REINHOLD ENVIRONMENTAL Ltd.

2019 REINHOLD Round Table Presentation

June 24 & 25, 2019, in Birmingham, Alabama / Hosted by Southern Company

Combustion-related Issues Faced in the Retrofit of a Pulverized Coal Fired Boiler Utilizing Oxy-coal Technology

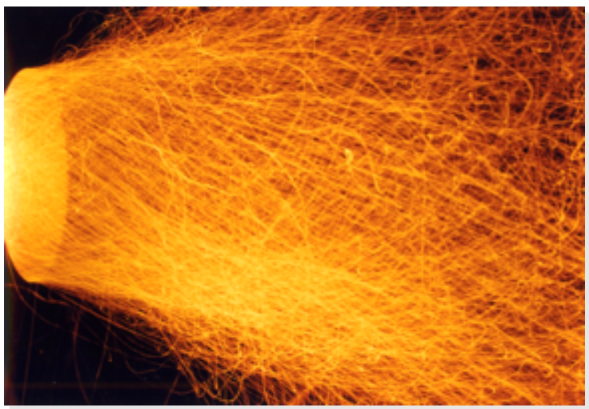
For Energy and Environmental Solutions

REACTION ENGINEERING INTERNATIONAL

Reinhold Round Table
June 24-25, 2019

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 founding in 1990
- Affiliates in Asia and Europe
- Established capabilities include advanced modeling, process evaluation and testing

CCUS

- Carbon Capture, Utilization, and Storage (CCUS) refers to methods and technologies for capture of CO_2 from flue gas while utilizing it in a manner resulting in safe and permanent storage
- Two large demonstrations have been undertaken at coal power plants in North America during the last decade:
  - SaskPower's Boundary Dam Power Station
  - NRG's Parish Generating Station

Petra Nova

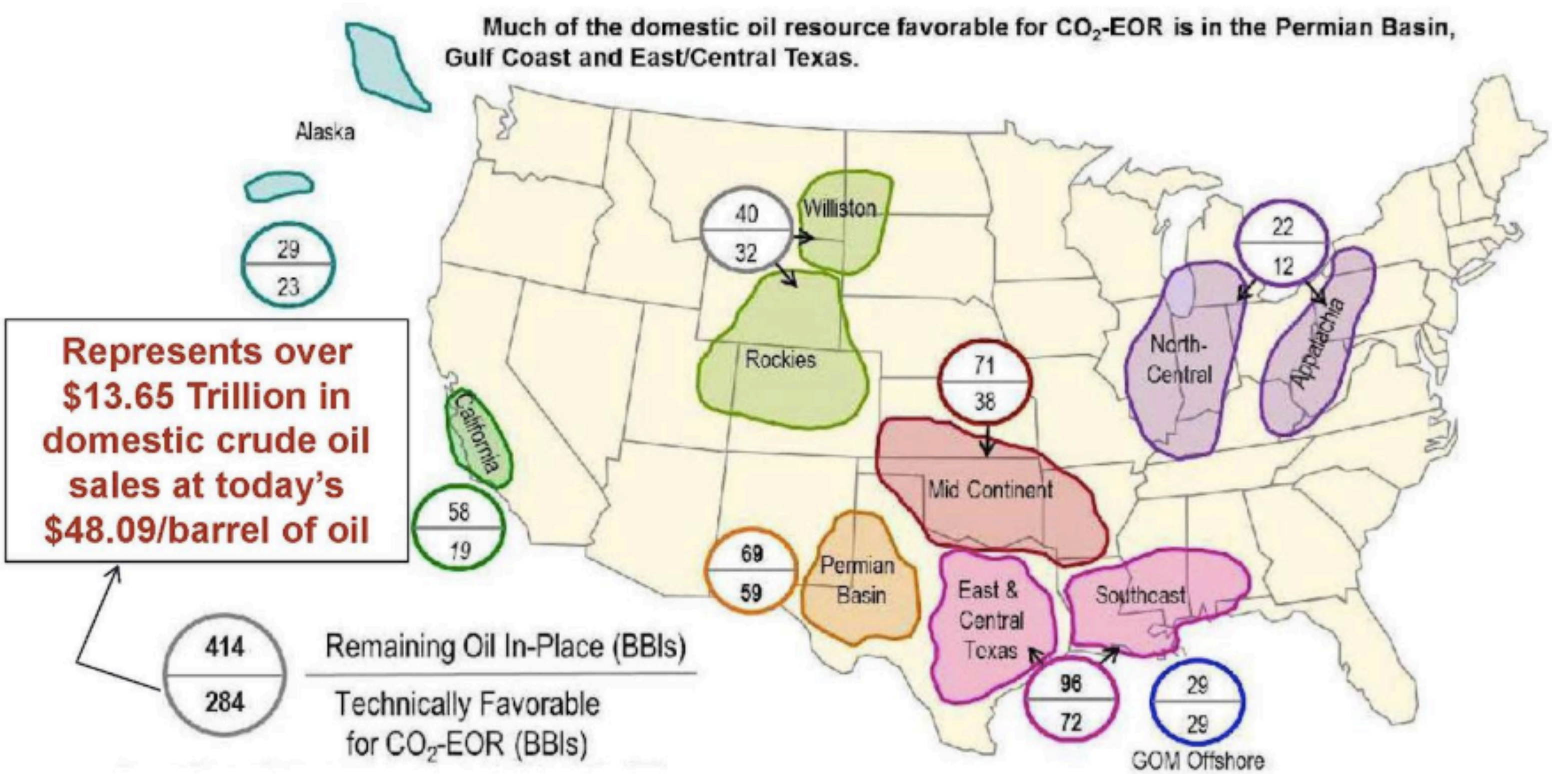
- Partnership including NRG and JX Nippon Oil&Gas
- Commercial operation commenced December 29, 2016 on budget and on schedule
- 240 MW equivalent slipstream from Parish Unit 8
- CO_2 used to enhance oil recovery in West Ranch oil field
- Project cost ~$1 billion; Substantial contributions from DOE and Japanese government; tax incentives from state of Texas; IRS Section 45Q tax credits

