In-Situ Acoustic Measurements of Temperature Profile in Extreme Environments

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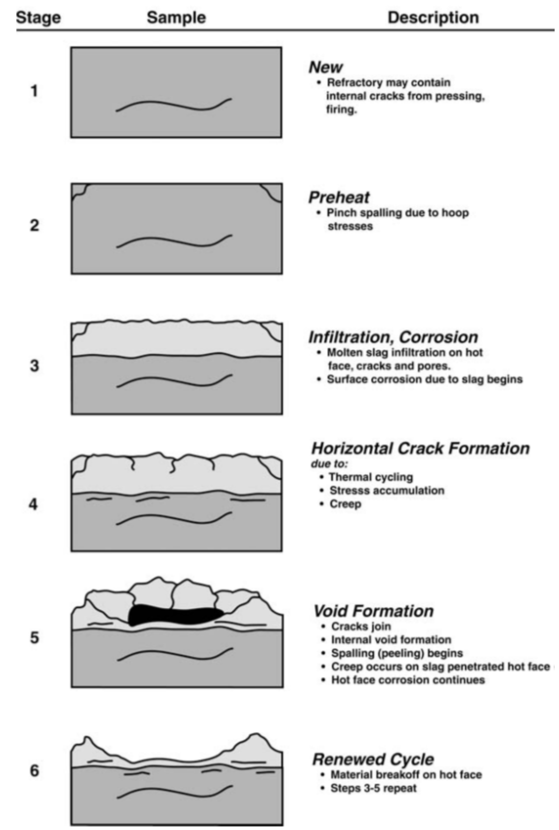
Introduction

- Harsh environment of coal gasification lead to rapid degradation of refractory which impacts reliability and economics of the process.

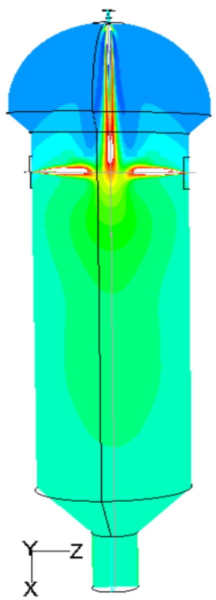
- Harsh gasification environment makes it difficult to utilize the tradition insertion sensors to monitor the process and the refractory.

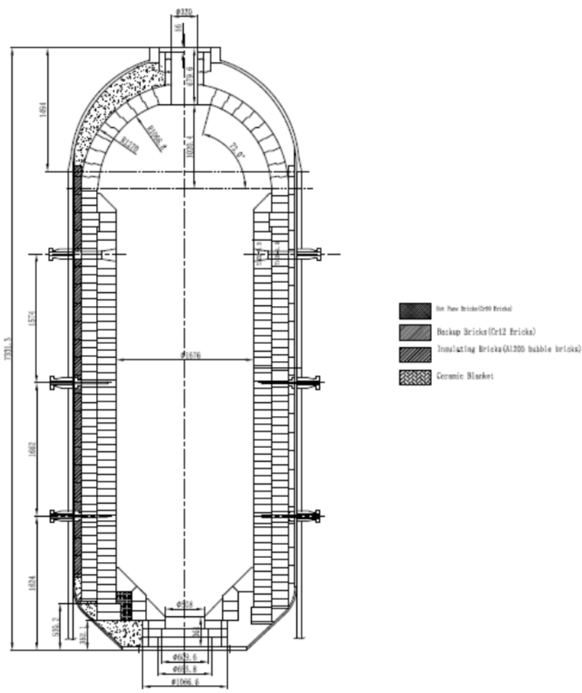
- This project adopts an approach of using noninvasive ultrasound methods to provide real-time, in-situ information about the refractory temperature and thickness.



Stages of refractory degradation [1].

Industrial Experience: Tsinghua University Coal Gasifier





Rosemount Sapphire TC

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

Solution Strategies

- ***Direct measurement*** : Develop hardened sensors that can withstand harsh environment for long time.
  - Heavy sheathing makes such devices less sensitive to dynamic changes in temperatures, which are important in the refractory life management since rapid temperature variations can introduce thermal stresses.

Thermocouple protection system for gasifier application [2].

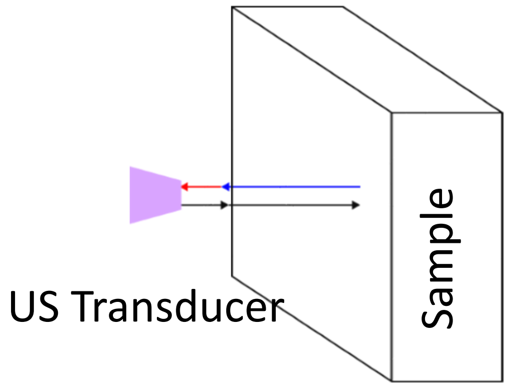
- ***Inferential approach***: *Indirect* (secondary) *measurements* that are easy to obtain (*T*, *P* and compositions of in/out streams) are used with appropriate <u>models</u> to *infer* otherwise inaccessible operating parameters inside the reactor zone and the state of the refractory.
  - Few examples in gasification: reactor temperature reported in ppm of methane -- Tampa Electric IGCC Demonstration Project [3]. Economically appealing option.
  - Quality of inferences is affected by modeling errors and uncertainties.
  - Measurement accuracy, sensitivity, and response time compare poorly with direct measurements.

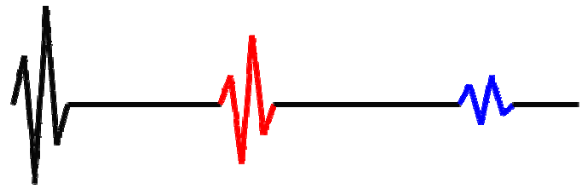
- ***Direct measurements using non-invasive methods***: Examples include optical and ultrasound measurements (e.g., *T* and gas composition during combustion [4]).

Acoustic Temperature Measurements

- Speed of sound is temperature dependent in gases, liquids, and solids. SOS can be obtained by measuring time of flight (TOF) of the test pulse:

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





- Key difficulty: ***<u>When temperature changes along the path of US propagation</u>***, the acoustic TOF measurements depend on temperature distribution in a complex way:

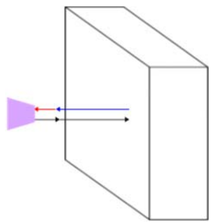
$$TOF = \int_{\mathrm{r_h}}^{r_c} \frac{2}{f(T(t,r))}\,\mathrm{d}r$$

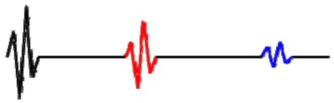
- Key uncertainty: How strong is SOS vs. T dependence?
  - The answer to this question determines achievable accuracy of temperature measurements.

Estimating temperature distribution from TOF measurements

- Experimentally establish the relationship between *T* and SoS/TOF and identify the function *f* (.):

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





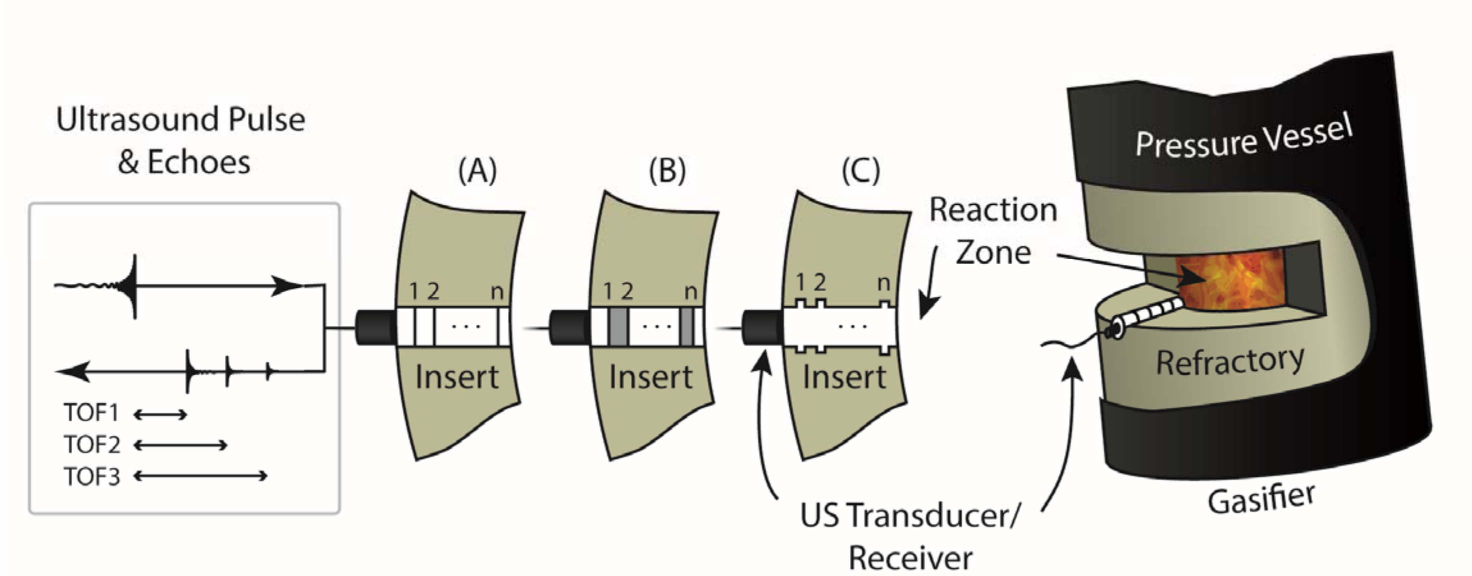
- Use the result and the heat transfer model

$$\rho C \frac{\partial T}{\partial t} = k \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial}{\partial r} \right) T$$

to *estimate* the temperature distribution

Direct US Measurements of Temperature Distribution

- Create multiple partial reflections that give information about temperature distribution in different segments of the refractory.
  - The ability to create partial internal reflections and their spacing determines achievable spatial resolution.



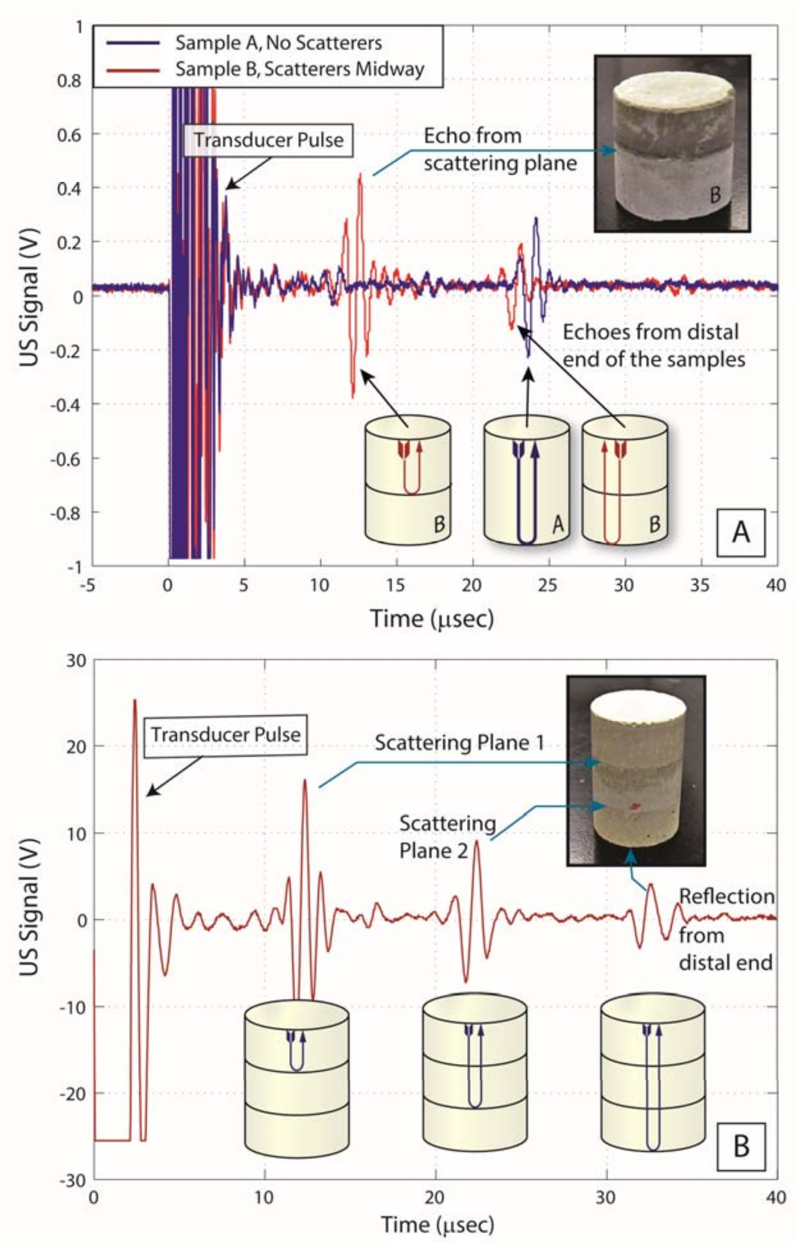
- Methods to create partial reflections:
  - Scatterers;
  - Change in US impedance;
  - Change in geometry

Two key questions to determine the feasibility of the proposed approach

- Is the speed of ultrasound propagation in the refractory temperature dependent?

