

REINHOLD ENVIRONMENTAL Ltd.



**2013 NO<sub>x</sub>-Combustion Round Table  
& Expo Presentations**

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# Oxygen-Enhanced Combustion with Natural Gas Retrofit

Bradley Adams, Timothy Shurtz

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*For Energy and  
Environmental  
Solutions*

**REACTION ENGINEERING INTERNATIONAL**

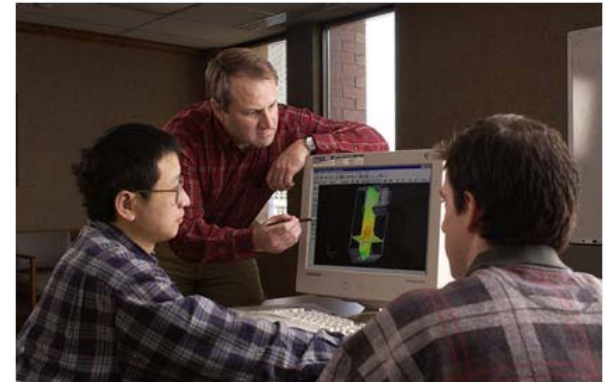
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# REI Background

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- ❑ **20+ Years of Fossil Fuel Combustion Experience**
- ❑ **Combustion, Fuel Conversion & Pollutant Emissions**
- ❑ **Proprietary Modeling Tools**
  - **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**



# Outline

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- Natural Gas Retrofit
- Oxy-Combustion Overview
- Oxy-Natural Gas Retrofit
  - Oxy-NG firing compared to air-firing
  - 350 MW Oxy-NG retrofit combustion evaluation
- Conclusions



# Outline

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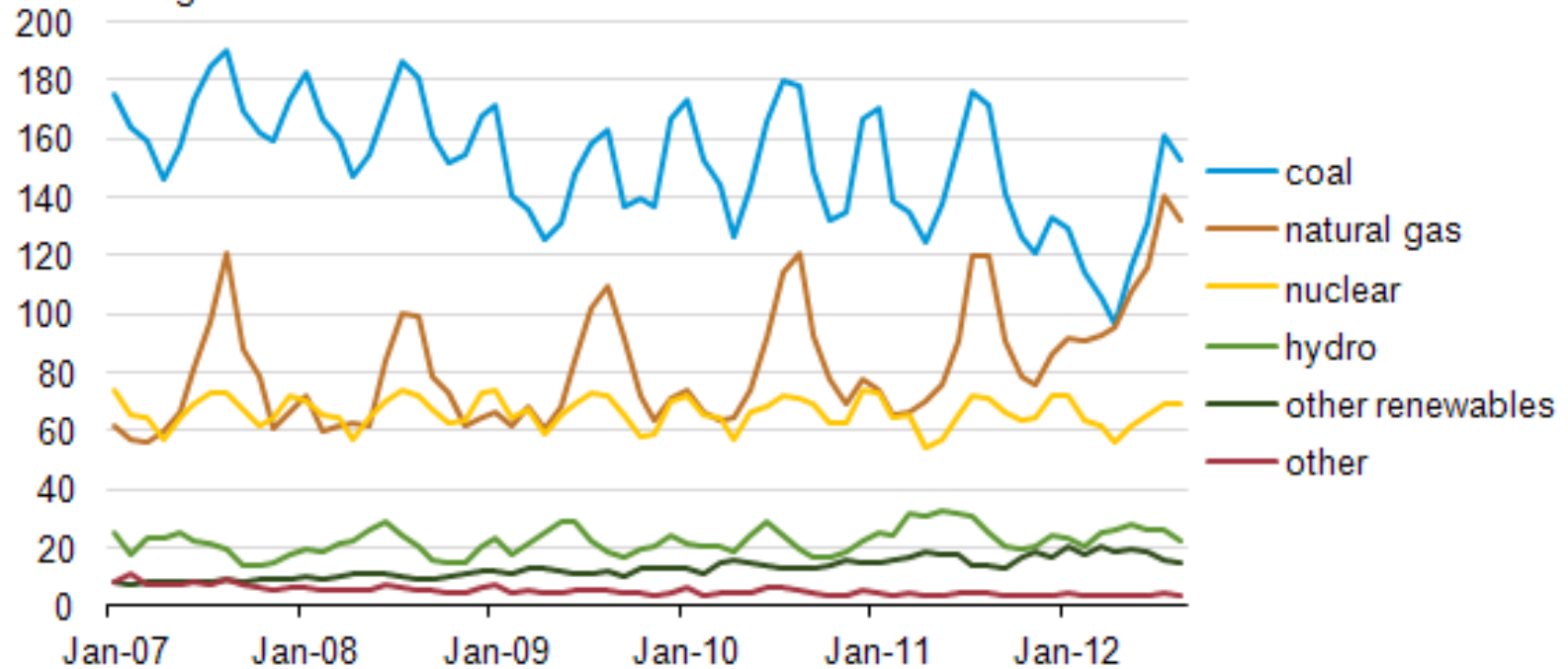
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# The Trend to Gas Firing



U.S. monthly net electric power generation, January 2007 – August 2012  
million megawatthours



# Why Retrofit to Natural Gas?

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- Reduced Fuel Cost
- Reduced Emissions (CO<sub>2</sub>, HCl, Hg, SO<sub>2</sub>, NO<sub>x</sub>, particulates)
- Increased Operational Flexibility
- Timing – required equipment upgrade
- Co-firing or Conversion (rather than repowering) Allows Option to Convert Back to Solid Fuel



# Combustion Retrofit Options

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- **Permanent Natural Gas Conversion**
  - Simplest conversion and operation
  - Emission benefits
  - Some loss in thermal efficiency
- **Co-firing Natural Gas with Coal**
  - Fuel flexibility (0-100% NG)
  - Only partial emissions benefits
- **Natural Gas Firing with Oxygen**
  - More complex conversion
  - May have efficiency benefits
  - Starts path to CO<sub>2</sub> capture



# Considerations with Retrofitting

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- ❑ Fuel Handling and Distribution
- ❑ Firing System (burners, windbox, OFA, controls)
- ❑ Equipment Impacts (APCDs, fans, air heater)
- ❑ Heat Transfer / Thermal Efficiency
  - Radiant Furnace Heat Transfer
  - Convective Pass Heat Transfer



# Fuel Handling and Distribution

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- Gas Supply Pipeline Proximity and Capacity
- Potential for Gas Supply Interruption
- Plant Piping and Controls
- Distribution to Burners



# Firing System

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- Burner Design and Performance**
  - Flame behavior (heat release, NO<sub>x</sub>/CO emissions)
  - Excess O<sub>2</sub> (3.5% wet for coal, 1.5% wet for natural gas)
  - Overfire air operation
- Pressure Part Changes**
- Piping/Windbox Layout**
- Control Systems**
  - Burner light-off, normal operation , load cycling
  - Pressure fluctuations
  - Windbox to furnace pressure differential



# Equipment Impacts

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## Air Pollution Control Equipment

- Performance can be impacted by changed flow rates, pressure drop, gas temperature and composition
- Can remove ESP/baghouse, FGD, Hg control
- Likely keep SCR for NO<sub>x</sub> control, but reduce ammonia due to NO<sub>x</sub> reduction from combustion modifications

## Fans

- Less excess air (15-20% for coal, 8% for NG) so lower flow rates
- Likely do not need upgrade