IRS Section 45Q Tax Credit

- Originally enacted under Energy Improvement and Extension Act of 2008
  - Program is capped at 75 million tons
  - $10/ton for qualified EOR project, $20/ton for geological storage
  - Rates are adjusted for inflation in subsequent years.
- Reformed February 2018
  - Cap removed
  - Party performing CO_2 capture no longer required to also handle sequestration
  - Credit claiming period is 12 years
  - $/ton increased (adjusted for inflation >2026)

	2017	2018	2019	2020	2021	2022	2023	2024	2025	**2026**
Tertiary injectant/other use	$12.83	$15.29	$17.76	$20.22	$22.68	$25.15	$27.61	$30.07	$32.54	**$35.00**
Sequestration only	$22.66	$25.70	$28.74	$31.77	$34.81	$37.85	$40.89	$43.92	$46.96	**$50.00**

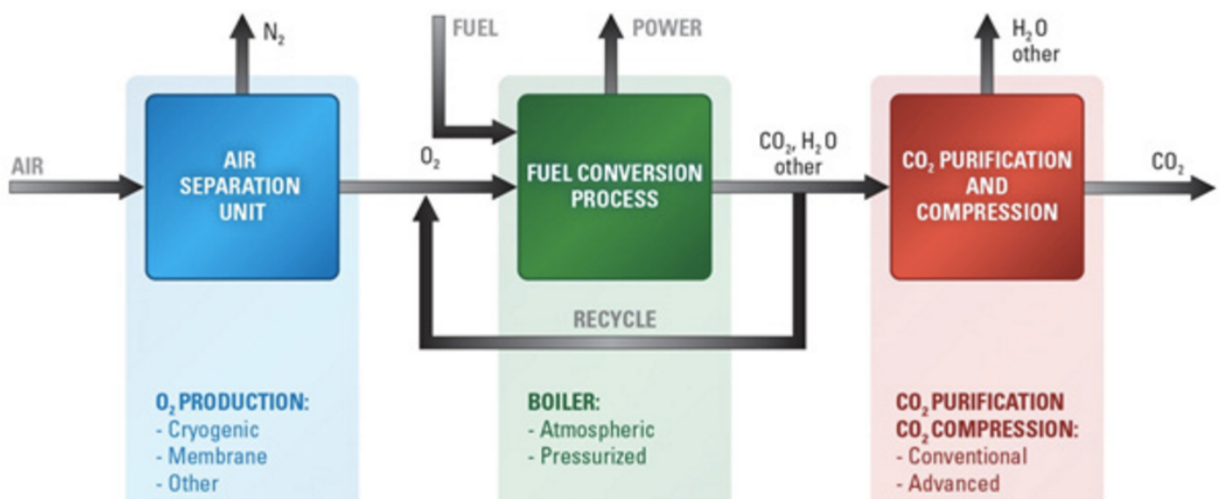
Regional CO_2-EOR Potential



Source: National Coal Council Report (*CO2 Building Blocks: Assessing CO2 Utilization Options*), Price of Oil: *Bloomberg Energy*

Motivation for Oxy-coal Combustion

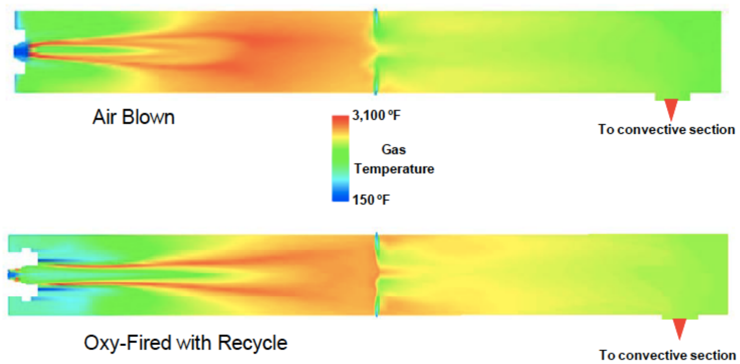
- Utilization of conventional coal conversion technologies in combination with existing CCUS technologies is economically challenging
- Advanced coal conversion systems involving high temperatures and/or pressures can be effectively integrated with state-of-the-art CCUS to support utilization of a valuable, secure resource by reducing emissions, increasing efficiency, reducing capital and operating costs

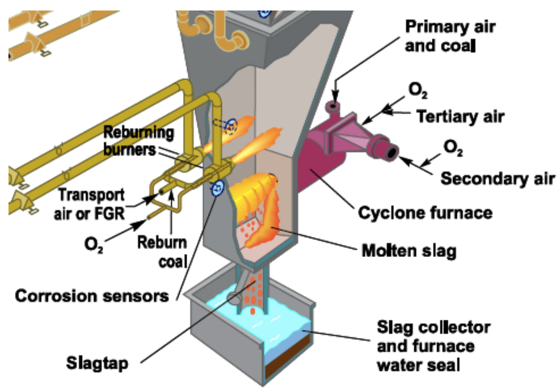


http://www.netl.doe.gov/research/coal/energy-systems/advanced-combustion/oxy-combustion

