REINHOLD ENVIRONMENTAL Ltd.

2012 Coal to Gas Conversion Round Table & Expo Presentation

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Modeling Furnace Performance and Impacts of Coal-to-Gas Conversion

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For Energy and Environmental Solutions

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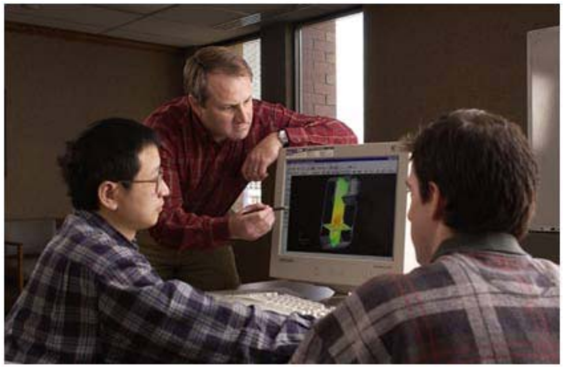
Overview

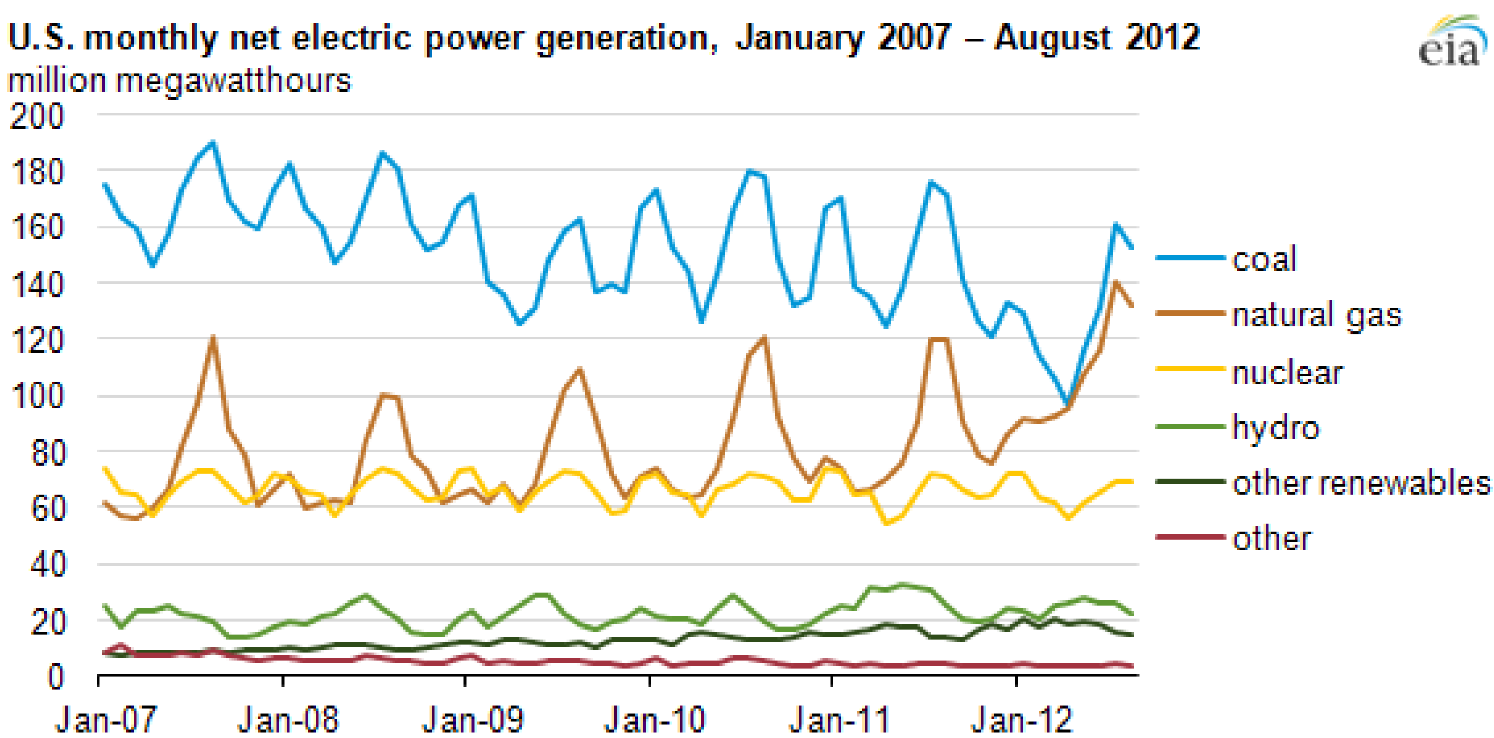
- Motivation for switching to gas firing
- Gas-firing options
- Challenges to retrofitting from coal to gas
- Modeling evaluation approach
- Examples
  - CFD of natural gas retrofit
  - Process model of heat transfer surface modifications
- Conclusions

REI Background

- 20+ Years of Fossil Fuel Combustion Experience
- Combustion, Fuel Conversion & Pollutant Emissions
- Proprietary Modeling Tools
  - Focus on modeling coal, trace pollutants and complex chemistry
  - CFD and process modeling tools
  - 200 utility boilers simulated
- R&D Testing Expertise
  - Bench-scale & pilot-scale facilities
  - Field demonstrations
- Specialized Equipment & Controls
- Customized Software Development



The Trend to Gas Firing



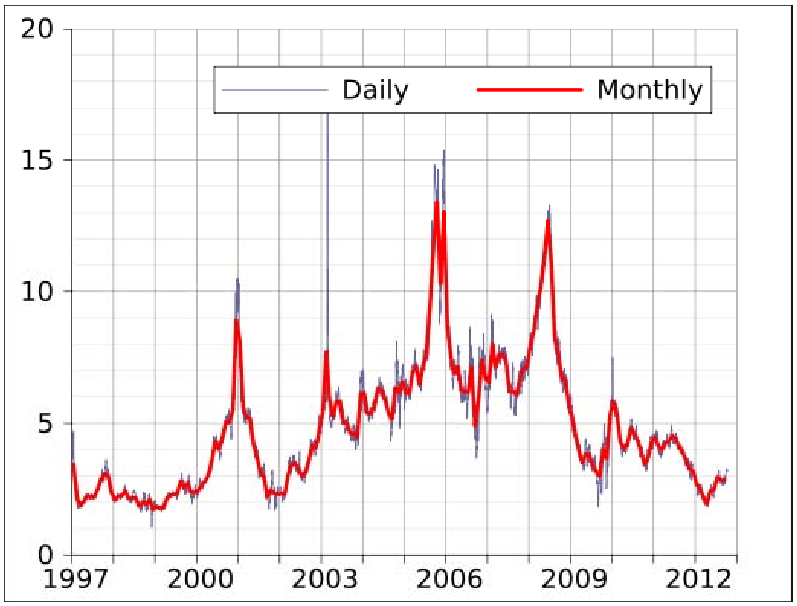
Why Retrofit to Natural Gas?

- Fuel Cost
- Emissions
- Operational Flexibility
- Timing – required equipment upgrade
- Efficiency – NGCC more efficient, but some thermal efficiency loss for retrofit
- Conversion (rather than repowering) allows option to convert back to solid fuel

Fuel Cost

- Current NG prices relatively low and stable, but pricing can change rapidly in short term

Historical Natural Gas Spot Prices (Henry Hub)

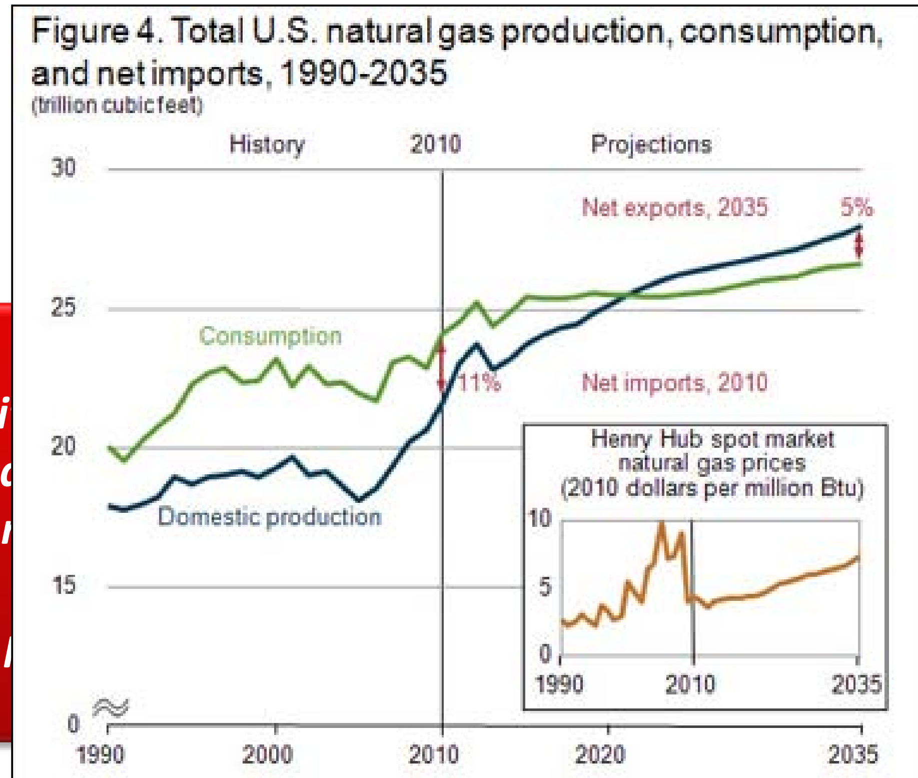


Natural gas spot prices (Henry Hub)

Source: Natural Gas Intelligence

Pricing Uncertainties

- Potential supply limitations
  - Environmental impacts with fracking (water, methane release)
  - Distribution costs
- Domestic demand
- Global demand



Bloomberg, June 13, 2012

Chevron Phillips Chemical Co. said i ***S.***
ethylene plants in more than a dec ***d***
gaining an edge in avoiding a poter
competitors such as Dow Chemical
factories in southeast Texas as gas
materials from the U.S. among the

Source: EIA report

Emissions

- Firing natural gas reduces emissions relative to coal firing

Fossil Fuel Emission Levels (Pounds per Billion Btu of Energy Input)			
Pollutant	Natural Gas	Oil	Coal
Carbon Dioxide	117,000	164,000	208,000
Carbon Monoxide	40	33	208
Nitrogen Oxides	92	448*	457*
Sulfur Dioxide	1	1,122*	2,591*
Particulates	7	84	2,744*
Mercury	0.000	0.007	0.016
Source: EIA - Natural Gas Issues and Trends 1998			

