REINHOLD ENVIRONMENTAL Ltd.

2018 NOx-Combustion Round Table & Expo Presentation

February 19-20, 2018, in St. Louis, MO / Hosted by Dynegy

Coal to Gas Conversion 101

Kevin Davis
Senior Principal and Co-President
For Energy and Environmental Solutions
REACTION ENGINEERING INTERNATIONAL

NOx-Combustion-CCR Round Table
Hosted by Dynegy
Marriot St Louis Airport Hotel, St Louis, MO
February 19-22, 2018

Reaction Engineering International

Privately held consulting firm recognized for independent analysis and evaluations involving a range of industrial combustion applications

- Technical focus on multi-phase, chemically reacting flows
- Serving the utility industry since 1990
- Affiliates in Asia and Europe
- Established capabilities include advanced modeling, process evaluation and testing

Coal-to-Gas Conversion Projects

- Extensive experience in fuel selection evaluations based on modeling and testing.
- Process evaluations specializing in multi-phase reacting flow CFD modeling incorporating detailed integration of steam-side optimization
- Teaming with combustion& emissions control equipment vendors and suppliers/installers of pressure part modifications

Coal-fired Units' Options under Environmental Challenges

Source: MHI 2015

Options	Advantages	Costs
Shut Down the Unit	Lowest capital cost option	Eliminate potential source of generation and potential capacity revenues and must incur de-commissioning cost (replacement generation cost possibly)
Install New Combined Cycle	Minimize emissions with an efficient generation source burning cheap gas	Very high capital cost > $1,250/kW
Re-power to Combined Cycle	Same benefits as combined cycle but re-using the steam turbine if possible	High capital cost >$1,000/kW
Install Capital Air Quality Control Systems	Installing the latest AQCS allows unit to remain operational with most fuel flexibility	High capital costs: FF ~$40/kW, Dry FGD ~ $125/kW, SCR ~ $160/kW, with increased equipment to maintain and manpower
Install Additives (DSI/ACI/SNCR) if Fuel has low enough S and N to comply	Low upfront cost while maintaining coal capability: ACI ~$5/kW, SNCR ~$14/kW, DSI ~$5/kW	Unit has no fuel flexibility & now has higher operational cost with boiler, air heater and ductwork impacts (corrosion, ammonia slip, material drop-out concerns, etc)
Convert to Natural Gas	A low cost operation ($26 – 65/kW) that eliminates nearly all Hg, particulate and sulfur emissions while deactivating coal equipment and associated manpower to maintain it	Gas supply line has to be available to be cost effective and efficiency goes down slightly
Become Dual Fuel Fired (Gas and Coal with Additives)	Unit can switch to lower cost fuel option instantaneously, and can meet future regulations	Paying for two separate systems upfront

Drivers of CTG Switching

Emissions

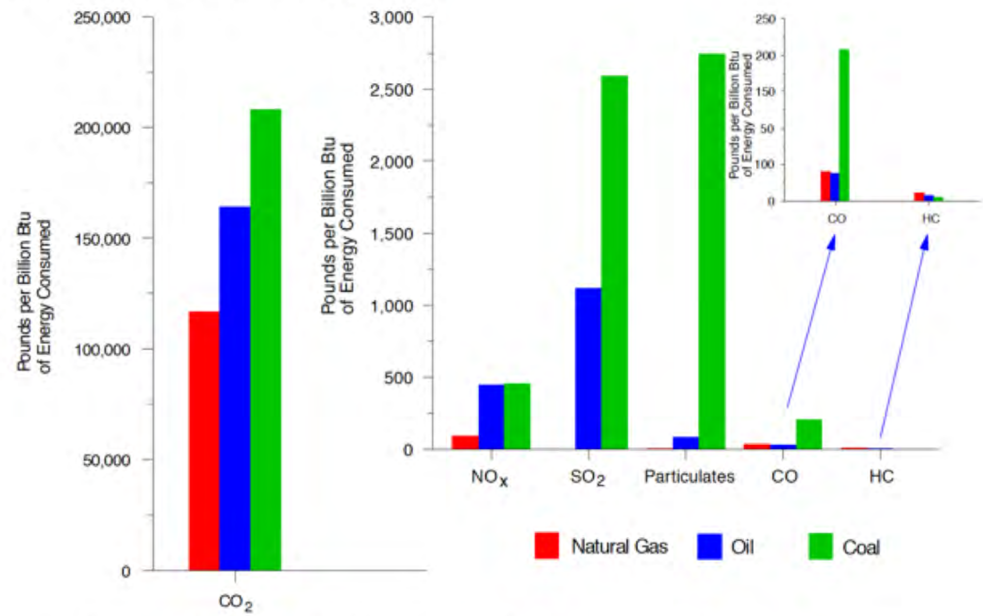
Fuel Cost

Emissions

- NG combustion releases lower carbon, NO_x, SO_x mercury and particulate matter
- Joliet conversion specifics: emissions reductions of 99.9 percent for sulfur dioxide, 97 percent for particulate matter, 34 percent for nitrogen oxides, plus a carbon dioxide reduction (Midwest Energy News, Feb 2017)

gram/GJ input	Natural Gas	Oil	Coal
Carbon Dioxide	50,301	70,507	89,424
Carbon Monoxide	17	14	89
Nitrogen Oxides	40	193	196
Sulfur Dioxide	0.4	482.4	1,113.9
Particulates	3	36	1,180
Mercury	0.000	0.003	0.007

Figure 22. Air Pollutant Emissions by Fuel Type



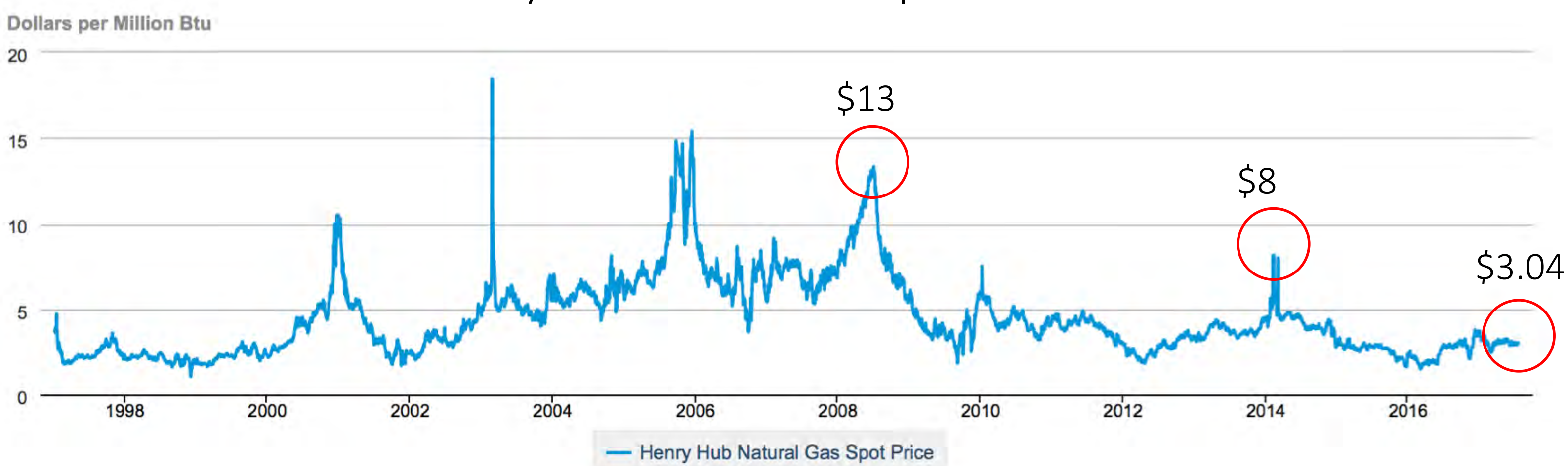
CO_2 = Carbon dioxide. No_x = Nitrogen oxides. SO_2 = Sulfur dioxide. CO = Carbon monoxide. HC = Hydrocarbon.
Note: Graphs should not be directly compared because vertical scales differ.
Source: Energy Information Administration (EIA) Office of Oil and Gas. **Carbon Monoxide:** derived from EIA, *Emissions of Greenhouse Gases in the United States 1997*, Table B1, p. 106. **Other Pollutants:** derived from Environmental Protection Agency, *Compilation of Air Pollutant Emission Factors*, Vol. 1 (1998). Based on conversion factors derived from EIA, *Cost and Quality of Fuels for Electric Utility Plants* (1996).

Source: EIA-Natural Gas Issues and Trends 1998

Natural Gas Cost

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

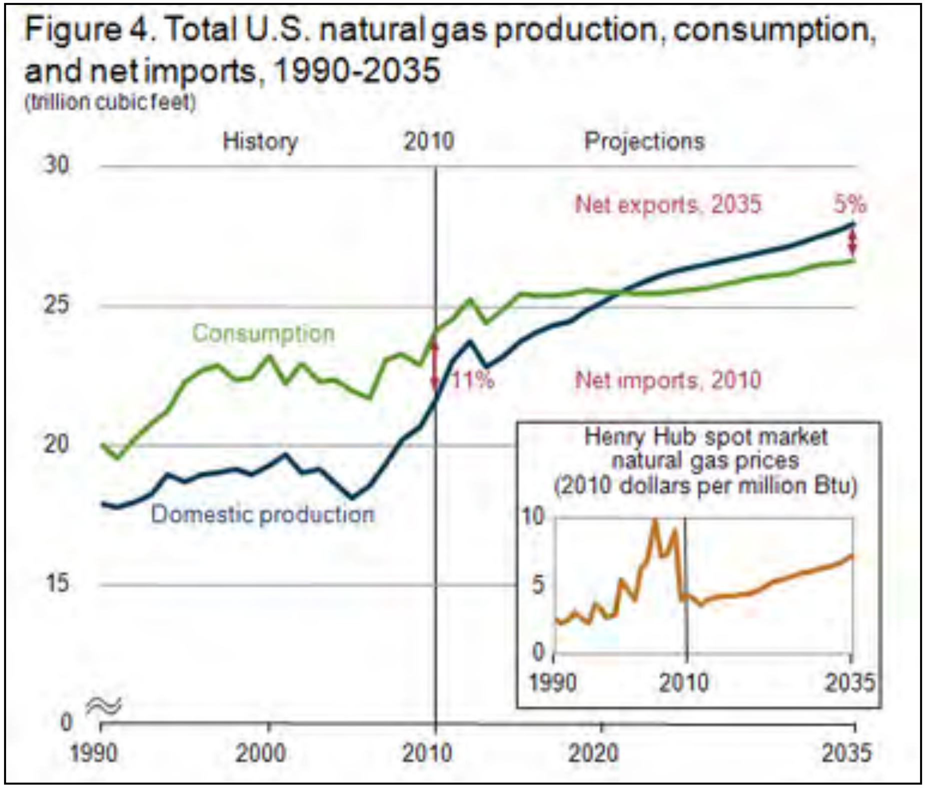
Henry Hub Natural Gas Spot Price



Source: eia.gov

Pricing Uncertainties

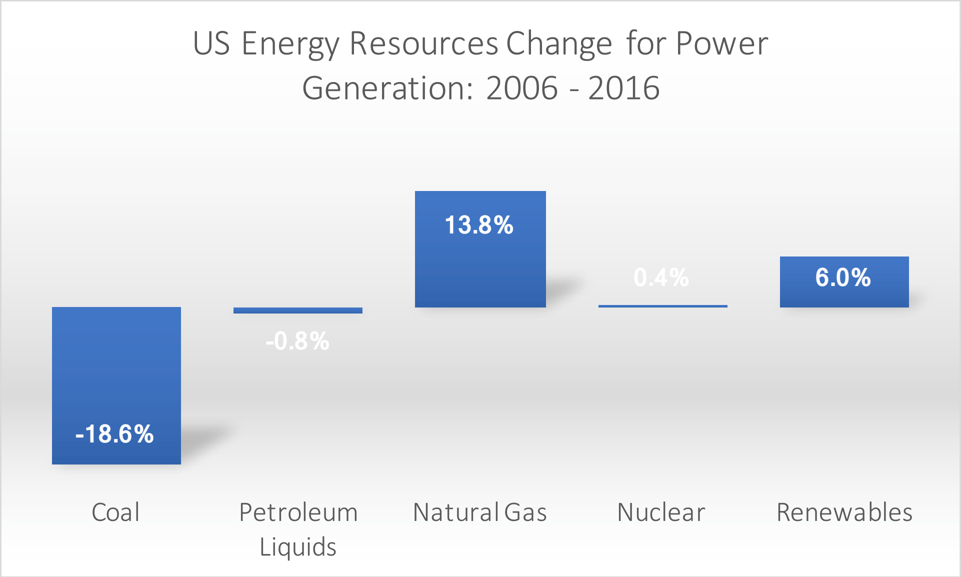
- Potential supply limitations
  - Environmental impacts with fracking (water, methane release)
  - Distribution costs
- Domestic demand
- Global demand



Source: eia.gov

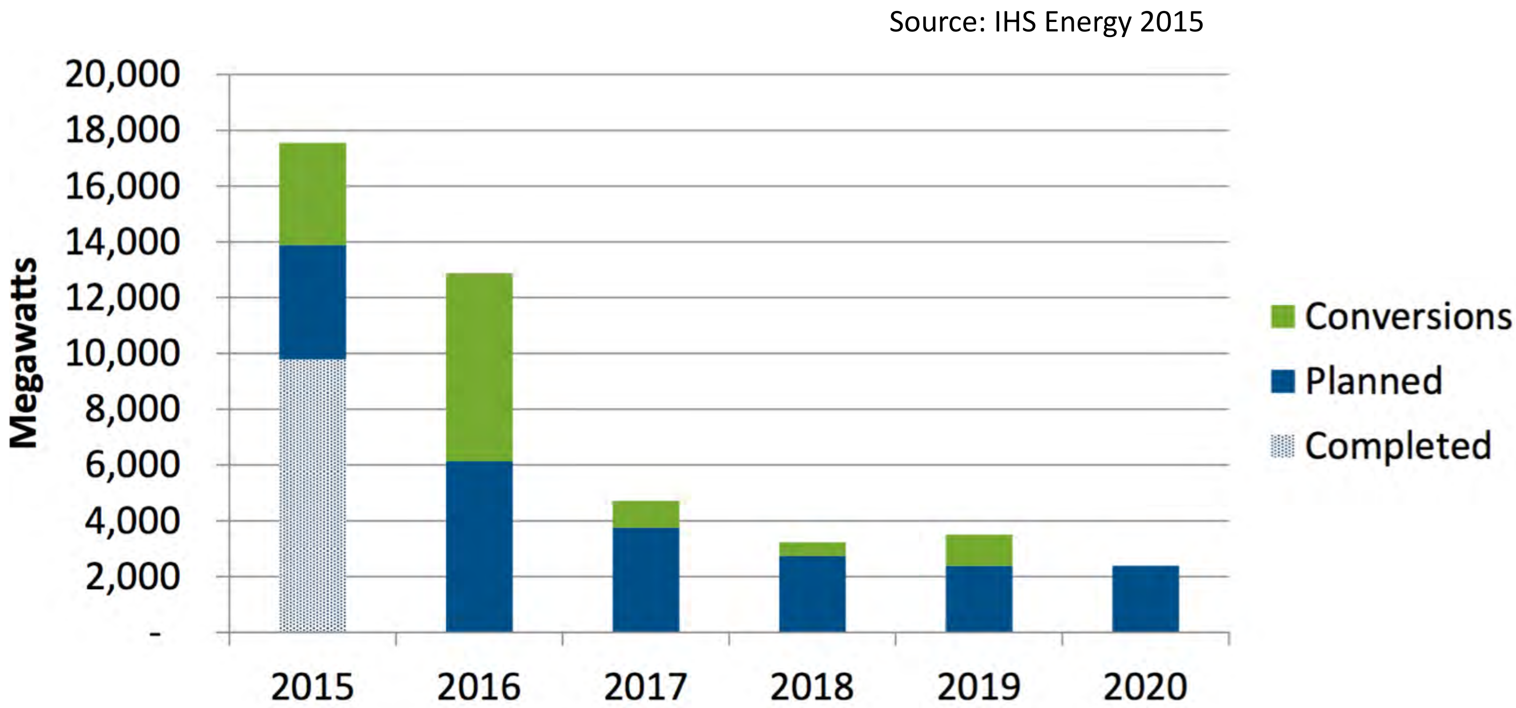
US Energy Resource Shift

- Total US power generation changed little from 2006 and 2016 (0.4% increase)
- However, the share of energy resources used for generation have changed dramatically



