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

Part 1: Development of Instrument Models

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Presentation Road Map

- Program objective, hierarchy and task objective
- Review of experimental quantities of interest
- New measurement devices with instrument models
  - Heat transfer surfaces
  - Wall thermocouples
  - Radiometers
- Example data set
- Summary & conclusions

Project Objective

Implementation of exascale computing with V&V/UQ to more rapidly deploy a new technology for providing low cost, low emission electric power generation

V&V/UQ – Verification & Validation with Uncertainty Quantification

CARBON CAPTURE MULTIDISCIPLINARY SIMULATION CENTER

Ultimate goal to design a next-generation 350 MWe oxy-coal boiler

ALSTOM

SCI www.sci.utah.edu

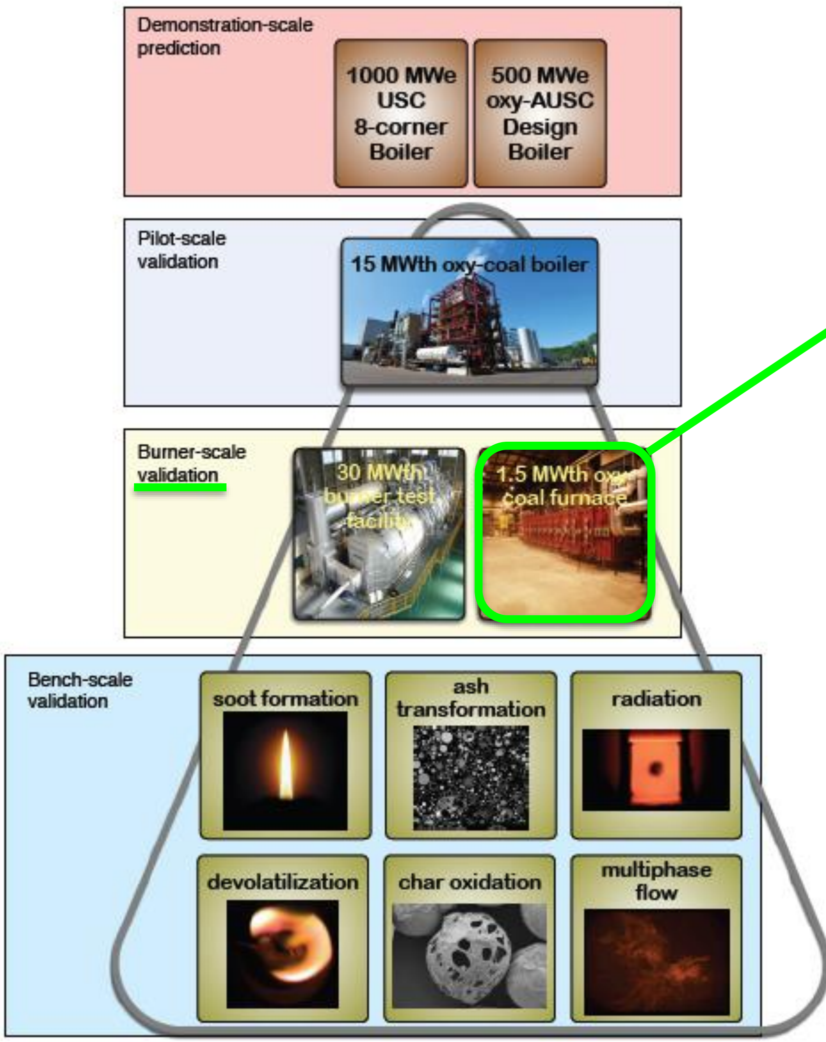
Berkeley UNIVERSITY OF CALIFORNIA

NNSA National Nuclear Security Administration

Institute for CLEAN AND SECURE ENERGY THE UNIVERSITY OF UTAH

BYU BRIGHAM YOUNG UNIVERSITY

Program Hierarchy



1.5 MW pulverized coal furnace (L1500)

Task Objectives

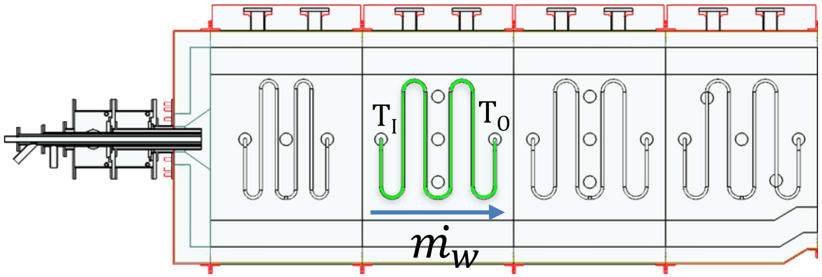
- Rework furnace measurement devices to accomplish the following:
  - Reduce the impact of measurement on the quantity of interest
  - Evaluate the relationship between the measured value and the quantity of interest
    - Simplify
    - Quantify through mathematical relationships (Instrument Model)
  - Assign value and uncertainty to the quantity of interest

