CARBON CAPTURE
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Density, Porosity, and Heat Capacity Characteristics of Ash Deposits from a 1.5 MW Coal Furnace

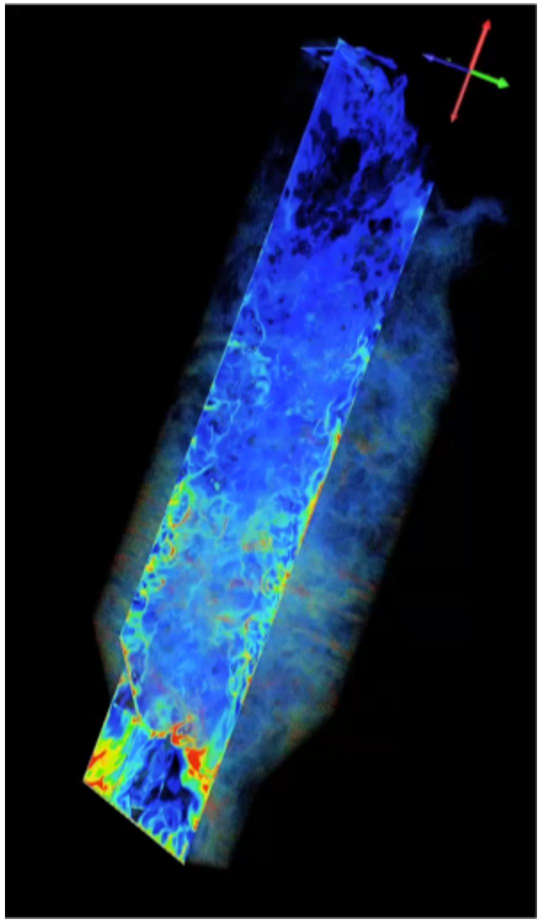
Oxyfuel Technologies I

The 41st International Technical Conference on Clean Coal & Fuel Systems

Lauren Kolczynski, Andrew Fry, Teri Draper, Terry Ring and Eric Eddings

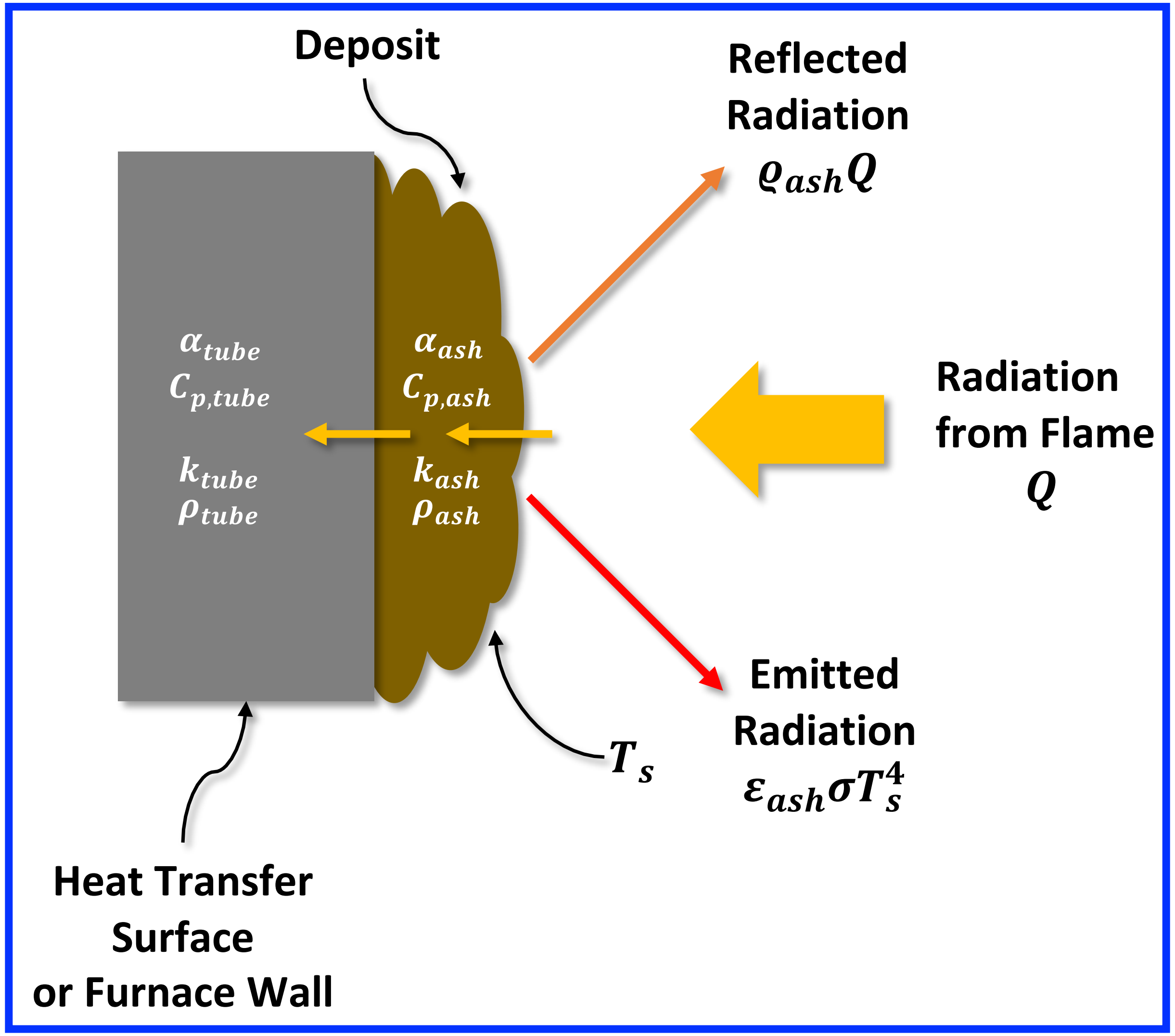
Department of Chemical Engineering, University of Utah

Introduction



- Carbon-Capture Multidisciplinary Simulation Center
- Simulations of oxy-coal boilers
- Model uncertainty reduced and characterized through **experimental** validation and verification/uncertainty quantification (V&V/UQ)
- Vary, compare, and contrast experiment and analysis techniques to capture uncertainty and error

Heat Transfer



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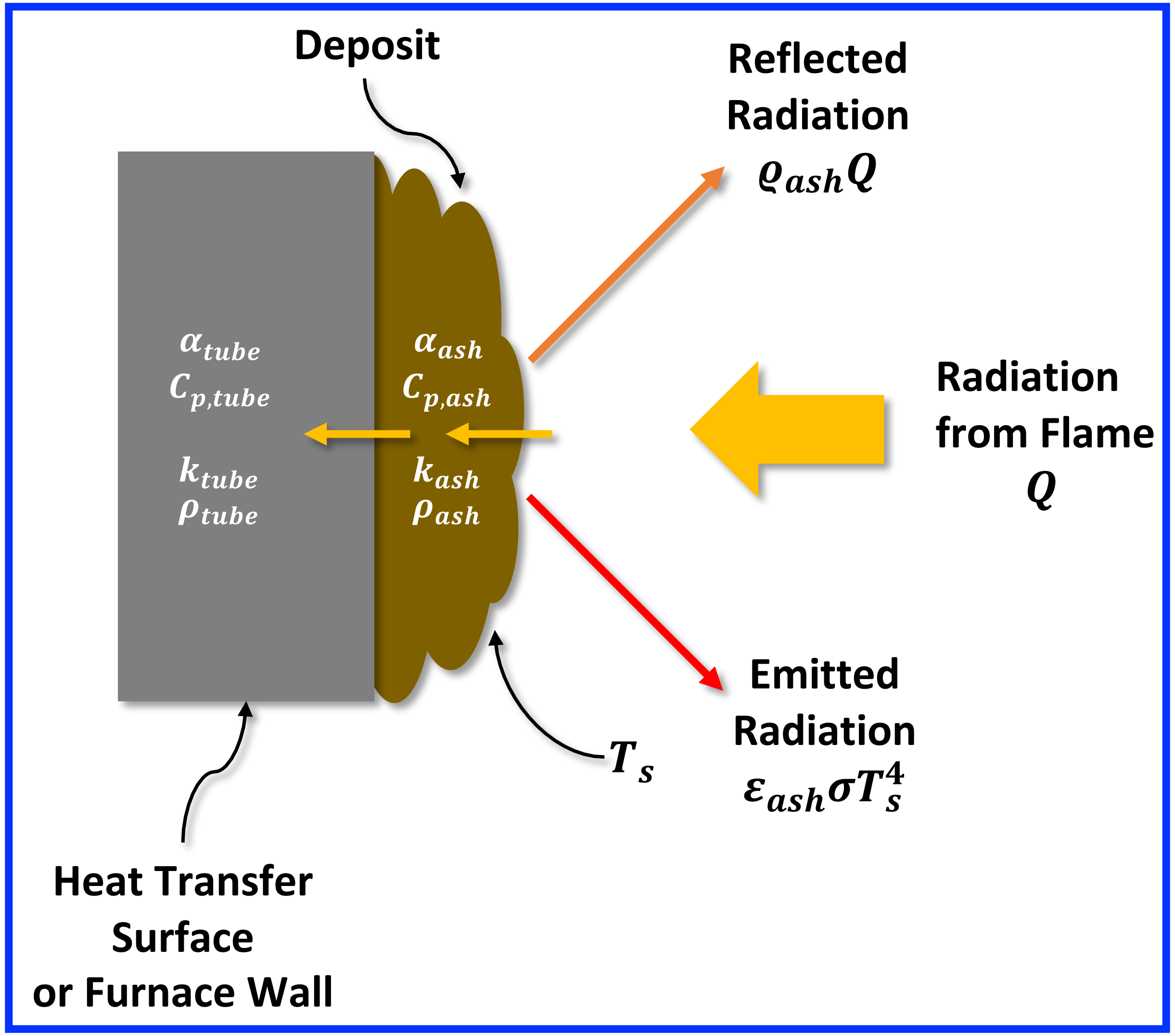

$\varrho =$ reflectivity

$\varepsilon =$ emissivity

$k =$ thermal conductivity

$\alpha =$ thermal diffusivity

$\rho =$ density

$C_p =$ heat capacity

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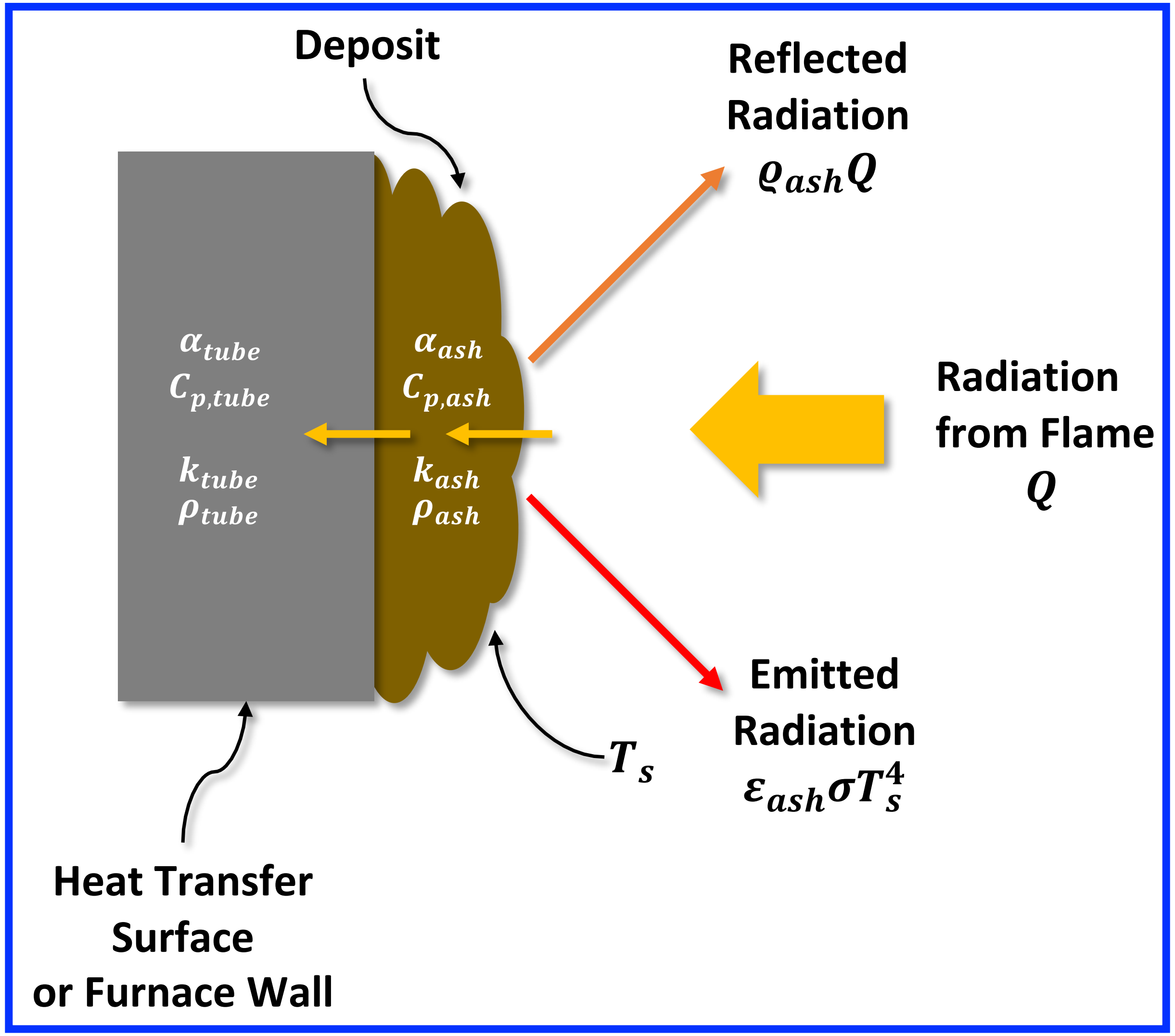

