

REINHOLD ENVIRONMENTAL Ltd.



2011 NO_x-Combustion Round Table & Expo Presentation

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Impacts of Oxy-combustion Retrofit for Coal-fired Boilers

Bradley Adams, Andrew Fry

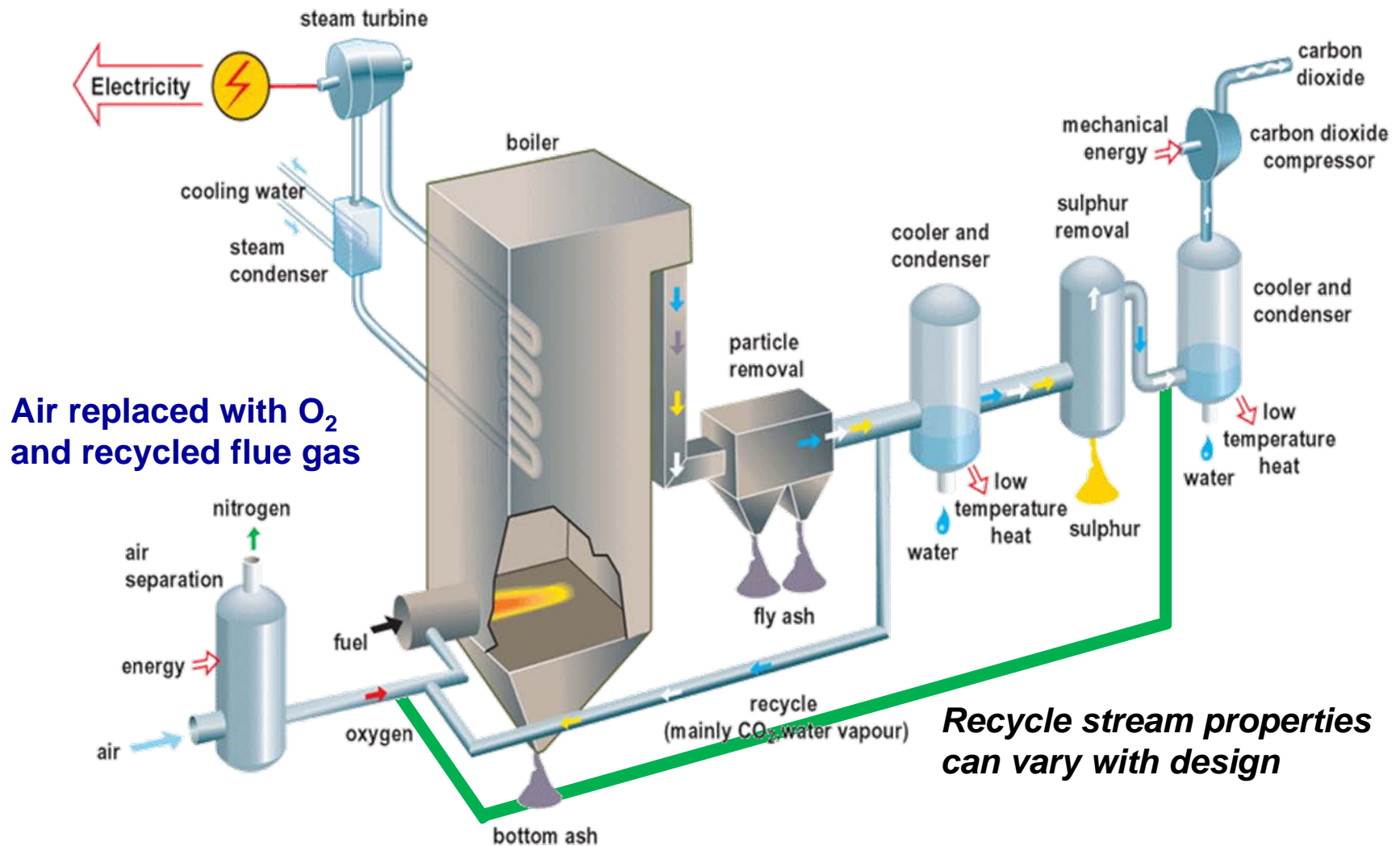
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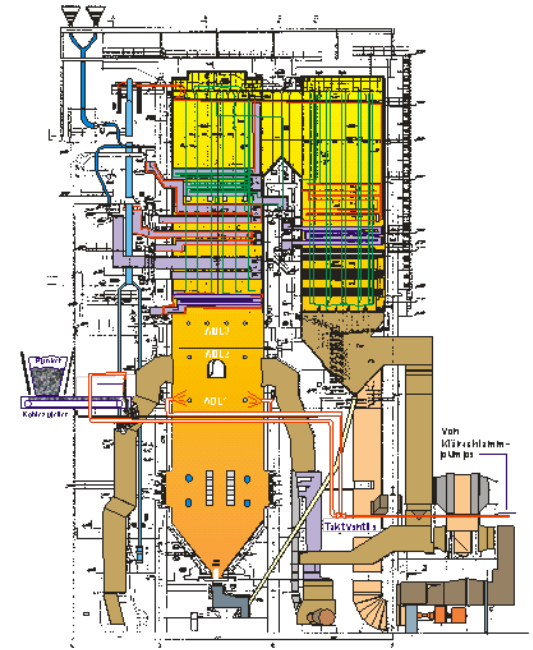


Oxy-Coal Power Plant Overview



Oxy-Combustion Advantages

- **Potential for high CO₂ recovery**
- **Applicable to new or existing plants**
 - New - more compact design
 - Existing - familiar design and operation
 - Applicable to CFB as well as PC plants
- **Trace pollutant benefits**
 - Lower NO_x, more oxidized Hg
 - May not need to clean flue gas as thoroughly for sequestration as for air-fired units



Oxy-Combustion Challenges

- **Higher plant cost**
 - Equipment (ASU, CO₂ compressor)
 - Design (materials, “plumbing”)
- **Lower plant efficiency**
 - Significant penalties from ASU and CO₂ compression
- **Technical challenges**
 - Balance of plant impacts
 - Operating availability with new technology

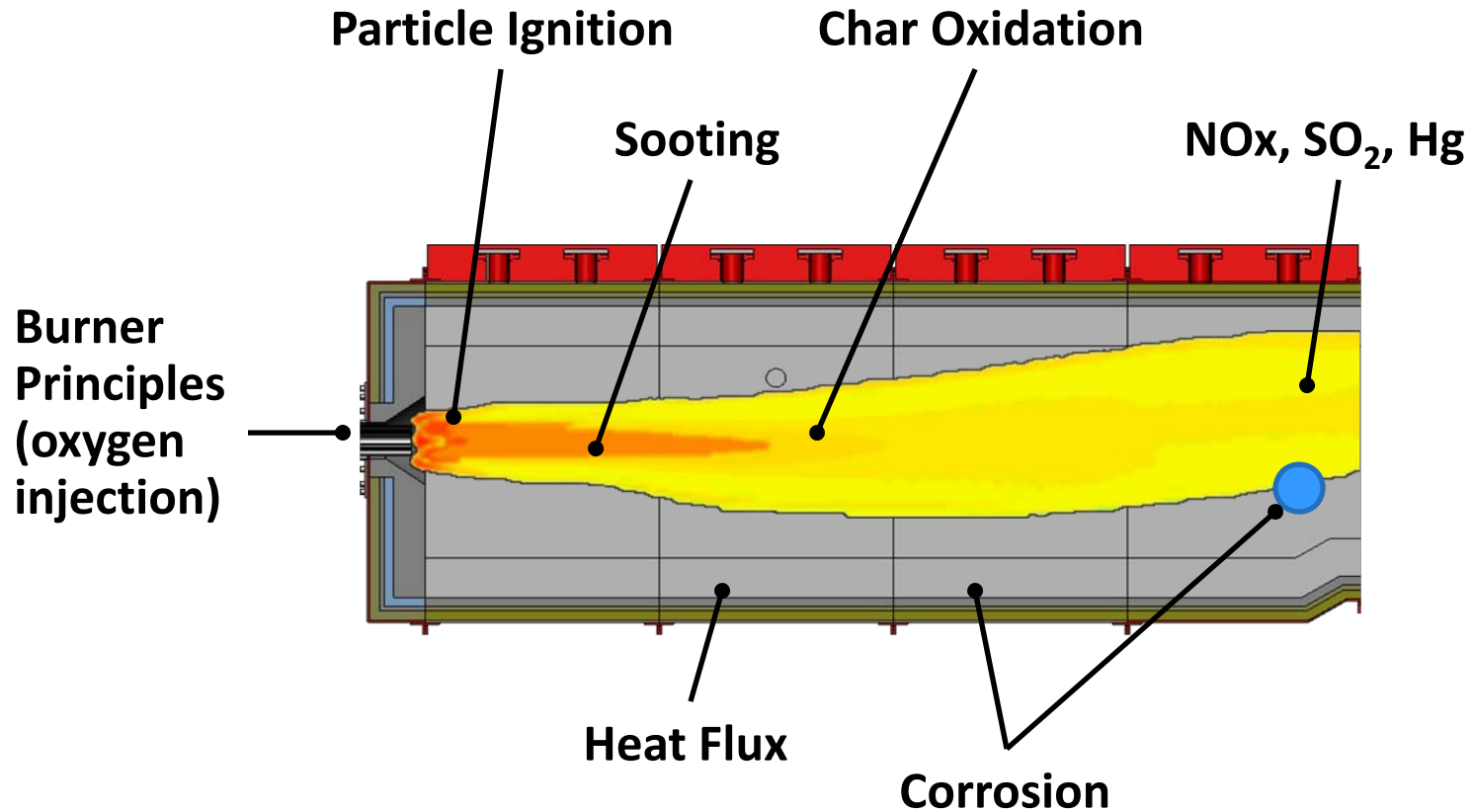


Oxy-Combustion Program Overview

- *3-yr \$3M DOE program to characterize performance and operational impacts of oxy-combustion retrofit designs on existing coal-fired boilers*
- Utilize theory and multi-scale testing to develop:
 - **Fundamental data** that describe flame characteristics, waterwall corrosion, and ash properties (slagging, fouling) in oxy-firing
 - **Validated mechanisms** that describe impacts of oxy-combustion
 - **Firing system principles** (effects of oxy-burner design, flue gas recycle)
- Incorporate validated mechanisms into **CFD models** and evaluate full-scale oxy-retrofit designs



