Characterization of Oxy-combustion Impacts in Existing Coal-fired Boilers (DE-NT0005288)

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For Energy and Environmental Solutions

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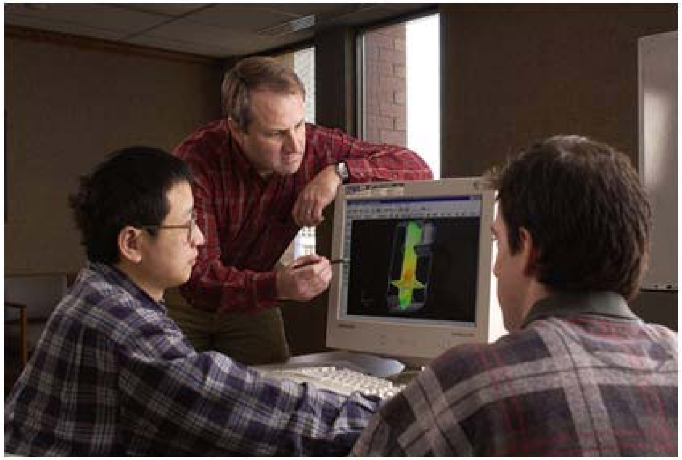
REI Profile

- **Energy And Environmental Consulting Firm**
  - Combustion System Design and Analysis
    - Combustion Performance, Emissions, Operational Impacts
  - Advanced CFD Simulations
  - Customized Process Software
  - R&D / Proof-of-Concept Testing
  - Specialized Test Equipment



- **Use Advanced Technology to Solve Industrial Challenges**

Oxy-Combustion Program Overview

- **<u>Objective:</u> Characterize and predict performance and operational impacts of *oxy-combustion retrofit* designs on *existing coal-fired boilers***
- **3-year program (10/1/08 – 9/30/11)**
  - **Recent no-cost extension to 3/31/2012**
- **Funding:**
  - **DOE Cost $2,276,327**
  - **FFRDC $100,000**
  - **Cost-Share $617,882**
  - **Total Program $2,994,209**

Project Team

Team Member	Project Role
REI	*program management, testing oversight, mechanism development, simulations*
University of Utah	*laboratory and pilot-scale testing, mechanism development*
Siemens Energy	*burner technology, firing system design*
Praxair	*oxygen and CO_2 supply*
Brigham Young Univ.	*soot measurements*
Corrosion Management	*corrosion tests, mechanism development*
Sandia National Labs	*bench-scale testing, mechanism development*
Vattenfall AB	*mechanism development, validation data*
PacifiCorp, Praxair, Southern Company, Vattenfall, DTE	*Advisory Panel provides industrial perspective on R&D needs, retrofit requirements and constraints, suggested assessment studies*

Project Approach

- **Utilize multi-scale testing and correlations to develop:**
  - **Fundamental data that describe flame characteristics, corrosion rates, and ash properties during oxy-coal firing**
  - **Validated mechanisms that describe oxy-combustion processes**
  - **Firing system principles that guide oxy-burner design and flue-gas recycle properties**
- **Incorporate validated mechanisms into CFD model to evaluate full-scale oxy-combustion retrofit designs**
  - **Predict flame characteristics and surface impacts for different full-scale oxy-firing designs and FGR properties**

Years 1 and 2 Focus

- **Mechanism identification**
- **Testing**
  - **Oxy-firing burner principles**
  - **Ignition & flame attachment**
  - **Char oxidation**
  - **NOx, SOx, Hg**
  - **Soot**
  - **Fine particulates**
  - **Heat flux profiles**
  - **Ash chemistry**
  - **Waterwall and superheat corrosion**

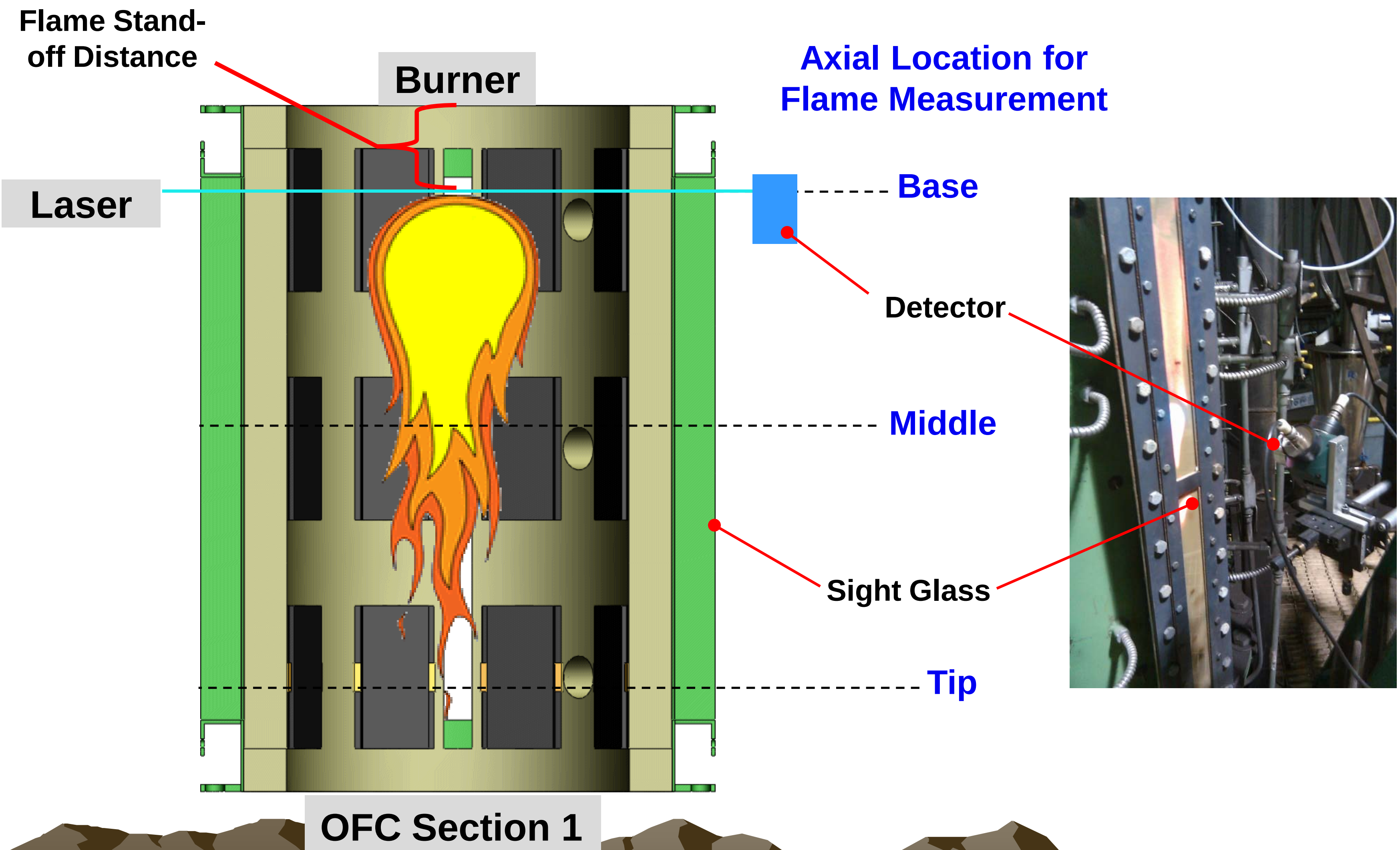
- **Mechanism refinement and implementation into CFD**
  - **Slagging sub-model**