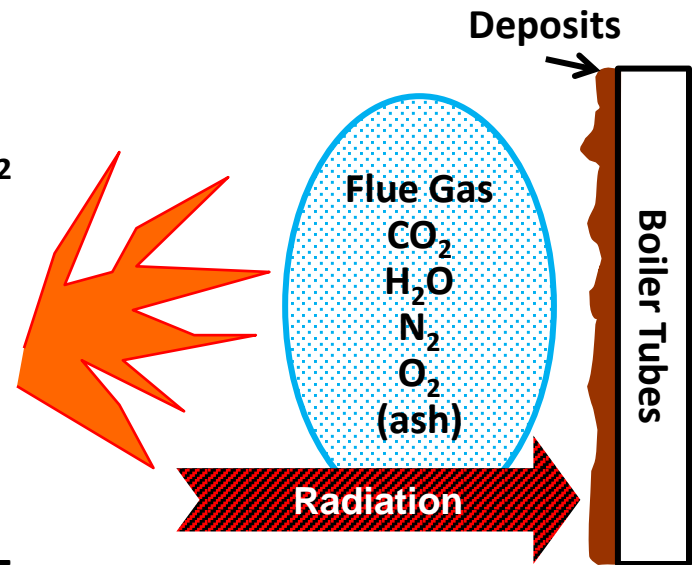
## Air Pre-Heater

- Lower flow rates likely okay, need to check flue gas temperatures



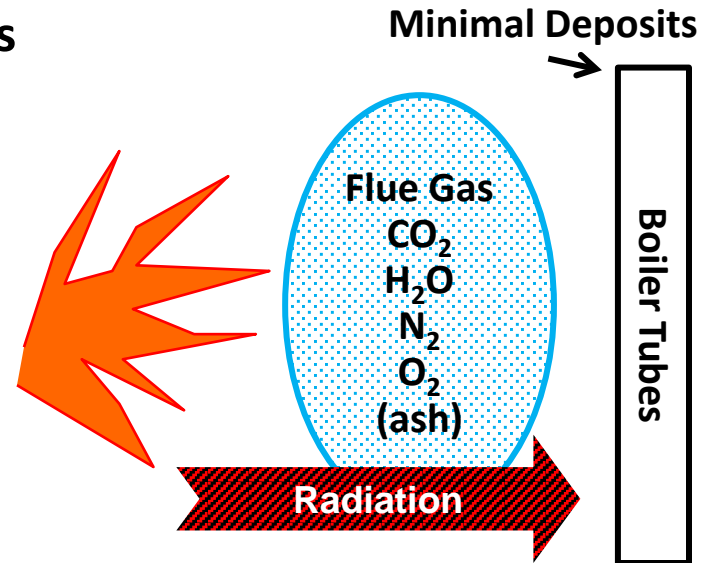
# Radiant Furnace Heat Transfer - Coal

- ❑ 85-90% of heat transfer by radiation
- ❑ Heat transfer to water tubes depends on:
  - Flame emission ( $E \propto \epsilon T^4$ )
  - Flue gas emissivity/absorptivity ( $H_2O$  &  $CO_2$  highest absorbers, fly ash scatters)
  - Water tube deposits (thicker deposit, less heat transfer)
- ❑ Coal-firing has:
  - High flame emissivity with coal particles, soot
  - Adiabatic flame temperatures of  $\sim 4,000$  °F (actual temperatures are lower)
  - Flue gas with 15%  $CO_2$ , 8%  $H_2O$  ( $\epsilon \sim 0.4$ )
  - Ash deposits on water tubes



# Radiant Furnace Heat Transfer – NG

- Natural gas firing changes flame, flue gas and deposit properties
  - Flame emission ( $\epsilon T^4$ ) decreases with decreasing emissivity and temperature
  - Flue gas may absorb more energy due to increased  $H_2O$
  - Heat transfer to water tube increases without deposits
- Heat transfer to tubes usually decreases



Fuel – Oxidant	AFT @ SR=1	Flame Emissivity	Flue Gas $CO_2$ / $H_2O$ (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

\*Based on ~FEGT; gas emissivities vary with temperature and path length



# Radiant Furnace Trends – NG

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- **Observed thermal efficiency decreases of 5-7%**
  - Reduced heat transfer to radiant water tubes
  - Increased moisture formation and latent heat losses
  - Convective pass design can impact efficiency
- **Heat release profile can be impacted by burner design**
  - Different flame shape, rate of heat release
- **Emissions can be impacted by firing system design**
  - Burner mixing, stoichiometric ratio (staging)
  - Gas recirculation and/or gas tempering



# Convective Heat Transfer Issues – NG

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- Maintaining heat transfer to superheater is most critical**
  - Radiant SH impacted by flame characteristics (radiant emission) and FGR (impacts flame temperature, absorbs radiation)**
  - Convective SH impacted by flue gas temperature and flow rate**
  - Reduced radiant heat transfer results in higher FEGT, increasing heat transfer in convective pass (need to 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**



# Outline

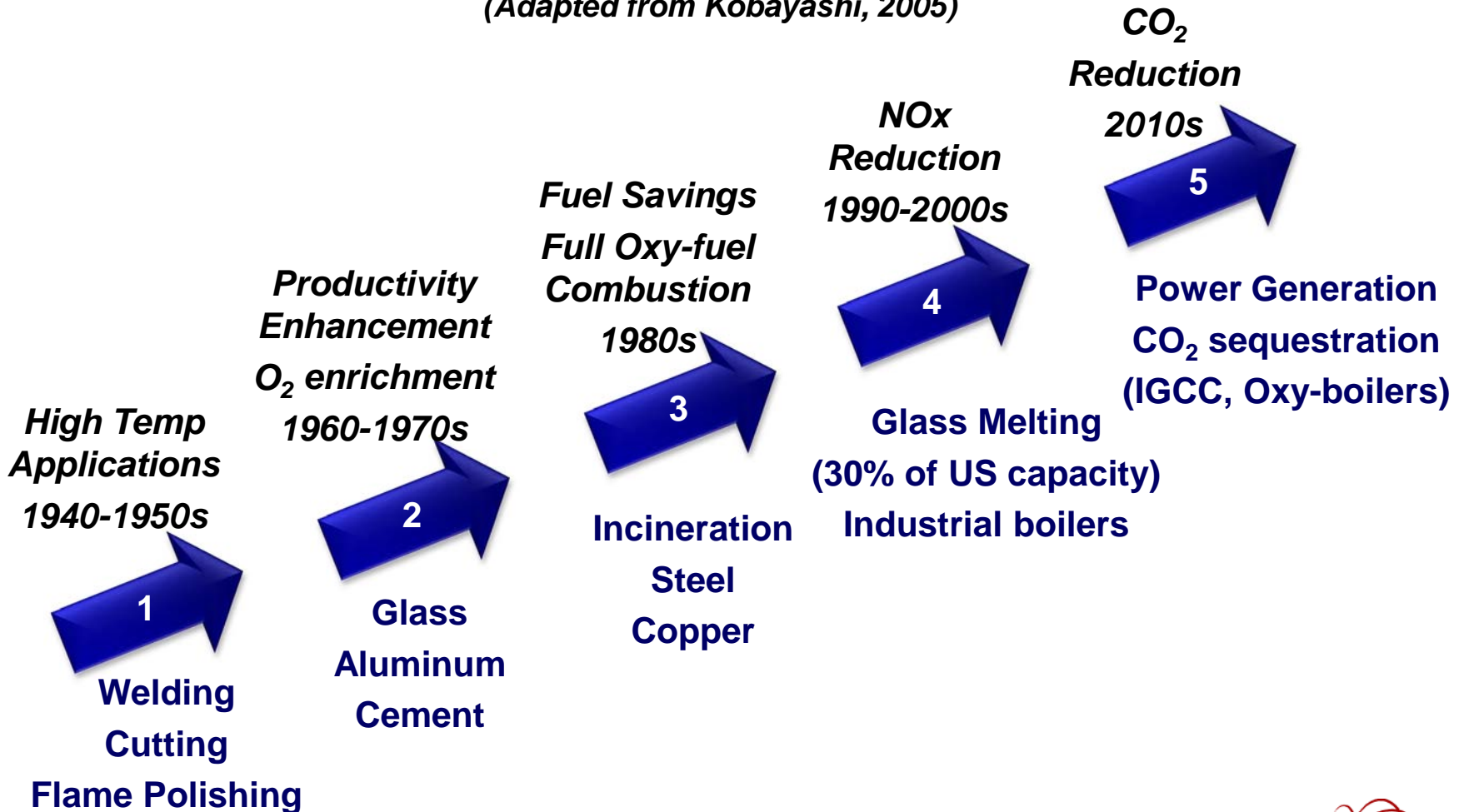
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- **Oxy-Combustion Overview**
- Oxy-Natural Gas Retrofit
  - Oxy-NG firing compared to air-firing
  - 350 MW Oxy-NG retrofit combustion evaluation
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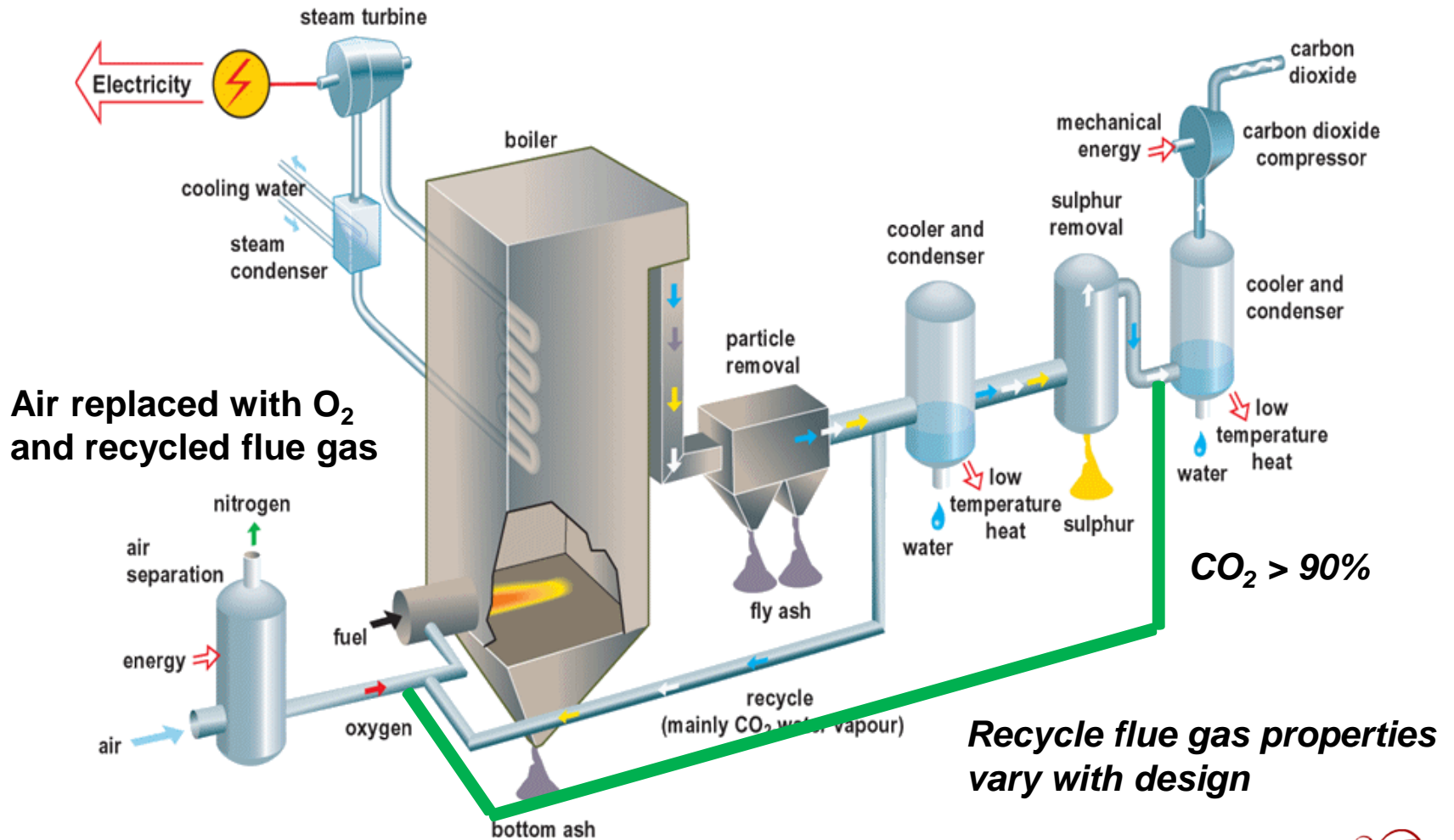