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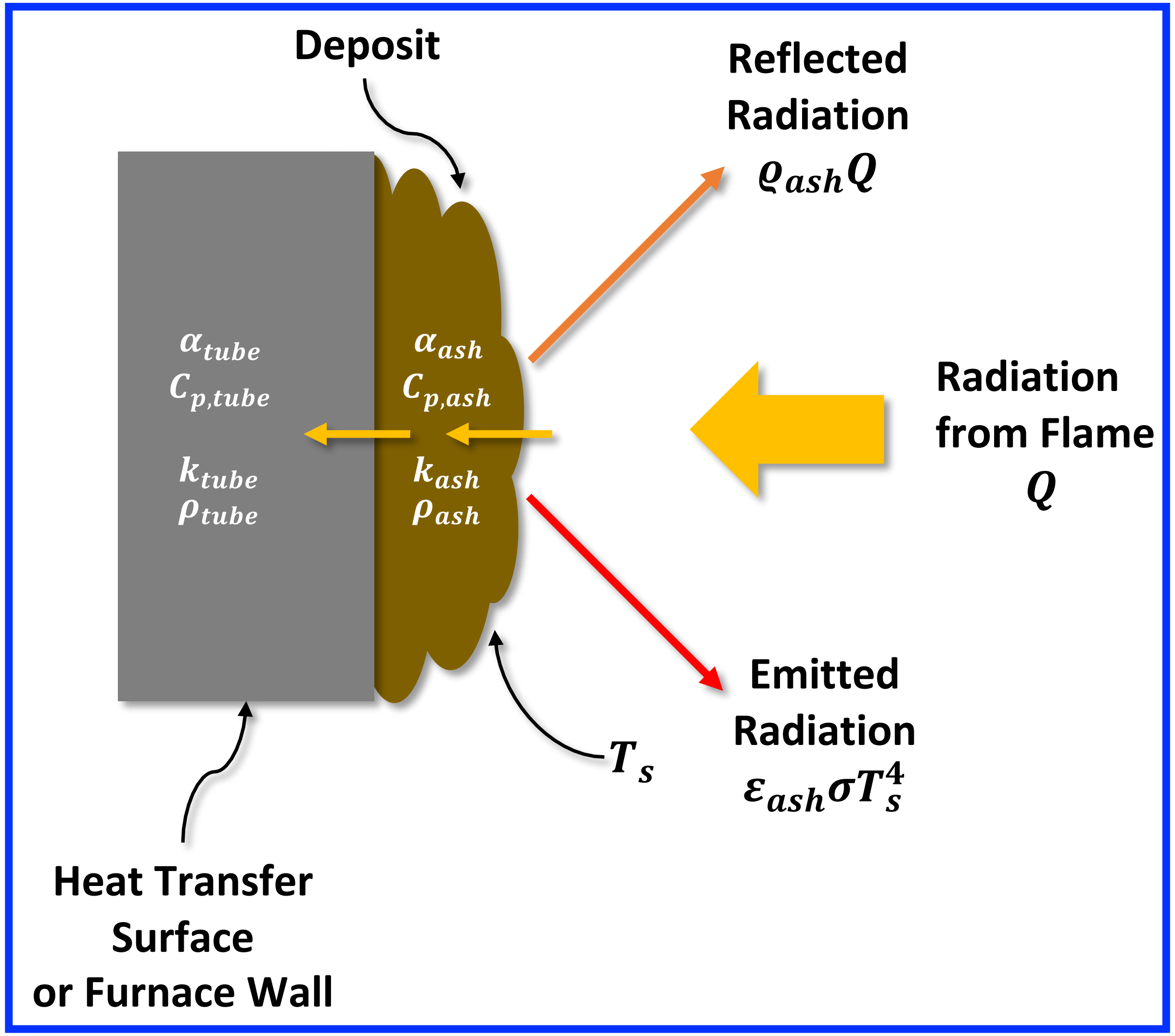
Tube/Wall

Characterized at high temperature

Heat Transfer



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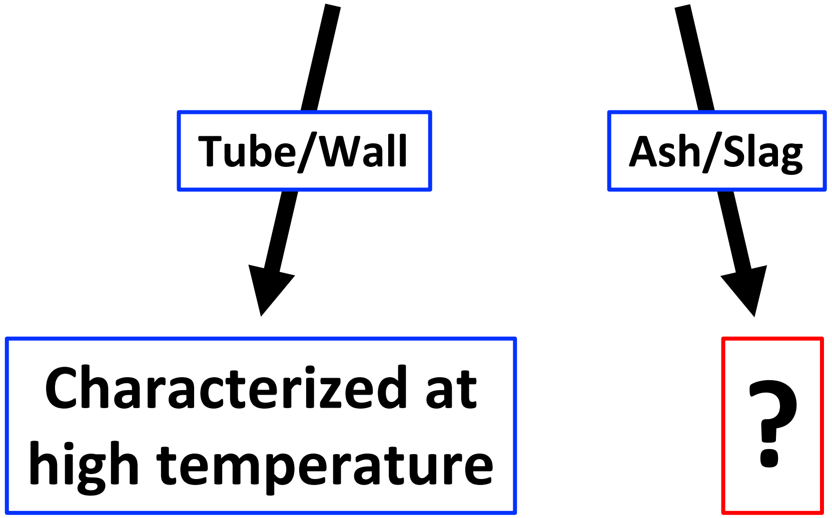

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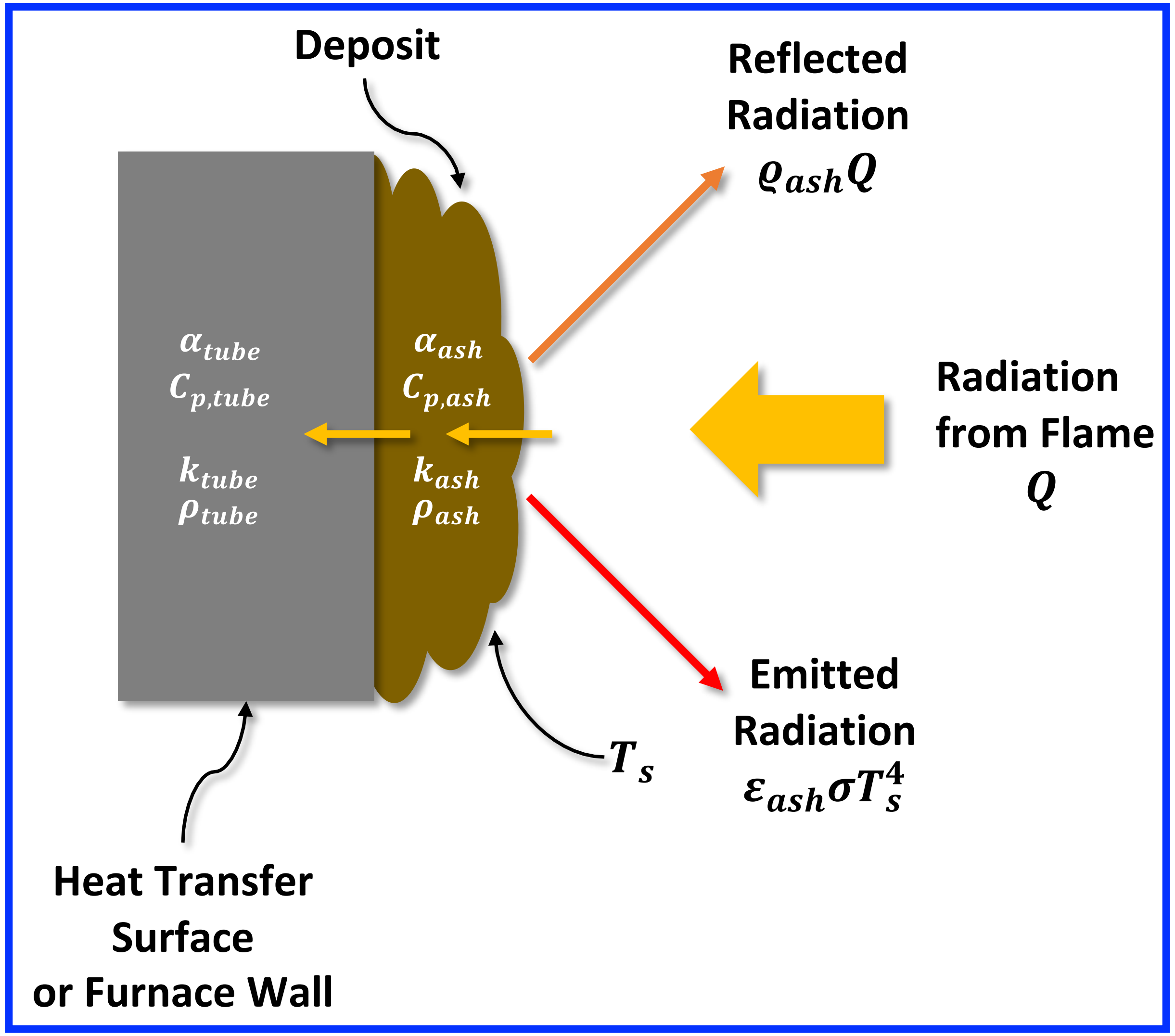
Heat Transfer



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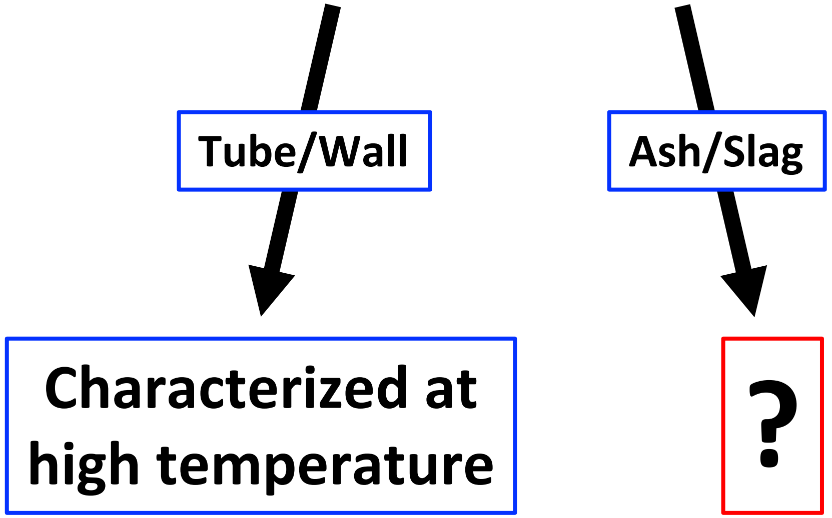

