In-Situ Acoustic Measurements of Temperature Profile in Extreme Environments

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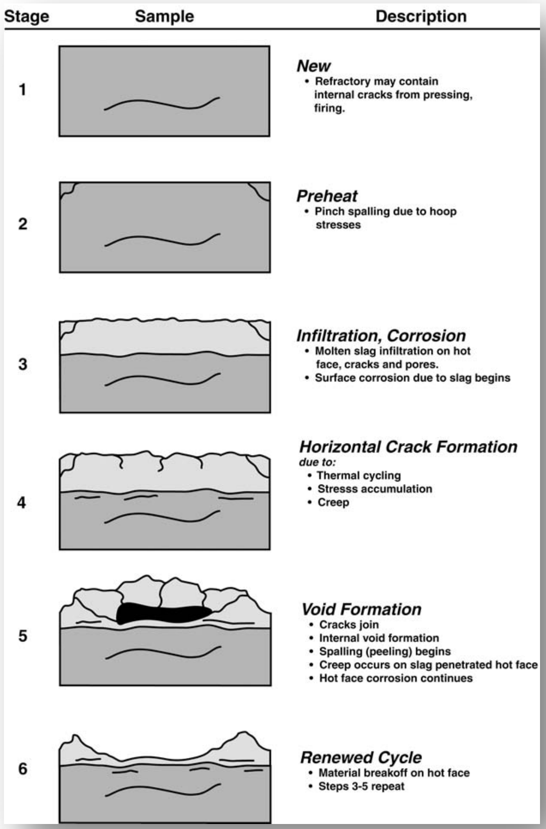
Introduction

- 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].

Solution Strategies

Thermocouple protection system for gasifier application [2].

- ***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.

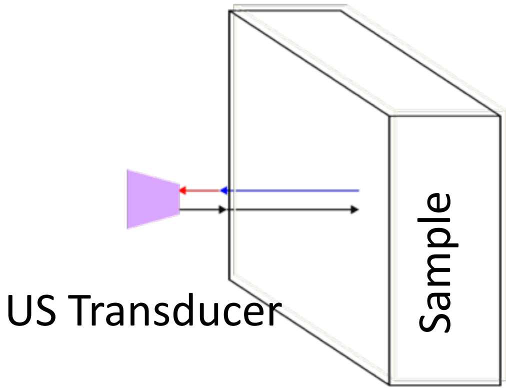
- ***Inferential approach***: *Indirect* (secondary) *measurements* that are easy to obtain (*T*, *P* and compositions of in/out streams) are used with appropriate models to *infer* otherwise inaccessible operating parameters inside the reactor zone and the state of the refractory.
  - Few examples in 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: ***When temperature changes along the path of US propagation***, the acoustic TOF measurements depend on temperature distribution in a complex way:

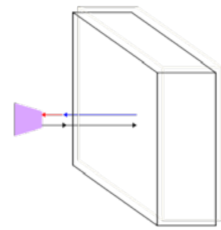
$$TOF = \int_{\mathrm{r_h}}^{r_c} f(T(t,r))\,\mathrm{d}r$$

- 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 $f(.)$:

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



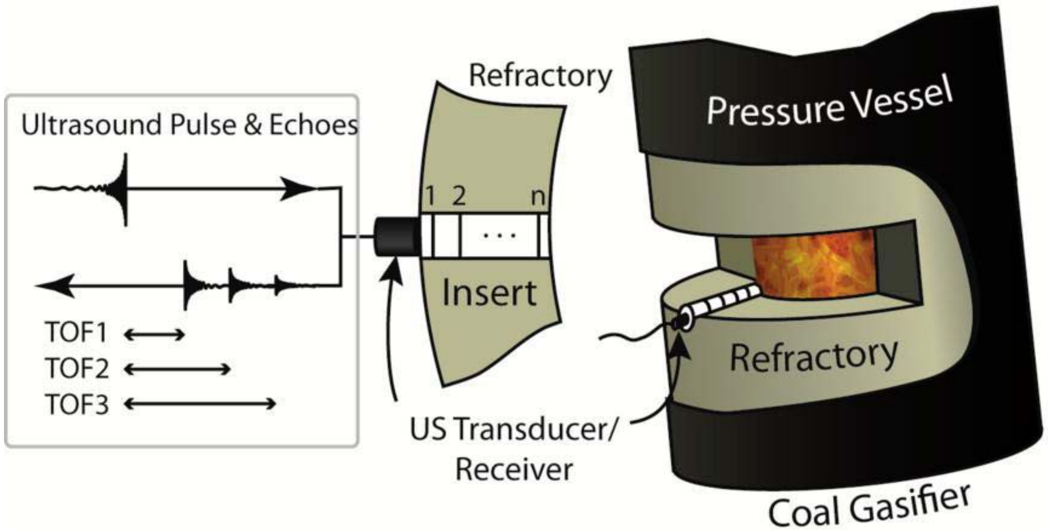
- Use the result and the heat transfer model

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

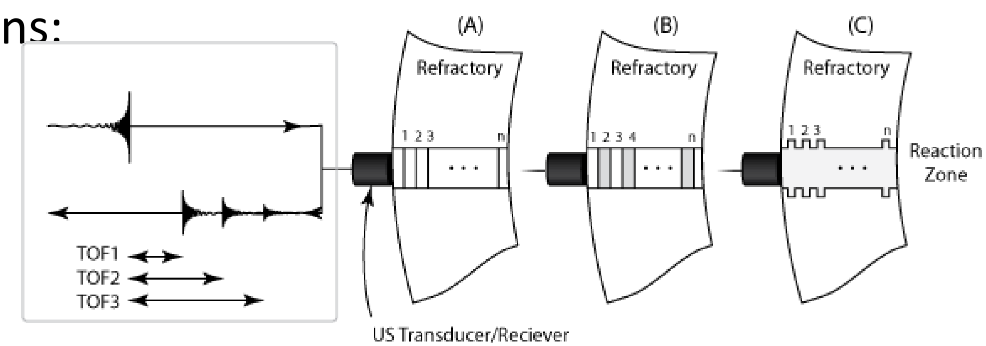
to *estimate* the temperature distribution

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.

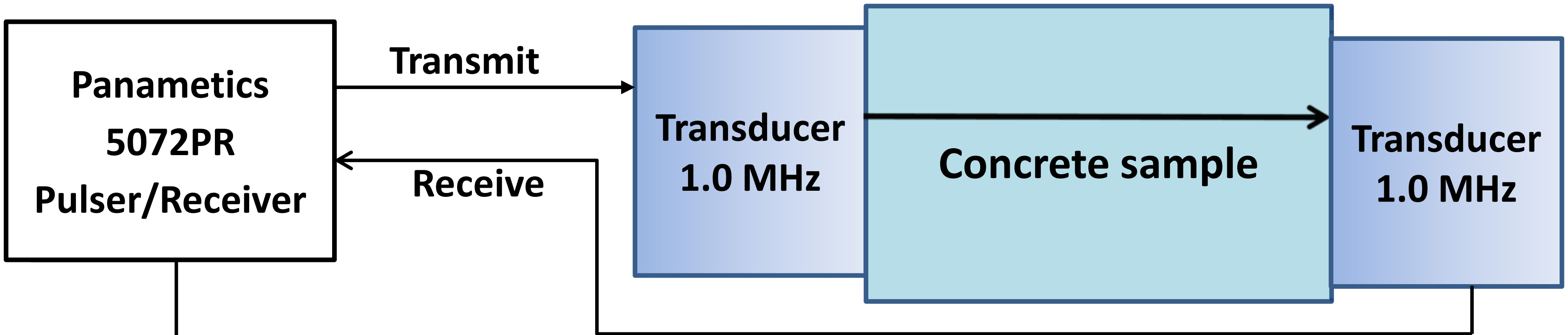


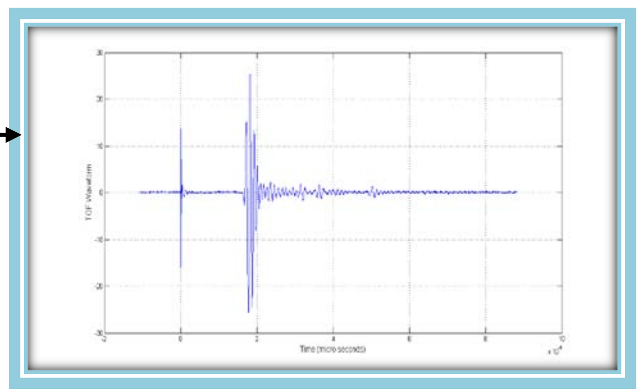
- Methods to create partial reflections:
  - Scatterers;
  - Change in US impedance;
  - Change in geometry