# History of Oxy-Combustion Applications

(Adapted from Kobayashi, 2005)

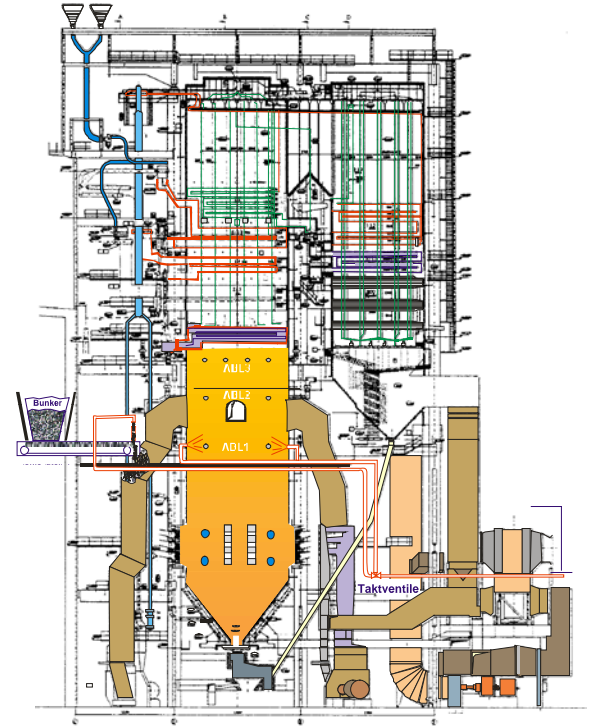


# Oxy-Coal Power Plant Overview



# Oxy-Combustion Advantages

- Potential for High CO<sub>2</sub> 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<sub>x</sub>, 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, CO<sub>2</sub> compressor)
- Design (materials, “plumbing”)

## □ Lower Plant Efficiency

- Significant penalties from ASU and CO<sub>2</sub> compression

## □ Technical Challenges

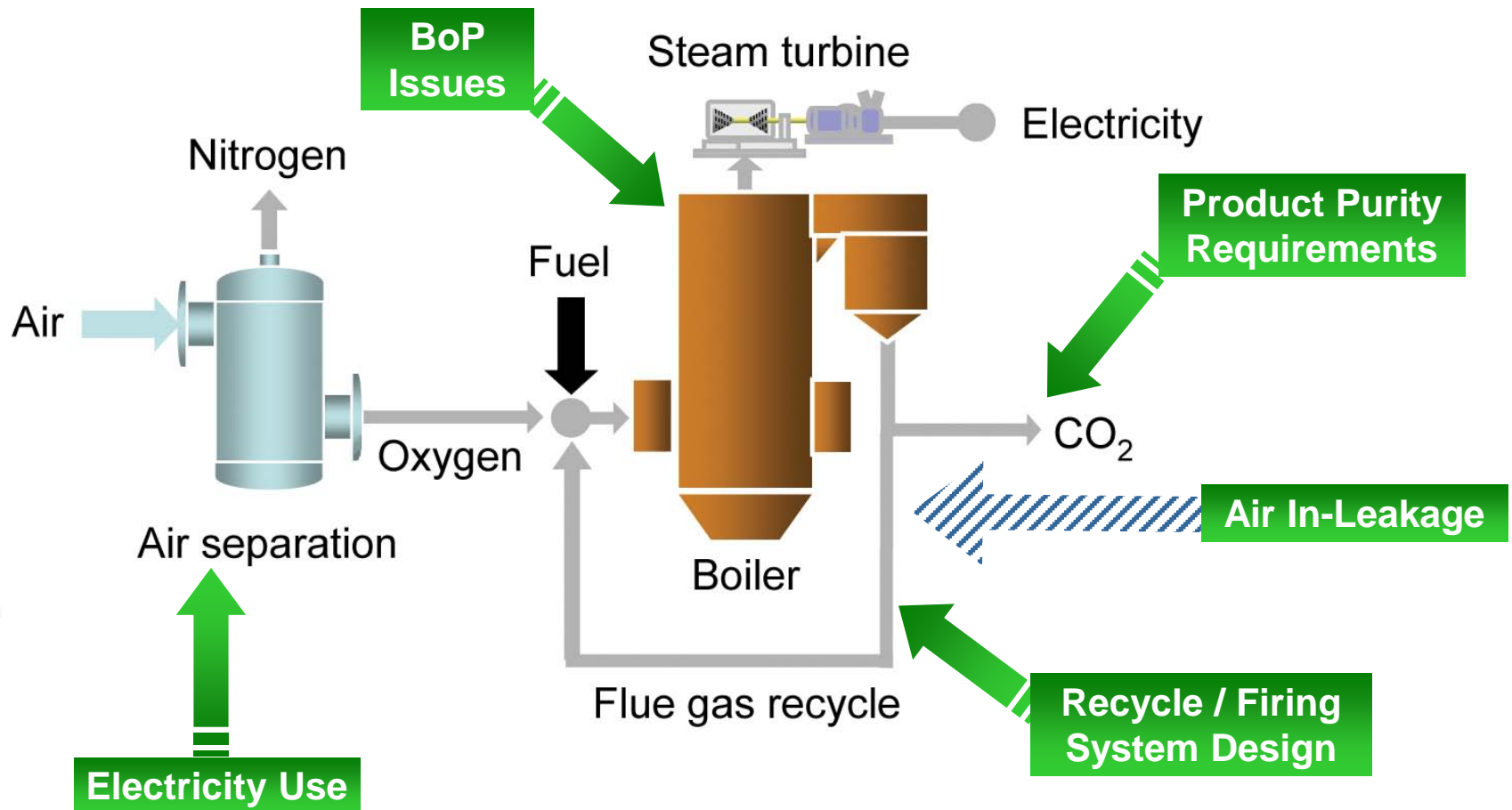
- Balance of plant impacts
- Operating availability with new technology



(Marion, 2009)



# Technical Challenges



# DOE Previous Oxy-Combustion Projects

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## Projects

- **Adv. Oxygen Production**
  - Praxair
- **CO<sub>2</sub> Purification**
  - Praxair, Air Products
- **Boiler Development**
  - Alstom, B&W
- **Corrosion**
  - Foster Wheeler

## Projects

- **Small Pilot Scale Studies**
  - Alstom Power
  - Babcock & Wilcox (B&W)
  - Jupiter Oxygen
  - Reaction Engineering Intl.
  - Southern Research Inst.