Testing Focus

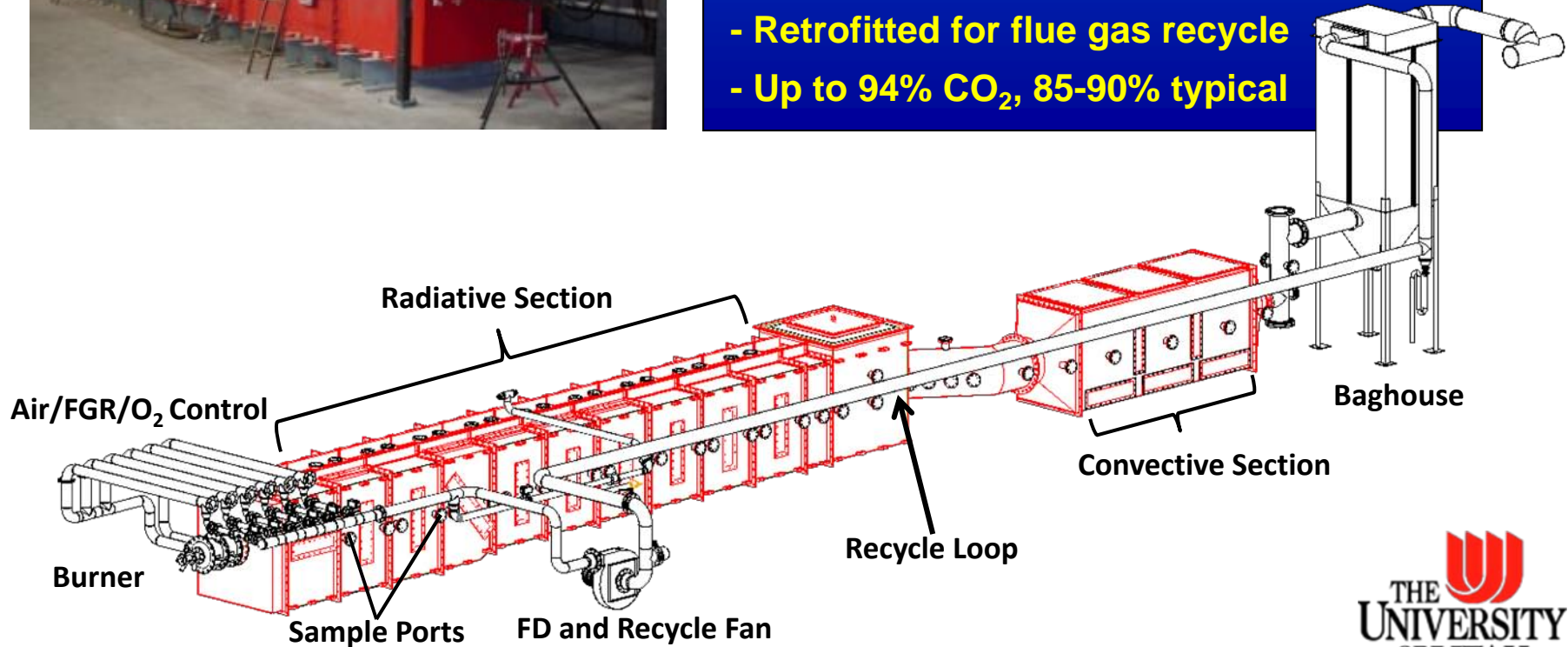


3.5 MBtu/hr Pilot-Scale Furnace (L1500)

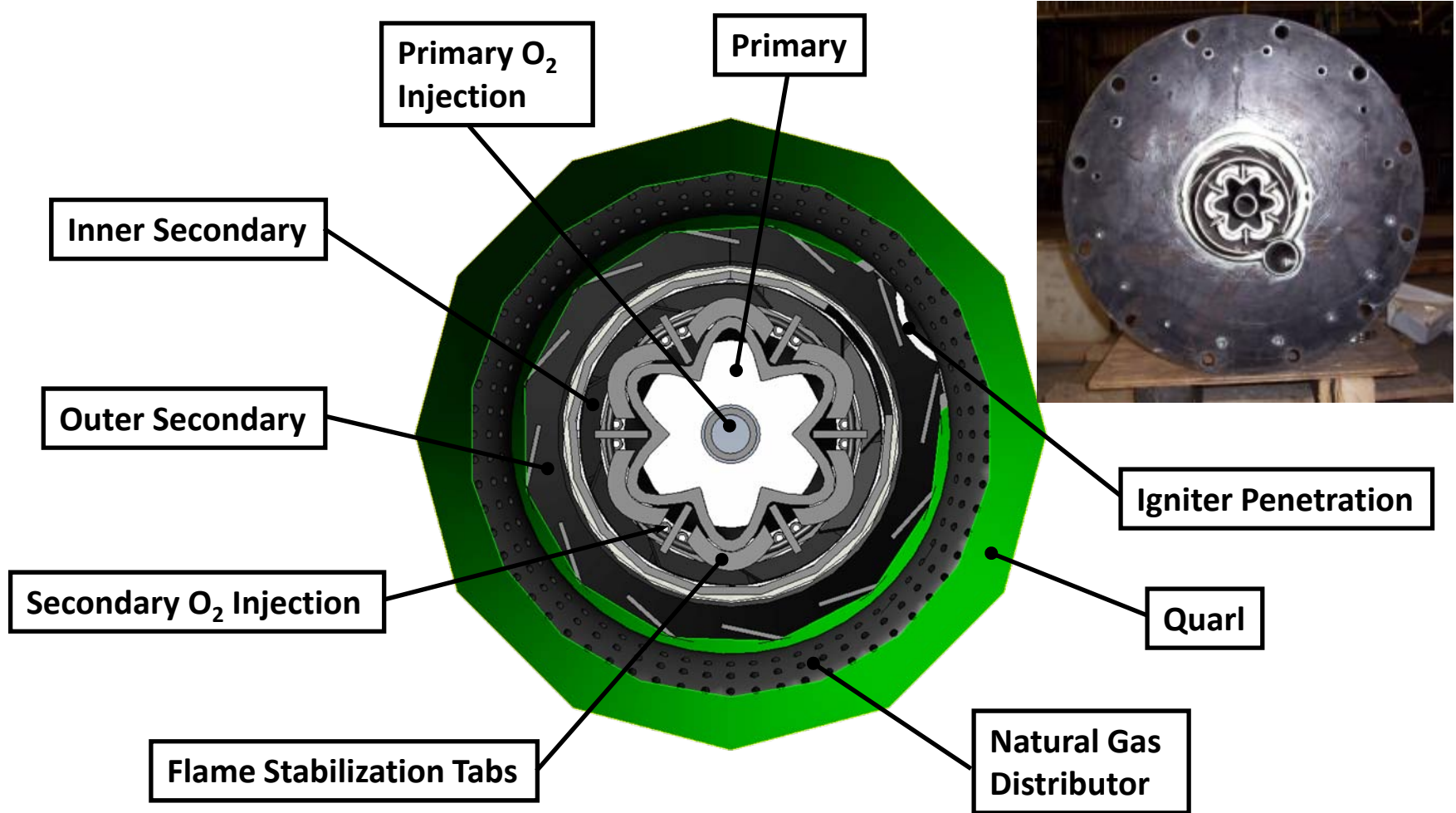


L1500 Capabilities:

- Realistic Burner Turbulent Mixing Scale
- Realistic Radiative Heat Flux Conditions
- Realistic Time - Temperature Profiles
- Retrofitted for flue gas recycle
- Up to 94% CO₂, 85-90% typical

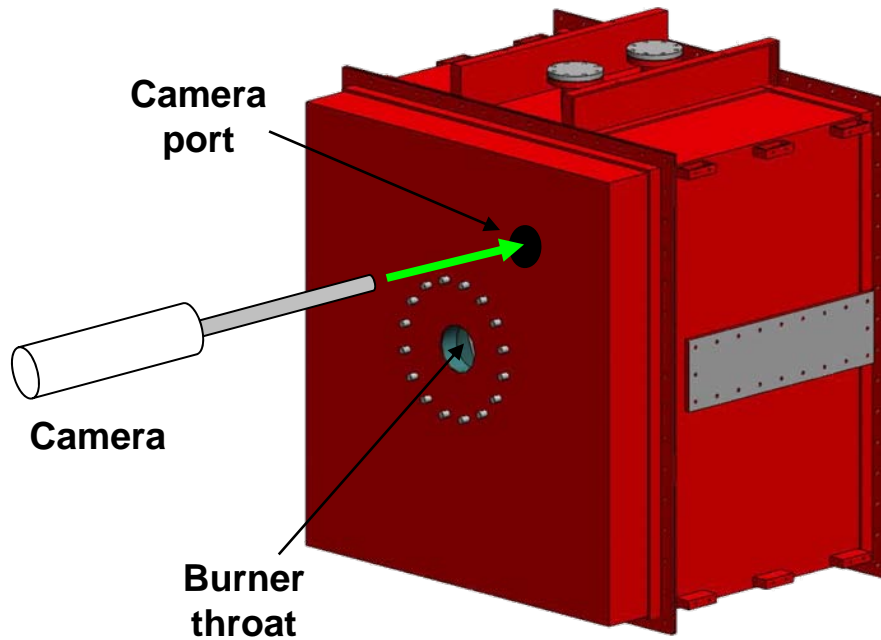


Oxy-Coal Research Burner Configuration

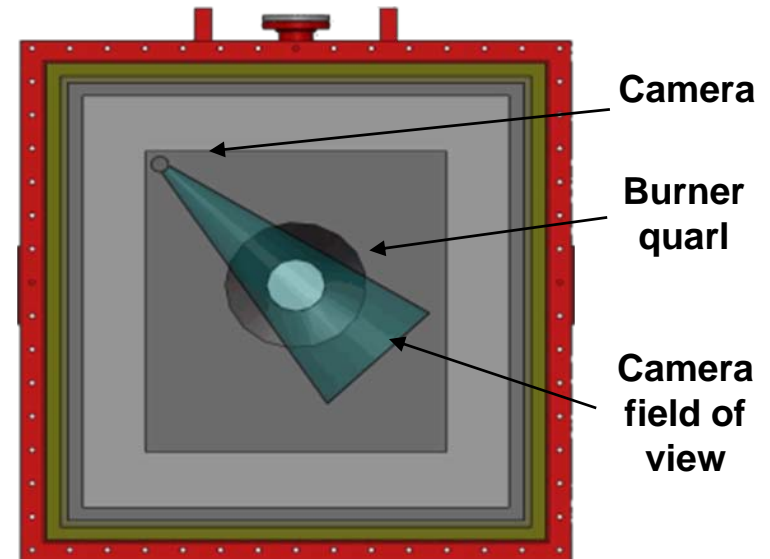


Camera Configuration

View from outside the furnace



View from inside the furnace
(looking towards the burner)



Burner Primary Questions

What primary retrofit conditions provide a stable flame?

Match primary:
Gas/fuel mass ratio?
Momentum?
Velocity?

Can we operate without O₂ enrichment of the primary?



Burner Results

- All burner test results for Utah bituminous coal
- All results have matched inner and outer secondary compositions and 20/80 inner/outer mass split
- CO₂ purity was ~88% (83% to 94% range)
- For primary “match” tests:
 - Burner SR was 0.9; overfire air/gas brought exit O₂ to ~3% dry
 - Primary O₂ concentration was ~21% (wet)
 - Overall O₂ in O₂-FGR mixture was ~27% (wet)



Comparison of Air and Oxy Flames

Air-Fired

BSR = 0.9

Air/Fuel = 1.8

IS/OS = 20/80



Oxy-Fired (matched gas-fuel ratio)

BSR = 0.9

Primary Gas/Fuel = 1.8

IS/OS = 20/80

Primary O₂ Conc. = 21%

Inner Secondary O₂ Conc. = 28.8%

Outer Secondary O₂ Conc. = 28.8%

Overall O₂ in O₂/FGR mixture = 27%



Primary Retrofit Conditions

Matched Velocity

BSR = 0.9

Primary Gas/Fuel = **2.0**

Primary O₂ Conc. = **21%**

Primary SR = **0.179**

Inner Secondary O₂ Conc. = 29.0%

Outer Secondary O₂ Conc. = 29.0%

Overall O₂ in O₂/FGR mixture = 27%



Low Primary O₂

BSR = 0.9

Primary Gas/Fuel = **1.80**

Primary O₂ Conc. = **2.7%**

Primary SR = **0.02**

Inner Secondary O₂ Conc. = 34.5%

Outer Secondary O₂ Conc. = 34.5%

Overall O₂ in O₂/FGR mixture = 27%



Burner Primary Retrofit Results

- Matching burner primary gas/fuel ratio or momentum ratio with air-fired operation produced a stable attached flame



- Matching primary velocity with air-fired operation did not provide a stable attached flame (may depend on burner flexibility)



- Matching O₂/fuel ratio requires unsafe O₂ concentration or gas/fuel ratio > 2.2

- Difference in devolatilization rates and ignition between air and oxygen/FGR firing

- A stable flame can be achieved with no oxygen enrichment in the primary



Burner Oxygen Injection Questions

How can we use O₂ injection to simplify retrofit and improve flame stability?

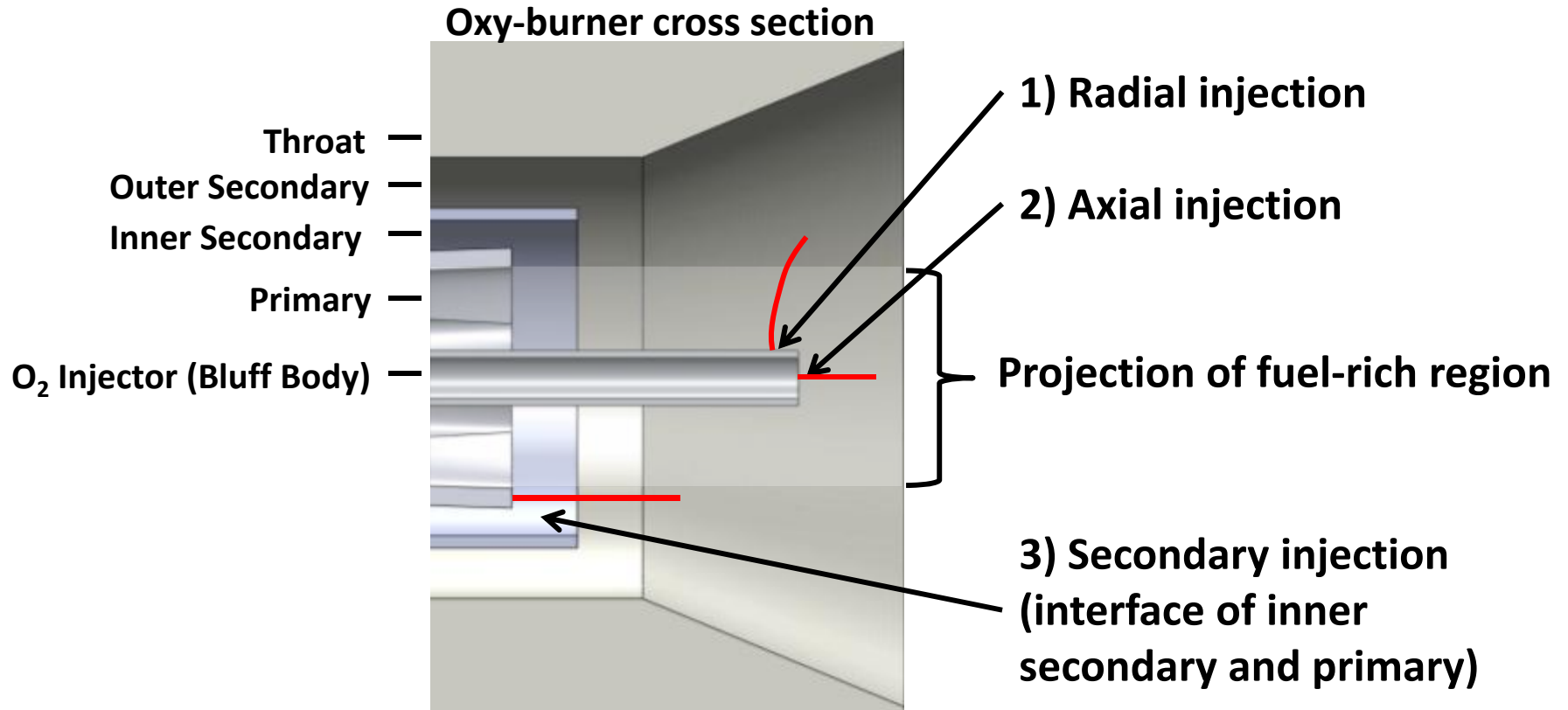
Primary oxygen replacement?

Injection in the burner primary or secondary?