Year 3 Focus

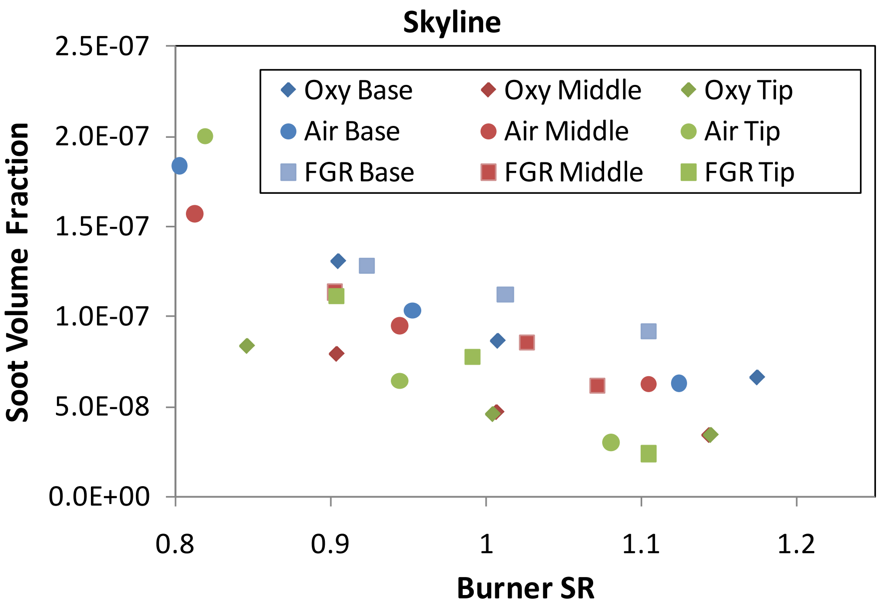
- **Complete Testing**
  - Soot
  - Fine particulates
  - Char oxidation
- **Complete mechanism refinement / validation and implement into CFD**
  - Char oxidation (done)
  - Gas radiation (done)
  - Soot (in-process)
  - Corrosion (in-process)
- **Full-scale oxy-retrofit assessment**
  - Candidate boiler firing-system design
  - CFD modeling

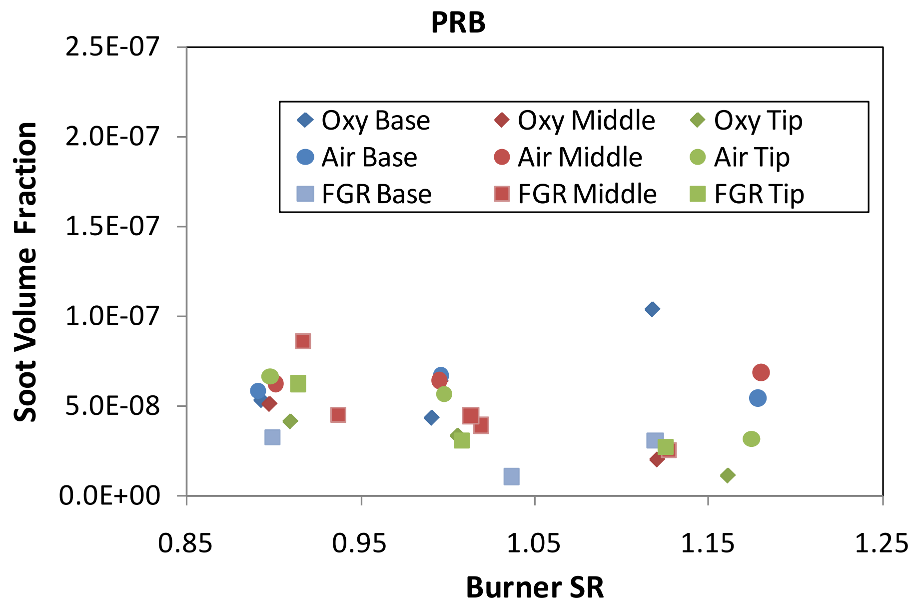
Line-of-sight Soot Measurements (OFC)

Experimental Setup



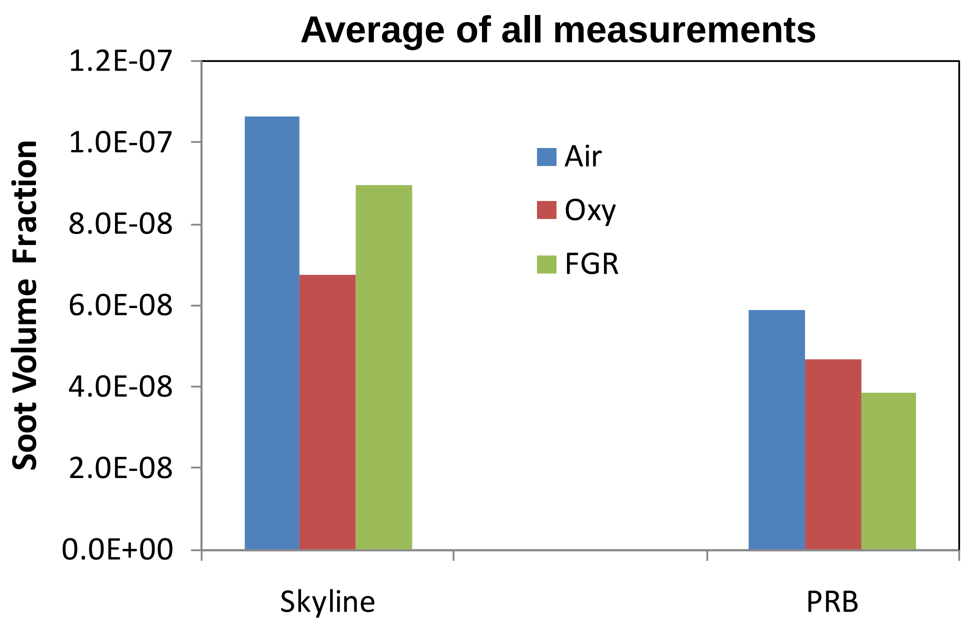
Line-of-sight Soot Measurement Data





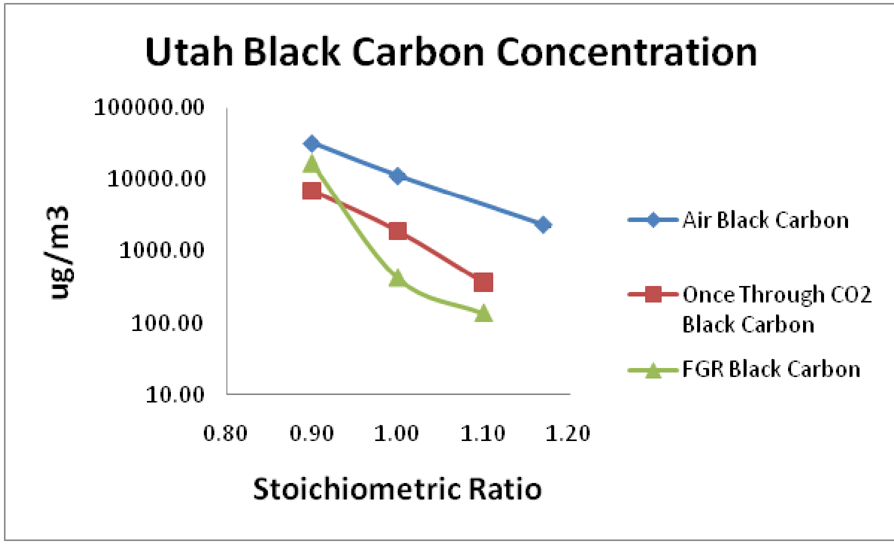
- **Soot volume fraction dependent on SR, increases with decreasing SR; PRB SR dependence less pronounced**
- **For Skyline coal, SVF generally highest at flame base and lowest at flame tip; PRB had less differentiation through flame**
- **SVF higher for Skyline coal than PRB coal**