[www.netl.doe.gov/technologies/coalpower/ewr/co2/OxyCombustion.html](http://www.netl.doe.gov/technologies/coalpower/ewr/co2/OxyCombustion.html)



# Current Oxy-Combustion Projects

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- **FutureGen 2.0**
  - \$1B+ project, just authorized for Phase II
- **DOE R&D Programs – 10 new projects**
- **Foreign Programs**
  - Vattenfall 30 MW<sub>t</sub> (operating)
  - Callide 30 MW<sub>t</sub> (operating)
  - CIUDEN 30 MW<sub>t</sub> CFB (operating)
  - 300-600 MW<sub>e</sub> plants designed



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# Oxy-Natural Gas Retrofit

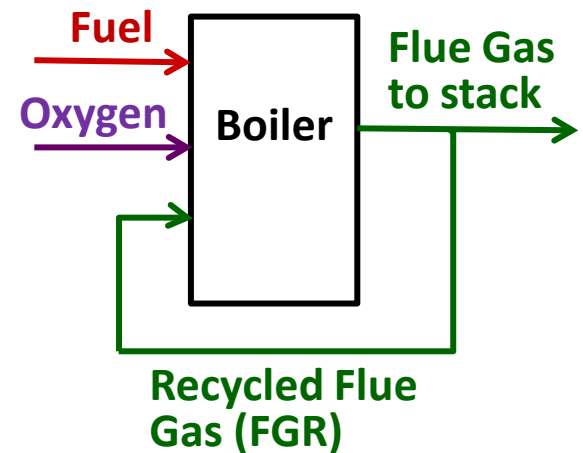
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## □ Oxy-Natural Gas Firing Provides

- Flexible flame temperatures
- Higher thermal efficiency than air-NG
- Very low emissions
- Easier CO<sub>2</sub> capture

## □ For retrofit, key is to match air-coal heat transfer in radiant furnace and convective pass

- What O<sub>2</sub> and FGR design will accomplish this?



# Additional Considerations with Oxy-NG

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- **Fuel Handling and Distribution**
  - Oxygen supply (pipeline, air separation unit)
  - Additional controls for oxygen
- **Firing System**
  - Oxygen-FGR mixture (> 21% concentration)
  - Additional piping and controls
  - Flue Gas Recycle System
  - Air in-leakage
- **Reduced flow rates to APCDs, Fans, APH**
  - Eliminate some APC equipment (SO<sub>2</sub>, Hg, particulate)
  - Different preheater role with FGR



# Heat Transfer Considerations

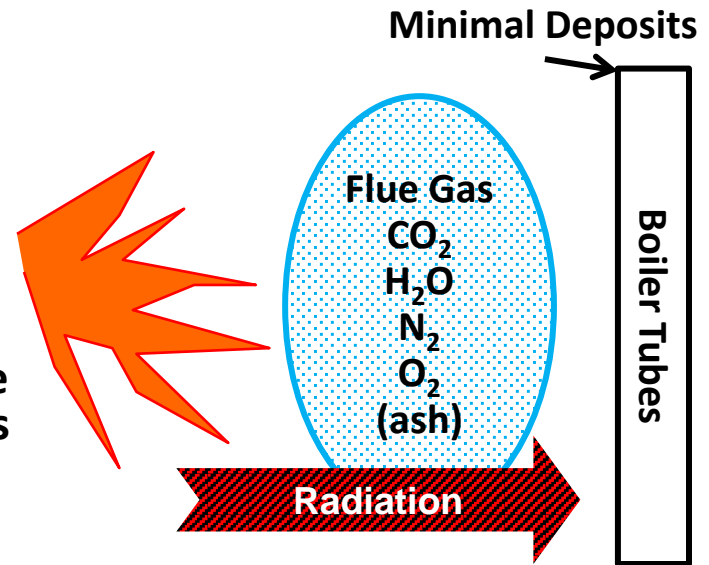
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- For retrofit, want to match air-coal heat transfer in radiant furnace and convective pass
  - FGR+O<sub>2</sub> inlet mixture controls heat transfer
  - What O<sub>2</sub> and FGR design will achieve match?
  - Mix FGR with oxygen or inject separately?
  - Warm or cool recycle stream (impacts efficiency)?
- Trade-off between Radiant Furnace and Convective Pass Heat Transfer



# Radiant Furnace Heat Transfer – Oxy-NG

- Oxy-NG firing changes flame temperature and flue gas properties
  - Much hotter flame temperature
  - Flame emission ( $\epsilon T^4$ ) increases with increasing flame temperature
  - Flue gas likely to absorb more energy due to significantly higher H<sub>2</sub>O concentrations
  - Flame temperature and heat transfer impacted by FGR design

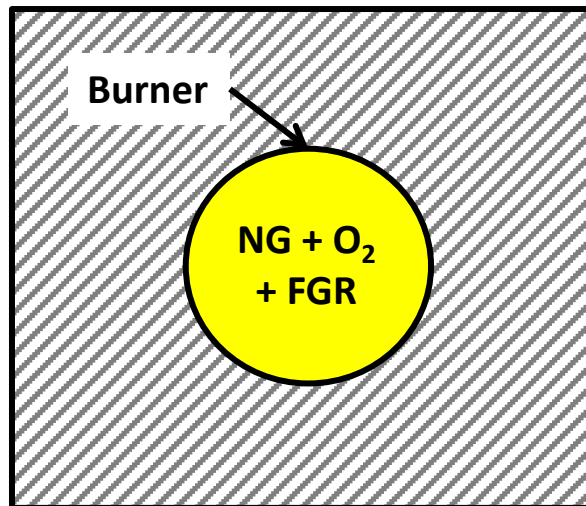


Fuel – Oxidant	AFT @ SR=1	Flame Emissivity	Flue Gas CO <sub>2</sub> / H <sub>2</sub> O (mol %)	Flue Gas Emissivity*	Deposit Res.
Coal – Air	~4000 °F	higher	15 / 8	0.40	higher
Nat Gas – Air	~3650 °F	lower	8 / 16	0.48	lower
Nat Gas – Oxy	~5600 °F	lower	32 / 64	0.66	lower

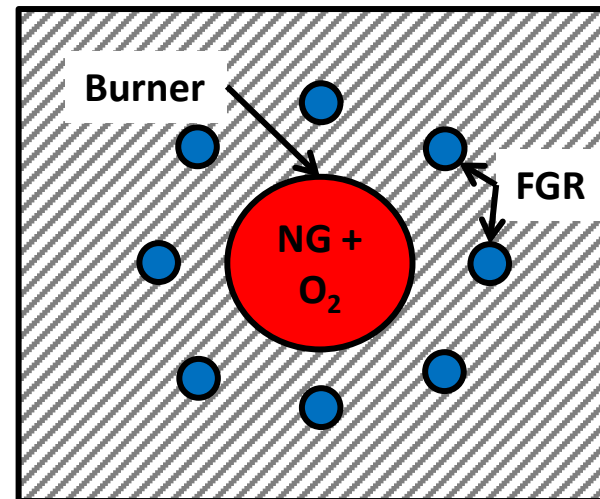
\*Based on ~FEGT; gas emissivities vary with temperature



# Oxy-NG Flame and FGR Impacts



- O<sub>2</sub> and FGR mixed in flame
- Cooler flame temperature, lower radiant emission
- Can target to match air-fired heat transfer



- FGR injected around flame
- Hotter flame temperature, higher radiant emission
- Amount and location of FGR impacts radiant heat transfer to water walls



# Oxy-NG vs Air-NG Heat Transfer

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- Thermal efficiency decreases of 5-7% (smaller decrease)
  - Reduced heat transfer to radiant tubes (significantly increased)
  - Increased moisture formation and latent heat losses (higher H<sub>2</sub>O)
  - Impacted by convective pass design (FGR plays larger role)
- Heat transfer profile can be impacted by burner design
  - Different flame shape, rate of heat release (still true)
- Emissions can be impacted by firing system design
  - Burner mixing, stoichiometric ratio (staging) (still true, but less N<sub>2</sub> for NO<sub>x</sub> formation)
  - Gas recirculation and/or gas tempering (FGR plays larger role)



# Convective Heat Transfer – Oxy-NG

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- Maintaining heat transfer to superheater is most critical
  - Radiant SH impacted by flame characteristics (radiant emission) and FGR (impacts flame temperature, absorbs radiation)
  - Higher flame temperature and radiant SH heat transfer
  - Convective SH impacted by flue gas temperature and flow rate
  - Lower FEGT, potentially lower flow rate
  - Reduced radiant heat transfer results in higher FEGT, increasing heat transfer in convective pass (need to avoid tube overheating)
  - Increased radiant HT, lower FEGT, reduced convective HT



# Convective Heat Transfer – Oxy-NG

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- Economizer heat transfer is less important, but can change boiler efficiency with changed FW or APH conditions
  - Likely lower economizer HT
- Can adjust convective heat transfer with attemperation, modified heat transfer surfaces, auxiliary heating
  - Still true