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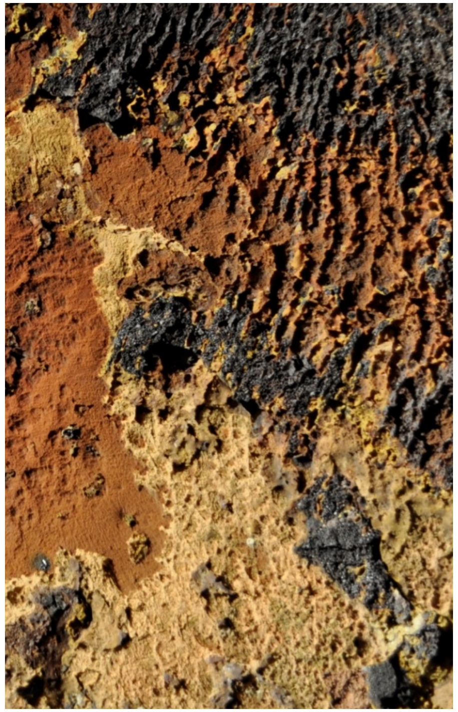
Deposits

- Highly variable
- Emissivity
  - Previous study with room temperature FTIR
- Thermal Conductivity
  - $\alpha = \frac{k}{\rho C_p}$
  - $k = \rho \alpha C_p$
  - Temperature dependence



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Experimental Design

- Industrial Combustion And Gasification Research Facility
- L-1500 Multifuel Furnace
  - 1.1m by 1.1m internal cross-section
  - 13.1m in length
- February 2015 oxy-coal campaign
  - Utah Sufco coal
  - Firing rate ~1.0 MW (3.5 MBtu/hr)
  - Coal feed rate: ~135 kg/hr (297 lb/hr)
  - Avg. excess oxygen ~3%
  - Exhaust CO_2 ~86-88%
  - Surface temperature (ceiling): ~1052 ˚C (1925 ˚F)

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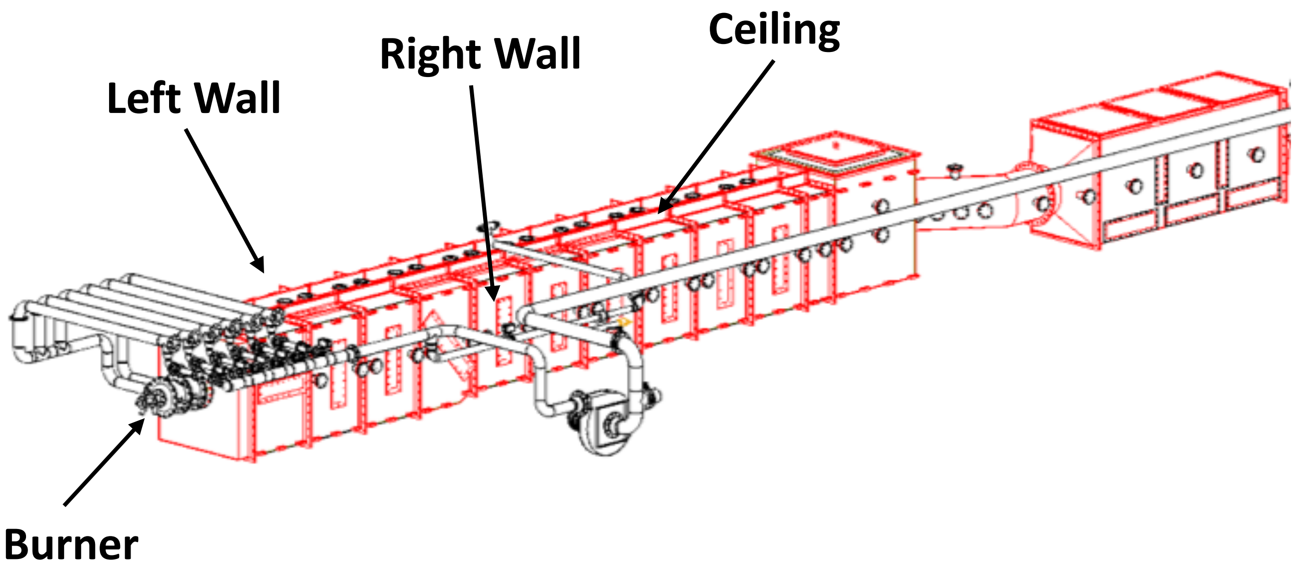
Experimental Design



- ~400 total sampling sights throughout the furnace in a 1 ft x 1 ft grid
  - Surfaces: left wall, ceiling, & right wall

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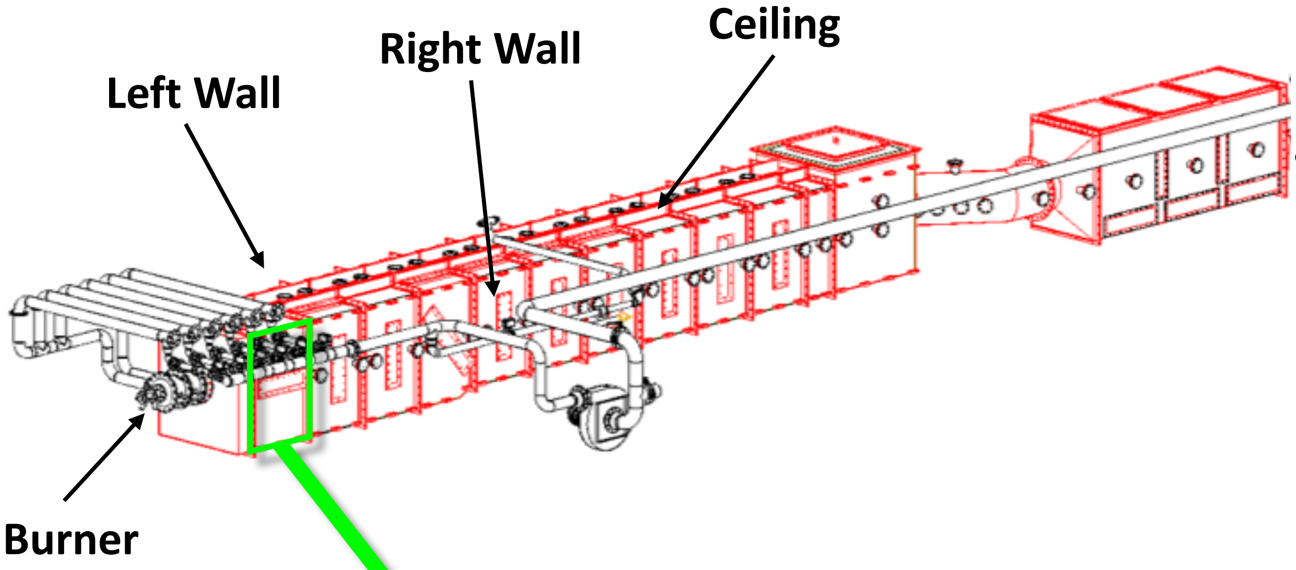
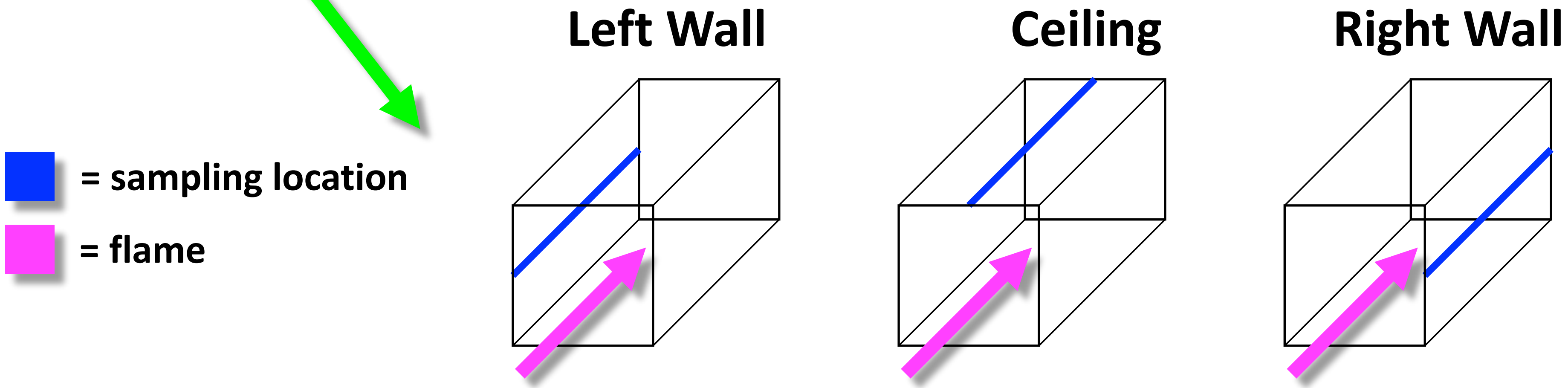
Experimental Design



- ~400 total sampling sights throughout the furnace in a 1 ft x 1 ft grid
  - Surfaces: left wall, ceiling, & right wall
- Twelve sampling sights chosen for a preliminary study
  - Location: midline of each surface
  - Depth: 1, 2, 3, and 4 feet from burner on each surface
  - Highly radiative section of the furnace



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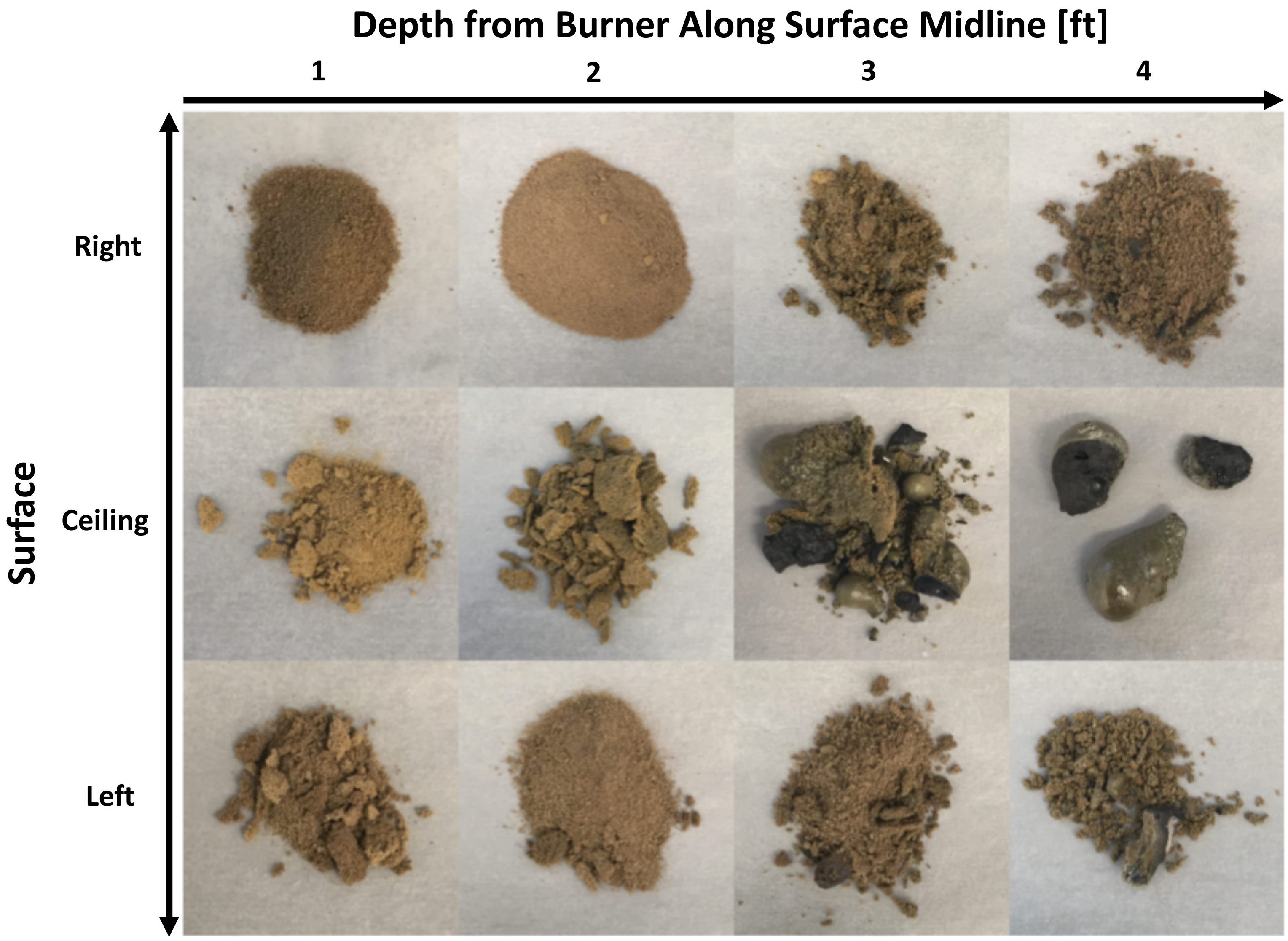
Samples