Oxygen Injection Configurations

- O_2 removed from the premixed primary and replaced by FGR to maintain gas/fuel ratio



Primary O₂ Replacement (Axial Injection)

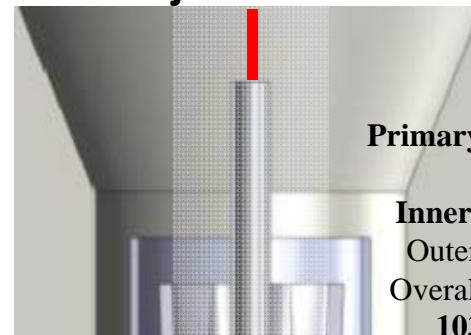


No Injection



BSR = 0.9
Primary Gas/Fuel = 2.08
IS/OS = 20/80
Primary O₂ Conc. = **21.4%** (Premixed)
Primary SR = **0.188**
Inner Secondary O₂ Conc. = **29.8%**
Outer Secondary O₂ Conc. = 29.2%
Overall O₂ in O₂/FGR mixture = 27%

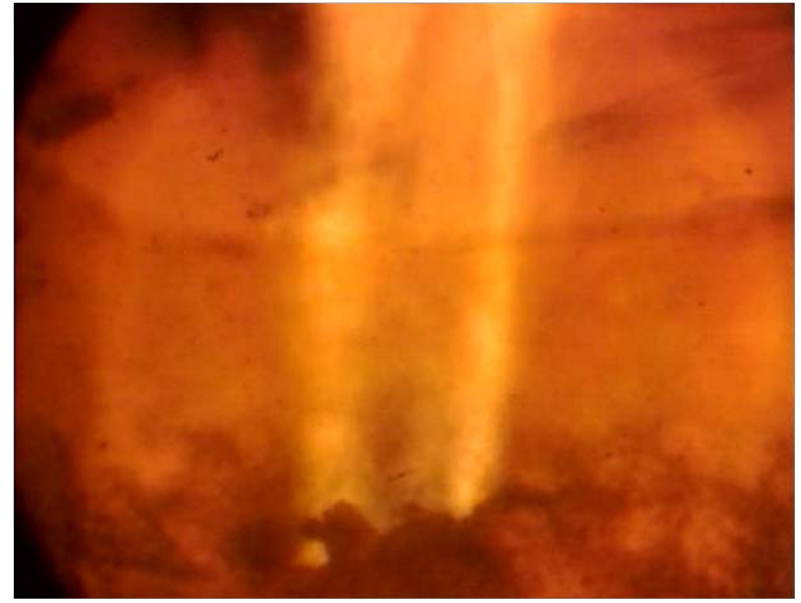
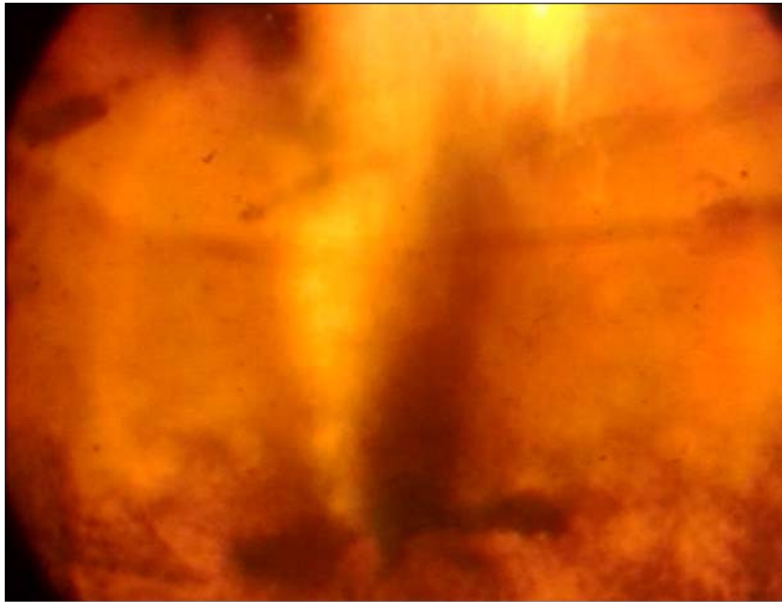
Axial Injection



BSR = 0.9
Primary Gas/Fuel = 2.05
IS/OS = 20/80
Primary O₂ Conc. = **2.46%** (Premixed)
Primary SR = **0.018**
Inner Secondary O₂ Conc. = **38.1%**
Outer Secondary O₂ Conc. = 29.5%
Overall O₂ in O₂/FGR mixture = 27%
103 lb/hr O₂ (Axial Injection)



Primary O₂ Replacement (Sec. Injection)

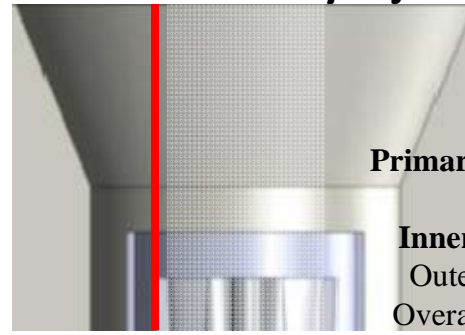


No Injection



BSR = 0.9
Primary Gas/Fuel = 2.04
IS/OS = 20/80
Primary O₂ Conc. = 20.9% (Premixed)
Primary SR = 0.180
Inner Secondary O₂ Conc. = 29.5%
Outer Secondary O₂ Conc. = 29.1%
Overall O₂ in O₂/FGR mixture = 27%

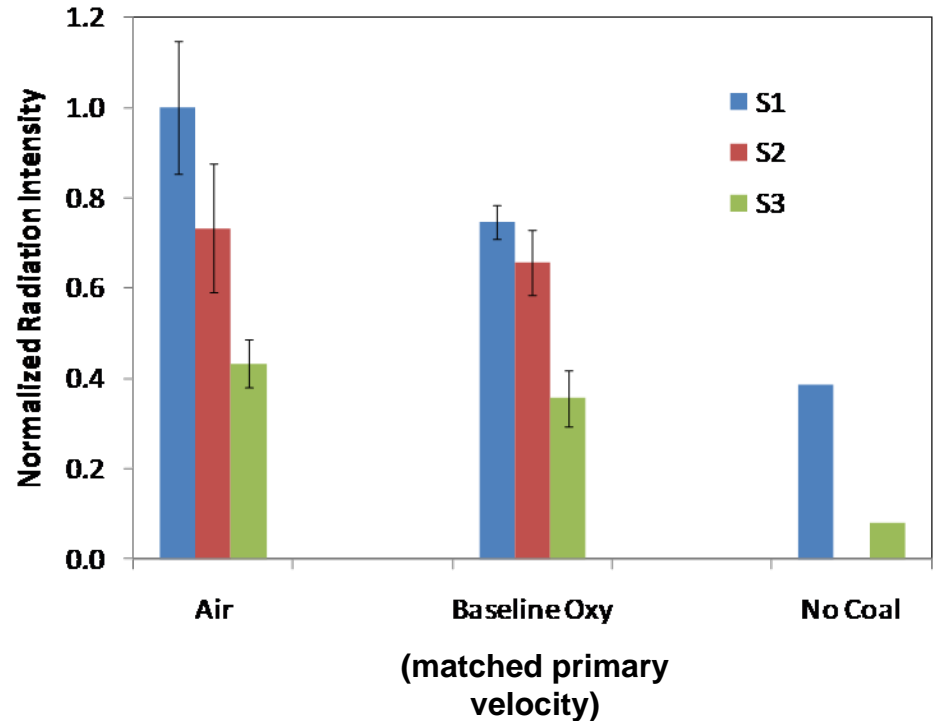
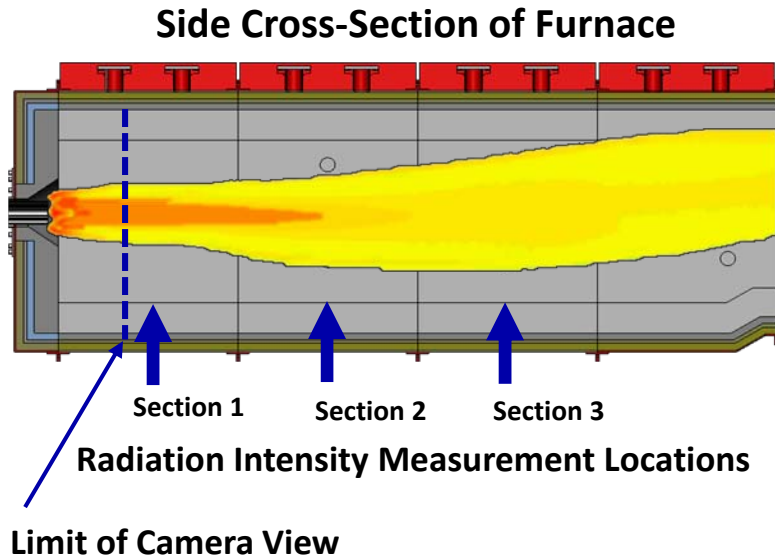
Inner Secondary Injection



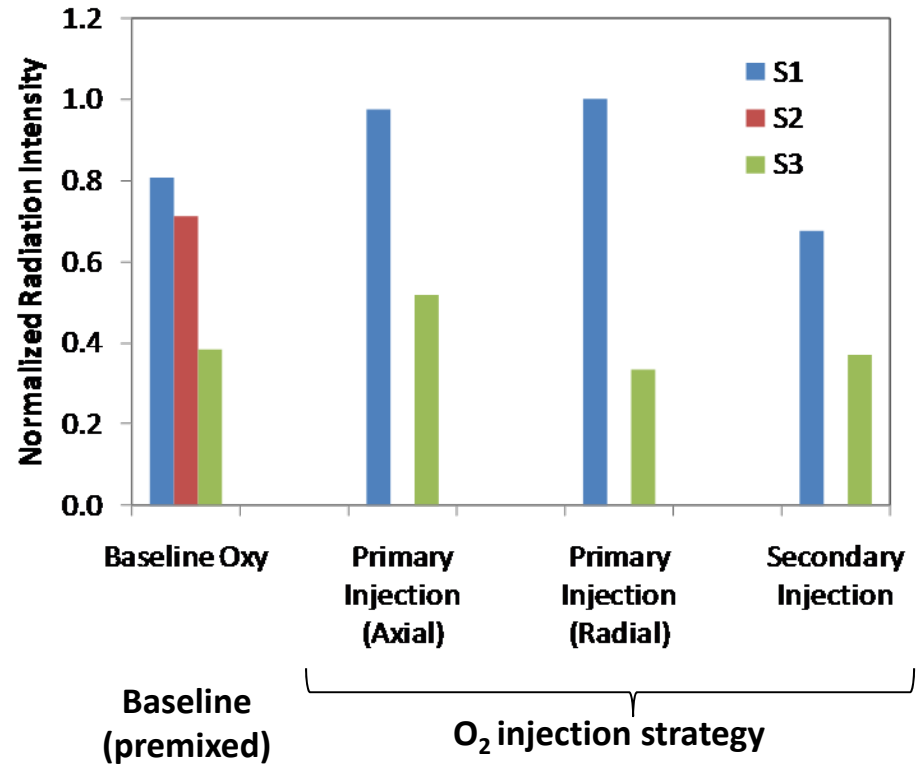
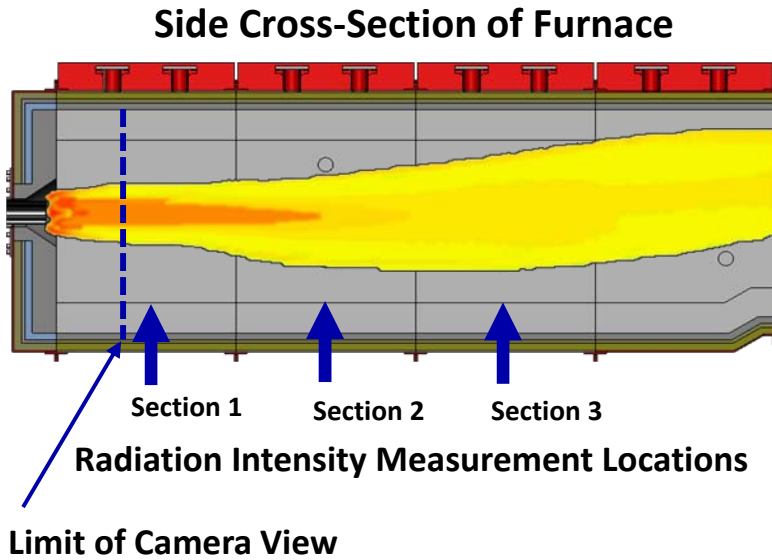
BSR = 0.9
Primary Gas/Fuel = 2.06
IS/OS = 20/80
Primary O₂ Conc. = 2.62% (Premixed)
Primary SR = 0.022
Inner Secondary O₂ Conc. = 40.6%
Outer Secondary O₂ Conc. = 29.4%
Overall O₂ in O₂/FGR mixture = 27%
100 lb/hr O₂ (Secondary Injection)



Radiation Intensity, Air- and Oxy Firing



Radiation Intensity, O₂ Injection

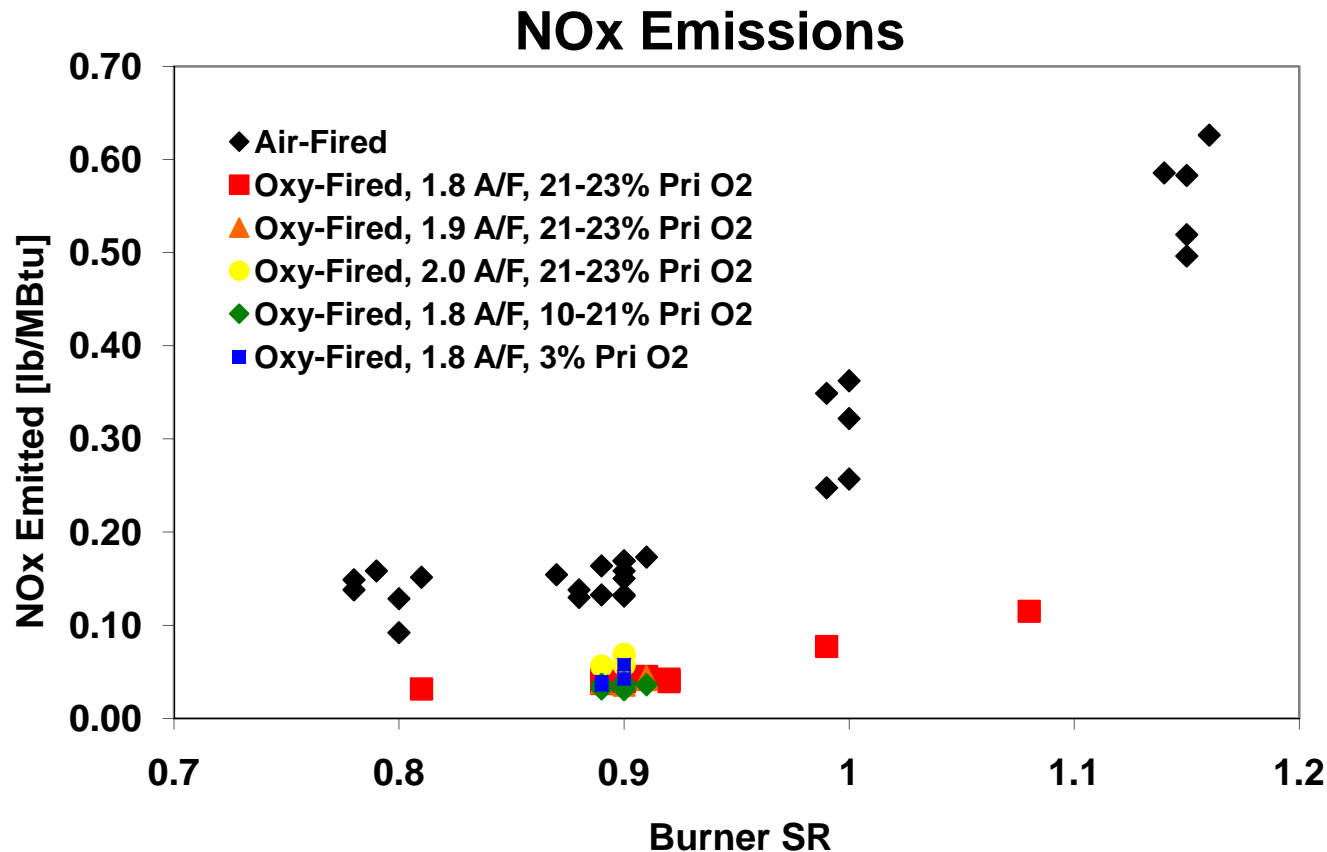


Oxygen Injection Conclusions

- Targeted oxygen injection at the burner primary-inner secondary boundary produced most effective flame stabilization and ignition
 - Axial injection produced a detached flame
 - Radial injection produced a wider flame, but did not improve flame attachment
- Axial injection in the primary produced a more intensely radiating flame downstream of burner; secondary injection produced less intense flame near burner
- For maximum pre-mixed primary O₂, adding small amounts of oxygen enrichment radially through the bluff body did not improve flame attachment