# Outline

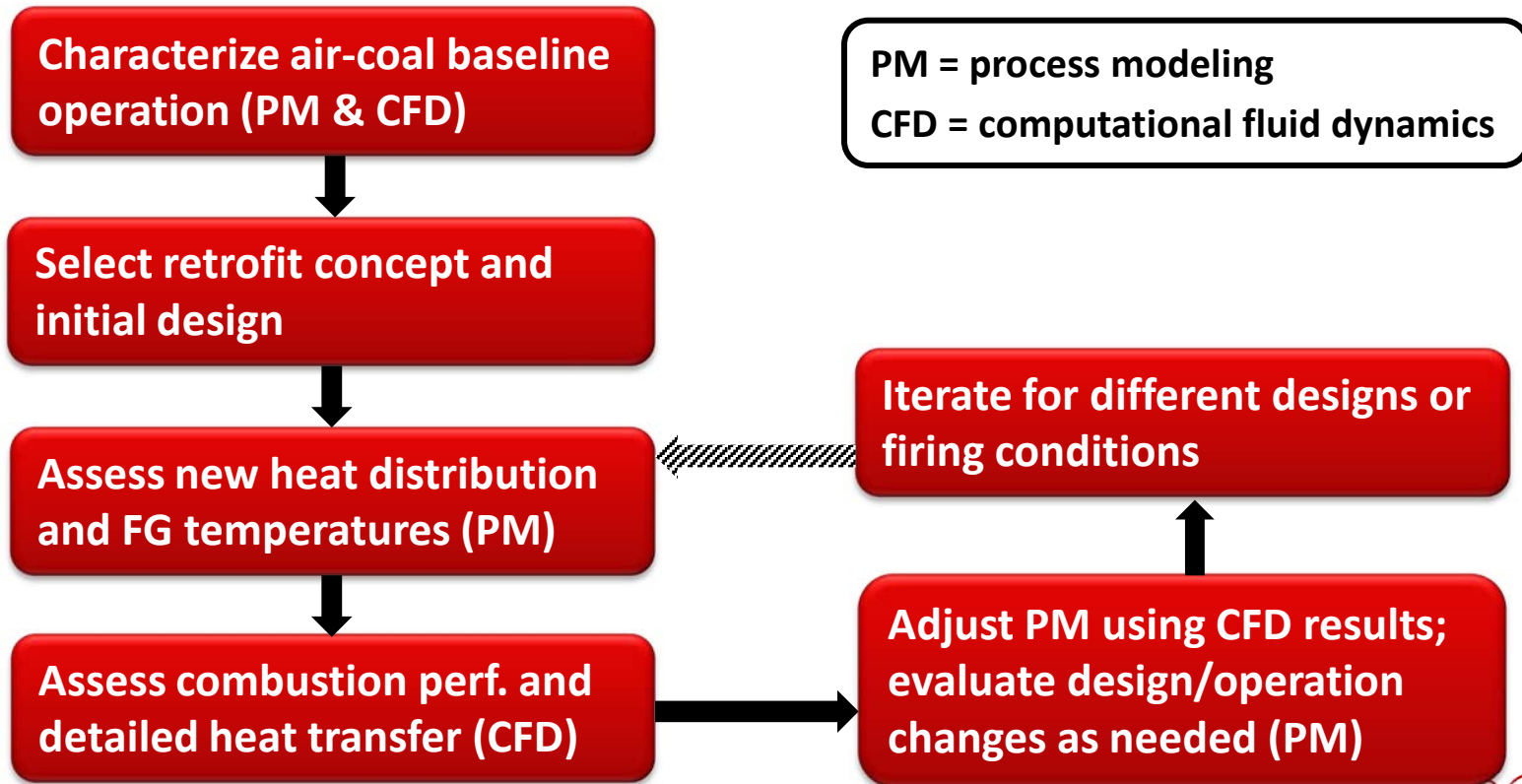
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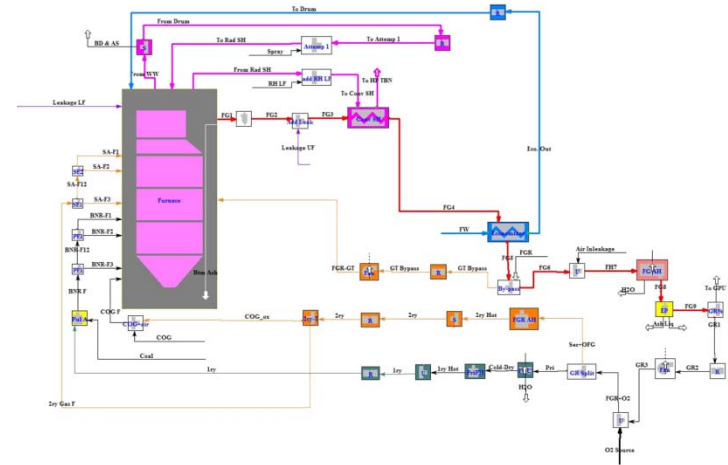
# Heat Transfer Evaluation Approach

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

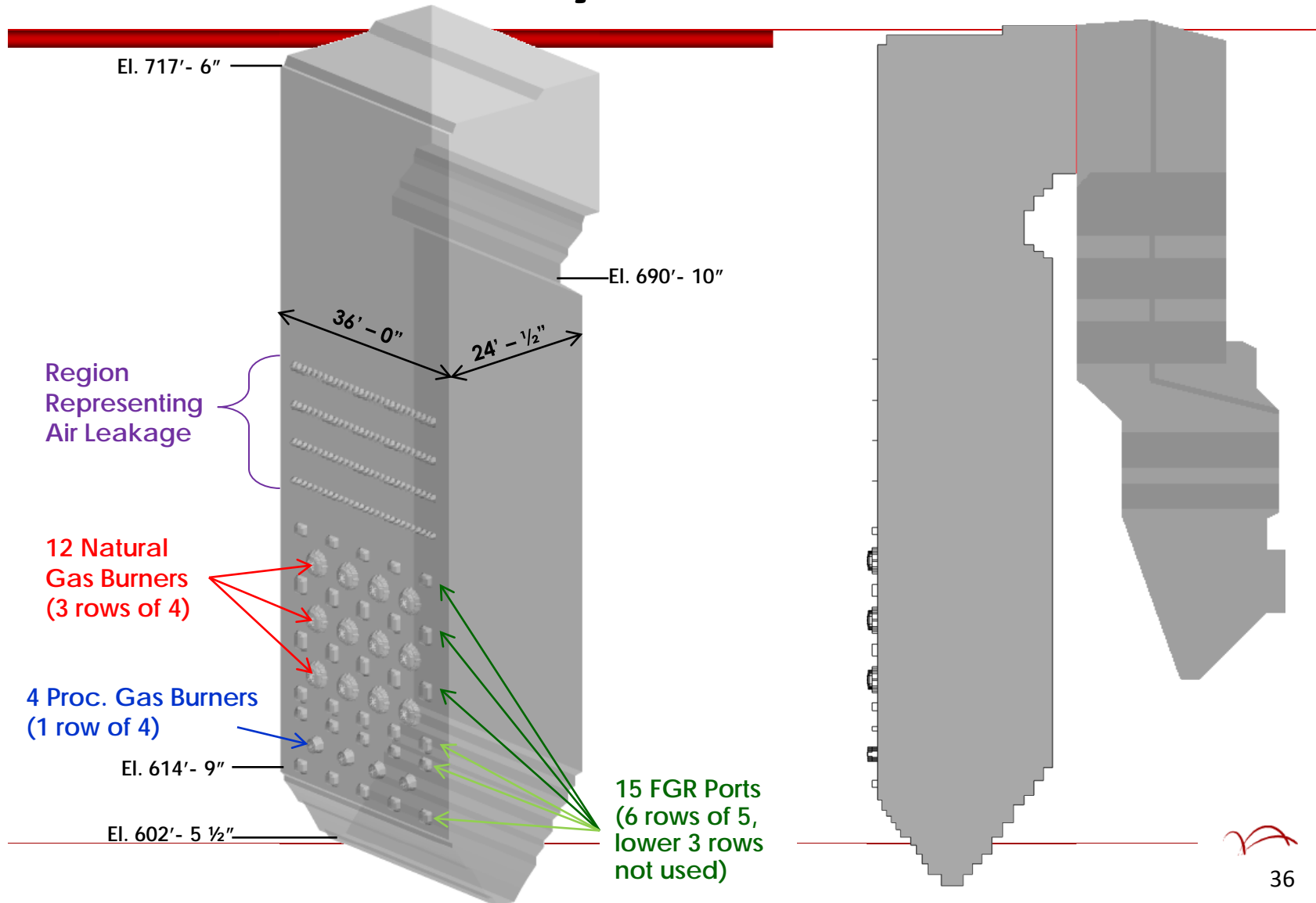


# CFD Model Overview

- Use CFD modeling to assess furnace performance when retrofitting a 350 MW coal-fired boiler from air-coal firing to oxy-natural gas firing
- 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

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## □ 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<sub>2</sub> (dry) at exit
  - 26.7% O<sub>2</sub> in O<sub>2</sub>+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)