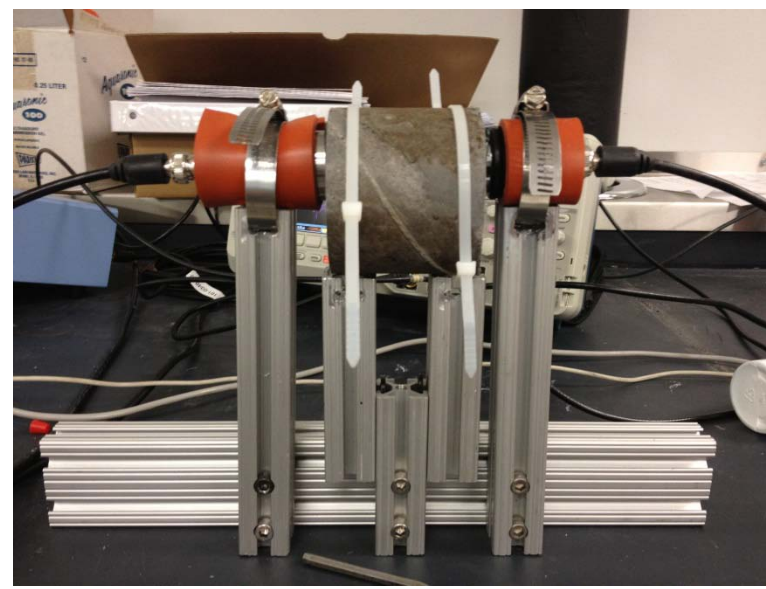
SOS as a Function of Temperature

Experimental Setup: Transmission setup

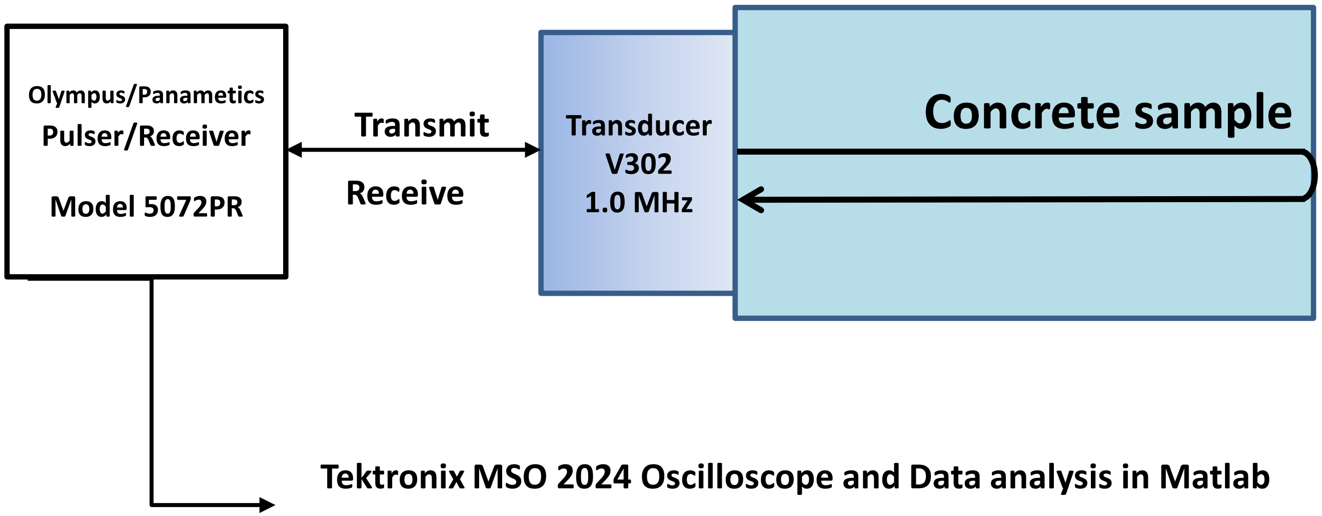




Tektronix MSO 2024 Oscilloscope



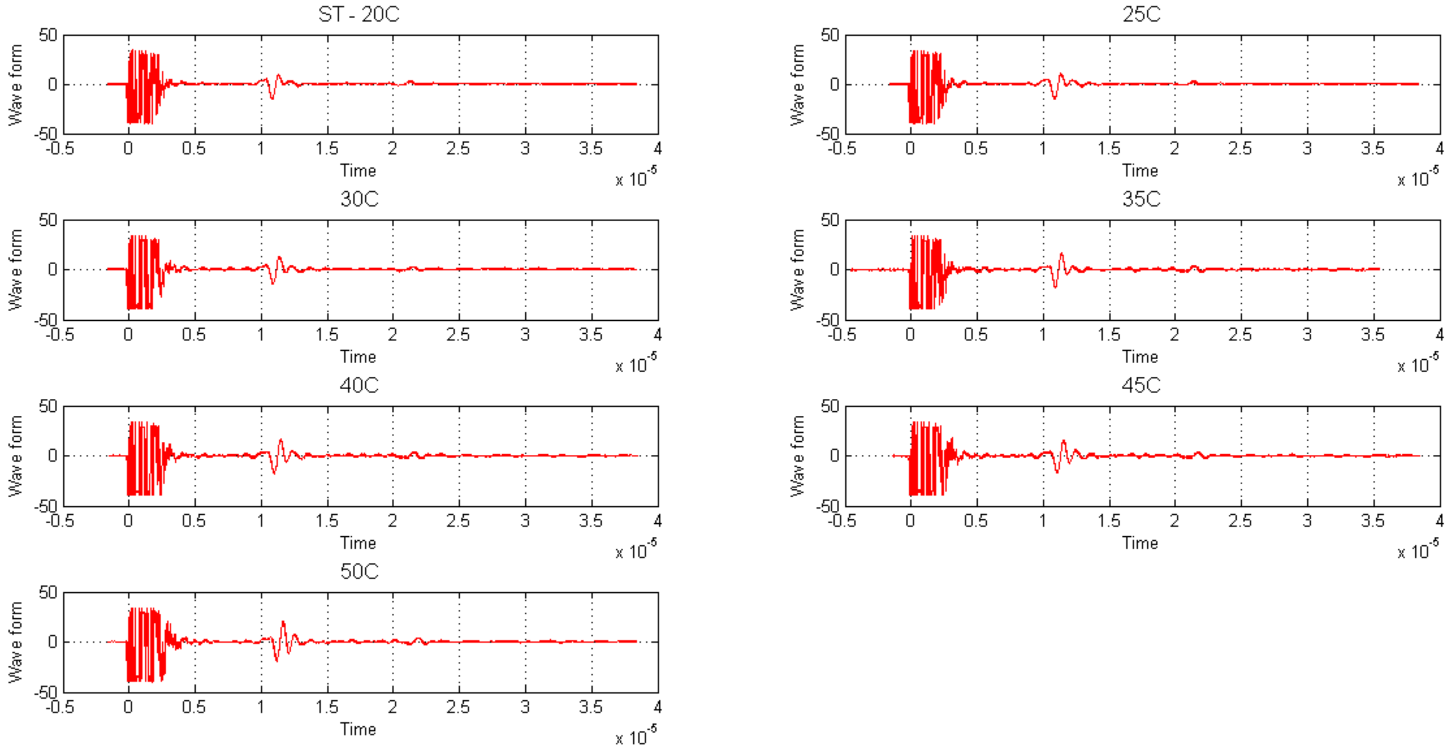
Experimental Setup: Reflected signals



Initial experiments were conducted in water bath:

- Simplifies coupling
- Convenience in maintaining uniform temperature distribution in a sample

Temperature effect

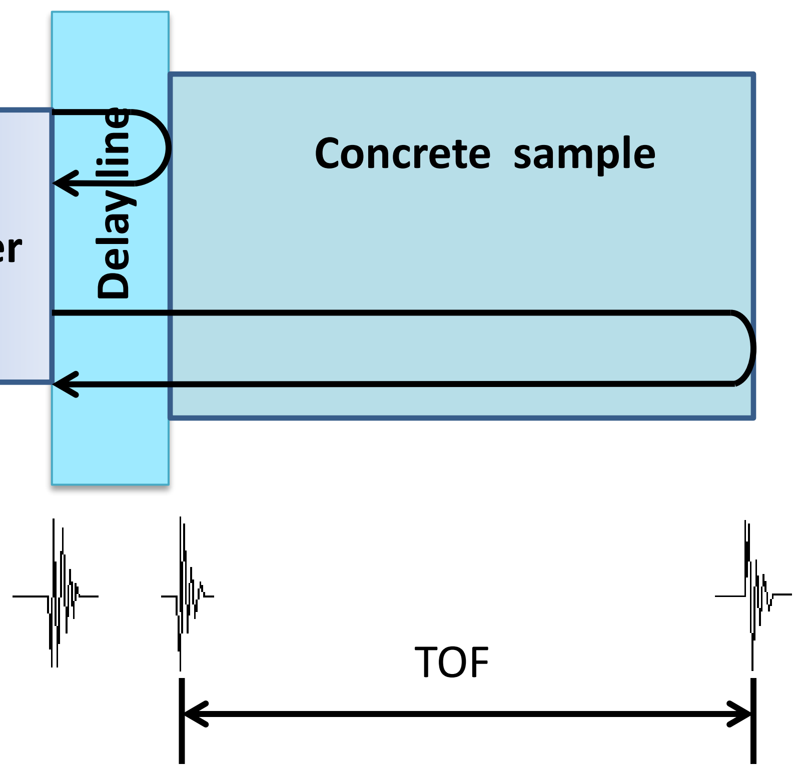


- Range: 20 ~ 50 °C
- Water bath maintained constant for more than 12 hr for each experiment
- “Initial bang” makes it difficult to measure TOF precisely

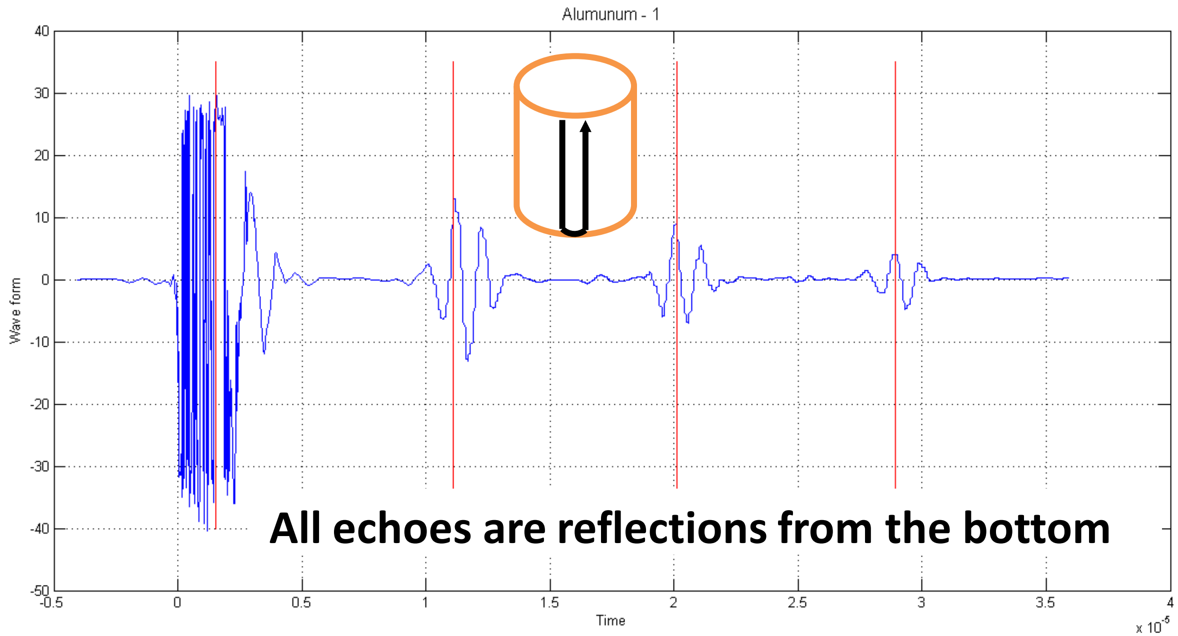
Measurements of TOF

TOF measurements: Delay line method

- Pros:
  - Elimination the effect of “initial bang”
  - Using Plexiglas (11.75 mm) as delay line
- Cons:
  - Decreases signal strength



Delay line method: Test with Aluminum sample

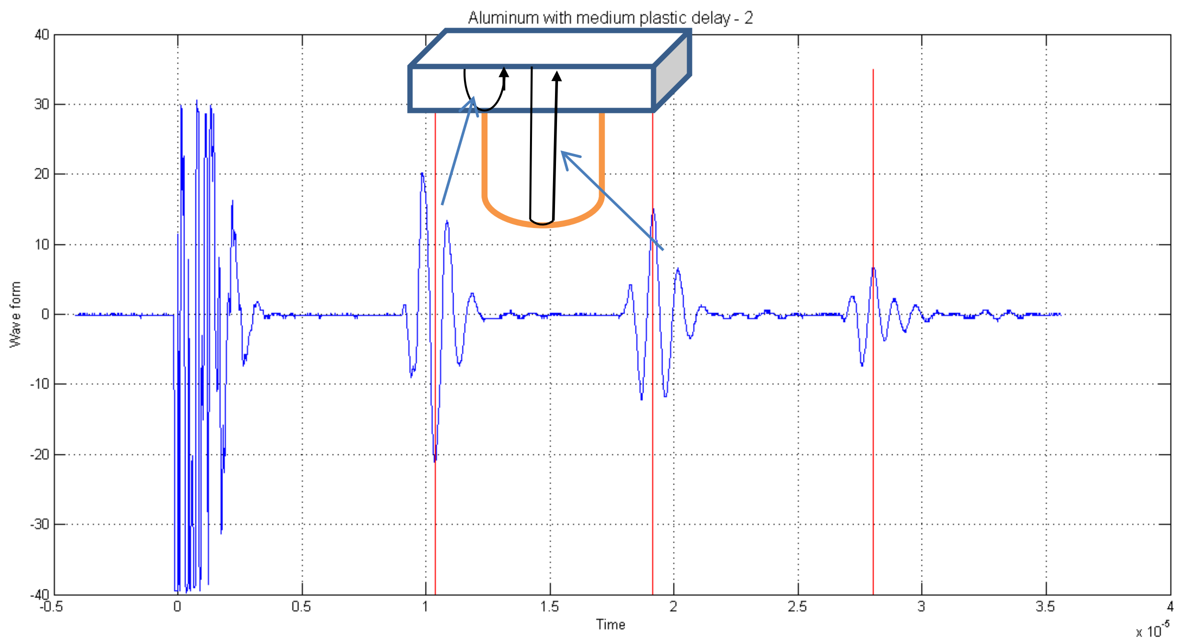


Results without delay line:

- SOS_{Al} =6443 m/s

Handbook value:

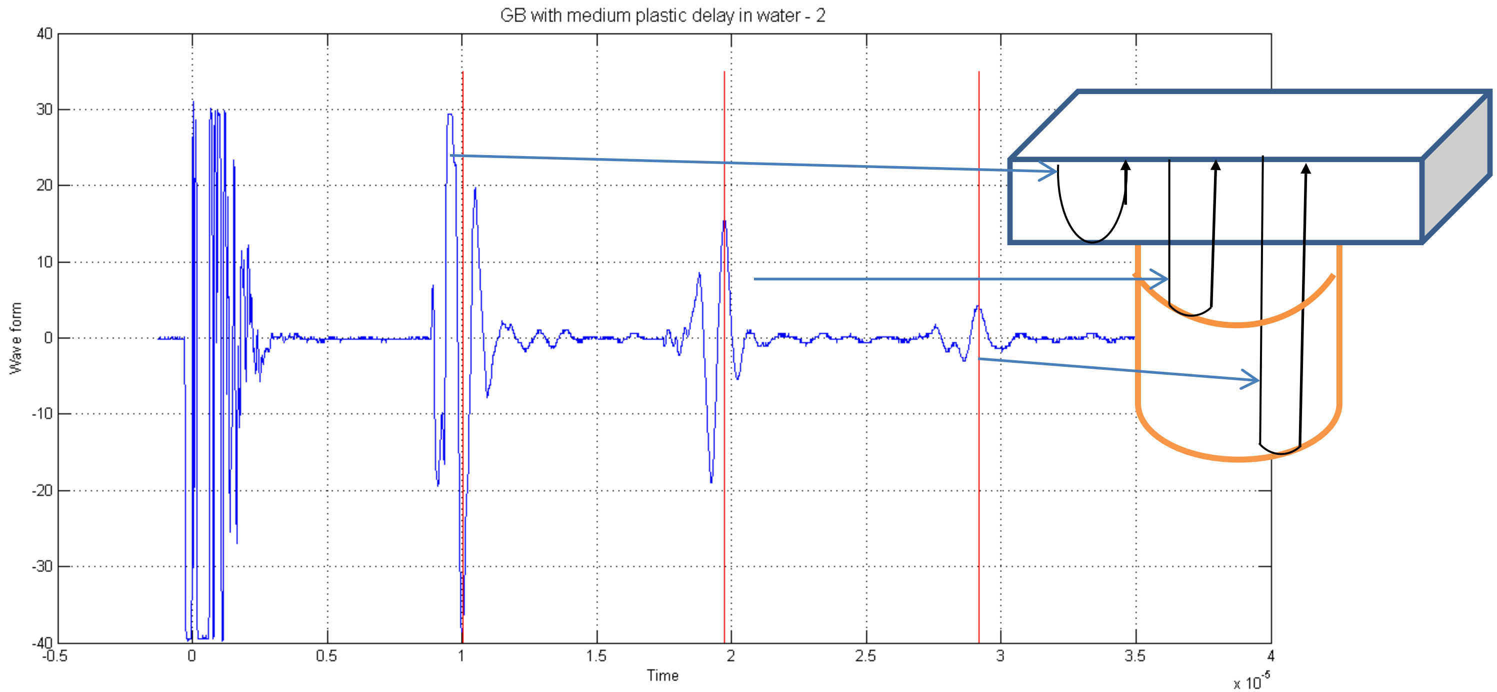
- SOS_{Al} =6420 m/s



Results with delay line:

- SOS_{Al} =6481 m/s
- 0.6% difference

Delay line method: Concrete samples

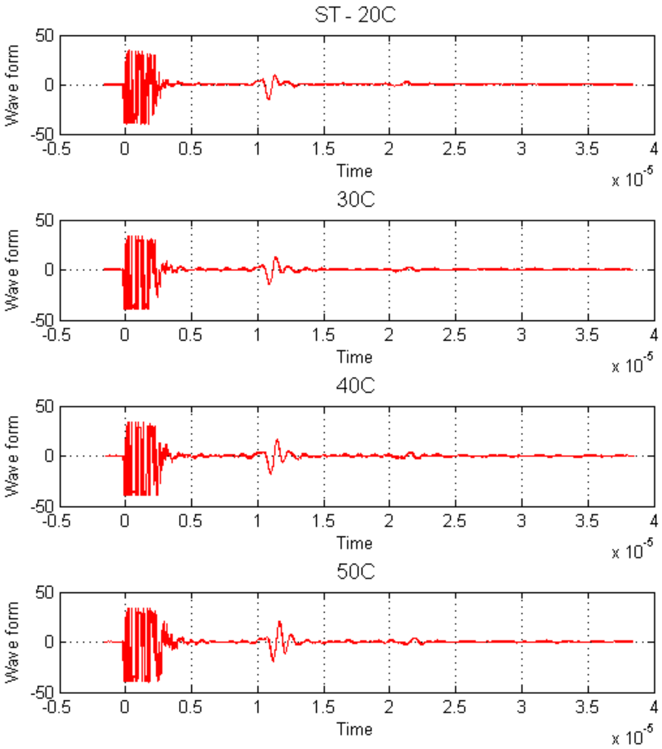


- Matlab code to determine the TOF between echoes was developed
- Method is based on matching a single point (e.g., zero crossing or peak value) which affects it robustness in dissipative medium

Cross-correlation method to measure change in the TOF

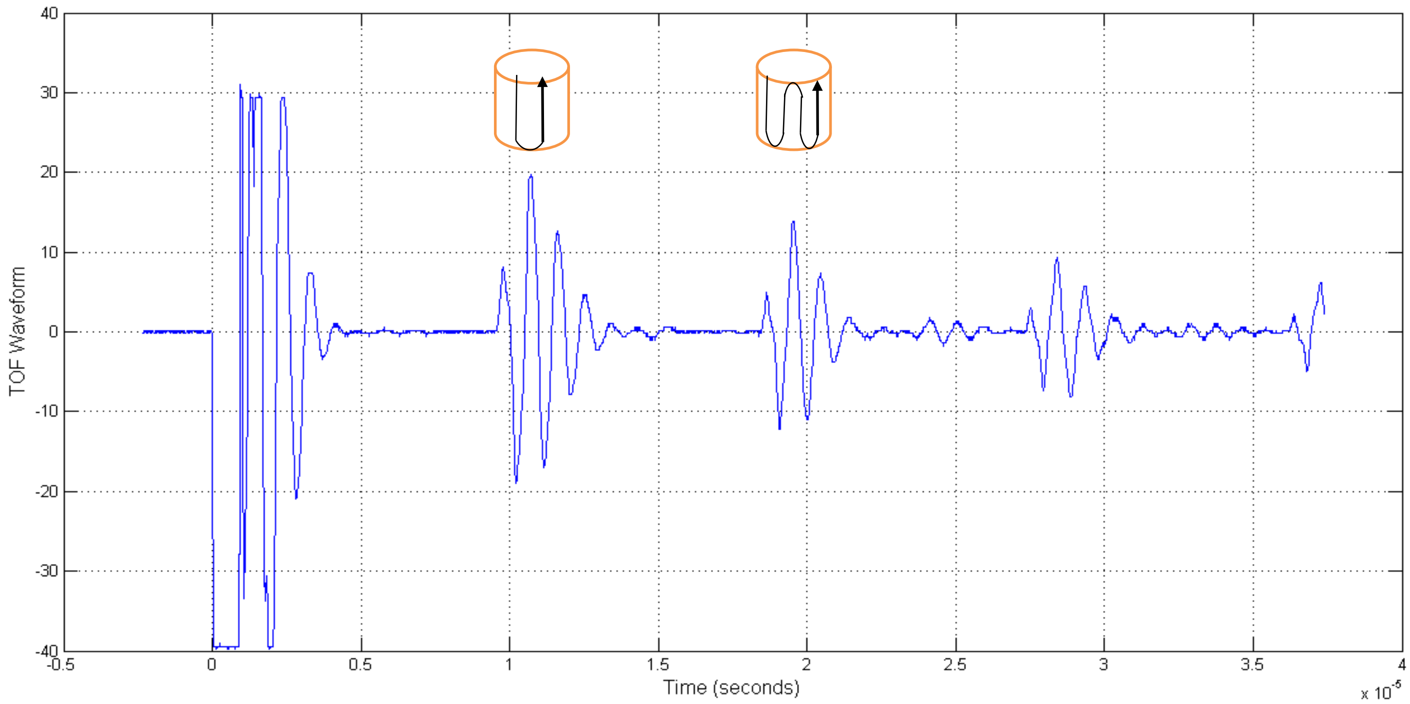
- Match the entire waveform instead of a single point.
- Provides robust method to measure ΔTOF

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

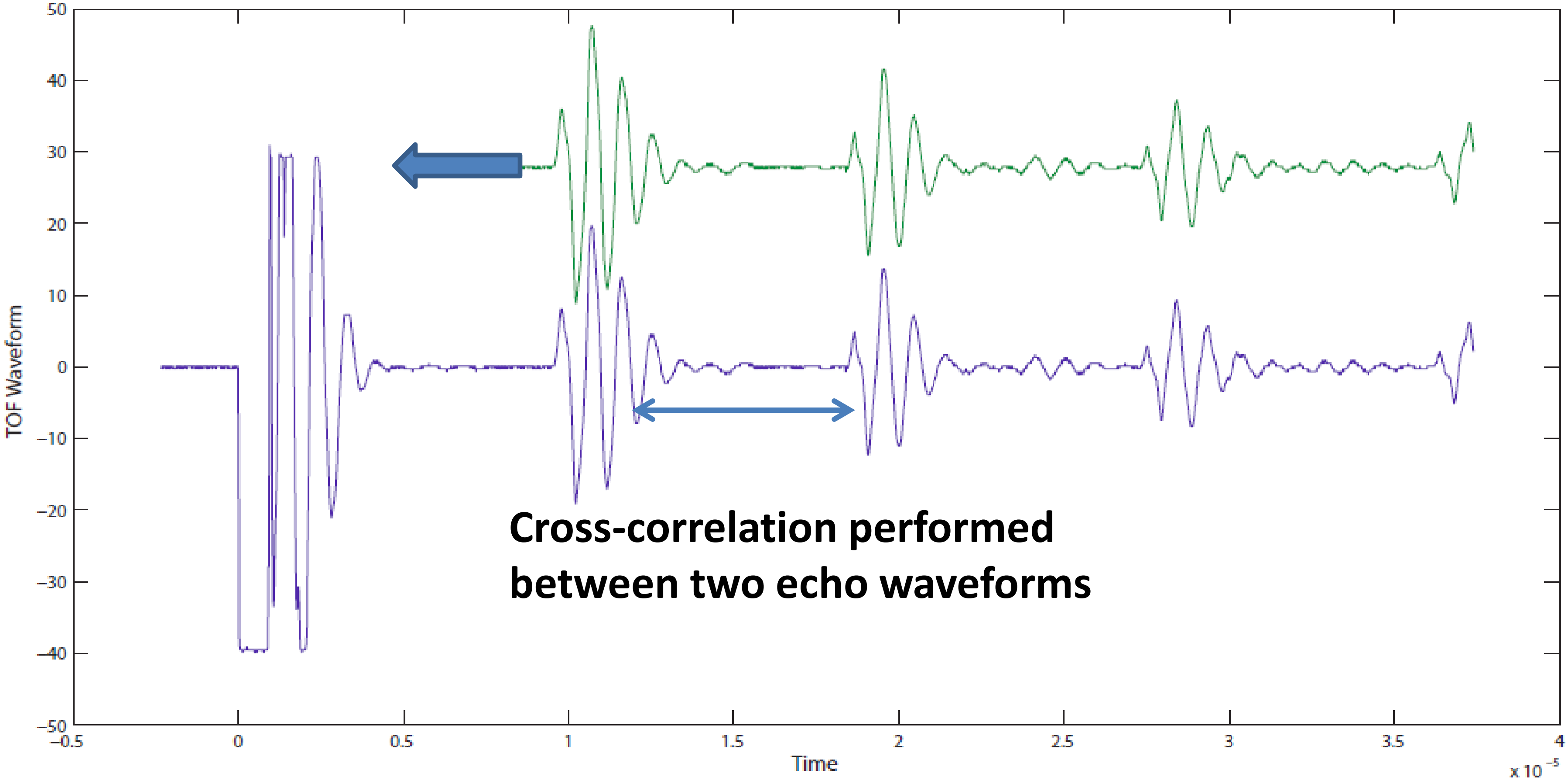


Cross-correlation method to measure TOF_{ref}

- Establish "zero" time by matching shapes of waveforms from multiple "round-trip" reflections in low dissipation sample
  - Illustration with aluminum sample