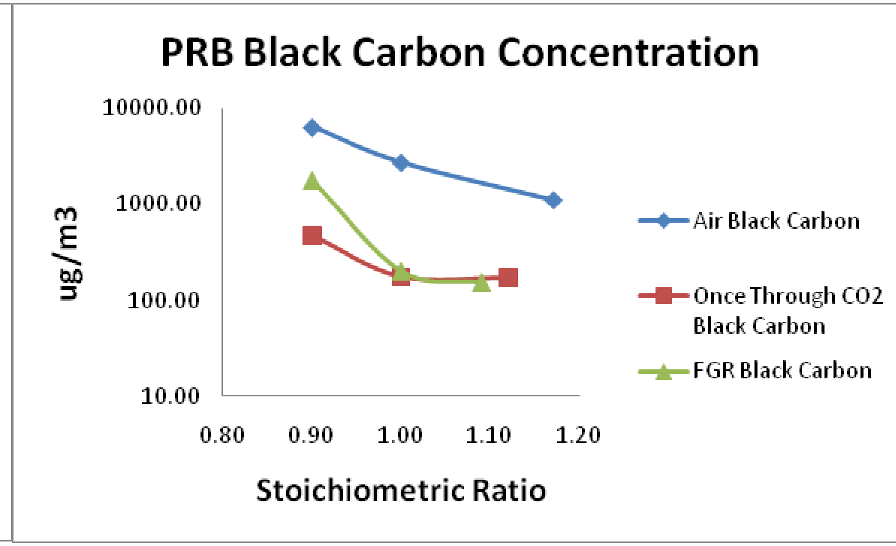
Line-of-sight Soot Measurement Data



- **SVF higher for Skyline coal than PRB coal**
- **SVF lower for oxy-combustion than air-combustion**
- **Soot generation/destruction tied to flame aerodynamics and gas stream mixing**

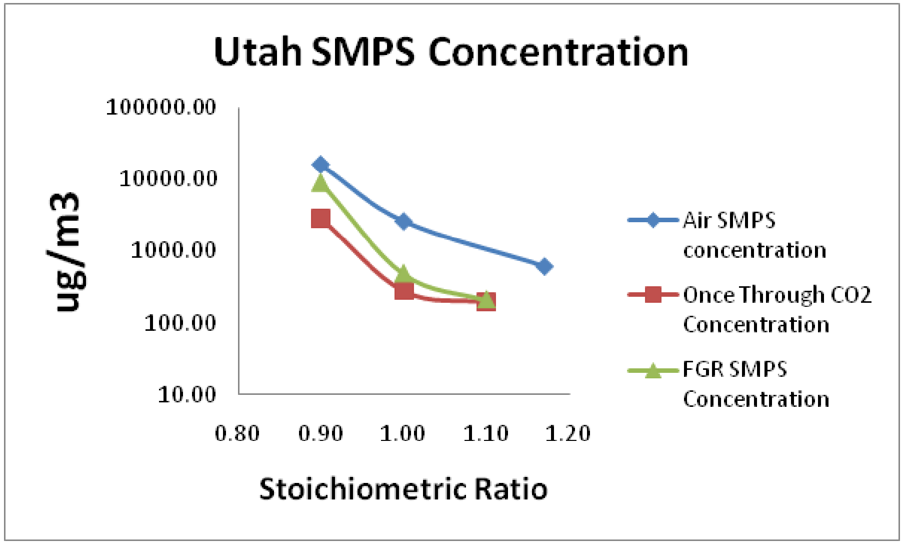
OFC Black Carbon Results (PA analyzer)

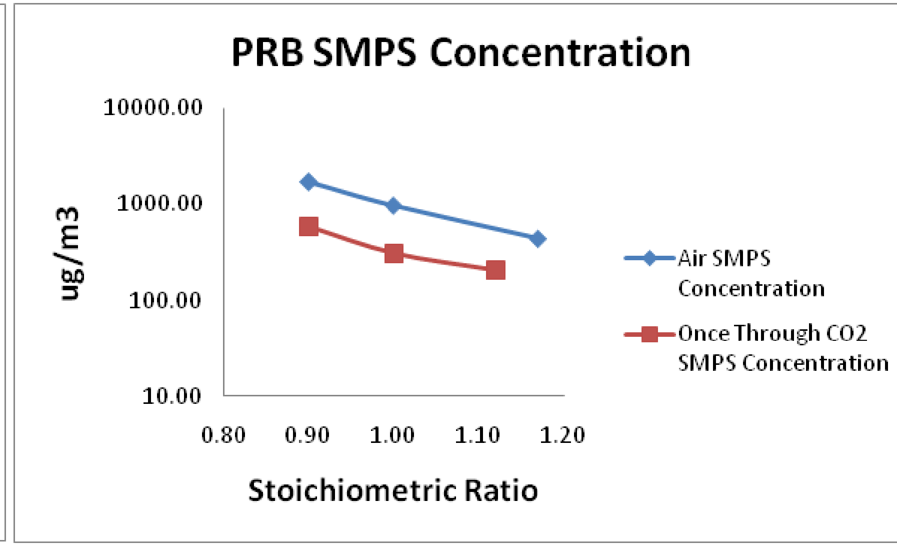




- **Black carbon emissions increase with decreasing SR**
- **Utah coal produced higher black carbon emissions than PRB**
- **Oxy-firing reduces black carbon emissions from flames when compared to air-firing for all coals tested (Utah, PRB, Illinois)**
- **The presence of >30% water vapor in RFG can potentially reduce black carbon emissions due to steam impact on combustion**

OFC Size Distribution Results (SMPS)