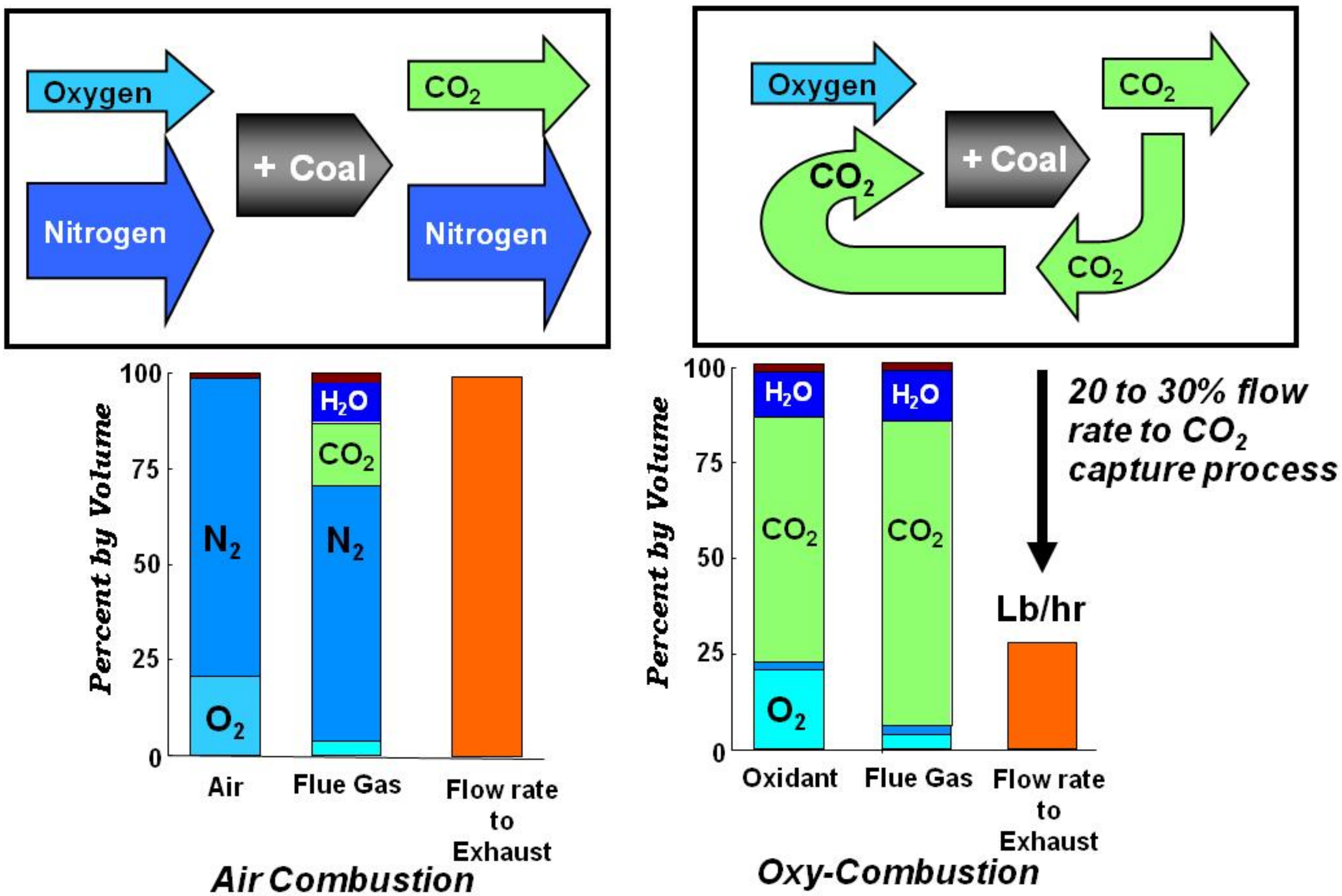
Selected Past REI Activity in Oxy-coal Applications

- Enhanced and targeted oxygen injection for NOx control in utility and industrial boilers and cement kilns (with Praxair)
- Optimization of oxygen-fired IGCC
- Development and validation of pyrolysis and oxidation models for oxygen firing with FGR
- Real-time corrosion monitoring in oxy-coal fired pilot-scale testing
- Oxy-combustion impacts during retrofit (with Univ of Utah and Praxair)
- CO_2 for EOR/ECBM (with Plasma/JOC)
- Optimization of oxy-coal burner design for a package boiler (with JOC)
- High flame temperature modular boiler concept development (with JOC)



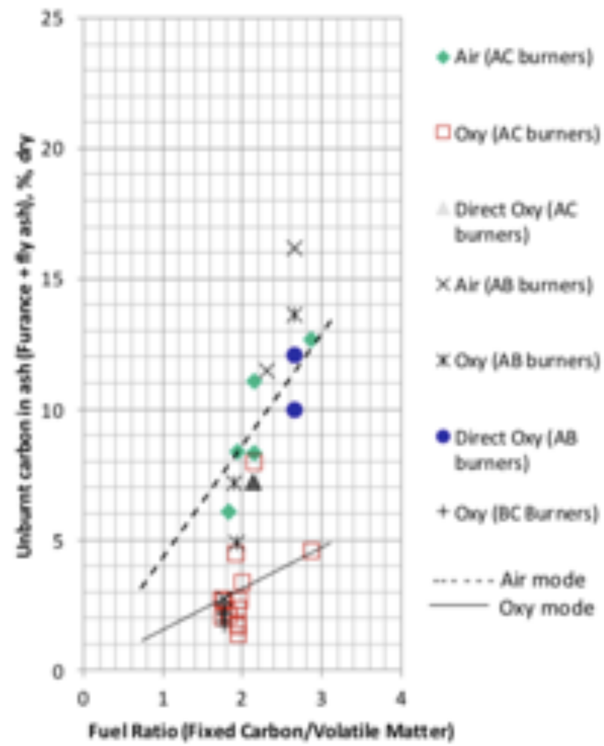


Overview of Oxy-combustion Technology [Denny Macdonald, *B&W 12/16/2010*]