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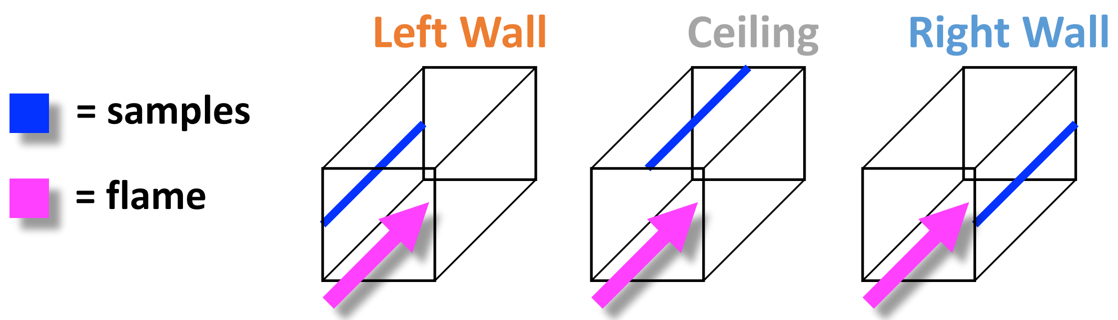
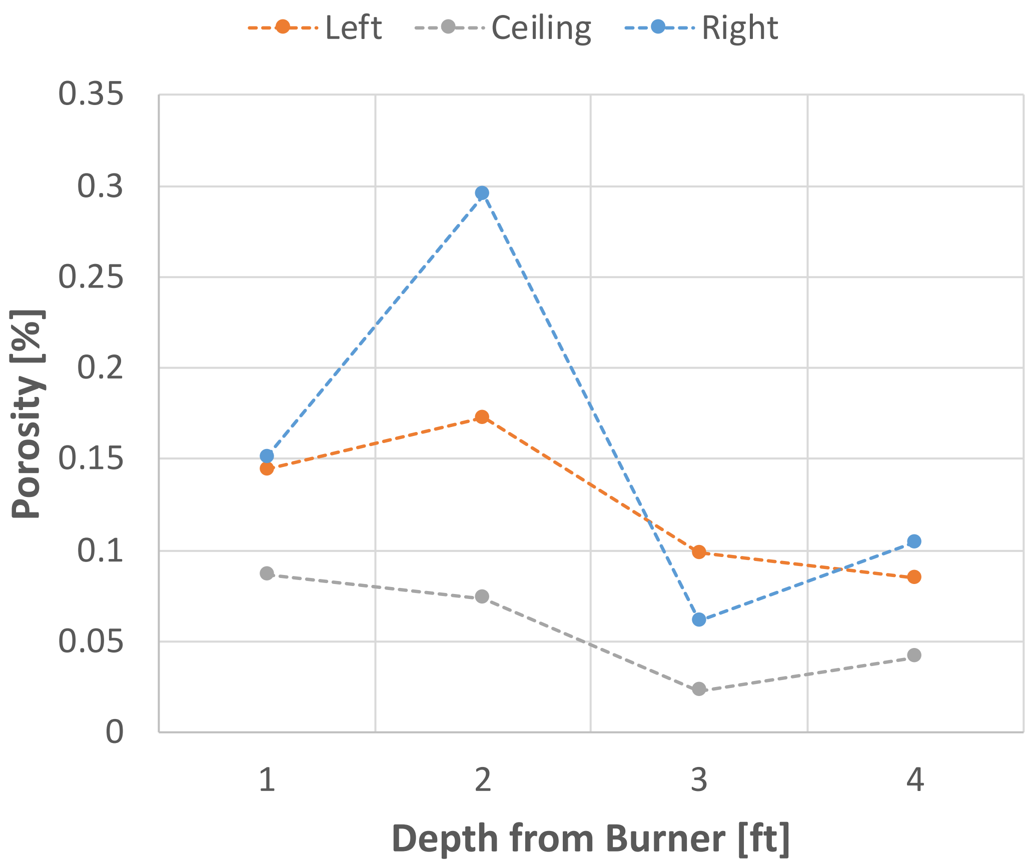
Porosity

- Porosity
- $\phi = \frac{V_{pores}}{V_{solid}+V_{pores}} \times 100\%$
- Total pore volume
  - BET analysis
- Total solid volume
  - Pycnometry
- Very low for all three surfaces
- Porosity does not appear to be a strong function of depth for the first four feet of the furnace
- Slightly higher in the left and right walls than in the ceiling





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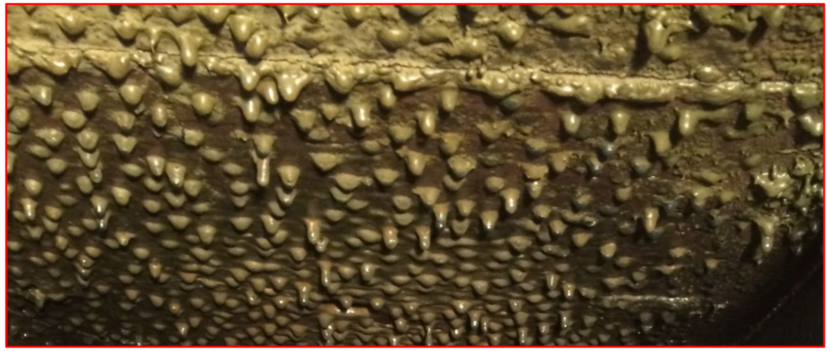
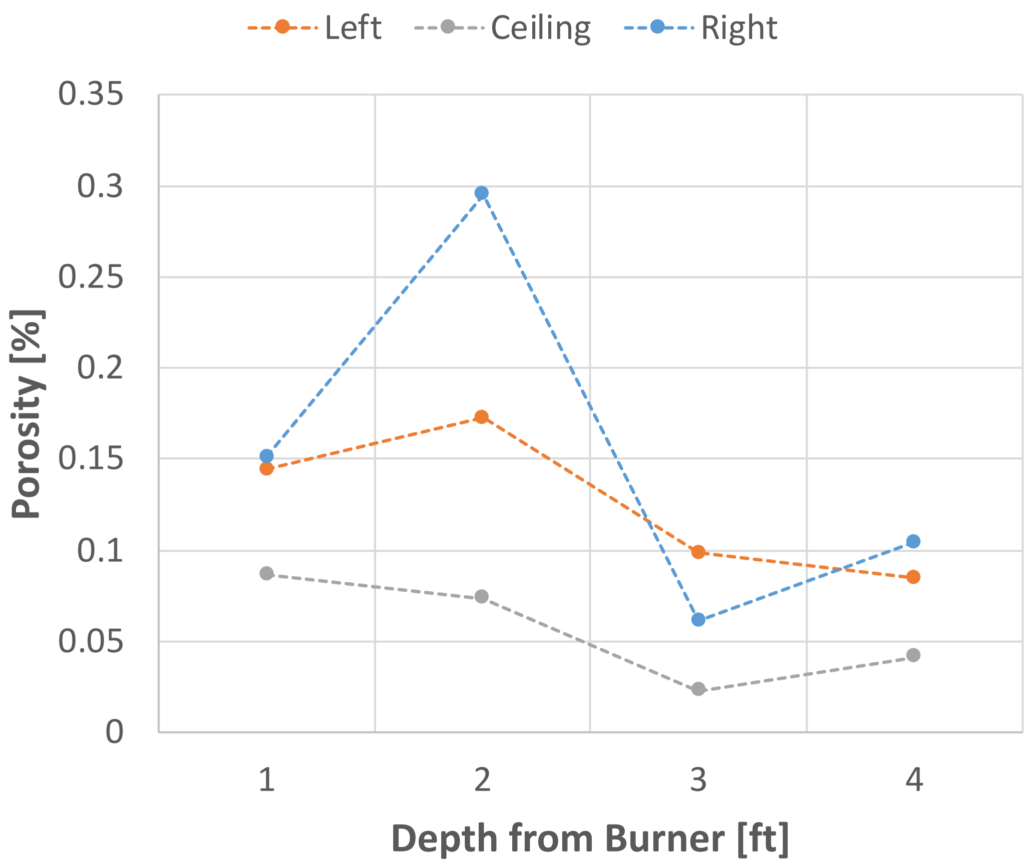
- Porosity does not appear to be a strong function of depth for the first four feet of the furnace
- Slightly higher in the left and right walls than in the ceiling
  - Ceiling deposits molten during operation





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Thermal Conductivity - Method

- Measurements of α, ρ, and C_p for deposit samples
- Higher temperature regimes when available (α, C_p)

$$\boldsymbol{k_{eff} = \rho_{meas} \alpha_{meas} Cp_{meas}}$$

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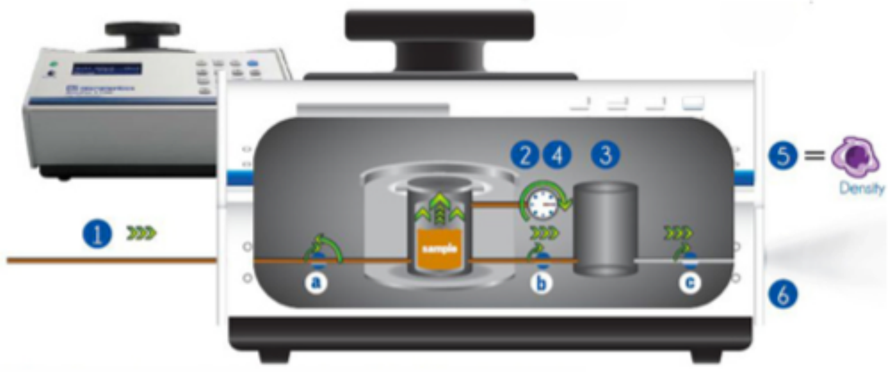

Automatic Helium Gas Pycnometry

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Automatic Helium Gas Pycnometry

IR Camera Thermal Image Processing

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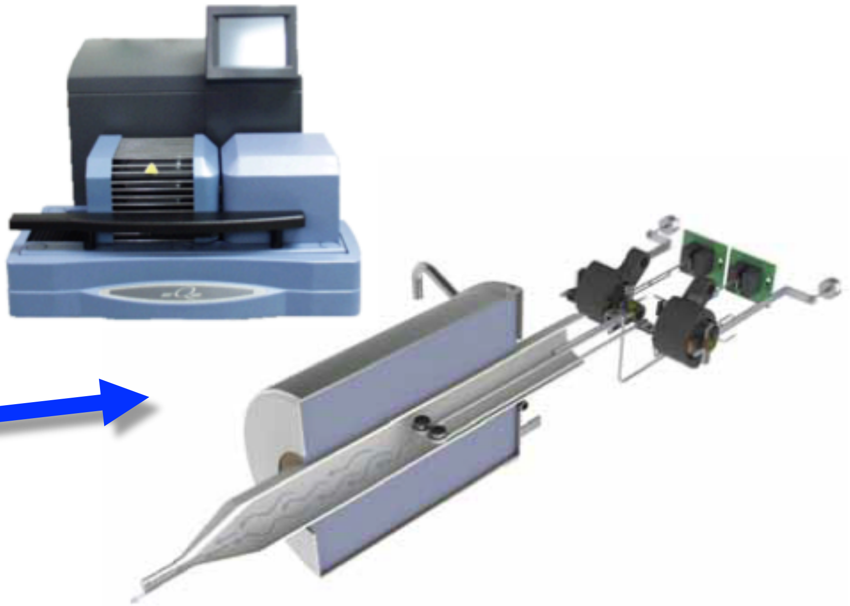
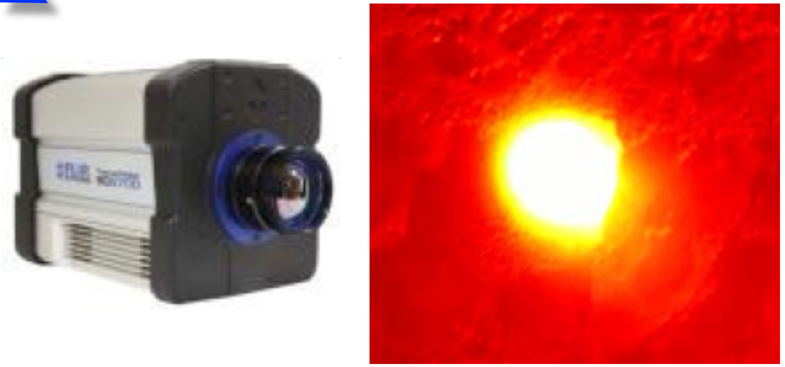