Impact of Staging on NO_x Emissions

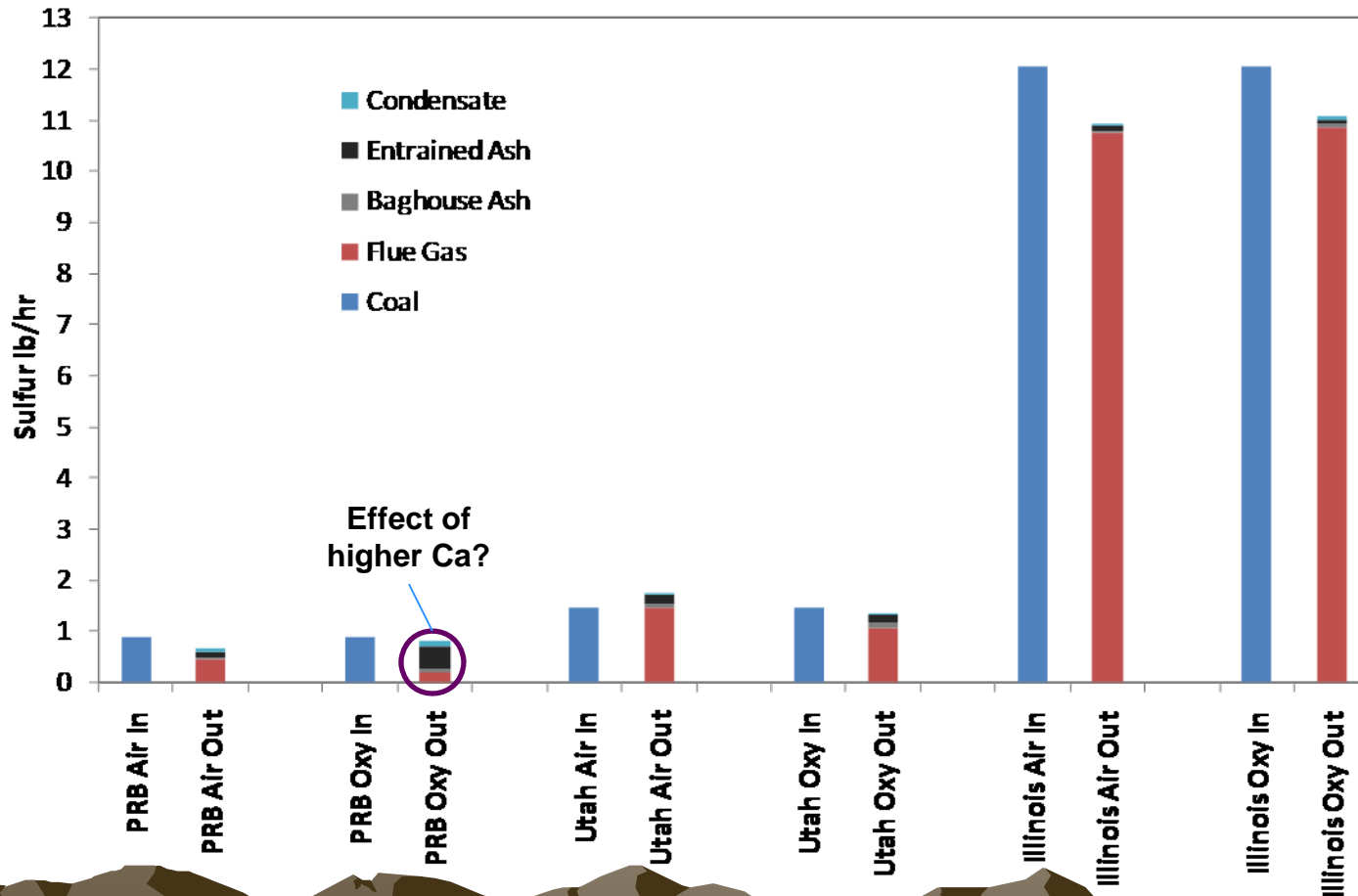


- **NO_x emissions up to 75% lower with oxy-firing; concentrations similar with staging, higher without**

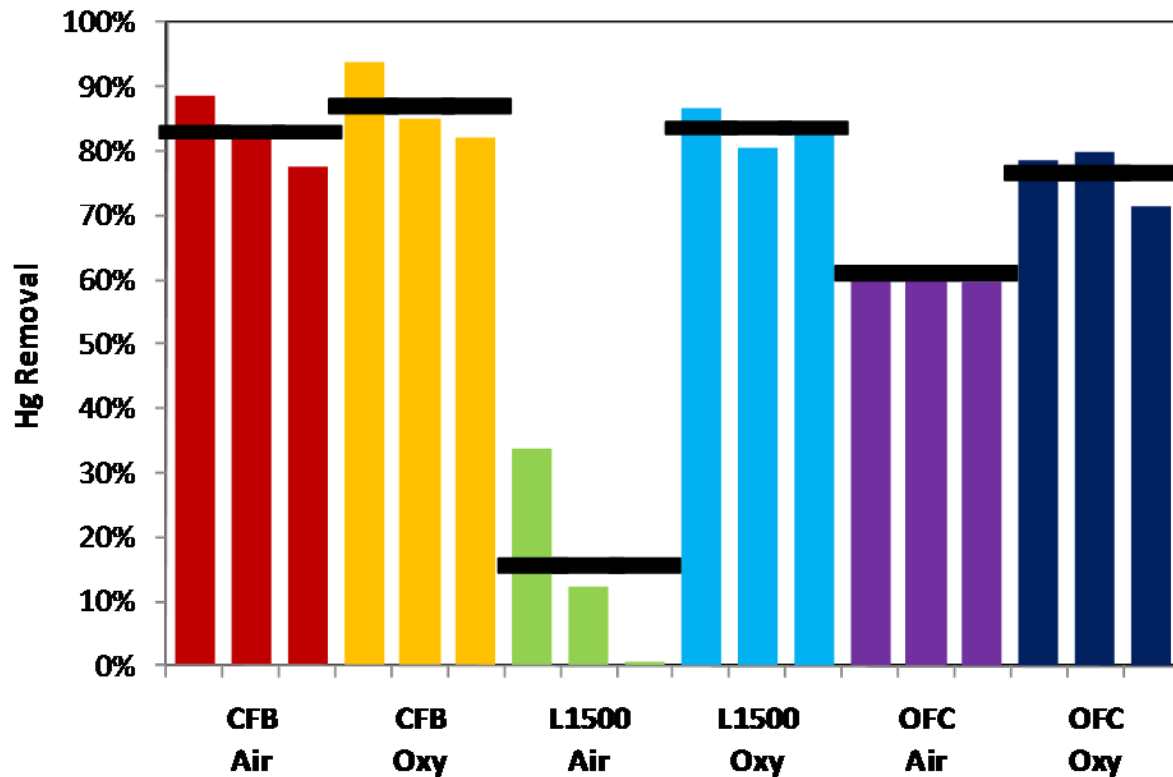


Sulfur Mass Balance

Coal	Firing Condition	Measured Ave SO ₂ Conc, ppmv
PRB	Air / Oxy	128 / 289
Skyline	Air / Oxy	445 / 1,737
Illinois	Air / Oxy	3,219 / 17,642



Native Mercury Removal

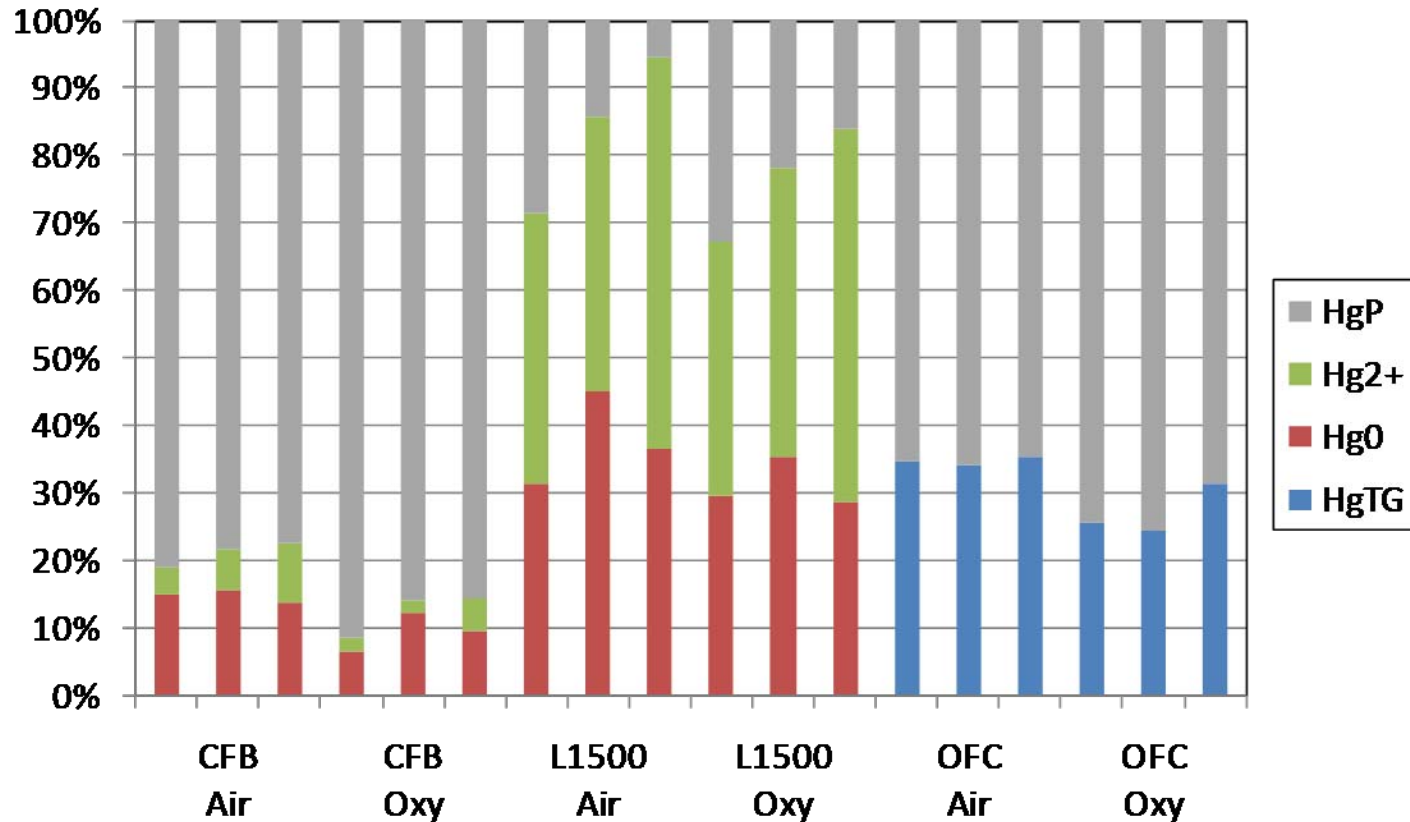


Native mercury removal was higher for all oxy cases; likely attributable to:

- elevated carbon in ash for the CFB and OFC
- scrubbing of FGR in L1500 baghouse filter cake (not included in balance)