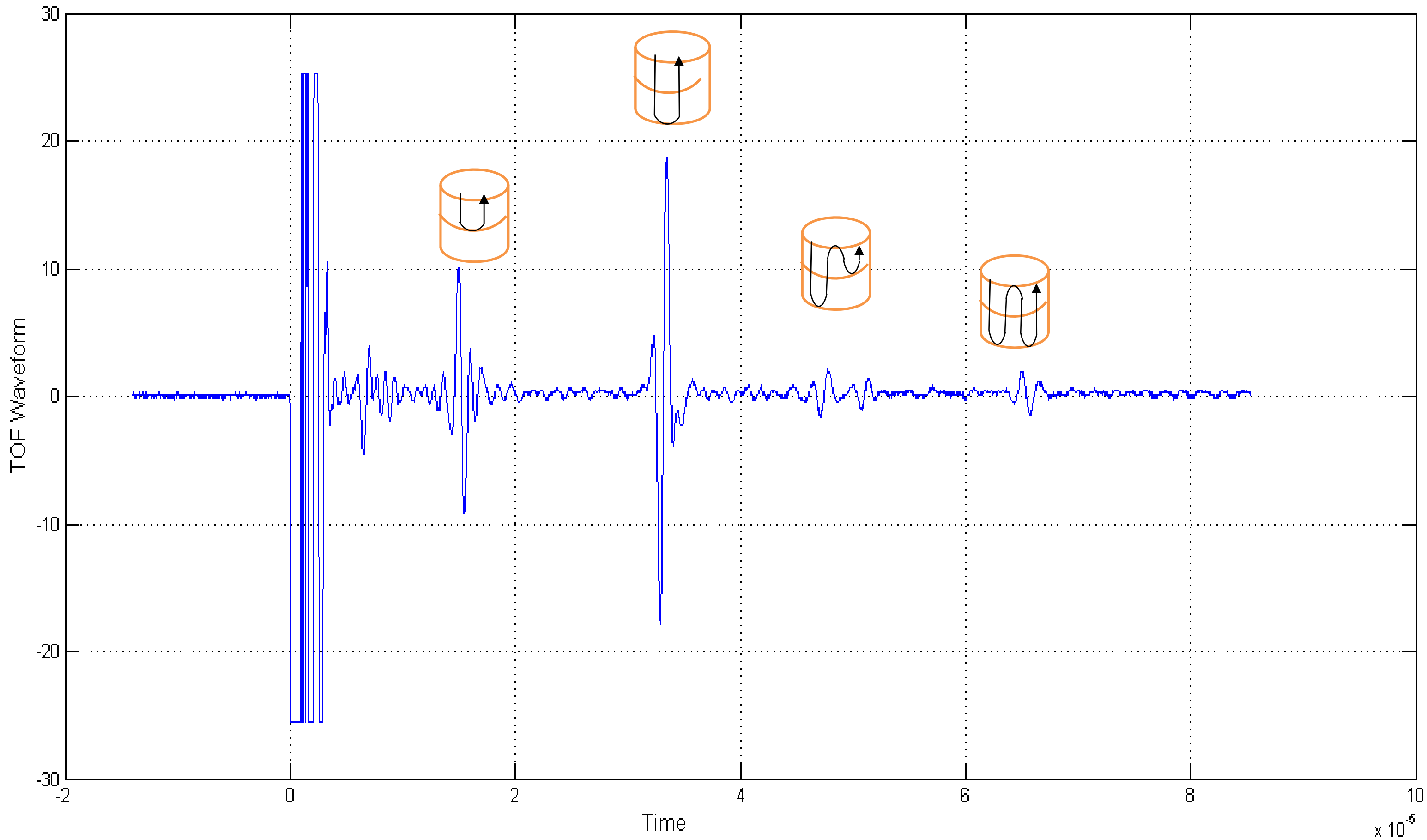
- Is it possible to create partial internal reflections along the path of the ultrasound propagation and what are the methods that can be used to create such reflection?

Engineering refractory to produce partial internal US reflections



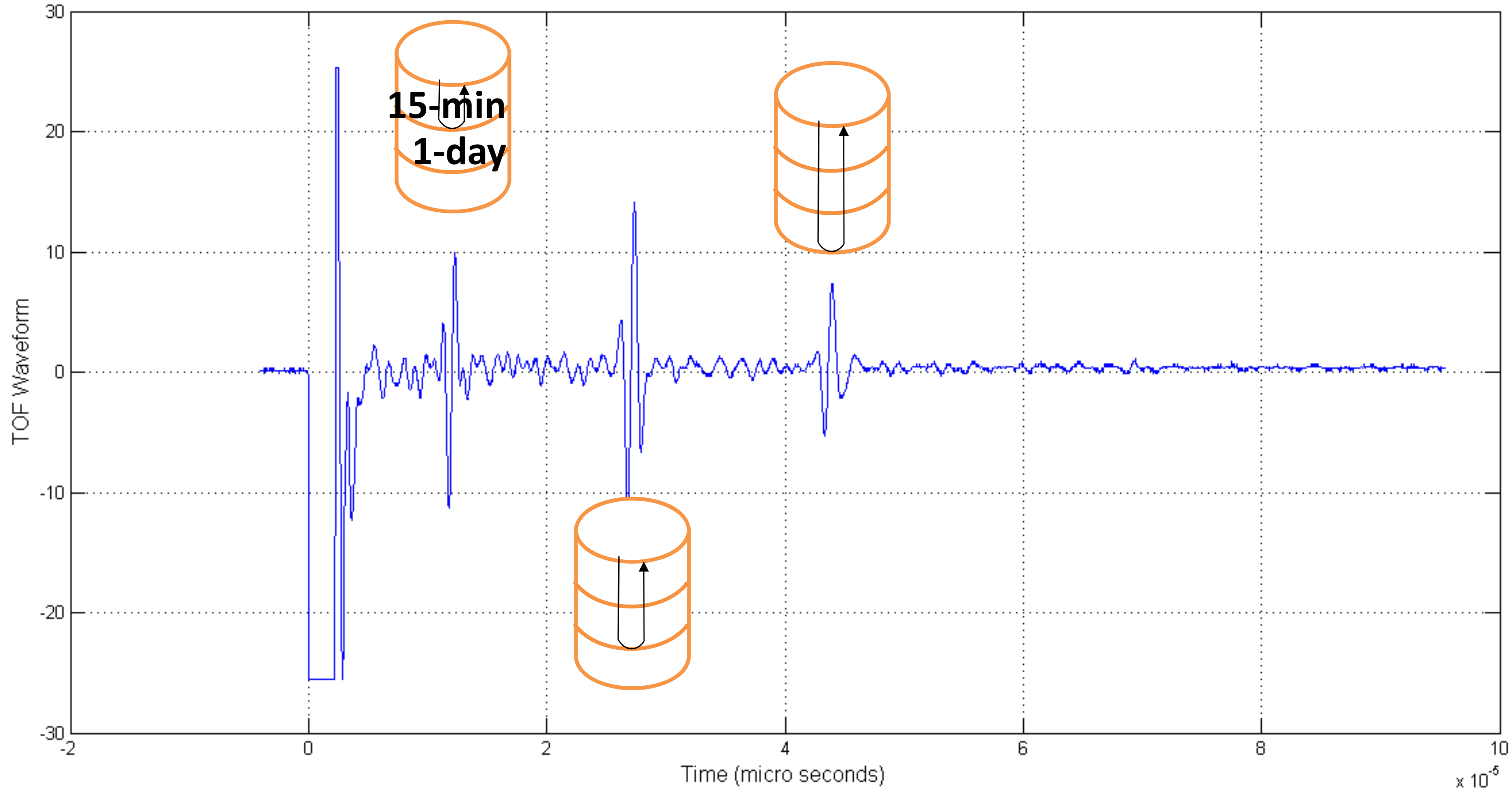
- A: Steel shots were embedded as ultrasound scatters to produce partial reflection at the midpoint of ultrasound propagation path
- B: Two internal interfaces obtained by sequentially casting three layer of identical formulation and allowing for a partial curing before casting the next layer

Single internal reflection



- Water/cement ratio = 0.5
- Recipe for “good” results: Cure first pour for 1 hour, then pour the second layer

Two internal reflections

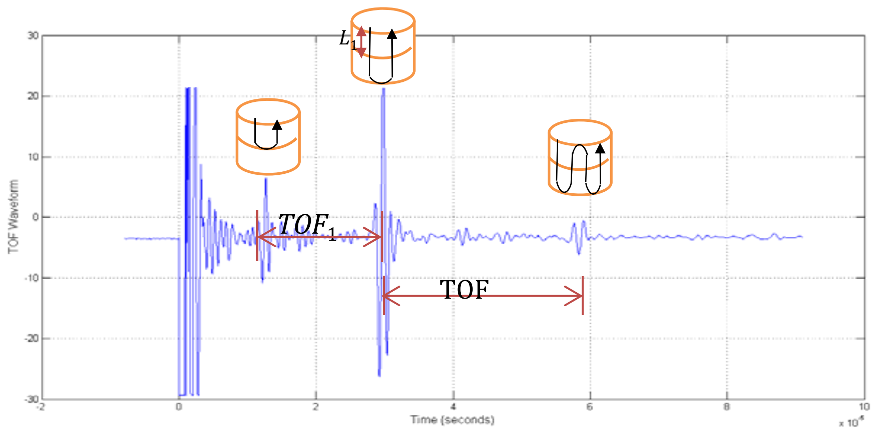


- Water/cement ratio = 0.35
- First layer cured for 15min. Second layer cured for 1day
- A more noisy signal, possibly due to entrapped air bubbles

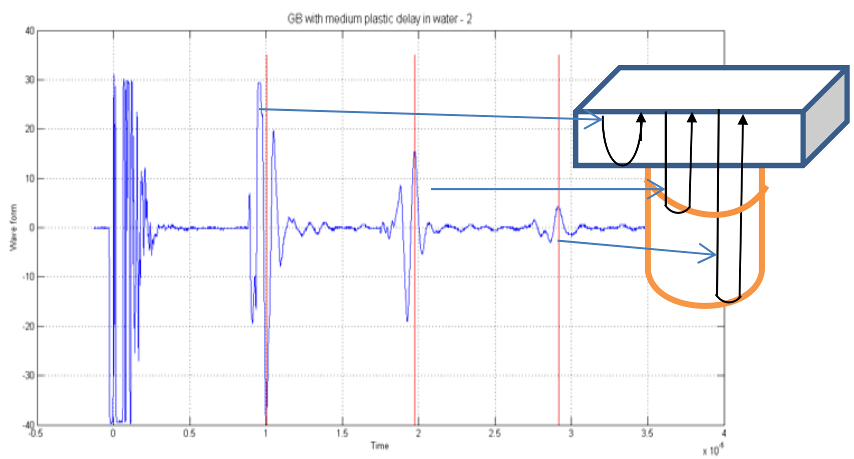
Measurements of TOF

Initial Bang Issues

- Find transducer's “zero” time using round-trip echoes



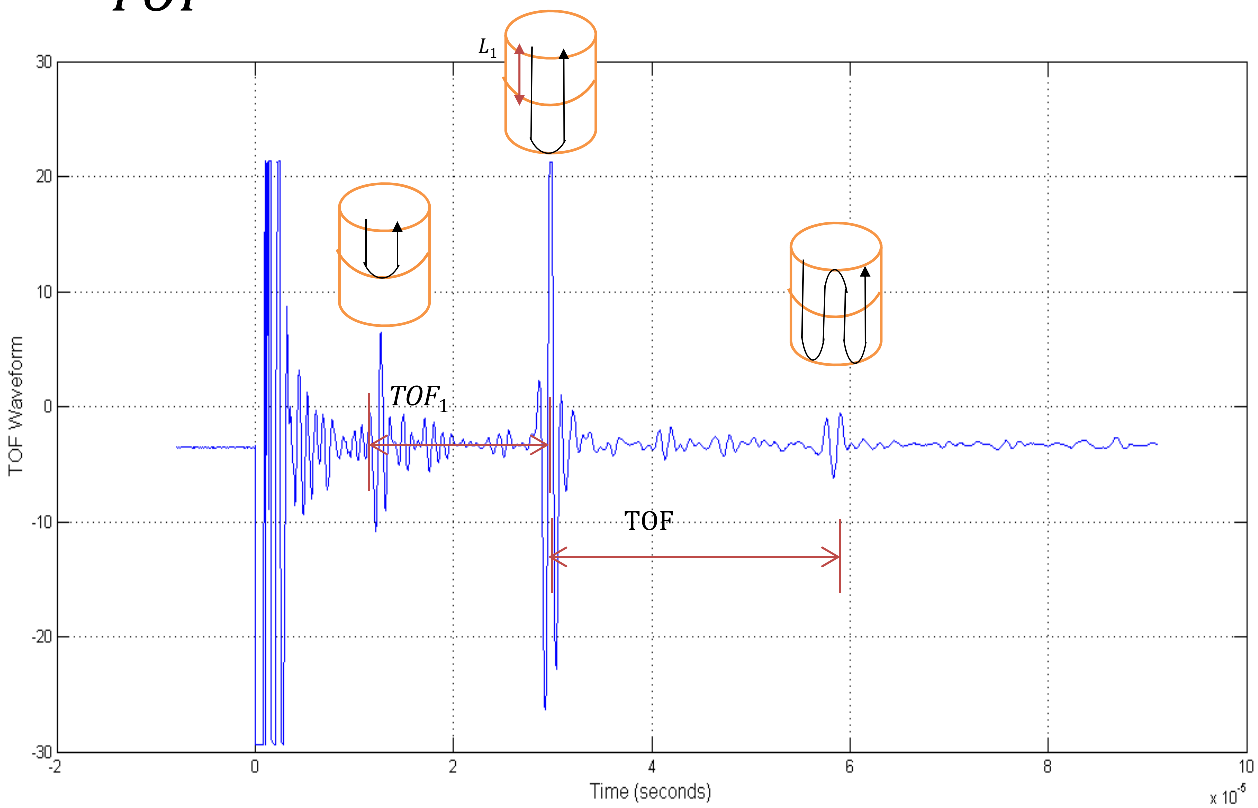
- Using delay line method to obtain zero time