Source: EIA 2017

US Completed and Planned Coal-Fired Utility Scale Retirements (2015-2020)



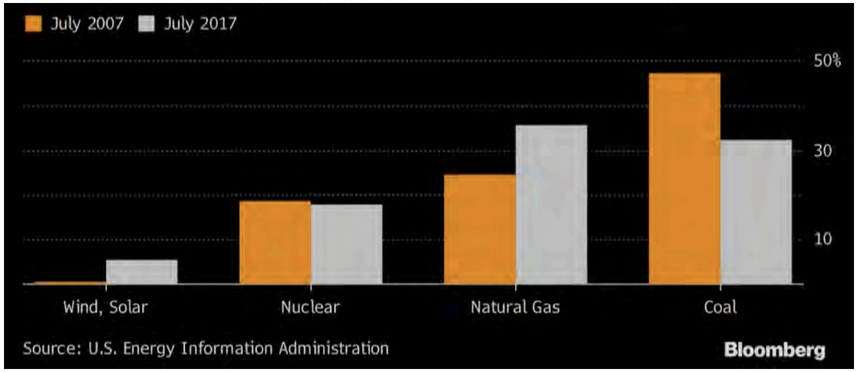
- 31.3 GW coal retirements from 2015-2020
- Over 40% of the retiring coal generation is set to convert from coal to biomass or natural gas

Typical Candidate for Conversion

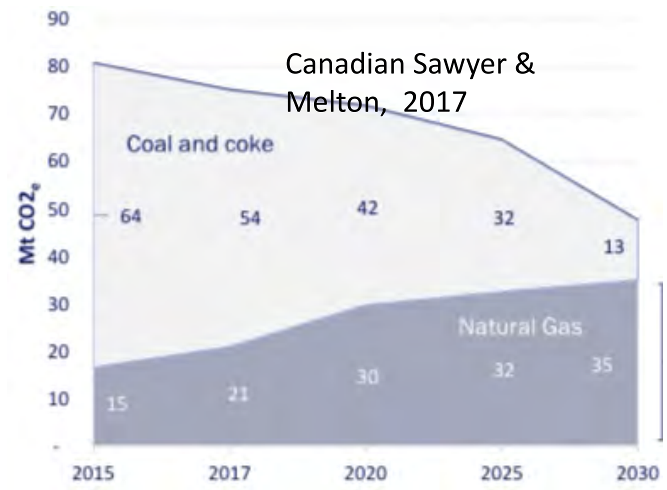
2015 Power Engineering "Coal to Gas Plant Conversion in the U.S." Scott Gossard of Babcock and Wilcox

- 50+ yrs old
- <300 MW
- Subcritical steam cycle
- "It would appear that the coal to gas conversion market has peaked and is now on the decline," Gossard wrote, as MATS deadlines were imminent and most companies have already planned for them. "Overall, switching to gas, even at current gas prices, is generally not an easy economic choice considering the capital cost, fuel costs, cycle efficiency, and future regulatory uncertainty."

Continuing Activity



- Duke Nov 2017 announcement:
  - $200 million in the next three years converting four North Carolina coal boilers for dual fuel operation.
  - Gas capability to range from 40-100%
  - Seen as a hedge against future fuel prices
- Two largest coal power producers in Alberta converting all coal boilers to gas by 2020 (Financial Post 2017)



Canadian Sawyer & Melton, 2017

Conversion Options

- Convert a coal-fired boiler to operate exclusively on natural gas (Complete Conversion)
- Convert a coal-fired boiler to operate on either coal or natural gas (Dual Fuel Conversion)
- Convert by adding the capability to simultaneously fire natural gas (Co-firing Conversion)
  - Addition of gas burners
  - Replacement of some coal burners with gas burners
  - Supplementation of coal burners with gas
  - Natural Gas Reburning (traditional or FLGR)

Conversion Benefits

- CO_2 reduction
- Air pollutant control system retrofits (sulfur, particulate, SCR, etc.)
- Improved cycling and minimum load capabilities
- Reduced O&M Costs
  - Coal and ash handling systems
  - Pulverizers
  - Primary air fans
  - Sootblowing equipment, piping & controls
  - Dust collection & suppression
  - Reduced manpower and parasitic load associated with above
- Limited boiler erosion/corrosion

Potential Issues in Conversion

Capacity & Heat Balance

Natural Gas Quality

Emission Control (NOx & CO)

Natural Gas Supply System (Piping, Valve, Control, etc.)

Fuel Injector (Burner)

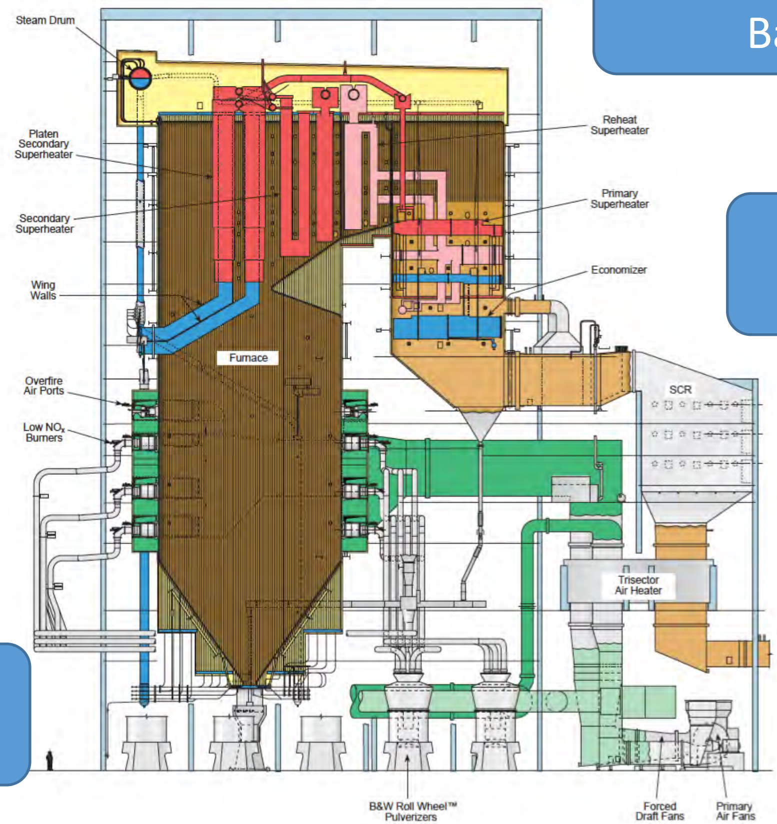


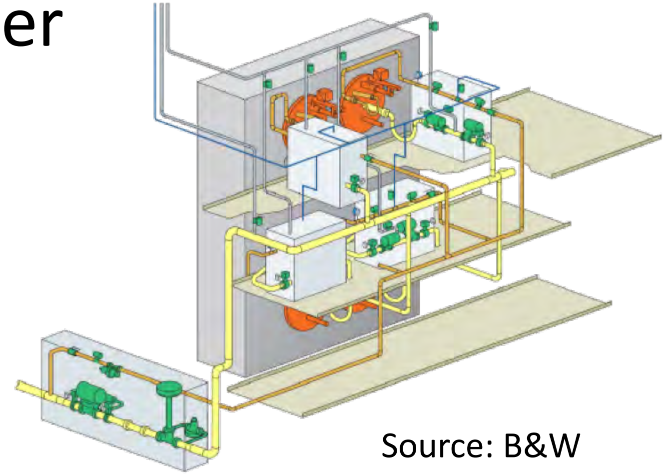
Image Source: Steam 41

Natural Gas Quality

- NG quality can vary based on the source
- Interstate pipeline quality gas
  - Conditioned
  - Dehydrated to a maximum water content (7 lbs water/Mscfh of gas)
  - Treated to remove any traces of H_2S
- Regional gas
  - Often not treated at all
  - May have sulfur inherent in the well
- Debris
  - From pipe & system cleanliness, pluggage of strainer

Natural Gas Supply System

- Gas pressure reducing and protection station
- Burner & igniter gas supply header
- Piping, valves and supports
- Electrical & I&C upgrade
- Fuel and vent piping
- DCS modification



Source: B&W

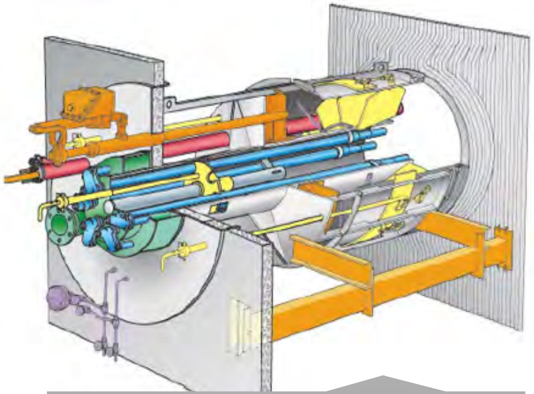
Source: Forney

Burner Application Options

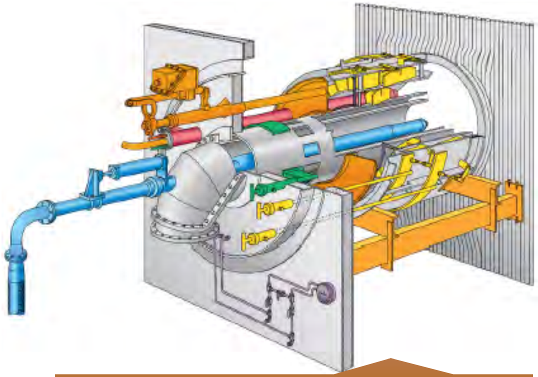
Objectives	Features
Completely abandon coal	• **Replace all burners with new gas only burners** • Highest cost & longest outage time • Allows for best combustion and boiler performance
Retain ability to fire coal *Where a unit is already equipped with PC burners, burner modifications can be supplied incorporating a gas element*	• **Incorporate gas elements into existing coal burners** • Lowest cost & shortest outage time • Performance compromise • Can modify all or some burners
Retain ability to fire coal *Where existing burners are not suitable for simple modifications, a complete PC burner with gas elements can replace existing burners*	• **New dual fuel burners (PC/NG)** • Higher cost & longer outage time • Allows for good compromise between fuel flexibility and combustion performance • Burner can be sized for reasonable pressure drop and/or to accommodate FGR
Continue to fire coal *In some cases where an owner plans to continue to fire coal but would like to augment with gas to lower emissions or improve turndown, some burners can be replaced or modified for gas firing*	• **Partial burner replacement/modification** • More applicable to larger units • Good tool for turndown improvement • Can be coupled with change to gas igniters for incremental increase in heat input on gas

Source: B&W

Burner Options

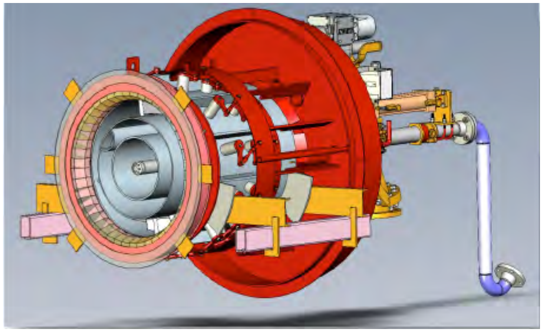


Natural Gas Burner



Coal Burner Retrofit

Partial or full retrofit

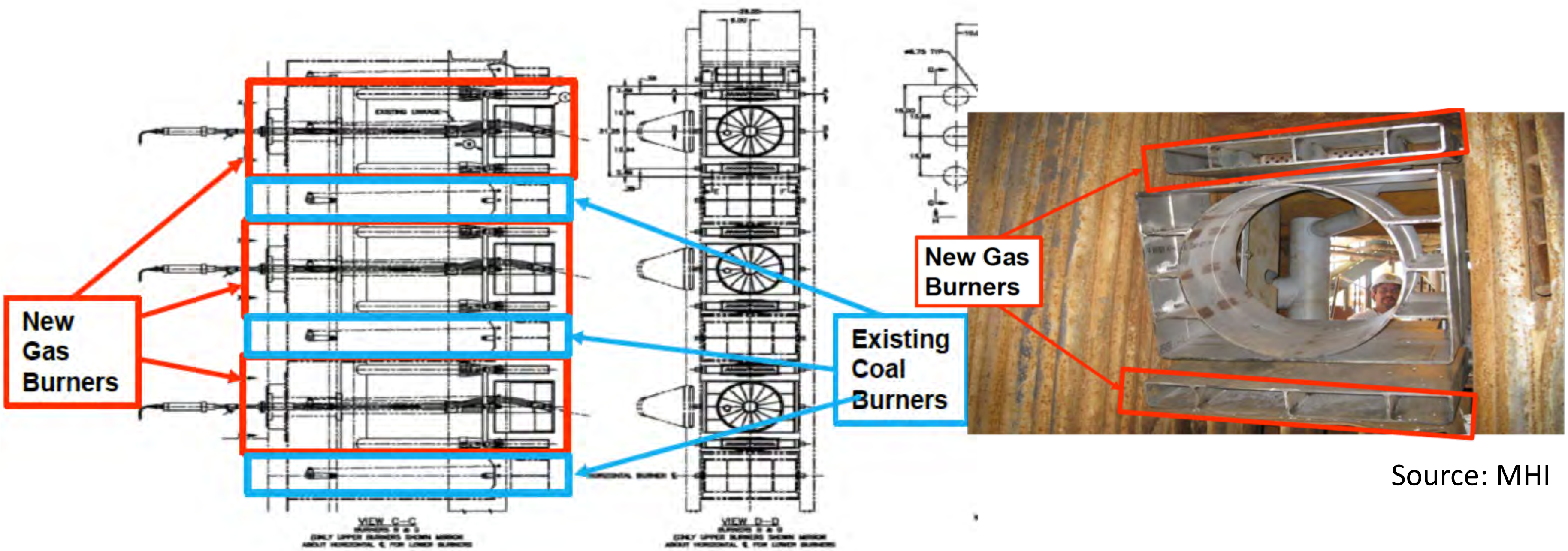


Dual (Coal/NG) Burner

Source: B&W

Decision on whether or not retaining coal firing capability can determine burner conversion strategy

T-fired Boiler Option

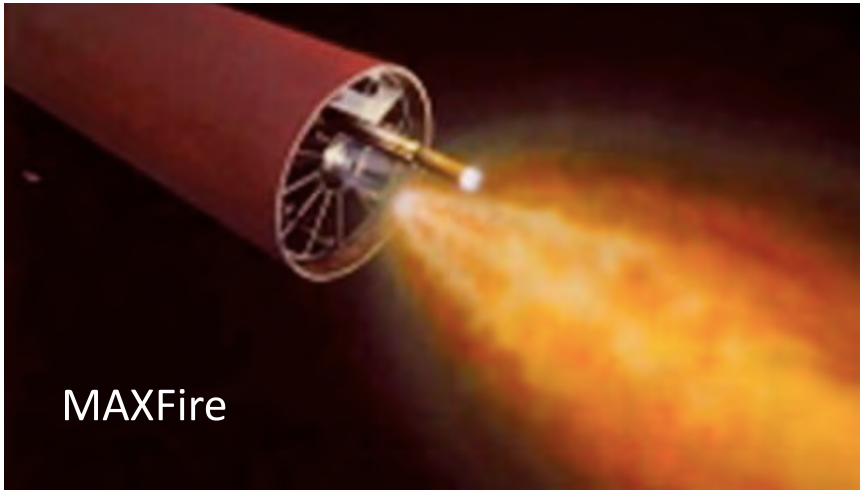


Source: MHI

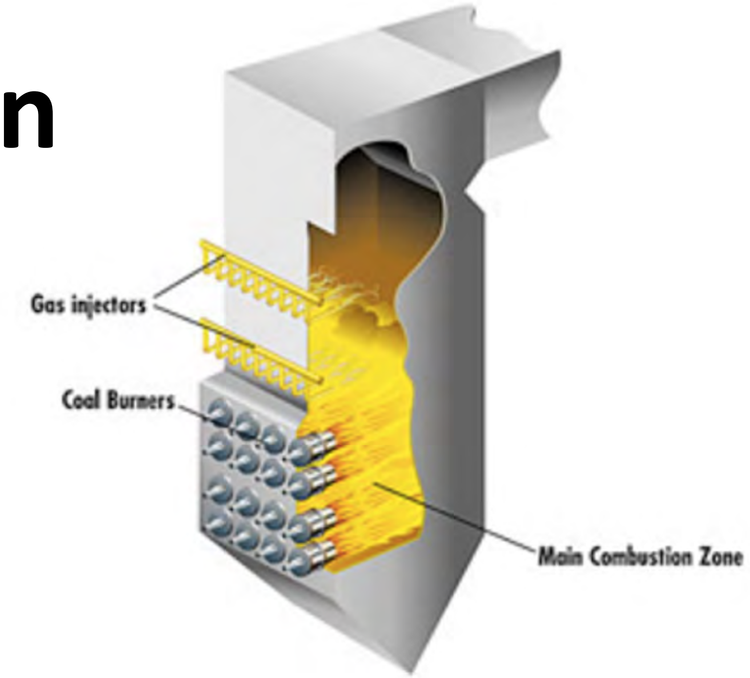
Burner modification for T-fired boilers can utilize existing ports in a burner column for gas injection