Quantities of Greatest Interest

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

Measuring Heat Removal Through Cooling Surfaces

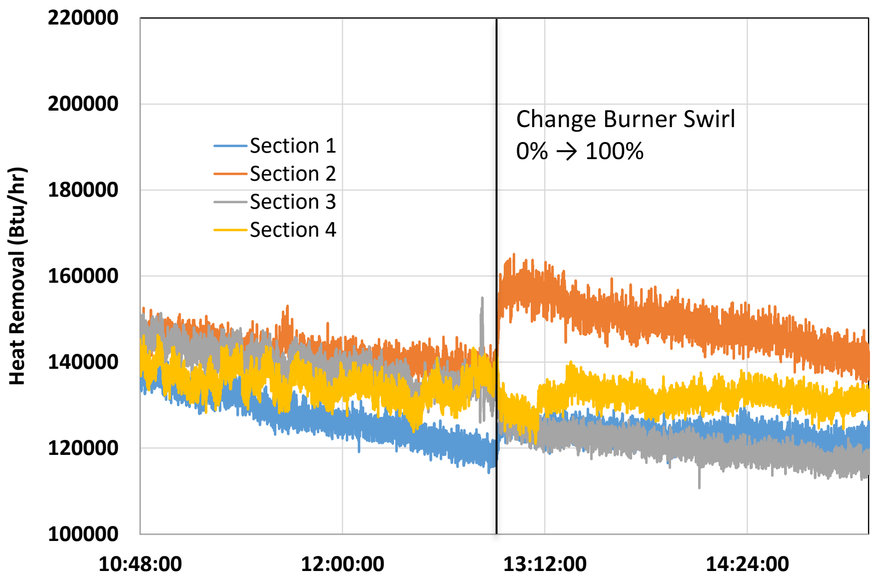
Cooling Coils and Panels



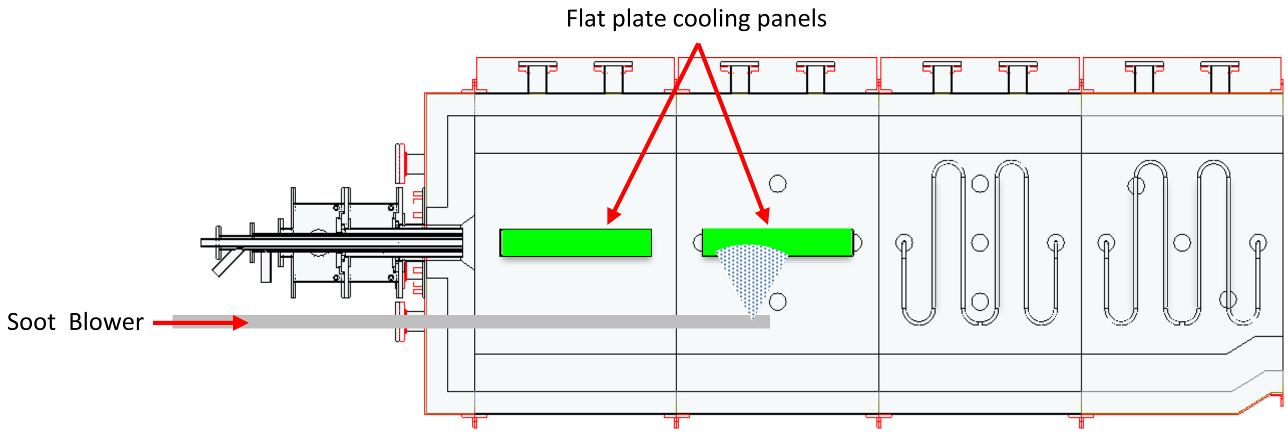
- Cooling surfaces are necessary to provide steady state temperature profile
- Heat removal is determined by measuring the mass flow of water and the temperature of the water in and out