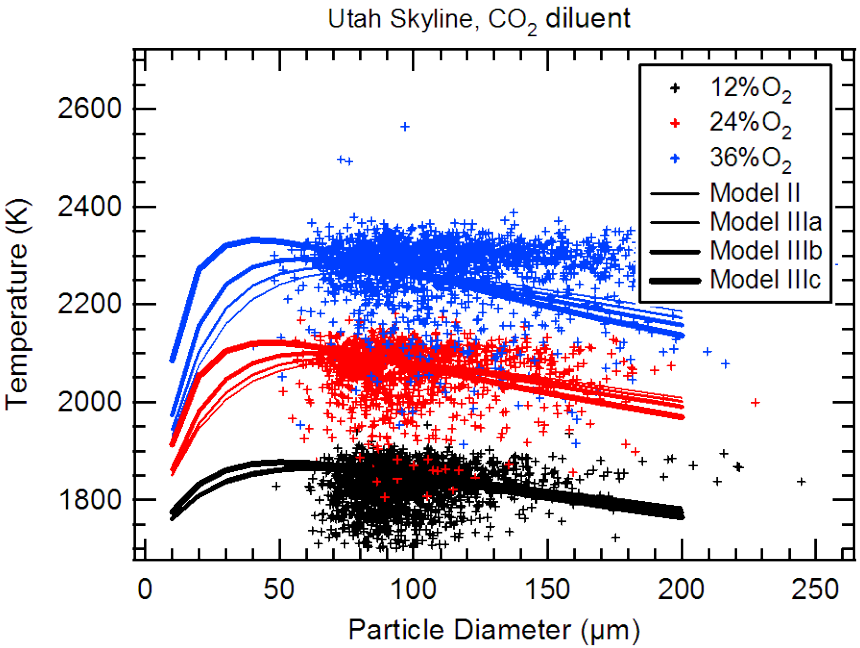


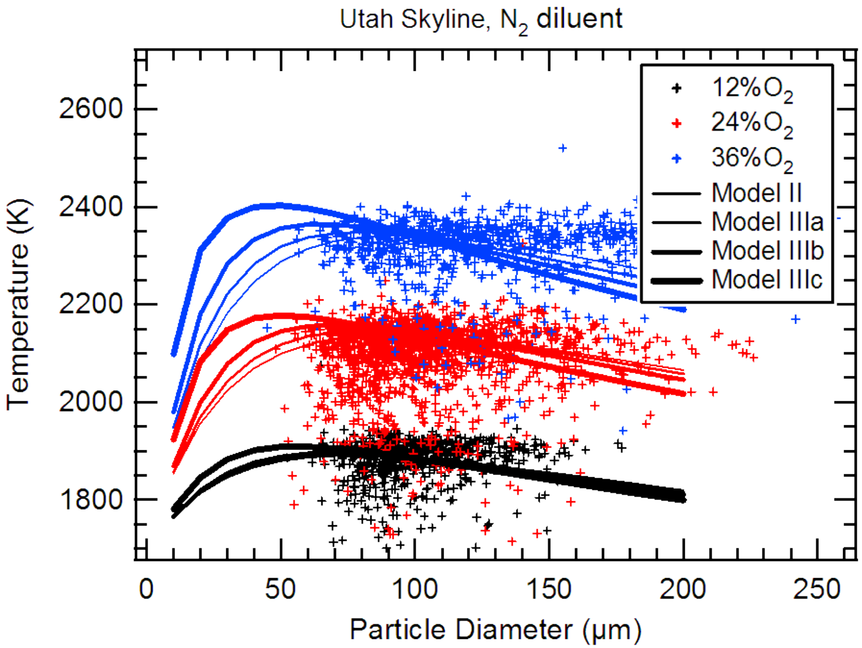
- **Ultrafine particle concentrations increase with decreasing SR**
- **Black carbon or soot particles are significant contributors to ultrafine particle concentrations**
- **When recycling untreated flue gas, it is possible to increase the concentration of ultrafine particles in the furnace**

Char Oxidation Mechanism

- Original mechanism has oxidation-only single film model, different behavior with oxy-combustion (higher O_2, CO_2, H_2O)
  - BL diffusion & reactions, gasification reactions
- Experimental investigation
  - Optical measurements on individual particles burning in controlled lab-scale environments (O_2, H_2O concentrations; N_2 or CO_2 diluent)
  - Measured particle temperature-size data as basis for model comparison and estimation of fitting parameters for use in CFD code
- Extended Single Film model
  - Include (heterogeneous) steam and CO_2 gasification reactions in commonly employed oxidation-only single film model
  - Fit rate parameters to match observed temperatures of 100 µm particles burning in N_2 (with 12% and 36% O_2) and CO_2 (36% O_2)
  - Predict char oxidation characteristics for both air and oxy-fired environments at different O_2 conc. and 10-200 µm particles

Extended Single-film Model Comparisons



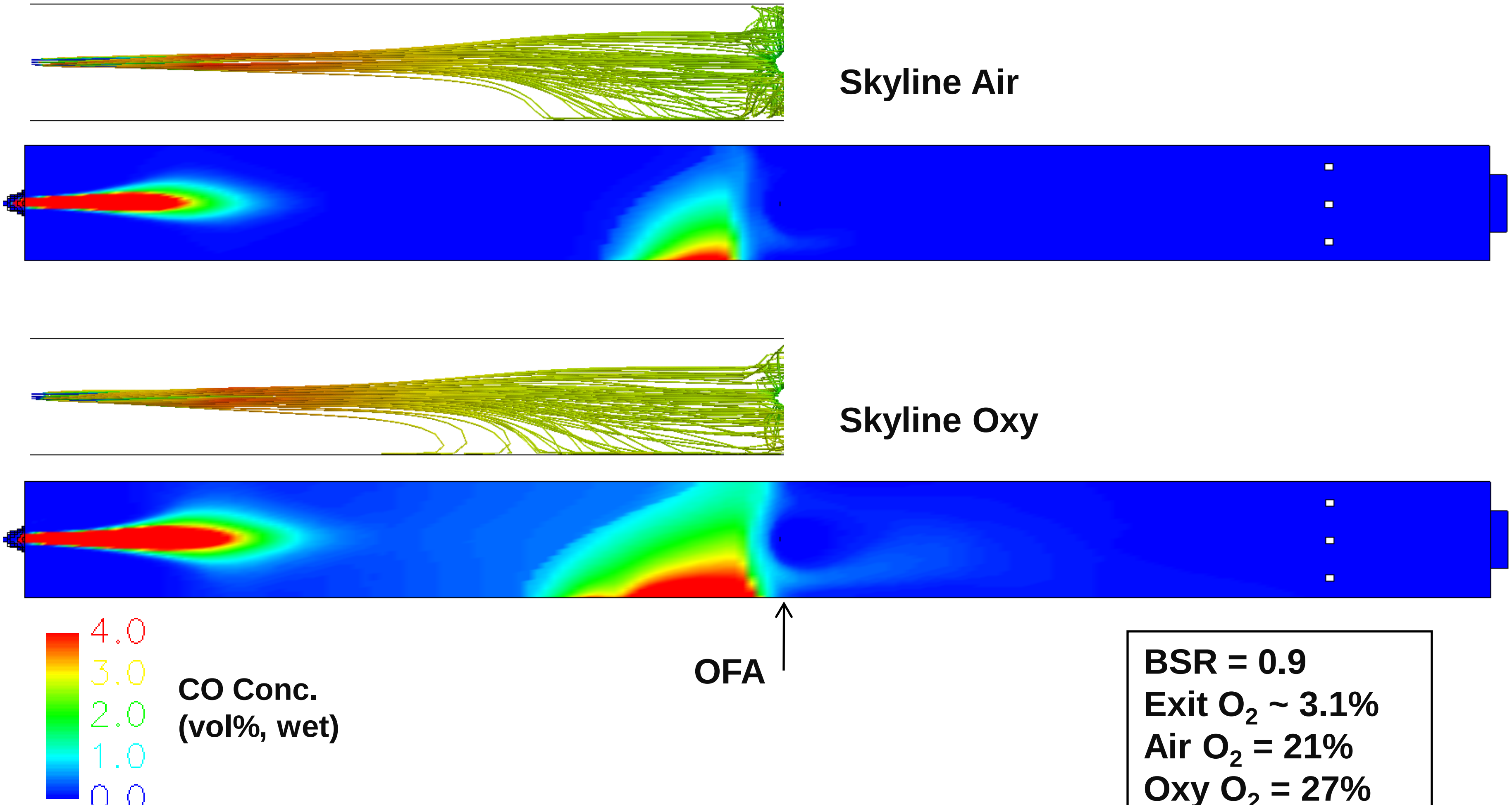


- **Char temperatures increase with increasing O_2 concentration, nearly independent of size**
- **Predictions capture temperature behavior of trusted size range (roughly 100 µm)**
- **Good agreement for both air & oxy environments**