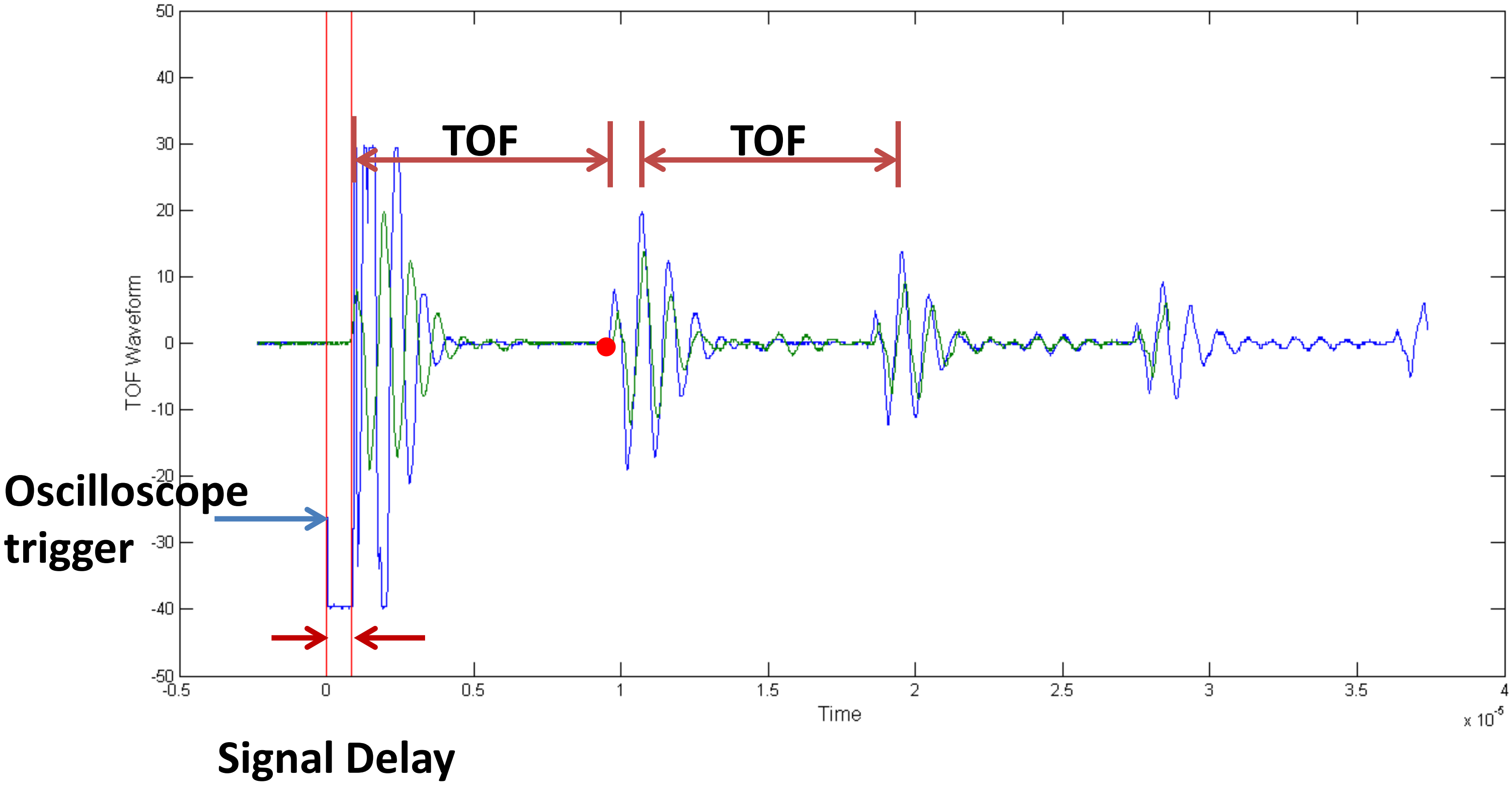
Cross-correlation method: Implementation



Use cross-correlation to establish reference zero time

- Test results for aluminum sample: SOS_{Al} = 6467 m/s

  Reference value: SOS_{Al} = 6420 m/s

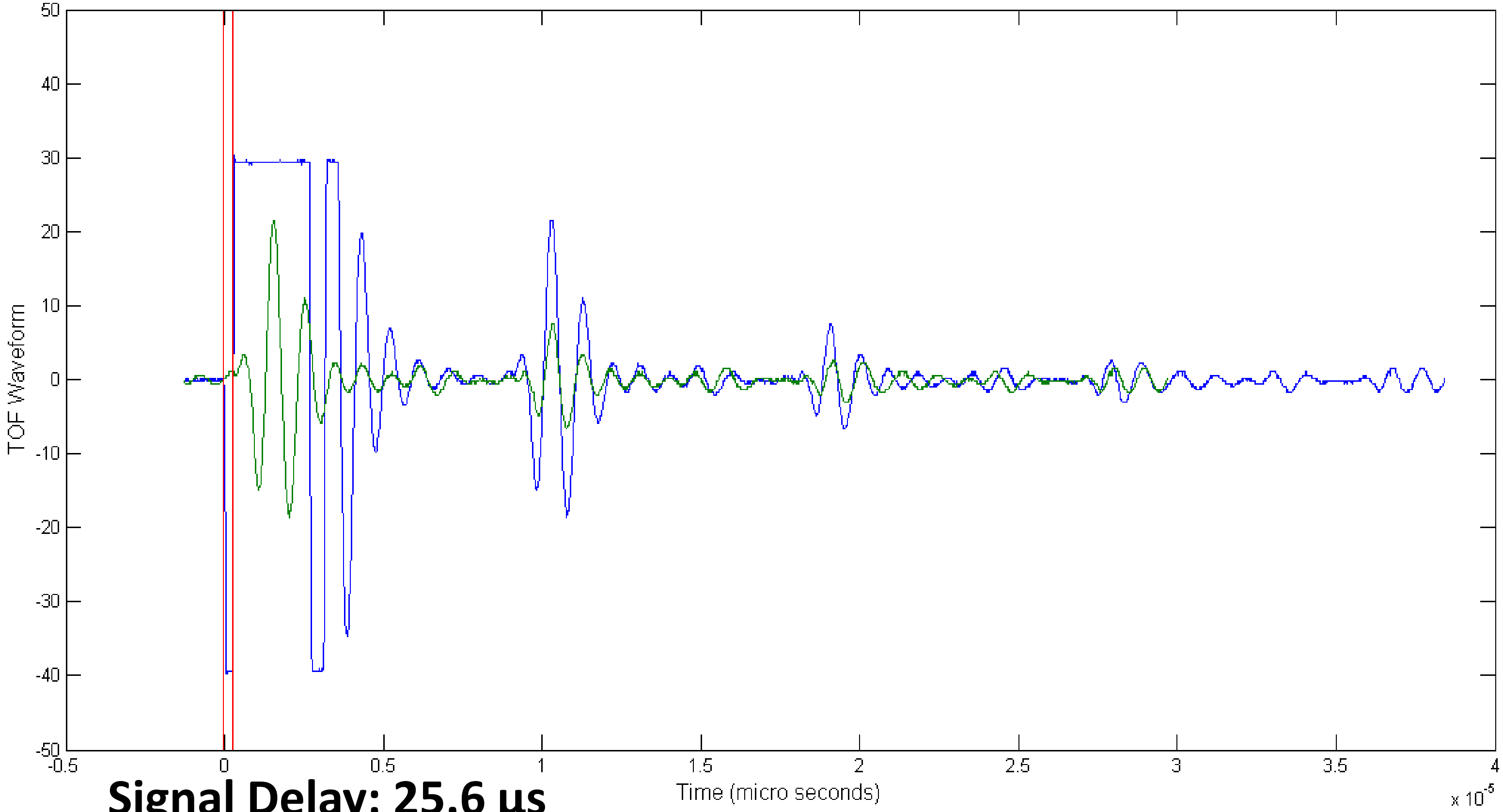


Is Signal Delay constant for different samples?

Material	Aluminum	Bronze	Stainless steel	Steel	Plastic
Signal delay after trigger (µs)	91.2	96	94.4	94.4	94.4

- Using transducer model V302 (1 MHz)
- Need more experimental tests to confirm

Signal delay is highly depended on the transducer

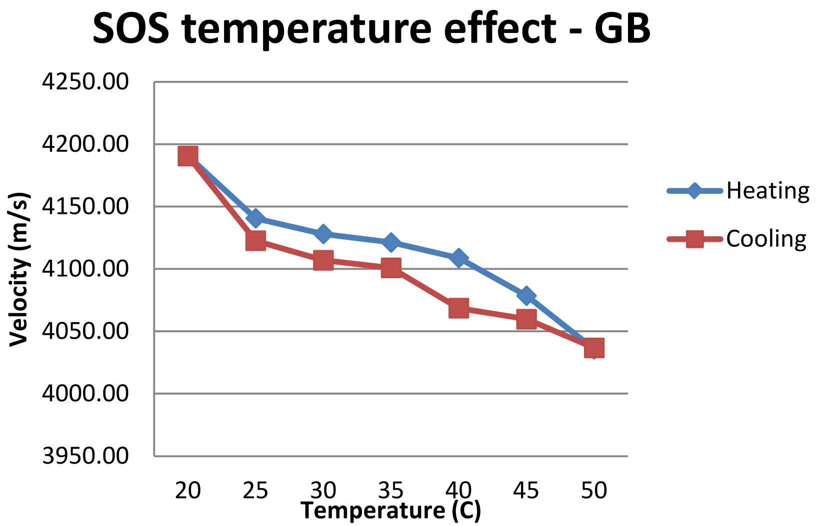


Signal Delay: 25.6 µs

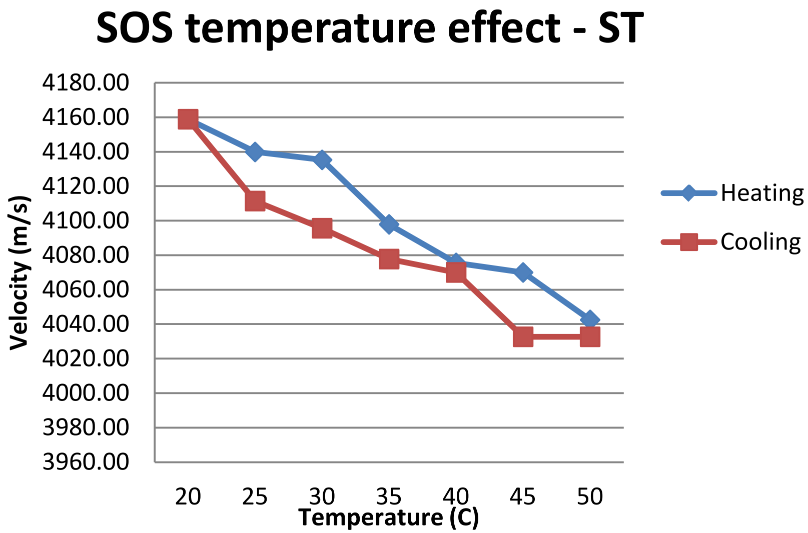
- Using transducer A114s (1 MHz) with the same aluminum sample

SOS as a Function of Temperature

Temperature effect on SOS in concrete samples

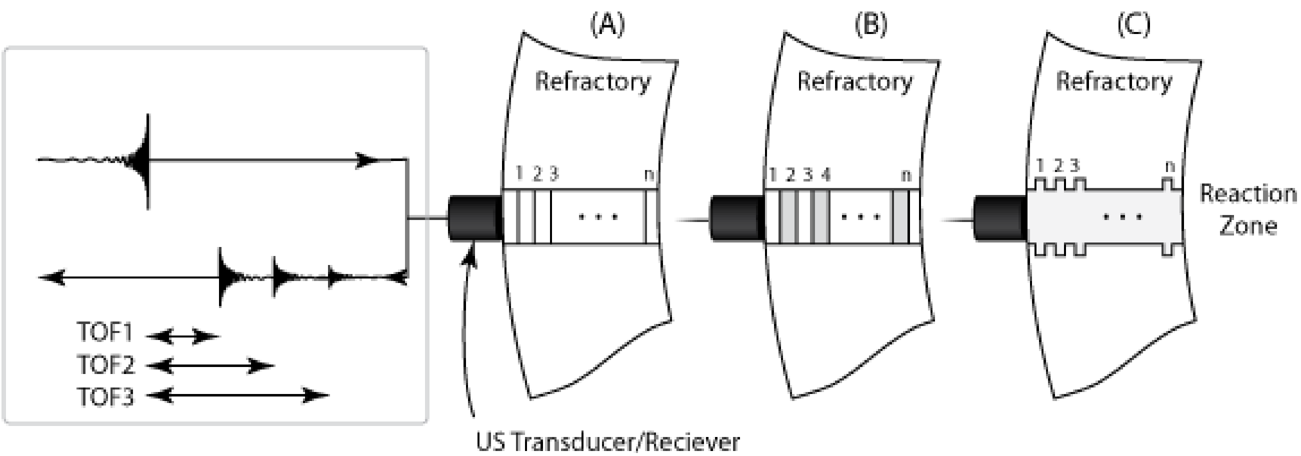


	GB (velocity, m/s)	
Temperature	heating	cooling
20	4190.49	4190.49
25	4140.62	4122.65
30	4128.05	4106.95
35	4121.23	4100.89
40	4108.78	4068.55
45	4078.53	4059.72
50	4035.63	4036.71



Surprisingly strong dependence!