High Heat Input Gas Igniters

- Low cost, easy-to-install burner alternative
- Co-firing or low-load without coal
- Installations:
  - Forney MAXFire at TECO Big Bend
  - Breen Dual Orifice at OUC Stanton

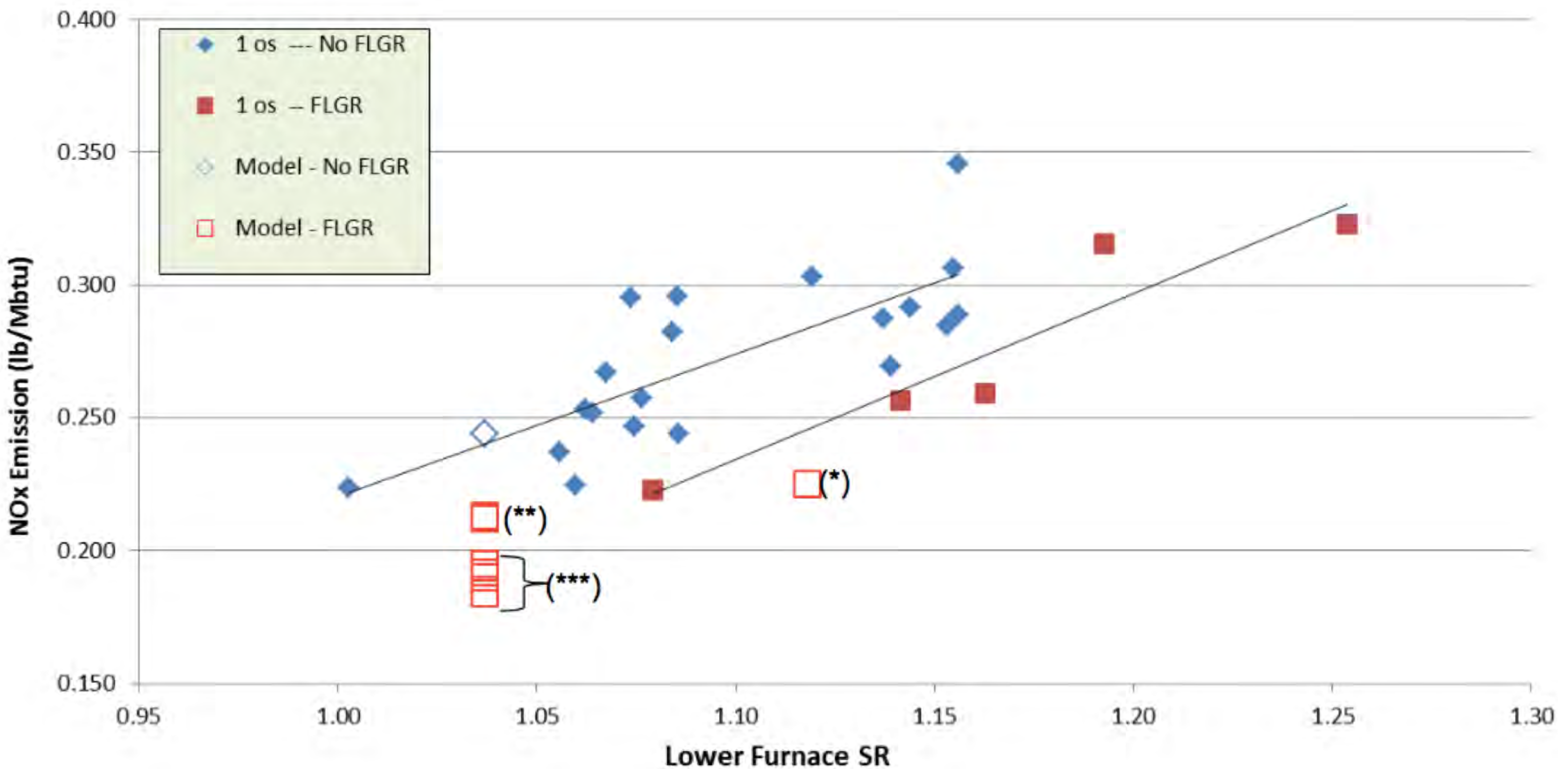


Fuel Lean Gas Reburn



- Utilization has trended with cost of natural gas
  - 13 commercial installations 1998-2001
  - Interest has been renewed due to recent decreases in natural gas in the US as well as interest in coal replacement in current political climate
- 5% - 10% Gas Heat Input results in a 20% - 30% NOx reduction
- Integration with low NOx firing systems can require care in injector installation – CFD modeling has proven valuable for optimization

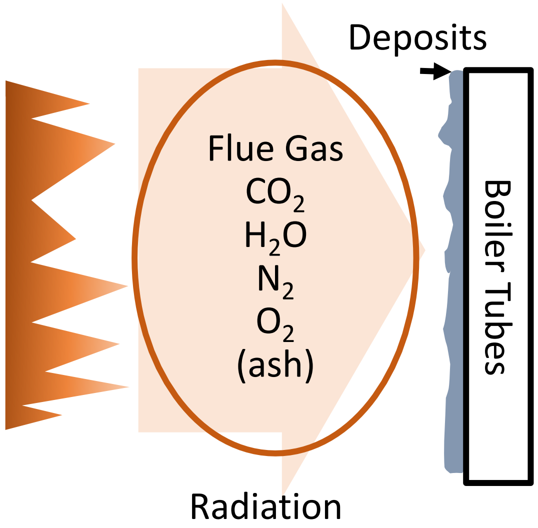
FLGR at Plant Stanton
(Lockert 2016)



CFD optimized results of 22% NOx reduction confirmed

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	~2480 K	higher	15 / 8	0.40	higher
Nat Gas – Air	~2280 K	lower	8 / 16	0.48	lower
Nat Gas – Oxy	~3370 K	lower	32 / 64	0.66	lower

*Based on ~FEGT; gas emissivities vary with temperature

Capacity and Pressure Parts

- Boilers are designed for specific fuels
  - Coal boiler is much larger in size than a gas boiler of the same capacity (MW)
  - When coal boiler is converted to gas, it is difficult to achieve main steam temperature and full load capacity
- Higher firing rate is needed to maintain boiler capacity
- Steam temperature can be maintained using various methods:
  - Excess air increase
  - Attemperation
  - Gas biasing
  - Gas recirculation
  - Pressure parts modification

Pressure Parts Considerations

- Coal to gas conversion changes heat transfer characteristics in a boiler:
  - Radiant section heat transfer is lower
  - Convective section heat transfer is higher
  - Flame, flue gas and deposit properties change
  - Net effect unclear, need detailed analysis with specific design to quantify
- Specifics:
  - Spray attemperator capacities need to be checked
  - Superheater, reheater, economizer surface adjustment may be required
- Appropriate modeling of coupled furnace heat transfer and steam circuit performance provides guidance

Natural Gas Performance

Source: MHI

	Case 1	Case 2	Case 3
Boiler	2	1	1
MW	131	225	355
Main Steam Flow, x10³ lb/hr	1200	1580	2500
Reheat Steam Flow	No	1324	2164
Airheater Arrangement	Bi-Sector (Hot PA Fan)	Bi-Sector (Hot PA Fan)	Bi-Sector (Hot PA Fan)
Coal Flow	105.8	158	257.7
Coal Quality, HHV Btu/lb	13,141	13,054	12,500
Total Heat Input, x10³ Btu/hr	**1390 --> 1443**	**2062 --> 2169**	**3221 --> 3396**
Burner Quantity	8 Front	12 Front	8 Front, 8 Rear
Burner Heat Input, x10³ Btu/hr	**173.8 --> 180.4**	**171.9 --> 180.8**	**201.3 --> 212.2**
Efficiency, %	**86.4 --> 83.1**	**88.1 --> 84.0**	**89.4 --> 85.5**

- Retrofit burner for gas injection case evaluation
- Need to increase firing rate to maintain full load
- Boiler efficiency drops between 3.5 – 5.5%, but parasitic load is also reduced → need overall economic analysis

Fan Capacity and Airheater

- FD fan capacity needs to be checked as all combustion air must be delivered by the FD fan through the existing secondary air ducts to the windbox and through the burners (and/or OFA system)
- Flue gas recirculation may pressure FD fan burden
- Airheater performance needs to be checked as air and flue gas flow can change

NOx Control

- Gas conversion lowers NOx emission as there is no fuel-bound nitrogen in natural gas
- Temperature and N_2 & O_2 availabilities are key parameters in gas-fired plant's NOx emission control
- Control strategies need manipulation of those key parameters
  - Staged combustion (Low NOx burner, OFA)
  - Flue gas recirculation
  - BOOS
  - Air heater bypass
  - SNCR, targeted water injection
- Optimized NOx control strategies can also reduce CO emission

Typical Scope of Work in CTG

Source: MHI

- Baseline Testing
- Boiler Thermal Modeling
- General Engineering Including: Drawings, P&IDs, Lists & Operation & Maintenance Manuals.
- CFD Model of Boiler Convection Pass
- Flue Gas Recirculation (FGR) Fan Foundation/Supports
- Natural Gas Burner Modifications:
  - CFD Modeling of Combustion Air Duct, Windbox, Burners & Furnace
  - Combustion Emissions Modeling
  - Burner Elements, including internal gas ring and multiple gas spuds
  - Igniters
  - Double Block & Vent Valve Spools
  - Pressure Regulating Valve (PRV) Skid With Vents
  - Flow Control Valve (FCV) Skid With Vents
  - Flexible Metal Hoses
  - Flame Scanners

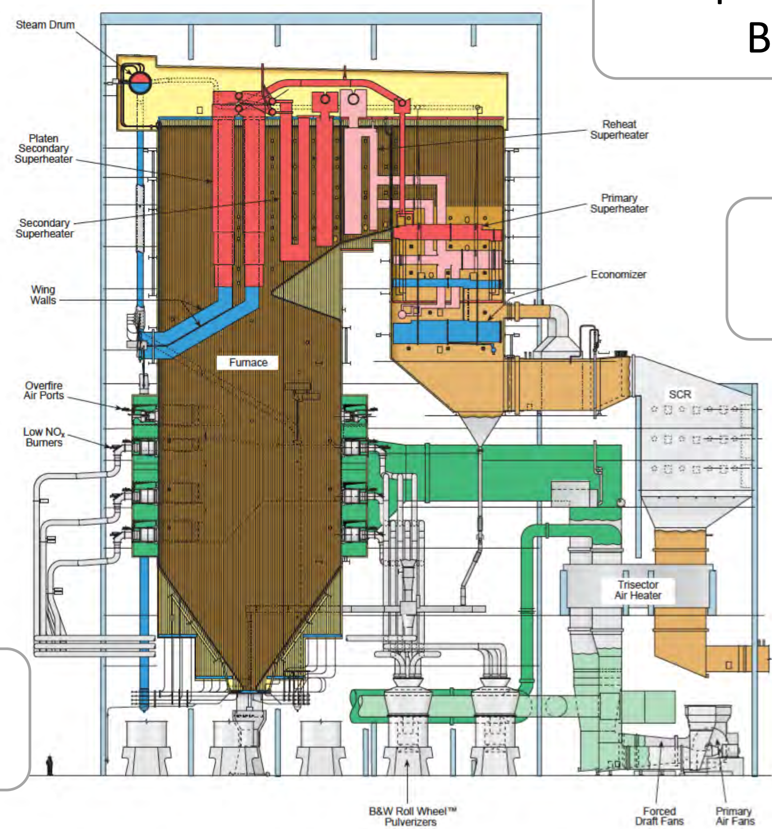
- Natural Gas Piping, Vent Piping, & Supports
- Flue Gas Recirculation (FGR) Fans with Electric Motor, Turning Gear & Inlet Damper Control
- FGR Injection Mixing Devices
- FGR Differential Pressure Transmitters
- FGR Fan Inlet & Outlet Ducts with Hangers, Supports, and Expansion Joints
- FGR Duct Dampers & Actuators
- Burner Management & Combustion Control System Engineering & Modifications (including Hardware, Software and Implementation)
- Demolition of Existing Equipment
- Erection of New Equipment
- Secondary Steel & Erection
- Disabling of Coal Firing Equipment, Including Electrical Isolation
- Blanking Plates for the Primary Air and Tempering Air Duct Systems
- Technical Advisors for Construction & Commissioning
- Electrical Device Upgrades of Existing Equipment (Option)

Potential Issues in Conversion

Natural Gas Quality

Natural Gas Supply System (Piping, Valve, Control, etc.)

Fuel Injector (Burner)



Capacity & Heat Balance

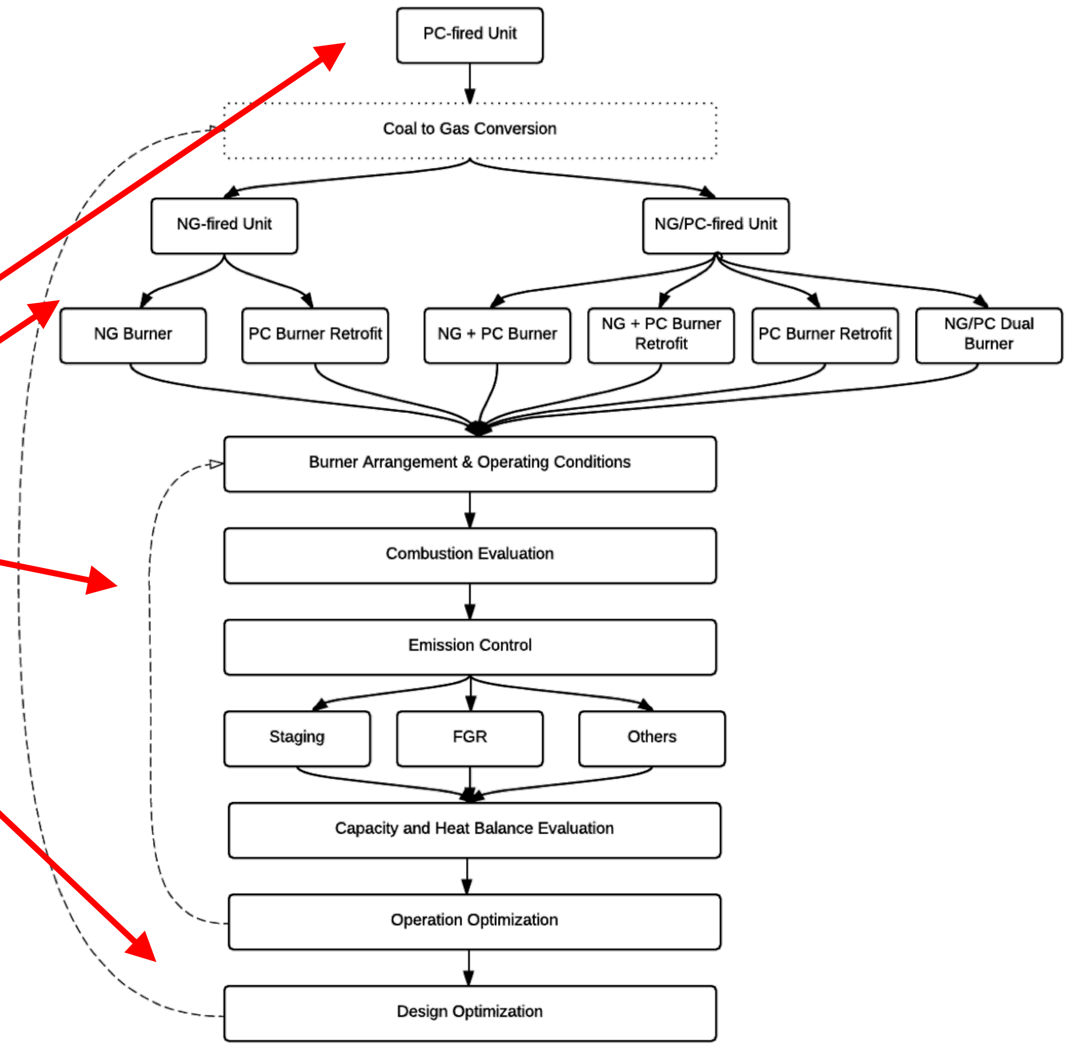
Emission Control (NOx & CO)