Char Oxidation Mechanism Summary

- **Extended Single Film model:**
  - Reliable CFD predictions seem feasible for both conventional and oxy-combustion environments if steam and CO_2 gasification reactions are included in Single-Film model
  - Char consumption rates appear to be similar for both CO_2 and N_2 environments at equal O_2 concentrations, but are sensitive to gasification rates at high particle temperatures (due to high O_2 concentrations)
  - Gasification reactions matter at high temperatures (high O_2), not only where CO_2 concentrations are high
- **Implement in CFD code and test impacts on model of L1500 pilot-scale furnace**

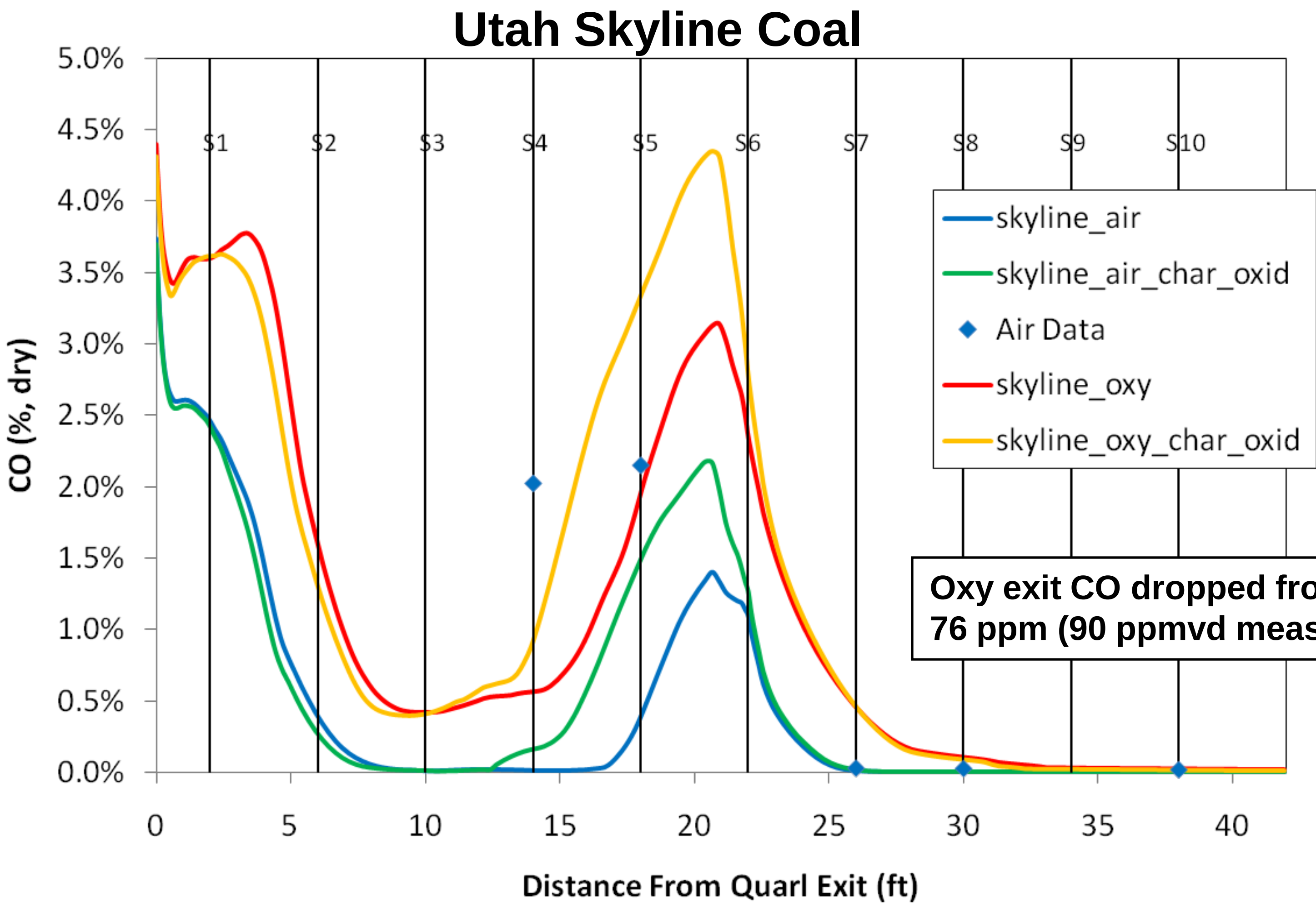
L1500 Particle Trajectories and CO Profiles



BSR = 0.9
Exit O_2 ~ 3.1%
Air O_2 = 21%
Oxy O_2 = 27%

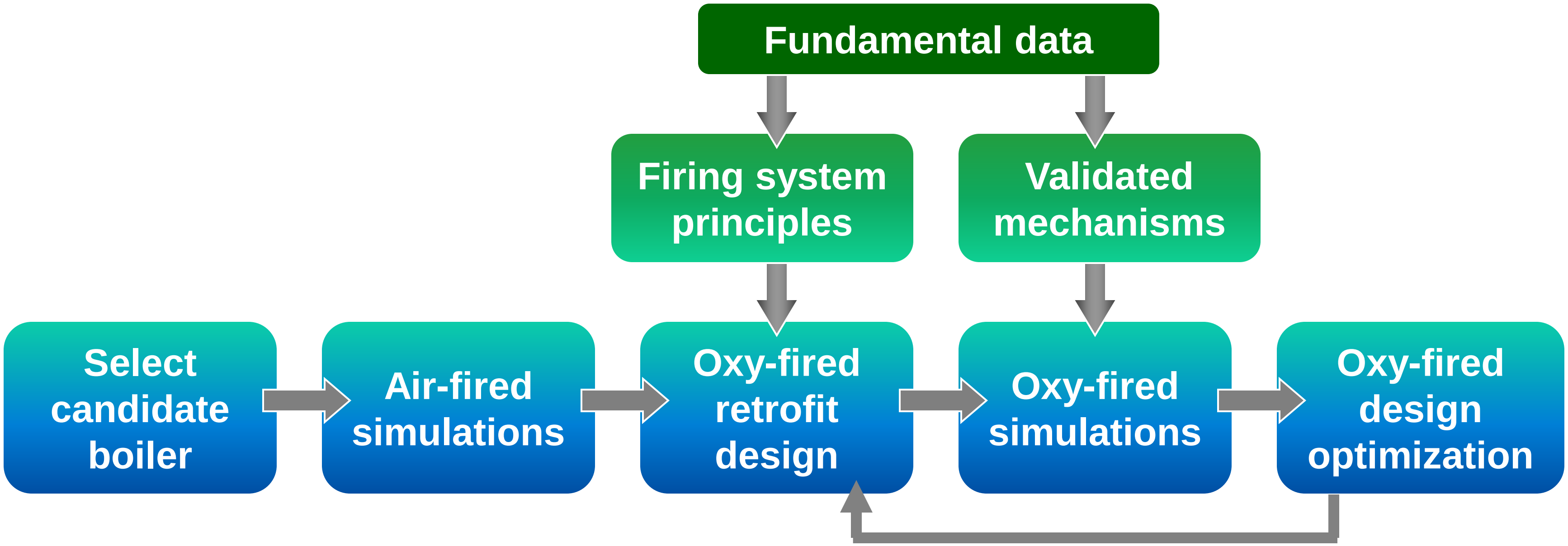
Average CO Concentration Comparison

(with extended char oxidation model)