*Controlled plants have lower emissions

Retrofit Options

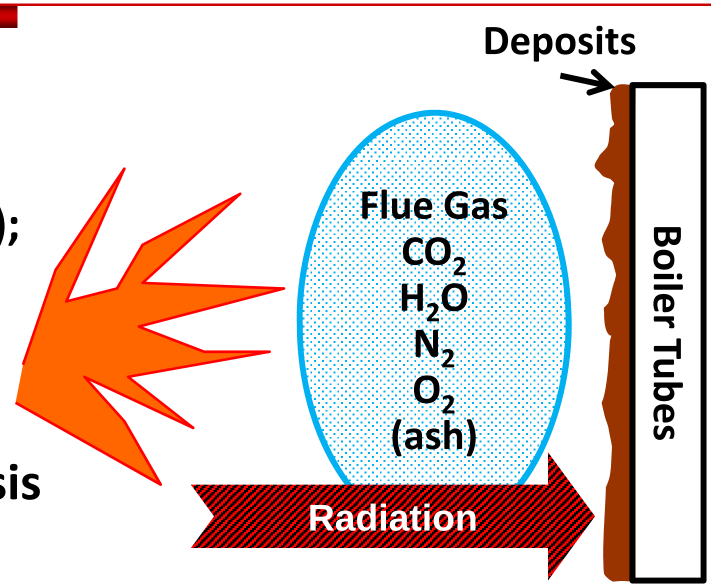
- Natural Gas Firing with Air
  - Simplest conversion and operation
  - Some loss in thermal efficiency
- Natural gas Firing with Oxygen
  - More complex conversion
  - May have efficiency benefits
  - Starts path to CO_2 capture
- Co-firing Natural Gas with Coal
  - Fuel flexibility
  - Only partial emissions benefits

Challenges to Retrofitting

- Firing System
  - Burner design and performance
  - Pressure part changes
  - Piping/windbox layout
  - Control systems
- Radiant Furnace Heat Transfer
- Convective Pass Heat Transfer
- Equipment Impacts (fans, air heater, APCDs)
  - Performance can be impacted by changed flow distribution, velocity, pressure drop, gas temperature and composition
  - Maintain, mothball or remove air pollution control devices?

Radiant Furnace Heat Transfer

- NG firing changes flame, flue gas and deposit properties
  - Energy emitted from flame changes (εT^4); flame impacted by firing system design
  - Flue gas may absorb more energy
  - Cleaner tubes increase heat transfer
- Net effect unclear, need detailed analysis with specific design to quantify



Fuel – Oxidant	AFT @ SR=1	Flame Emissivity	Flue Gas CO_2 / H_20 (mol %)	Flue Gas Emissivity*	Deposit Res.
Coal – Air	~4000 °F	higher	15 / 8	0.40	higher
Nat Gas – Air	~3650 °F	lower	8 / 16	0.48	lower
Nat Gas – Oxy	~5600 °F	lower	32 / 64	0.66	lower

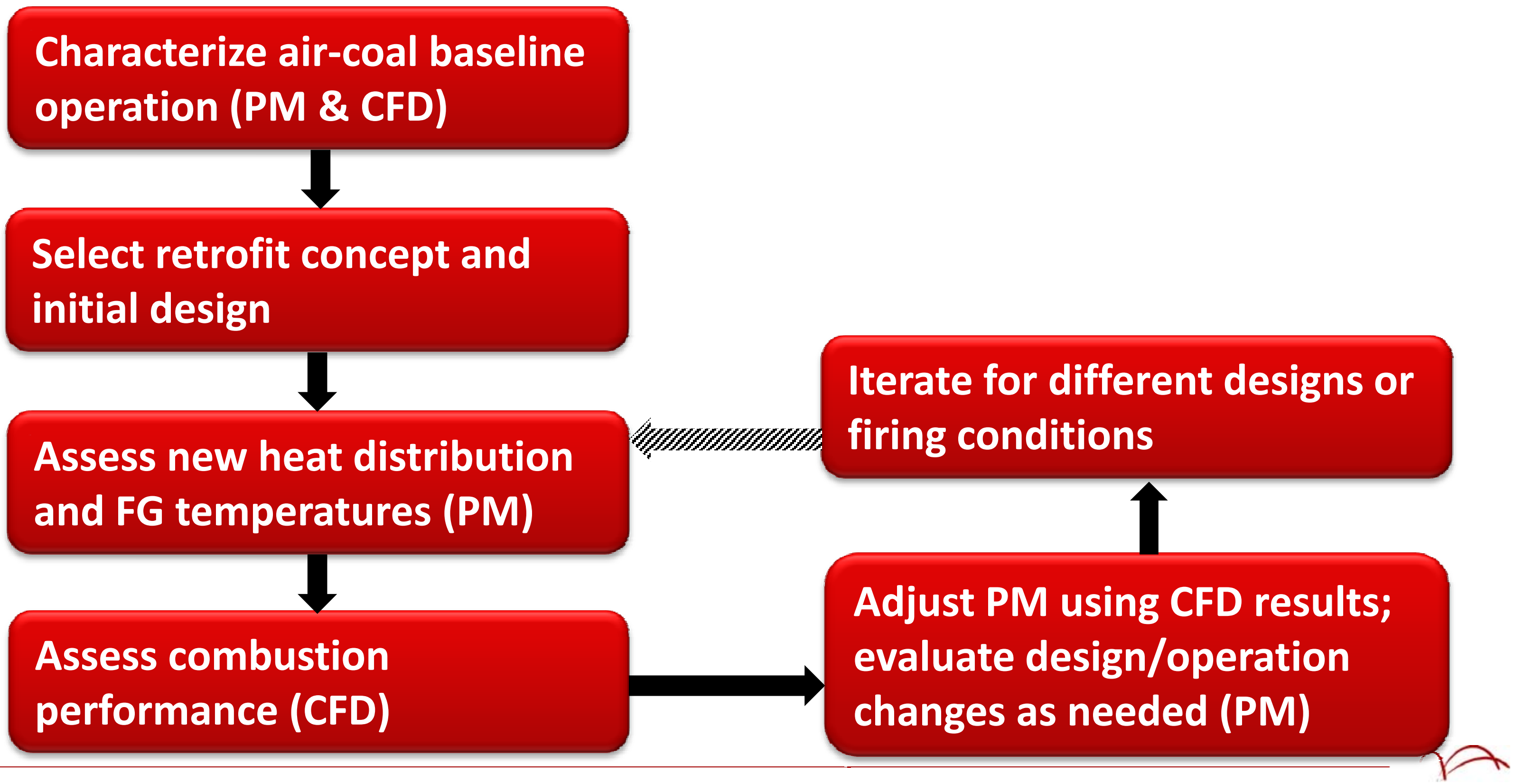
*Based on ~FEGT; gas emissivities vary with temperature

Convective Heat Transfer Issues

- **Maintaining heat transfer to superheater is most critical**
  - **Radiant SH impacted by flame characteristics and FGR**
  - **Convective SH impacted by flue gas temperature and flow rate**
  - **Lower flame temperatures or absorbed energy (at same firing rate) result in higher FEGT, potentially causing too much heat transfer in convective pass (must avoid tube overheating)**
- **Economizer heat transfer is less important, but can change boiler efficiency with changed FW or APH conditions**
- **Can adjust convective heat transfer with attemperation, modified heat transfer surfaces, auxiliary heating**
- **Appropriate modeling of coupled furnace heat transfer and steam circuit performance provides guidance**

Modeling Evaluation Approach

- How does new system heat transfer compare to existing?
- If needed, how can heat transfer be modified?

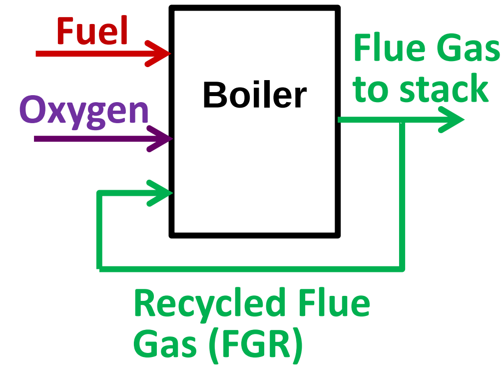


Examples

- Illustrate use of modeling tools useful in evaluation of natural gas retrofit of coal-fired boilers
- Example 1 – CFD modeling of air-coal to oxy-NG retrofit
- Example 2 – SGE process modeling of convection surface area modifications

Example 1 – Oxy-NG Retrofit

- Oxy-natural gas firing provides
  - Flexible flame temperatures
  - Higher thermal efficiency than air-NG firing
  - Very low emissions (less flow out stack)
  - Potential for easier CO_2 capture