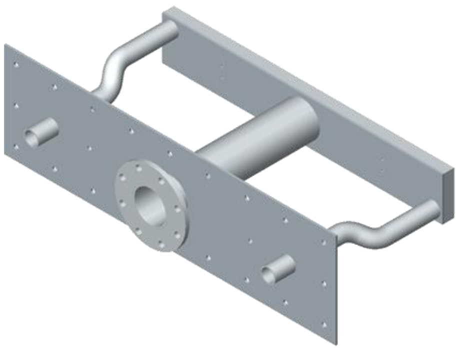
$$Q = \dot{m}_w \cdot c_p(T_O - T_I)$$

- Measurement is very sensitive to particle deposition



Cooling Coils and Panels





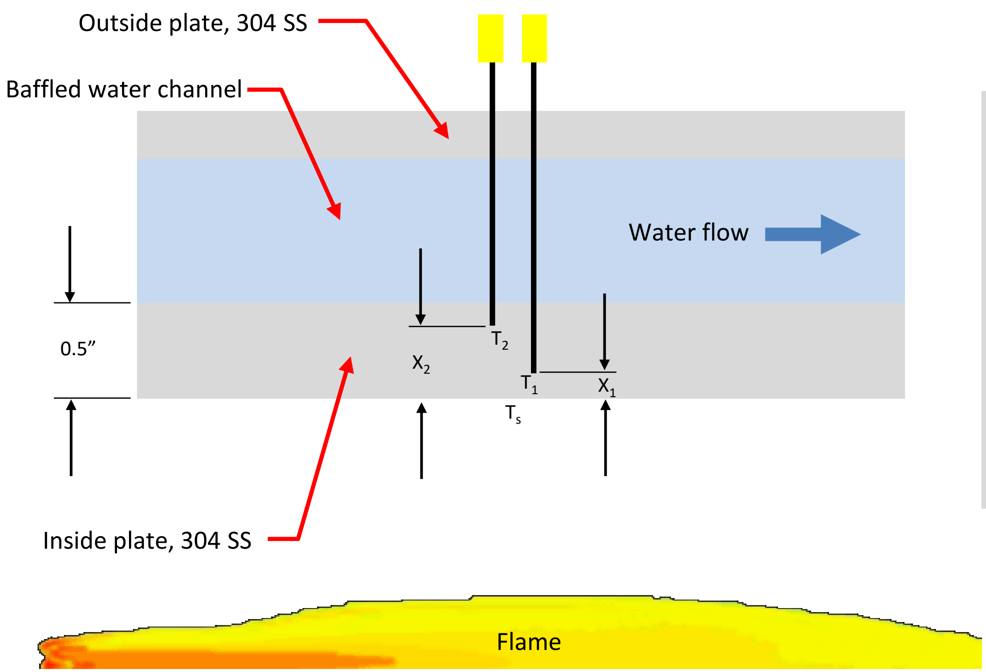
Multiple depth thermocouples placed in the hot-side plate for heat flux measurements

2 thermocouple sets / heat exchanger

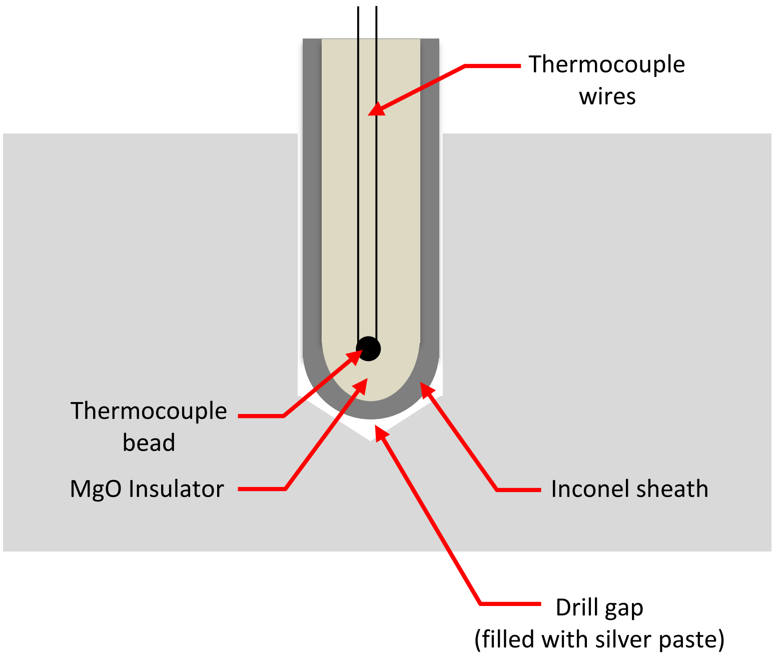
8 total heat flux measurements

Cooling Coils and Panels

Cooling panel cross section



Thermocouple cross section



Cooling Coils and Panels Instrument Model

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 mathematical description:

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

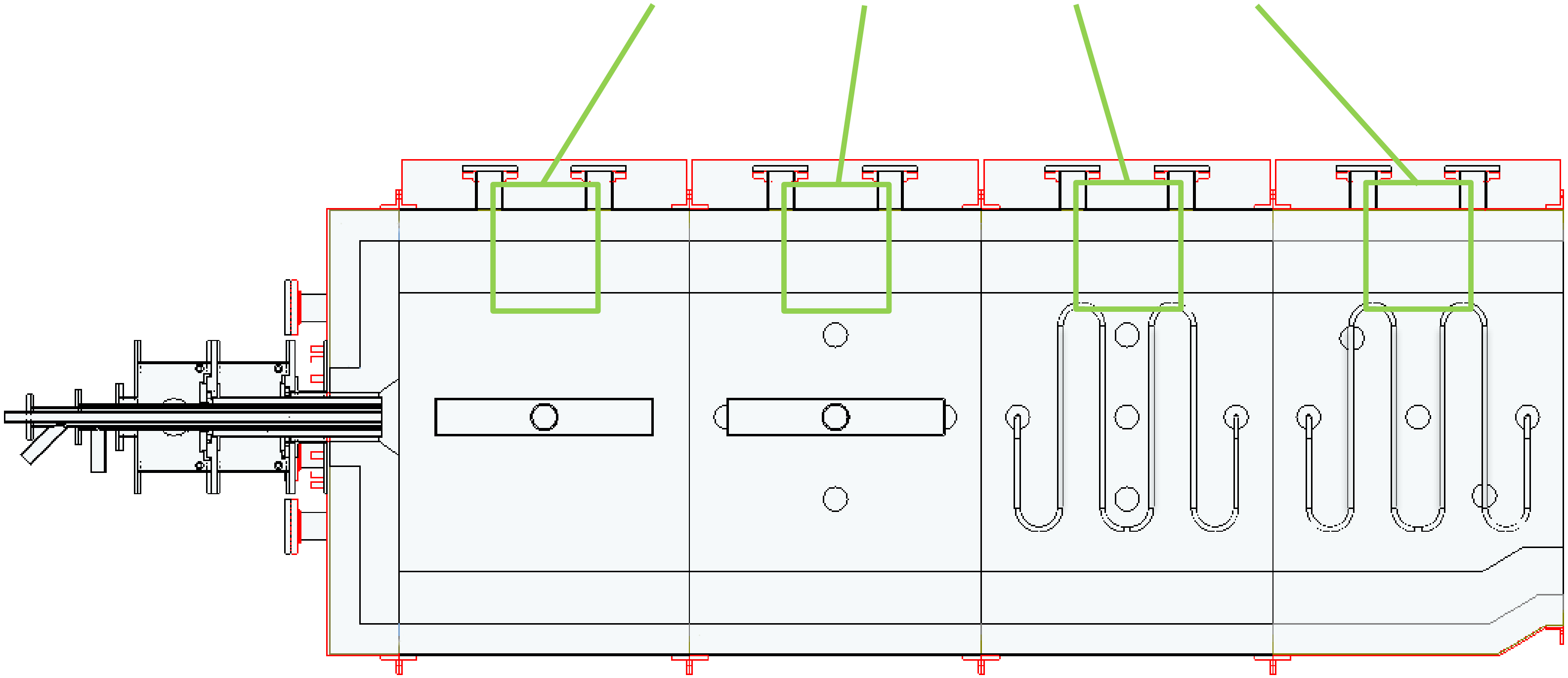
Quantifiable sources of error:

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

Measuring Wall Temperatures and Wall Refractory Heat Flux

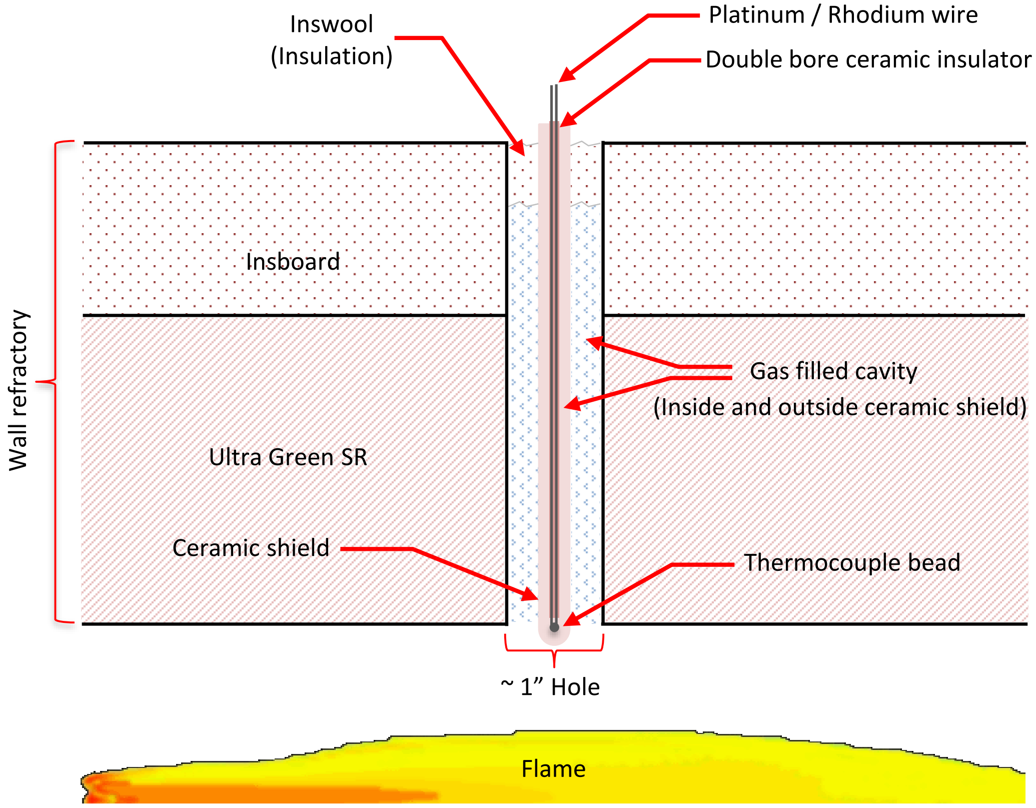
Wall Thermocouples

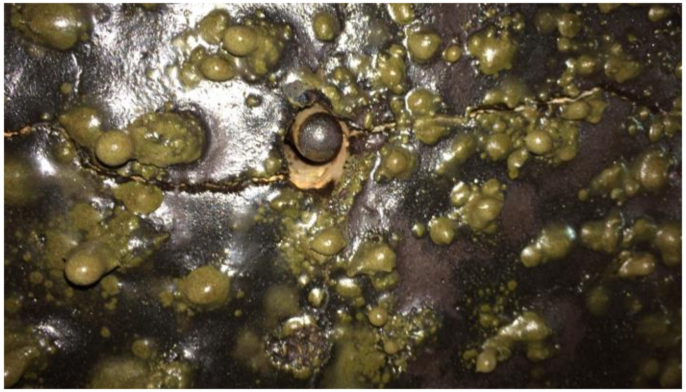
Installed in the center of the top wall of each section



Permanently installed indicator of temperature profile
(continuous data)

Old Wall Thermocouple Device

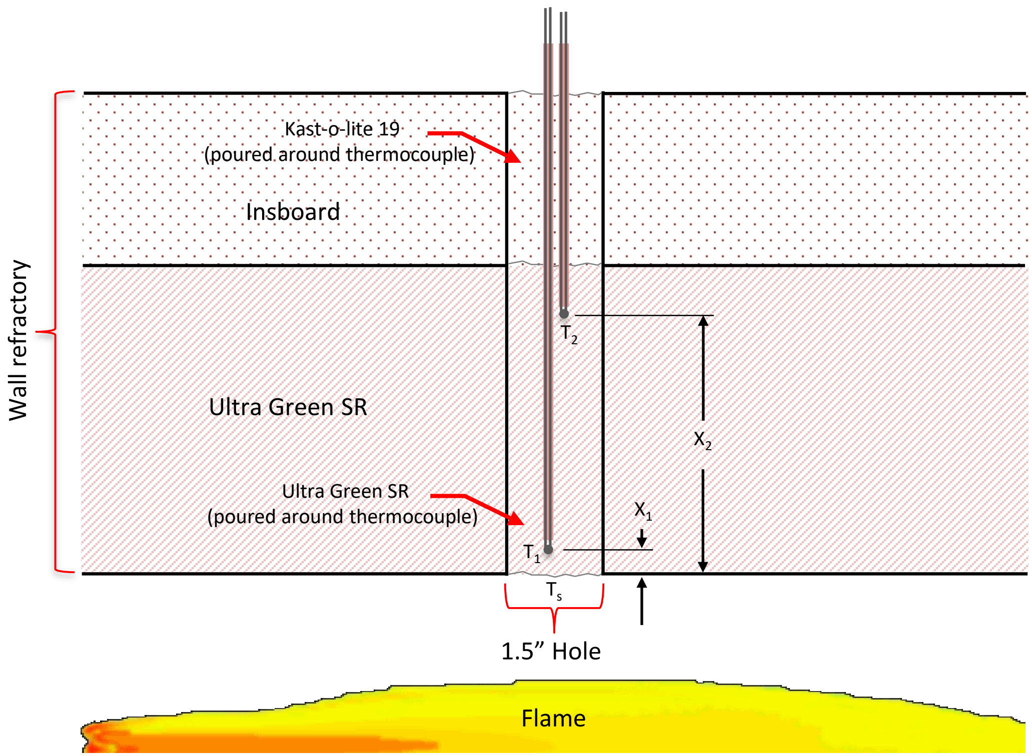




Measured temp is not of the wall

- 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

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
- Difficult to install

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-B thermocouple bead
- Variability in thermocouple set depth measurement
- Variability in material thermal properties

Expected Behavior:

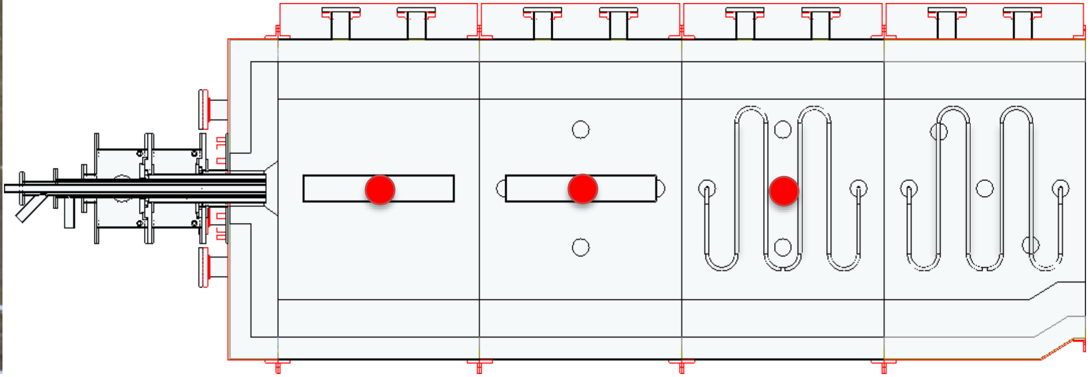
ΔT = 748 to 894 ± 5 (°C)

q = 1651 to 1971 ± 171 (W/m^2)