Image Source: Steam 41

Technical Approach

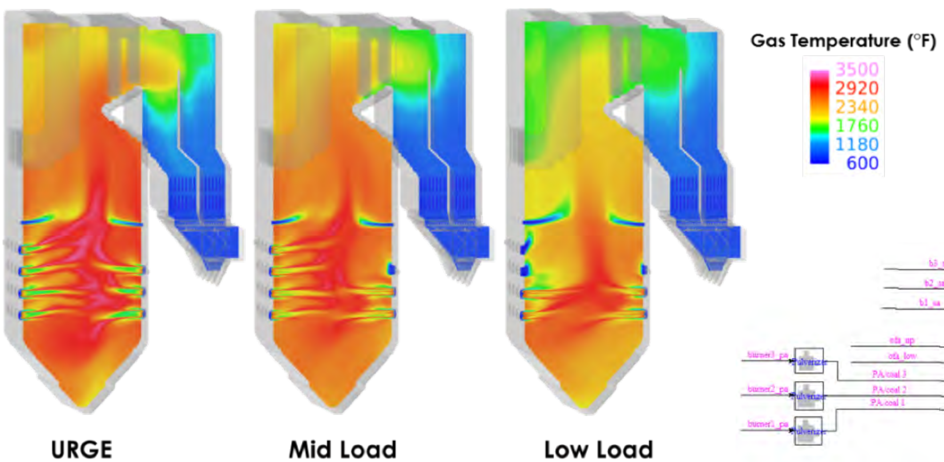
Final objective is to provide optimized coal to gas boiler configuration with operating condition guideline

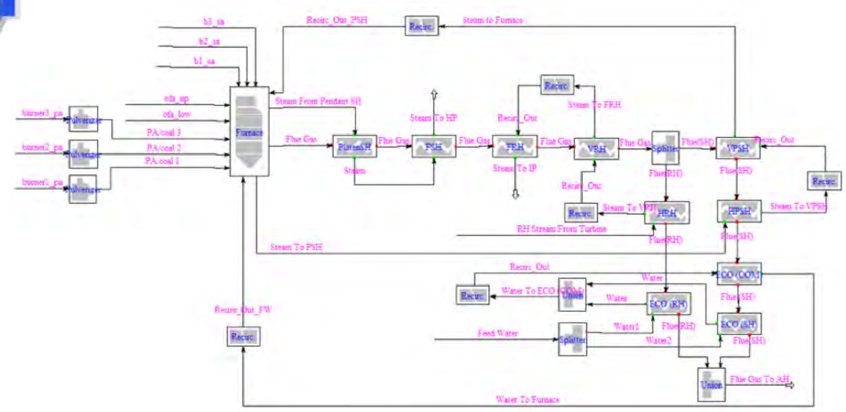
- Target boiler identification
- Firing strategy decision
- Evaluation & optimization of combustion, emission, capacity, heat balance, operation
- Operating condition & design optimization
- Iteration, if necessary



Boiler Modeling

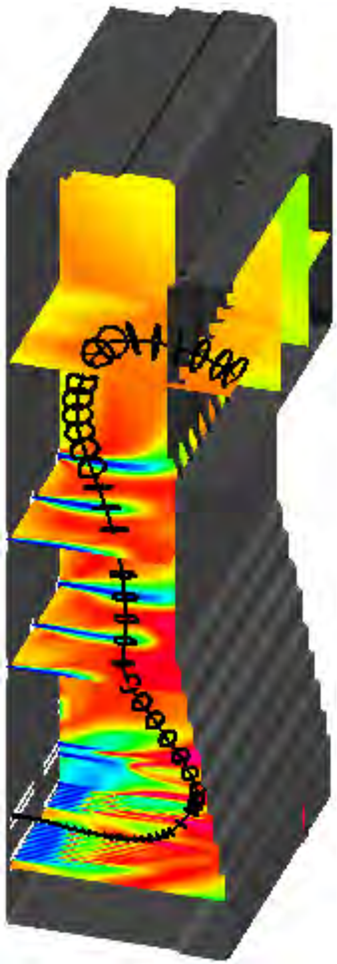
Modeling is critical to understanding the impacts of coal to gas conversion and to optimize performance





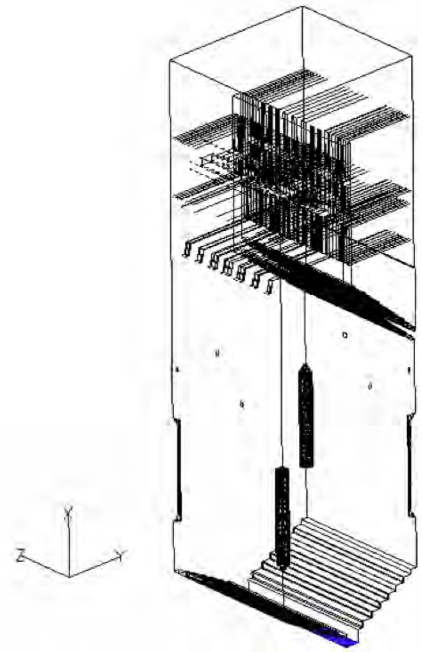
REI's Modeling Experience

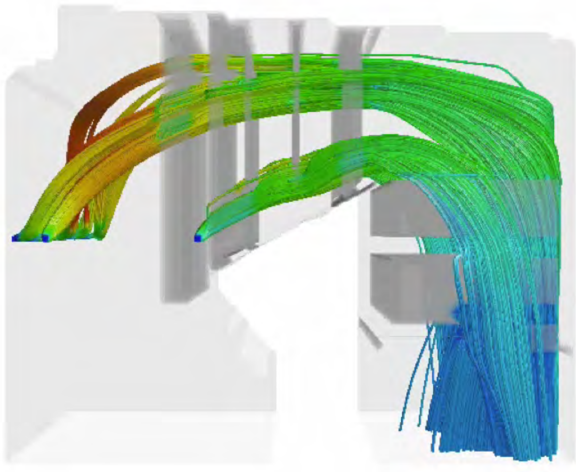
- Over 250 boilers, burners, process furnaces, kilns, and incinerators in several countries burning a range of fuels including coal, oil, gas, wood, straw, petcoke, tires, hazardous waste
- Complementary relationships with OEMs, owners and service/equipment providers to develop solutions in areas including:
  - Corrosion and deposition
  - Heat flux
  - NOx/SOx control
  - CO, hydrocarbon emissions
  - Carbon-in-flyash
  - Opacity
  - Air toxics (fine particulate, mercury, soot)
  - Burner/furnace design/optimization



CFD Tools: GLACIER

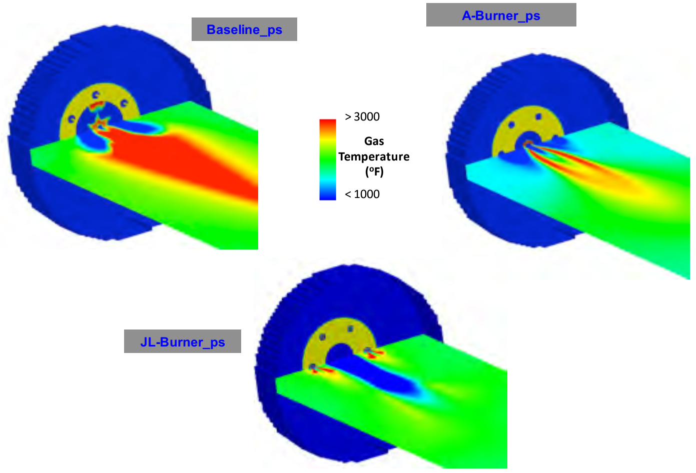
- Developed specifically for application to solid fuel fired furnaces and boilers
- Verified in application to over 300 boilers, furnaces and gasifiers
- 3D, steady-state, turbulent flows
- Coupling between turbulent fluid mechanics, radiative and convective heat transfer, homogeneous and heterogeneous reactions
- Statistical description of particles including particle dispersion
- Pollutant formation kinetics for NOx, SOx, CO, Hg and fine particles
- Utility boiler, cement kiln, etc.
- Still evolving

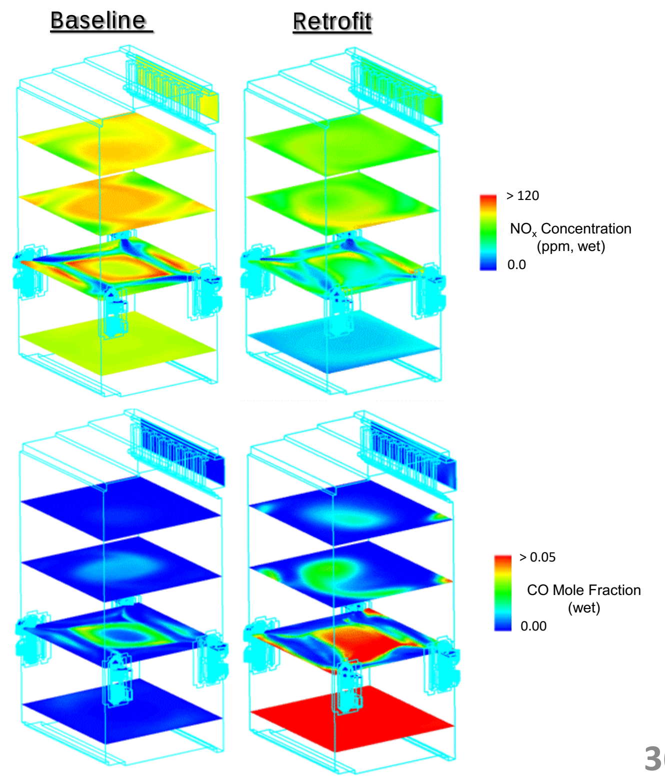




CFD Tools: ADAPT

- Improved ability to solve combustion problems in which disparate scales are involved or finite rate chemistry effects are critical
- Adaptive grid algorithm that uses an orthogonal grid with local mesh refinement to accurately describe intricate components of gas burners and combustion
- Other emphases are:
  - Turbulence-chemistry coupling
  - Finite-rate chemical kinetics
  - Reduced mechanisms
  - Turbulent mixing parameters
  - Computational efficiency
  - *Approach has broken new ground in analysis of ultra-low NOx burners*

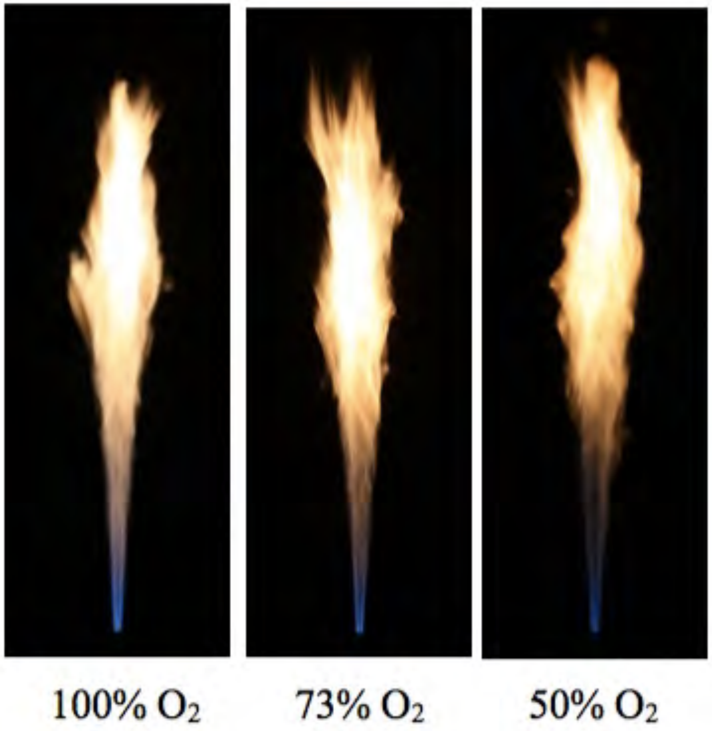




Developmental Concepts

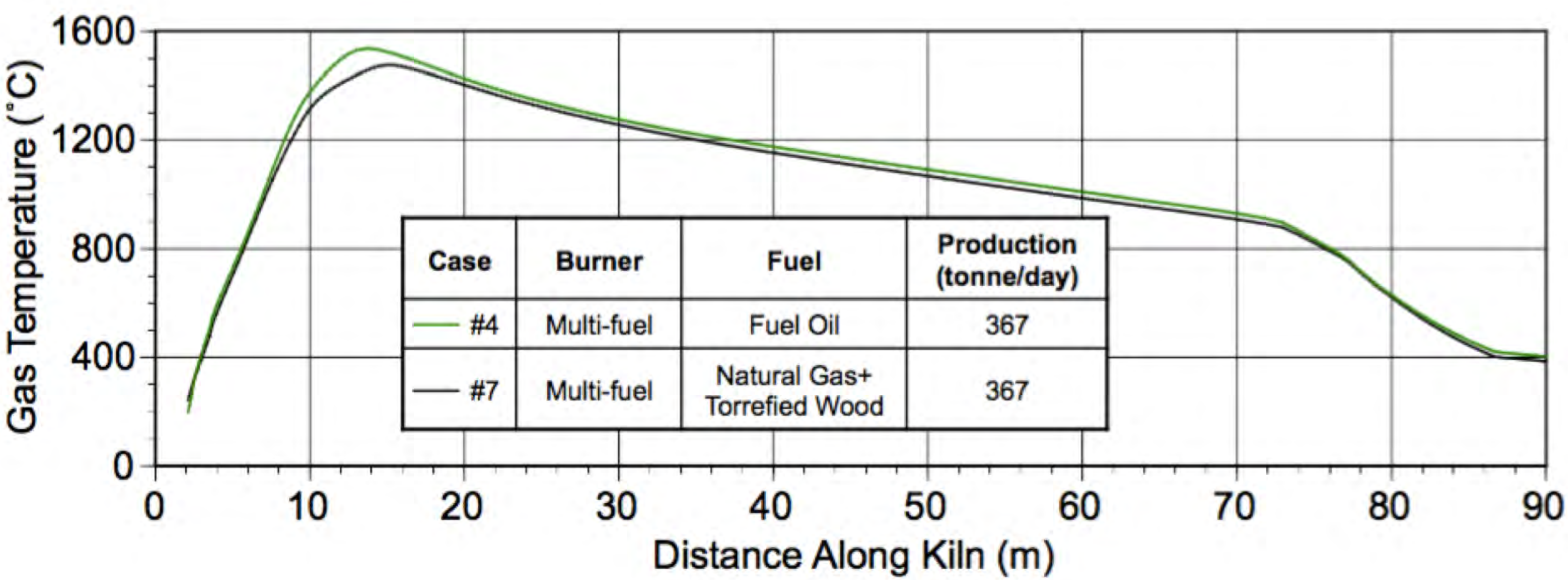
Limited effort has been invested in the development of new concepts for optimizing natural gas firing in solid fuel boilers

- Co-firing of natural gas with renewable solid fuel
- Enhanced radiation combustion
  - High temperature oxy-natural gas
  - Sooting oxy-natural gas flames at intermediate levels of oxygen enrichment



Co-firing of Renewable Fuels with Natural gas

- Oil to gas conversion in lime kilns result in >10% derating due to reduced heat transfer
- Co-firing 23% torrefied wood with natural gas will match the heat transfer profile of the design fuel