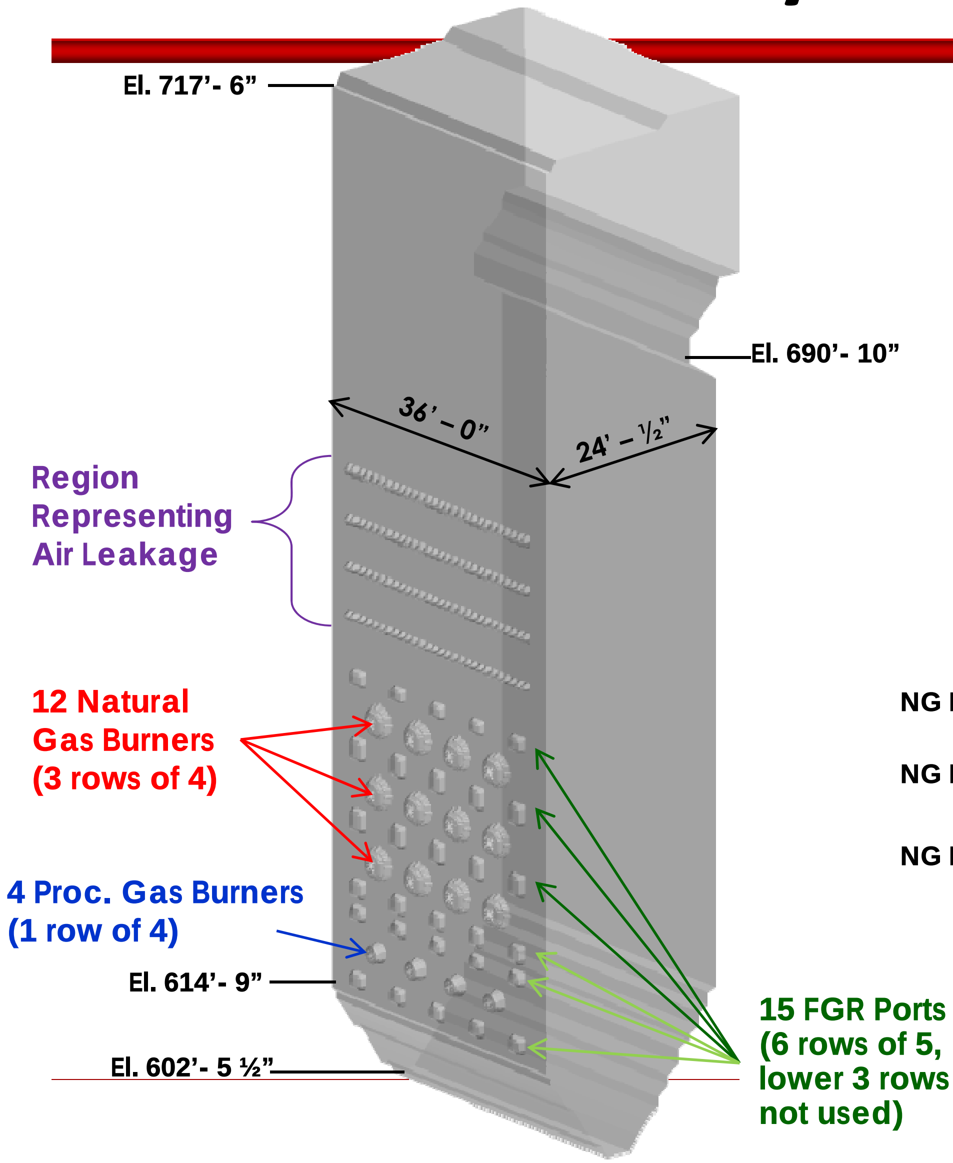


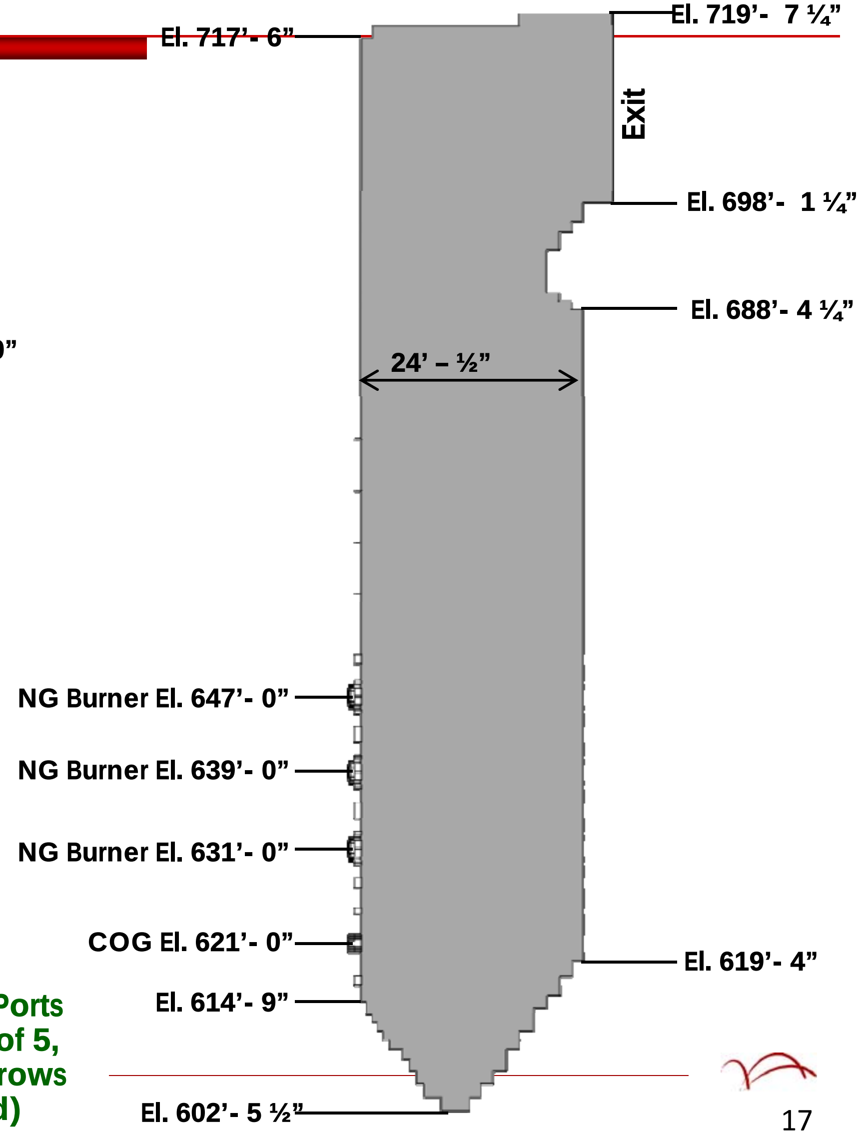
- For oxy-firing, FGR+O_2 inlet mixture impacts radiant furnace and convective pass heat transfer
  - FGR absorbs energy, adds mass flow
  - FGR amount and injection location impact flame temperature and heat flux profile
- Key parameter is heat transfer distribution in radiant and convective sections

Model Overview

- Use CFD modeling to assess furnace performance when retrofitting from air-coal firing to oxy-natural gas firing in a 350 MW coal-fired boiler
- Compare oxy-NG to air-coal firing results for:
  - Flame temperature
  - Furnace exit gas temperature
  - Heat transfer in radiant furnace
  - Peak furnace wall temperatures
  - Flue gas flow rates
  - Heat transfer in convective section

Furnace Geometry





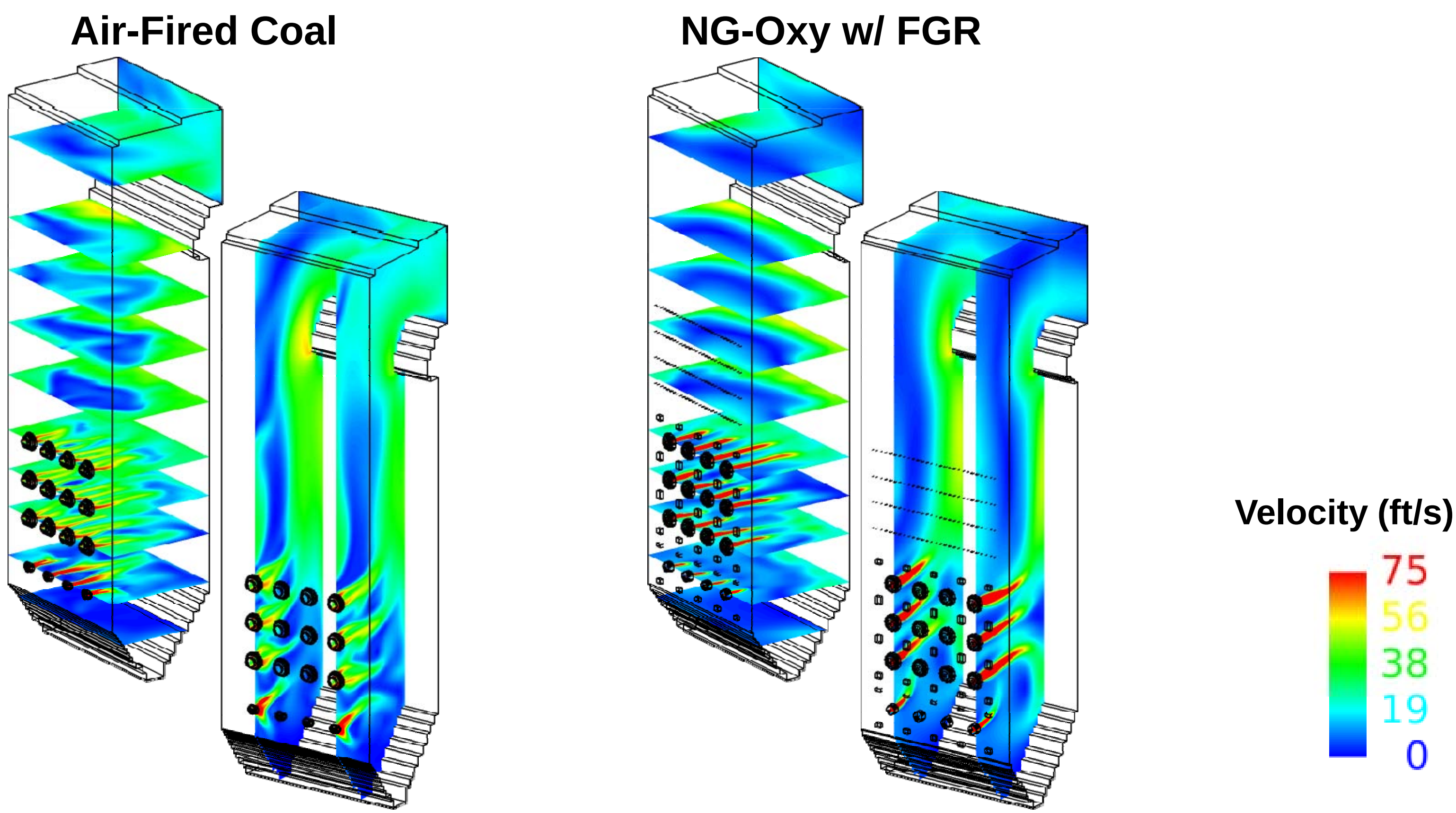
Model Basis

- Operational Characteristics
  - Furnace firing rate was maintained when changing from air-coal to oxy-natural gas firing
  - Process gas (PG) fired at same rate as baseline coal case
  - Air in-leakage estimated at 3% of total flow rate
  - FGR composition and oxygen injection rate based on maintaining 3% excess O_2 (dry) at exit
  - 26.7% O_2 in O_2+FGR mixture (estimated to match air-fired HT)
- Generic NG burner design used; flue gas injected in burner zone but not mixed directly with NG-oxy streams (based on Jupiter Oxygen high temperature concept)