Range is from section 1 through 10 device distributions

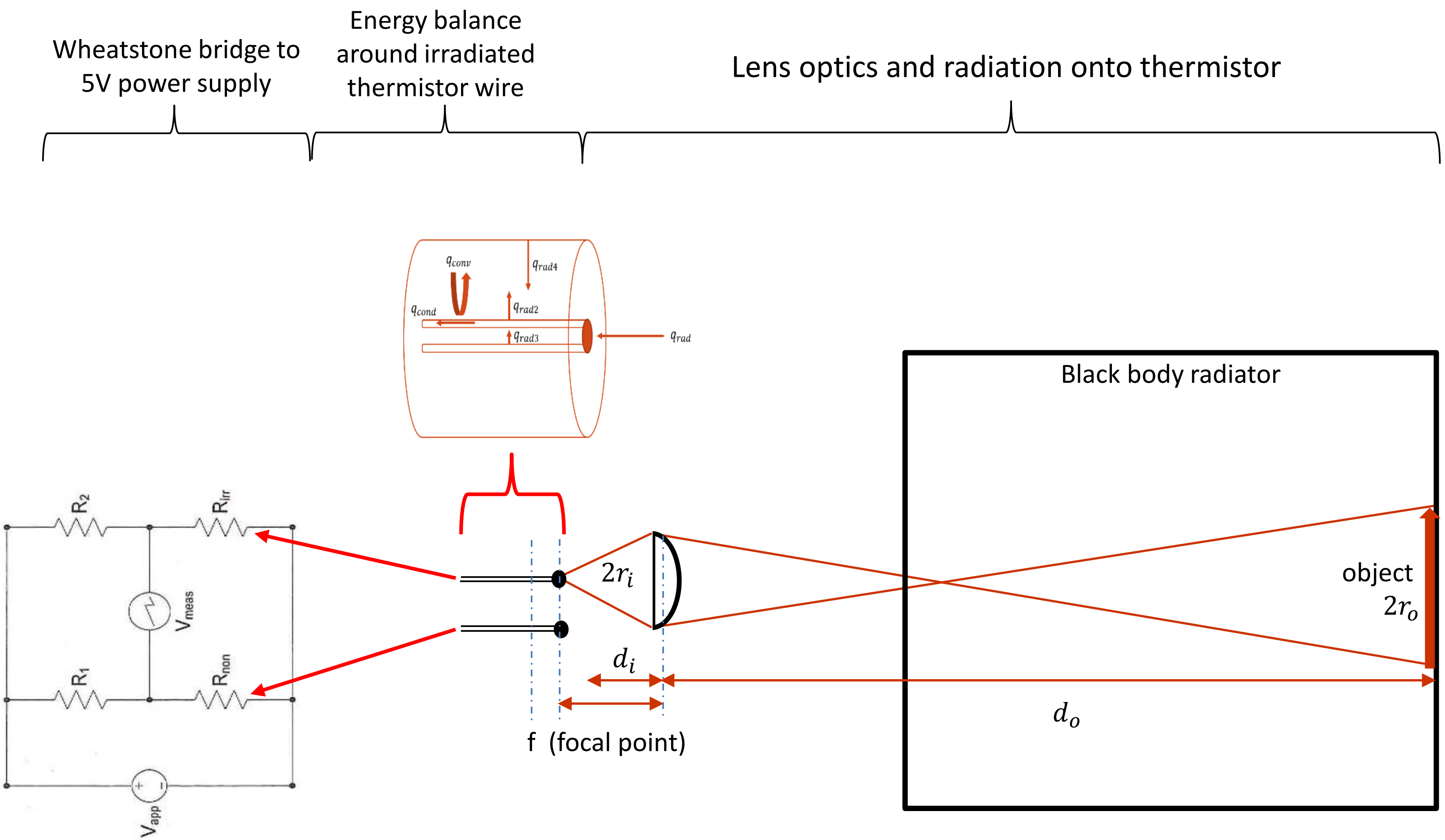
Measuring Radiative Heat Flux

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



Radiometer Instrument Model

Mathematical Description:

$$d_i = \frac{1}{\frac{1}{d_o} + \frac{1}{f}} \qquad r_i = \frac{d_i r_o}{d_o}$$

Lens optics

$$I_i = I_o \left(\frac{r_{lens}}{r_i} \right) (1 - \rho)$$

$$q_{rad} = \pi r_i^2 I_i$$

Thermistor irradiation

$$q_{rad} + q_{rad3} + q_{rad4} = q_{cond} + q_{conv} + q_{rad2}$$

$$R_t = R_{ref} exp \left(A + \frac{B}{T_t} + \frac{C}{T_t^2} + \frac{D}{T_t^3} \right)$$

Energy balance

$$V_{meas} = V_{app} \left(\frac{R_{non}}{R_{non} + R_1} - \frac{R_{irr}}{R_{irr} + R_2} \right)$$

Wheatstone bridge

L1500 Heat Balance

L1500 Heat Balance (High Temp Oxy-coal)