- Use though transmission and match waveforms

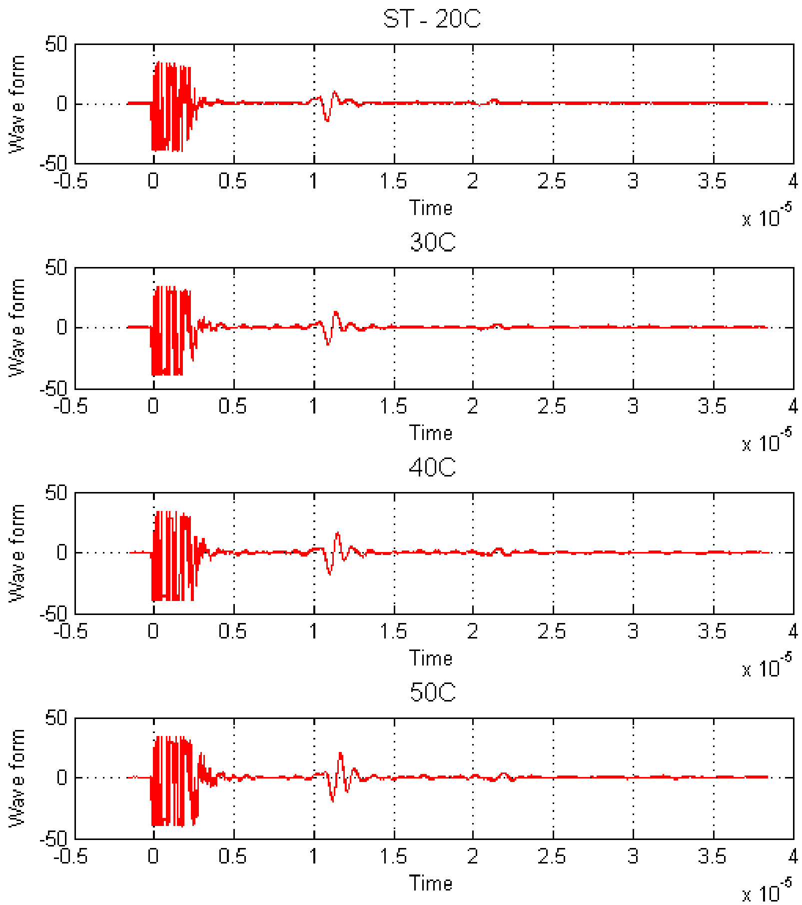
Direct TOF measurements

- Directly measure TOF
  - Multiple round trips or delay line methods to establish "zero" time
  - $SOS = \frac{2L}{TOF}$



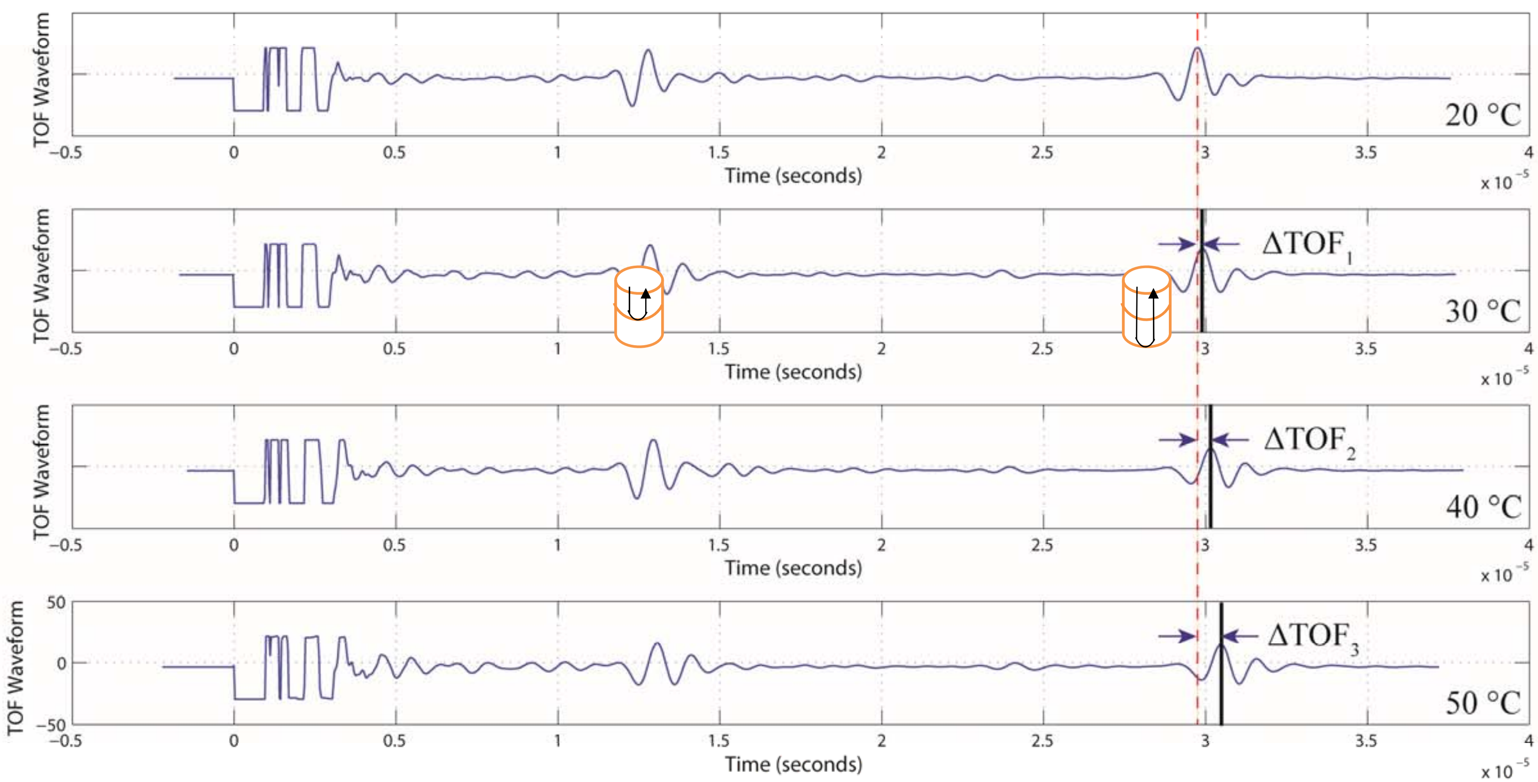
Cross-correlation method to measure change in TOF

- Match the entire waveform instead of a single point.
- Provides robust method to measure ΔTOF



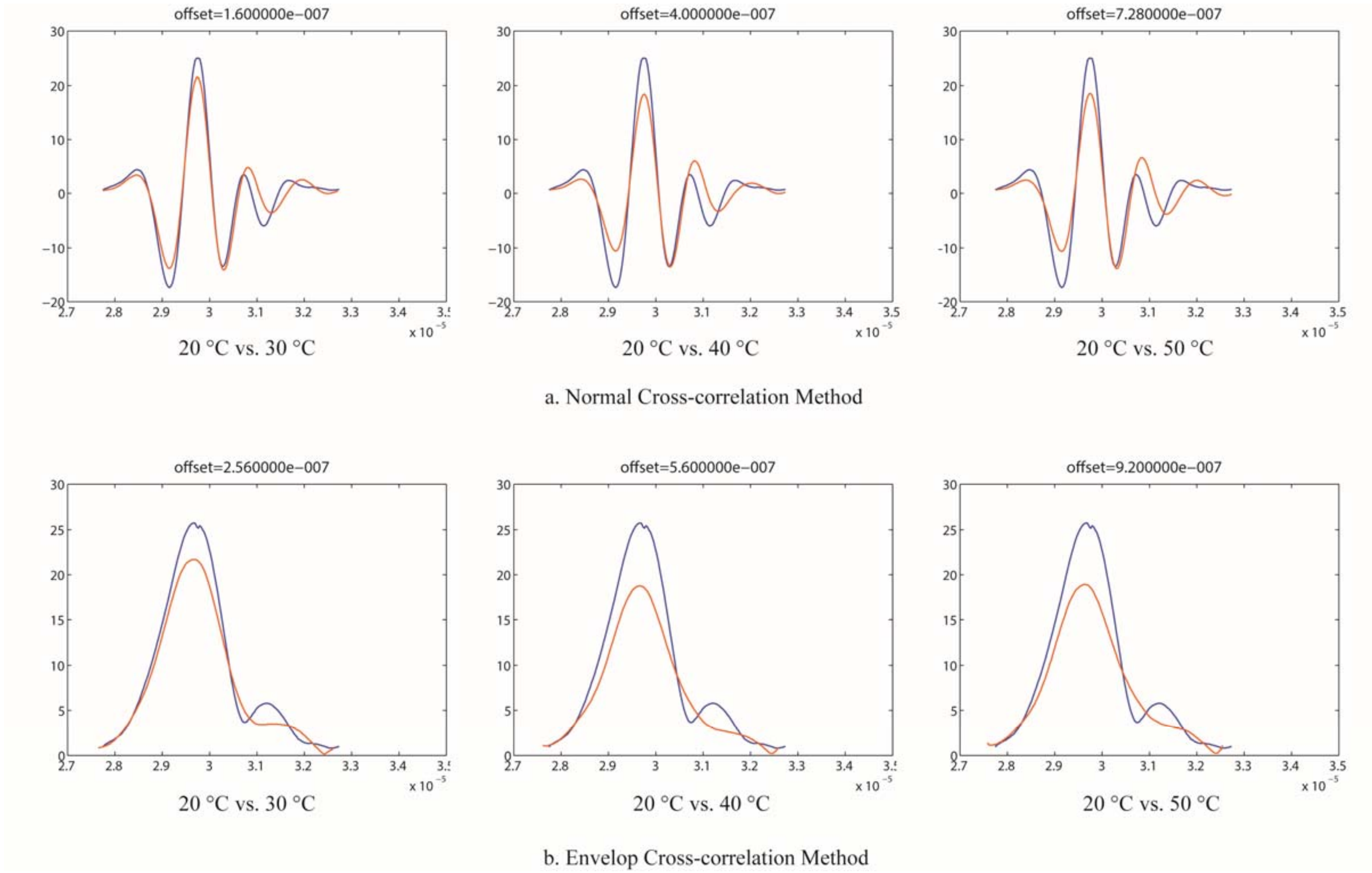
Change in TOF measurements

$$SOS(T) = \frac{2L}{TOF_{ref} + \Delta TOF_{(T_{ref}-T)}}$$



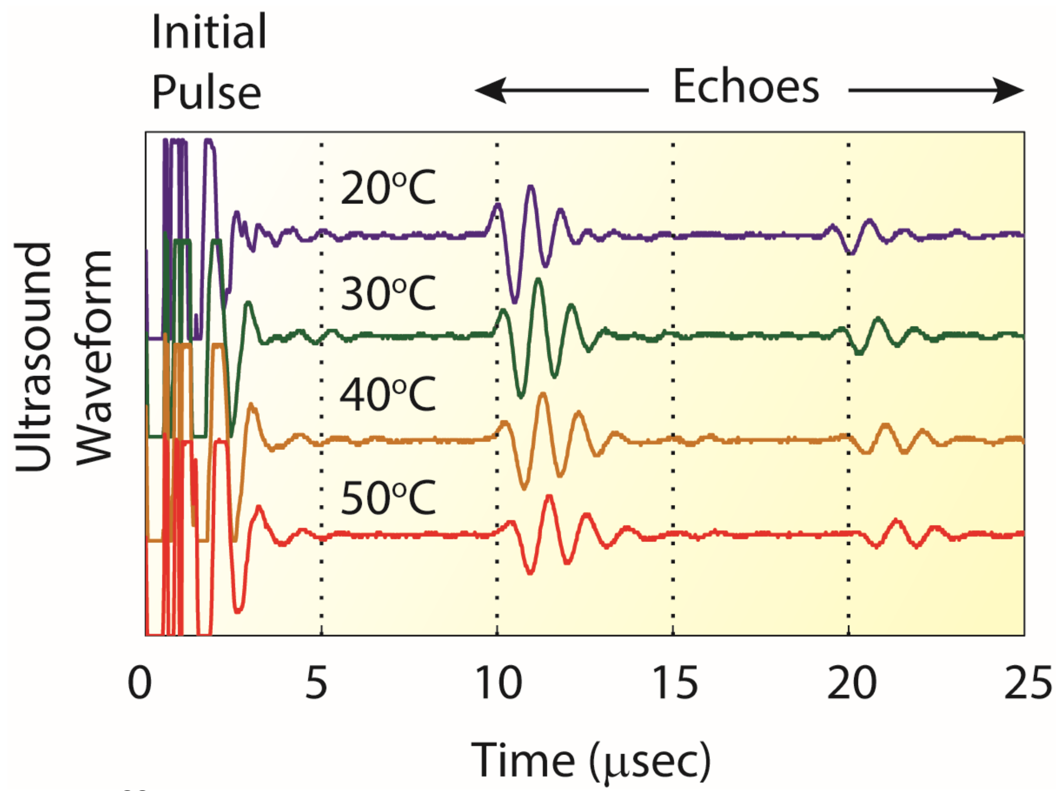
Waveform and envelop cross-correlation

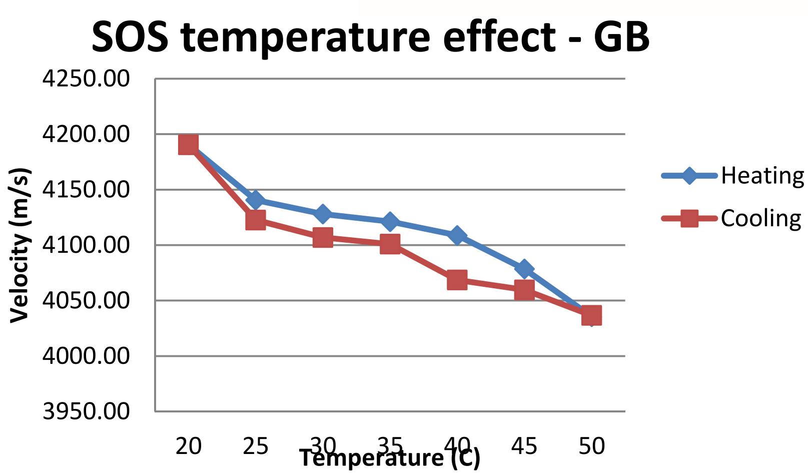
- Two methods give similar trend of increasing TOF with temperature but differ in values of ΔTOF
- The envelop cross-correlation method is less sensitive to the waveform distortion