Oxy exit CO dropped from 126 to 76 ppm (90 ppmvd measured)

Full-scale Boiler Assessment Approach

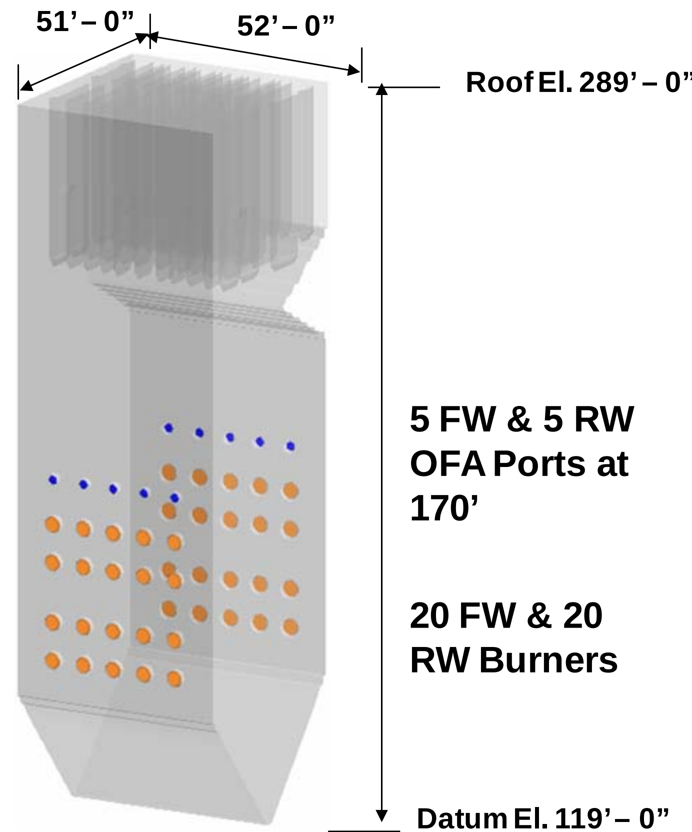


Design and optimization criteria:

- Match air-fired heat duties
- Maximize combustion efficiency
- Minimize surface impacts (corrosion, slagging, fouling)
- Minimize trace pollutant emissions

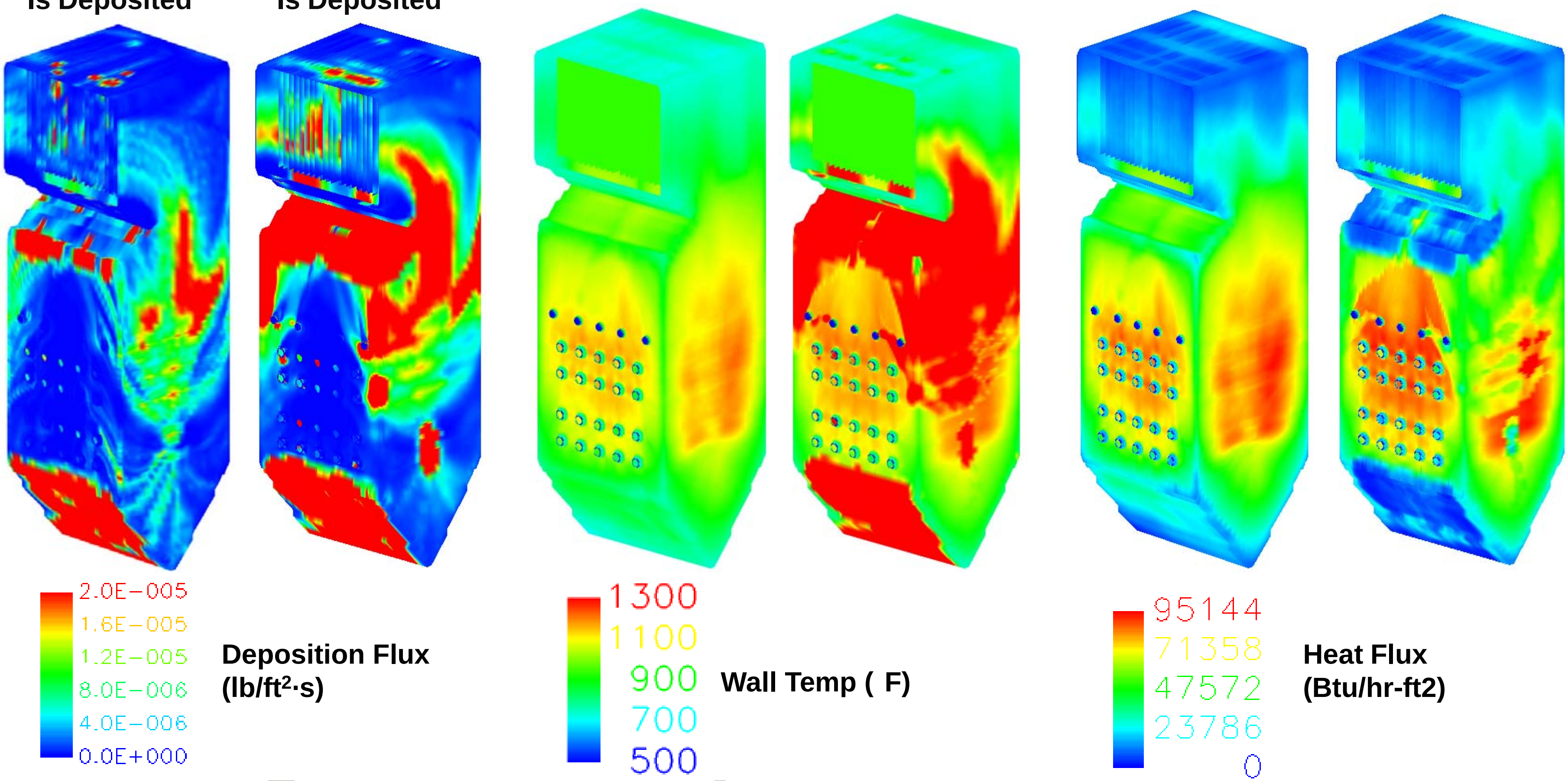
PacifiCorp Hunter Unit 3

- **460 MW_e opposed wall-fired**
- **40 Staged low-NOx burners with 10 overfire air ports**
- **Fires Utah bituminous coal**
- **Steam cycle well-characterized during LNB/OFA retrofit**
- **Modeling includes radiant furnace and back pass**
  - **CFD model for local detail (combustion, deposition, heat transfer, pollutants)**
  - **Process model for steam circuit impacts**