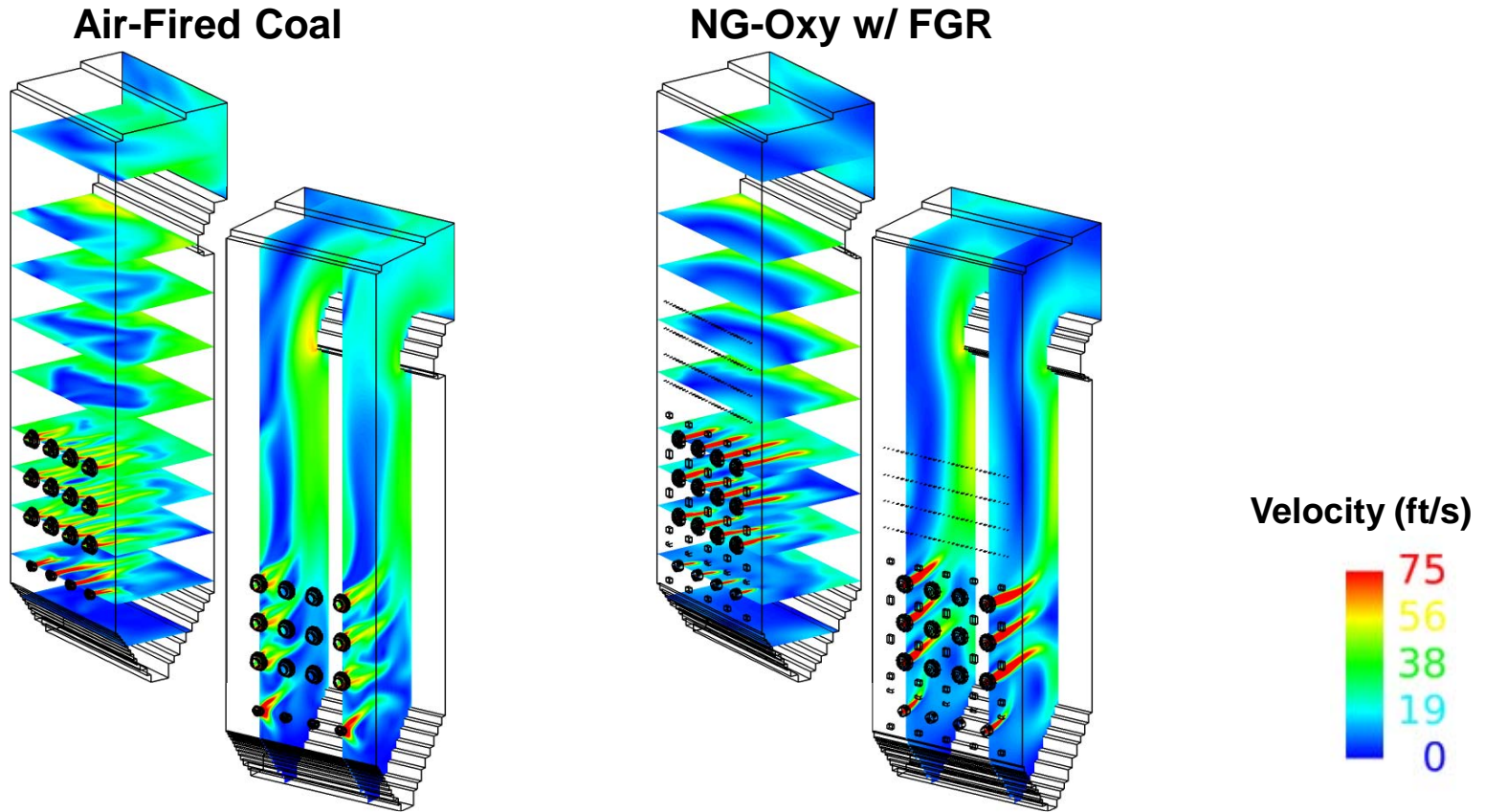
# Overall Operating Conditions

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<b>Furnace Operating Conditions</b>	<b>Air-Coal</b>	<b>Oxy-NG</b>
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 <sub>2</sub> +FGR Flow Rate (klb/hr)	924	549
Theoretical Excess O <sub>2</sub> (% , wet)	4.7%	1.2%
Theoretical Excess O <sub>2</sub> (% , 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



