Pilot-Scale Investigation and Modeling of Heat Flux and Radiation from an Oxy-coal Flame

Andrew Fry, Ignacio Preciado, Oscar Diaz, Jennifer Spinti and Eric Eddings

Dept. of Chemical Engineering and Institute for Clean and Secure Energy

University of Utah

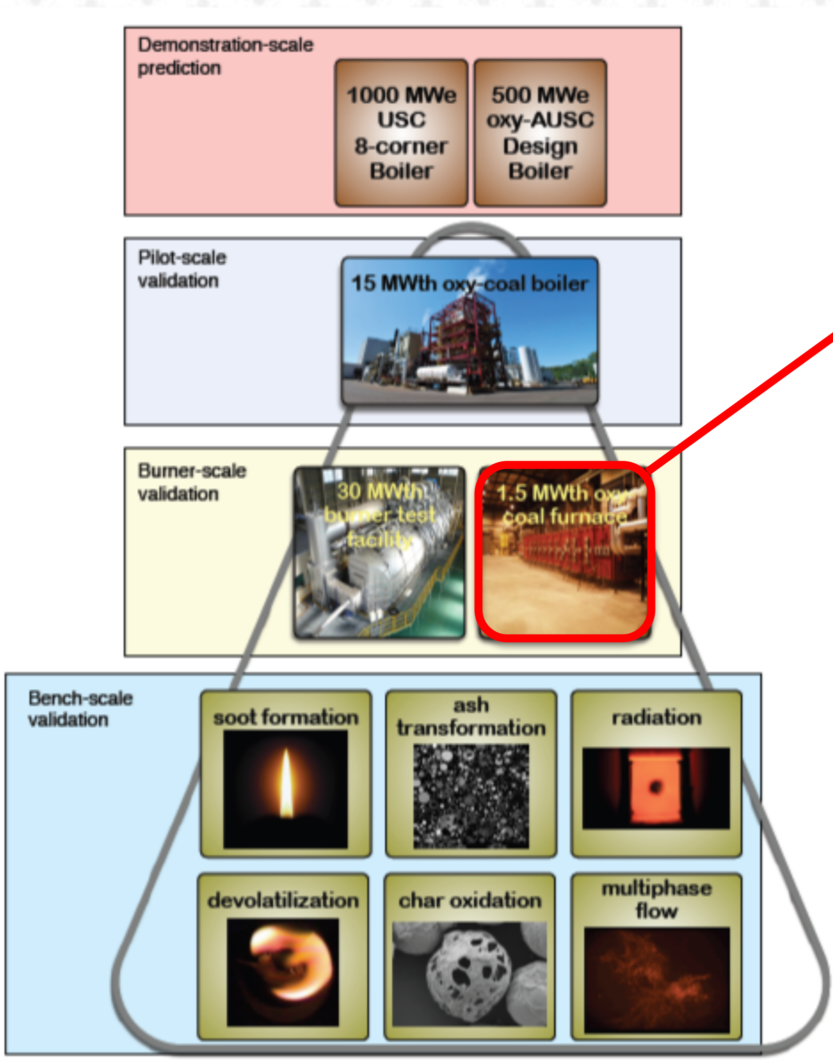
Carbon Capture Multidisciplinary Simulation Center (CCMSC) at the University of Utah

- Funded by DOE/NNSA Predictive Science Academic Alliance Program (PSAAP II)
- CCMSC Mission is to demonstrate:
  - Exascale computing
    - with formalized use of Verification, Validation and Uncertainty Quantification (V&V/UQ)
  - Accelerated technology development and deployment using simulations
    - provide <u>predictions</u> with quantifiable uncertainty bounds
  - Target technology: Next generation oxy-coal-fired utility boiler