Overall Operating Conditions

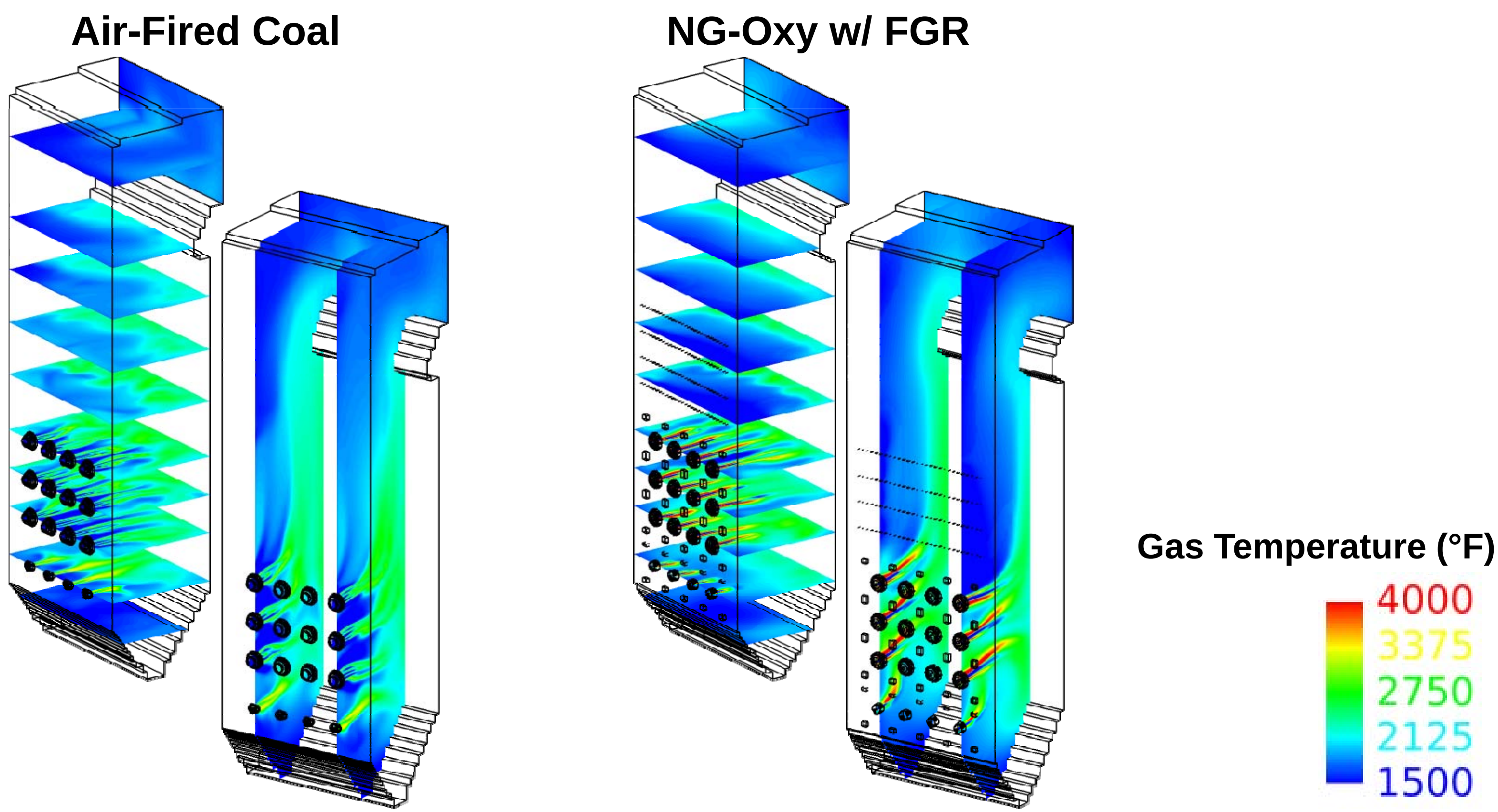
Furnace Operating Conditions	Air-Coal	Oxy-NG
Total Furnace Firing Rate (MBtu/hr)	940	940
Coal/Natural Gas Firing Rate (MBtu/hr)	857	857
Process Gas (PG) Firing Rate (MBtu/hr)	83	83
Total Air or O_2+FGR Flow Rate (klb/hr)	924	549
Theoretical Excess O_2 (%, wet)	4.7%	1.2%
Theoretical Excess O_2 (%, dry)	5.1%	3.0%
Overall Furnace Stoichiometric Ratio	1.31	1.09
Coal Burner SR	1.26	
NG Burner SR		0.984
PG Burner SR	1.76	0.984

Gas Velocity



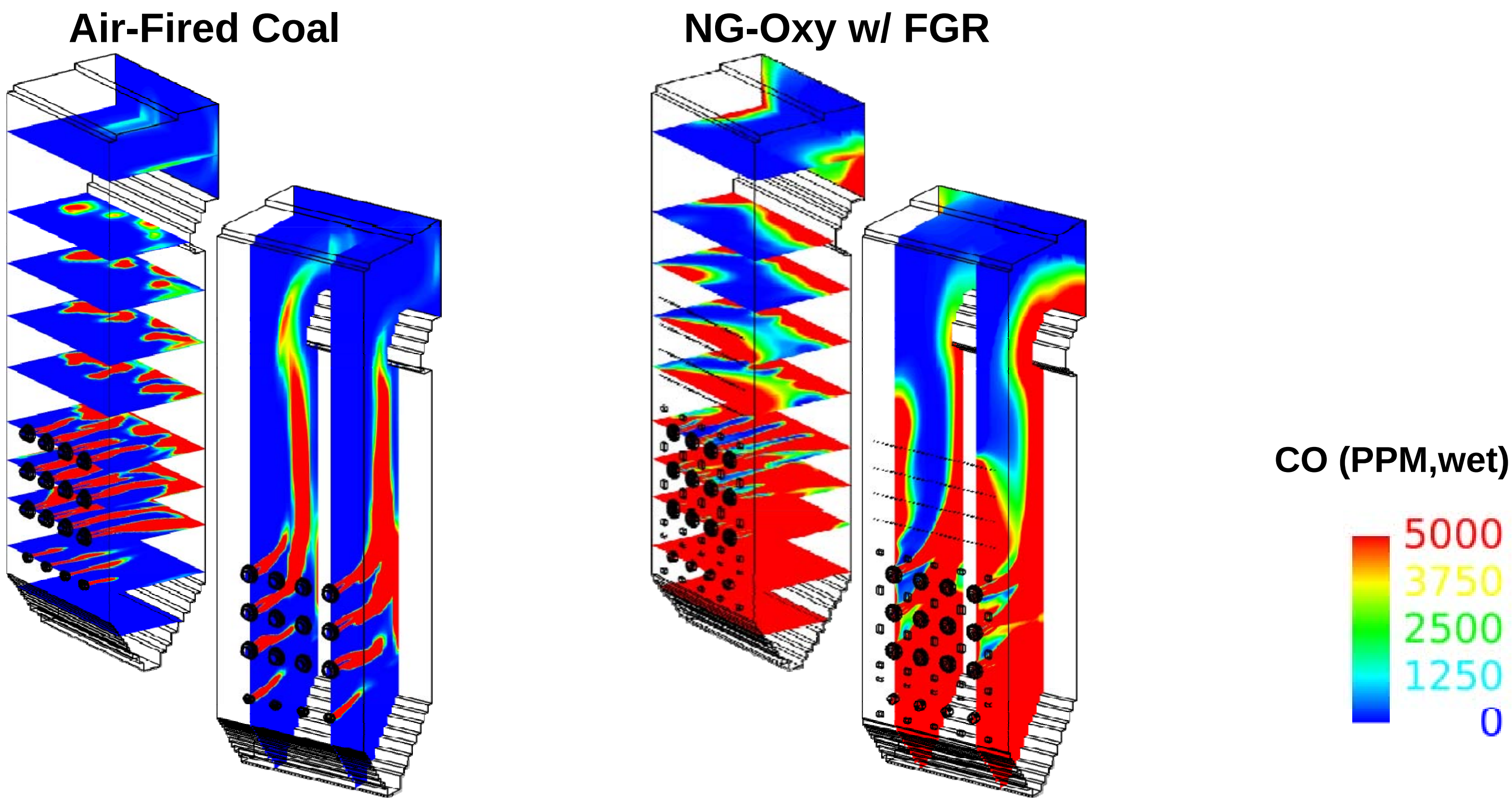
General flow patterns similar for both cases; exit gas velocities lower for NG-Oxy due to lower volumetric flow.

Gas Temperature



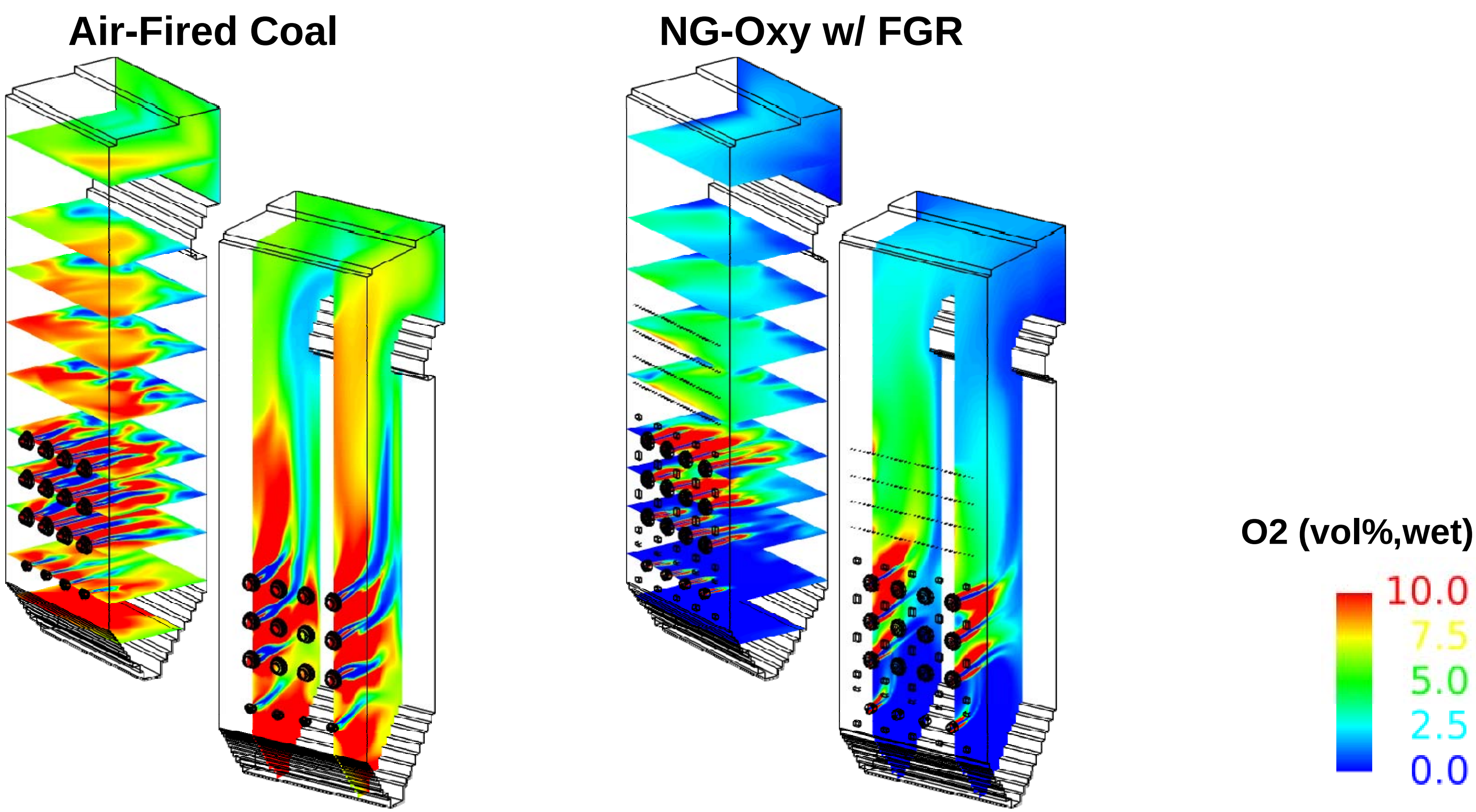
For NG-Oxy, significant amount of flame surface over 4500 F; FGR rate and injection location impacts local and exit gas temperatures.