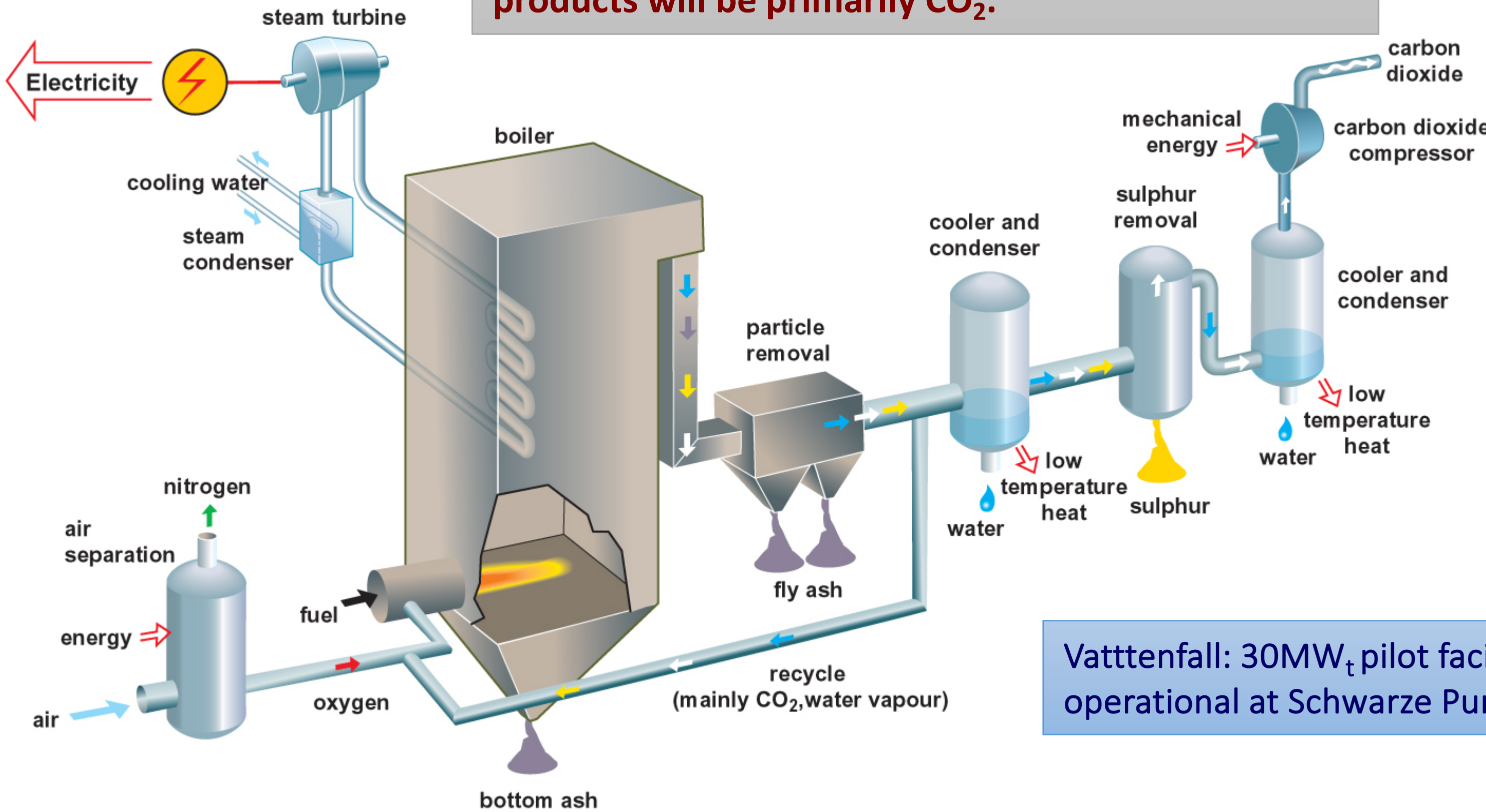
Oxy-coal Demonstrations

- Vattenfall
  - Schwarze Pumpe Large Scale Pilot Plant
  - Janschwalde Oxy fuel combustion (250 MW) and post-combustion (50MW) FEED
- Callide
  - Largest oxyfuel demonstration in the world when it completed its demonstrati phase in March 2015



Schwarze Pumpe Pilot Testing

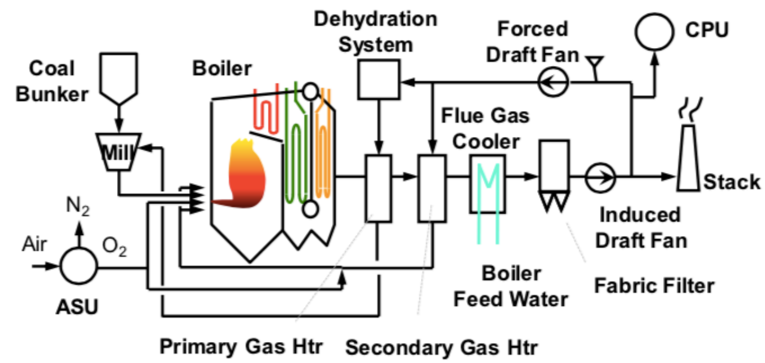
Oxygen diluted with Recycled Flue Gas mimics combustion air (Stromberg, 2004). Dry combustion products will be primarily CO_2.