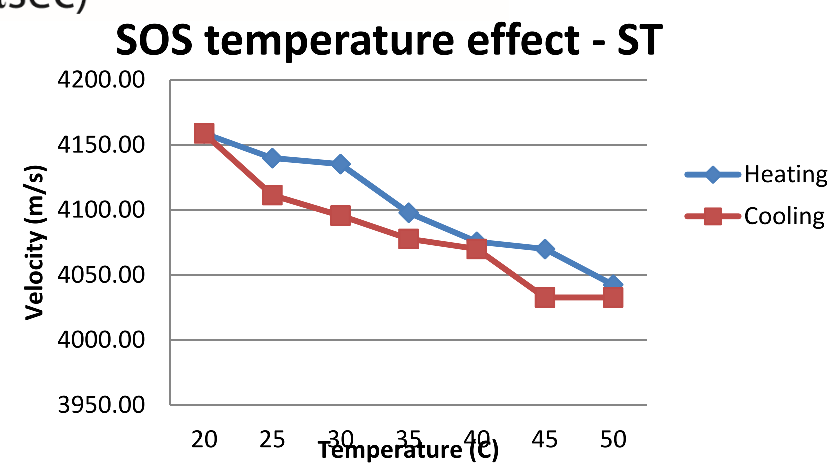


SOS as a Function of Temperature

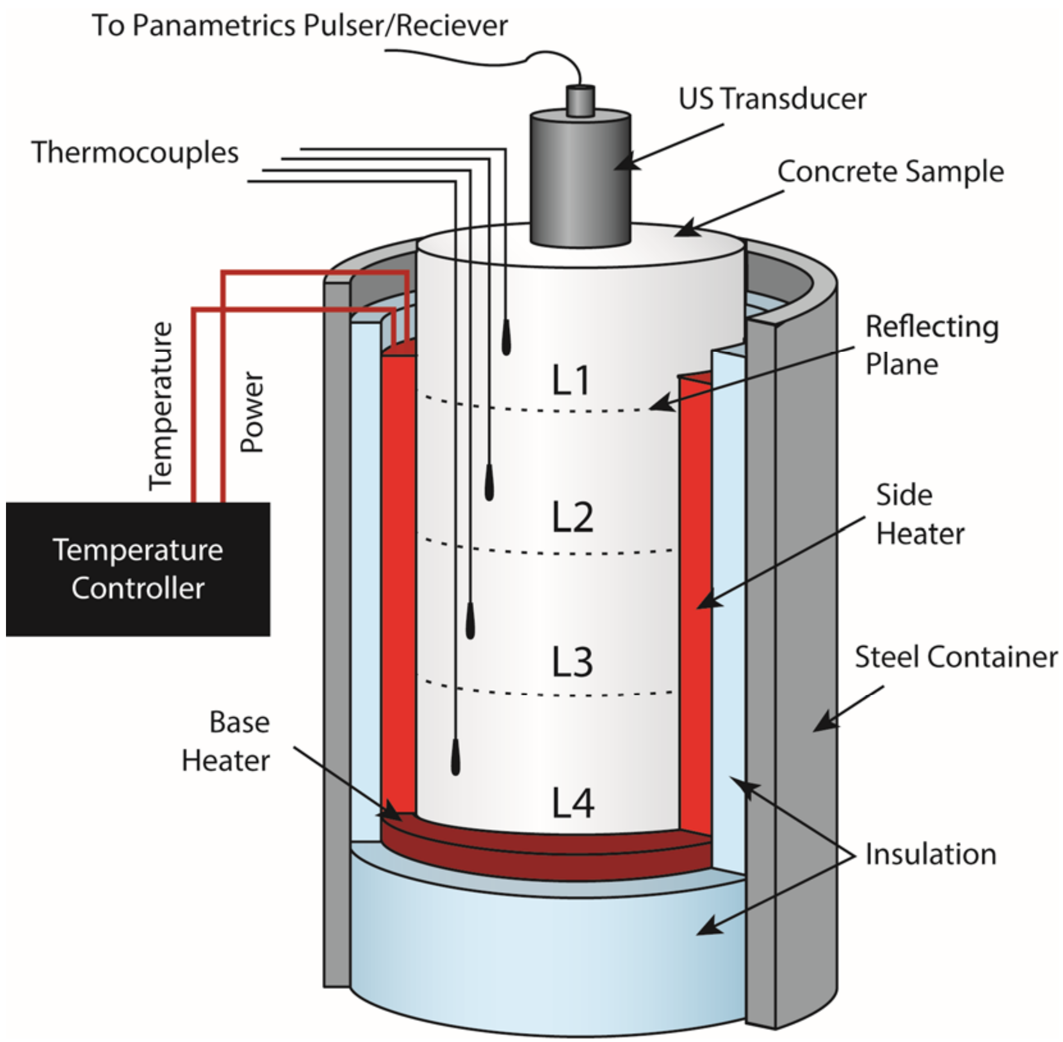
Very first results







Experimental Setup



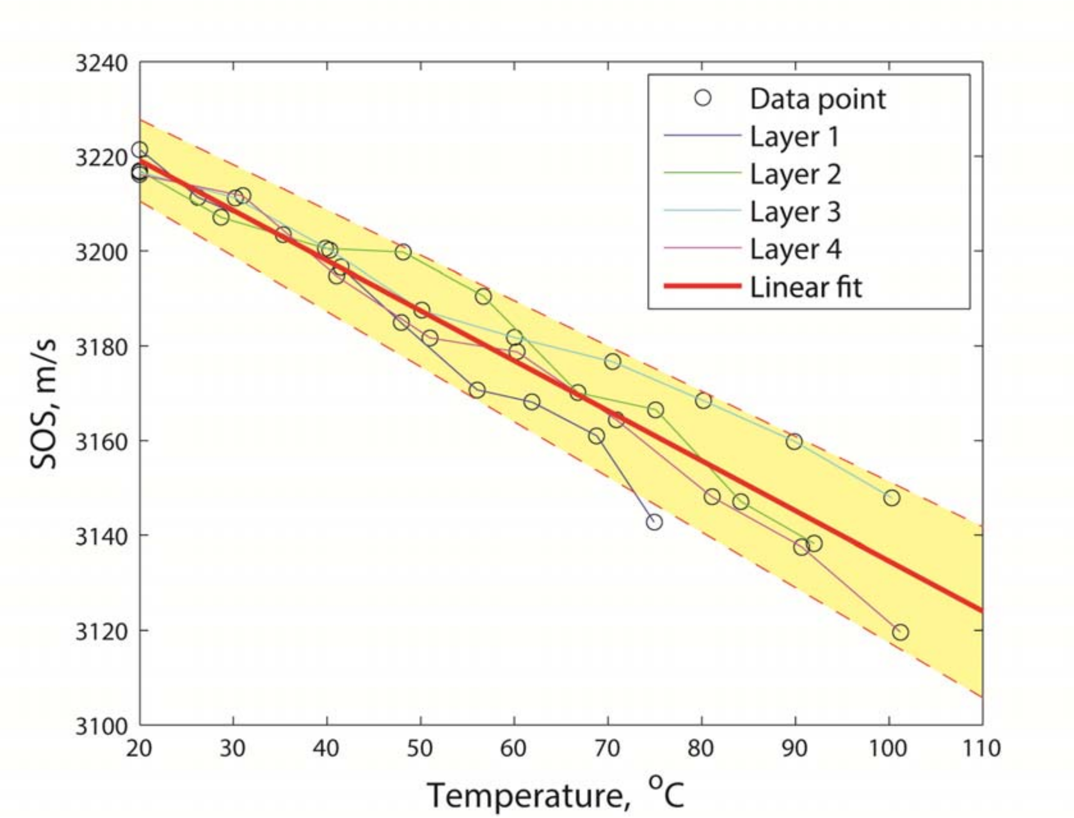
- 4”-sample with four layers of Portland cement. Top layer plays the role of delay.
- Silicon rubber heating blanket
- Insulation on the sides and bottom of the fixture
- Surface temperature measured by TCs attached in the middle of each layer
- Temperatures changed in 10°C increments, from 20 to 100°C

Experimental procedure and data analysis

- Zero time found & kept the same for all measurements
- Reference temperature selected to be 20 °C
- Tests were repeated at least 6 times in random order
- The envelop cross-correlation between the reference and the waveform at a given temperature is used to find ΔTOF relative to the reference temperature
- The SOS in each layer is calculated at each temperature using the following equation

$$SOS = \frac{2L}{Ref\ TOF + \Delta TOF}$$

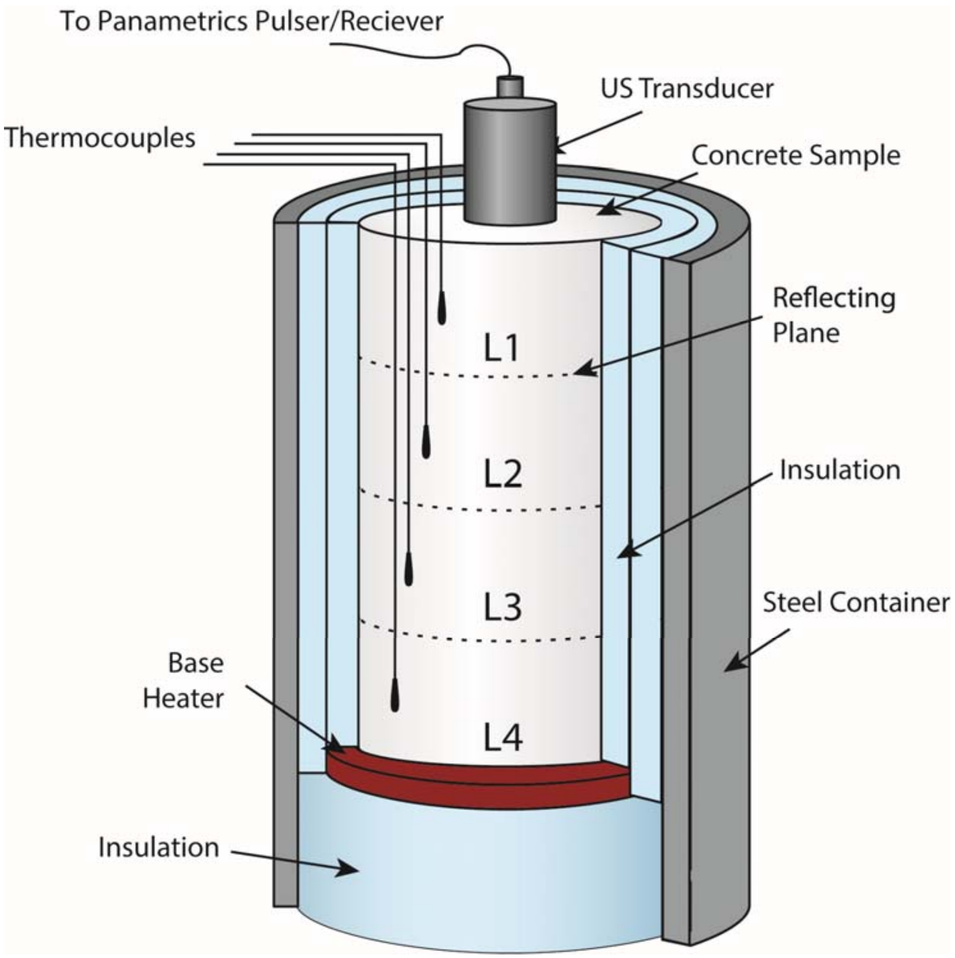
SOS vs. temperature calibration curve



- Linear fit SOS = SOS(T) is based on data for all four layers
- Shaded area shows 95% confidence interval for the obtained linear fit

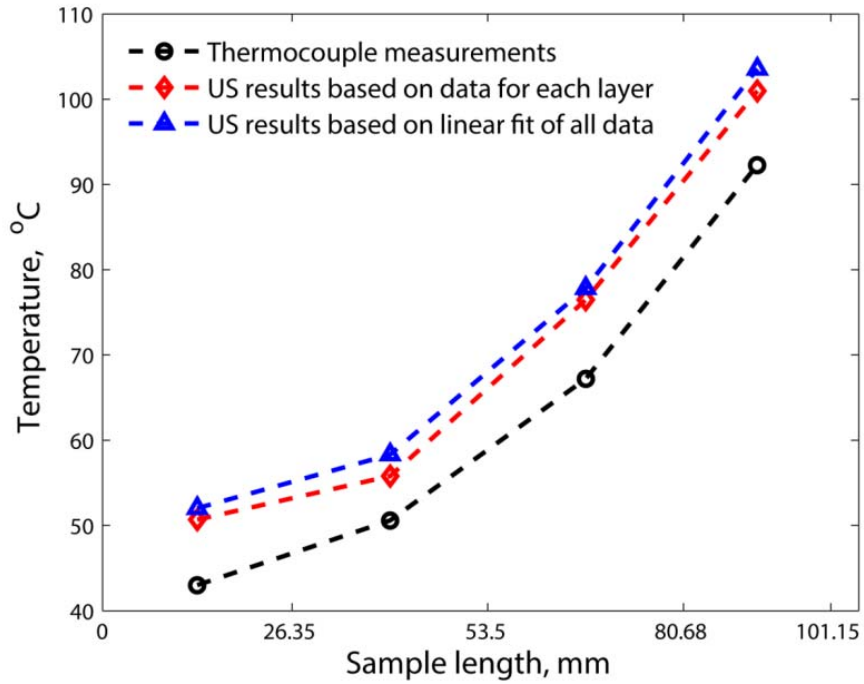
Ultrasound Measurements of Temperature Distribution

Temperature distribution experimental setup



- Heated only by base heater
- Surface temperature measured by TCs
- Experiments repeated least 6 times to calculate 95% confidence interval
- **Piecewise constant temperature distribution is assumed**