CARBON CAPTURE MULTIDISCIPLINARY SIMULATION CENTER

THE UNIVERSITY OF UTAH

Validation Hierarchy



1.5 MW oxy-fired pulverized coal furnace (L1500)

Increasing complexity

Increasing physical scale

Decreasing fidelity of data

CARBON CAPTURE MULTIDISCIPLINARY SIMULATION CENTER

THE UNIVERSITY OF UTAH

Overall V/UQ Approach

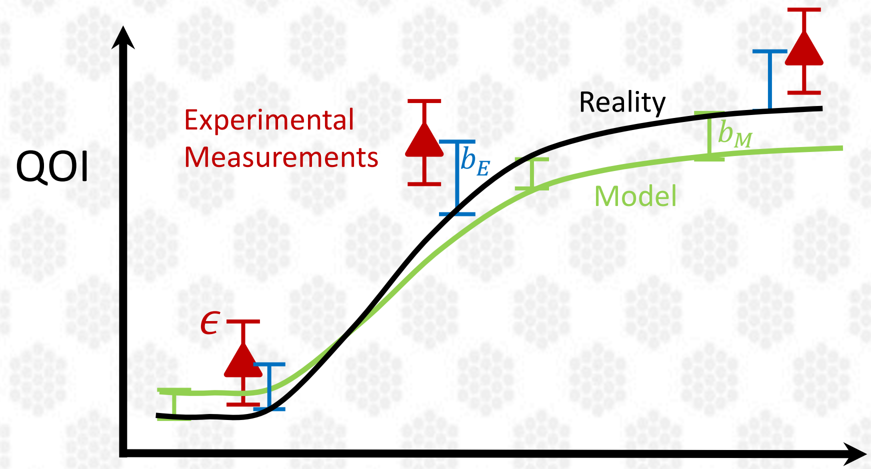
- Perform simulations for each entity (block) in the hierarchy using an iterative process for V/UQ
- *Example*: 1.5 MW Furnace (L1500)
  - performed simulations for prescribed range of conditions
  - performed full V/UQ analysis, using data from previous year test campaign
  - Identified potential for improvements in the model, and in experimental data collection to:
    - Reduce the impact of the measurement on the quantity of interest
    - Provide more accurate assessment of experimental uncertainty
    - Improve instrument models

Zero Swirl Case – All Axial Flow
Utah Coal – Oxyfiring

L1500 LES-based Oxycoal Simulation
Part 1: Residence Time Distribution
Part 2: Gas Temperature Distribution

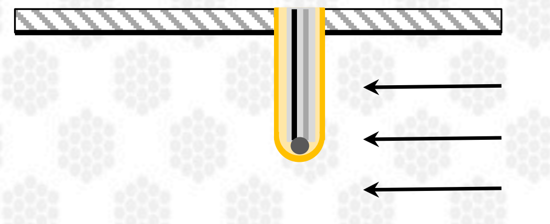
Importance of Instrument Models

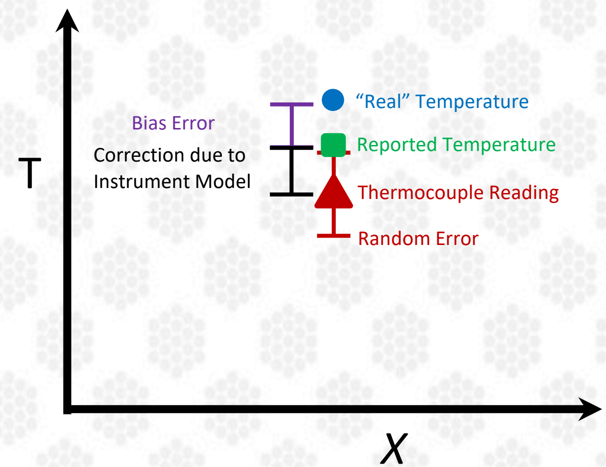
- Instrument models relate the actual measured value to the desired quantity, for comparison with the simulation *(e.g., relates measured voltages > temperatures > heat flux)*
- Careful development and critical evaluation of instrument models:
  - Reduces bias errors, and thereby bring reported experimental values closer to real values
  - Provides more accurate model validation
  - Provides for more accurate fitted model parameters (model "calibration")



Simple Example: Shielded Thermocouple for Measuring Gas Temperature

- Principles of Operation:
  - Thermocouple (TC) is housed inside ceramic sheath to minimize radiation losses from TC bead to furnace walls, or to prevent deposition problems
  - Hot combustion gases flow past the sheath and heat it to equilibrium (steady state) temperature
  - TC measures temperature inside of ceramic sheath
- Instrument model considerations to estimate gas T:
  - Heat transfer (HT) calculations
    - convective & radiative HT to ceramic shield
    - contact resistance between TC and shield (if HT paste used, what is thickness and properties)
    - conduction heat losses from ceramic shield to outside of furnace
    - conduction along TC sheath
    - exposed bead TC or not (could require additional sheath calculation)
  - Other potential errors: TC junctions, flowrate and pressure measurement (T correction), T dependence of properties, deposition, calibrations





CARBON CAPTURE MULTIDISCIPLINARY SIMULATION CENTER

THE UNIVERSITY OF UTAH

Quantities of Greatest Interest that were Addressed in the L1500 V/UQ Effort

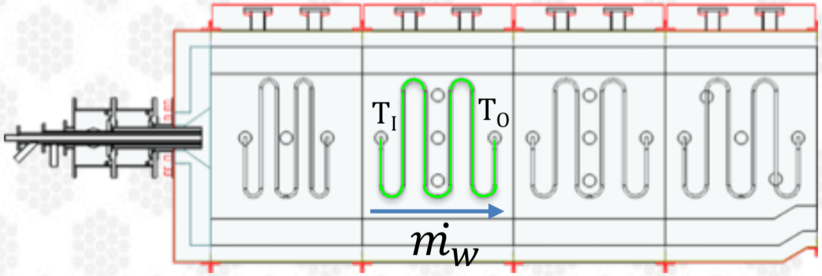
- Heat removal through cooling surfaces
- Refractory temperatures at the flue gas interface
- Heat flux through the walls
- Radiative intensity