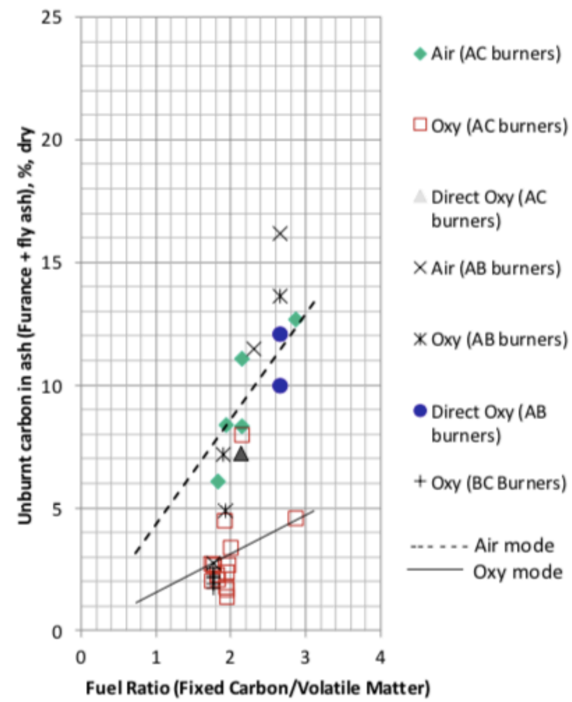


Vatttenfall: 30MW$_t$ pilot facility operational at Schwarze Pumpe.

Callide Demo

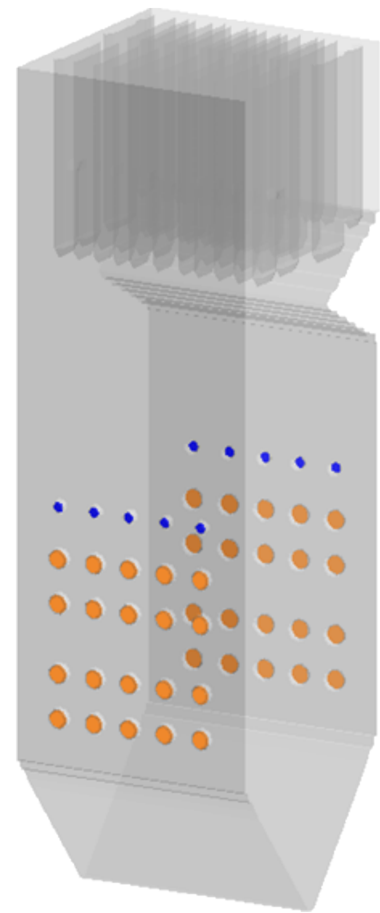
- >10,000 hrs of operation
- 4 coals
- Unit reliability of 90% achieved during final year
- Significant improvement in combustion efficiency, measured as a reduction in carbon-in-ash (typically 50% reduction);
- Significant reduction in NOx mass emission rate (mg NOx/MJ fuel) – ~60%
- Slight reduction in particulate specific emission rates (mg/kWh).





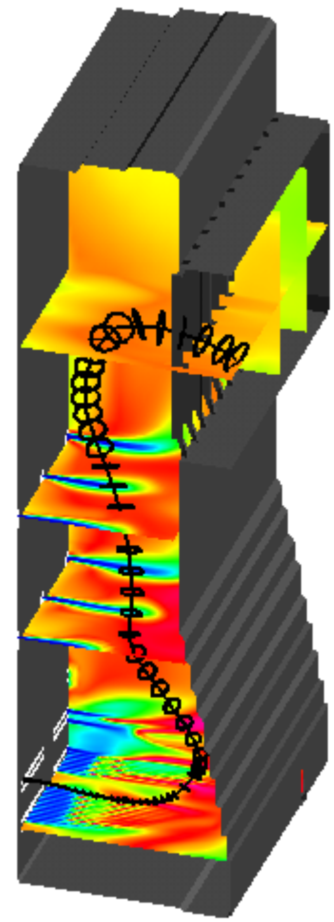
Hunter 3 Oxy-combustion

- Evaluate impact of flue gas recycle (FGR) rate on heat transfer in 490 MWe Hunter 3 coal-fired boiler under oxy-firing conditions
- Adjust FGR to match air-fired heat transfer in radiant and convective sections
  - Evaluate 21%, 25%, 27% and 32% O_2 (wet)
- Baseline SGE model:
  - Include all radiant and convective HT surfaces
  - Flue gas-steam heat transfer behavior tuned to match air-fired data



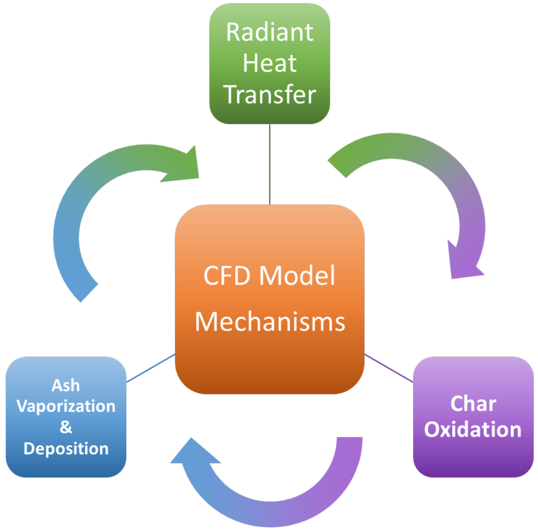
REI's Modeling Experience

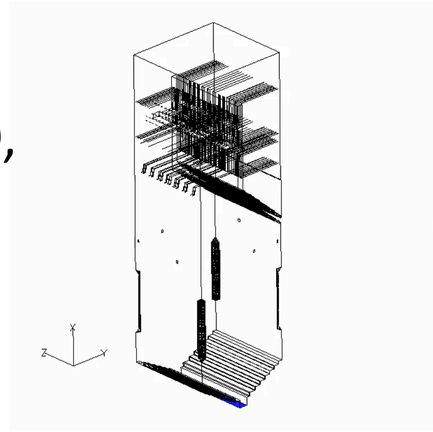
- Over 250 boilers, burners, process furnaces, kilns, and incinerators in several countries burning a range of fuels including coal, oil, gas, wood, straw, petcoke, tires, hazardous waste
- Complementary relationships with OEMs, owners and service/equipment providers to develop solutions in areas including: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