Examples

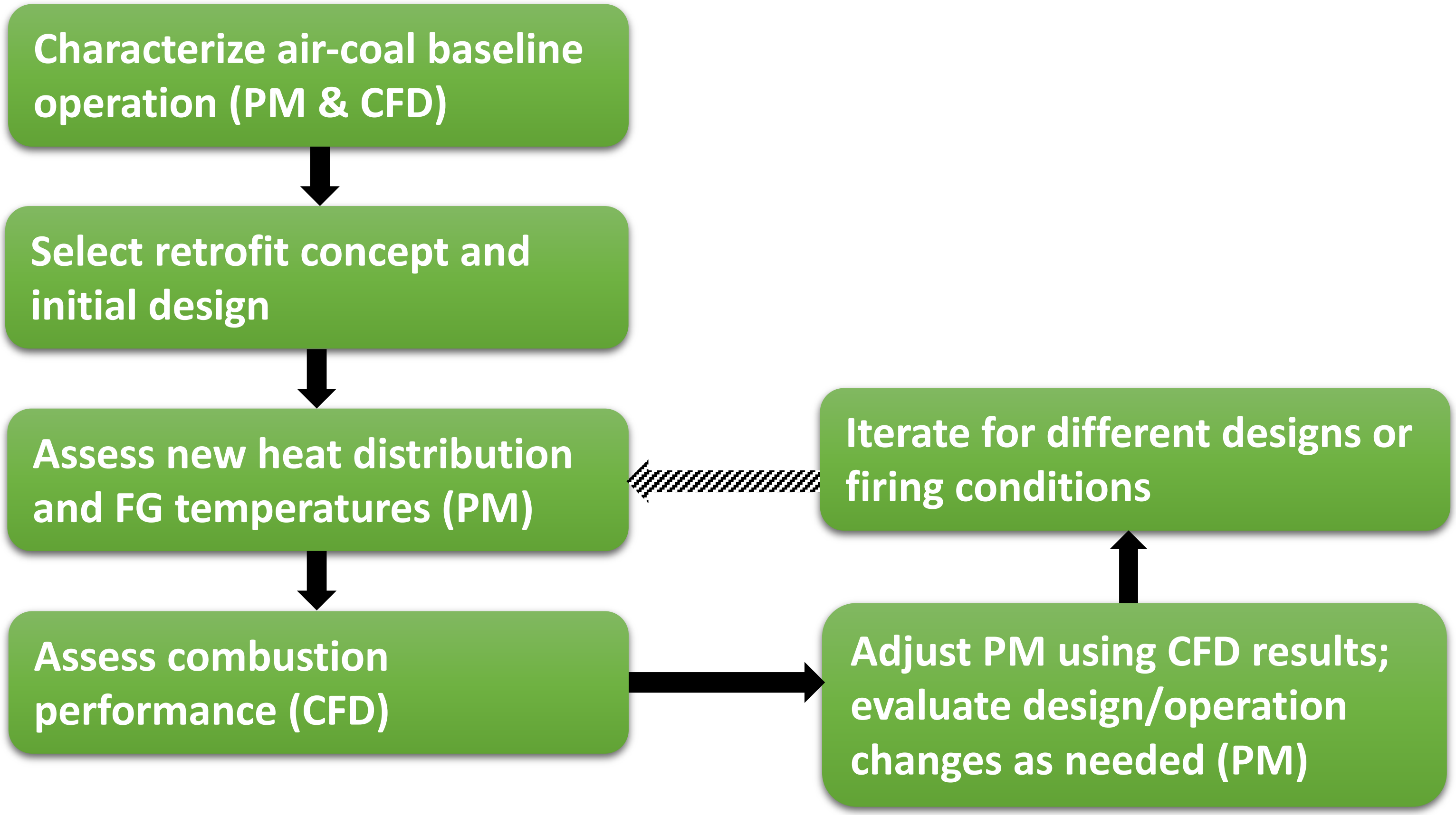
- Illustrate use of modeling tools useful in evaluation of natural gas retrofit of coal-fired boilers

- Example 1 – CFD modeling of air-coal to oxy-NG retrofit

- Example 2 – SGE process modeling of convection surface area modifications

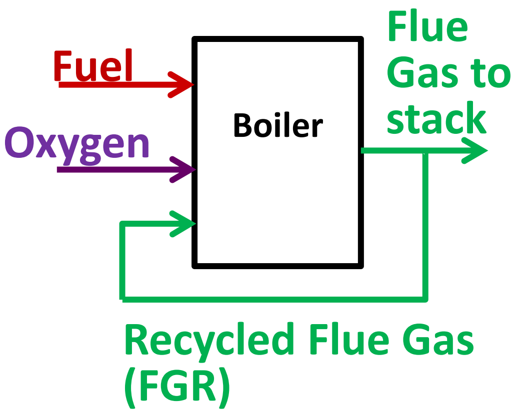
Modeling Evaluation Approach

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



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 CO2 capture

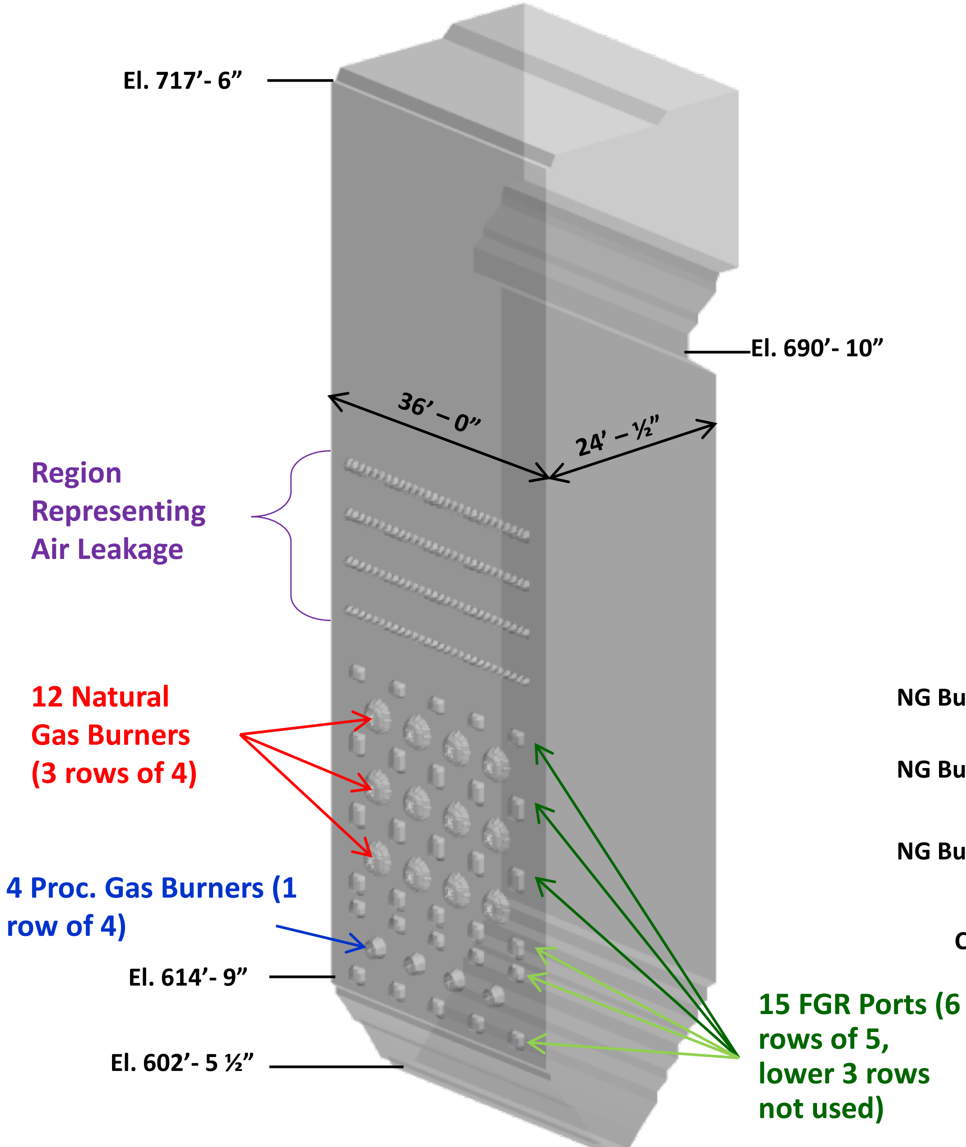


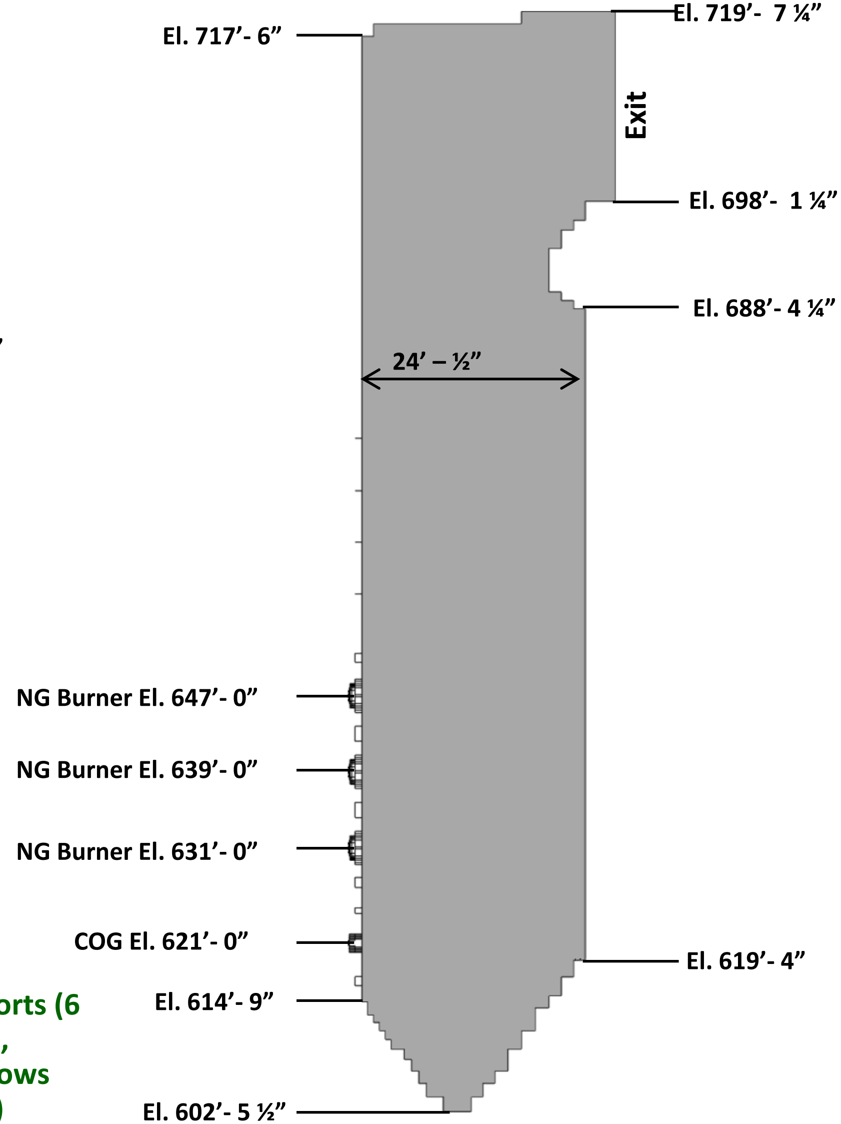
- For oxy-firing, FGR+O2 inlet mixture impacts radiant furnace and convective pass heat transfer
  - FGR absorbs energy, adds mass flow
  - FGR amount and injection location impact flame temperature and heat flux profile
- Key parameter is heat transfer distribution in radiant and convective sections