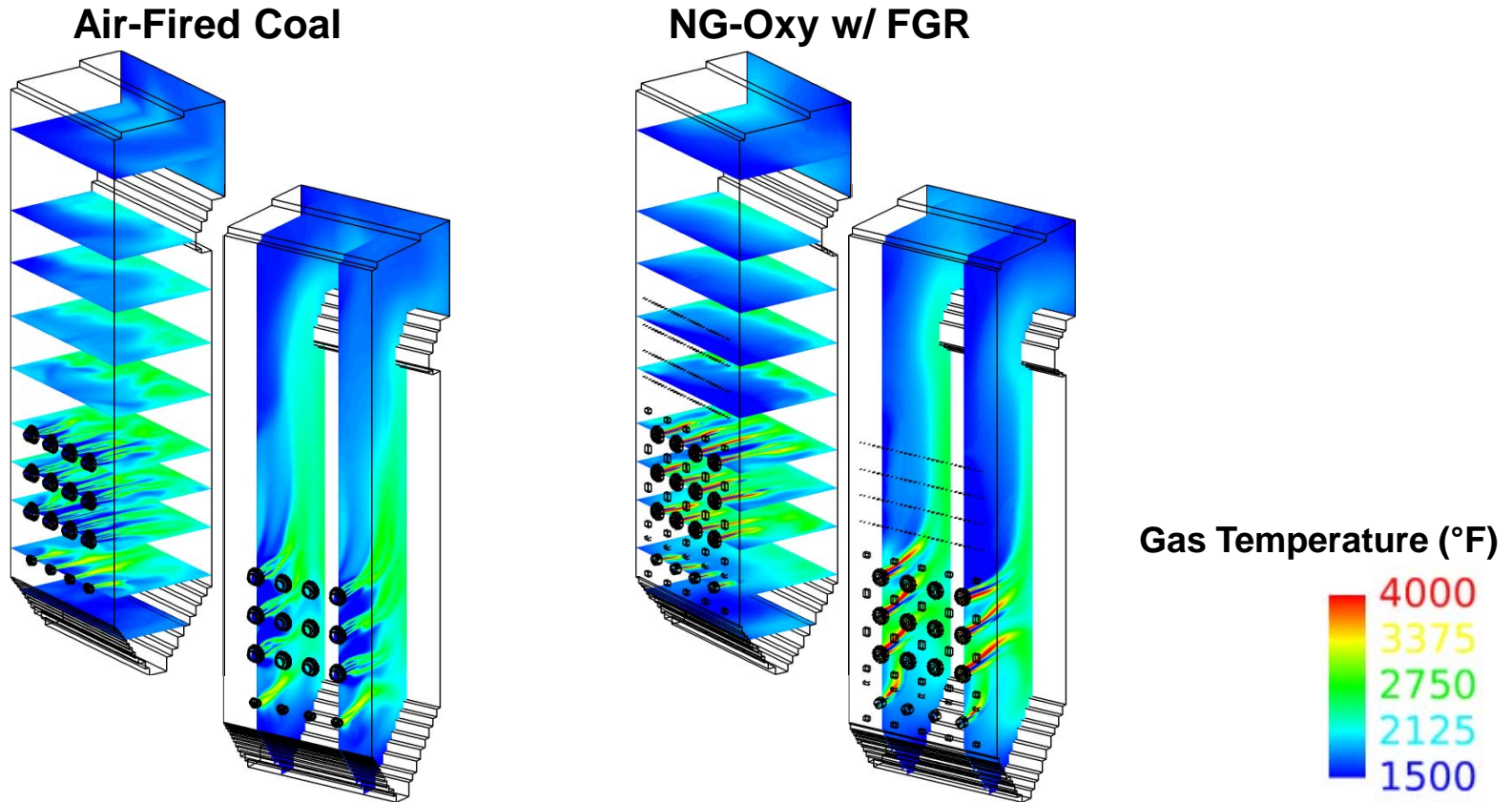
# Gas Velocity



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



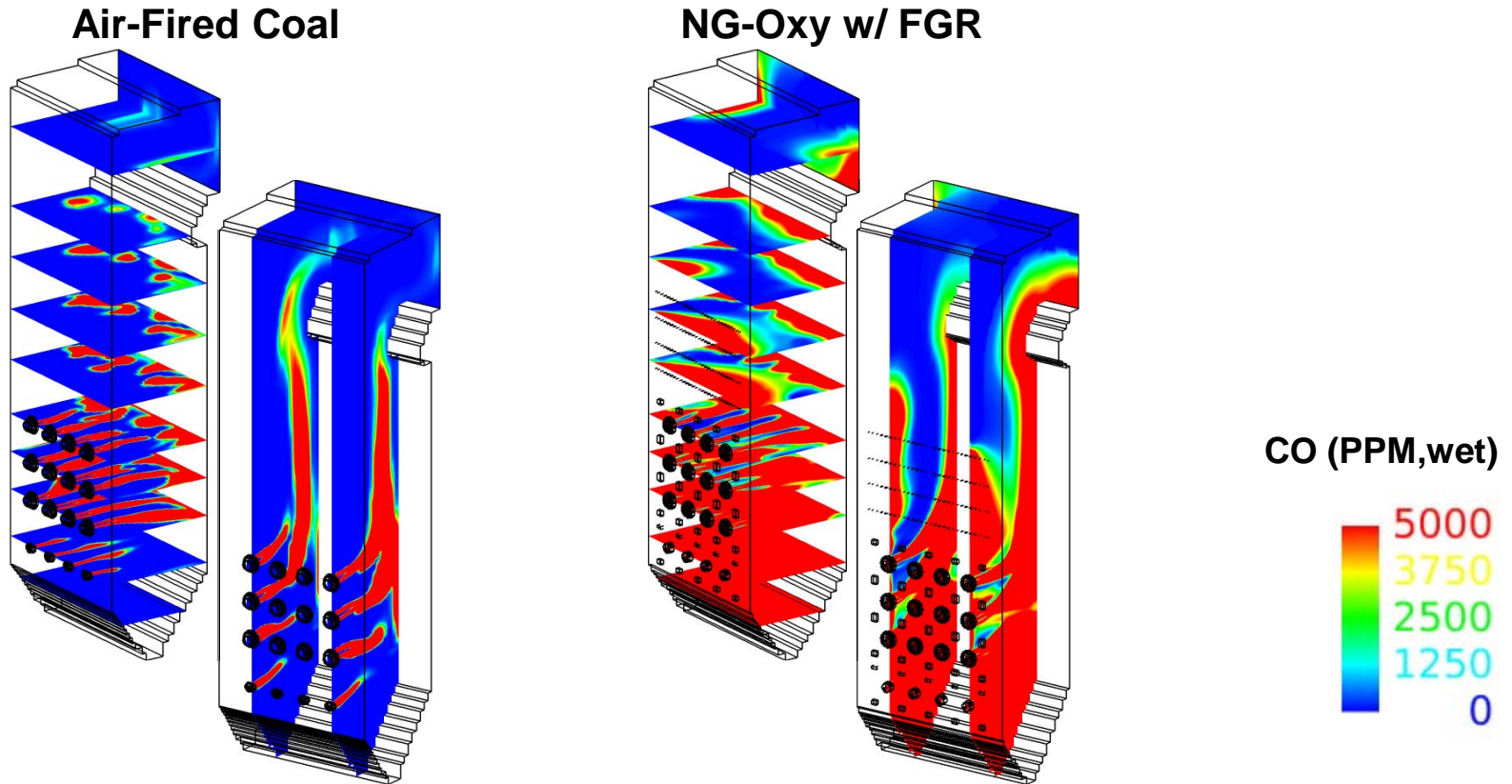
# Gas Temperature



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



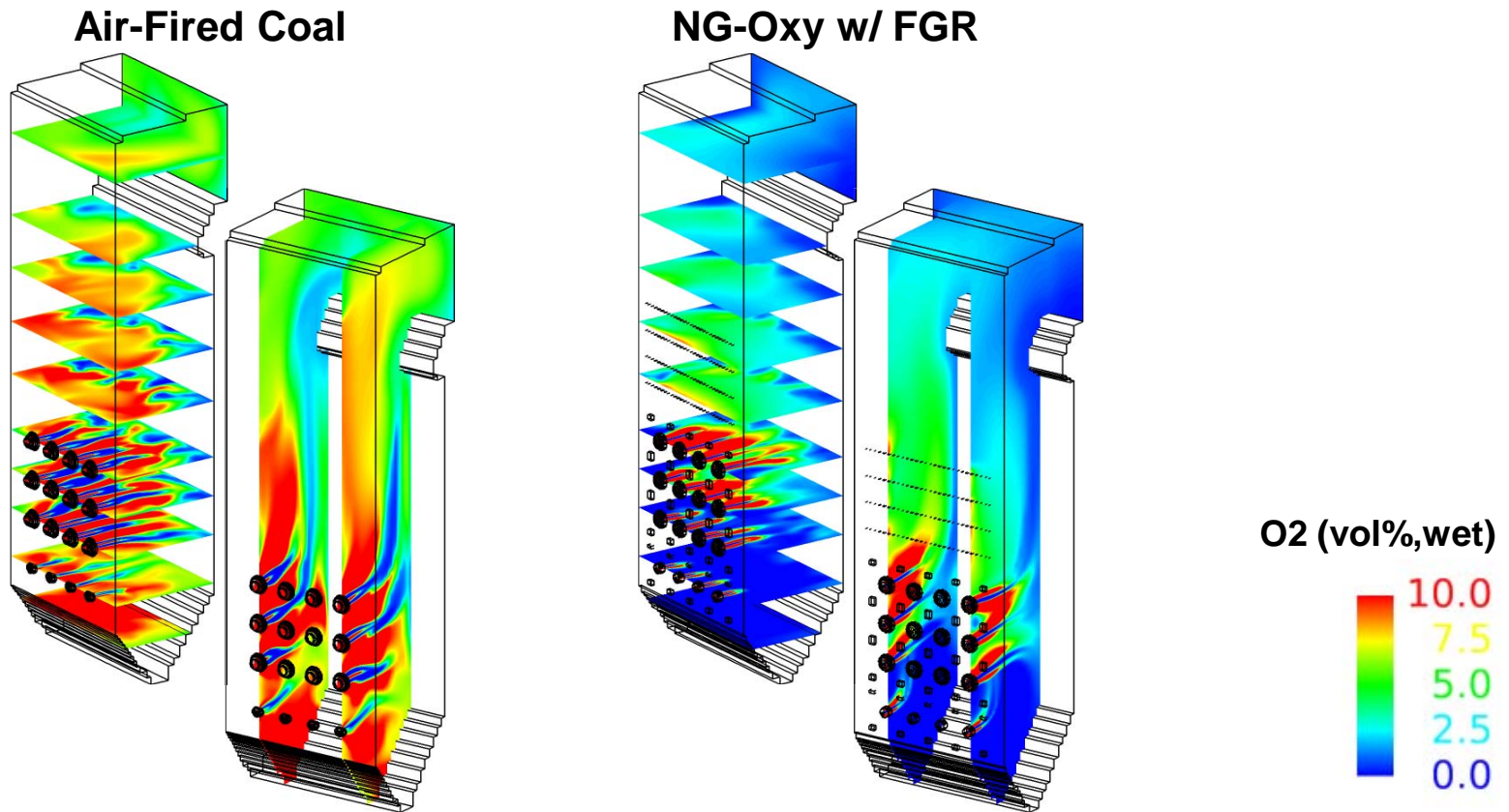
# CO Concentration



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<sub>2</sub> Concentration

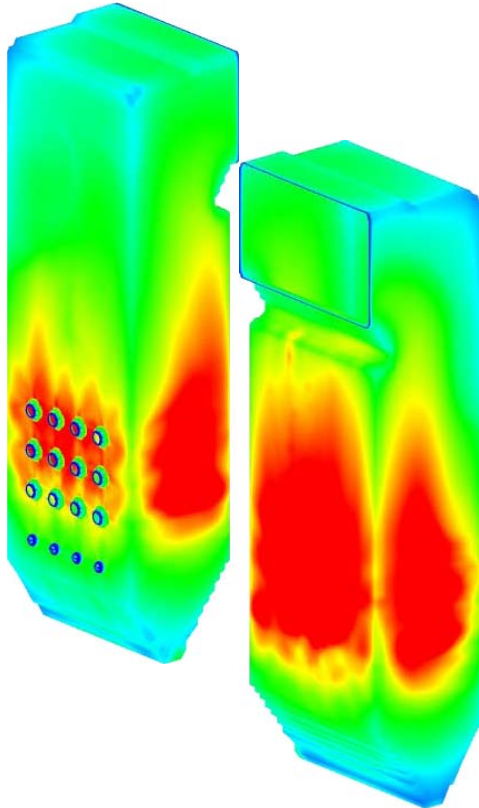


O<sub>2</sub> higher in air-coal case due to higher operating O<sub>2</sub>; no O<sub>2</sub> in lower furnace for NG-Oxy case due to sub-stoichiometric PG burners

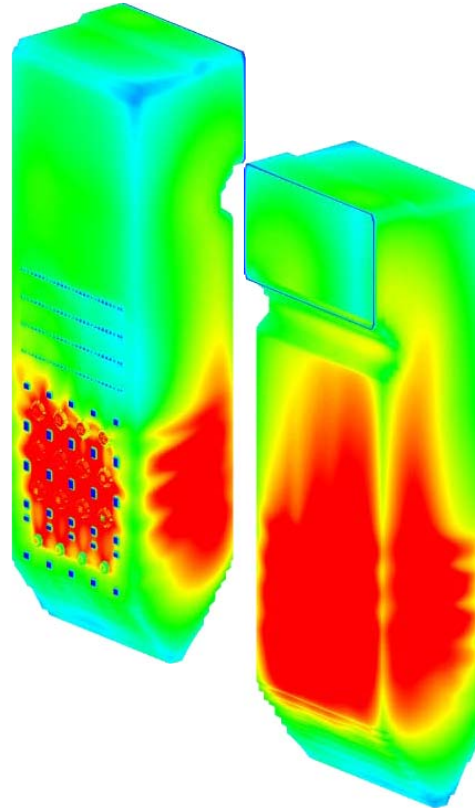


# Net Wall Heat Flux

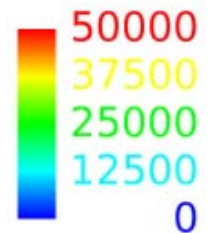
Air-Fired Coal



NG-Oxy w/ FGR



Heat Flux (Btu/h-ft<sup>2</sup>)