Hunter 3 Air-fired Results

Baseline	Slagging	Baseline	Slagging	Baseline	Slagging
12.7% of Coal Mineral Matter Is Deposited	27.0% of Coal Mineral Matter Is Deposited			T_{ex} = 1862 F UBC = 7.0%	T_{ex} = 1938 F UBC = 4.6%

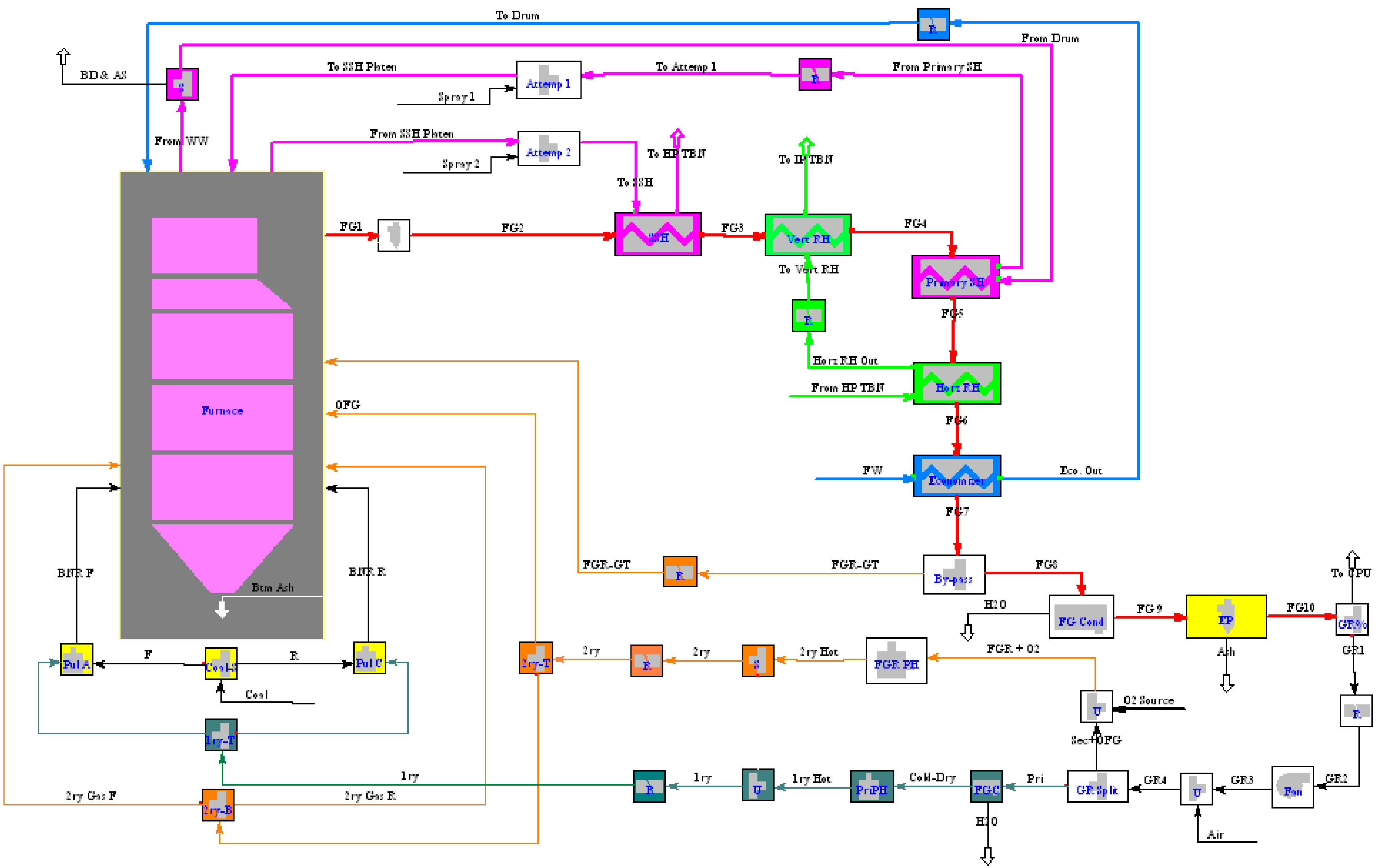


Graphics from Intelligent Light’s *Fieldview* Software

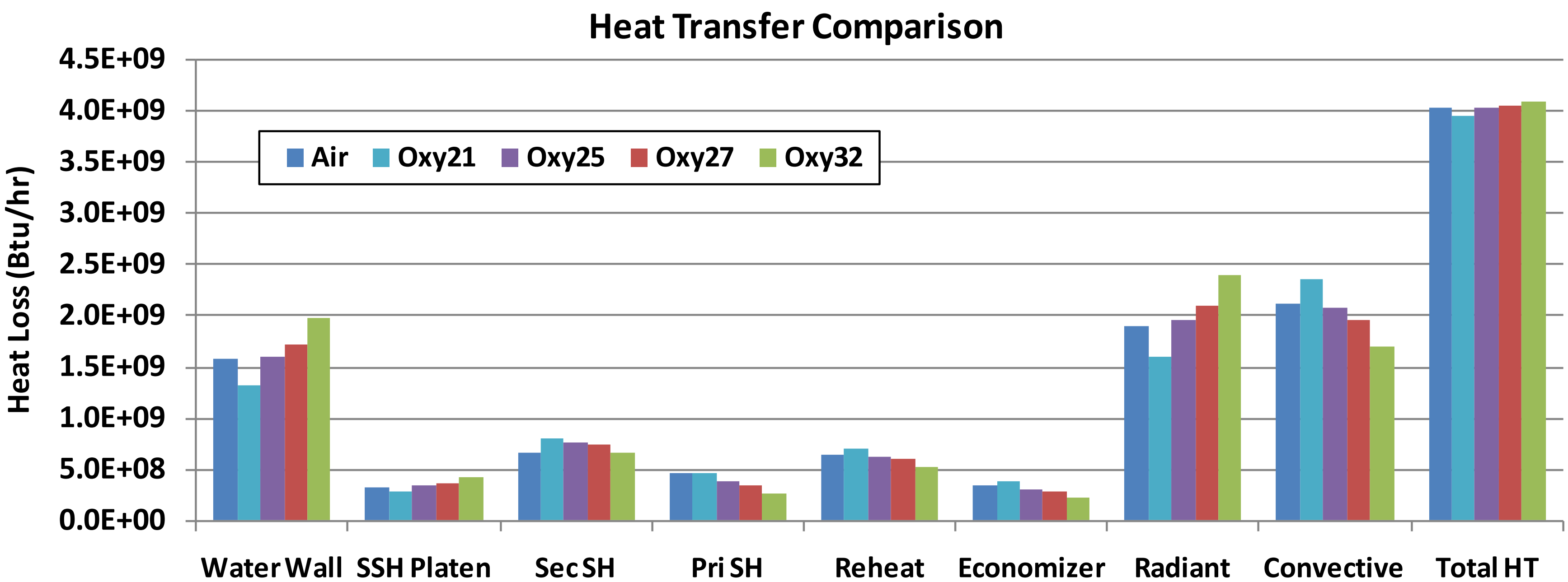
Overview of Firing System Design

- **SteamGen Expert (process model) used to estimate heat transfer during air-firing and oxy-firing at various oxygen concentrations and FGR flow rates**
  - **Air-fired boiler measurements used to guide setup of radiant and superheat heat exchanger modules**
- **Calculations performed to determine whether burners should be designed for air or oxy-fired conditions**
  - **Calculations based on Siemens' new burner design to determine register velocities under air- and oxy-fired conditions**