CO Concentration



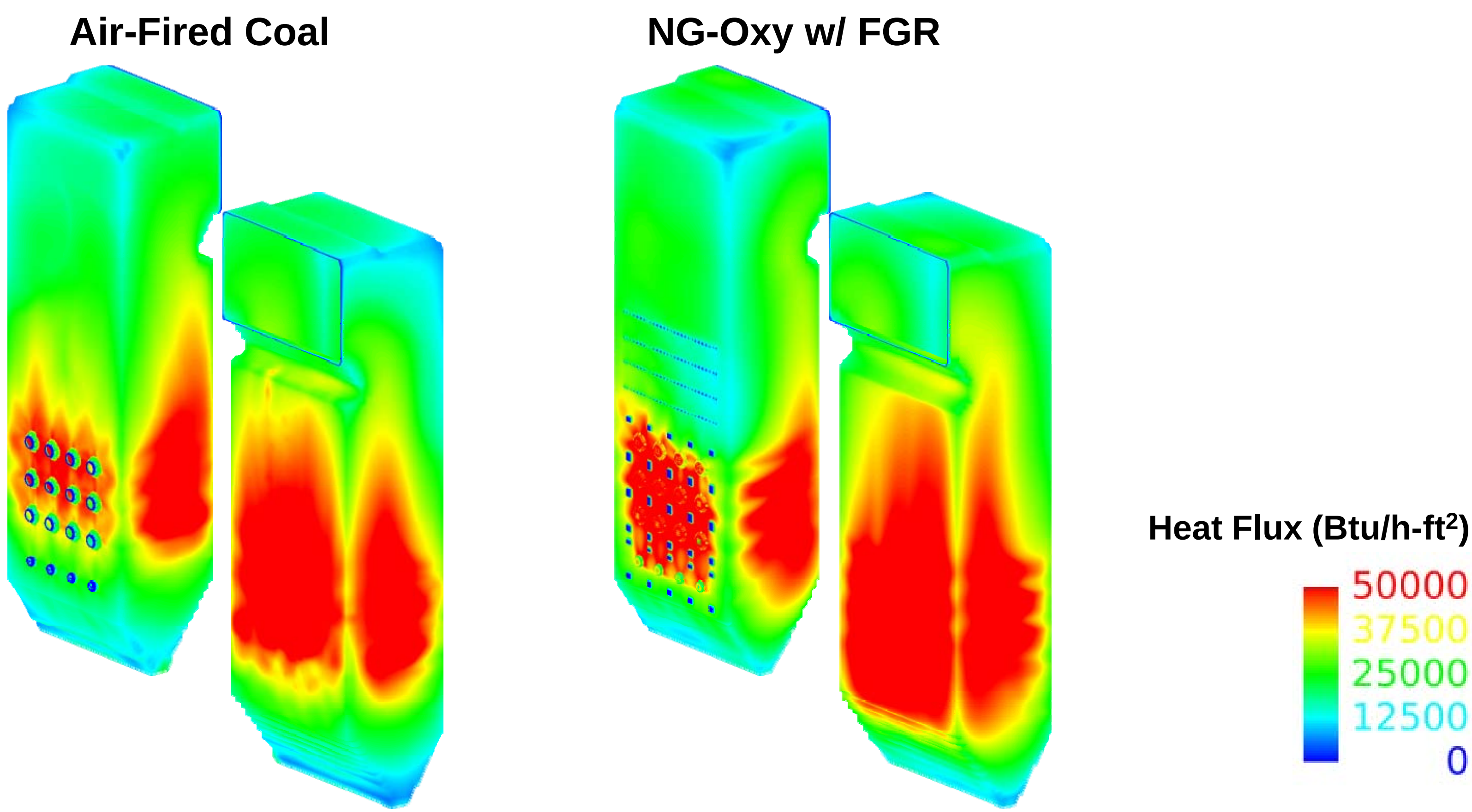
Higher CO in lower furnace because PG and NG burners are sub-stoichiometric (0.984) and FGR and air in-leakage assumed to enter in and above burner zone. FGR injection location can be optimized to reduce CO.

O_2 Concentration



O_2 higher in air-coal case due to higher operating O_2; no O_2 in lower furnace for NG-Oxy case due to sub-stoichiometric PG burners

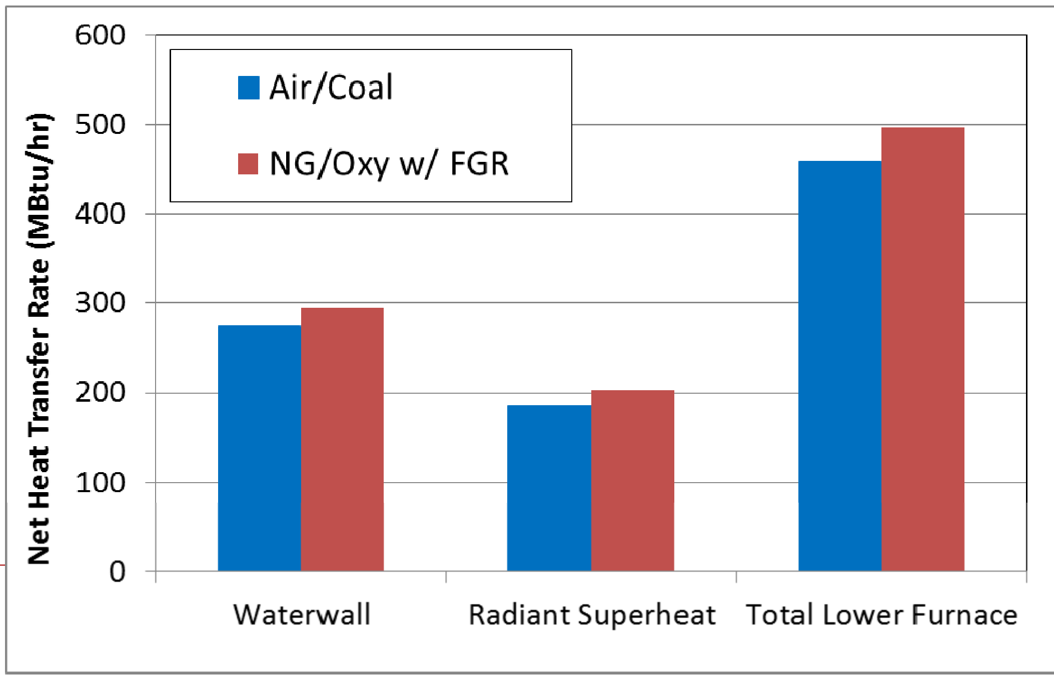
Net Wall Heat Flux



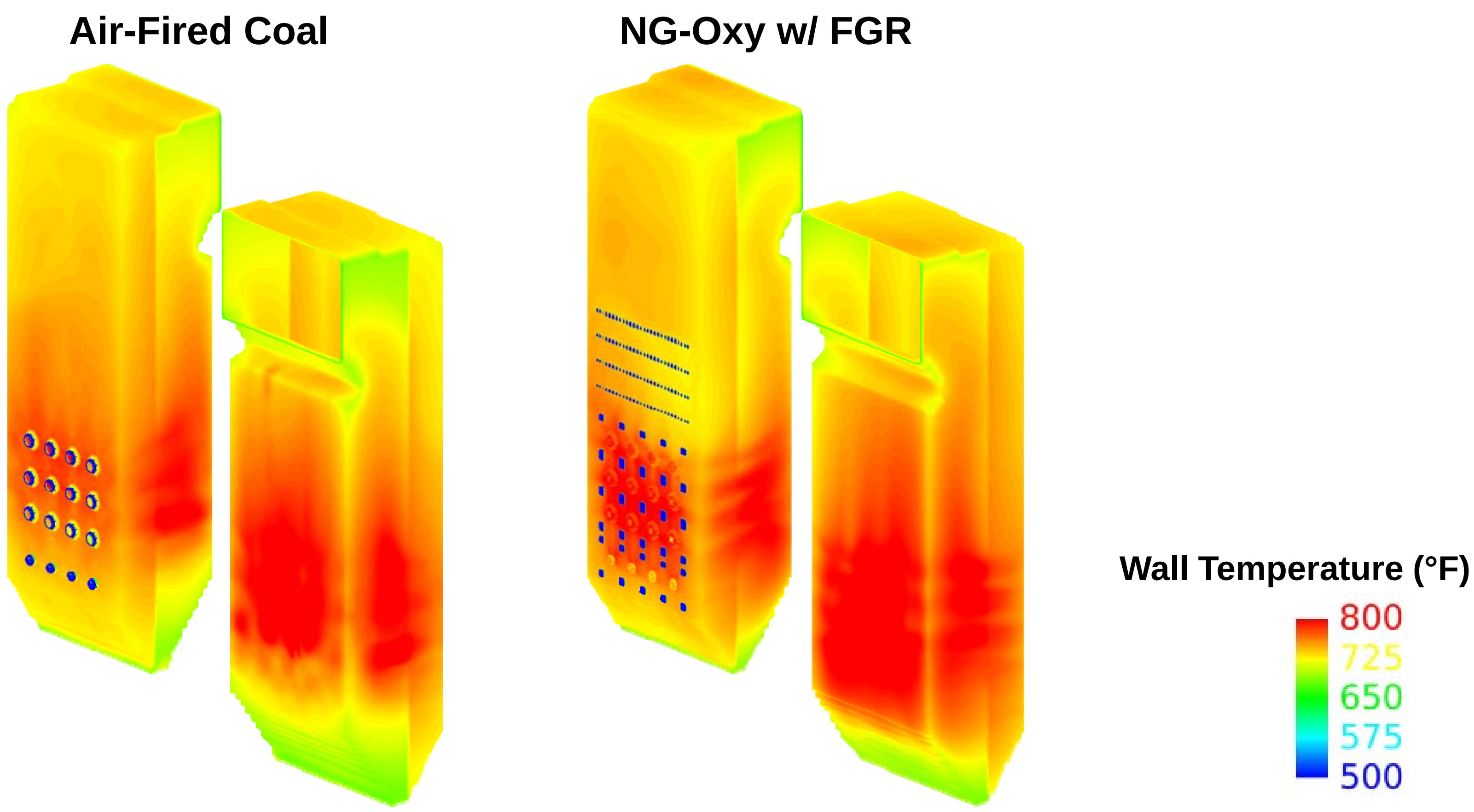
Cases have similar net heat fluxes

Heat Transfer by Furnace Zone

	Baseline Air-Coal		Oxy-NG (w/ FGR)	
Zone	Heat Transfer (MBtu/hr)	% of Total	Heat Transfer (MBtu/hr)	% of Total
1	42	9.1	54	10.9
2	154	33.6	188	37.9
3	189	41.2	170	34.1
4	74	16.1	84	17.0
Total	459		497	