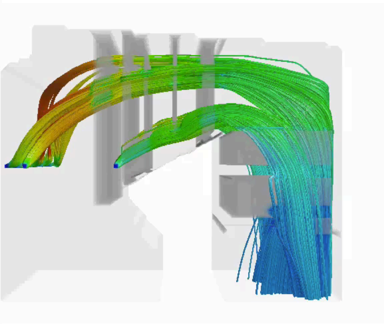


CFD Tools: GLACIER

- REI's in-house CFD software
- Developed specifically for application to solid fuel fired furnaces and boilers
- 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
- Continually evolving including recent developments for atmospheric pressure and pressurized oxy-coal applications



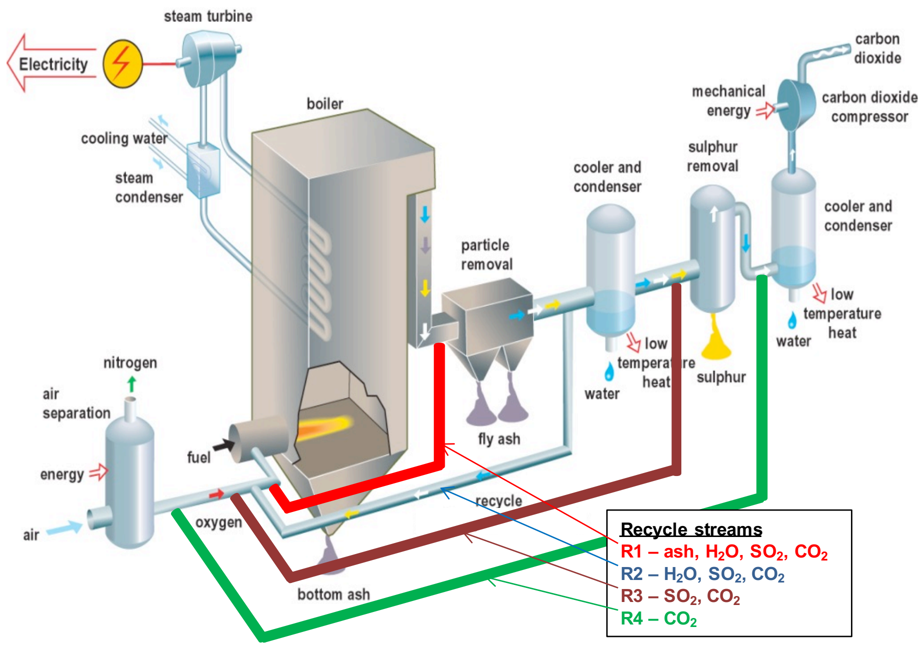




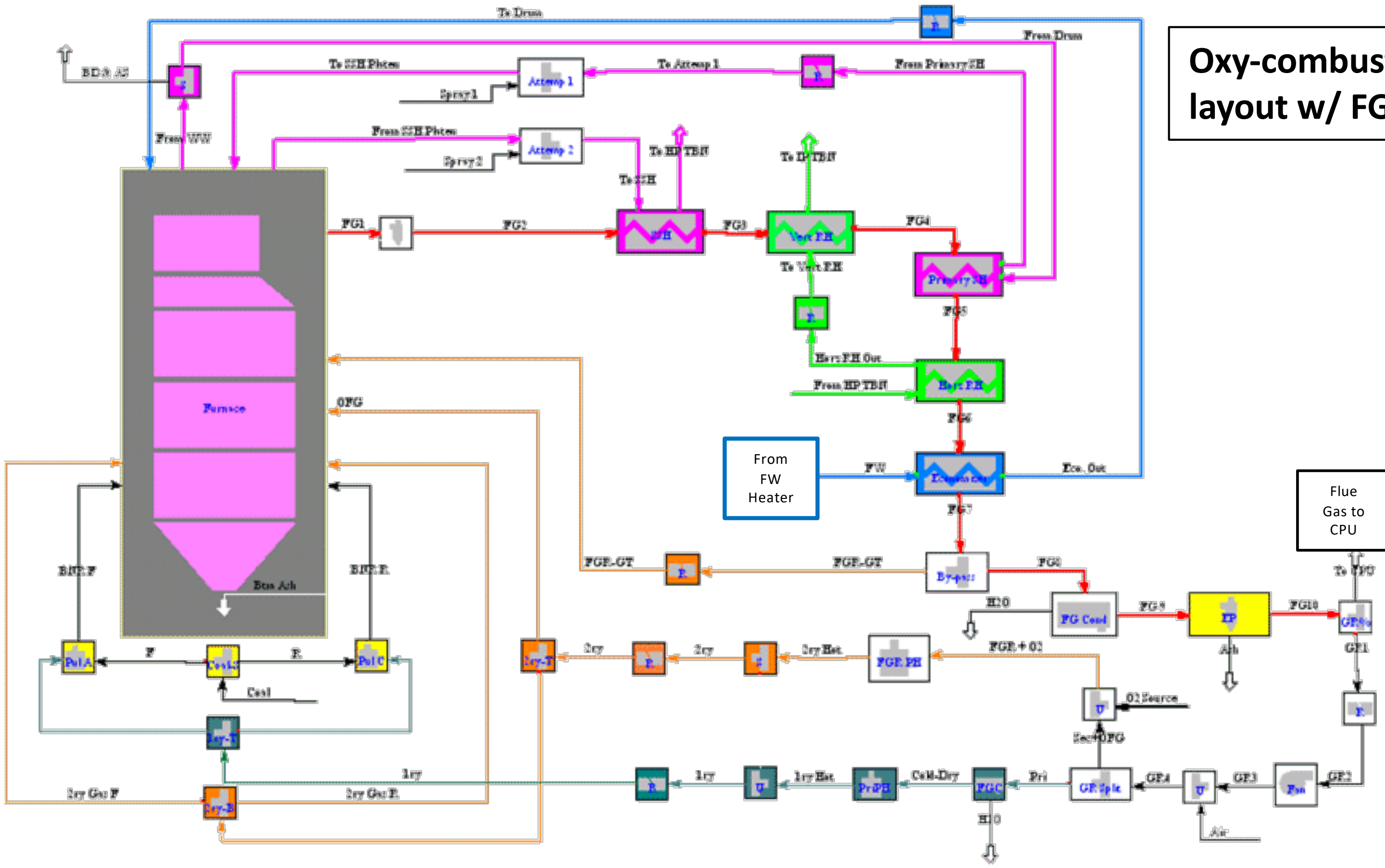
Oxy-combustion FGR Optimization