Measuring Heat Removal Through Cooling Surfaces

CARBON CAPTURE MULTIDISCIPLINARY SIMULATION CENTER

THE UNIVERSITY OF UTAH

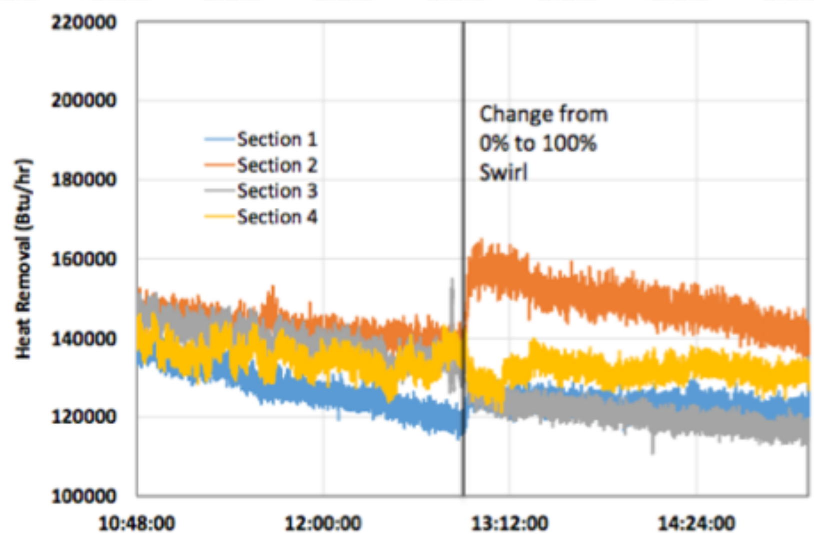
Previous Configuration: Cooling Panels



- Cooling surfaces are necessary to provide steady state temperature profile
- Heat removal is determined by measuring the mass flow of water and the temperature of the water in and out

$$Q = \dot{m}_w \cdot c_p(T_O - T_I)$$

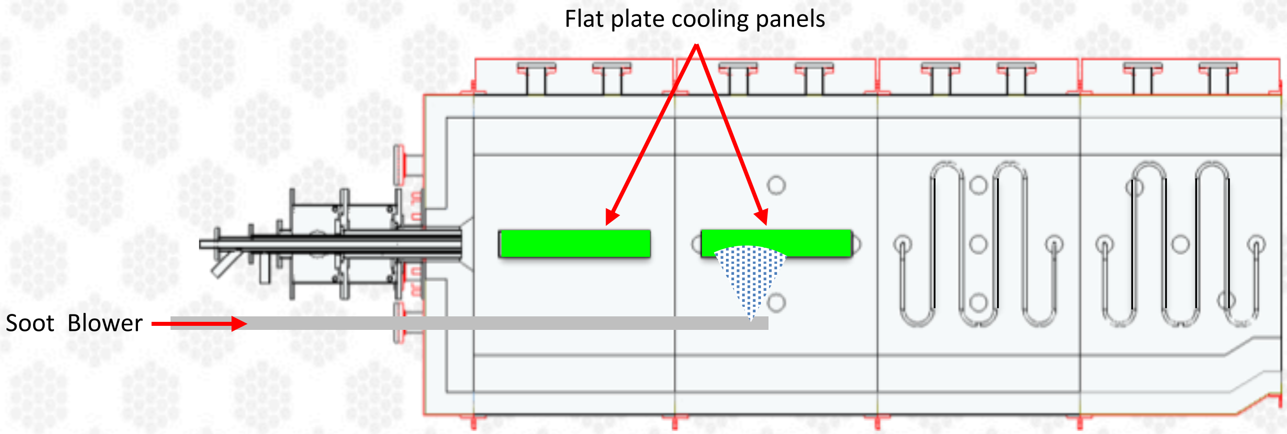
- Measurement is very sensitive to particle deposition

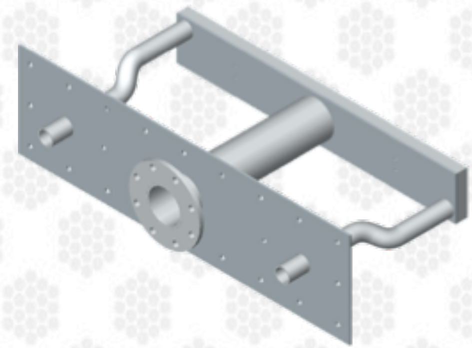


CARBON CAPTURE MULTIDISCIPLINARY SIMULATION CENTER

THE UNIVERSITY OF UTAH

Modification: Flat Plate Cooling Panels





Multiple depth thermocouples placed in the hot-side plate for heat flux measurements