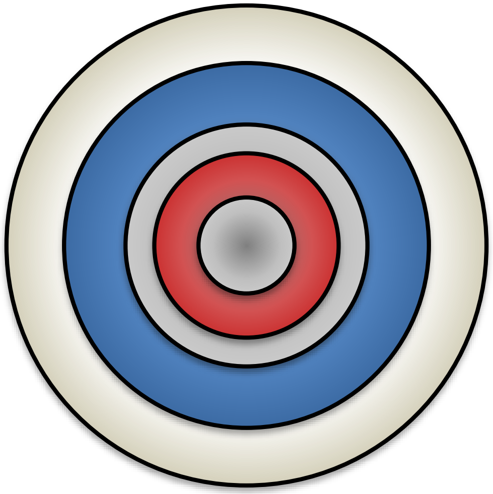
Targeted Conditions

Firing Rate	Btu/hr	3.0
Coal Rate	lb/hr	238
Primary Air/FGR	lb/hr	302
Primary O_2	lb/hr	55
Inner Secondary Air/FGR	lb/hr	
Inner Secondary O_2	lb/hr	478
Inner Secondary Temp	˚F	100
Outer Secondary Air/FGR	lb/hr	
Outer Secondary O_2	lb/hr	
Outer Secondary Temp	˚F	

Skyline Coal Composition

C	70.60
H	5.05
N	1.42
S	0.53
O	10.39
Ash	8.83
Moisture	3.18
Volatile Matter	38.6
Fixed Carbon	49.4
HHV, Btu/lb	12606

* all values in mass % unless otherwise specified

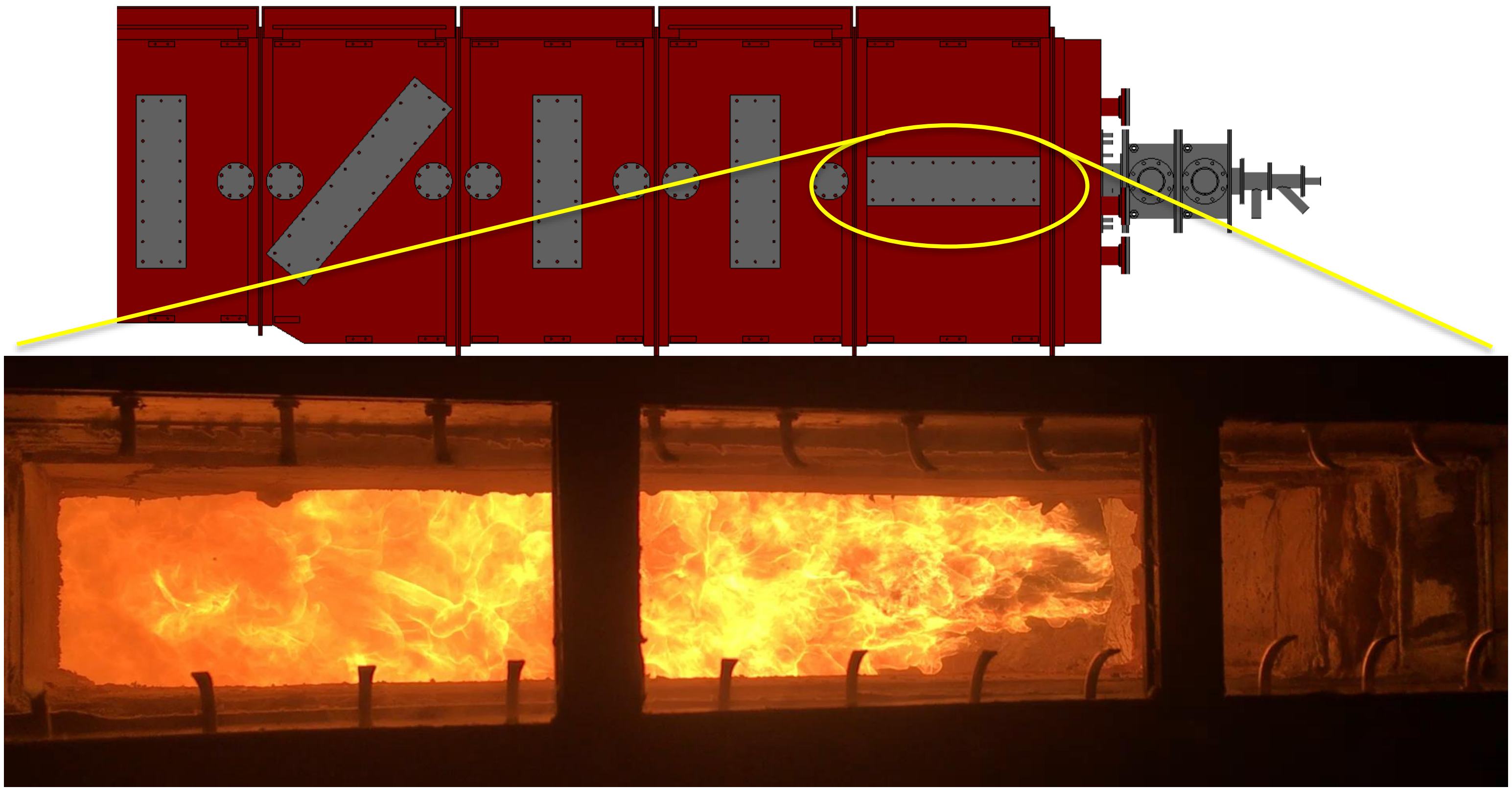


- Primary Gas / Coal

- Secondary Gas (O_2)