Mercury Speciation

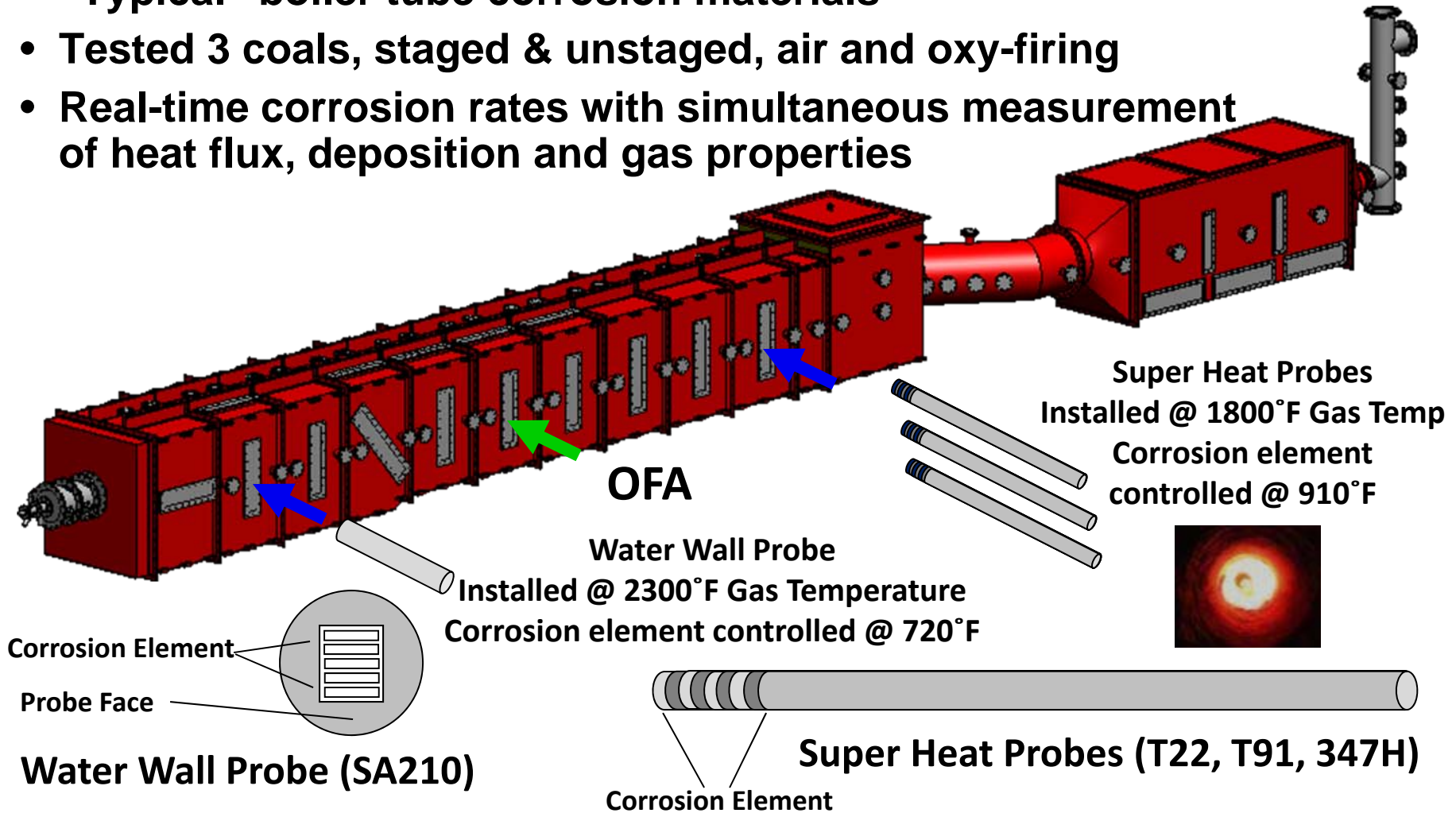


Slightly lower total gas mercury under oxy-fired conditions, consistent with higher native capture

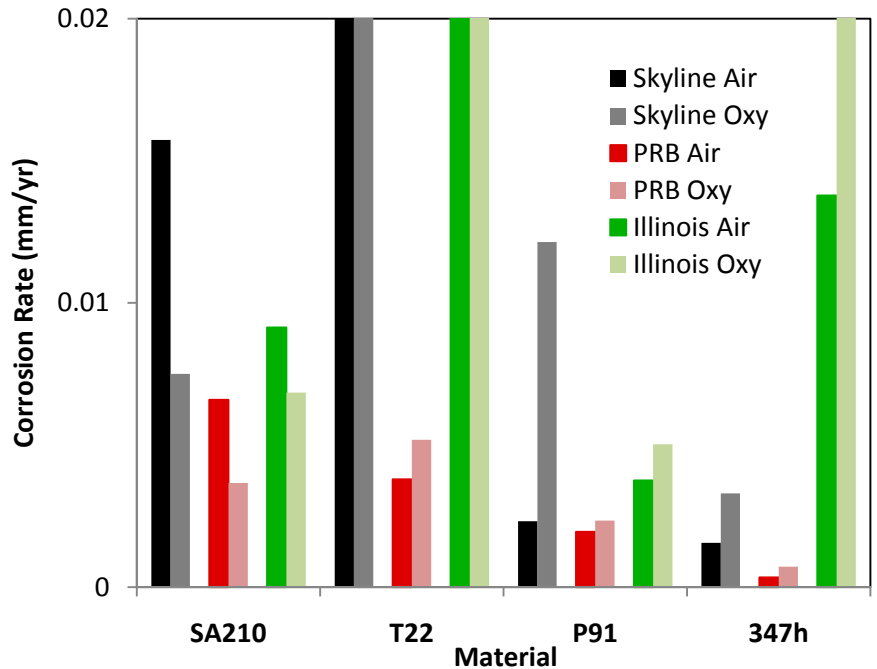
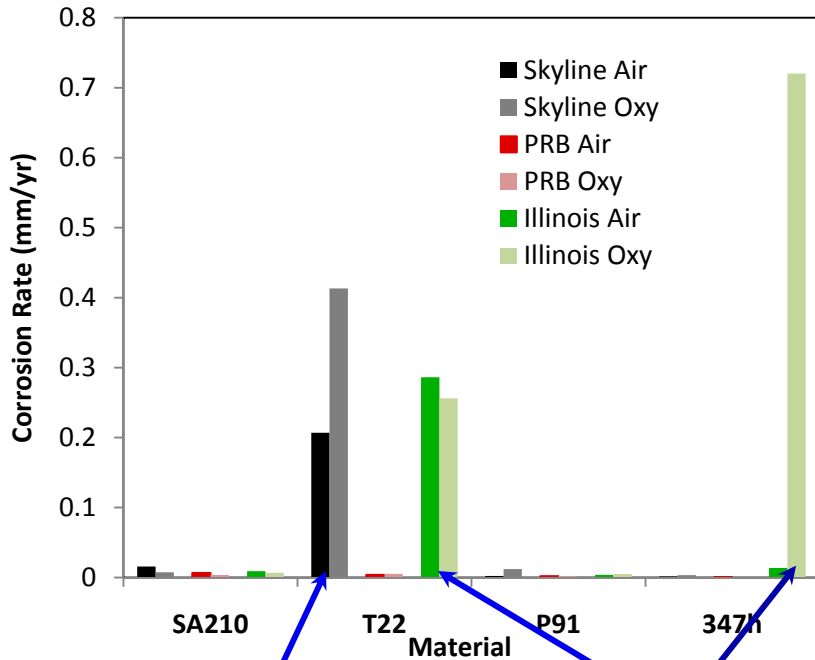


Corrosion Testing

- “Typical” boiler tube corrosion materials
- Tested 3 coals, staged & unstaged, air and oxy-firing
- Real-time corrosion rates with simultaneous measurement of heat flux, deposition and gas properties



Average Corrosion Rates (baseline conditions)



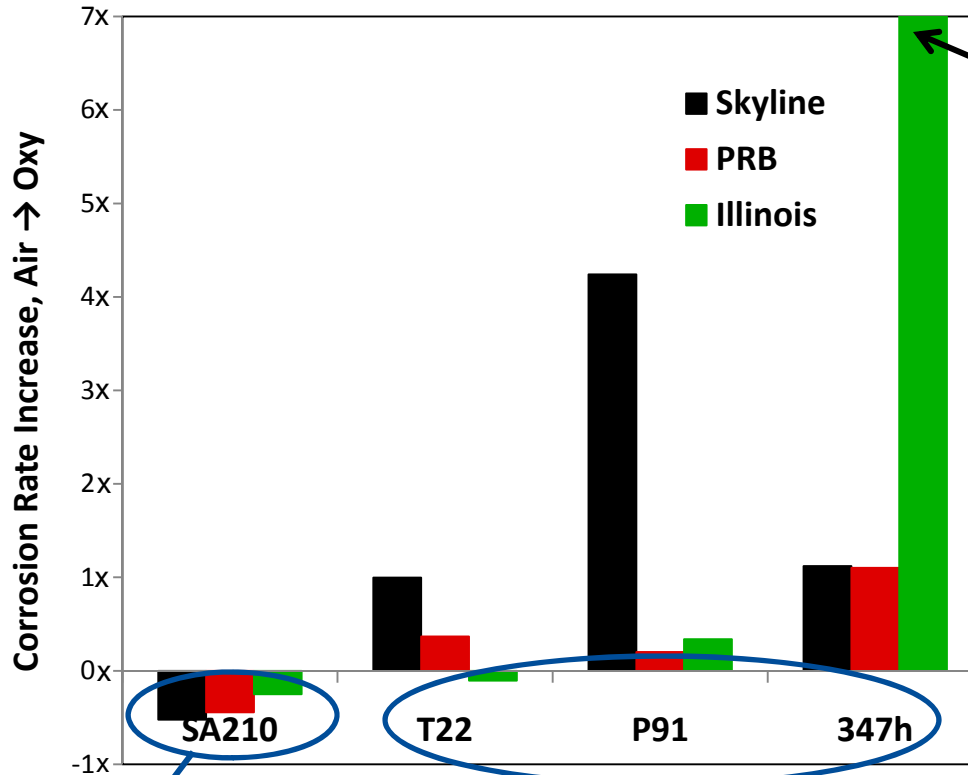
High corrosion rates for high SO₂ conditions (3,000 – 17,000 ppmv)

All other corrosion rates very low

High corrosion rates for low-alloy T22 with Utah and Illinois coals



Increase in Corrosion Rate Air → Oxy



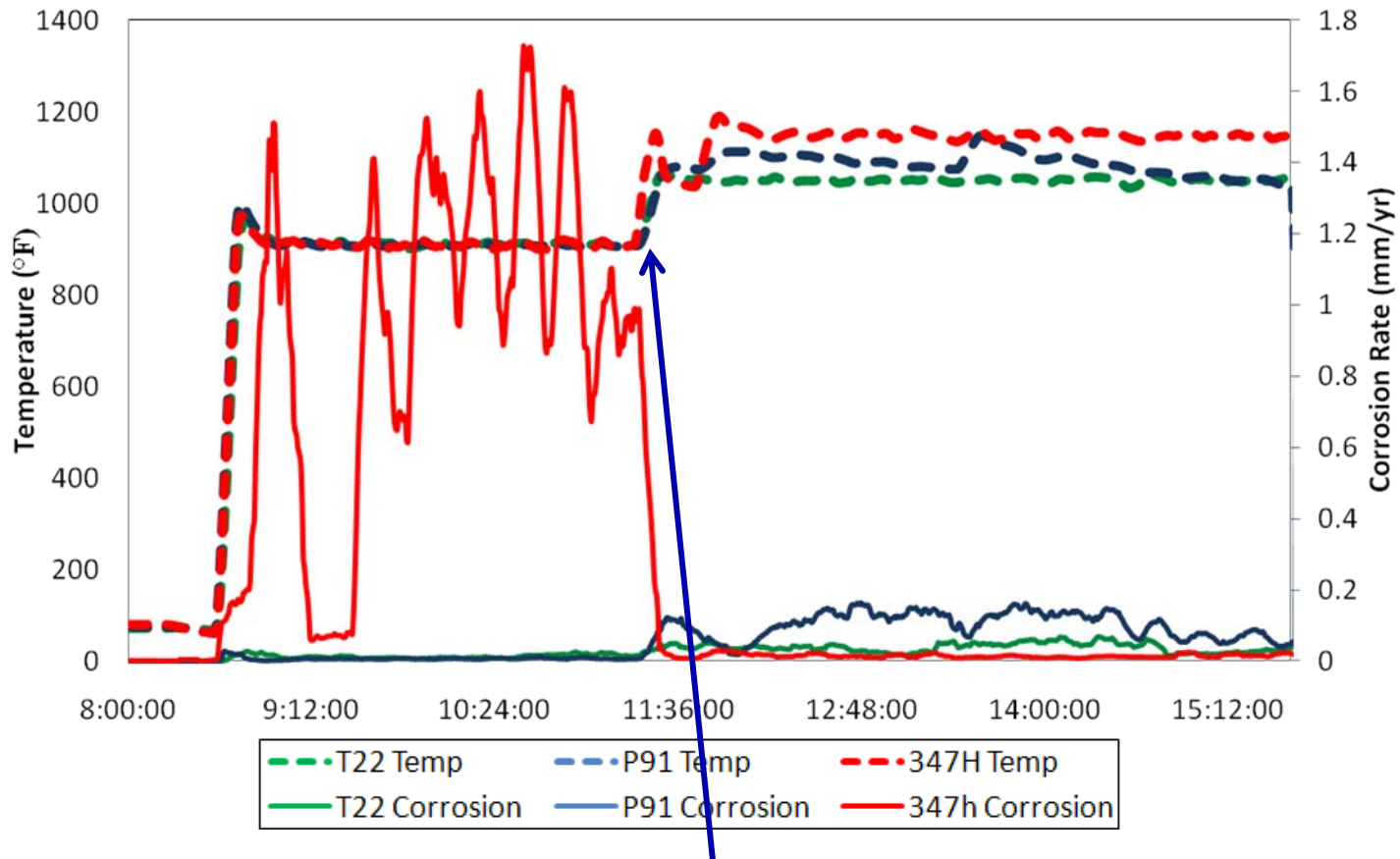
50x higher! Why?