- In oxy-combustion, FGR rate determines O_2 concentration in FGR/O_2 mixture (at fixed 3% exit O_2)

  Increased O2 increases AFT, which increases radiant heat transfer; reduces flue gas volume which reduces convective heat transfer



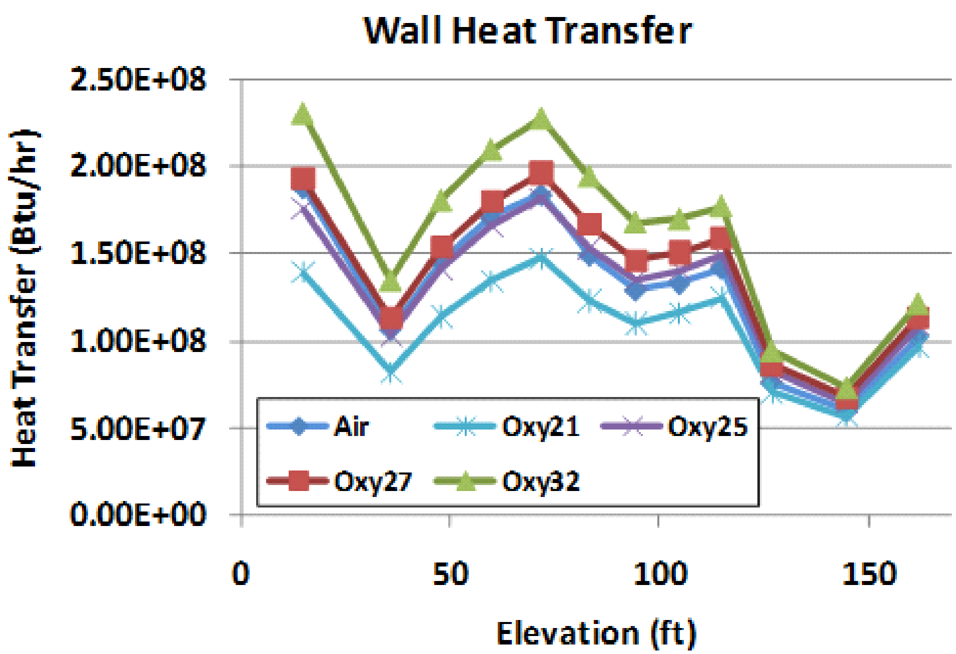
Integrated CFD and steam-side process modeling for Oxy-coal Retrofit



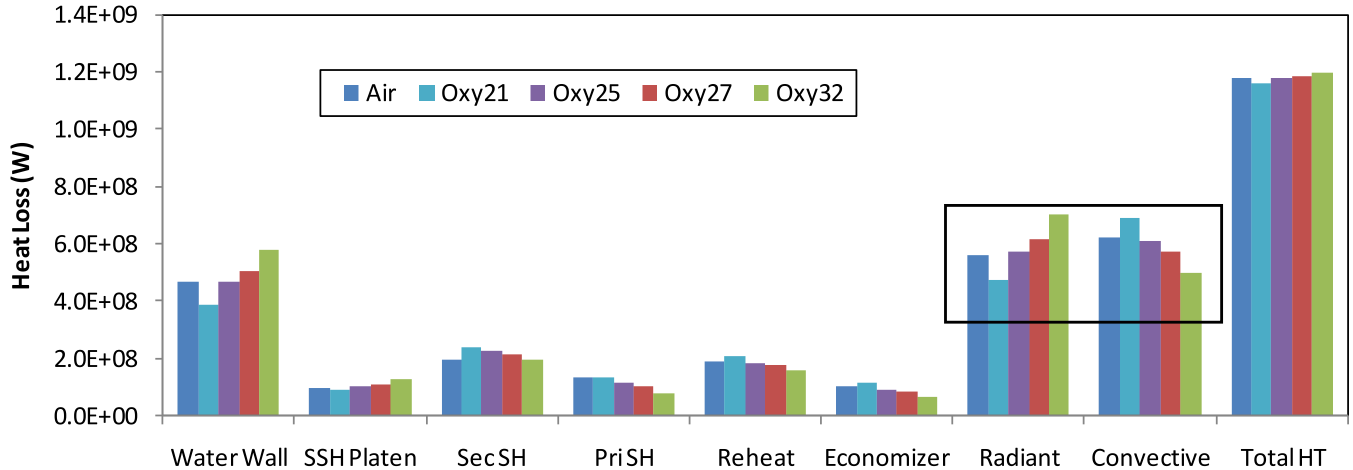
Oxy-combustion layout w/ FGR

Furnace Wall HT Results

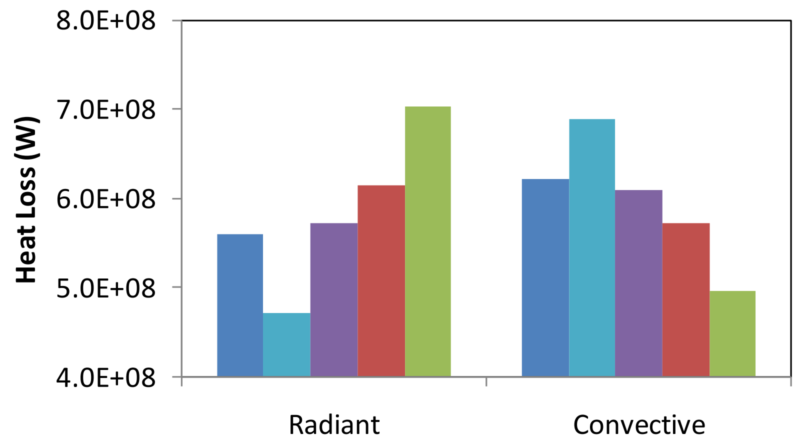
- Oxy25 is best match to air-fired furnace wall heat transfer