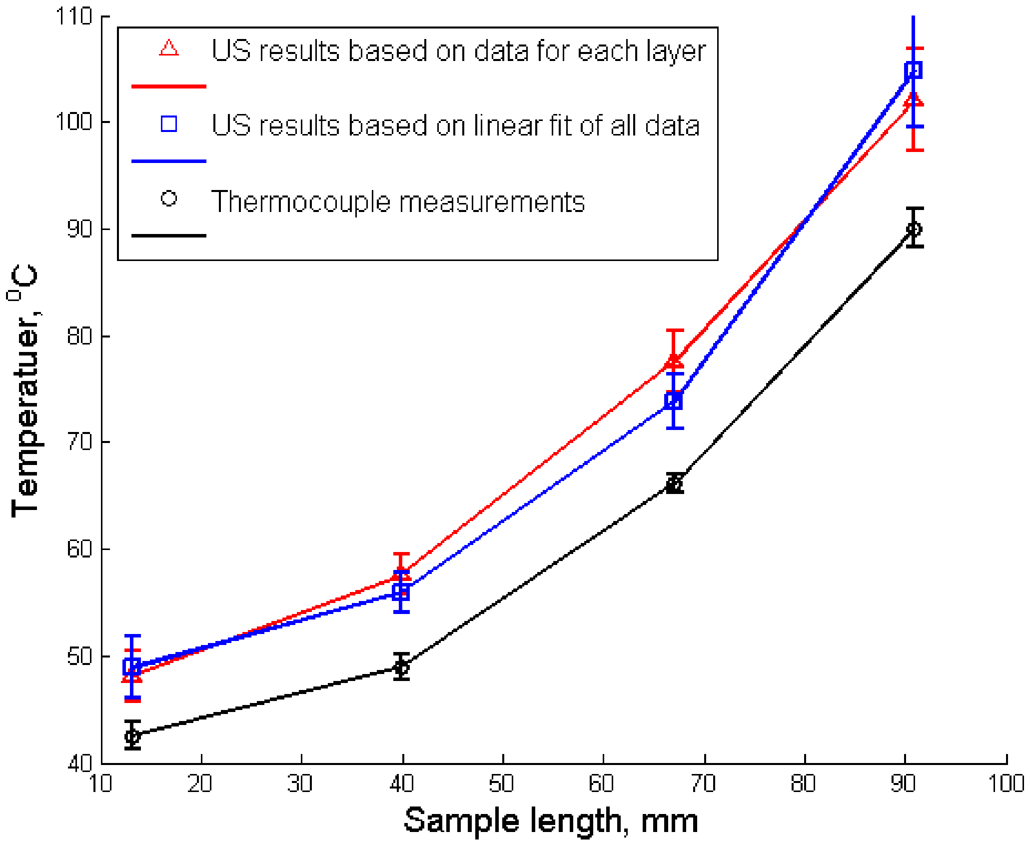
Comparison of TC and US measurements: **Initial Results**



Y. Jia et al. "Ultrasound Measurements of Temperature Profile Across Gasifier Refractories: Method and Initial Validation," Energy Fuels, Article ASAP DOI: 10.1021/ef3021206

- Note similar trends in temperature distribution and an excellent agreement in estimated axial thermal fluxes
- The surface temperatures should be lower than the internal temperature measured by ultrasound
- Thermocouples provide point-wise distribution. US measurements depend on temperature distribution along the entire sample

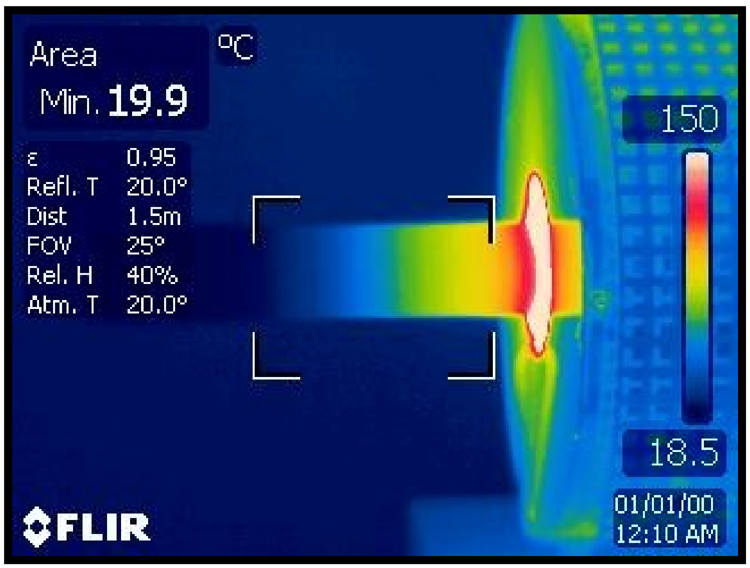
Comparison of TC and US measurements: **6 Repeats**

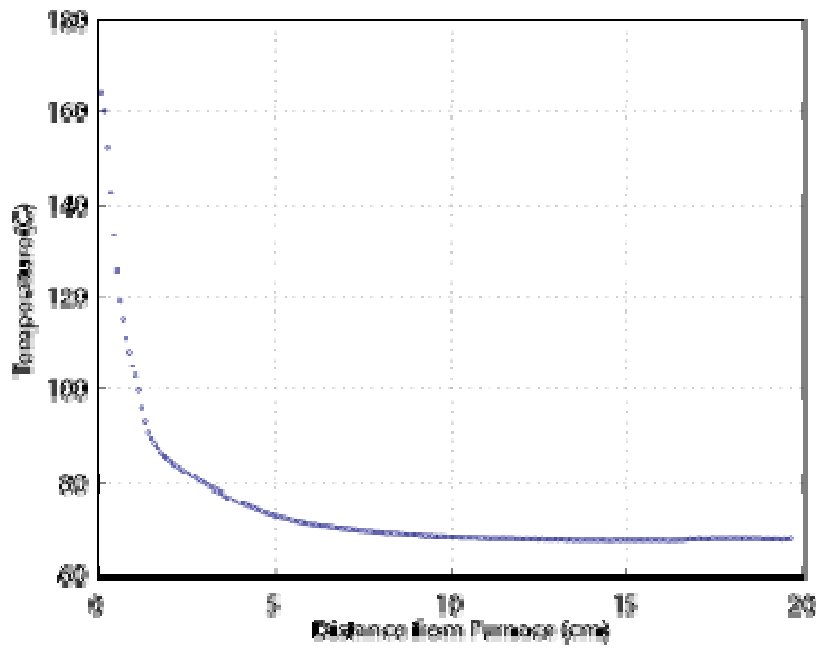


Thermal modeling: Obtaining better parameterization of the temperature distribution

Thermal Modeling

- Sub-grid model: Develop a heat transport model of the refractory and the model-based method for estimating the refractory temperature distribution based on the measurements of $T_{ave}(t)$ and the surface temperature of the refractory on the cold side, $T_c(t)$.





Temperature declines rapidly down the length of the cylinder from the furnace

Linear temperature distribution

- Assuming linear relationship between the temperature T and location of sample
$$T = pr + q$$
- Assuming linear relationship between the *SOS* and temperature T
$$SOS = aT + b$$
- The TOF of an ultrasound echo between spatial locations r_c and r_h can be expressed as
$$TOF_{total} = \int_{r_c}^{r_h} \frac{2}{SOS(T(r))} dr$$
$$= \int_{r_c}^{r_h} \frac{2}{a(p \cdot r + q) + b} dr$$
$$= \frac{2}{ap} \ln[a(pr + q) + b]\Big|_{r_c}^{r_h}$$

  - *Coefficient a and b are from SOS vs. T calibration curve*
  - *Coefficient p and q are from thermocouple measurements on sample surface*

Piecewise linear temperature distribution

- Assuming the temperature distribution is linear in but the slopes and the intercepts are not necessarily the same each layer of the sample

$$T_i = m_i r + n_i$$

- Assuming linear relationship between the *SOS* and temperature *T*

$$SOS_i = a(m_i r + n_i) + b$$

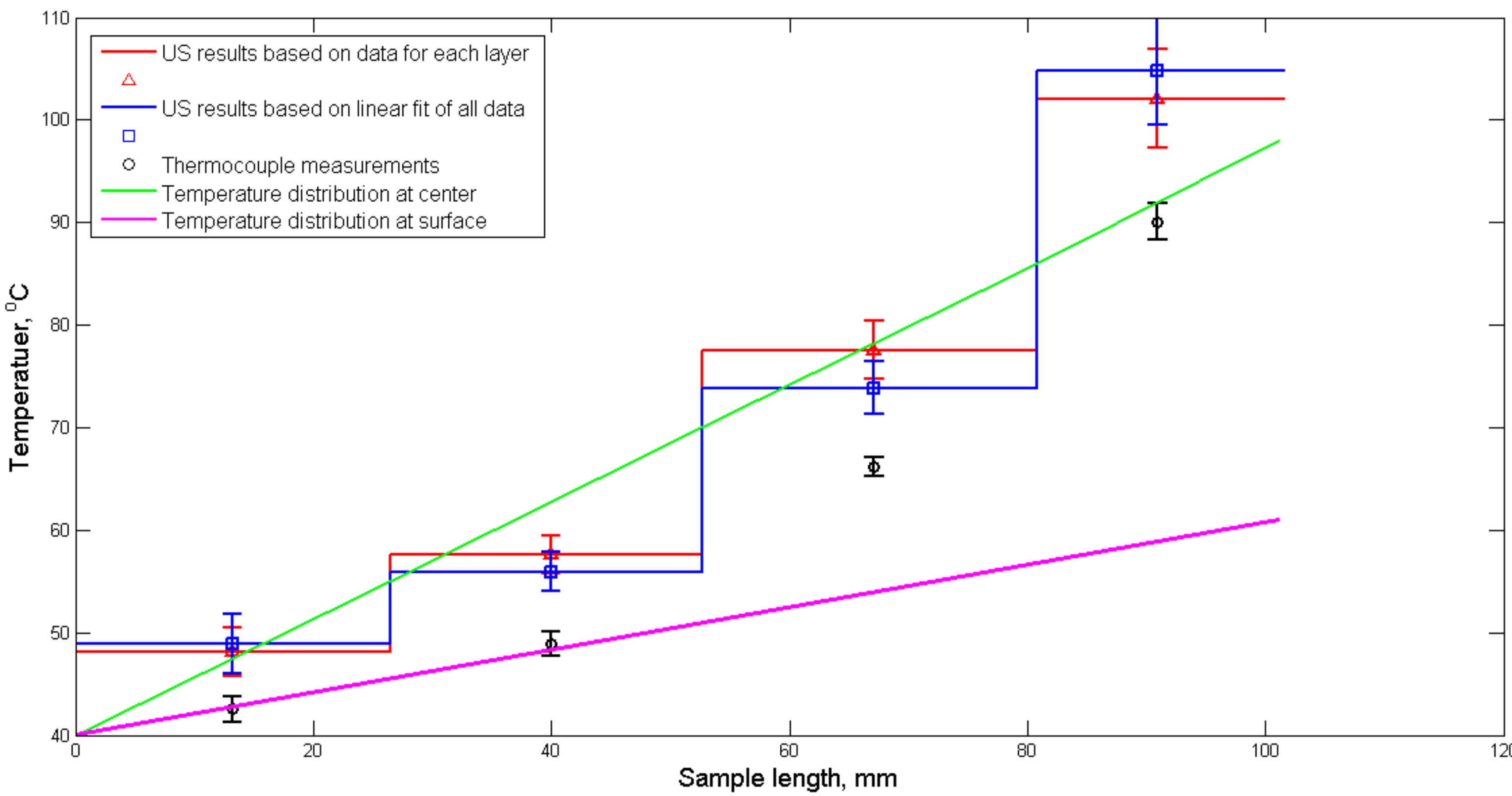
- Temperatures at interface are the same

$$T_0 = m_1 r_0 + n_1 = m_1 \cdot 0 + n_1 = n_1$$
$$T_1 = T(r_1) = m_1 r_1 + n_1 = m_2 r_2 + n_2$$
$$T_2 = T(r_2) = m_2 r_2 + n_2 = m_3 r_3 + n_3$$
$$T_3 = T(r_3) = m_3 r_3 + n_3 = m_4 r_4 + n_4$$

- The time of flight for the first echo, TOF_1, can then be calculated as

$$TOF_1 = \int_{r_0=0}^{r_1} \frac{2}{a \cdot (m_1 \cdot r + n_1) + b} dr = \frac{2}{am_1} \ln[a(m_1 r + n_1) + b]\Big|_0^{r_1}$$
$$TOF_2 - TOF_1 = \frac{2}{am_1} \ln[a(m_1 r + (m_1 - m_2) \cdot r_1 + n_1) + b]\Big|_{r_1}^{r_2}$$
$$TOF_3 - TOF_2 = \frac{2}{am_3} \ln[a(m_3 r + (m_2 - m_3) \cdot r_2 + n_2) + b]\Big|_{r_2}^{r_3}$$
$$TOF_4 - TOF_3 = \frac{2}{am_4} \ln[a(m_4 r + (m_3 - m_4) \cdot r_3 + n_3) + b]\Big|_{r_3}^{r_4}$$

Temperature distributions obtained based on TOF measurements and different parameterizations are compared with thermocouple measurements



- Accurate estimation of the temperature distribution strongly depends on the assumptions about the shape of that distribution and the method used to interpret the measurements of the ultrasound TOF

Thermal modeling

- Thermal model developed in COMSOL
  - 2D model in cylindrical coordinates:

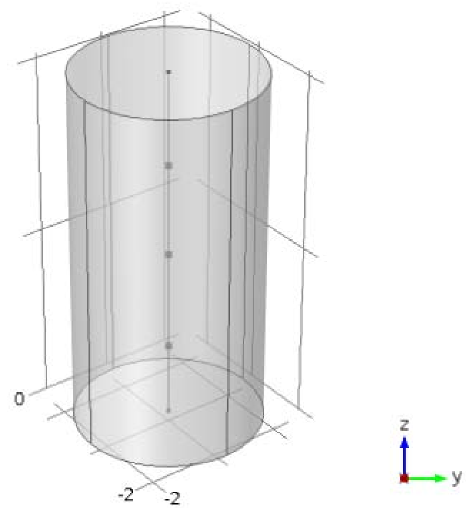
$$\rho C_p \frac{\partial T}{\partial t} = k\left(\frac{1}{x}\frac{\partial}{\partial x}x\frac{\partial T}{\partial x}\right) + \frac{\partial^2 T}{\partial r^2}$$