Waterwall Probe - corrosion decreases moving from air to oxy combustion

Superheat Probes – corrosion increases going from air to oxy combustion



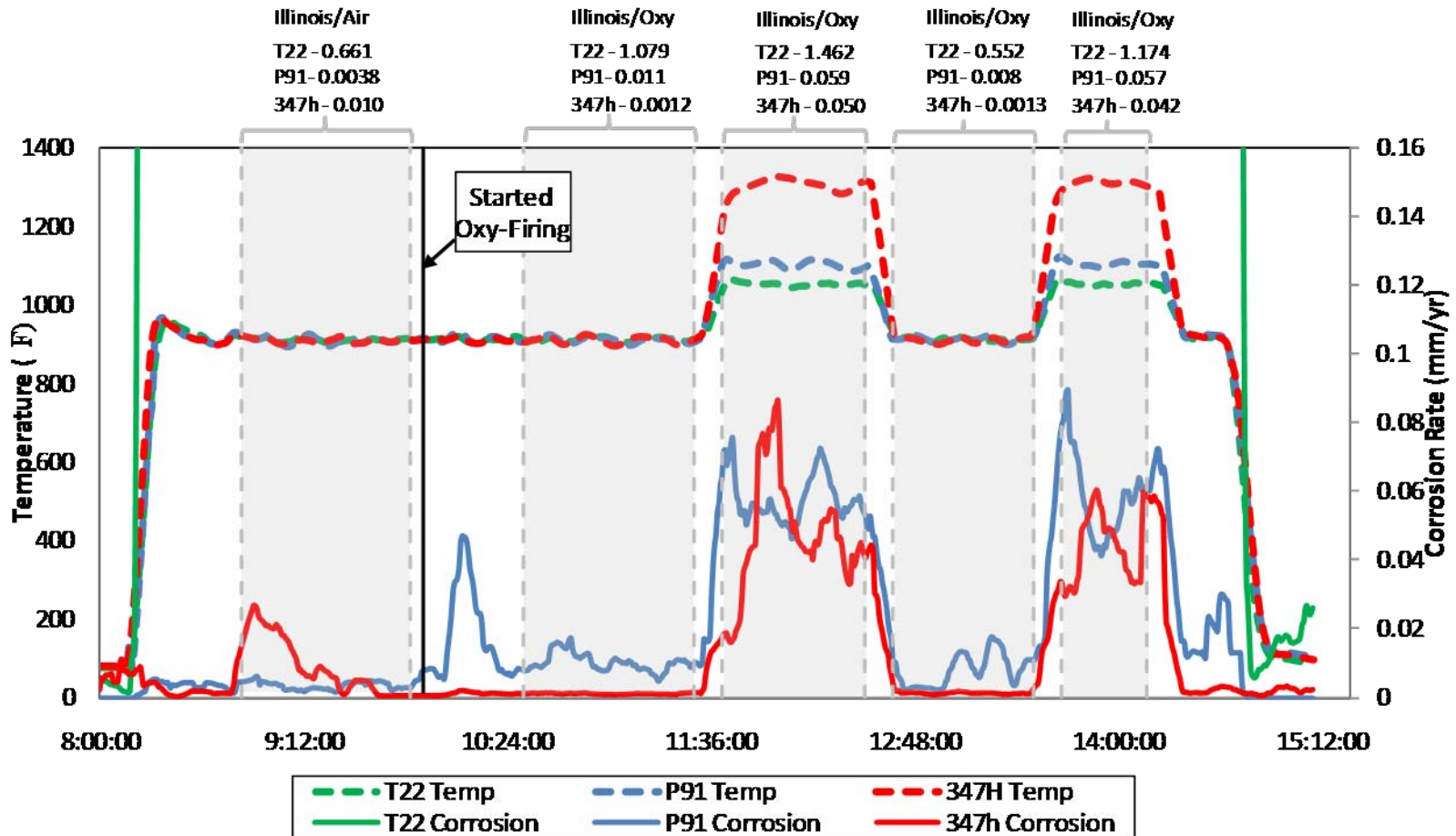
Temperature Effects on Corrosion



Possibly due to trisulfate formation at lower temperatures and high SO₂ concentration (Illinois coal) – not where 347H typically used



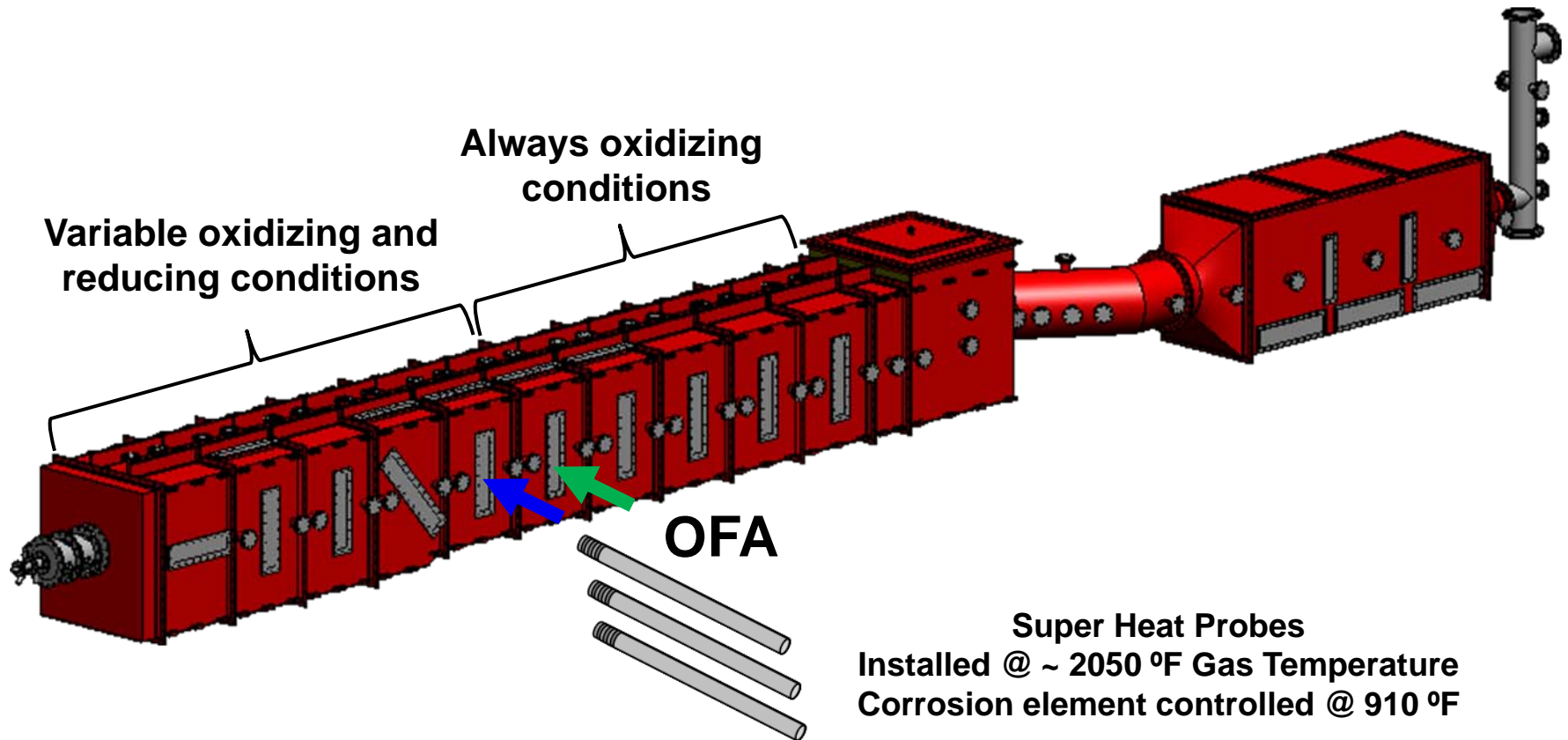
Temperature Effects on Corrosion



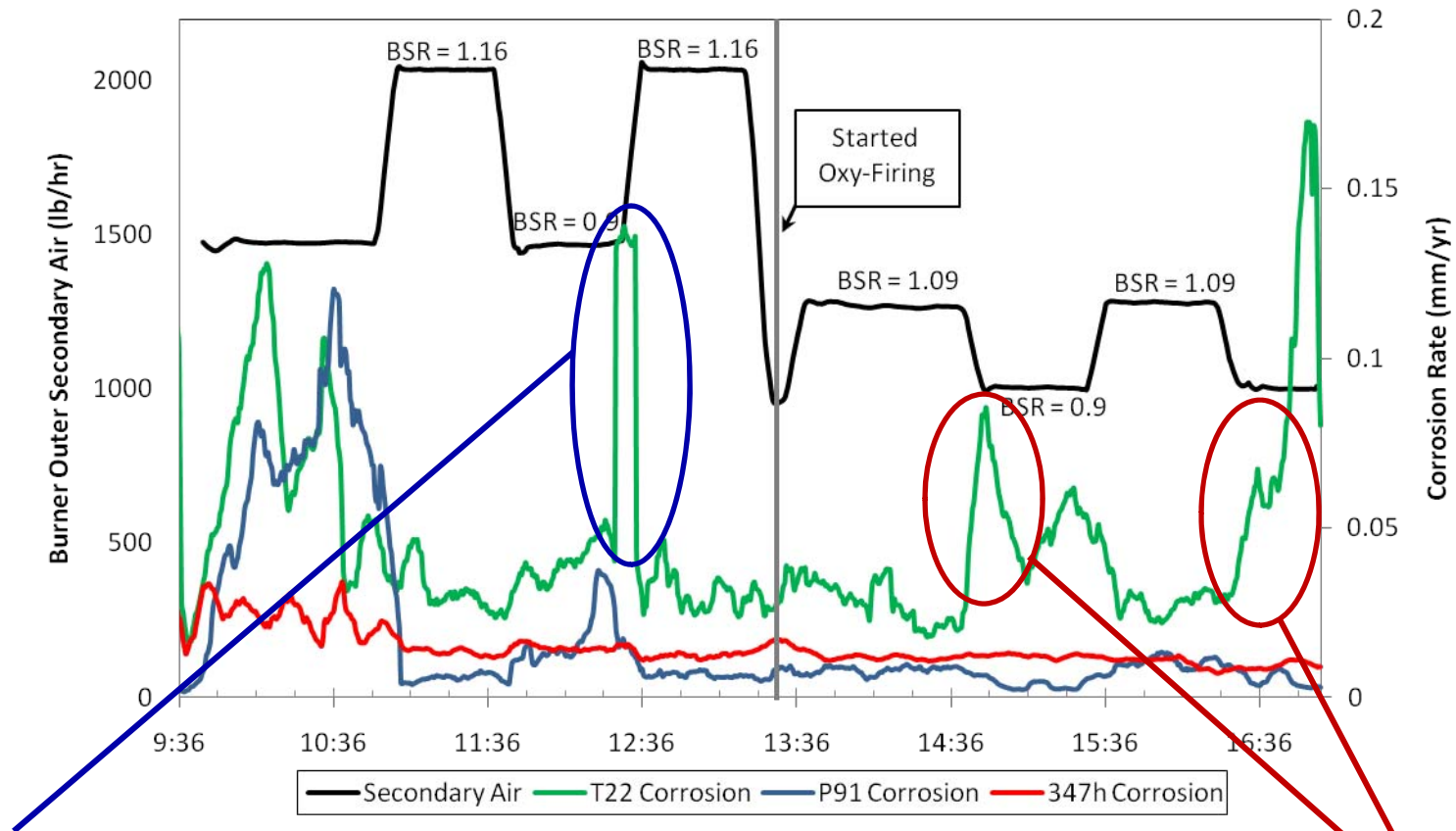
Temperature dependence of corrosion with reproducibility



Probe Position for Stoichiometry Tests



Effect of Stoichiometric Ratio



(Air) T22 corrosion rate spikes when going from reducing to oxidizing
T22 rate spikes when going from oxidizing to reducing **(Oxy)**



Corrosion Testing Conclusions

- **Waterwall (SA210) corrosion rates decreased when converting from air to oxy-firing for all coals**
- **Superheater (T22, P91 and 347H) rates generally increased when converting from air- to oxy-firing**
- **Corrosion for lower alloyed materials (SA210, T22) increased during transients between oxidizing-reducing conditions**
 - Likely to contribute to in-plant corrosion in near-burner and near-OFA port regions
 - Transient effects cannot be resolved using coupon tests
- **347H corrosion rates increased significantly for high sulfur and low temperature conditions**
- **The dependence of corrosion rate on material temperatures was demonstrated along with the repeatable nature of the results**



Summary

- **Oxy-coal testing has been completed on a 3.5 MBtu/hr pilot-scale furnace using a specially designed oxy-research burner. General trends with oxy-firing:**
 - Similar burner flame attachment and heat flux profile possible
 - NO_x emissions lower, SO₂ levels higher with FGR
 - Native Hg removal higher, gas-phase speciation similar
 - Waterwall corrosion lower; superheat corrosion higher
 - Changes to char oxidation, sooting and ash composition still under study
- **Next steps:**
 - Use data to validate mechanisms; implement in CFD code
 - Design full-scale oxy-firing system and use CFD to evaluate oxy-combustion retrofit for utility boiler



Acknowledgements

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Brydger VanOtten from REI for mercury measurements

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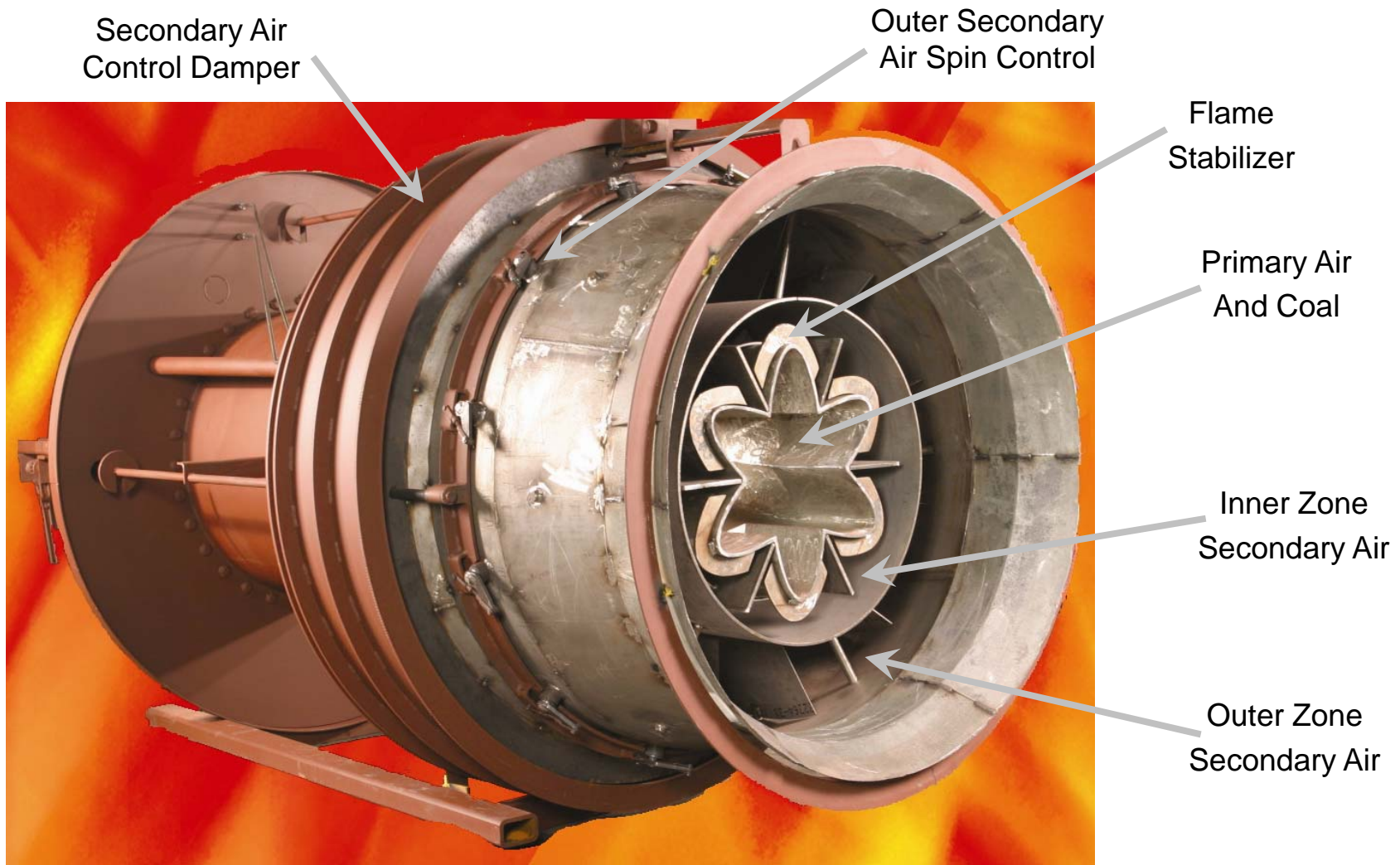
OXY-FUEL LOW NOX BURNER DESIGN CONSIDERATIONS