SteamGen Expert Process Modeling

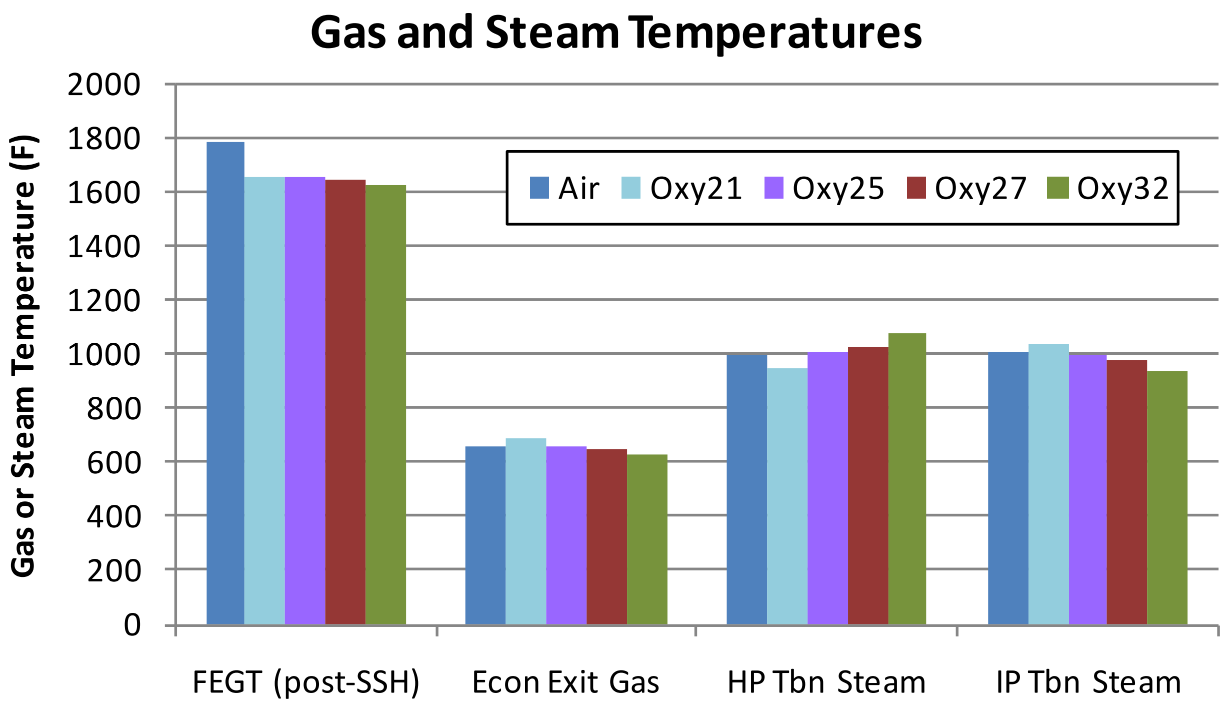


Heat Exchanger Comparison (SGE)



- Waterwall HT increases with increasing O_2 due to hotter flames
- Convective HT decreases with increasing O_2 due to decreased gas flow
- Oxy25 appears to best match air-fired heat transfer (see also next slide)

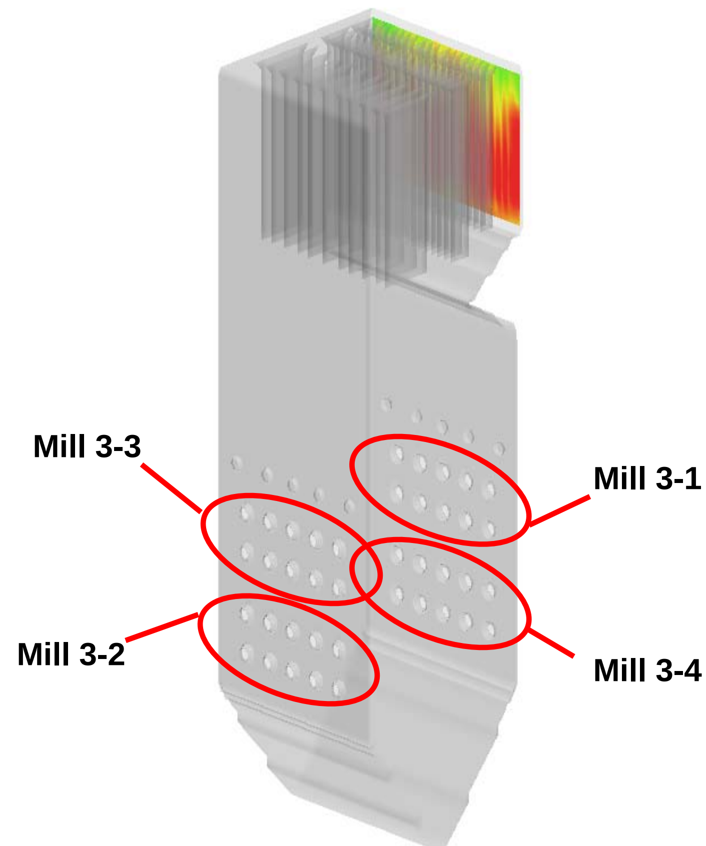
Gas and Steam Temperature Comparison (SGE)



- **Oxy FEGTs lower than air, similar (furnace gas temperature changes balanced by heat absorption changes)**
- **HP turbine steam temp trend opposite SSH absorption trend, but consistent with waterwall and platen absorption trends, which dominate**
- **IP turbine steam temp trend matches RH absorption trend**

Determination of Burner Retrofit Approach

- When designing burners for air-fired conditions, oxy-firing velocities are much lower
  - Determine what increase in velocity is caused by removing one mill from service and operating with 30 burners on oxy-firing at the same firing rate
- The oxy-firing velocities were too high with one mill out of service
  - Significant modifications to the firing conditions (BSR and Pri Gas/Fuel) necessary to match design velocities
- Therefore the burner should be designed for oxy-firing
  - Concessions may be necessary on emission performance or firing rate during air-firing



4 mills total, 10 burners on each mill

Firing System Design Summary

- SteamGen Expert was used to model heat transfer during oxy-firing at various oxygen concentrations
  - 25% O_2 and 27% O_2 were found to best match air-fired heat transfer rates, therefore 26% O_2 was chosen as the design criteria for oxy-firing
- Burner should be designed for oxy-fired conditions and the operation may be modified when air-firing
  - FGR assumed clean (~90% SO_2 removal)
  - 21% O_2 wet in primary for air and oxy-firing
- Calculated burner register velocities for Siemens' new burner used for oxy and air-fired modeling inputs

Program Status Summary

- Bench-, Lab-, Pilot-Scale Testing Completed
- Remaining Key Tasks
  - Complete validation and refinement of remaining mechanisms; implement in CFD code
  - Complete conceptual full-scale retrofit firing system design
  - Assess oxy-combustion retrofit impacts on existing boilers
    - PacifiCorp Hunter 3; DTE River Rouge 3
  - Document results in final report to DOE
- Future Objectives
  - Model ~15-30 MW_{th} pilot-scale oxy-fired unit for validation
  - Support oxy-combustion demonstration on full-scale unit

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Questions?

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