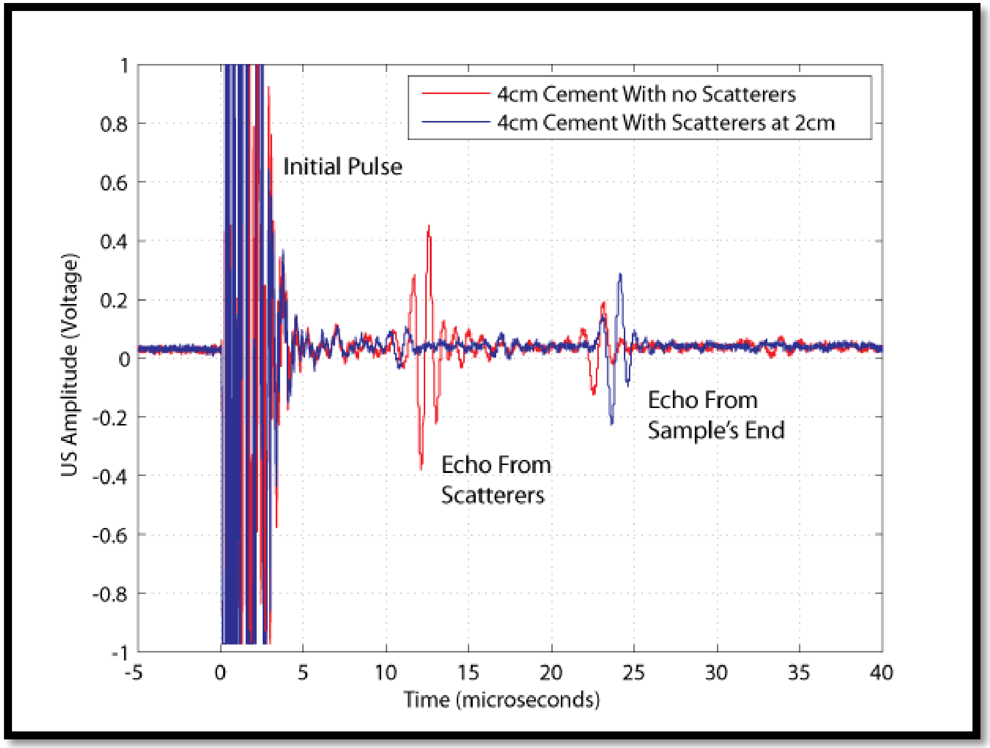
Engineering refractory to produce partial internal reflections



Concrete samples with embedded scatterers

- We tried a variety of materials:
  - Glass beads
  - Styrofoam
  - Steel shots
  - Walnut shells
- 1.25” diameter, 2” long
- Scatterers are placed as we pour cement in stages

Example: Steel shot scatterers

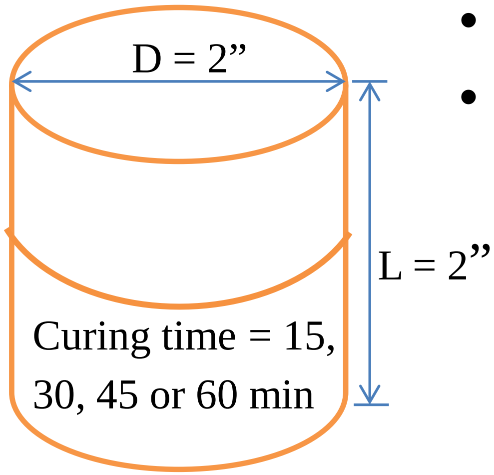


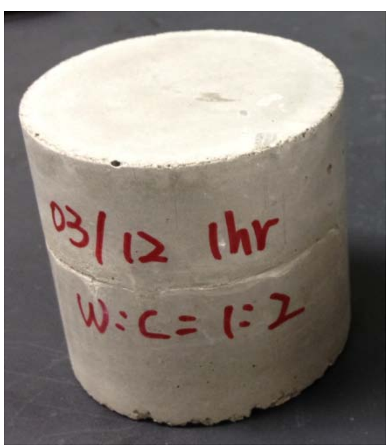
Issues:

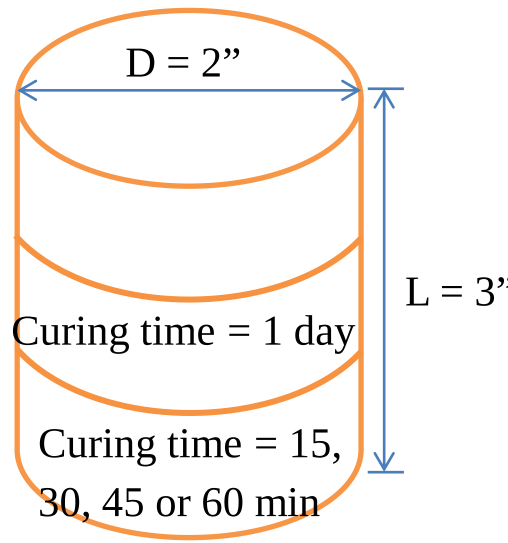
- Need to avoid thermal stresses and
- Maintain overall properties of the refractory

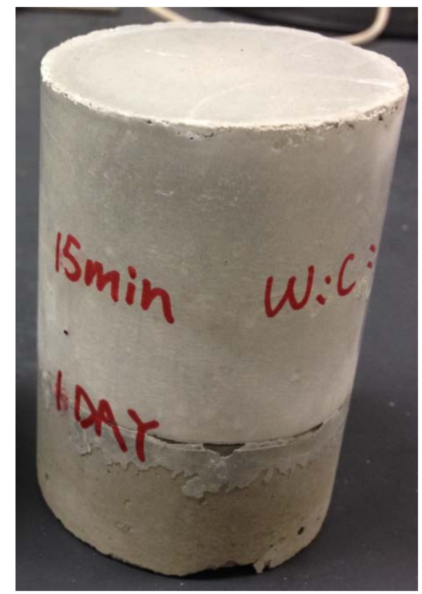
Hypothesis: Small changes in concrete formulation will create partial reflections

- Water/cement ratio: 0.35 ~ 0.5
- Curing time: 15 min ~ days
- Vibrate on remove bubbles