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





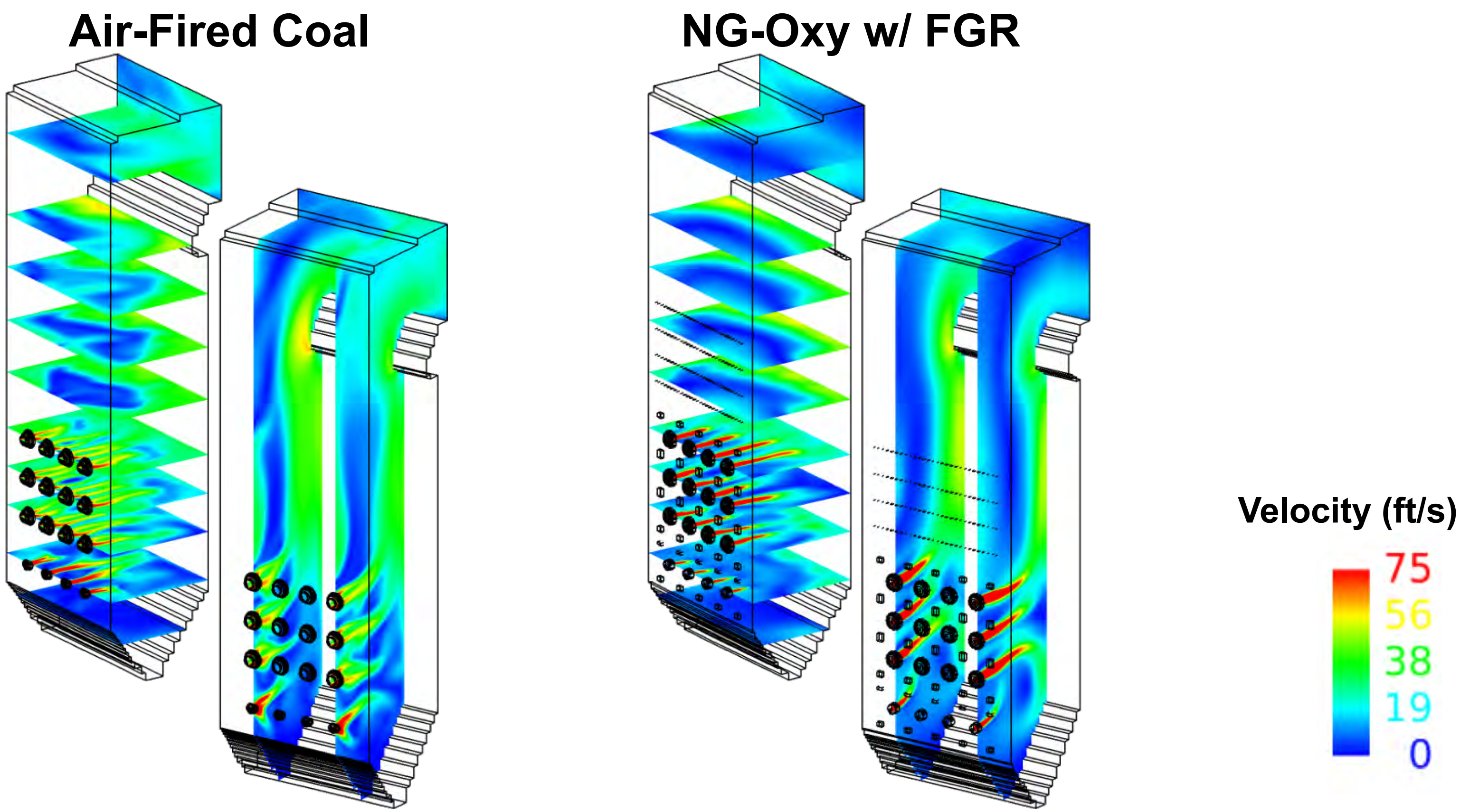
Model Basis

- **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

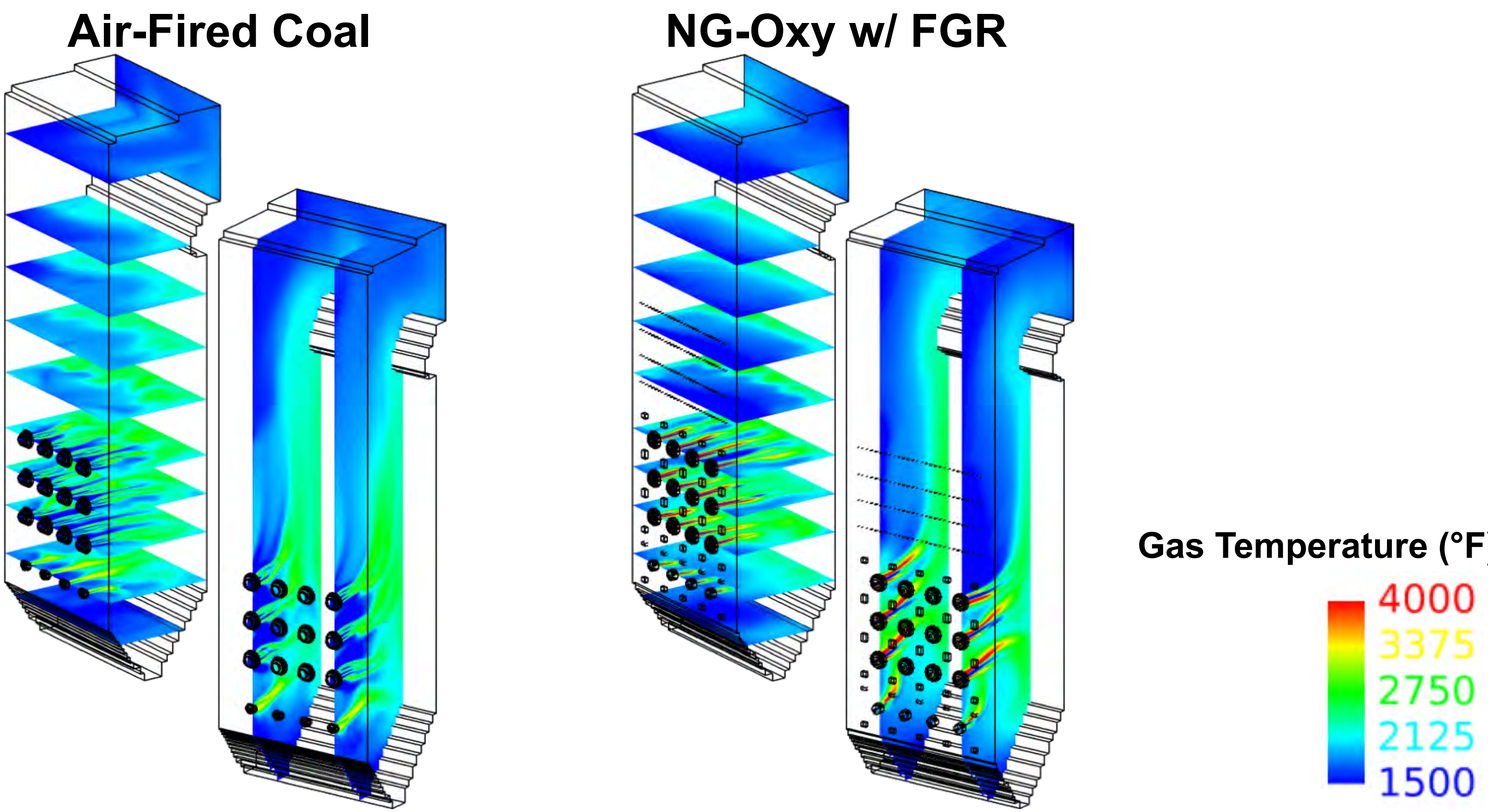
Furnace Operating Conditions	Air-Coal	Oxy-NG
Total Furnace Firing Rate (MBtu/hr)	940	940
Coal/Natural Gas Firing Rate (MBtu/hr)	857	857
Process Gas (PG) Firing Rate (MBtu/hr)	83	83
Total Air or O_2+FGR Flow Rate (klb/hr)	924	549
Theoretical Excess O_2 (%, wet)	4.7%	1.2%
Theoretical Excess O_2 (%, dry)	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



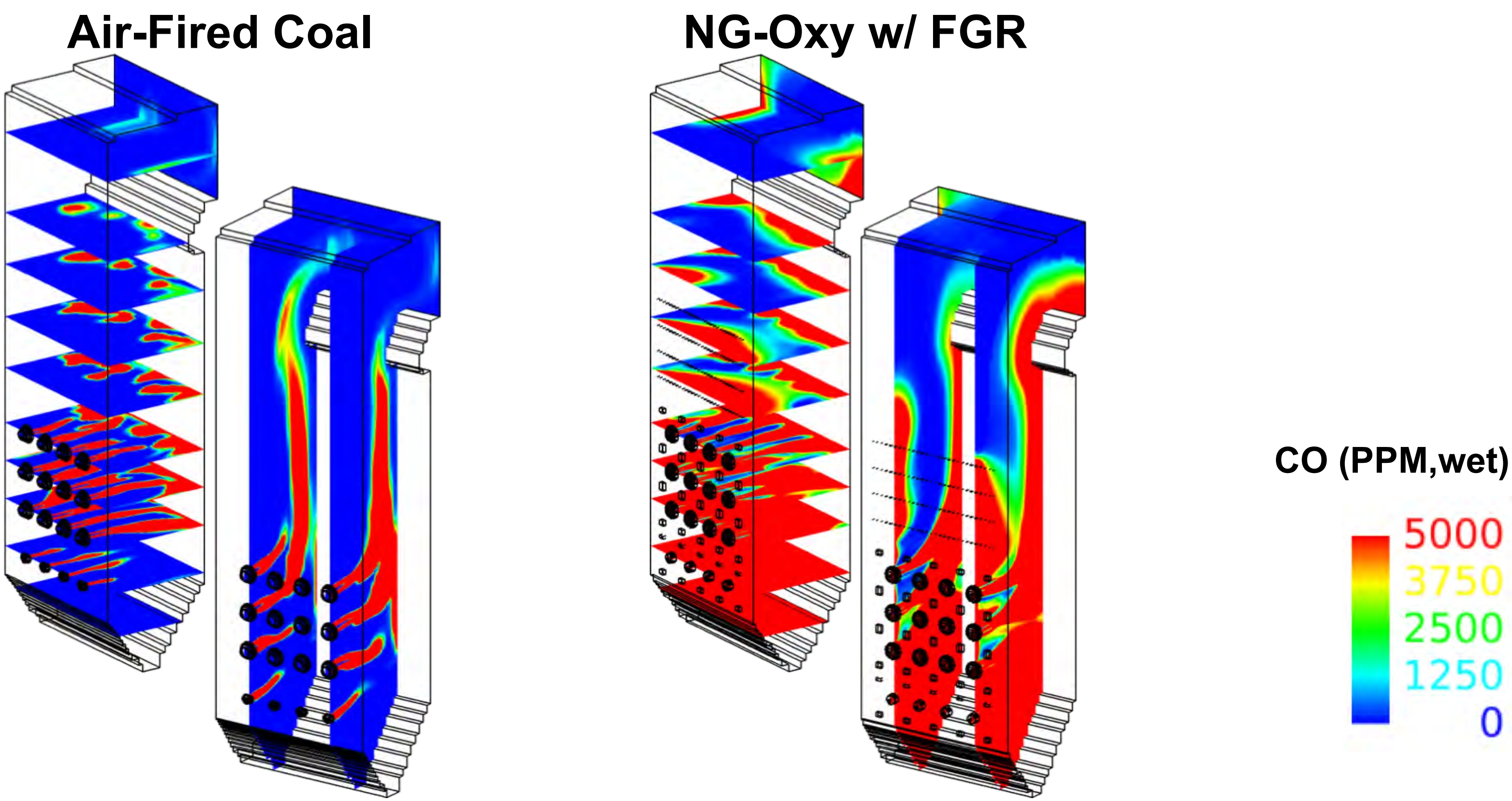
General flow patterns similar for both cases; exit gas velocities lower for NG-Oxy due to lower volumetric flow.

Gas Temperature



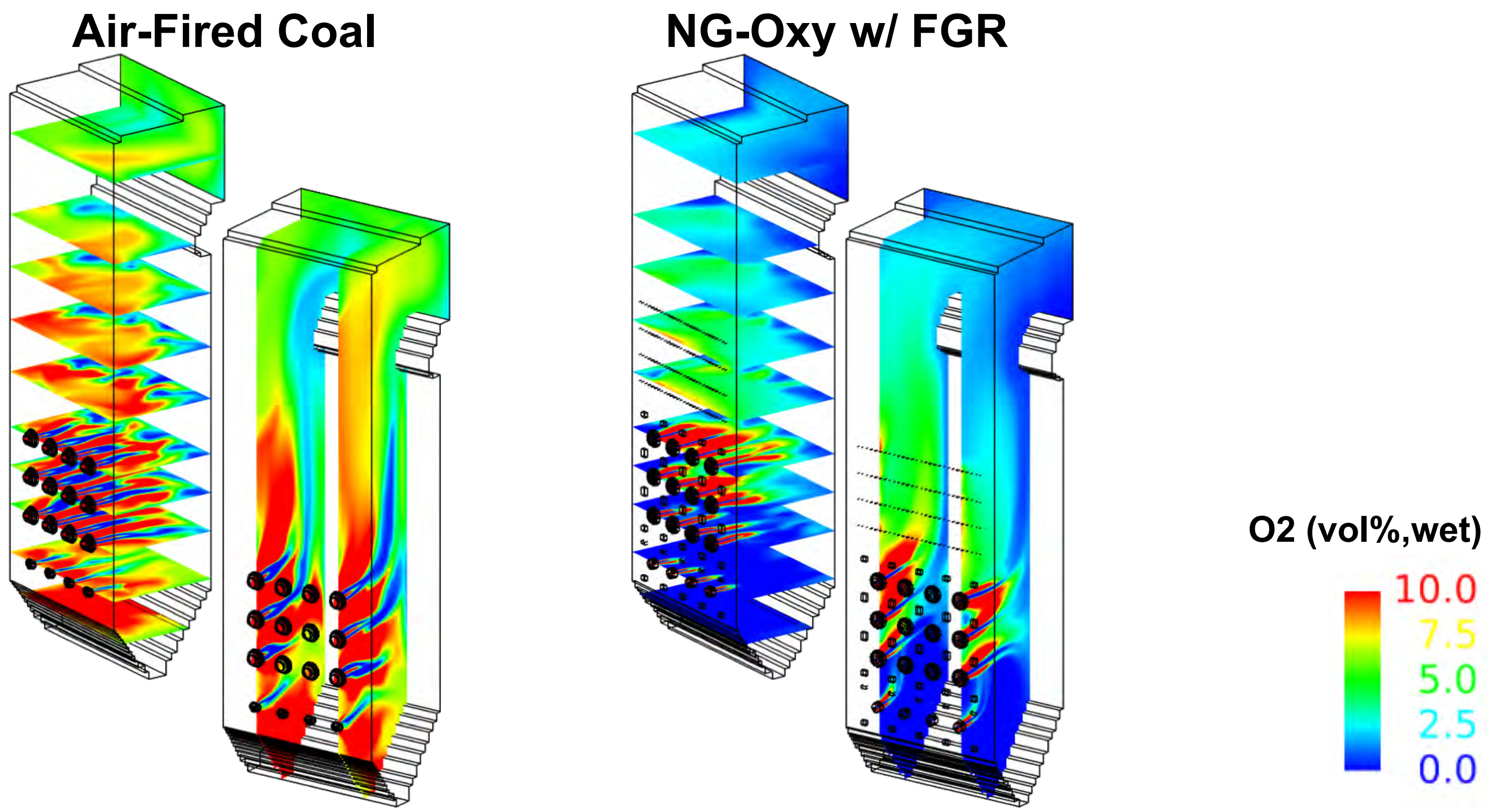
For NG-Oxy, significant amount of flame surface over 4500 F; FGR rate and injection location impacts local and exit gas temperatures.

CO Concentration



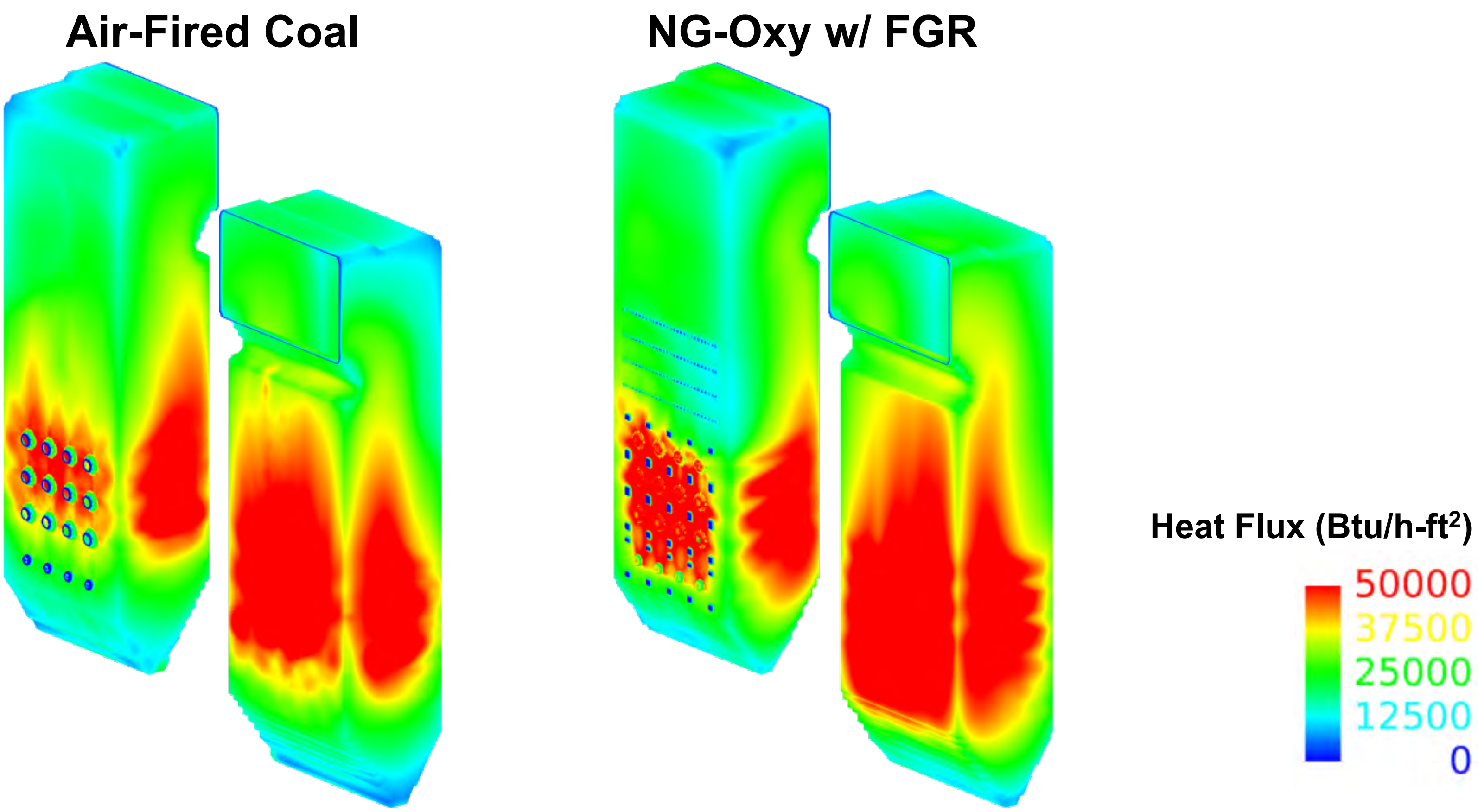
Higher CO in lower furnace because PG and NG burners are sub-stoichiometric (0.984) and FGR and air in-leakage assumed to enter in and above burner zone. FGR injection location can be optimized to reduce CO.