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Commercial Burner Design



Oxy-Fuel Burner Design Criteria

Design criteria for the pilot scale research burner:

- ✓ **Flexible mixing ratios for oxygen, flue gas recirculation and fuel**
- ✓ **Attached, stable flame for both air and oxy-fired operation**
- ✓ **Targeted oxygen injection at multiple locations**

A constant velocity scaling factor is used, whereby the design velocity of the commercial burner was identical to the pilot scale burner. This scaling approach has been documented in papers presented at the International Flame Research Foundation.



CFD Burner Modeling Cases

Case Identifier	Case Description
LNB-A	Existing Low-NOx Burner (Air-Fired)
LNB-O	Existing Low-NOx Burner (Oxy-Fired)
OXY-A	Oxy-Research Burner, Design 1 (Air-Fired)
OXY-O	Oxy-Research Burner, Design 1 (Oxy-Fired)
OXY-Vel80A	Oxy-Research Burner, Design 1, 24.4 m/s (80 ft/s) Primary (Air-Fired)
OXY-Vel80O	Oxy-Research Burner, Design 1, 24.4 m/s (80 ft/s) Primary (Oxy-Fired)
OXY-Vel70A	Oxy-Research Burner, Design 1, 21.3 m/s (70 ft/s) Primary (Air-Fired)
OXY-Vel70O	Oxy-Research Burner, Design 1, 21.3 m/s (70 ft/s) Primary (Oxy-Fired)
OXY-Vel60A	Oxy-Research Burner, Design 1, 18.3 m/s (60 ft/s) Primary (Air-Fired)
OXY-Vel60O	Oxy-Research Burner, Design 1, 18.3 m/s (60 ft/s) Primary (Oxy-Fired)
OXY-ParA	Oxy-Research Burner, Design 2, 21.3 m/s (70 ft/s) Primary (Air-fired)
OXY-ParO	Oxy-Research Burner, Design 2, 21.3 m/s (70 ft/s) Primary (Oxy-Fired)
OXY-ParLO2	Oxy-Research Burner, Design 2, Low Primary O2 (Oxy-Fired)
OXY-ParPRBA	Oxy-Research Burner, Design 2, PRB Fuel (Air-fired)
OXY-ParPRBO	Oxy-Research Burner, Design 2, PRB Fuel (Oxy-Fired)
OXY-ParREFA	Oxy-Research Burner, Design 2, Refined Mesh (Air-Fired)
OXY-Qua4A	Oxy-Research Burner, Design 2, 10.16 cm (4 in.) Quarl (Air-Fired)
OXY-Qua6A	Oxy-Research Burner, Design 2, 15.24 cm (6 in.) Quarl (Air-fired)
OXY-Qua4O	Oxy-Research Burner, Design 2, 10.16 cm (4 in.) Quarl (Oxy-Fired)

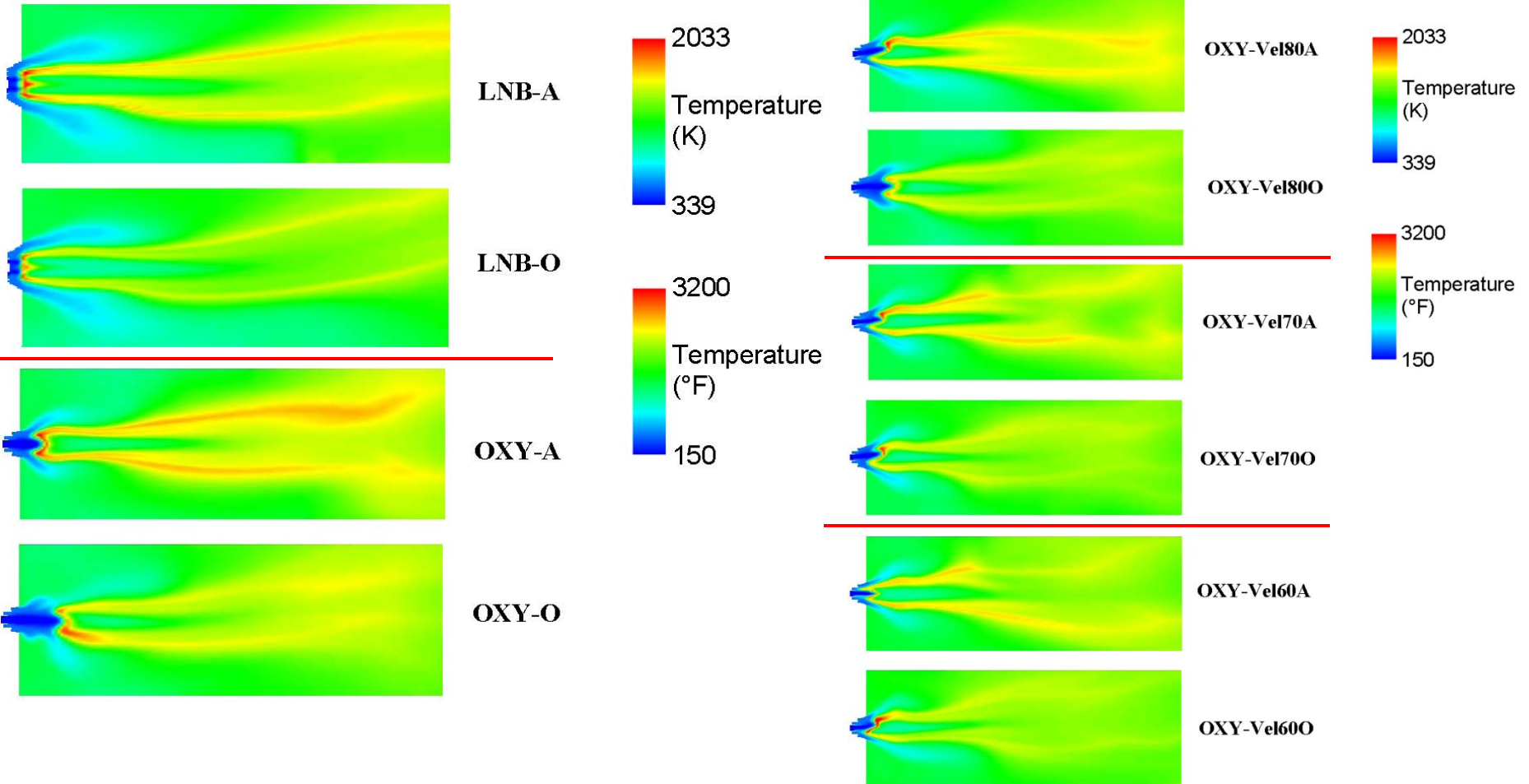


Baseline Burner and Oxy-Fuel Design 1

	LNB-A	LNB-O	OXY-A	OXY-O	OXY-Vel60A	OXY-Vel70A	OXY-Vel80A	OXY-Vel60O	OXY-Vel70O	OXY-Vel80O
Firing Rate (MBtu/hr)	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Fuel	Bit. Coal	Bit. Coal	Bit. Coal	Bit. Coal	Bit. Coal	Bit. Coal	Bit. Coal	Bit. Coal	Bit. Coal	Bit. Coal
Oxidizer	Air	O2 + FGR	Air	O2 + FGR	Air	Air	Air	O2 + FGR	O2 + FGR	O2 + FGR
Burner SR	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Total Coal Flow (kg/s)	0.03523	0.03523	0.03515	0.03515	0.035154	0.035154	0.035154	0.035154	0.035154	0.035154
Total Coal Flow (lb/hr)	279.6	279.6	279.0	279.0	279.0	279.0	279.0	279.0	279.0	279.0
Primary Gas / Fuel	1.8	1.8	1.86	2.36	1.24	1.45	1.65	1.62	1.91	2.21
Primary Velocity (m/s)	20.5	14.4	26.8	25.3	18.29	21.33	24.38	18.29	21.33	24.38
Primary Velocity (ft/s)	67.2	47.2	88	83	60	70	80	60	70	80
Primary Flow (kg/s)	0.06342	0.06342	0.06539	0.08281	0.04355	0.05080	0.05805	0.05707	0.06731	0.07755
Primary Flow (lb/hr)	503.3	503.3	519.0	657.2	345.6	403.2	460.7	452.9	534.2	615.5
Inner Sec. Flow (kg/s)	0.06007	0.06656	0.03561	0.02320	0.03597	0.03597	0.03597	0.02390	0.02390	0.02390
Inner Sec. Flow (lb/hr)	476.8	528.3	282.6	184.1	285.5	285.5	285.5	189.7	189.7	189.7
Outer Sec. Flow (lb/hr)	0.18022	0.19968	0.20178	0.21942	0.22637	0.21911	0.21186	0.25705	0.24679	0.23655
Outer Sec. Flow (lb/hr)	1430.3	1584.8	1601.4	1741.4	1796.6	1739.0	1681.4	2040.1	1958.7	1877.4
Primary Feed O2 (wt %)	N/A	24.6%	N/A	17.7%	N/A	N/A	N/A	27.2%	22.6%	19.3%
Inner Sec. Feed O2 (wt %)	N/A	24.6%	N/A	41.9%	N/A	N/A	N/A	41.0%	41.0%	41.0%
Outer Sec. Feed O2 (wt %)	N/A	24.6%	N/A	17.7%	N/A	N/A	N/A	14.9%	15.7%	16.4%