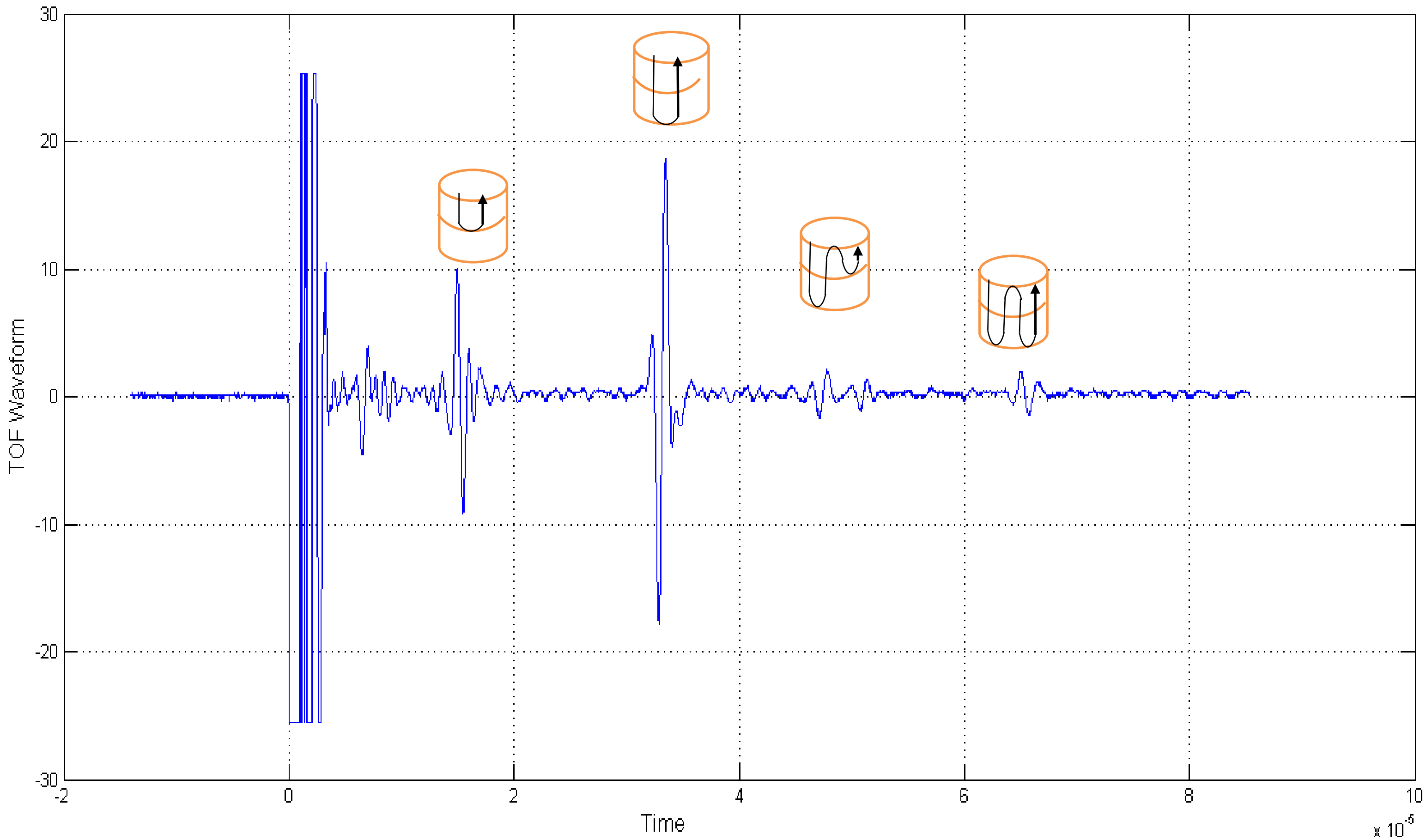






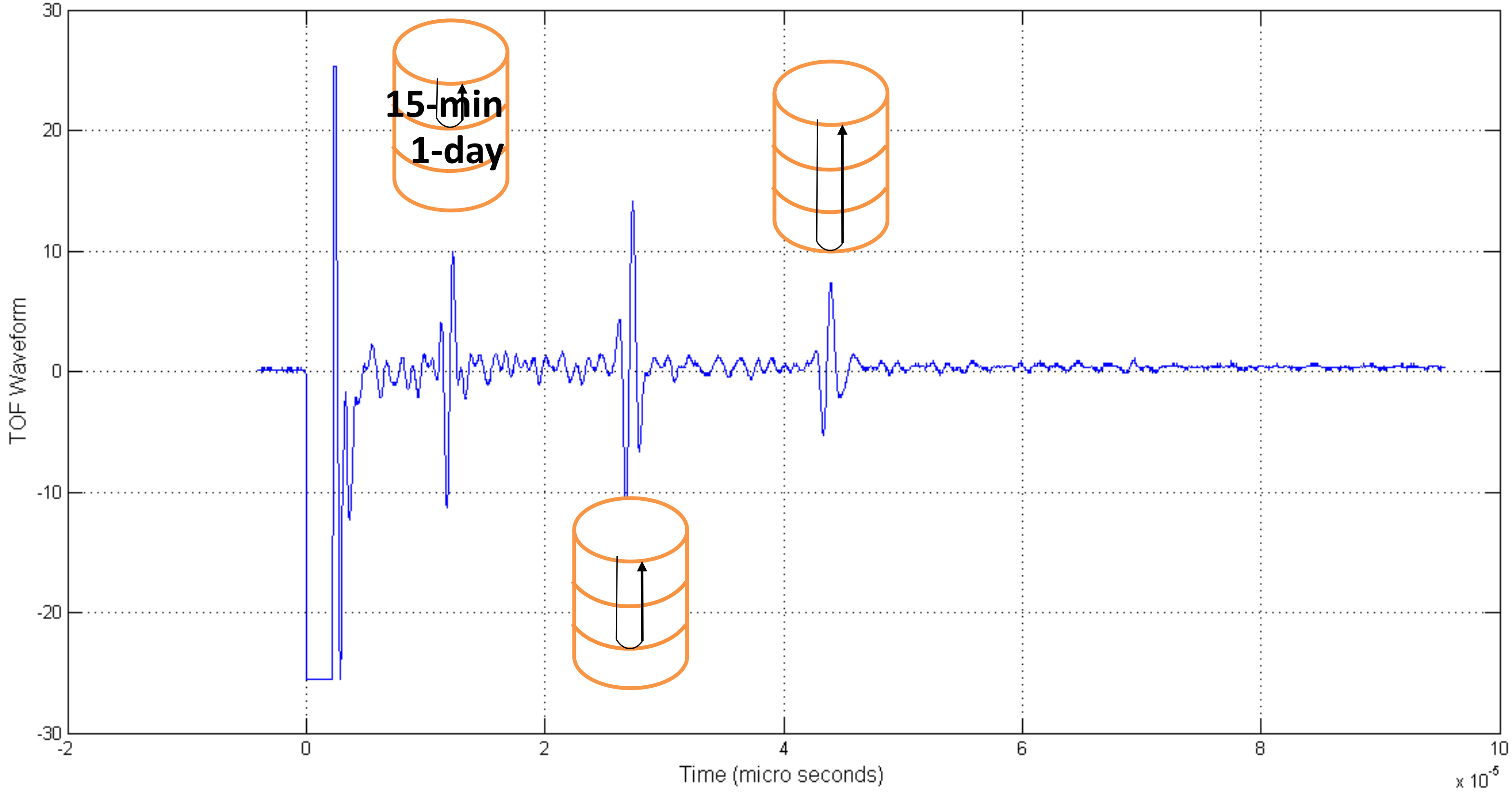


Single internal reflection



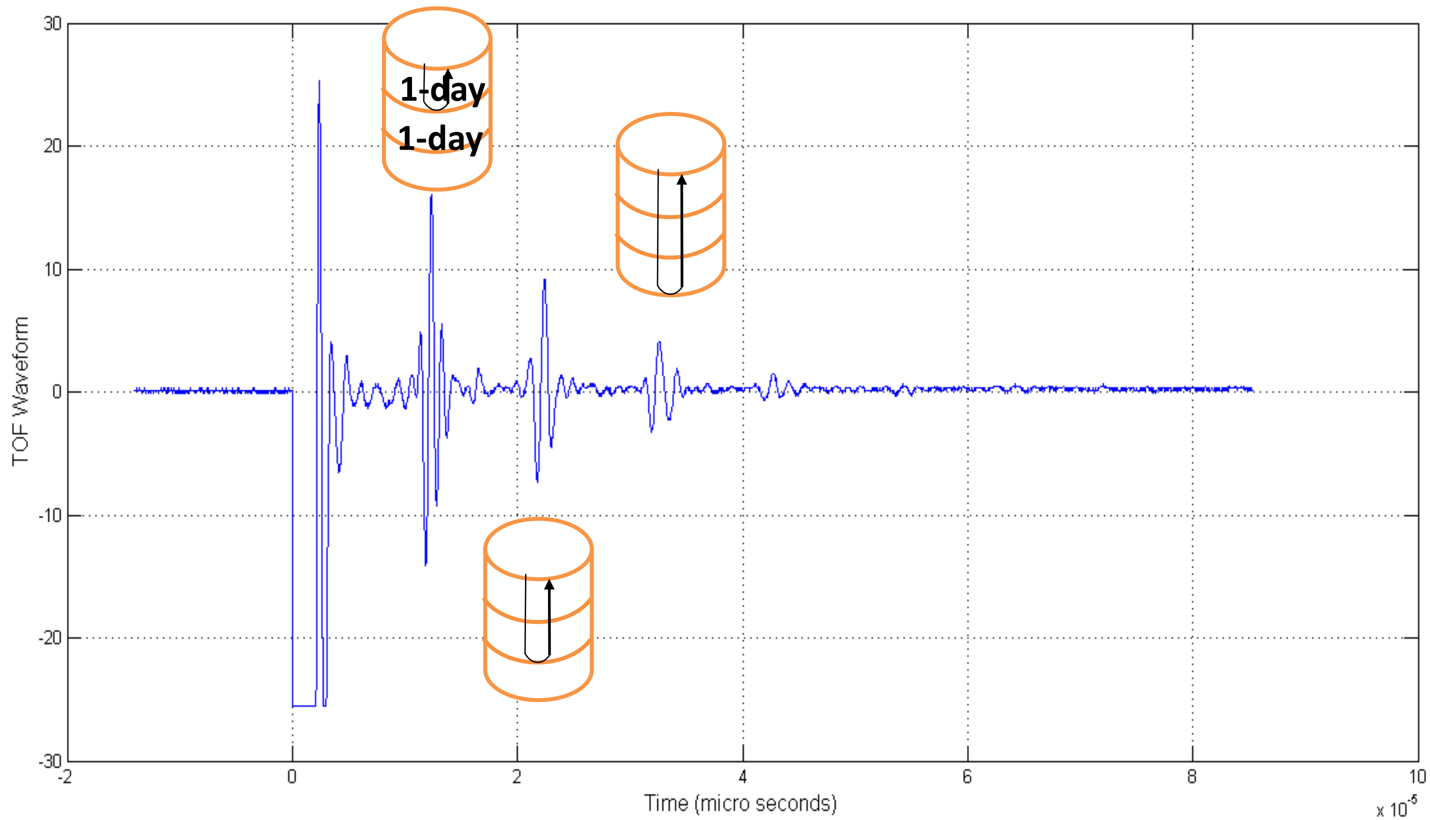
- Water/cement ratio = 0.5
- Recipe for “good” results: Cure first pour for 1 hour, then pour the second layer

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

Higher water content and longer curing result in "cleaner" internal reflection signal



- Water/cement ratio = 0.44
- Curing time 1day + 1day for this triple pour sample

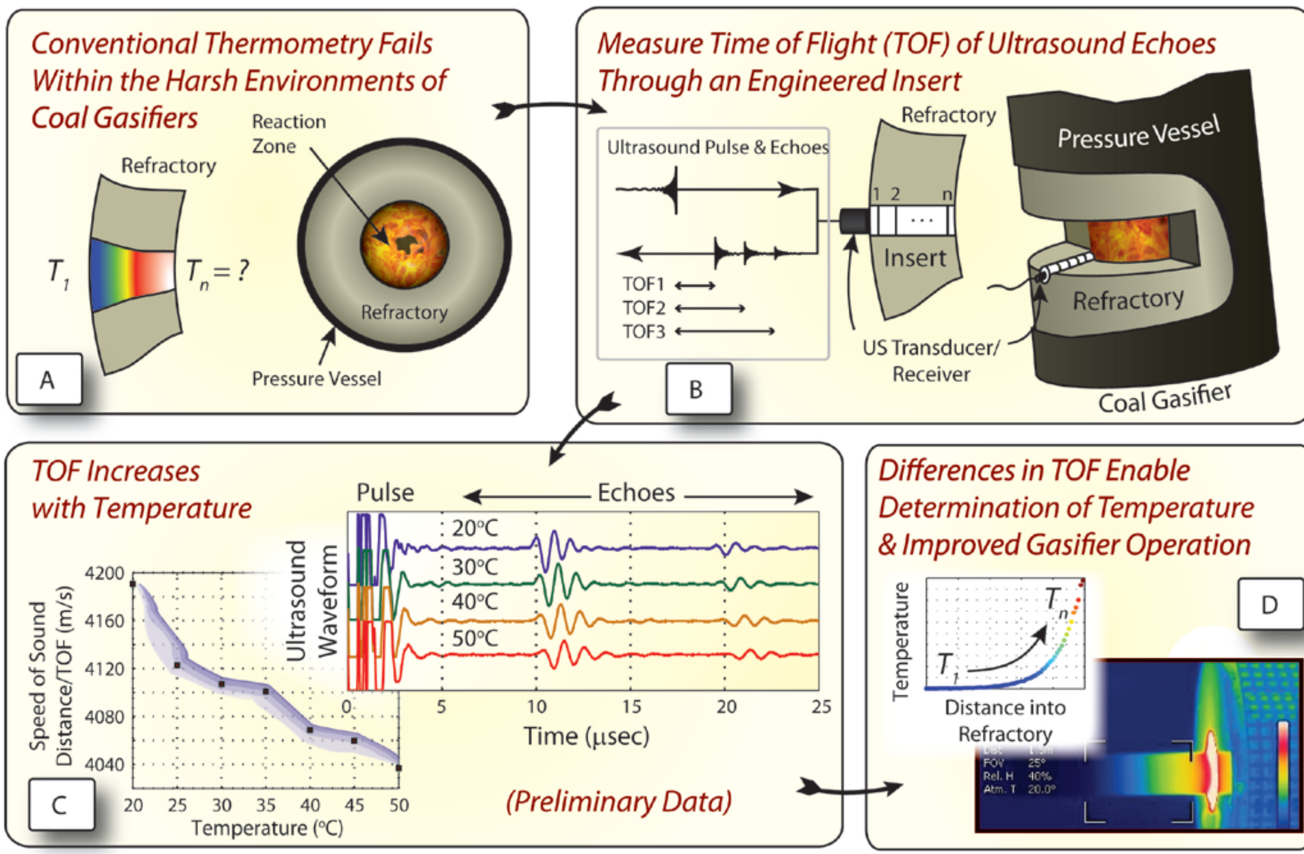
Partial internal reflections: Observations

- Water/cement ratio: 0.44 to 0.5
  - Easy to mix and place, high strength concrete
- Vibrate: Reduces air bubbles in the sample and signal degradation
- Curing time: 1 hour for strong partial reflections; No reflections if cured for less than 15 min
- Spatial resolution: We can identify internal reflections between layer ~0.7 inch apart
- Sample length: Only 4 inch cement sample with the current instrument.

Summary: Low temperature range

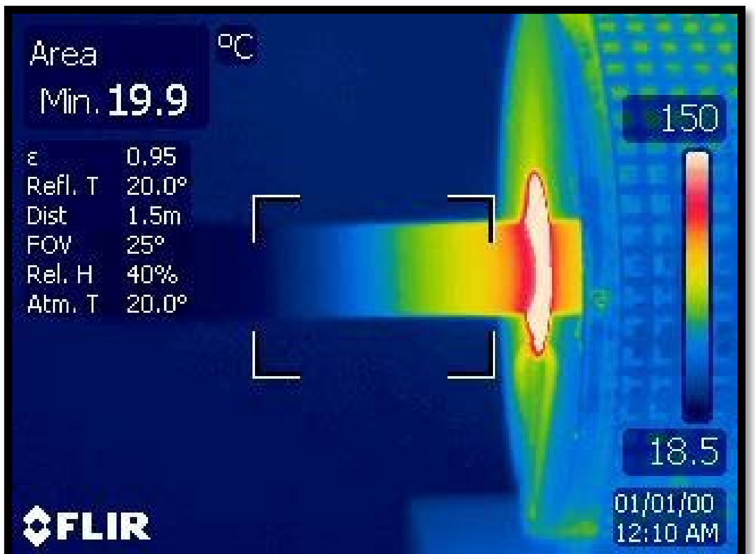
- SOS vs. T dependence is surprisingly strong. It may be possible to measure temperature with ± 1°C accuracy. The key to achieving high measurement accuracy is precise measurements of the TOF (perhaps with an accuracy of 10ns)

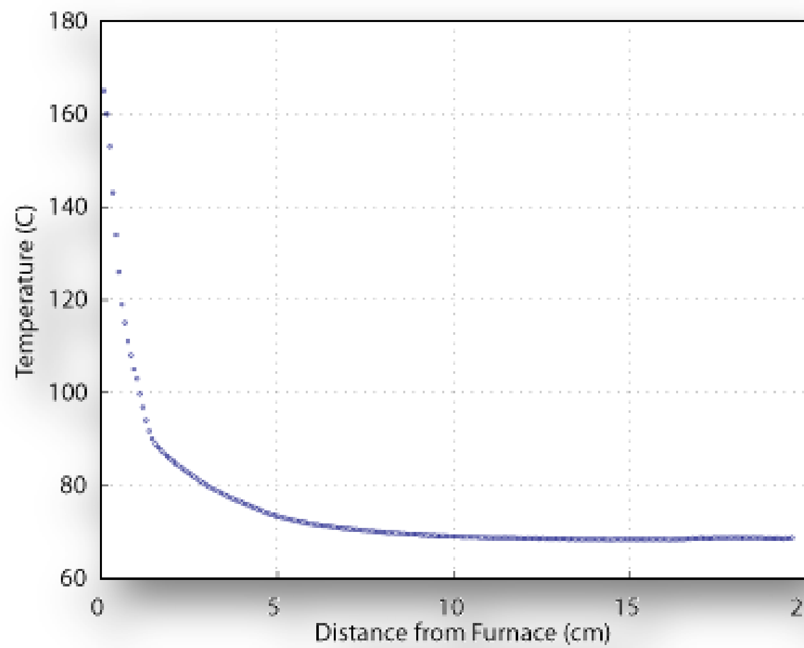
- Spatial resolution of temperature distribution measurements may be as fine as ~1 cm. Is higher resolution possible?