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

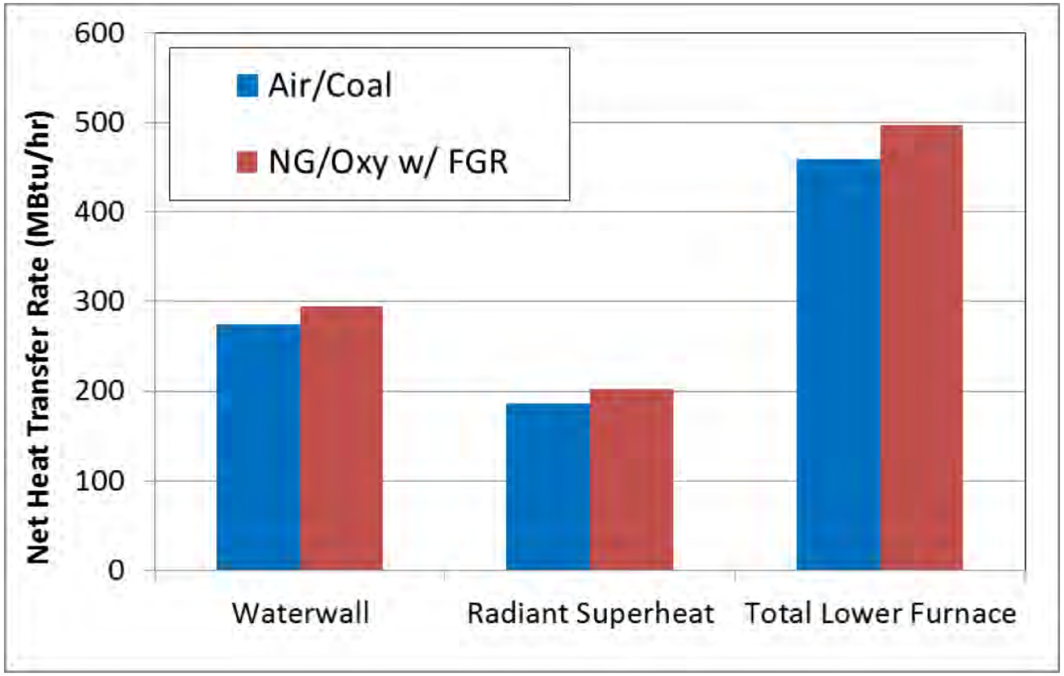
Net Wall Heat Flux



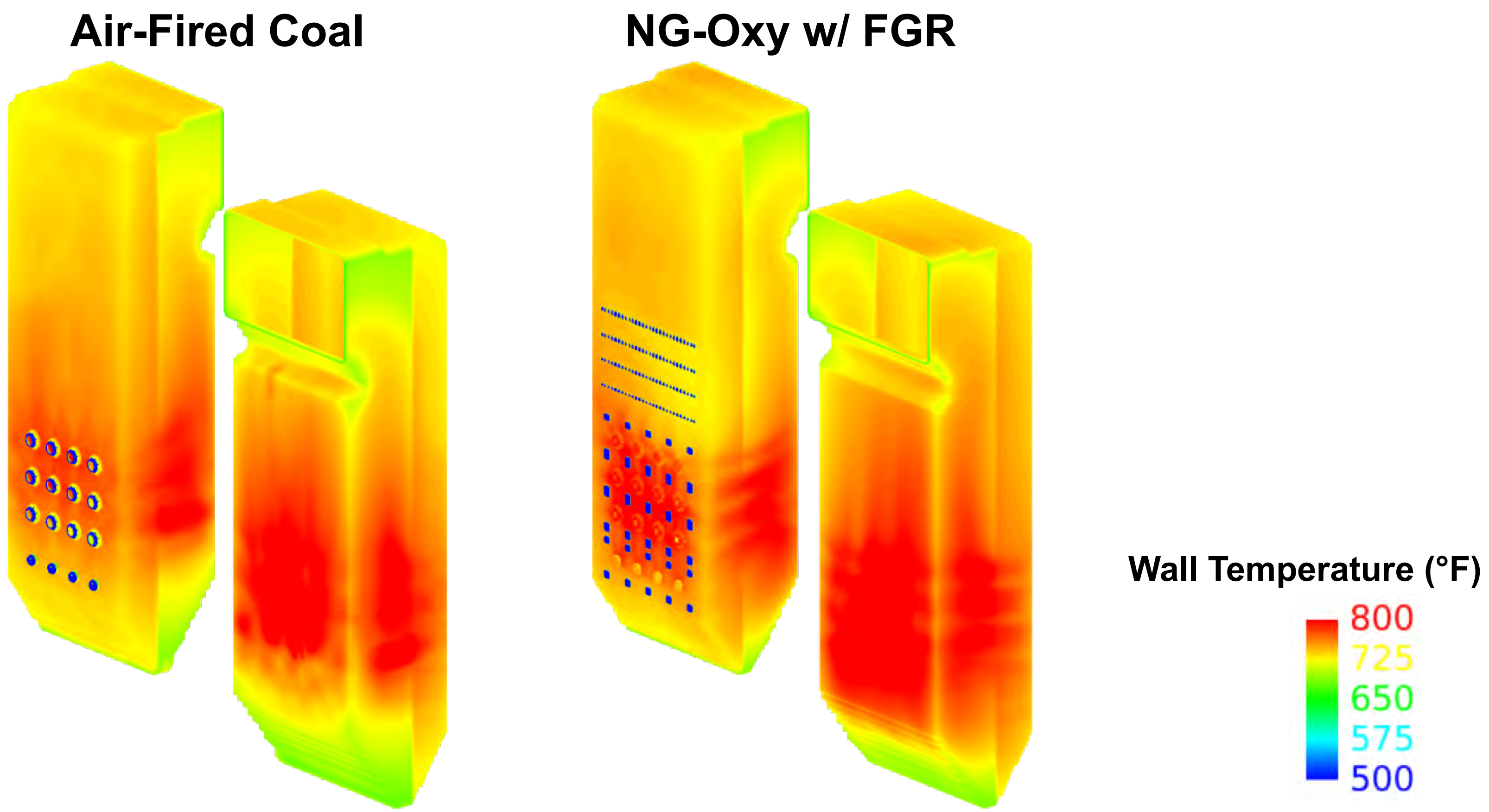
Cases have similar net heat fluxes

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	



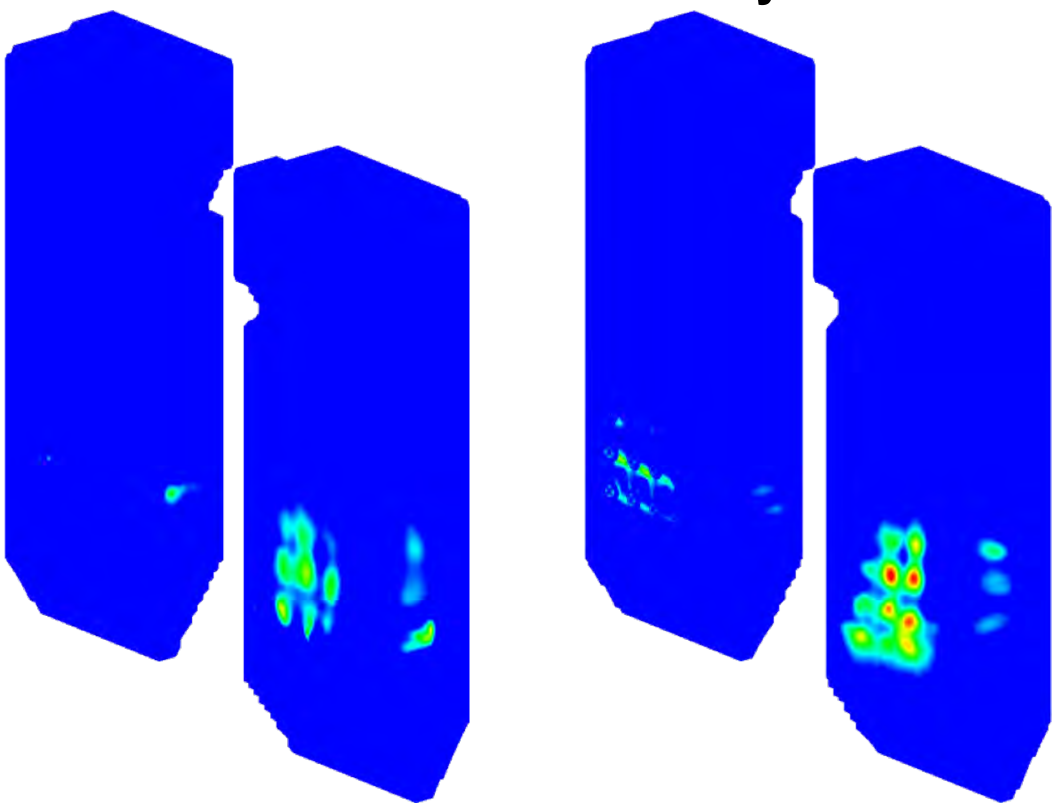
Wall Temperature



Wall temperatures mimic wall heat flux; cases have similar fluxes

Peak Wall Temperature

Air-Fired Coal   NG-Oxy w/ FGR



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

Wall Temp (°F)

(tight scale highlights peak temperatures)

Example 1 CFD Model Results

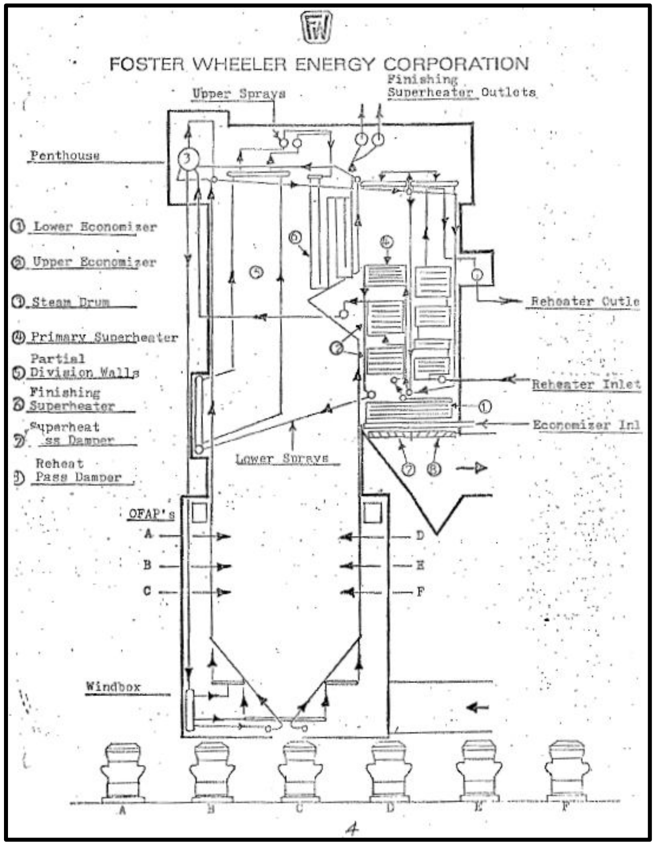
Result	Baseline Coal-Air	NG-Oxy w/ FGR
Furnace Exit Gas Temperature (°F)	1850	1925
Exit CO Concentration, wet (ppm)	138	2044
Exit O_2 Concentration, wet (%)	4.7	1.3
Peak Wall Temperature (°F)	840	852
Radiant Furnace Heat Transfer (MBtu/hr)	459	497
Backpass Flue Gas Flow Rate (klb/hr)	1011	582
Heat Transfer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

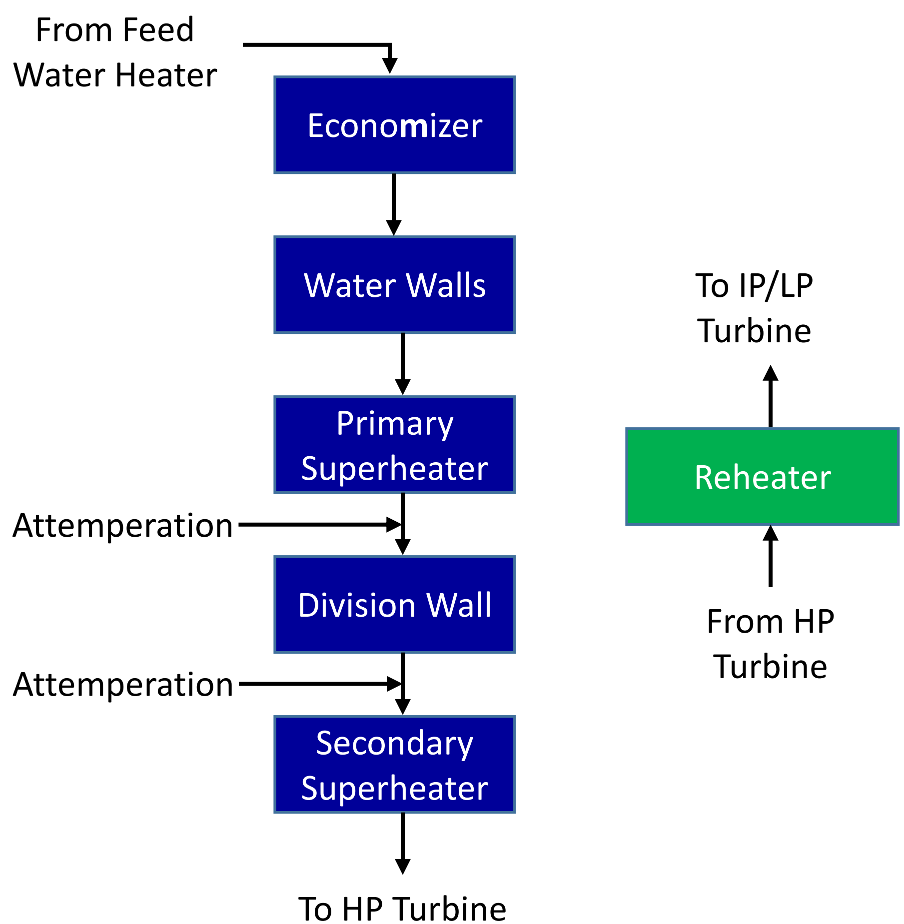
Modeling Conclusions

- **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 MWe wall-fired coal boiler with a split back pass