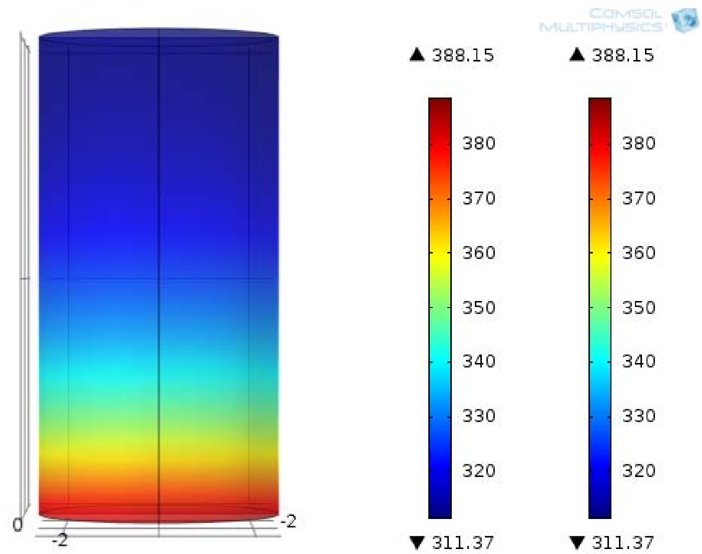
  - Boundary conditions
    - Temperature on the cold/hot side of the sample provided by thermocouple measurements and thermal images
    - Heat loss from thermally “insulated” cylindrical surface is given by heat flux

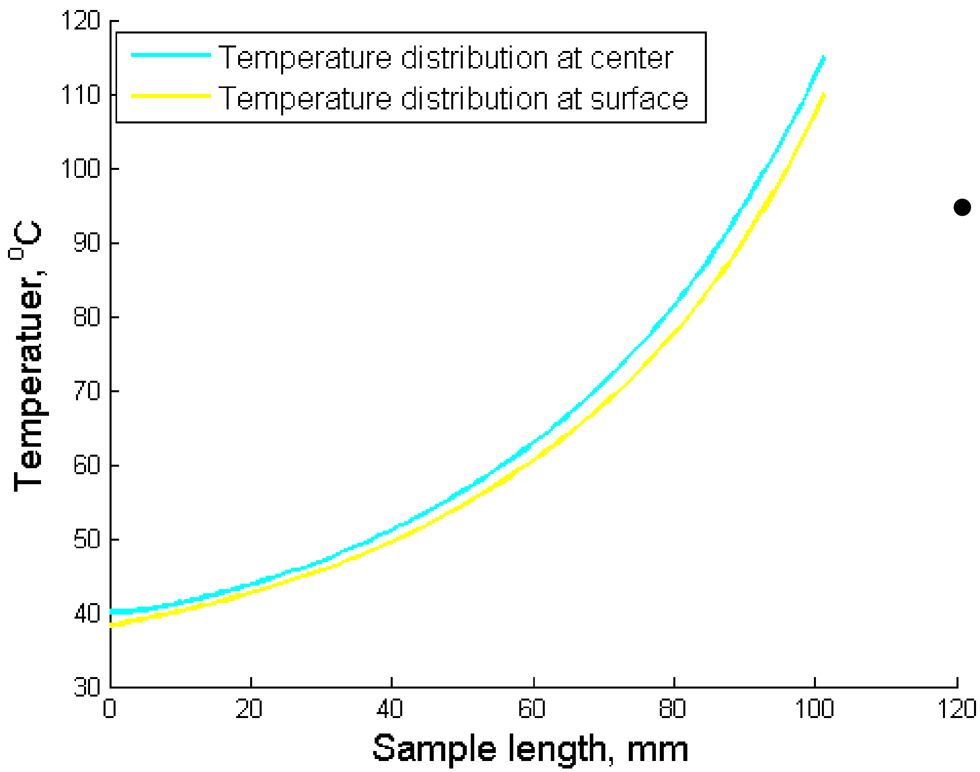
$$q = h \cdot (T_a - T)$$

where *h* is selected to match surface TC measurements

- Obtained temperature distribution is used to calculate TOF based on the SOS vs. *T* calibration data
- Found TOF is compared with experimental results and heat transport properties (e.g., *h*) adjusted to match experimental TOF and measured surface temperatures

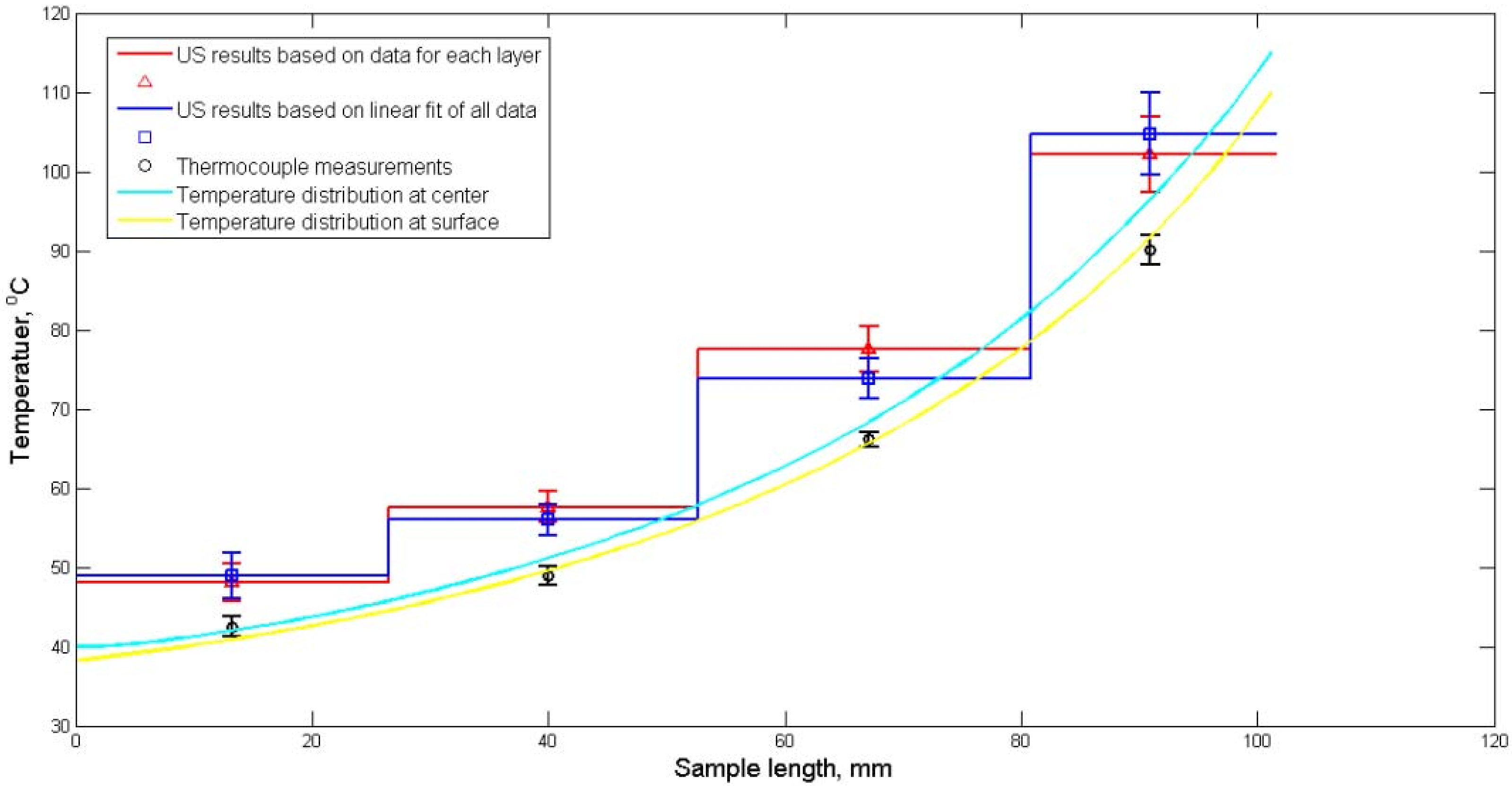






- Top and bottom temperatures were obtained from TC measurements and thermal imaging

Estimated distribution based on thermal modeling

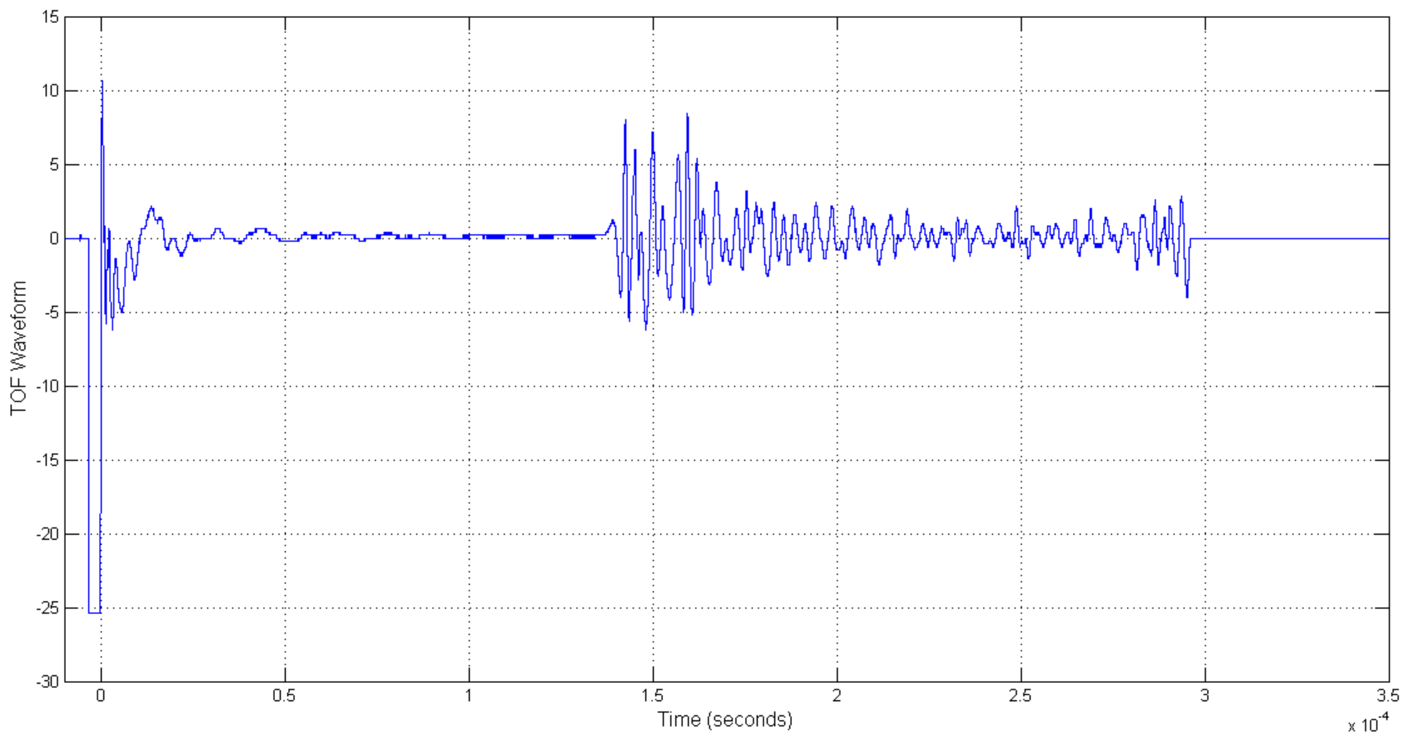


- Temperature distribution found to match the measured TOF and surface temperature measured by TC.
- Top and bottom temperatures were obtained from TC measurements and thermal imaging

High Temperature Experiments

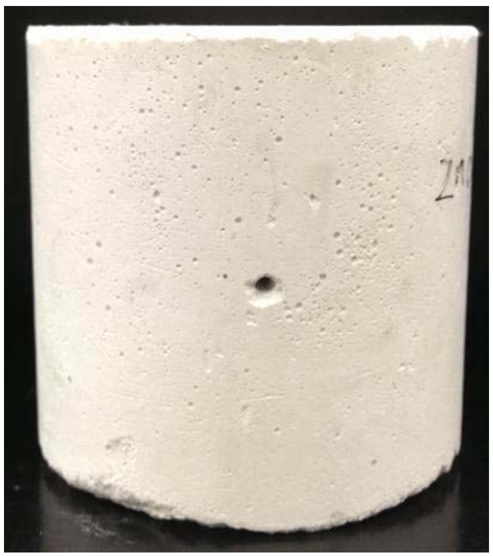
High temperature refractory materials

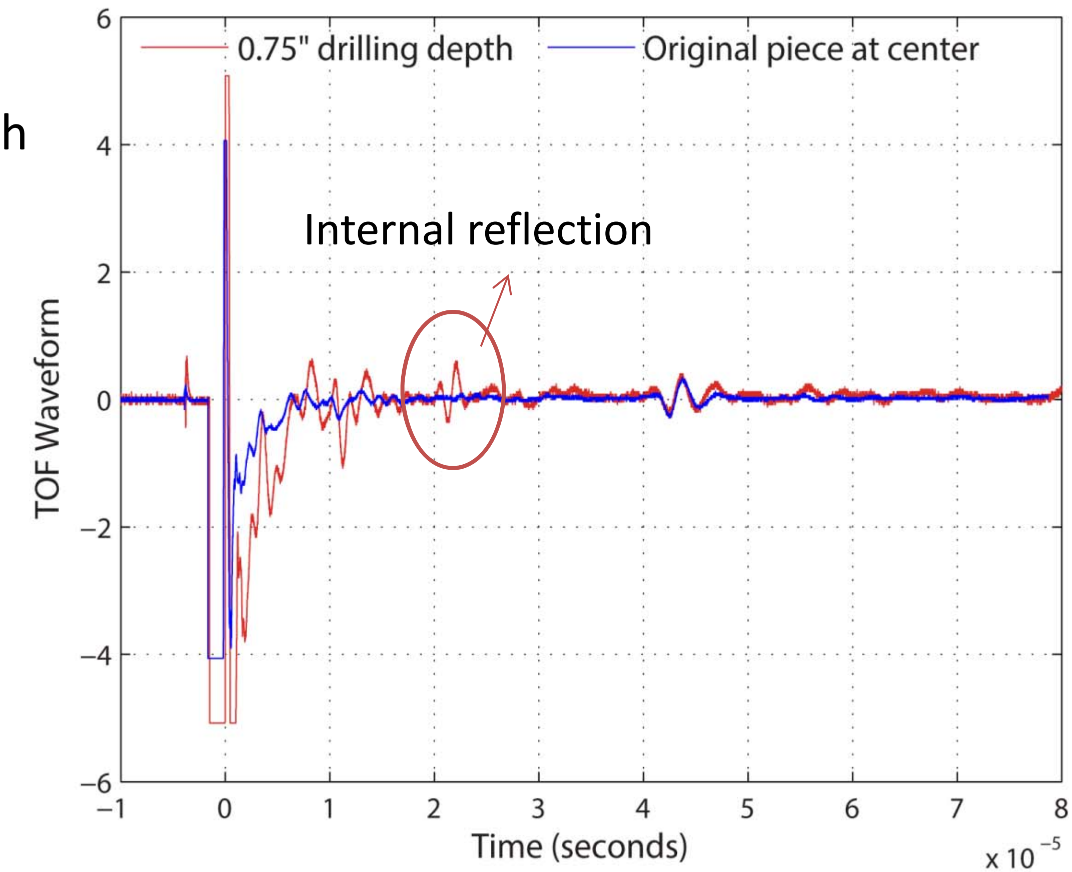
- Al_2O_3 castable ceramic and machinable ceramic rod : max temperature 3000 °F
- US pulse-echo measurements of 1” x 12” Al_2O_3 rod (96% purity)