Differential Scanning Calorimetry

Automatic Helium Gas Pycnometry



IR Camera Thermal Image Processing

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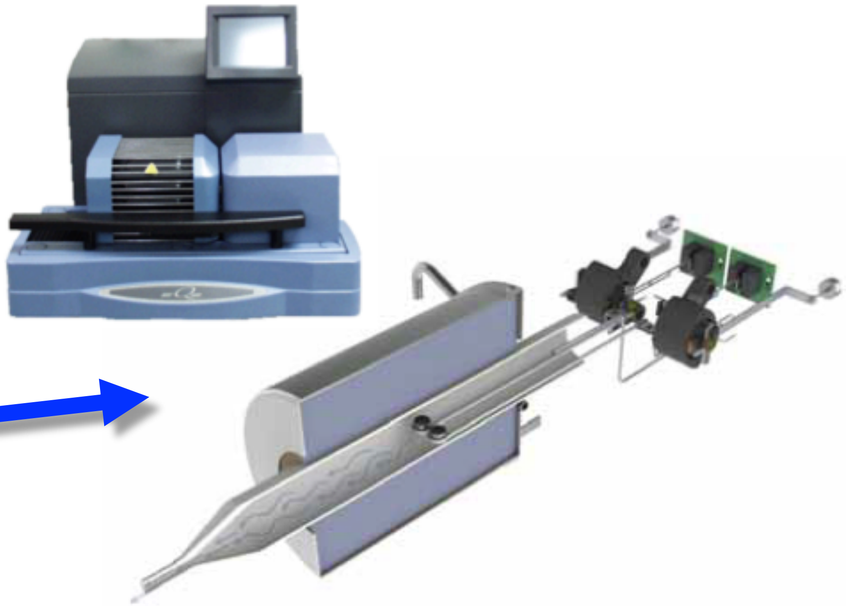

Differential Scanning Calorimetry

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IR Camera Thermal Image Processing

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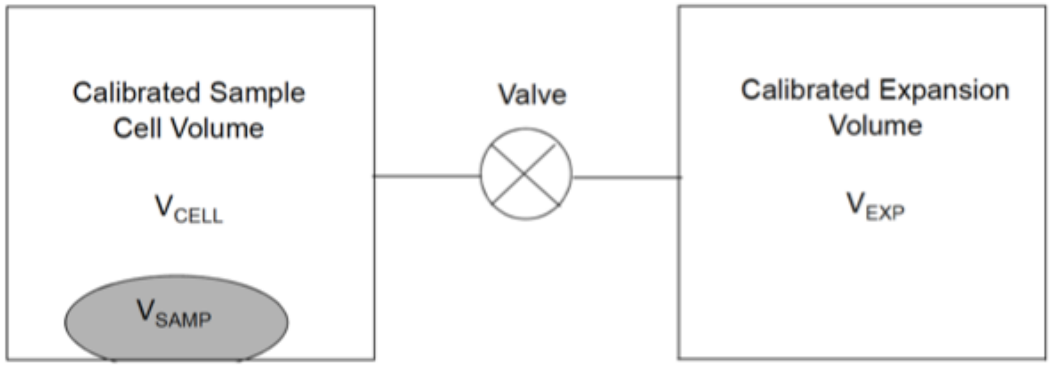
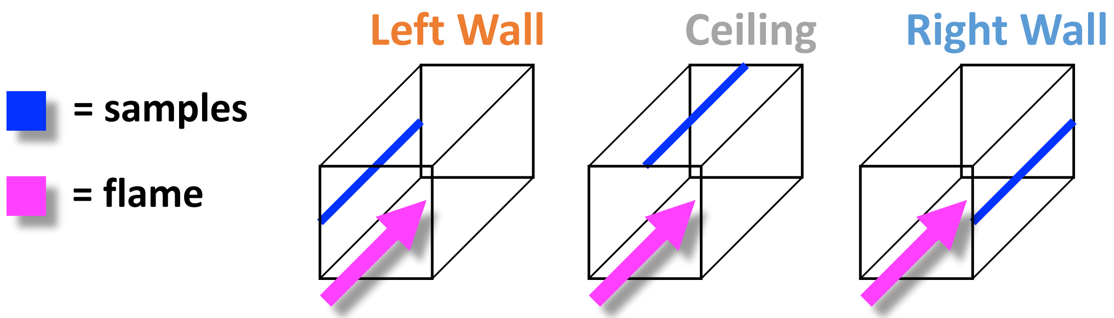
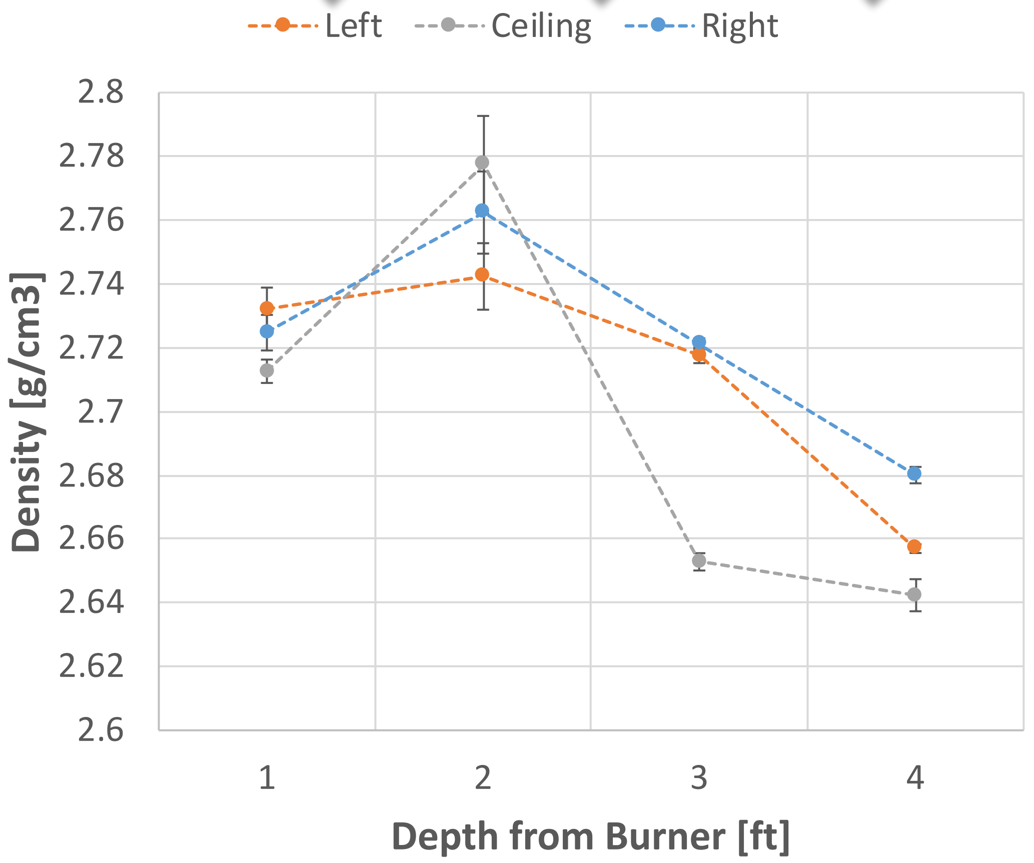
Solid Density



- Pycnometry
- $V_{samp} = V_{cell} - \frac{V_{exp}}{\frac{P_{1g}}{P_{2g}} - 1}$
- $\rho = \frac{m}{V}$
- Direct measurement of true (skeletal) density of samples
- Three replicates to capture instrument run error
    - 2 x Std. Dev.





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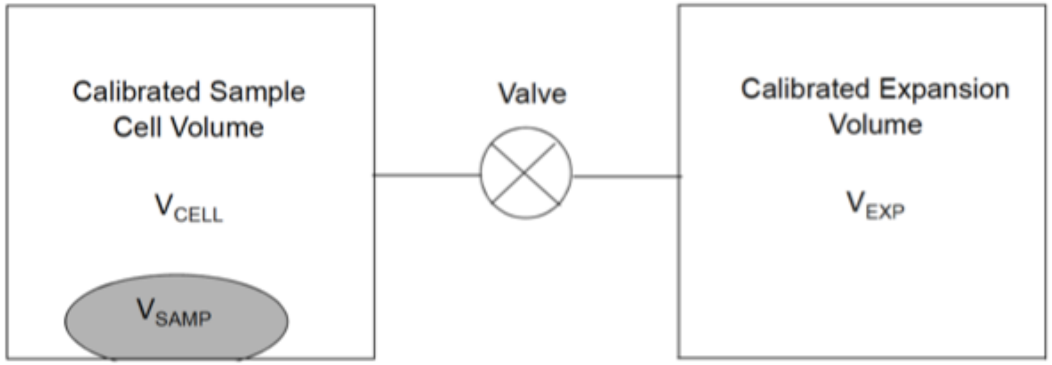

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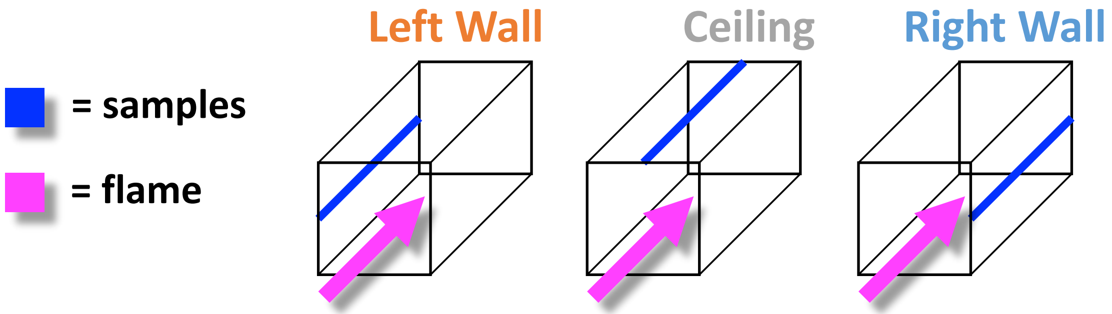
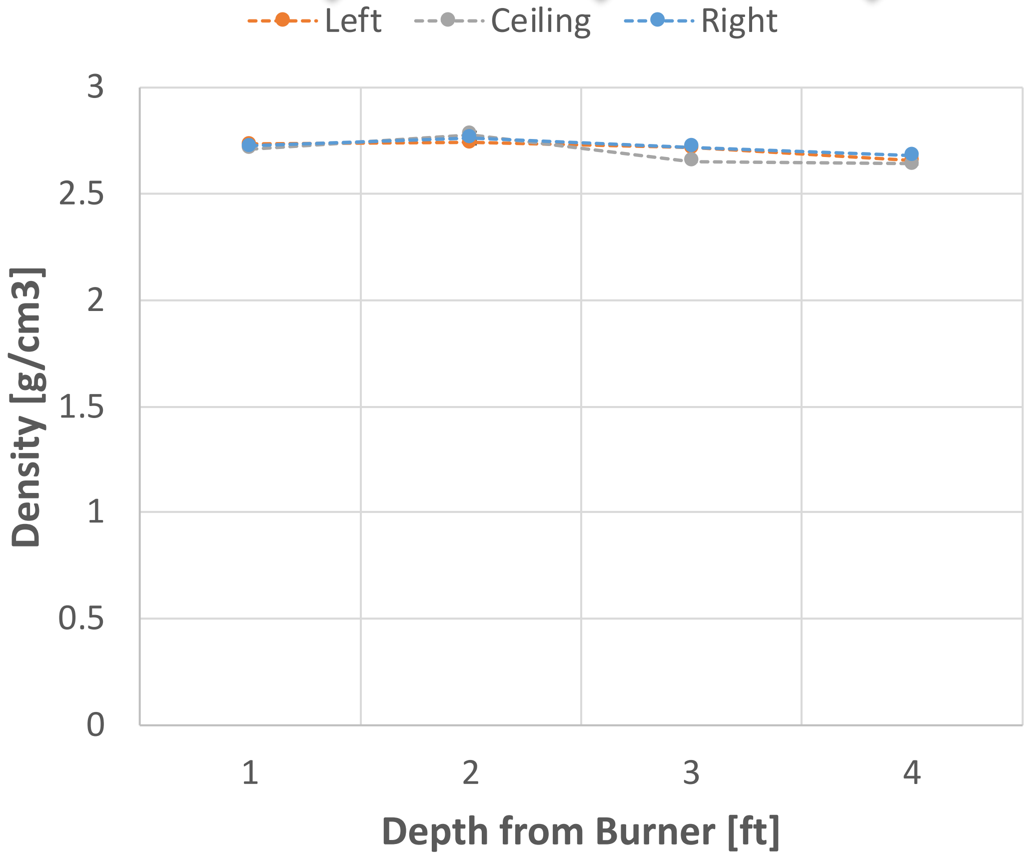
- Three replicates to capture instrument run error
  - 2 x Std. Dev.
- Density does not appear to be a strong function of depth for the first four feet of the furnace