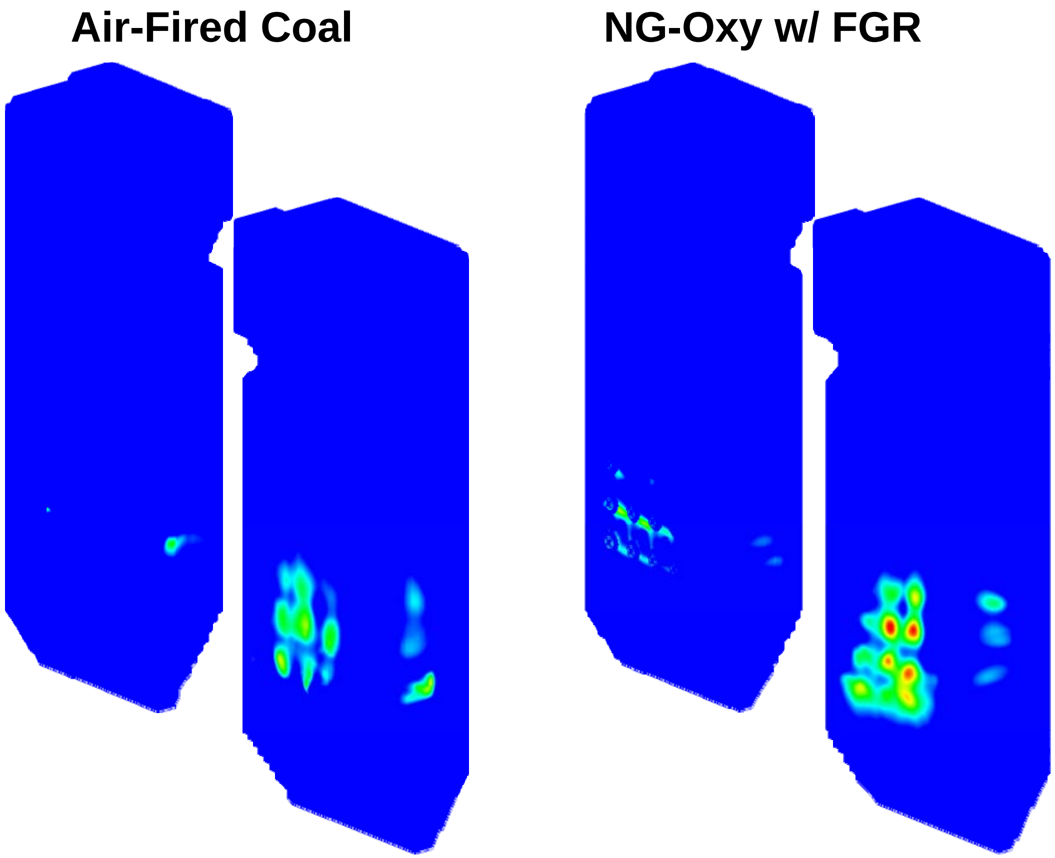


Wall Temperature

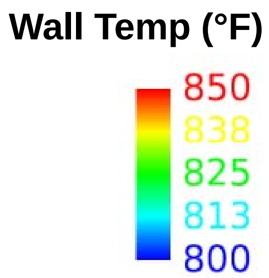


Wall temperatures mimic wall heat flux; cases have similar fluxes

Peak Wall Temperature



Maximum Wall Temperature (°F)	
Air-Coal	840
Oxy-NG	852



(tight scale highlights peak temperatures)

Example 1 CFD Model Results

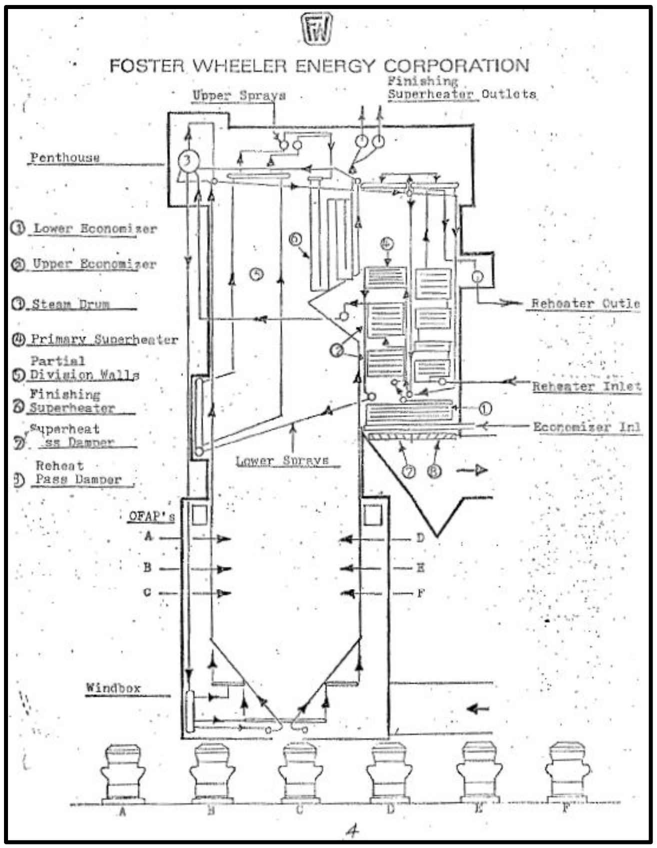
Result	Baseline Coal-Air	NG-Oxy w/ FGR
Furnace Exit Gas Temperature (°F)	1850	1925
Exit CO Concentration, wet (ppm)	138	2044
Exit O_2 Concentration, wet (%)	4.7	1.3
Peak Wall Temperature (°F)	840	852
Radiant Furnace Heat Transfer (MBtu/hr)	459	497
Backpass Flue Gas Flow Rate (klb/hr)	1011	582
Heat Transfer to Superheater (MBtu/hr)	255	247
Heat Transfer to Economizer (MBtu/hr)	110	66
Flue Gas Temperature Leaving Economizer (°F)	626	538

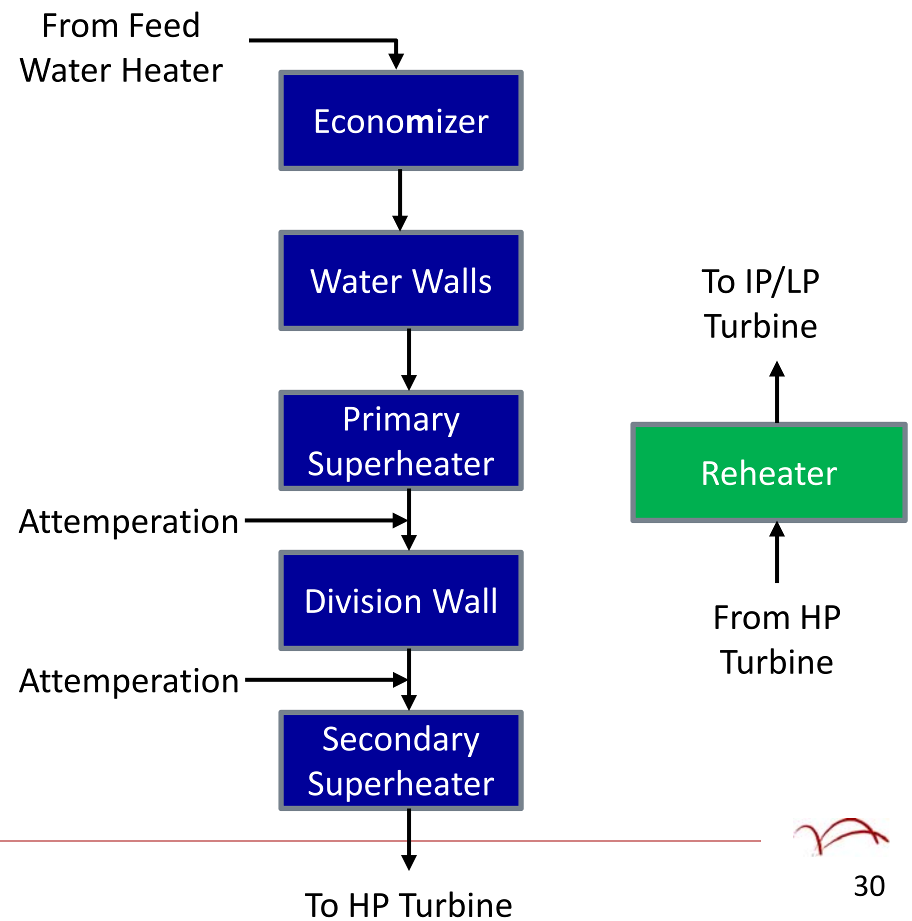
Modeling Conclusions

- Results showed oxy-NG firing is feasible for mimicking air-coal fired furnace heat transfer, but firing system will need to be optimized for specific furnace design
  - Oxy-NG burners produced high flame temperatures (>4800 °F) which aided furnace heat transfer (higher than air-NG flames)
  - 25-27% oxygen in FGR+O_2 inlet mixture gave similar radiant furnace heat transfer
  - Firing system produced similar radiant furnace heat flux distribution and peak wall temperatures
  - Burner design and FGR layout can be used to manipulate furnace heat transfer and CO
  - Reduced flue gas flow slightly decreased heat transfer in backpass SH and significantly decreased heat transfer in economizer

Example 2 – Modified HT Surfaces

- **Evaluate impact of changes to convective pass heat transfer surface areas in a 540 MW_e wall-fired coal boiler with a split back pass**