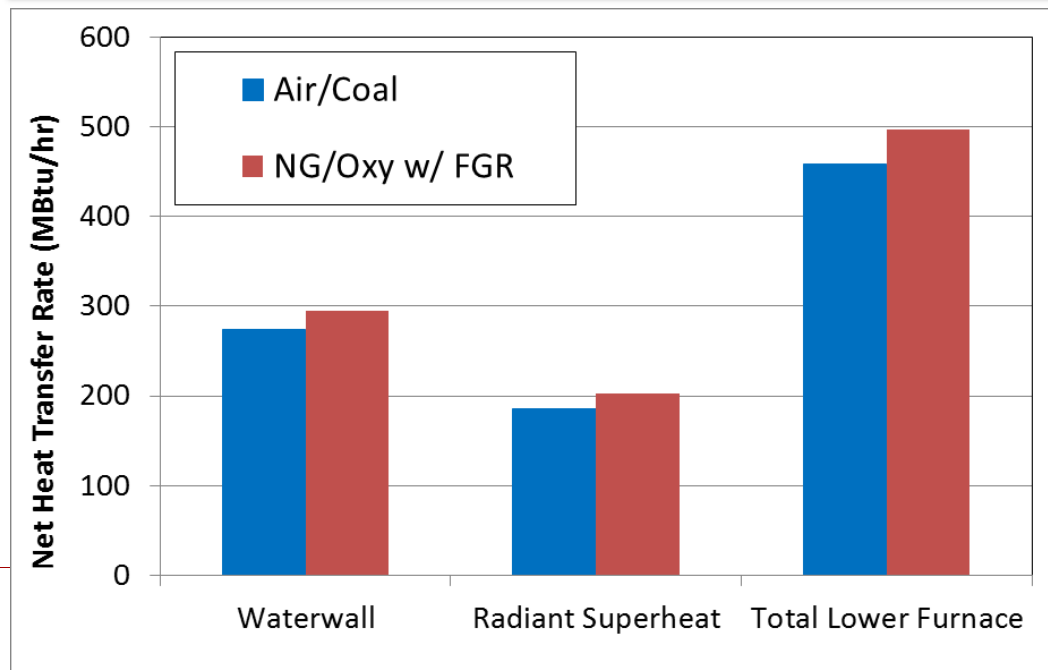


Cases have similar net heat fluxes



# Heat Transfer by Furnace Zone

Zone	Baseline Air-Coal		Oxy-NG (w/ FGR)	
	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
<b>Total</b>	<b>459</b>		<b>497</b>	

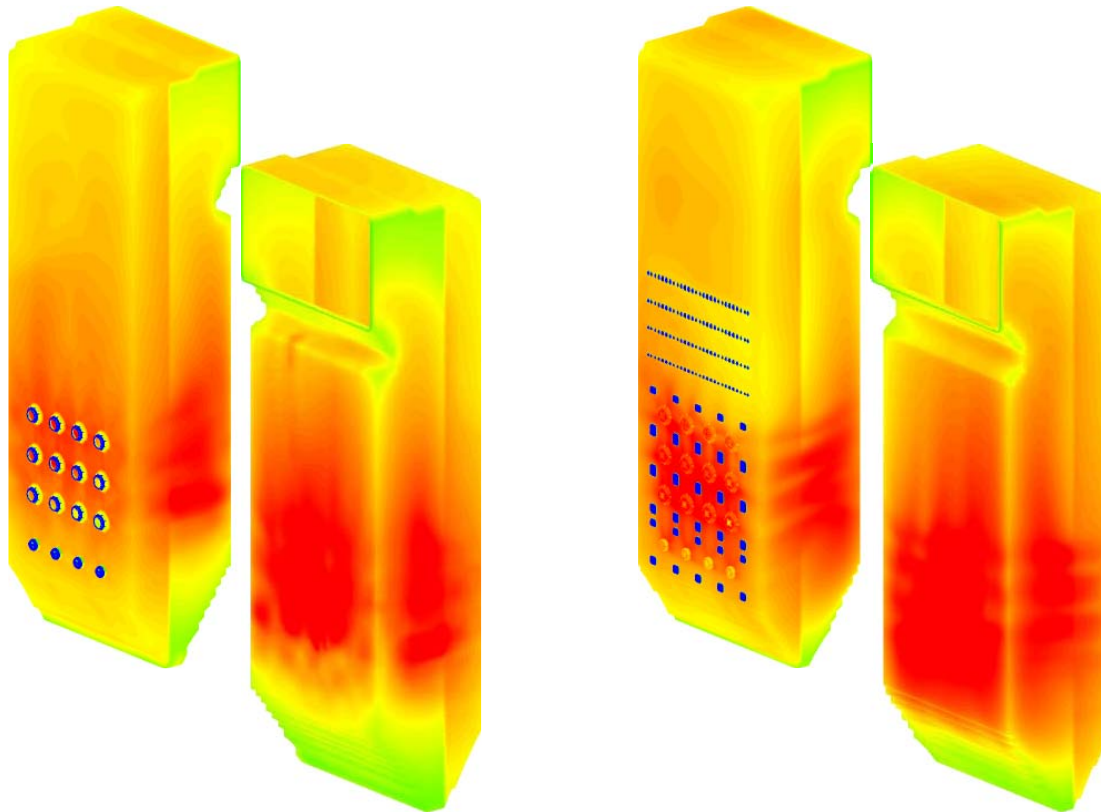


# Wall Temperature

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Air-Fired Coal

NG-Oxy w/ FGR



Wall Temperature (°F)

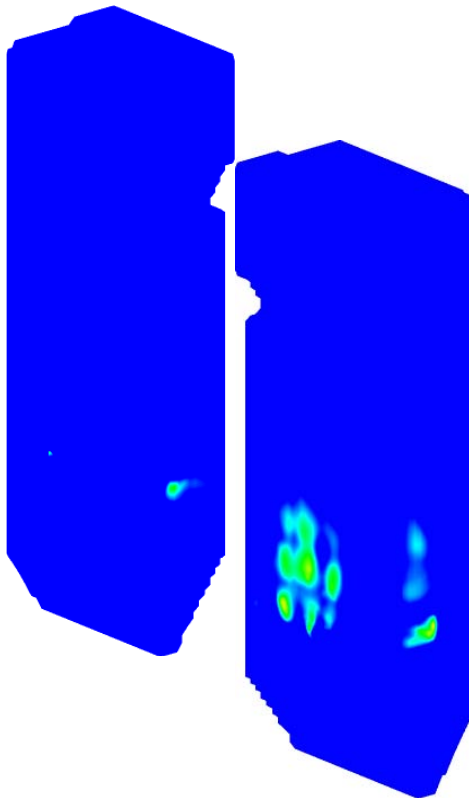


Wall temperatures mimic wall heat flux; cases have similar fluxes

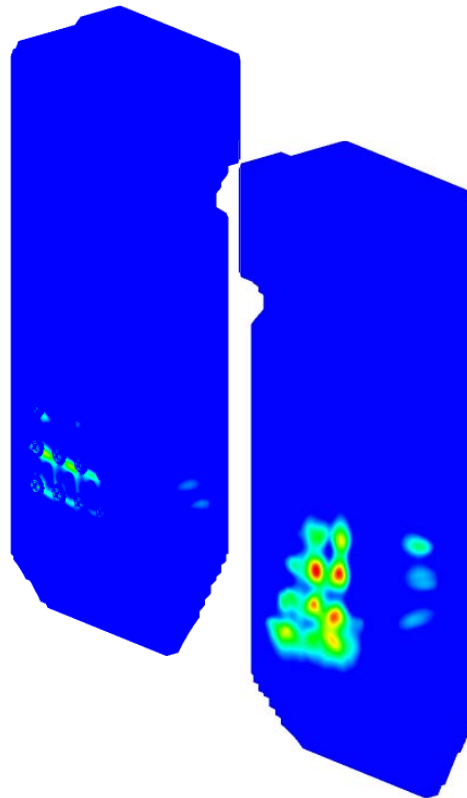


# Peak Wall Temperature

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)



# CFD Model Results

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Result	Baseline Coal-Air	NG-Oxy w/ FGR
Furnace Exit Gas Temperature (°F)	1850	1925
Exit CO Concentration, wet (ppm)	138	2044
Exit O <sub>2</sub> 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

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- **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<sub>2</sub> 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 should be used to manage furnace CO concentration**
  - **Reduced flue gas flow slightly decreased heat transfer in backpass SH and significantly decreased heat transfer in economizer**



# Conclusions

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- Continued increase in gas-fired power generation
- Natural gas retrofit provides reduced emissions and fuel costs, but at reduced boiler efficiency
  - Retrofit or co-firing retains coal option
- Oxy-NG retrofit retains NG benefits while providing air-coal like heat transfer (better efficiency)
  - What is availability of gas and oxygen supply?
  - Do heat transfer benefits outweigh oxygen costs?
  - What are additional impacts on plant equipment and operation?
  - Technical feasibility may not translate to economic feasibility
  - Provides path to CO<sub>2</sub> capture
- Modeling can expand range of retrofit solutions and increase confidence in retrofit performance and impacts



# Acknowledgements

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- ❑ Oxygen-natural gas modeling results used with permission of Jupiter Oxygen Corp
- ❑ CFD graphics created with Fieldview by Intelligent Light ([www.ilight.com](http://www.ilight.com))
- ❑ Questions: Brad Adams [adams@reaction-eng.com](mailto:adams@reaction-eng.com)