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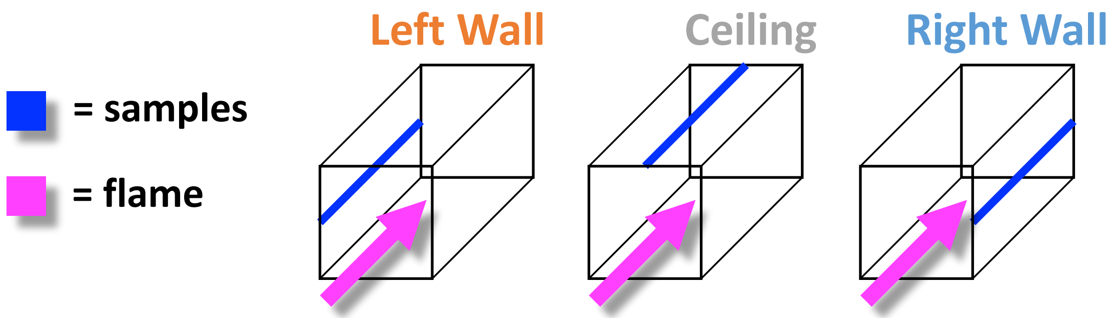
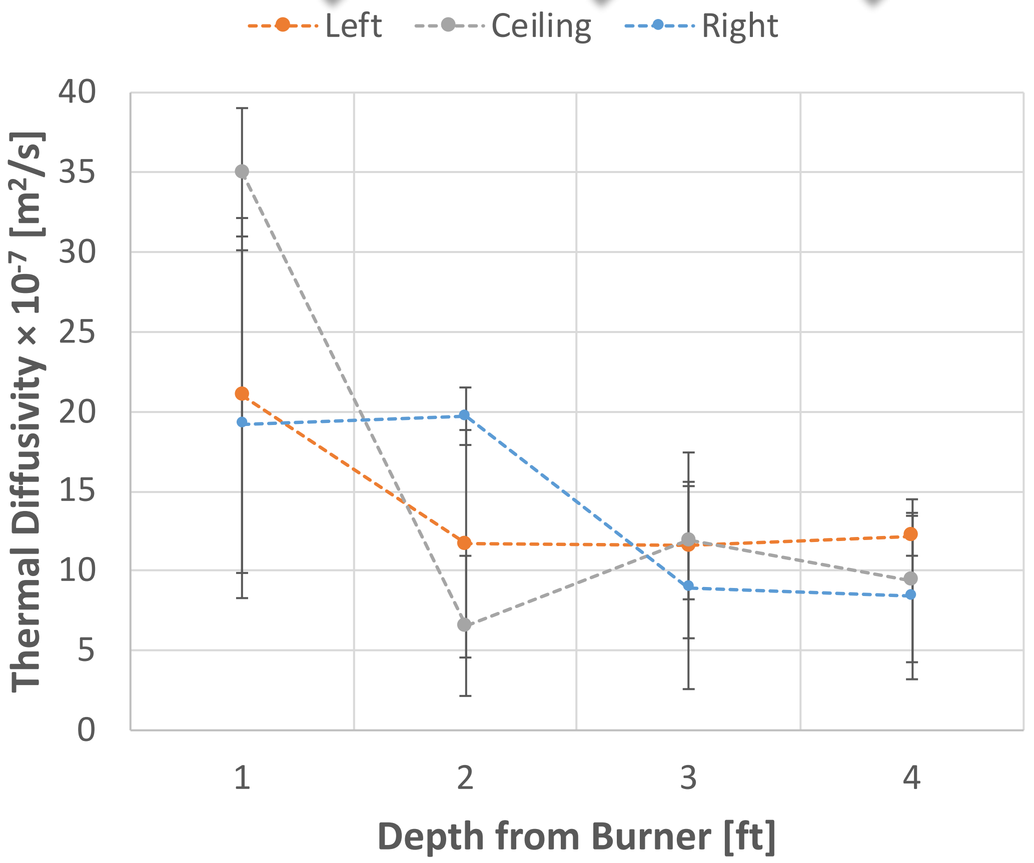
Thermal Diffusivity

- Thermal diffusivity determined in previous work using novel technique
- Surfaces covered in deposit were heated using an oxy-acetylene torch
- Infrared camera video was taken of the heated area
- Diminishing area of the heat was tracked with MATLAB using a threshold value
- Two-dimensional radius used to approximate hemispherical volume of dissipating heat
- The slope of the heat volume versus time was compared to a COMSOL simulation of pure refractory and related to yield the thermal diffusivity.
- Three replicates to capture measurement error
  - 1 x Std. Dev.
- Thermal diffusivity does not appear to be a function of depth for the first four feet of the furnace





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Courtesy Teri Draper

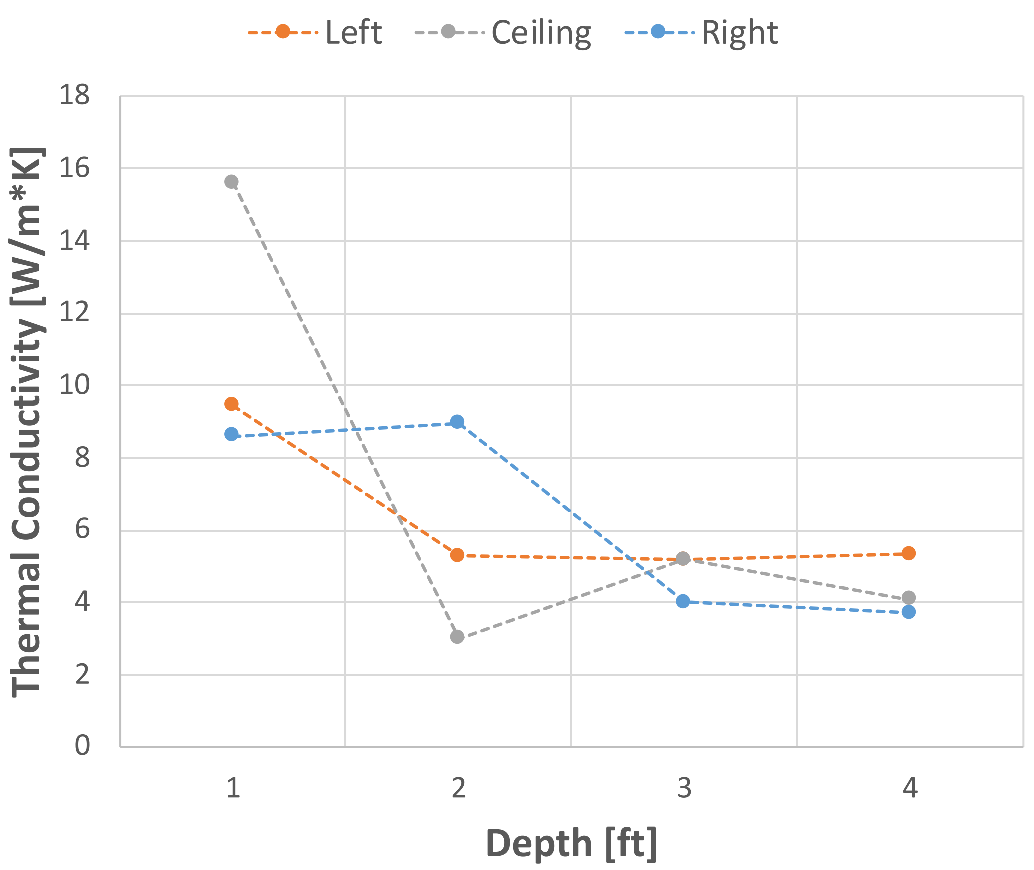
Heat Capacity

- Differential scanning calorimetry
- Direct measurement of heat flow
- Heat capacity calculated
  - $C_p = \frac{1}{m}\frac{(\delta Q/d\tau)}{(dT/d\tau)}$
- Data at 700 ˚C for ceiling sample at 1 ft depth – two runs
  - Low enough temperature to avoid molten state and glass transition
- High standard deviation

	Heat Capacity [J/kg*K]
Run 1	1404
Run 2	1884
Average	1644
Std. Dev.	340
2 x Std. Dev.	680

Thermal Conductivity - Result

- $k_{eff} = \rho_{meas}\alpha_{meas}C_{p,meas}$
- *Approximated using C_p measurement from sample for ceiling at 1 ft depth for a temperature of 700 ˚C
- Thermal conductivity does not appear to be a strong function of distance in the first four feet of the furnace
- High thermal conductivity may be due to potential sintering of samples – indicated by very low porosity
- Uncertainty in thermal diffusivity measurements from new technique may contribute to high thermal conductivities



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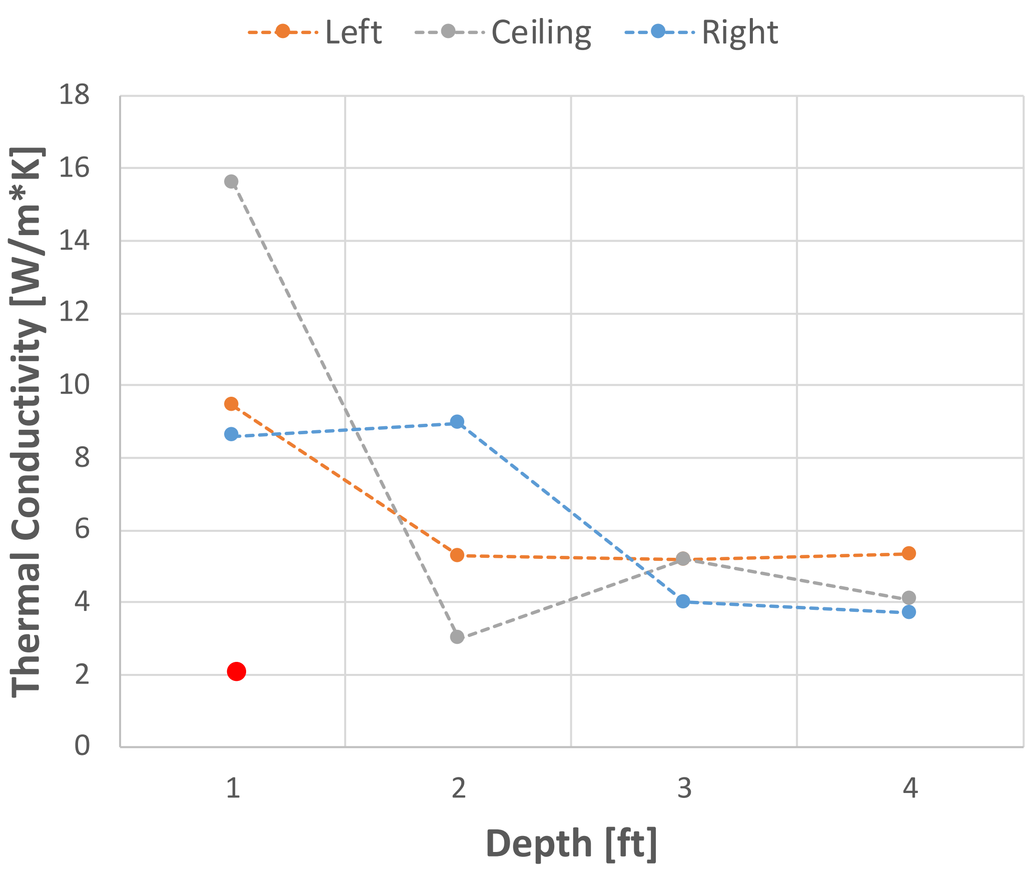
  - Using a smaller literature value for α of 4.5 x 10^{-7} [m^2/s] gives $k_{eff} = 2.01\ [W/m*K]$ for the ceiling at 1 ft depth



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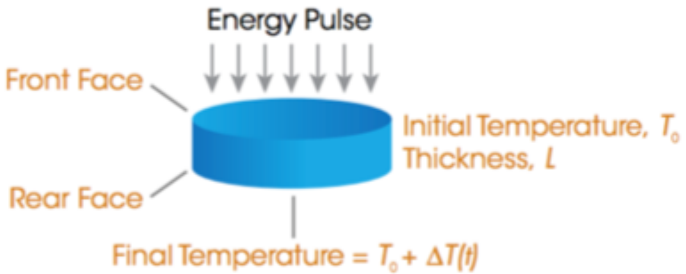
Flash Method Validation