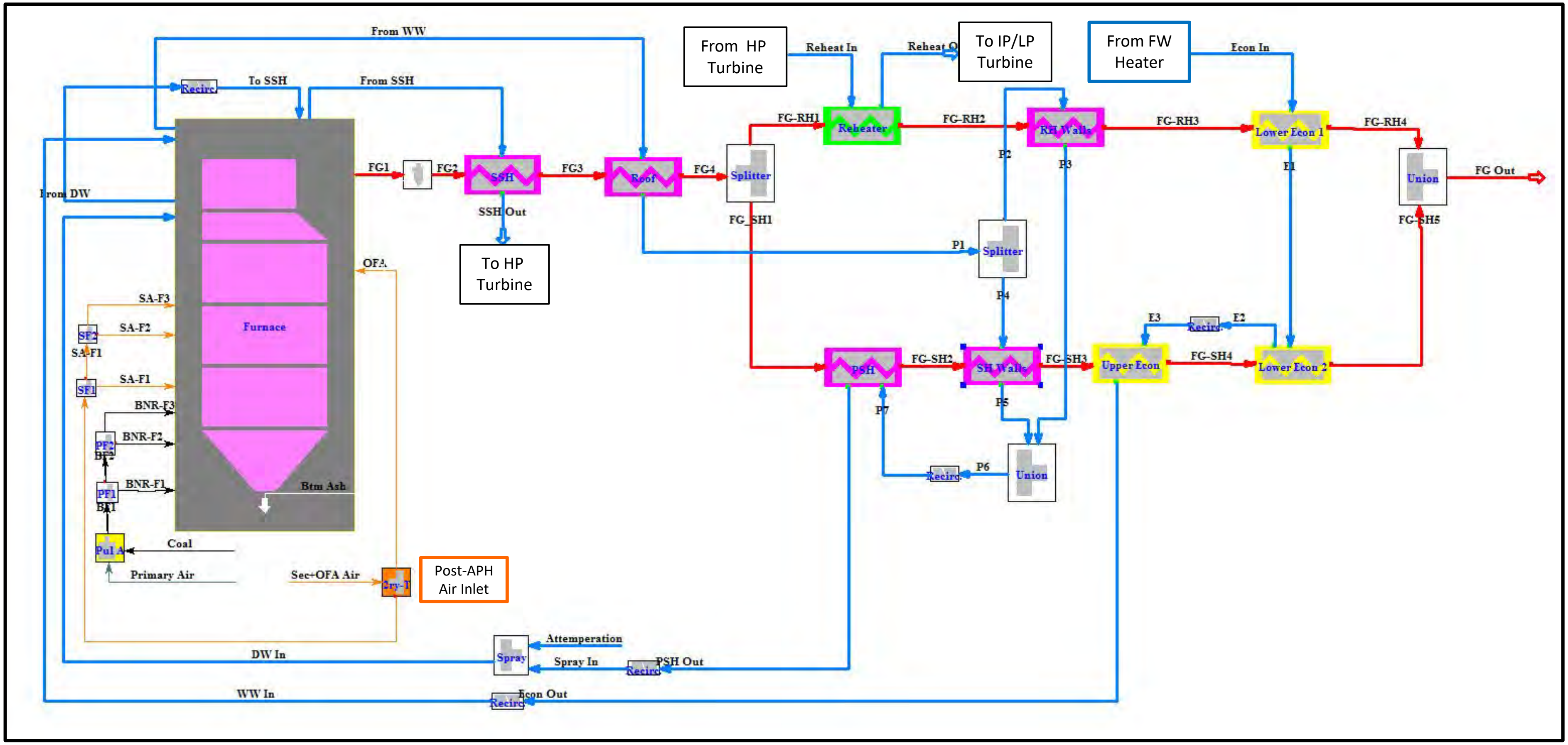




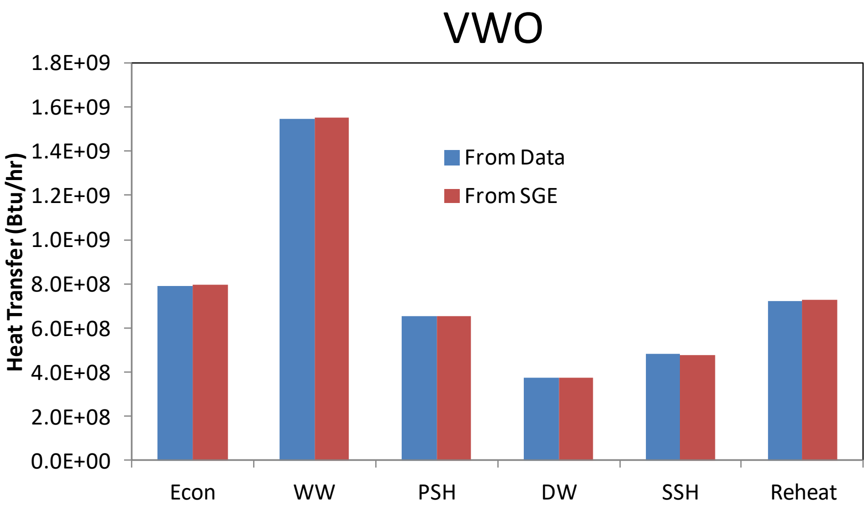
Example 2– SGE Model Setup

- 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

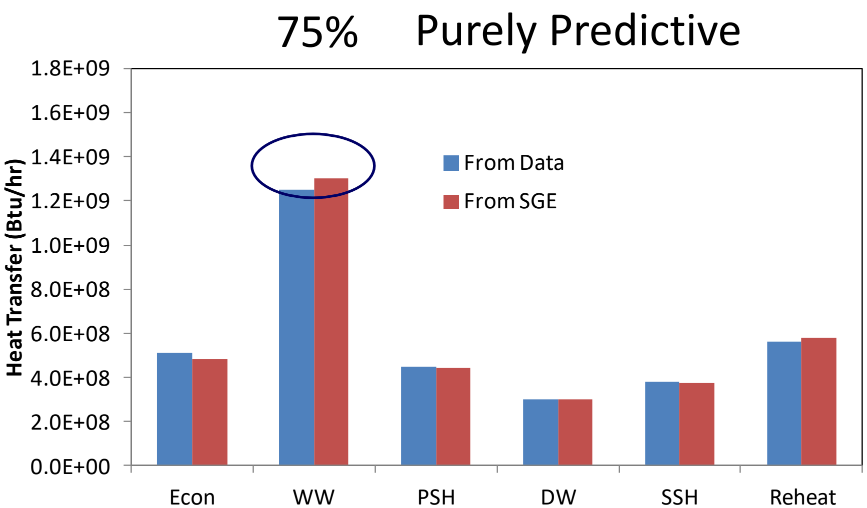
Example 1 – SGE Model

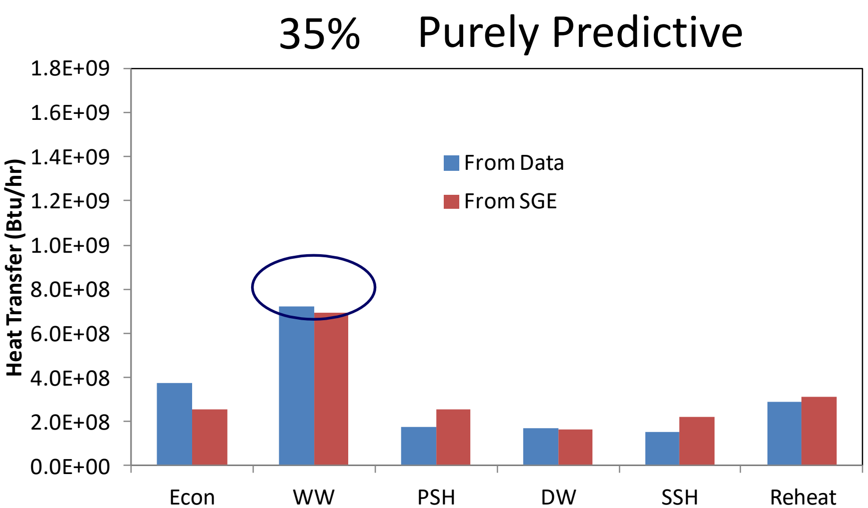


Example 1 - Results (VWO, 75% & 35%)

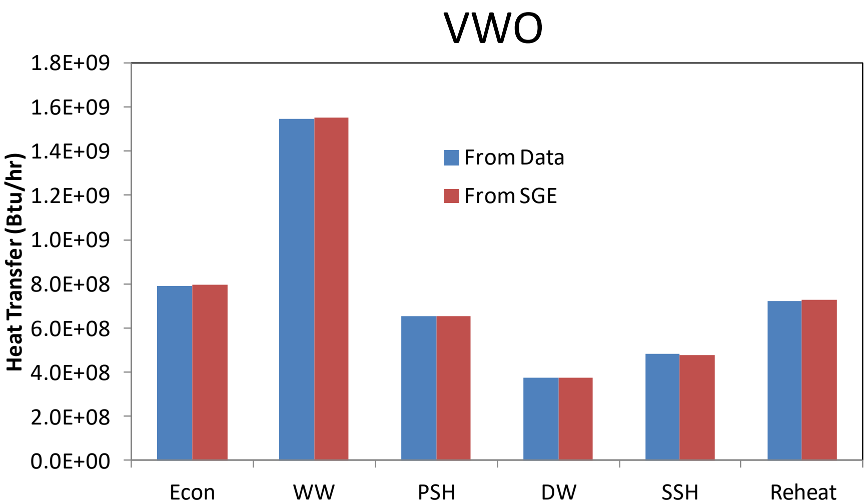


SGE model tuned to VWO data (where available); 75% and 35% loading predicted

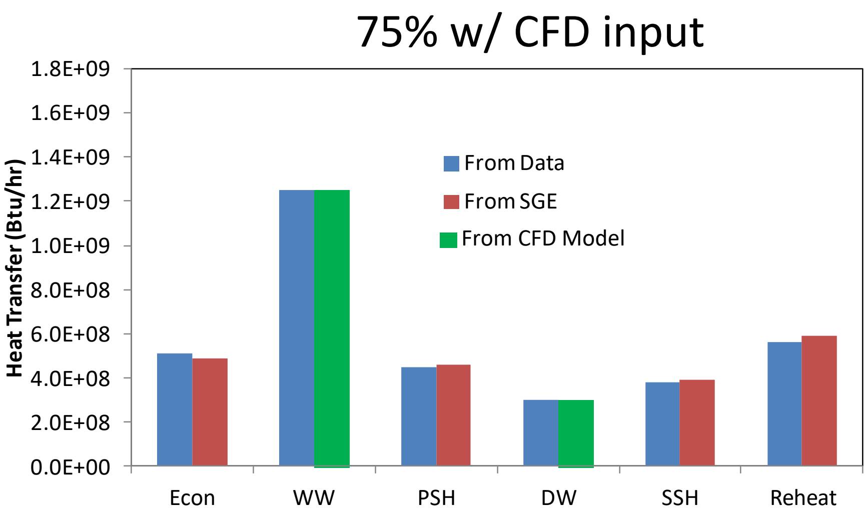


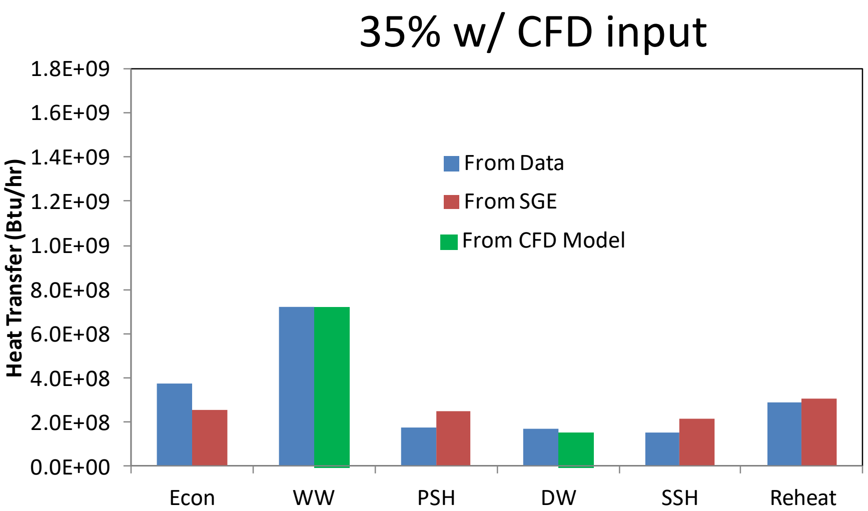


Example 1 - SGE Results w/ CFD Input



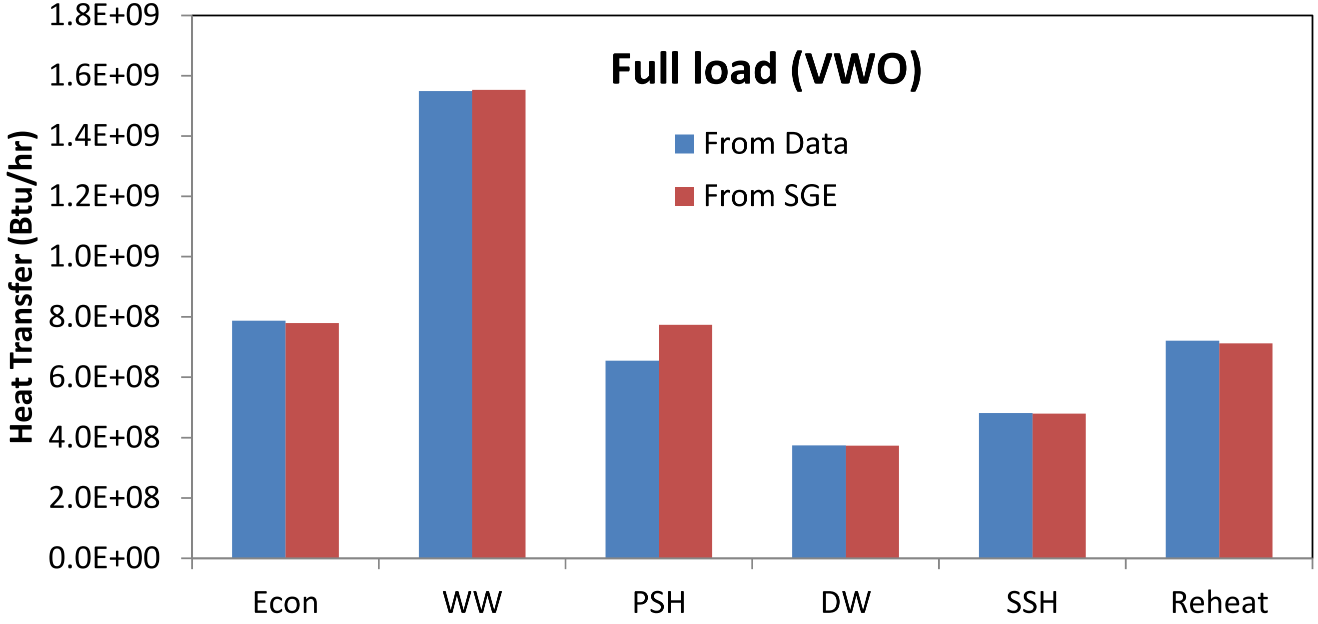
75% and 35% loading predictions improved when using CFD model results for radiant furnace water wall (WW) and division wall (DW)





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

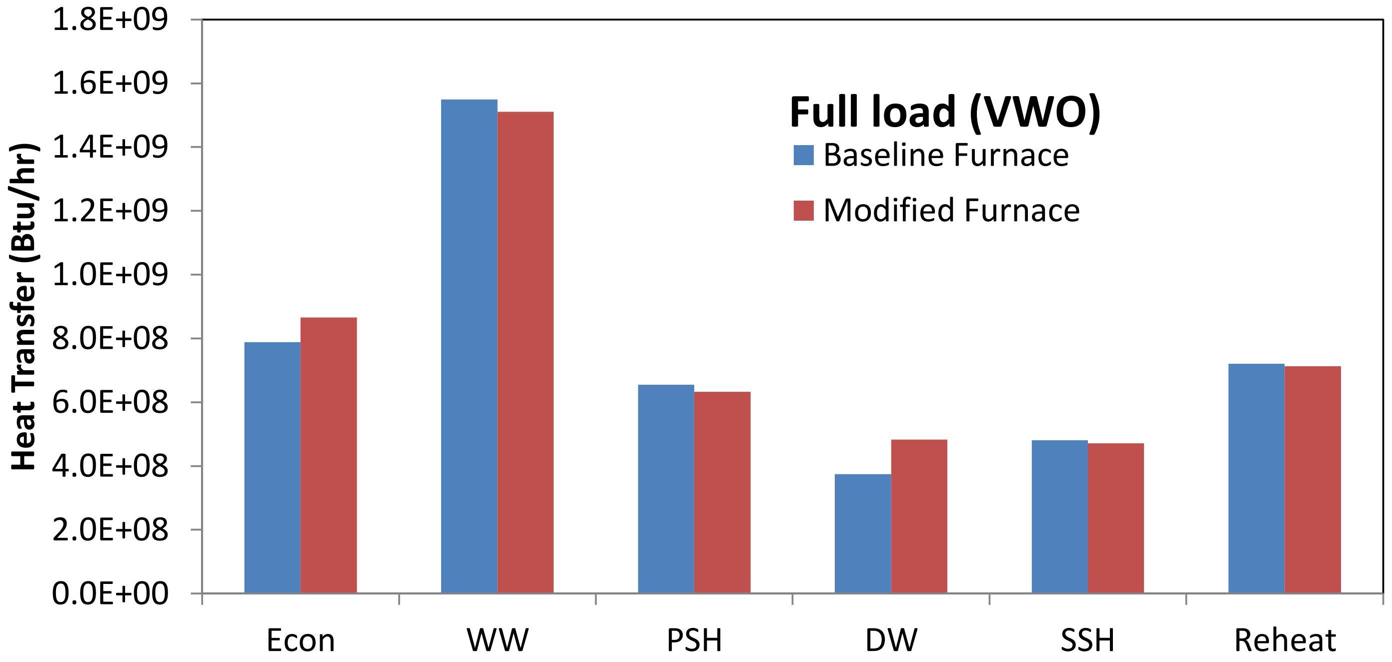
- Heat transfer in primary superheat increased
- Heat transfer in original economizer downstream of the PSH decreased, but that loss was balanced by increase HT in new post-convection economizer tubes

	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

Modeling 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

Summary

- Coal-to-gas conversions have played an important role in extending the life of utility boiler assets in a cost-effective manner while satisfying regulatory pressures
- The conversions continue in both the U.S. and Canada
- Careful consideration of a range of issues should be completed during decision process:
  - Current and possible future regulation
  - Current and possible future fuel costs
  - Access to gas supply
  - Capital and O&M costs
- Optimal conversion technology and implementation will vary for each individual plant

Reaction Engineering International

ENERGY & ENVIRONMENTAL CONSULTING

Committed Individuals, solving challenging problems.

www.reaction-eng.com

746 East Winchester Street, Suite 120
Murray, Utah 84107
U. S. A.
T: +1.801.364.6925
info@reaction-eng.com