2 thermocouple sets per heat exchanger

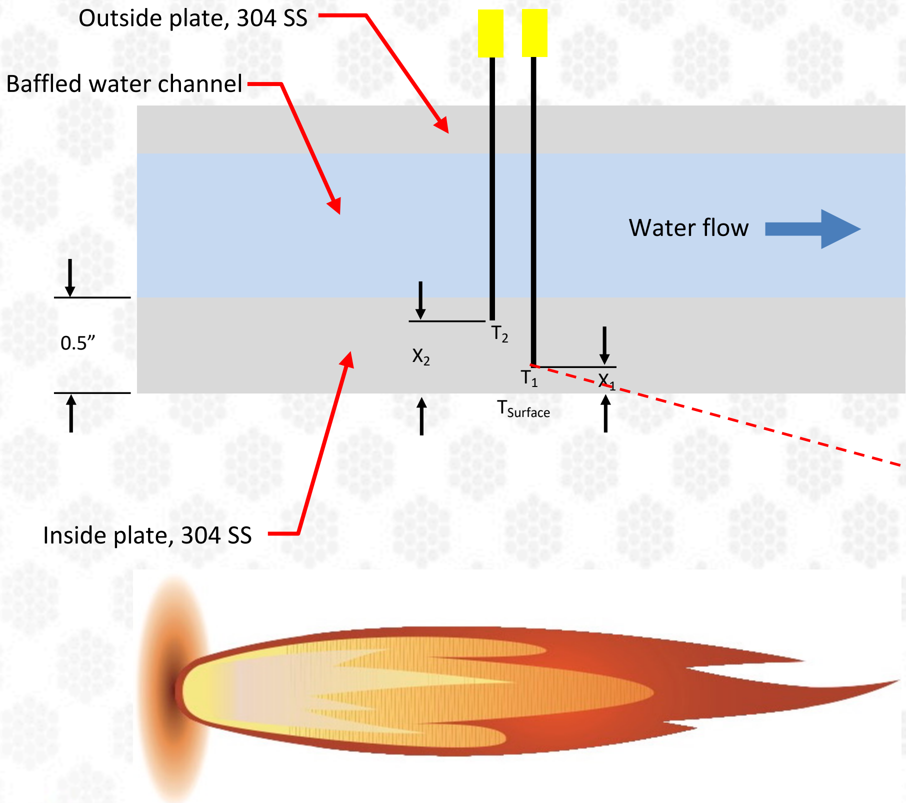
8 total heat flux measurements

CARBON CAPTURE MULTIDISCIPLINARY SIMULATION CENTER

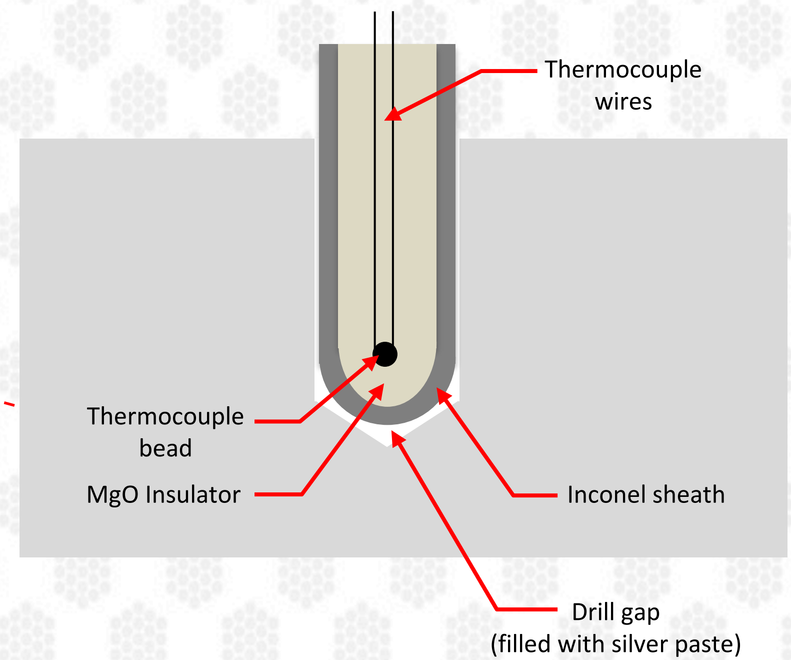
THE UNIVERSITY OF UTAH

Multiple-depth TC's in Cooling Panels

Cooling Panel Cross Section



Detail: Thermocouple Cross Section



CARBON CAPTURE MULTIDISCIPLINARY SIMULATION CENTER

THE UNIVERSITY OF UTAH

Cooling Coils and Panels Instrument Models

Multi-depth thermocouple mathematical description:

Temperature profile to the thermocouple sheath

$$q = k_{ref}\frac{(T_1 - T_2)}{(X_1 - X_2)} \qquad T_s = T_1 + q\left(\frac{X_1}{K_{ref}}\right)$$

Assumption: The 1/16" thermocouple does not impact heat flux

Temperature profile within the thermocouple to bead

$$T5 = T1 - q\left[\left(\frac{X_{Sil}}{K_{Sil}}\right) + \left(\frac{X_{inc}}{K_{inc}}\right) + \left(\frac{X_{MgO}}{K_{MgO}}\right)\right]$$

Assumption: Flux through plate = flux through thermocouple

Energy balance for heat absorption mathematical description:

$$Q = \dot{m}_w \cdot c_p(T_O - T_I)$$

Quantifiable sources of error:

- Standard error in type-k thermocouple bead
- Variability in thermocouple set depth measurement
- Variability in material thermal properties
- Error in flow rate measurement

CARBON CAPTURE MULTIDISCIPLINARY SIMULATION CENTER

THE UNIVERSITY OF UTAH

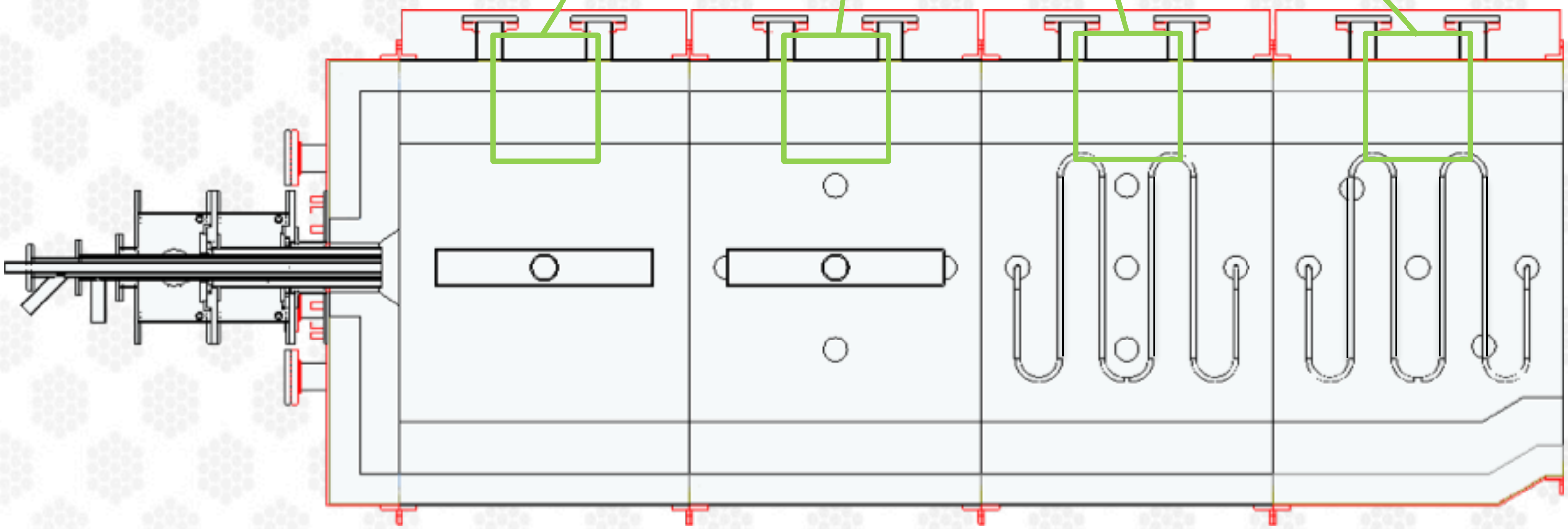
Measuring Wall Temperatures and Heat Flux