- Flash Measurement Technique
  - Measurements up to 2000 ˚C for validation of the presented approach to calculating effective thermal conductivity
  - Direct measurement of sample thermal diffusivity
  - Also produces heat capacity and thermal conductivity information



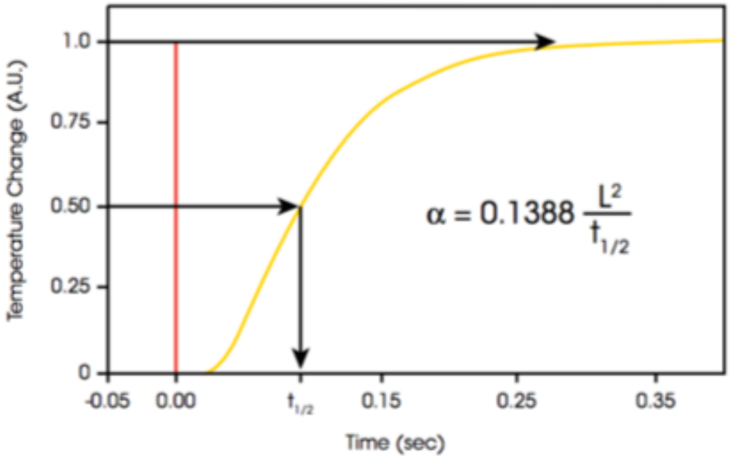


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Figure and plot: http://www.tainstruments.com/wp-content/uploads/BROCH-ThermalConductivityDiffusivity-2014-EN-2.pdf

Summary

Conclusions

- Results for first four feet of L-1500 furnace
  - Low overall porosity
    - Samples may have sintered during furnace operation
  - Density does not strongly depend on depth
    - Low uncertainty in measurements due to low error
  - Thermal diffusivity does not seem to depend on depth
    - High uncertainty in measurements due to large error
  - Thermal conductivity is high for the oxy-coal deposits
    - May be due to potential sintering of samples
    - High uncertainty of thermal diffusivities from new technique
  - Thermal conductivity does not strongly depend on depth
    - High uncertainty in calculation due to approximation using only one sample heat capacity measurement at this time
- Overall, high temperature effective thermal conductivity has potential to be approximated by combining various property measurements
  - Will require further refinement in future work

Future Work

- Larger sample size
  - Farther from burner
  - Increase spread on surfaces
  - Up to 400 samples available
- High temperature density measurements
- Validation/verification of thermal diffusivity
  - Flash method
  - Refine technique to account for refractory contribution
- More detailed analysis of heat capacity
  - Higher temperatures with glass transition
- X-ray fluorescence and SEM to determine composition and structure
- High temperature FTIR
- Development of instrument models for the various measurement techniques to fully characterize sources of uncertainty

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Instrument Figure References

Pycnometer figure (slides 17-20): http://www.micromeritics.com/Product-Showcase/AccuPyc-II-1340.aspx

IR camera figure (slides 18-20): http://www.flir.com/science/display/?id=44791

TGA-DSC figure (slides 19-20): http://www.tainstruments.com/wp-content/uploads/sdt.pdf

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Thank you.
Questions?

Acknowledgement

This material is based upon work supported by the U.S. Department of Energy, National Nuclear Security Administration, under Award Number DE-NA0002375. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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National Nuclear Security Administration

Supplemental

Other Institute Presentations

- Wednesday, June 8th
  - 70. "Heat Transfer and Temperature Behavior of a Maximum O2 Concentration Oxy-Coal Flame"
    - 11:50 am – Oxyfuel Technologies I
  - 67. "Pilot-Scale Investigation and Modeling of Heat Flux and Radiation from an Oxy-coal Flame"
    - 4:00 pm – Oxyfuel Technologies II
  - 52. "Thermal Characterization of a 1.5 MW Pulverized-coal Furnace Using Infrared Heat Flux, Total Heat Flux and Measured Heat Loss"
    - 4:40 pm – Oxyfuel Technologies II
- Thursday, June 9th
  - 76. "Simulation and Validation of 15 Mwth Oxy-Coal Power Boiler"
    - 10:30 am – Oxyfuel Technologies III
  - 78. "Uncertainty Quantification for Coarse-Grained Modeling of Coal Devolatilization"
    - 11:10 am – Oxyfuel Technologies III
  - 79. "Towards Next Generation Simulations of Full-Scale Coal-Fired Boilers"
    - 11:30 am – Oxyfuel Technologies III

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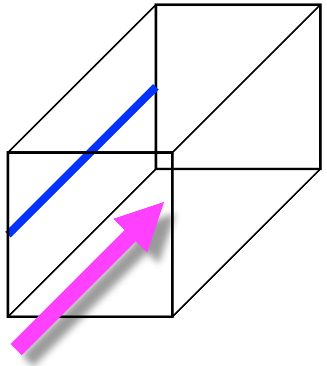
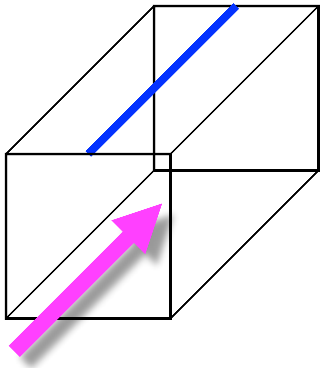
Extra Plots - Porosity

= sampling location = flame

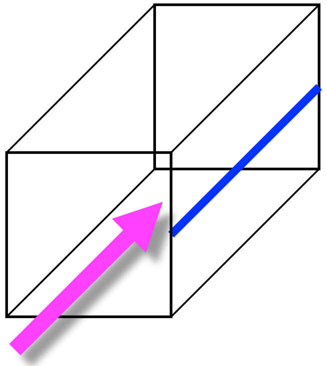
Left Wall

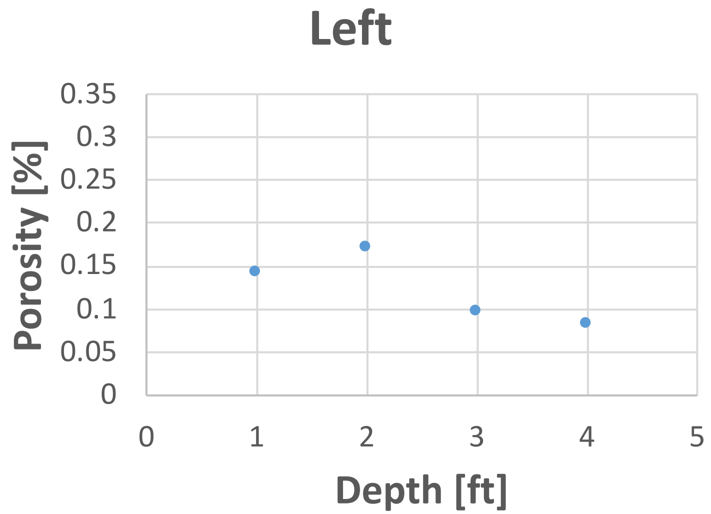


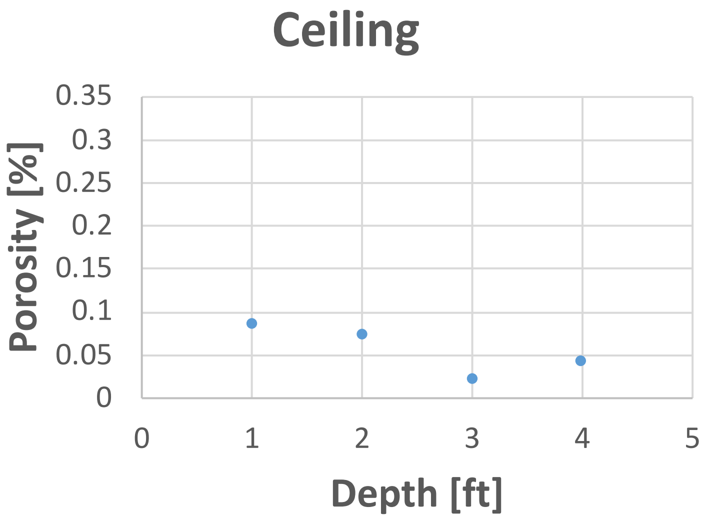
Ceiling

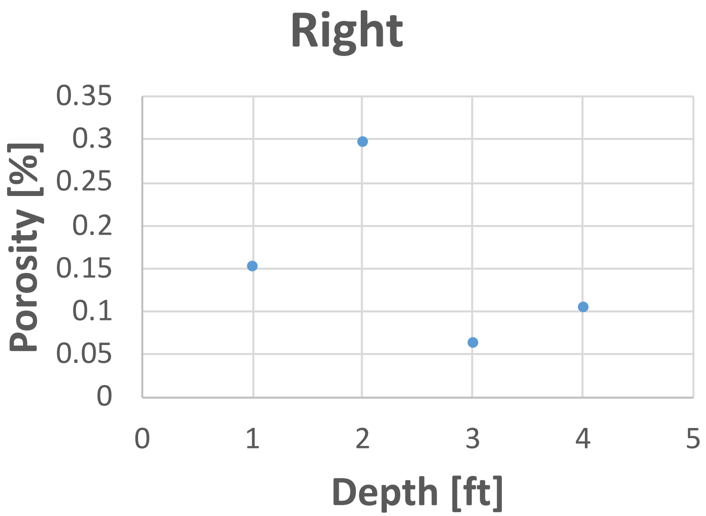


Right Wall





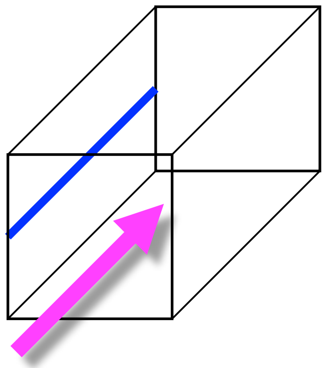




Extra Plots - Density

= sampling location **= flame**

Left Wall



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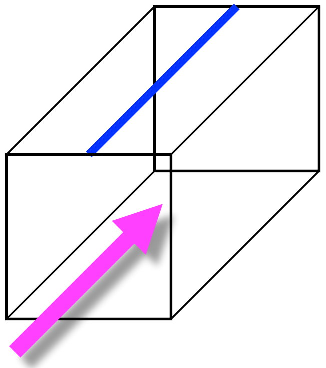
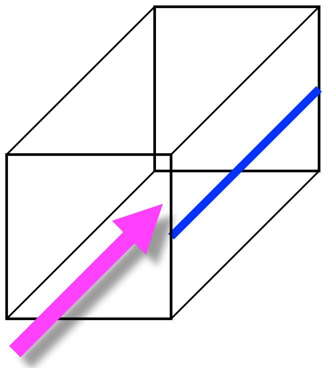
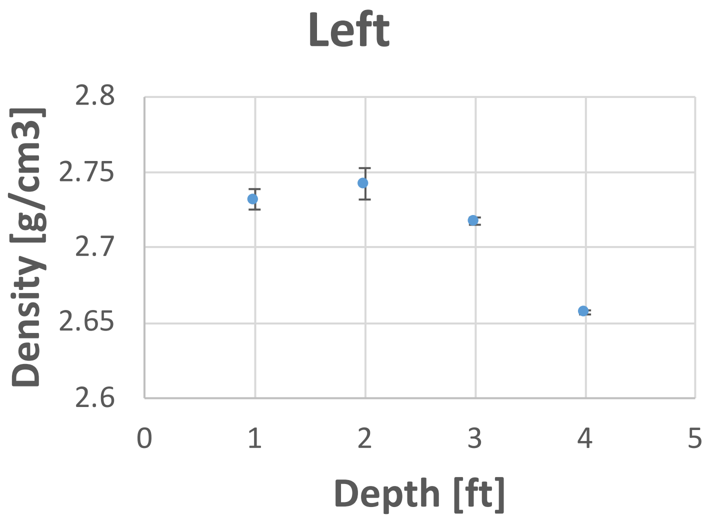
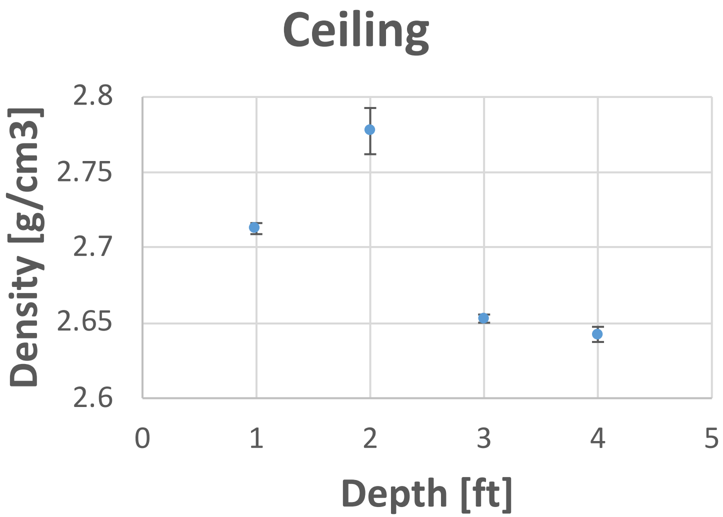
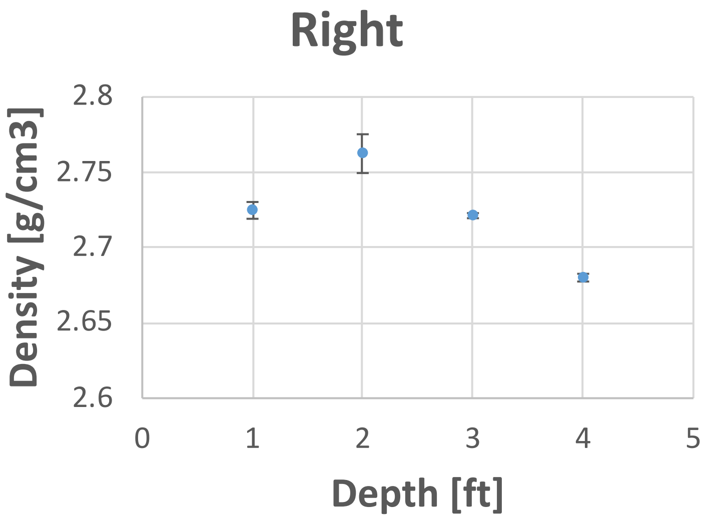