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

Further questions

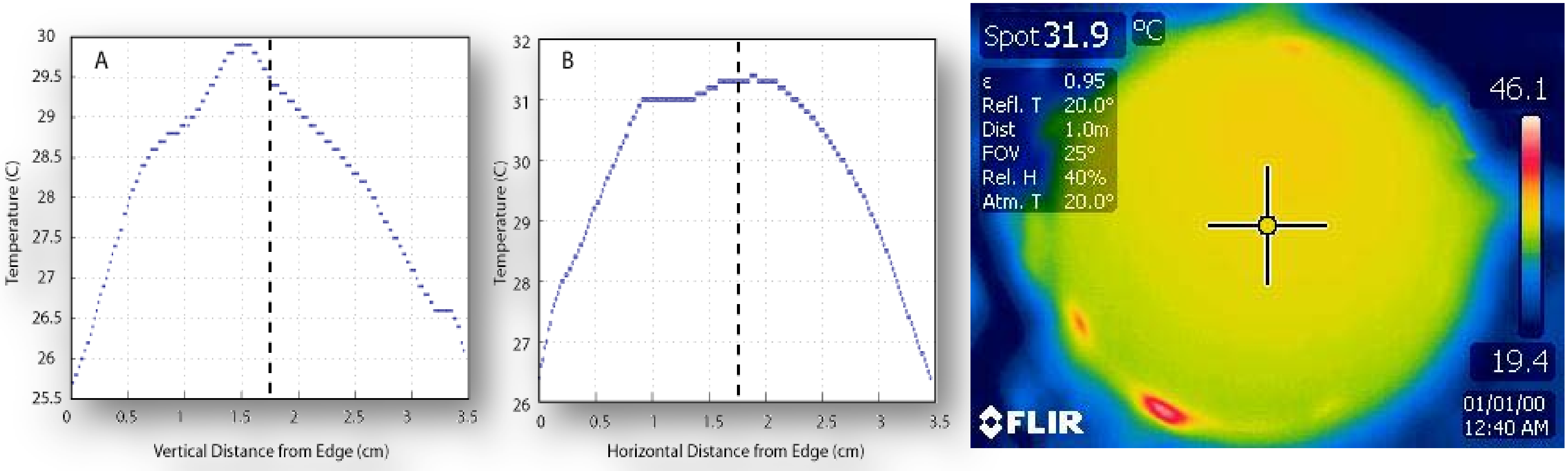
- Can changes in material properties be detected? Compare results of directly measured and the estimated temperature distribution to assess if the change in material properties. (e.g., thermal conductivity $k(r)$) can be detected.

- Can changes in refractory thickness be simultaneously measured?
  - Thickness, L, affects the TOF
  - The temperature-compensated and uncompensated measurements of L may be different

- 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.

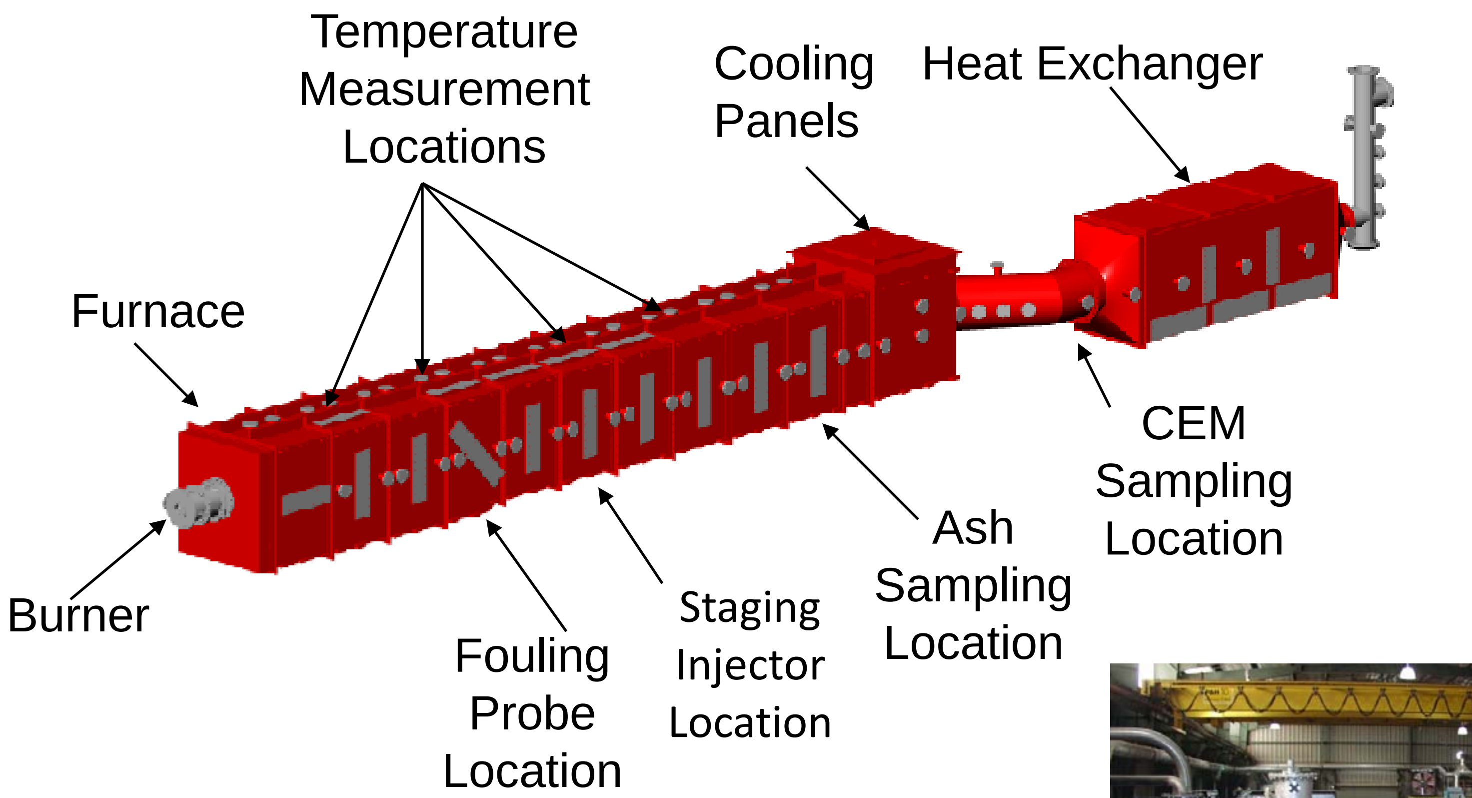
Performance at High Temperatires

- Experimentally test and quantify the developed methods in terms of their accuracy, response time, and robustness. The testing will progress from the *laboratory bench top* and furnace testing, to eventual testing in a *pilot-scale coal combustor*. Our ultimate goal is to test these methods in the pilot scale coal gasifier.

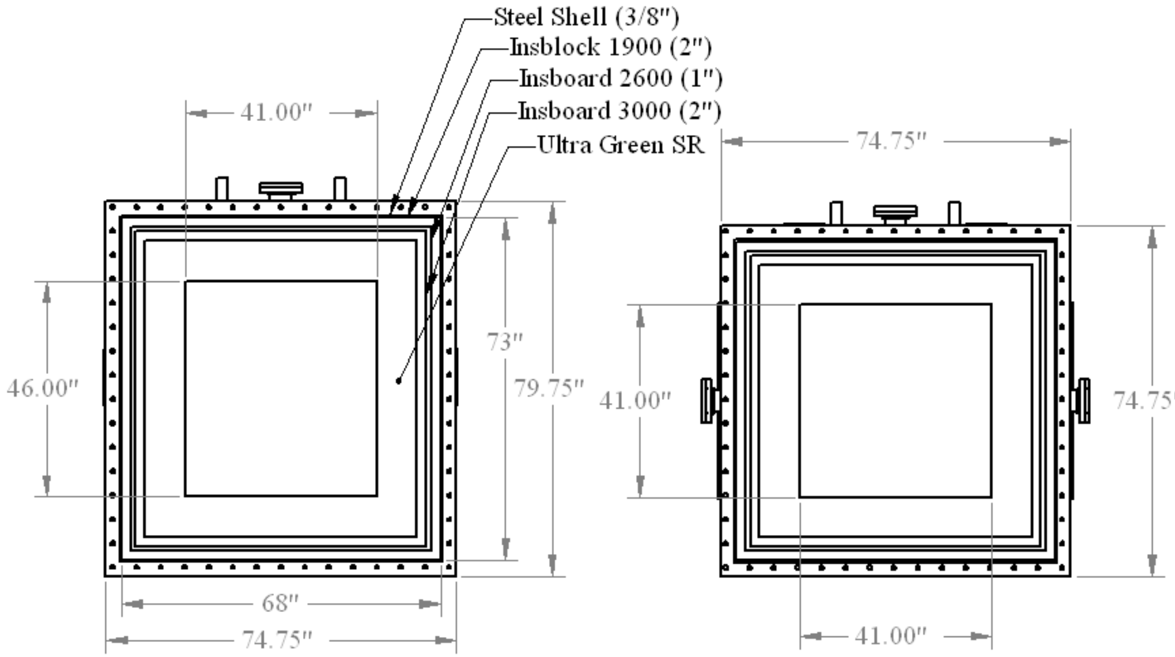


Thermal imaging suggests that heating inside laboratory oven is axially symmetric.