CFD Temperature Plots

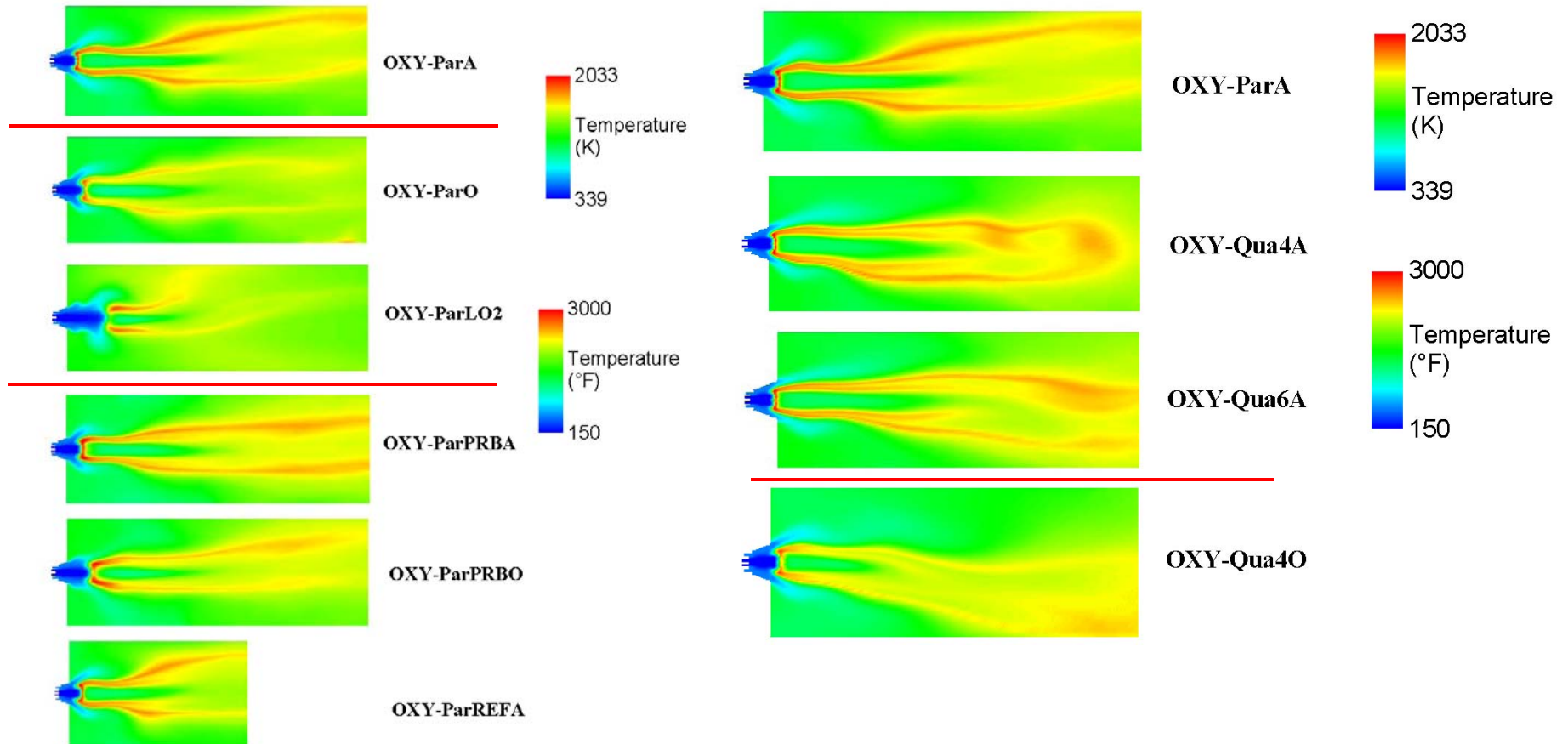


Oxy-Fuel Design 2 and Quarl Depth

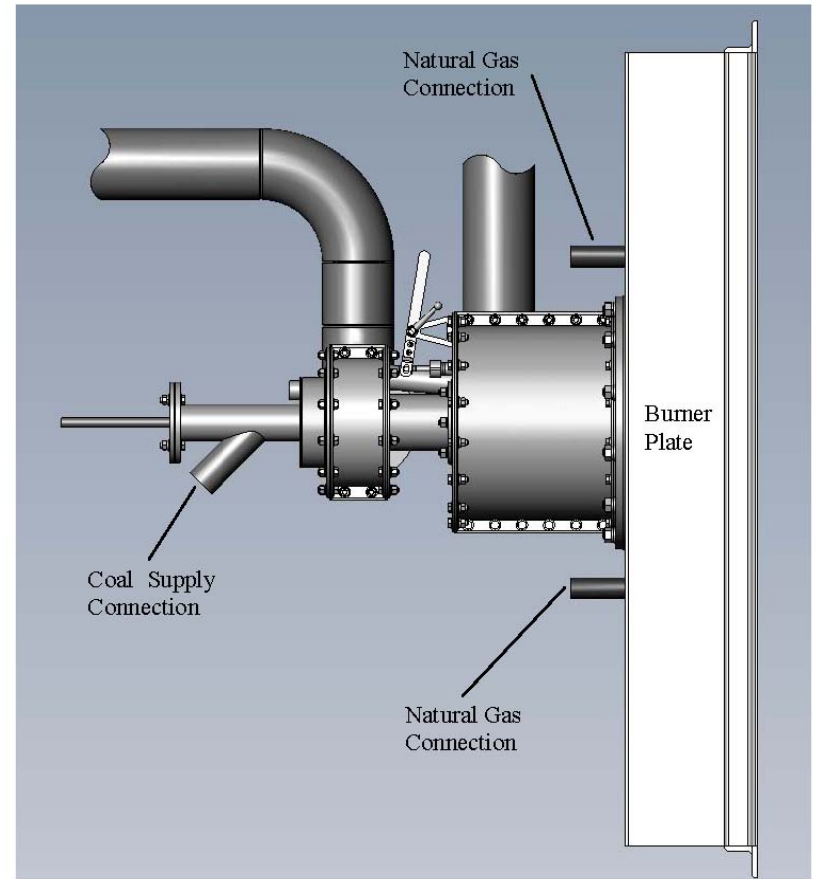
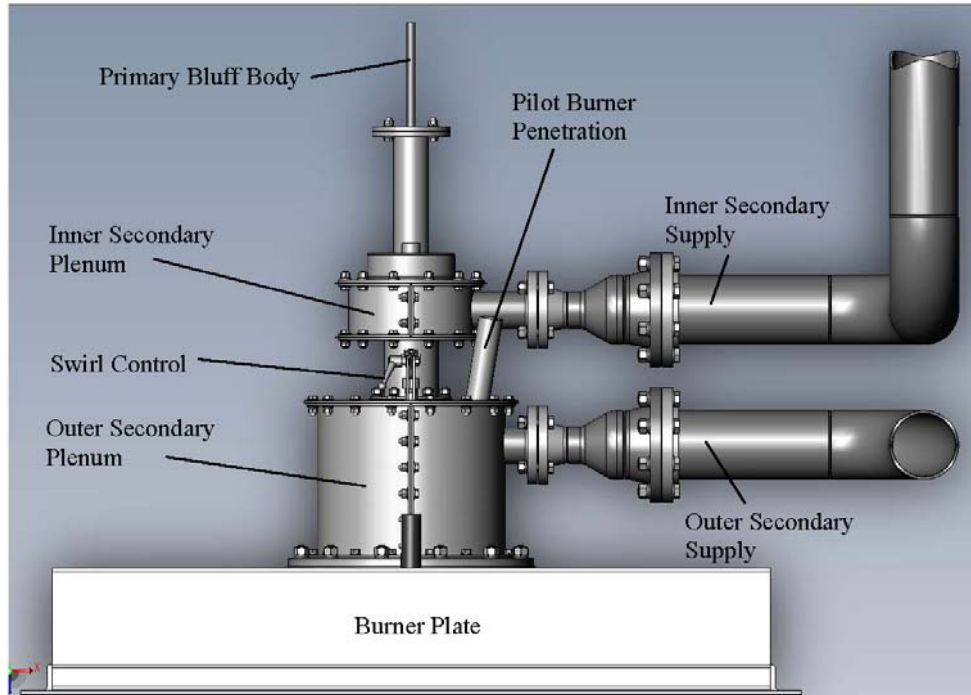
	OXY-ParA	OXY-ParO	OXY-ParLO2	OXY-ParPRBA	OXY-ParPRBO	OXY-ParREFA	OXY-Qua4A	OXY-Qua6A	OXY-Qua4O
Firing Rate (MBtu/hr)	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Fuel	Bit. Coal	Bit. Coal	Bit. Coal	PRB	PRB	Bit. Coal	Bit. Coal	Bit. Coal	Bit. Coal
Oxidizer	Air	O2 + FGR	O2 + FGR	Air	O2 + FGR	Air	Air	Air	O2 + FGR
Burner SR	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.91
Total Coal Flow (kg/s)	0.03515	0.03515	0.03515	0.04048	0.04048	0.03515	0.03515	0.03515	0.03515
Total Coal Flow (lb/hr)	279.0	279.0	279.0	321.3	321.3	279.0	279.0	279.0	279.0
Primary Gas / Fuel	1.88	2.45	2.52	1.88	2.44	1.88	1.88	1.88	2.45
Primary Velocity (m/s)	21.9	21.0	21.0	25.0	24.4	21.9	21.9	21.9	21.0
Primary Velocity (ft/s)	72	69	69	82	80	72	72	72	69
Primary Flow (kg/s)	0.06606	0.08606	0.08859	0.07610	0.09877	0.06606	0.06606	0.06606	0.08606
Primary Flow (lb/hr)	524.3	683.0	703.1	604.0	783.9	524.3	524.3	524.3	683.0
Inner SA Flow (kg/s)	0.03597	0.02390	0.02500	0.03401	0.02201	0.03597	0.03597	0.03597	0.02309
Inner SA Flow (lb/hr)	285.5	189.7	198.4	269.9	174.7	285.5	285.5	285.5	189.7
Outer SA Flow (kg/s)	0.20384	0.22805	0.22442	0.19272	0.20968	0.20384	0.20384	0.20384	0.22805
Outer SA Flow (lb/hr)	1617.8	1809.9	1781.1	1529.5	1664.1	1617.8	1617.8	1617.8	1809.9
Primary Feed O2 (wt %)	N/A	17.1%	5.6%	N/A	17.3%	N/A	N/A	N/A	17.1%
Inner Sec. Feed O2 (wt %)	N/A	41.0%	47.0%	N/A	41.2%	N/A	N/A	N/A	41.0%
Outer Sec. Feed O2 (wt %)	N/A	17.1%	20.8%	N/A	17.3%	N/A	N/A	N/A	17.1%
Primary SR	0.1961	0.2133	0.0919	0.2297	0.2515	0.1961			



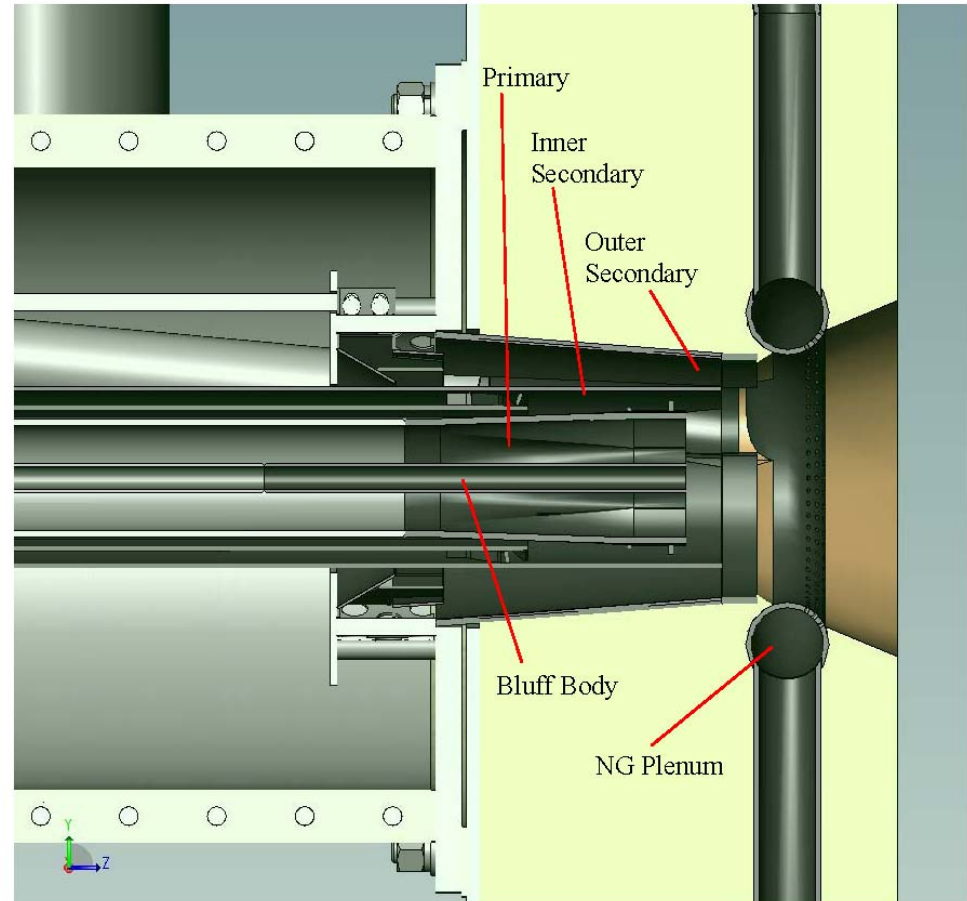
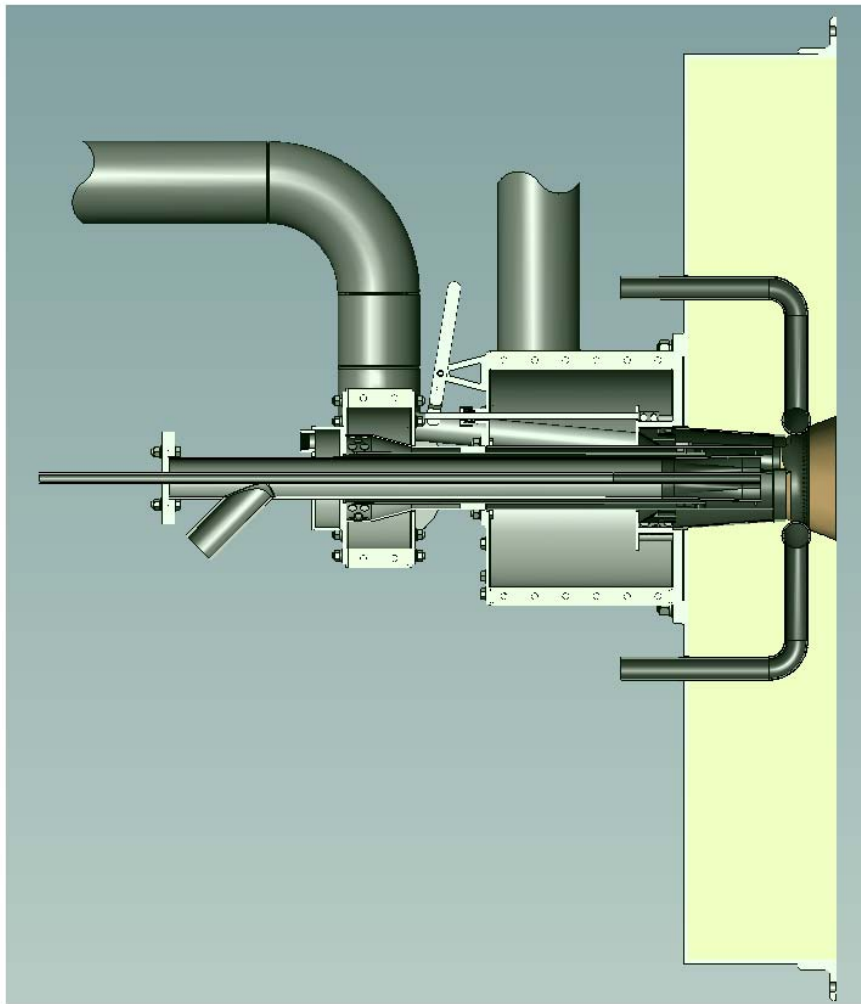
CFD Temperature Plots



Oxy-Fuel Pilot Burner



Oxy-Fuel Pilot Burner



Full Scale Burner Design Considerations

Considerations for full scale burner design:

- ✓ **Scaling factors for full scale sizing**
 - Confirmation of scaling factors through modeling
- ✓ **Modification of commercial burner adjustment devices to accommodate oxy-fuel needs**
 - Design of secondary air flow dampers to accommodate total range of air flow adjustment required for both air and oxy-fuel firing
- ✓ **Stable flame at low O₂ concentration in the burner nozzle**
 - Redesign flame stabilization components of burner nozzle and swirl inducers to maximize dual fuel firing



Full Scale Burner Design Challenges

- ✓ **Flexibility to operate at varying air and oxy conditions**
 - **Sizing of all flow components will be designed so that the operating conditions of both fuels will overlap in their respective velocity criteria**
- ✓ **Little or no change to boiler operation**
 - **Results of the pilot scale burner testing in the furnace will be reviewed and used to set burner design parameters to produce flame characteristics as near the “existing” air fired flames as possible**



Disclaimer

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