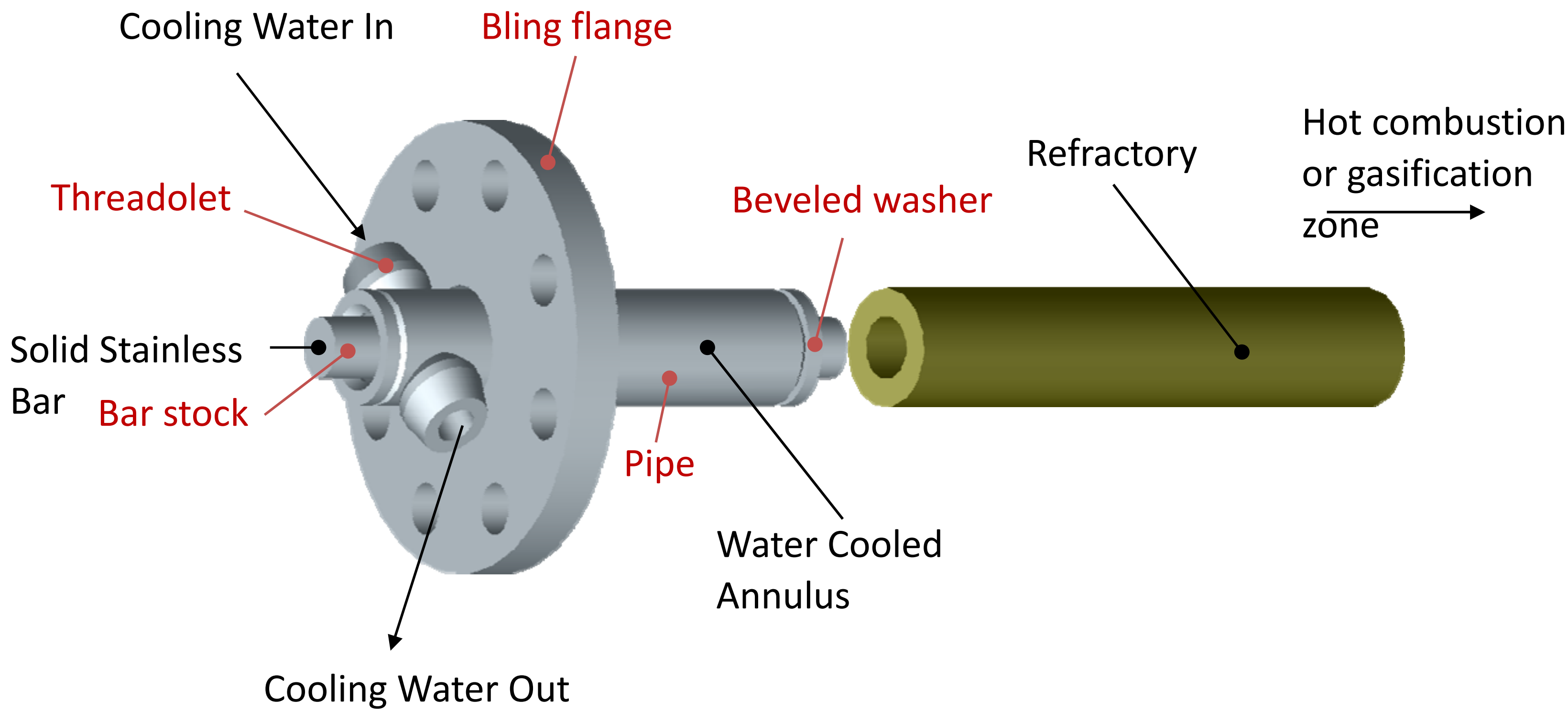
Engineering refractory with partial internal reflections

- Tested in castable Al_2O_3 Ceramic
- 2" I.D. and 2" height sample
- 1/16" I.D. carbide drill bit
- US tested with 1/4" drilling depth





Preliminary design for the ultrasound temperature probe mounting construction

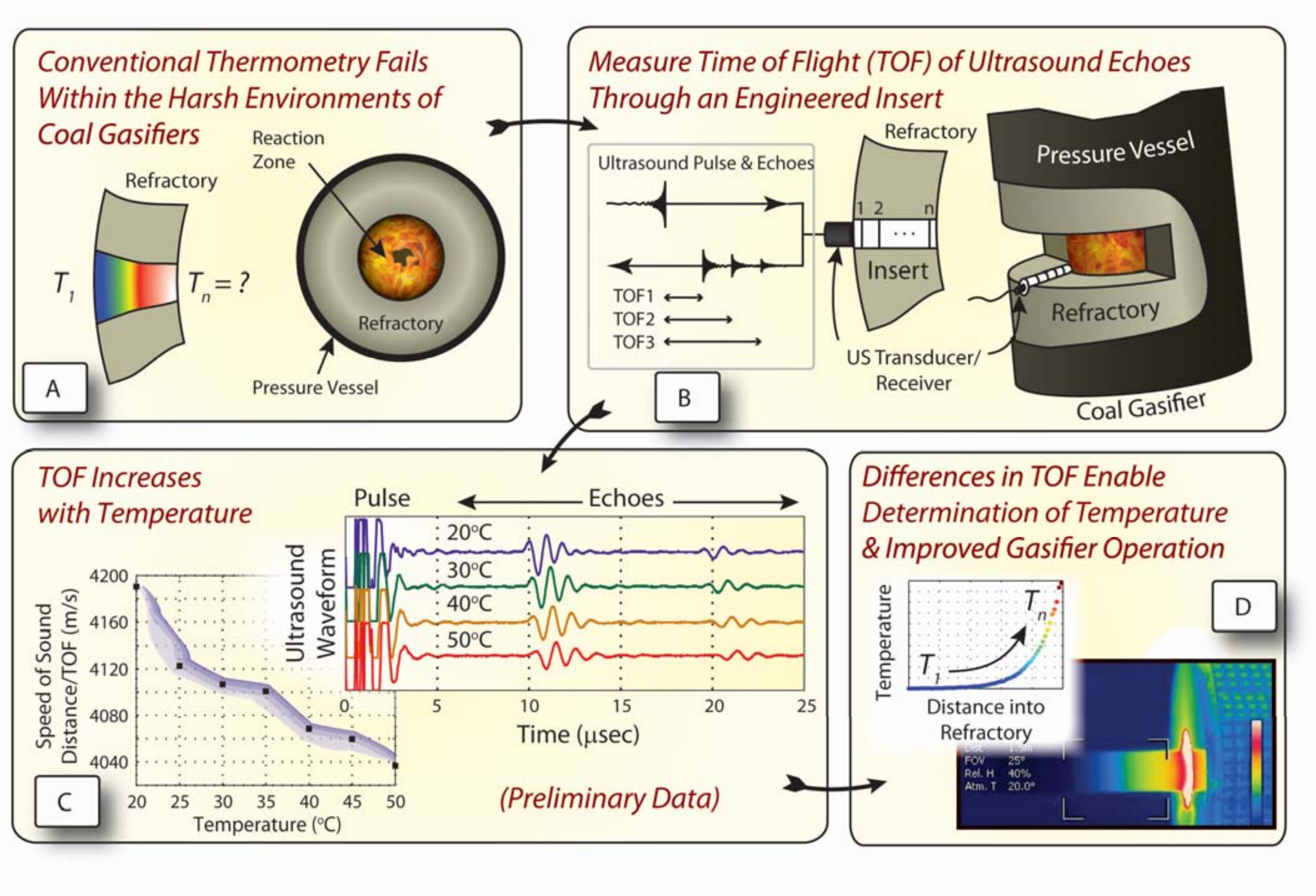


- Design consideration
  - confinement integrity
  - the ultrasound coupling
  - active cooling

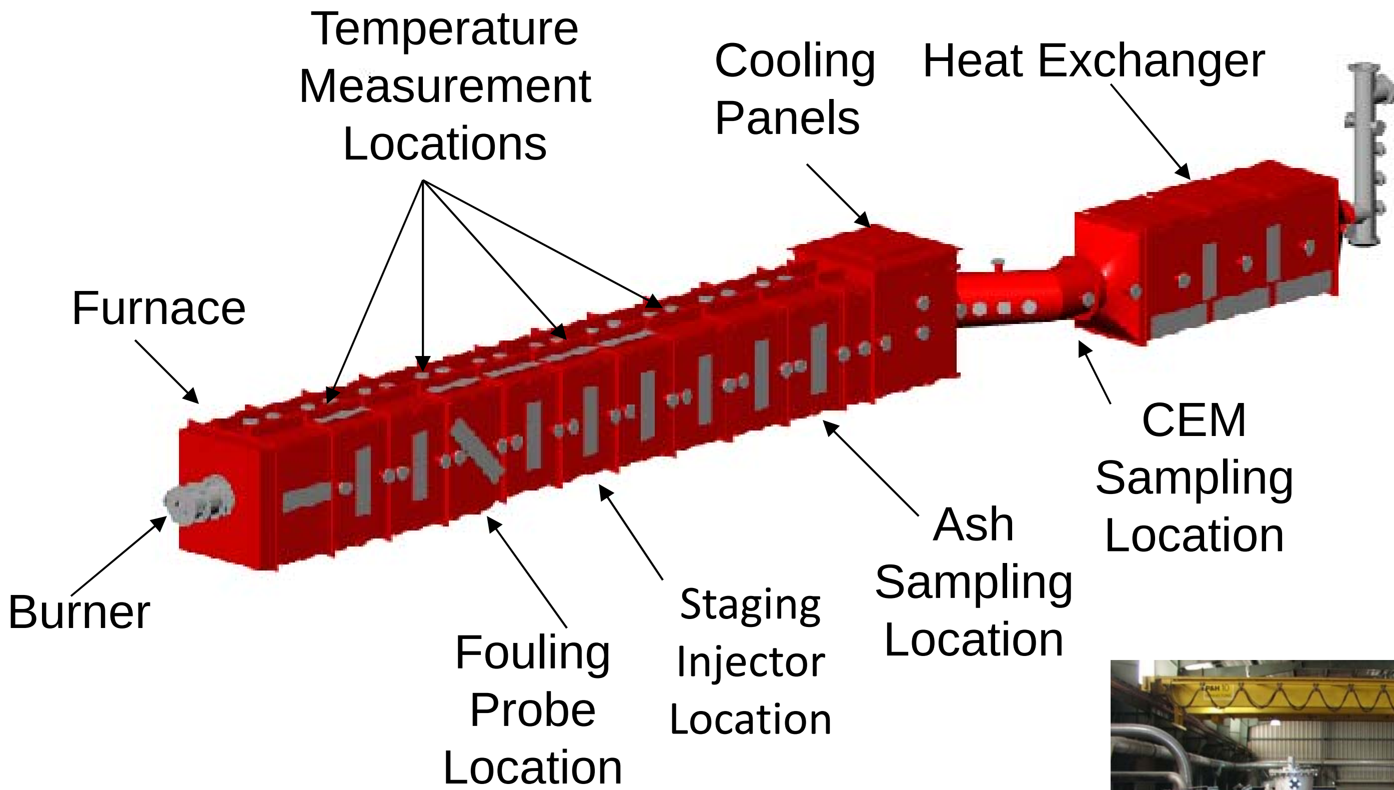
Summary: Low temperature range

- SOS vs. T dependence is surprisingly strong. It may be possible to measure temperature with ± 1°C accuracy. The key to achieving high measurement accuracy is precise measurements of the TOF (perhaps with an accuracy of 10ns)

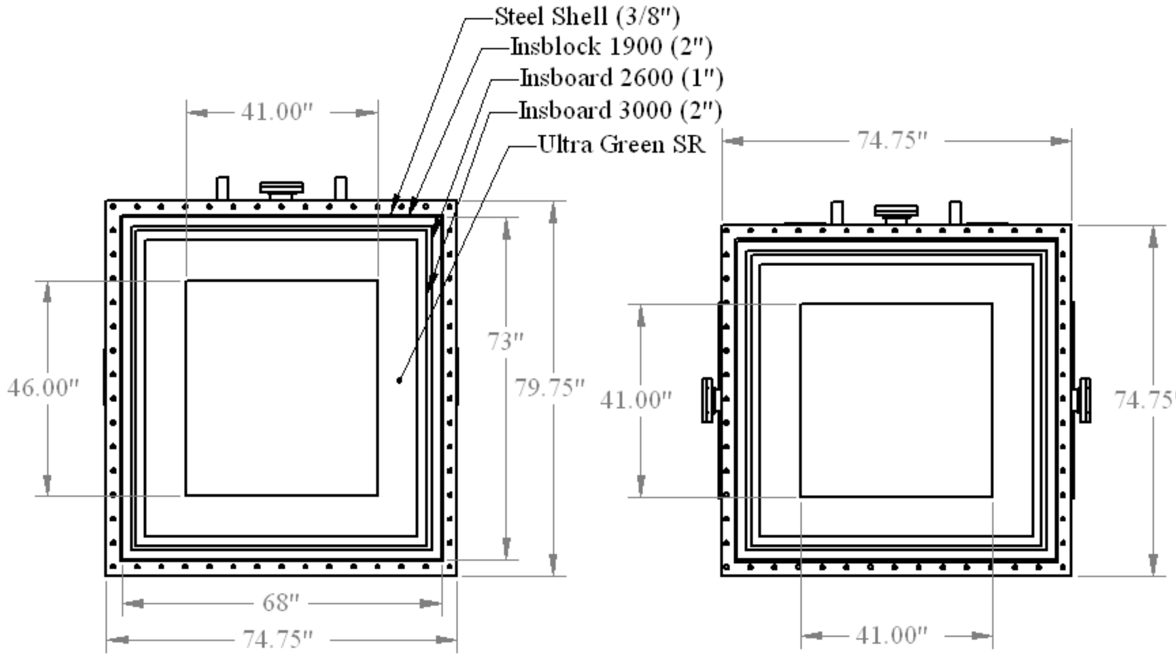
- Spatial resolution of temperature distribution measurements may be as fine as ~1 cm. Is higher resolution possible?



