformative Applications

- Structure-integrated measurements in hypersonic vehicles:
  - Internals and externals of propulsion system
  - Control of heat rejection
  - Operate at the edge of envelope
  - Zero/low/predictive maintenance
- Sensing in integrated and monolith systems produced by additive manufacturing



References

1. M. Skliar, K. Whitty, and A. Butterfield, "Ultrasonic temperature measurement device," US Patent 8,801,277, 2014; and US Patent 9,212,956, 2015.
2. Y. Jia, Melissa Puga, A. Butterfield, D. Christensen, K. Whitty, and M. Skliar "Ultrasound Measurements of Temperature Profile Across Gasifier Refractories: Method and Initial Validation," *Energy & Fuels* 27.8 (2013): 4270-4277.
3. Y. Jia and M. Skliar, "Anisotropic diffusion filter for robust timing of ultrasound echoes," *2014 IEEE International Ultrasonics Symposium* (IUS), Chicago, Il, pp. 560--563, 3-6 Sept. 2014.
4. Y. Jia and M. Skliar, "Noninvasive Ultrasound Measurements of Temperature Distribution and Heat Fluxes in Solids," *Energy & Fuels*, 30:4363–4371, 2016.
5. Y. Jia, V. Chernyshev, and M. Skliar, "Ultrasound measurements of segmental temperature distribution in solids: Method and its high-temperature validation," *Ultrasonics,* 66:91-102, 2016.
6. M. Roy, K. Walton, J. B. Harley and M. Skliar, "Ultrasonic Evaluation of Segmental variability in Additively Manufactured Metal Components," *2018 IEEE International Ultrasonics Symposium* (IUS), Kobe, Japan, 2018.

Special Thanks

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Questions