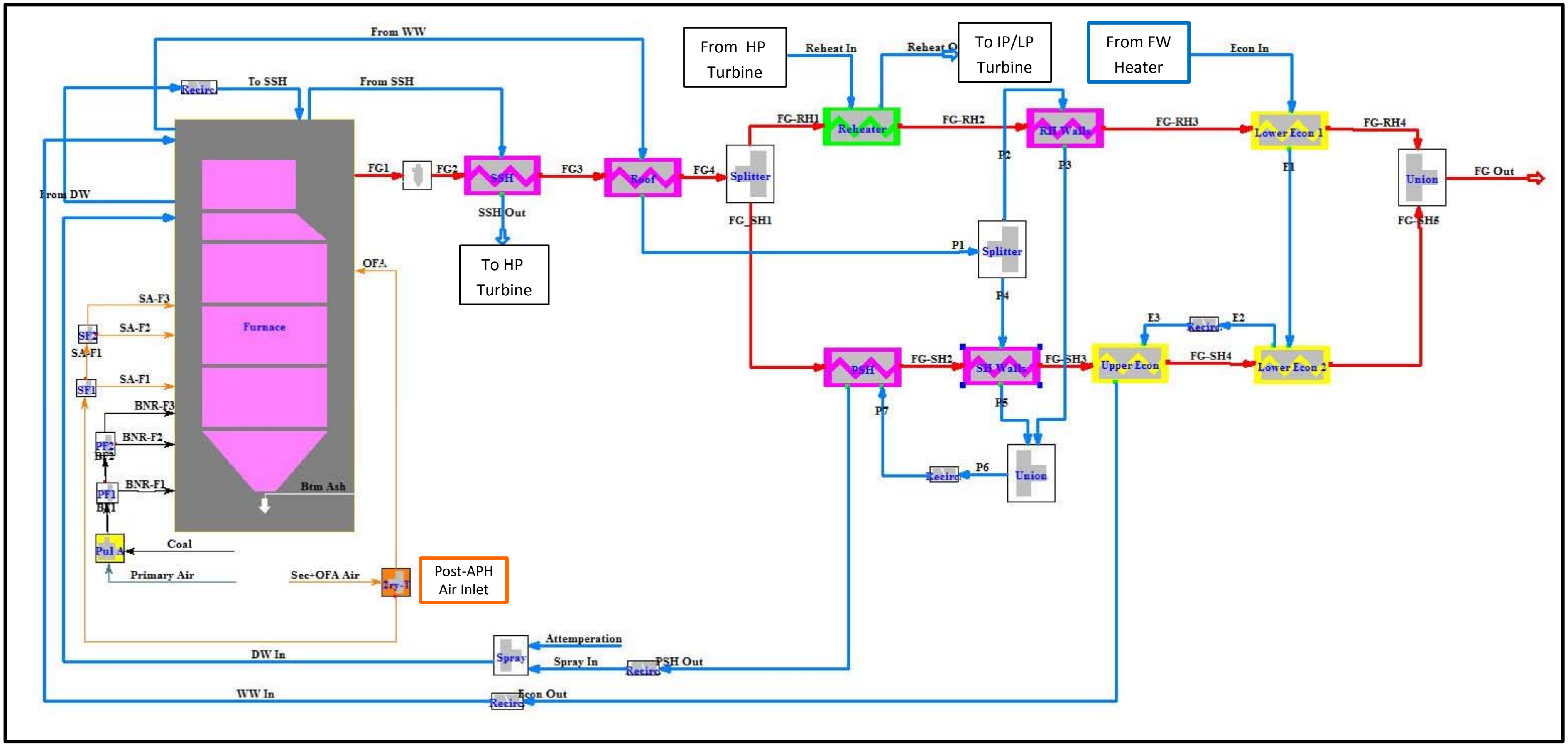




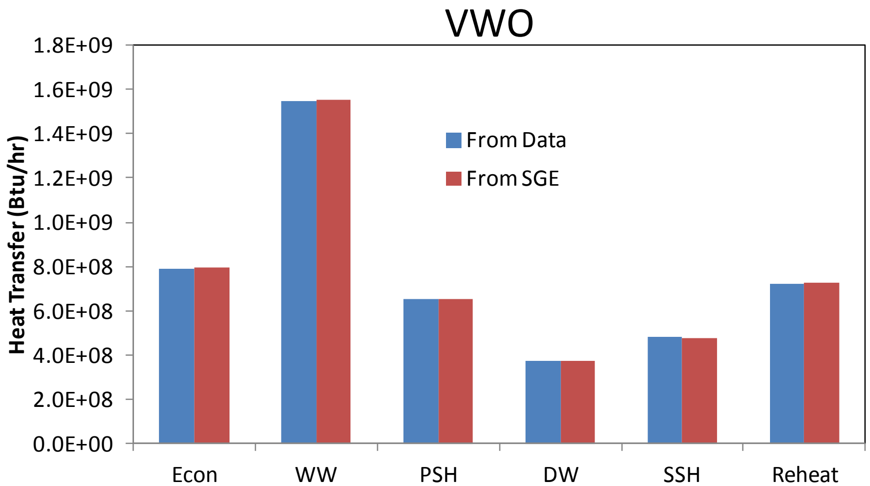
Example 2– SGE Model Setup

- SteamGen Expert (SGE) is a heat and mass balance (HMB) process model used to predict coupled flue gas and steam circuit heat transfer
- SGE model included:
  - Fireside from post air heater to post economizer
  - Steam side from the economizer inlet to the HP turbine and from the reheater inlet to the IP/LP turbine
- Heat transfer tuning approach:
  - Total surface area of the convective heat exchangers was maintained at calculated/estimated value from boiler drawings
  - Outside fouling resistance was tuned for all HT surfaces to accurately predict HT for valves wide open (VWO) condition

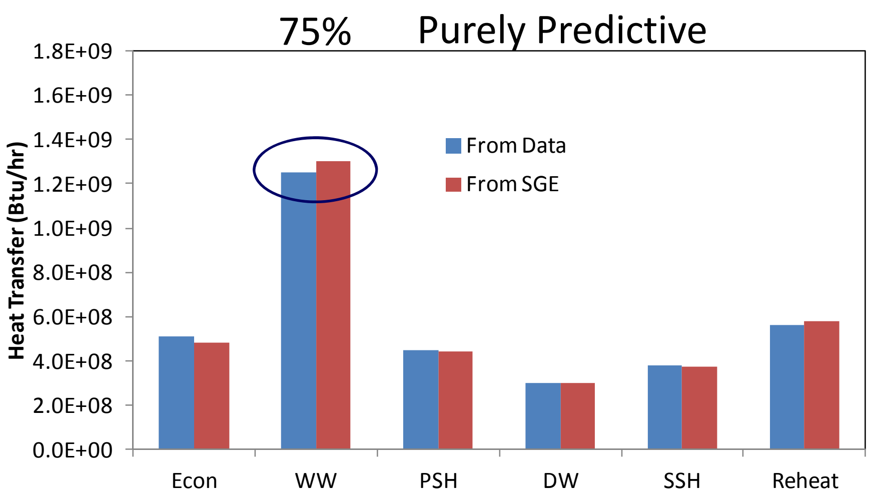
Example 1 – SGE Model

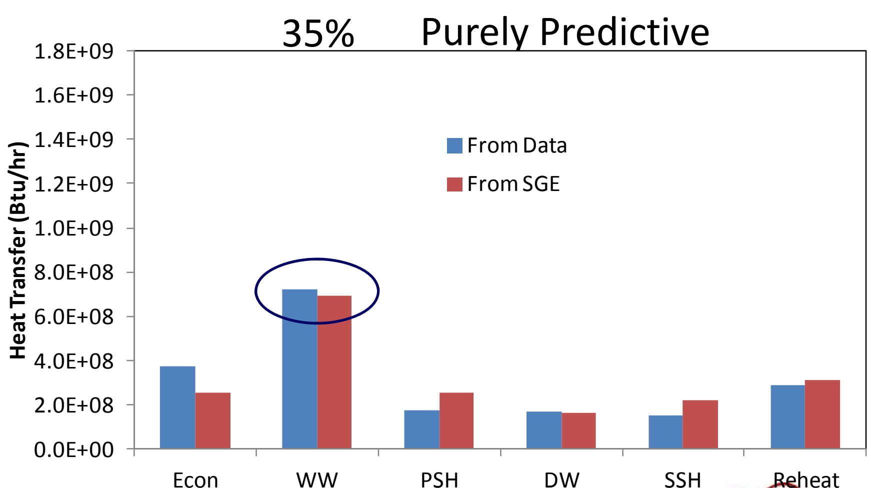


Example 1 - Results (VWO, 75% & 35%)