CARBON CAPTURE MULTIDISCIPLINARY SIMULATION CENTER

THE UNIVERSITY OF UTAH

Wall Thermocouples

Installed in the center of the top wall of each section

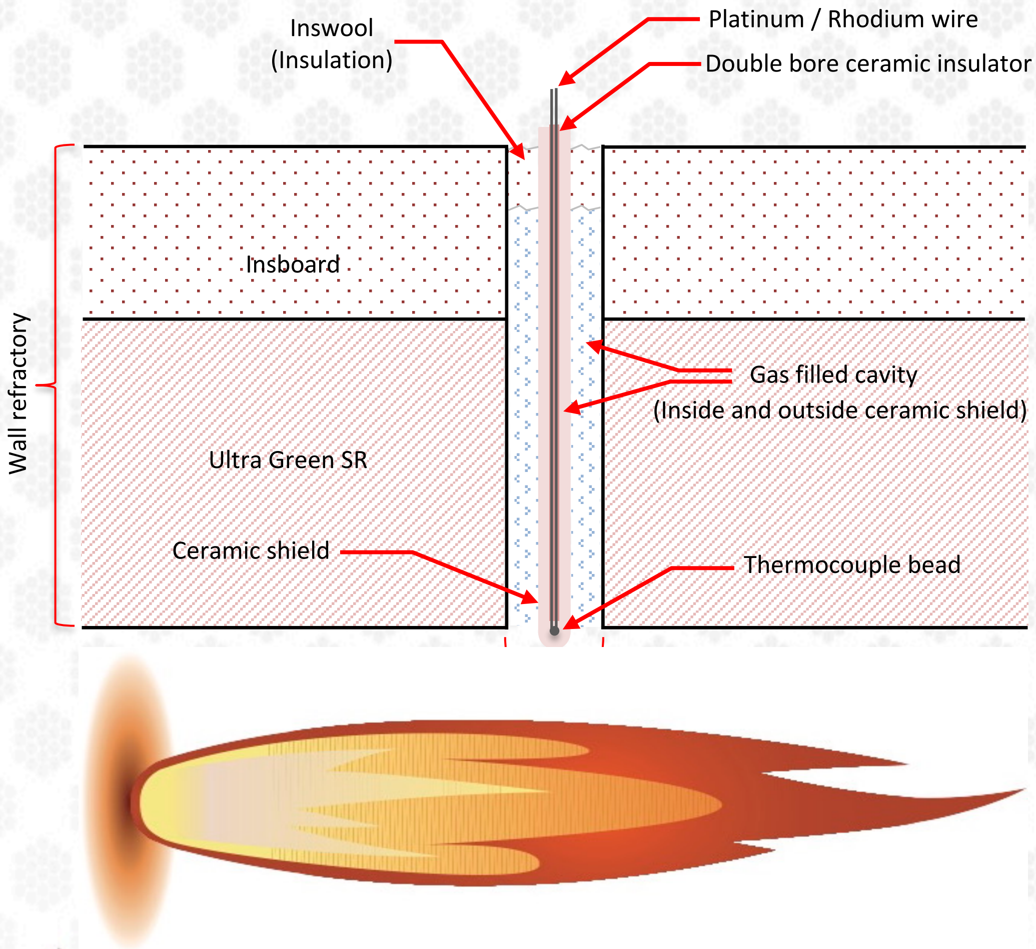


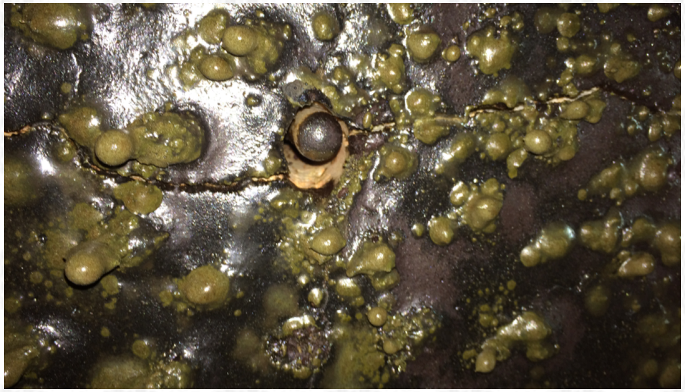
Permanently installed indicator of temperature profile (continuous data)