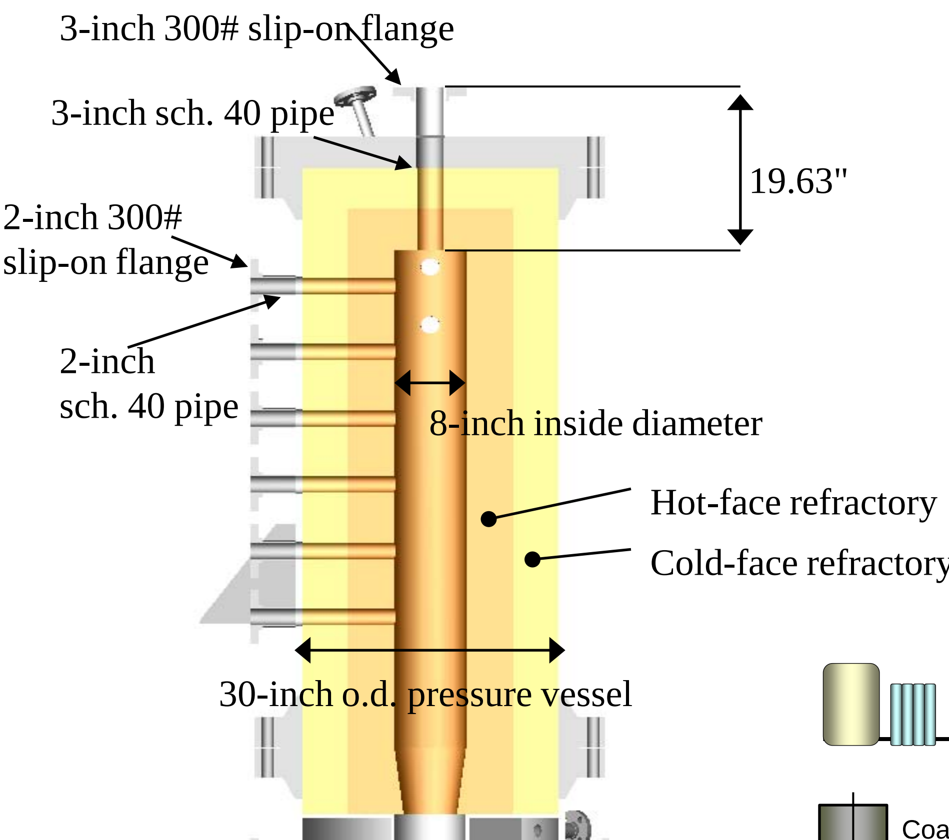
Pilot Scale Testing:
L1500 1.5 MW_{th} Coal Combustor

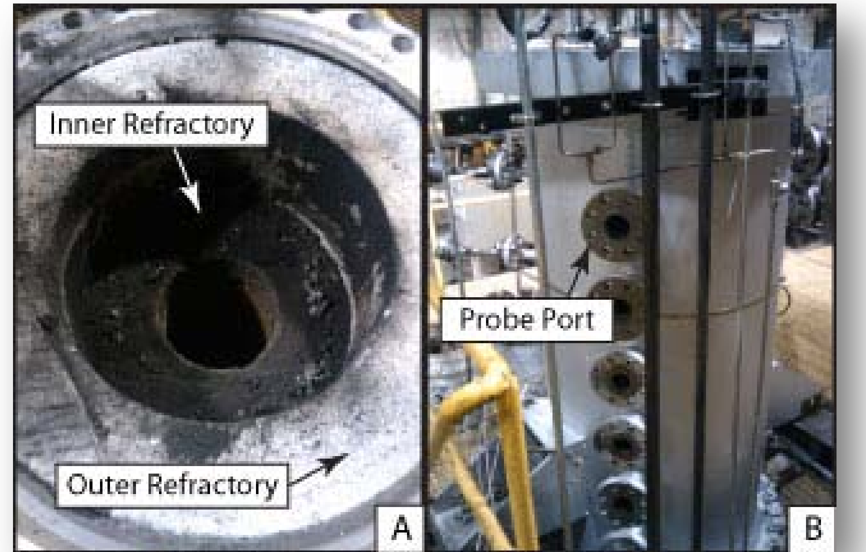


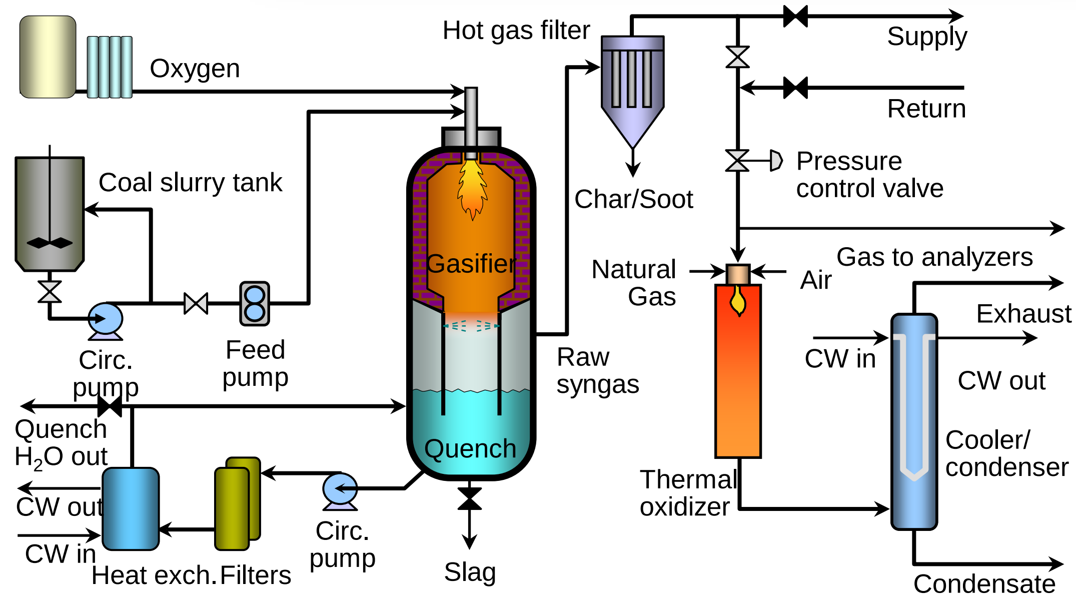
Furnace Cross-section



Pilot-scale Entrained Flow Gasifier



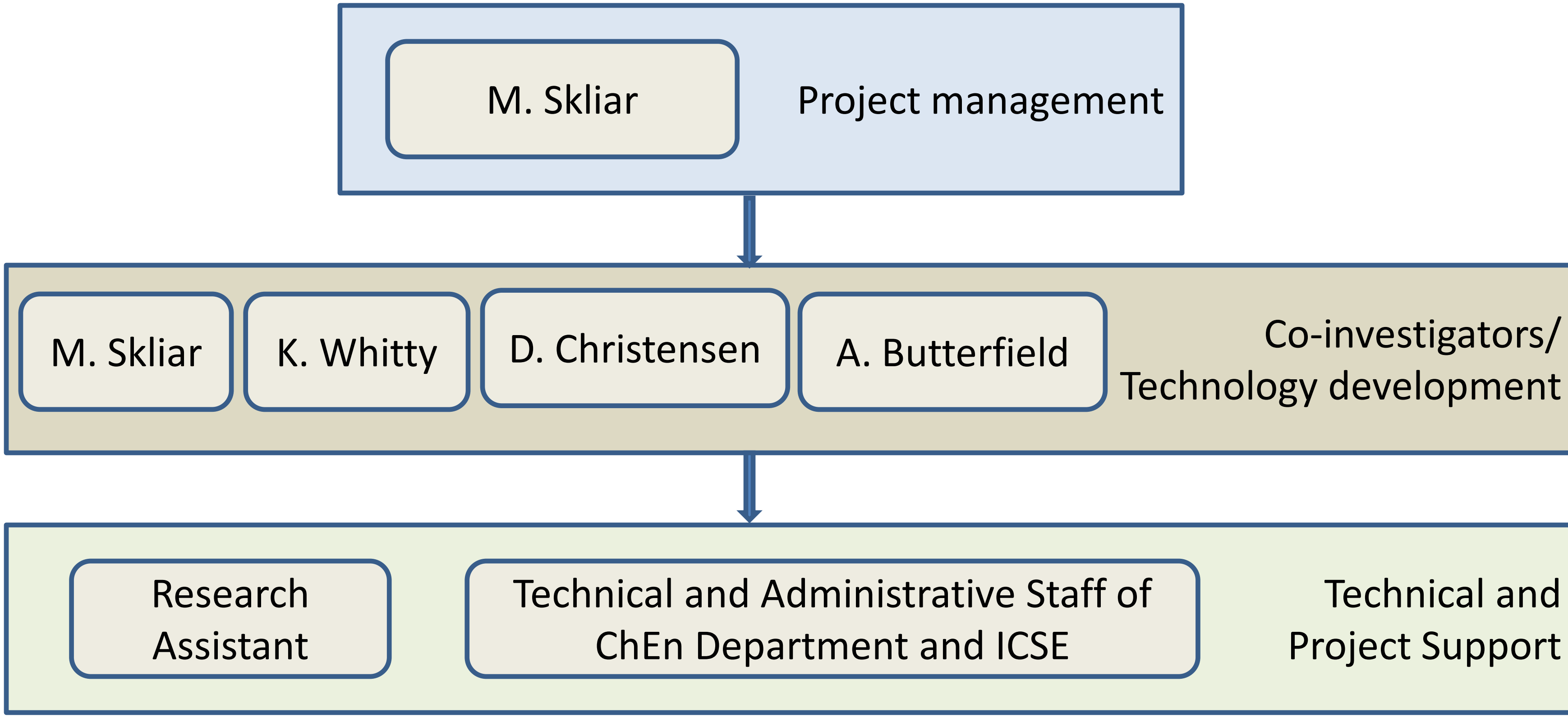




Tasks and Schedule

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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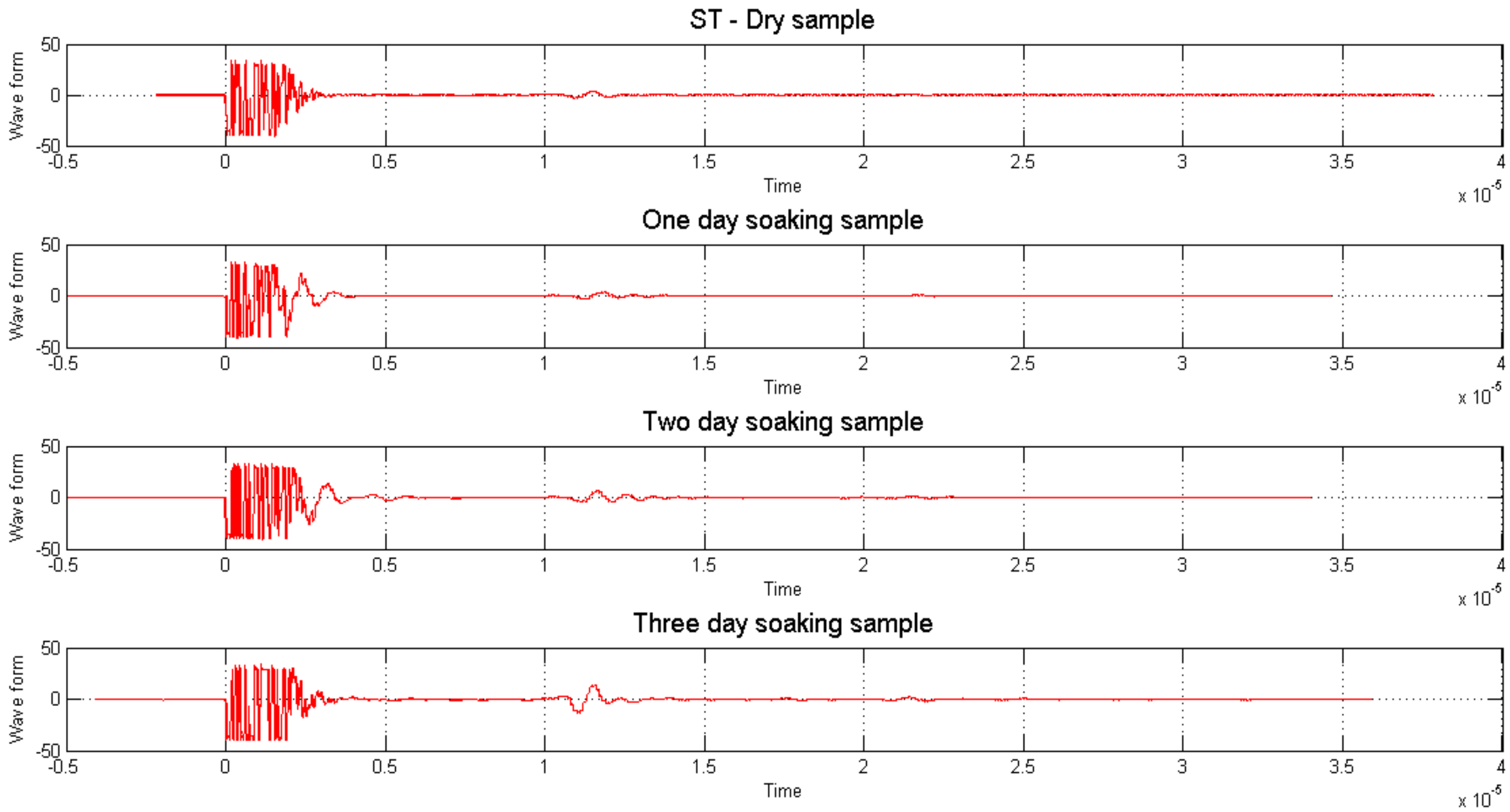
Dry vs. Saturated Samples

- Saturated samples produce stronger response
- TOF appears to be unaffected by the saturation



Preliminary transmission results