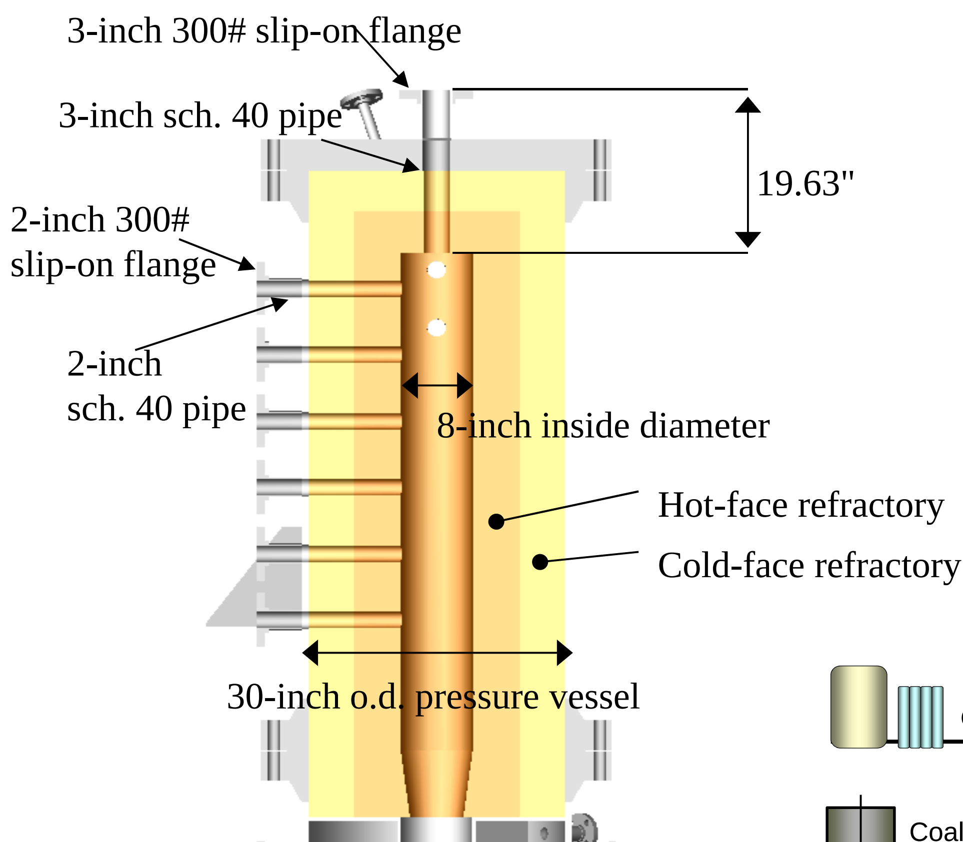
Pilot Scale Testing:
L1500 1.5 MW_{th} Coal Combustor

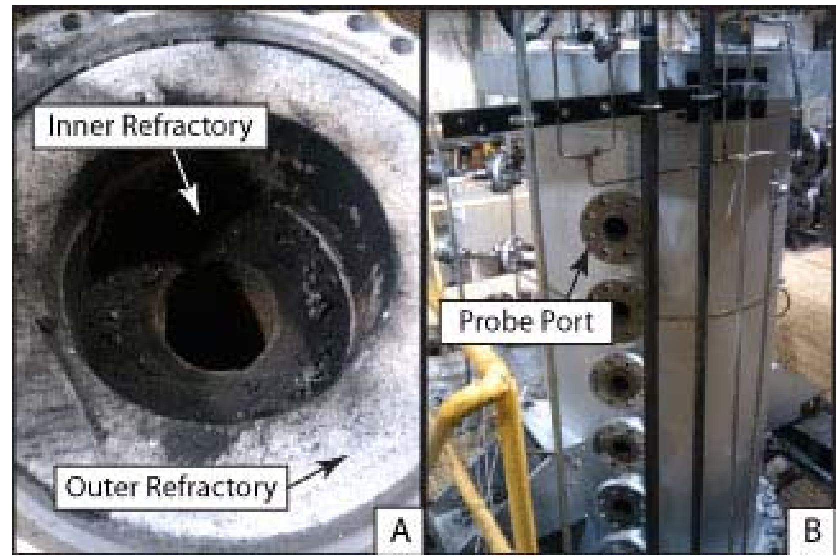


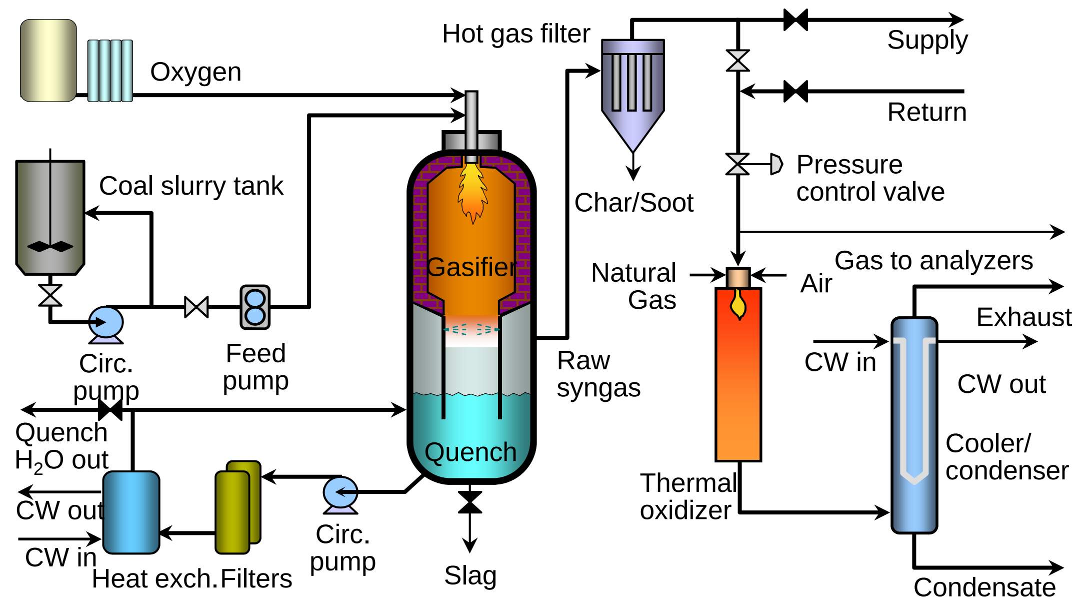
Furnace Cross-section



Pilot-scale Entrained Flow Gasifier







Industrial testing

- Tsinghua University 1st generation coal gasifier (500 ton/day)

Further questions

- Can changes in material properties be detected? Compare results of directly measured and the estimated temperature distribution to assess if the change in material properties. (e.g., thermal conductivity *k*(*r*)) can be detected.

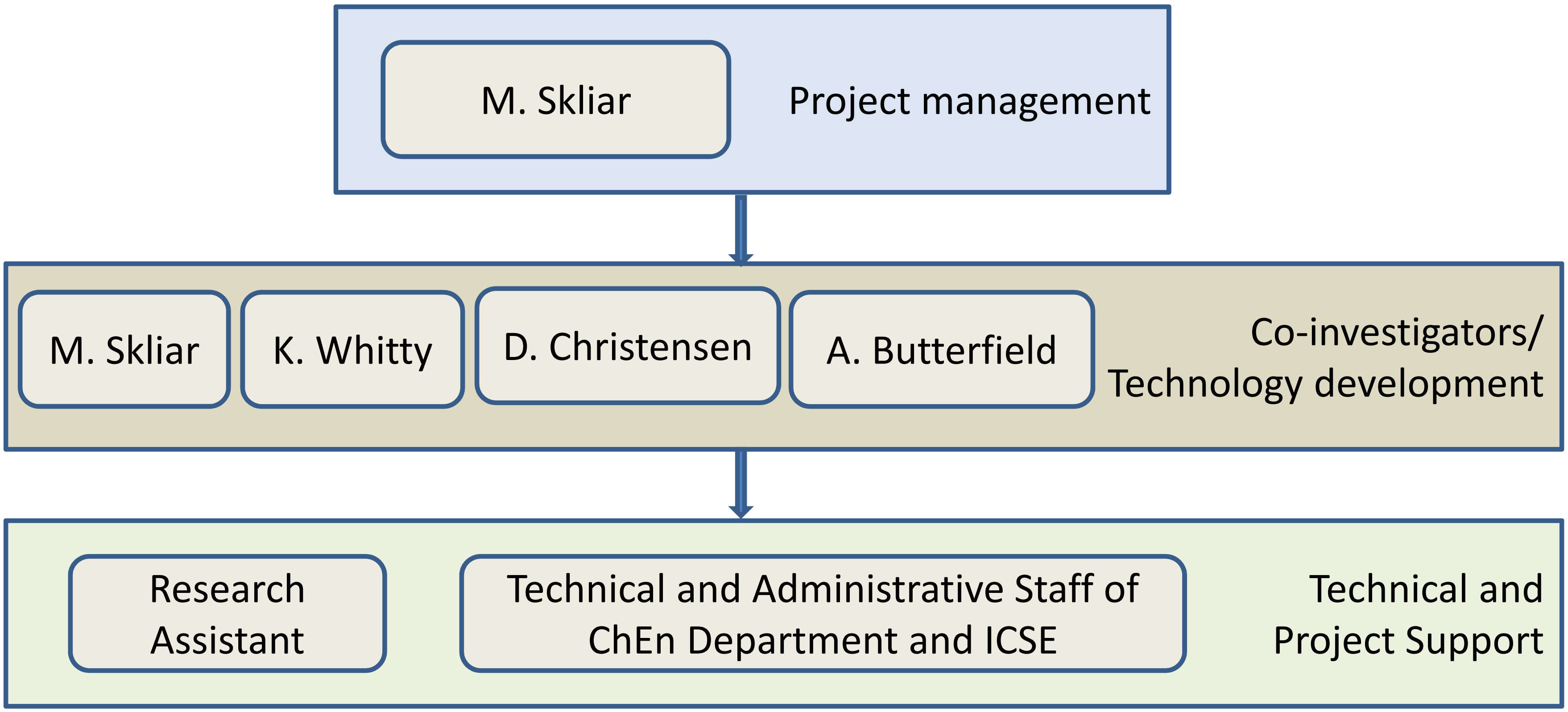
- Can changes in refractory thickness be simultaneously measured?
  - Thickness, *L*, affects the TOF
  - The temperature-compensated and uncompensated measurements of *L* may be different
    - Per Prof. Zhang: "Refractory on the vertical walls must be replaced every 14,000 hours (~580 days). Refractory at the bottom of gasifier must be replaced every 4-6K hours (170-250 days)"

- Can we detect formation of small cracks?
  - We will also investigate if small cracks, formed at an early state of refractory degradation, introduce new ultrasound scatterers that can be detected at a receiver and used to monitor the degradation.

Tasks and Schedule

PHASE I		
Task 1	Year 1 annual topical report (30 days after end of the period) is completed	Month 13
Task 1	Go/no-go decision on whether to continue to Year 2 is made	Month 12
Task 2.2	The method for model-based estimation of refractory temperature distribution is developed	Month 12
Task 3	1. The method to measure an average refractory temperature is tested in 20-100C temperature range 2. The system for high-temperature laboratory testing of the developed methods is constructed and commissioned	Month 12 Month 12
PHASE II		
Task 1	Completion of Year 2 annual topical report (30 days after end of period)	Month 25
Task 1	Go/no-go decision on whether to continue	Month 24
Task 2.3	Develop method for direct US measurement of the refractory temperature distribution	Month 24
Task 3	1. Test the method to measure an average refractory temperature in the testing chamber. 2. Test in the chamber the method for the model-based estimation of refractory temperature distribution 3. Develop laboratory model of refractory degradation by applying thermal shock and chemical exposure	Month 24 Month 24
PHASE III		
Task 1	Submission of the final report (90 days after end of project)	Month 39
Task 2.4	1. Method for temperature-compensated US measurement of refractory thickness is developed 2. A model-based method to estimate the thermal conductivity profile based on the measured temperature profile is developed	Month 36 Month 36
Task 3	**1. Test and correlate the effect of degradation on thermal conductivity** **2. Test in laboratory chamber and pilot-scale coal combustor the method for direct US measurement of the refractory temperature distribution** **3. Test the temperature compensated thickness measurements using US method**	Month 36 Month 36 Month 36

Team



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Questions

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