CARBON CAPTURE MULTIDISCIPLINARY SIMULATION CENTER

THE UNIVERSITY OF UTAH

Old Wall Thermocouple Device





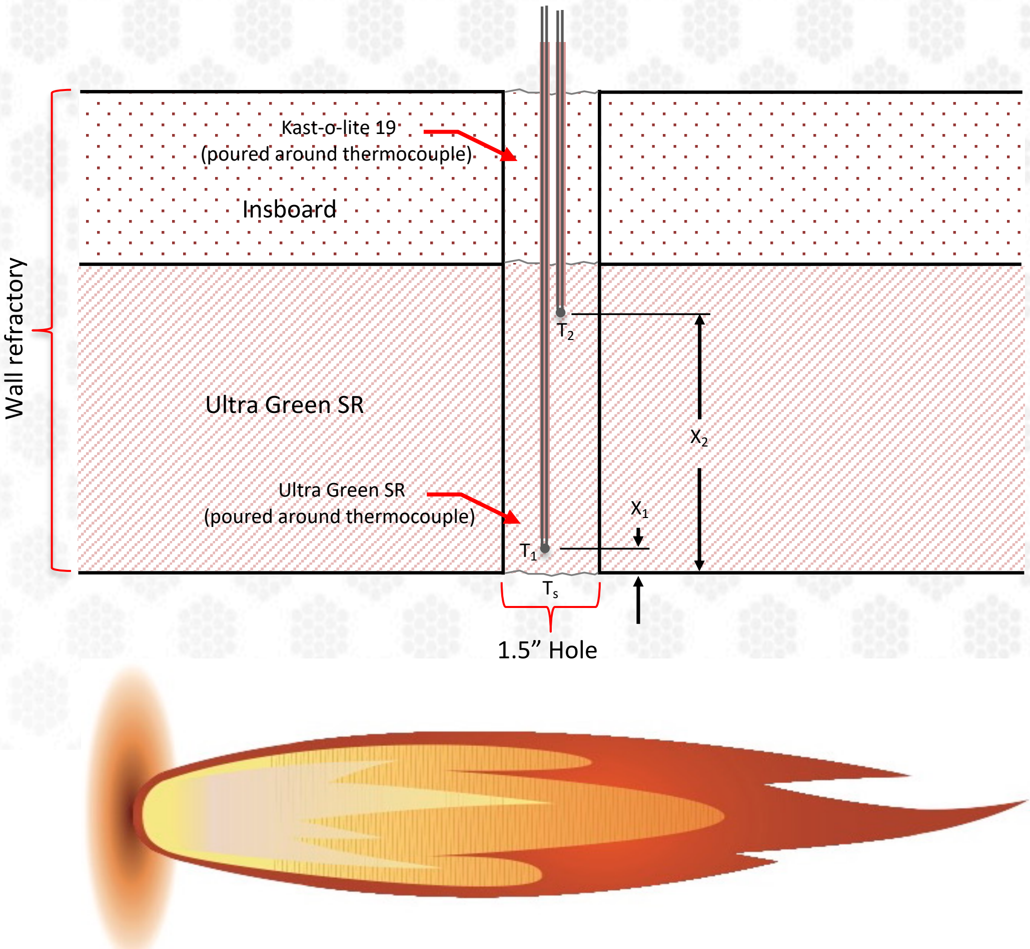
Measured T is not of the wall

- Heat transfer characteristics of measurement device are dissimilar to surroundings
- Ceramic, wire and air gaps vs. refractory
- Placement of bead is uncertain
- Interpretation of the data requires a complicated model which includes the surrounding environment

CARBON CAPTURE MULTIDISCIPLINARY SIMULATION CENTER

THE UNIVERSITY OF UTAH

New Wall Thermocouple Device



Advantages:

- Environment closely approximates the natural furnace wall
- Simple mathematical description of temperature profile
- Both surface temperature and heat flux can be acquired

Disadvantages:

- Expensive (type B Pt/Rh TC's)
- Difficult to install

THE UNIVERSITY OF UTAH

New Wall Thermocouple Instrument Model

Mathematical Description:

$$q = k_{ref}\frac{(T_1 - T_2)}{(X_1 - X_2)} \qquad T_s = T_1 + q\left(\frac{X_1}{K_{ref}}\right)$$

Assumption: The wire and double bore ceramic do not impact the temperature profile

Quantifiable sources of error:

- Standard error in Type-K thermocouple bead
- Variability in thermocouple set depth measurement
- Variability in material thermal properties

Expected Behavior:

ΔT = 748 to 894 ± 5 (°C)

q = 1651 to 1971 ± 171 (W/m^2)

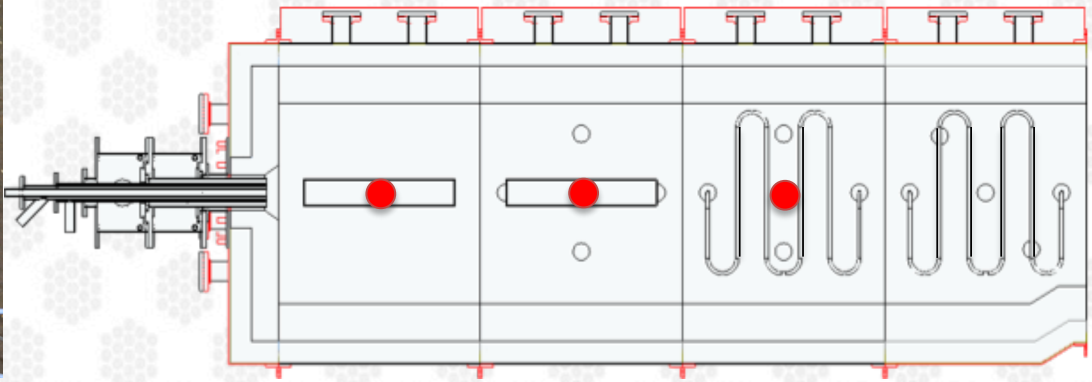
Range is from section 1 through 10 device distributions