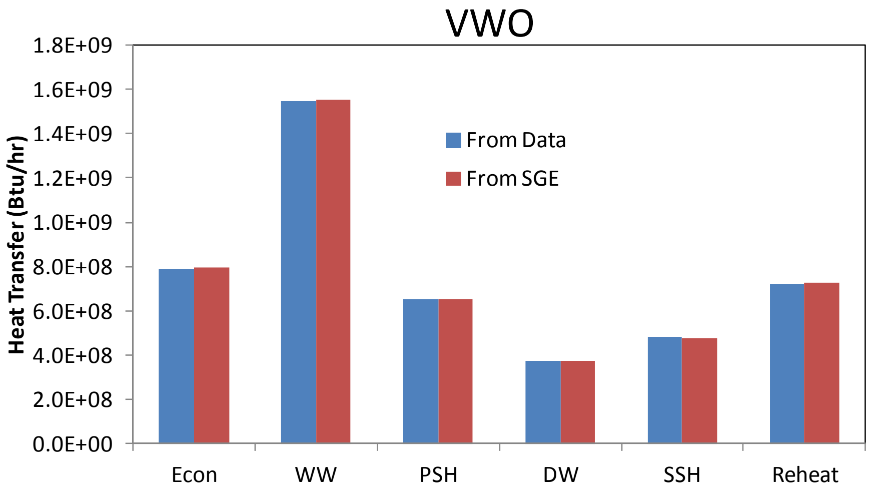


SGE model tuned to VWO data (where available); 75% and 35% loading predicted

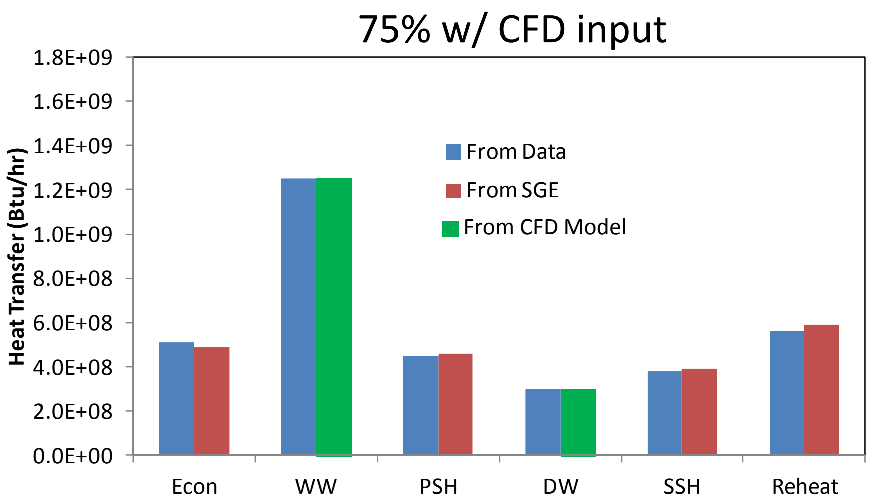


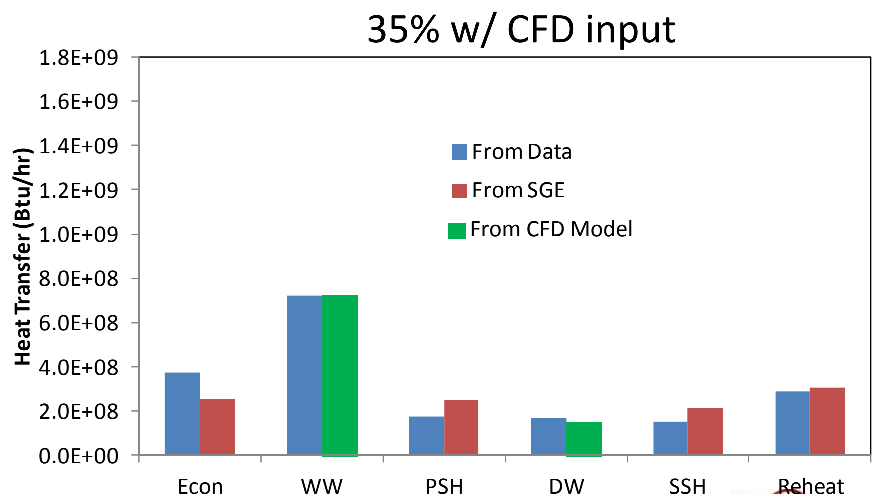


Example 1 - SGE Results w/ CFD Input



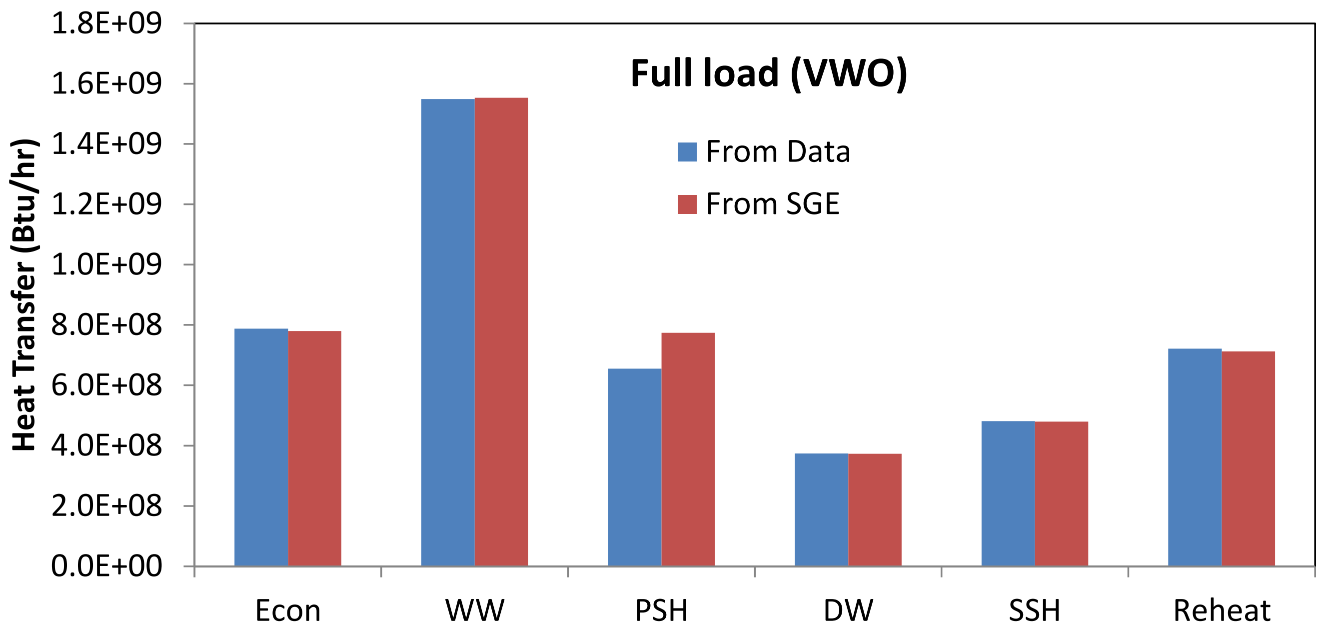
75% and 35% loading predictions improved when using CFD model results for radiant furnace water wall (WW) and division wall (DW)





Surface Area Modification 1 – Results

- Changes to Existing Heat Transfer Surface
  - Addition of new primary superheat tubes
  - Removal of tubes from upper bank of economizer in heat recovery area
- New Heat Transfer Surface (external economizer)
  - Addition of economizer tubes in modified duct downstream of convection exit



Surface Area Modification 1 – Summary

- Heat transfer in primary superheat increased
- Heat transfer in original economizer downstream of the PSH decreased, but that loss was balanced by increase HT in new post-convection economizer tubes

	Baseline	Mod 1
Spray Flow (kpph)	45	95.6[1]
Boiler Exit Temp (F)	823	881[2]
Air Heater Inlet Temp (F)	823	784[3]

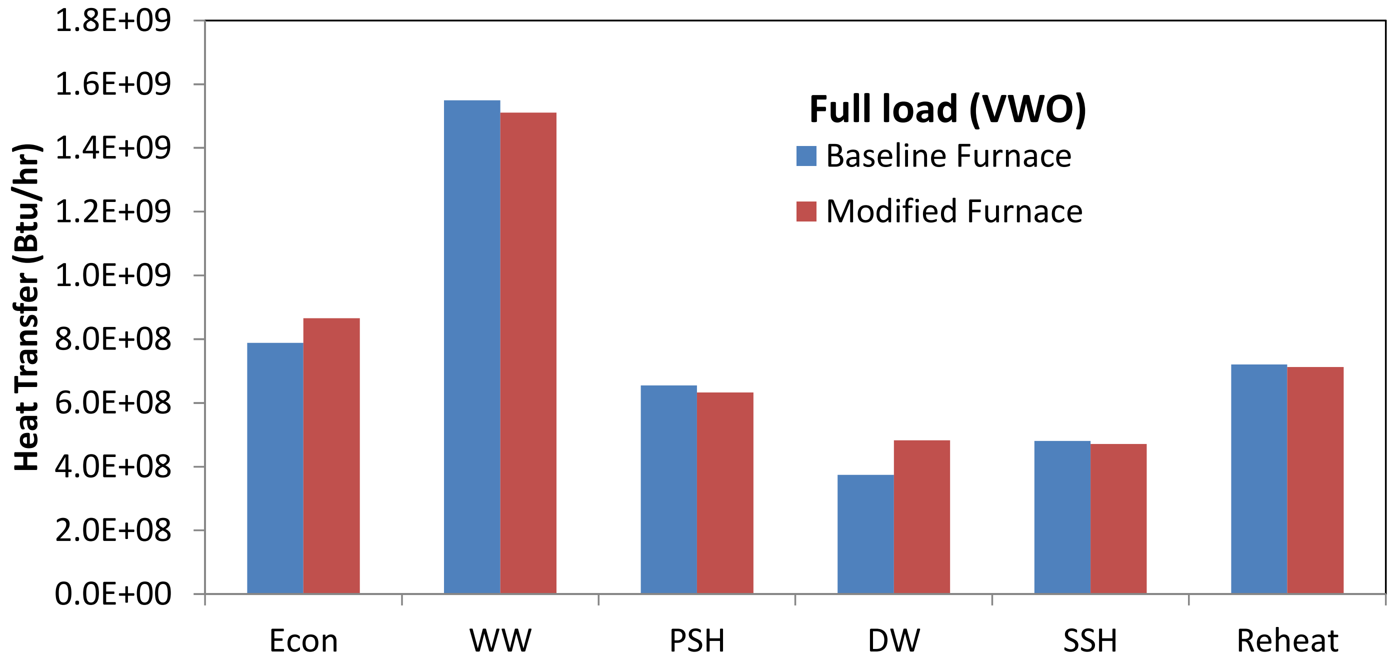
[1] maintain 1005 °F HP turbine inlet temperature w/ higher PSH

[2] removal of some original economizer tubes

[3] additional heat removed by external economizer

Surface Area Modification 2 – Results

- **Changes:**
  - **Expanded surface area of division walls in radiant boiler**
  - **Addition of a modular external economizer**



Surface Area Modification 2 – Summary

- Increase in division wall (DW) and economizer heat transfer; slight decrease in waterwall (WW), primary superheat (PSH), and reheat (RH) heat transfer rates

	Baseline	Mod 2
Spray Flow (kpph)[1]	45	123.4[1]
Boiler Exit Temp (F)	823	829[2]
Air Heater Inlet Temp (F)	823	774[3]

[1] maintain 1005 °F HP turbine inlet temperature w/ higher DW

[2] no change to existing economizer

[3] additional heat removed by external economizer

Conclusions

- Modeling tools can help evaluate conversion of boilers from coal to natural gas firing
  - CFD can evaluate trade-offs between radiant and convective heat transfer for different fuels, oxidizers, burner designs, firing rates and flue gas recycle rates in retrofit boiler designs
  - CFD can evaluate retrofit impacts on APCD performance
  - SGE useful for coupled steam circuit and flue gas heat transfer
  - SGE can evaluate impacts on steam circuit heat transfer, spray flow, and gas exit temps with modified heat transfer surfaces
- Modeling can expand range of retrofit solutions and increase confidence in retrofit performance and impacts

Acknowledgements

- Oxygen-natural gas modeling results used with permission of Jupiter Oxygen Corp
- CFD graphics created with Fieldview by Intelligent Light (www.ilight.com)

- Questions: Brad Adams adams@reaction-eng.com