L1500 Heat Balance

Example Data Set



* Air-fired flame at the end of the high temperature oxygen test

L1500 Heat Balance

Example Data Set

Methods:

- Furnace heat removal can be assessed in two ways
  - Enthalpy of the reactants minus the enthalpy of the flue gas at the furnace exit
  - Direct measurement of active heat removal through water cooled surfaces plus heat loss through the refractory wall

L1500 Heat Balance

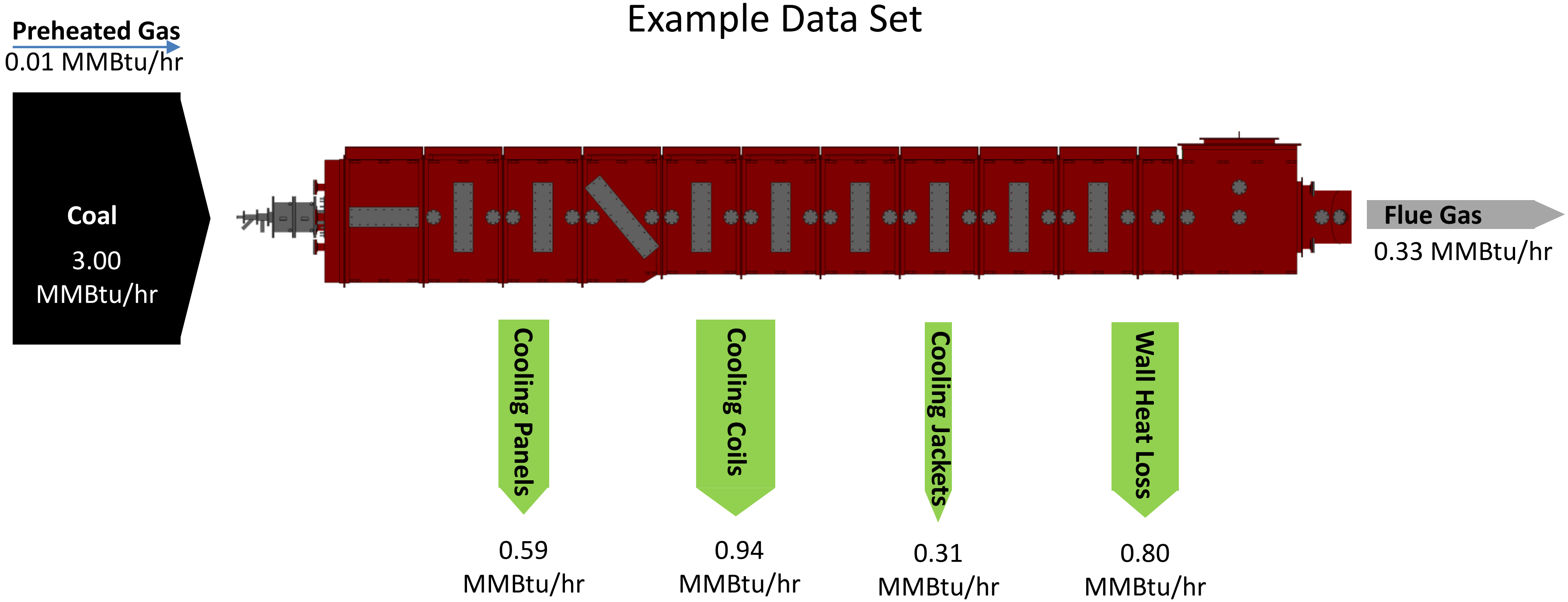
Example Data Set

Assumptions:

- Heat loss through the refractory wall is significant
  - Can be estimated using the measured heat flux in the roof of each section.
  - Heat loss is assessed by applying the measured heat flux uniformly across each furnace section
  - Heat flux through the burner plate is assumed to be the same as in section 1
  - Heat flux through section 11 and 12 is assumed to be the same as section 10
  - Heat removal through both radiation heat exchangers is assumed to be the same.

L1500 Heat Balance

Example Data Set



Heat Loss From Furnace

2.69 MMBtu/hr

1.3 % Difference

Measured Heat Removal

2.64 MMBtu/hr

Summary & Conclusions

- Weaknesses of year 1 measurements performed in the 1.5 MW oxy-coal unit have been identified
- Measurement devices have been upgraded to quantify:
  - Heat transfer through cooling surfaces
  - Wall temperatures
  - Radiation intensity
- Instrument models have been developed
- Pathway for uncertainty quantification has been developed

Questions