CARBON CAPTURE MULTIDISCIPLINARY SIMULATION CENTER

THE UNIVERSITY OF UTAH

Measuring Radiative Heat Flux

Narrow-angle Radiometer Configuration



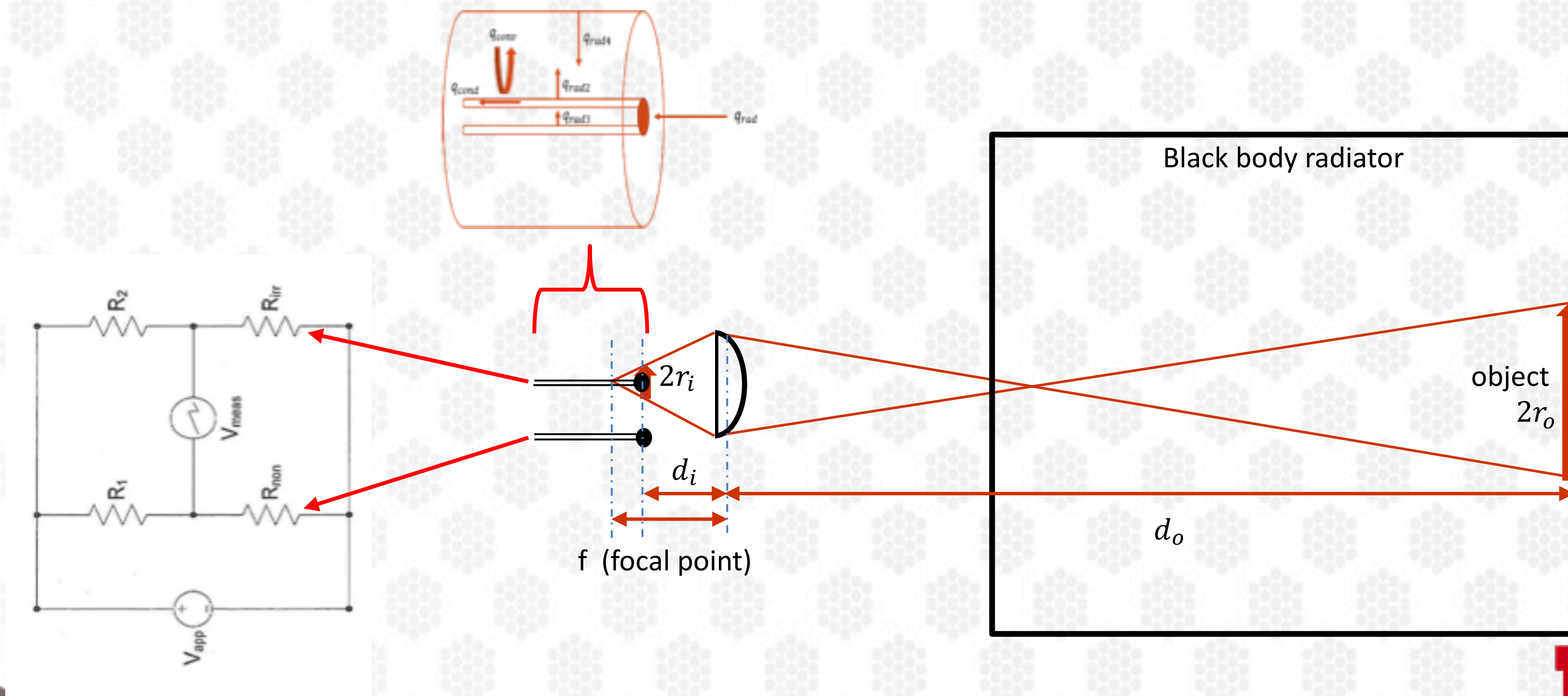
- Installed on the center port in the first three sections of the furnace
- Open 4" cavity (optically dark) on the opposite side of the furnace
  - Minimize the wall effects and measure only flame properties

Physical Processes of the Radiometer

Wheatstone bridge to 5V power supply

Energy balance around irradiated thermistor wire

Lens optics and radiation onto thermistor



Radiometer Instrument Model

Mathematical Description:

$$\left.\begin{aligned} d_i = \frac{1}{\frac{1}{d_o} + \frac{1}{f}} \qquad r_i = \frac{d_i r_o}{d_o} \end{aligned}\right\} \text{Lens optics}$$

$$\left.\begin{aligned} I_i &= I_o \left(\frac{r_{lens}}{r_i}\right)(1-\rho) \\ q_{rad} &= \pi r_i^2 I_i \end{aligned}\right\} \text{Thermistor irradiation}$$

$$\left.\begin{aligned} q_{rad} + q_{rad3} + q_{rad4} &= q_{cond} + q_{conv} + q_{rad2} \\ R_t &= R_{ref} exp\left(A + \frac{B}{T_t} + \frac{C}{T_t^2} + \frac{D}{T_t^3}\right) \end{aligned}\right\} \text{Energy balance}$$

$$\left.\begin{aligned} V_{meas} = V_{app}\left(\frac{R_{non}}{R_{non} + R_1} - \frac{R_{irr}}{R_{irr} + R_2}\right) \end{aligned}\right\} \text{Wheatstone bridge}$$

CARBON CAPTURE MULTIDISCIPLINARY SIMULATION CENTER

THE UNIVERSITY OF UTAH

Radiometer Instrument Model

Quantifiable Sources of Error:

- Input voltage
- Thermistor position
- CO_2 flow rate (purge gas)
- Lens orientation
- Refractive index (focal point)
- Ambient temperature variations

Additional Measurements

- Determination of flame temperature through high speed IR imaging
- Determination of ash deposit physical properties
  - Surface Emissivity
    - *Measure at representative furnace temperatures over wide range of wavelengths*
  - Density, porosity, heat capacity, thermal diffusivity
    - *Leads to calculation of thermal conductivity*
- Deposition rate on heat transfer surfaces and temperature controlled coupons

Summary & Conclusions

- Model validation methodology described and illustrated for simulations of 1.5 MW oxy-coal combustion facility
- V/UQ analysis explored consistency and magnitude of uncertainties
  - Process identified areas for improvement in previous year measurements
  - Experimental facility and associated measurement devices were upgraded to improve reported values for:
    - Heat transfer through cooling surfaces
    - Wall temperatures and wall heat flux
    - Radiation intensity
- Instrument models were developed and assessed by team to facilitate estimate of experimental bias errors
- Will generate new data June 2016 for next V/UQ iteration

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.

QUESTIONS?