Right Wall

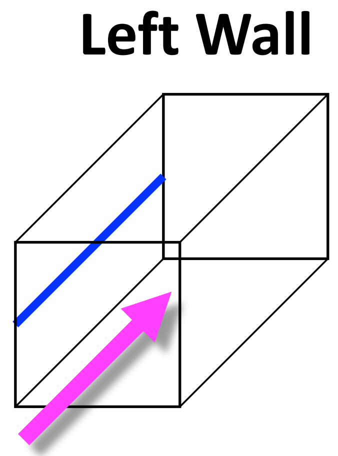


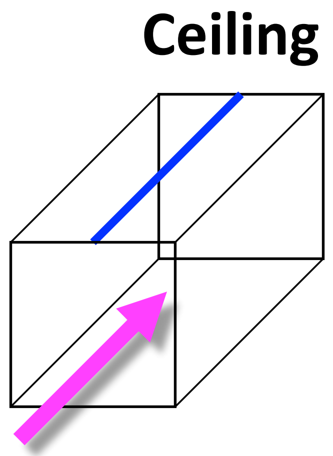


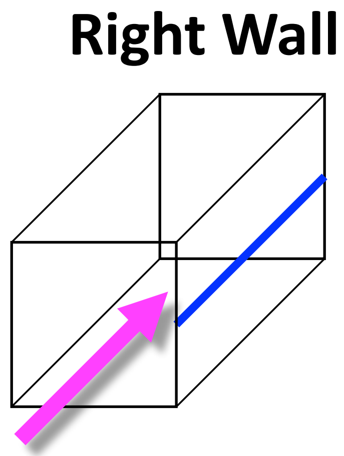


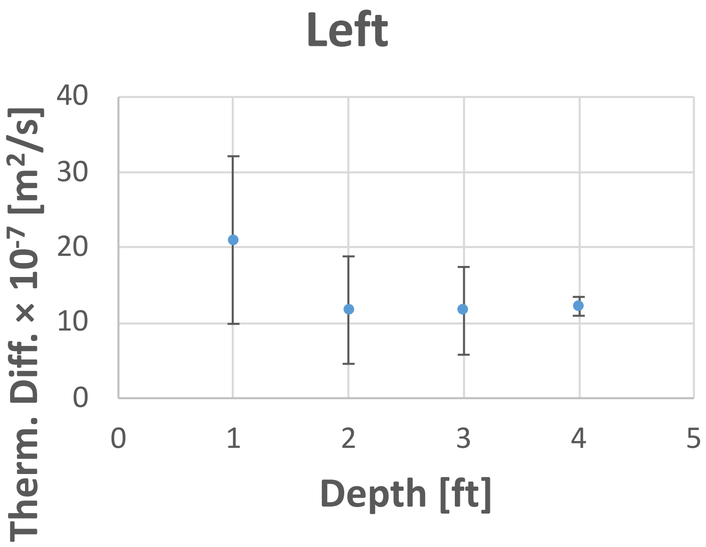


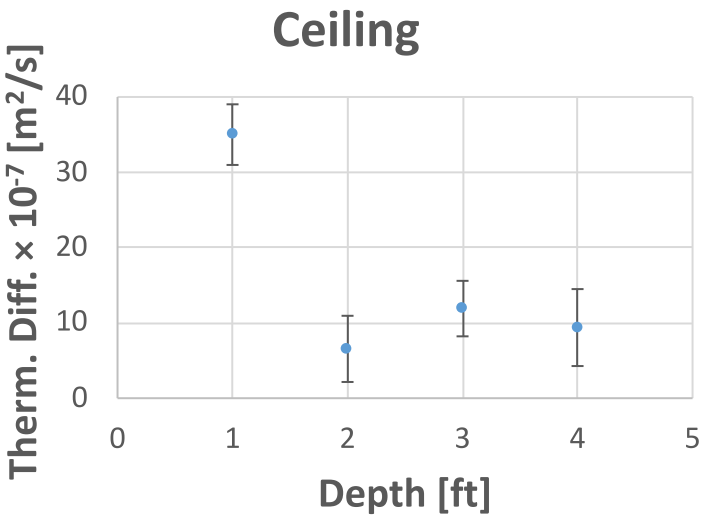
Extra Plots – Thermal Diff

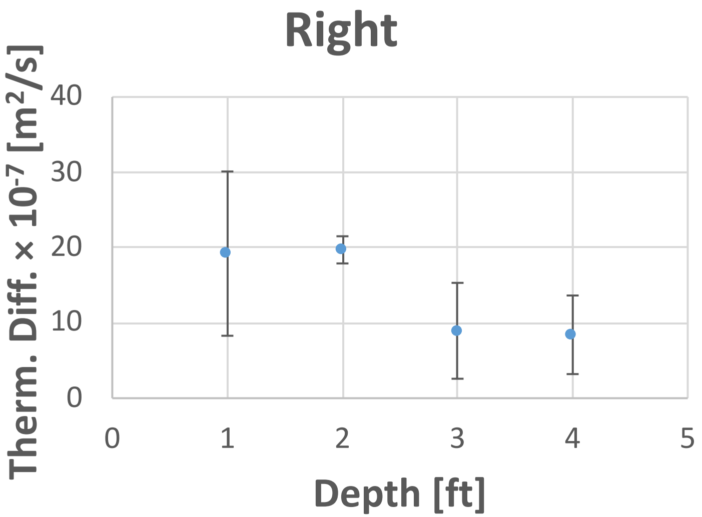












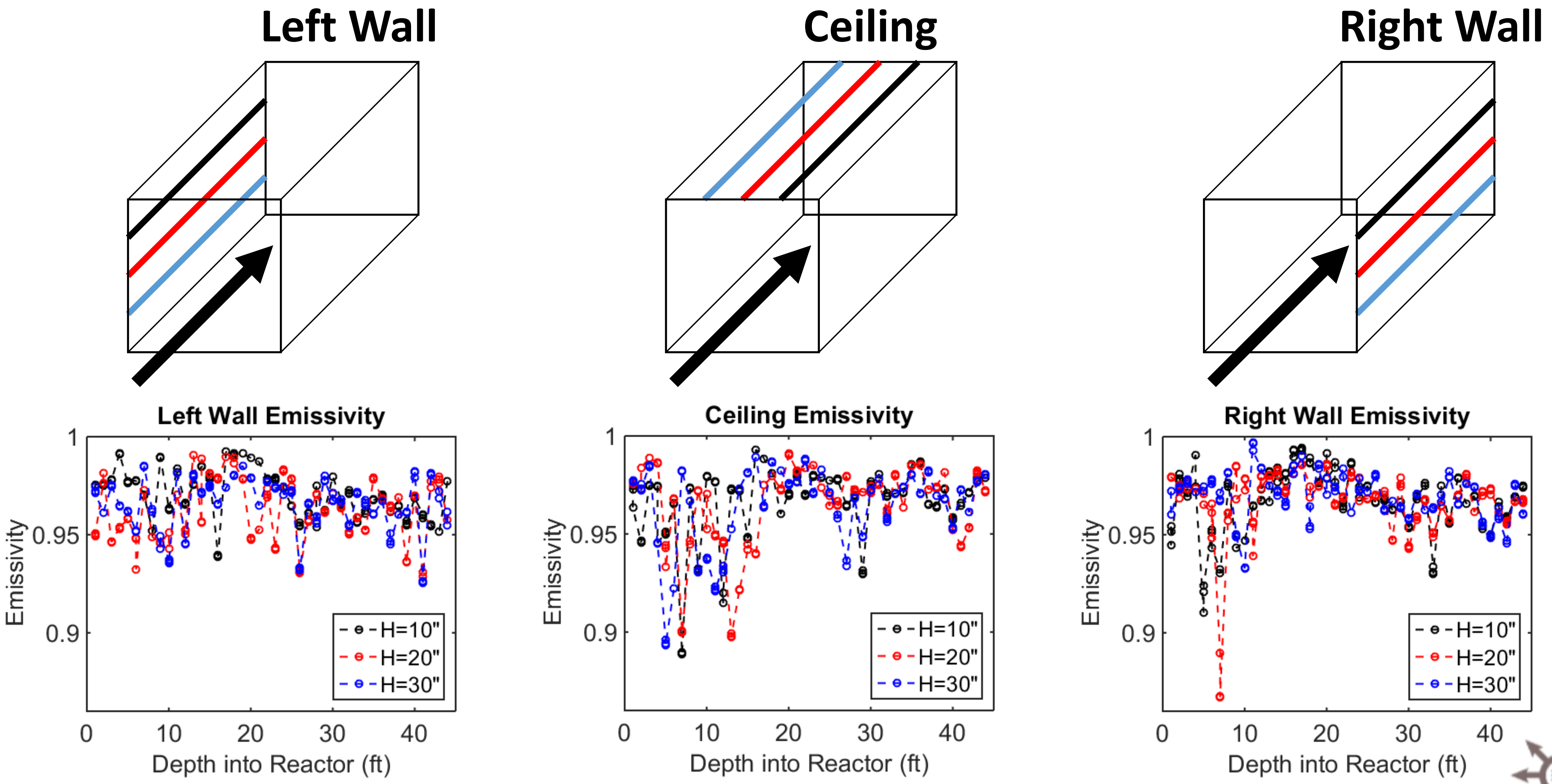
Emissivity

- Diffuse reflectance cell in FT/IR to measure complex refractive index, n_λ and k_λ, of the deposits at room temperature
- Spectral reflectivity:
  - $\rho_\lambda = \frac{(n_\lambda - 1)^2 + k_\lambda^2}{(n_\lambda + 1)^2 + k_\lambda^2}$
- Kirchhoff's law (ε_λ=α_λ) and radiation balance:
  - $\varepsilon_\lambda + \rho_\lambda + \tau_\lambda = 1$
- Assuming opaque medium:
  - $\varepsilon_\lambda = 1 - \rho_\lambda$
- Total emissivity approximated:
- $\varepsilon \approx \frac{\int_{2.5\ \mu m}^{25\ \mu m} \varepsilon_\lambda E_{b,\lambda}}{\int_{2.5\ \mu m}^{25\ \mu m} E_{b,\lambda}}$

Courtesy Teri Draper

CARBON CAPTURE MULTIDISCIPLINARY SIMULATION CENTER

Emissivity



CARBON CAPTURE
MULTIDISCIPLINARY
SIMULATION CENTER

Courtesy Teri Draper