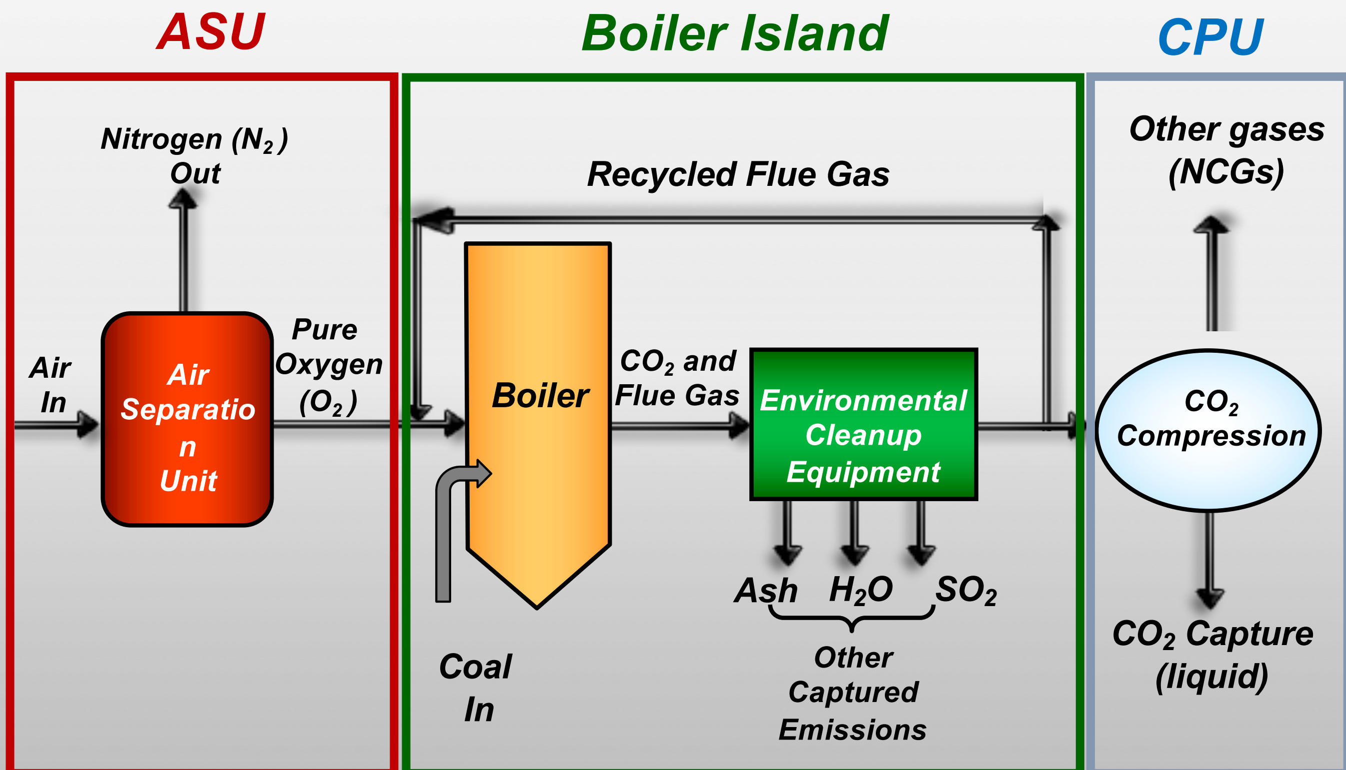
System Heat Transfer Results



- Radiant heat transfer increases with increasing O_2 concentration
- Convective heat transfer decreases with increasing O_2 concentration
- Best match at 25% O_2 in the O_2/FGR mixture



FutureGen 2.0 Oxy-Coal Plant Configuration



Oxy-Coal Air Emissions

	Air-Fired Plant	IGCC Plant (2) w/CCS	Oxy-Fuel Plant w/CCS	Air-Fired Plant	Oxy-Fuel Plant w/CCS
Fuel Type	Bituminous	Bituminous	Bituminous	Sub-bit	Sub-bit
Steam Conditions (PSI/F/F)	3600/1100/1100		3600/1100/1100	3600/1100/1100	3600/1100/1100
Plant Performance					
Gross MW	598	745	733	604	733
Net MW	550	556	550	550	550
Net Plant Heat Rate (Btu/kWh)	8662	10505	10143	9250	10831
Capacity Factor (%)	85%	80%	85%	85%	85%
Conventional Emissions (Expected)					
NOx (lb/MBtu)	0.06	0.0470	Note 1	0.06	Note 1
SOx (lb/MBtu)	0.04	0.010	Note 1	0.08	Note 1
Particulate (lb/MBtu)	0.015	0.007	Note 1	0.012	Note 1
Hg (lb/TBtu) (3)	0.784	0.571	Note 1	0.820	Note 1
CO2 Emissions (Expected)					
CO2 Removal Efficiency (%)	0	90.0%	92.5%	0	92.5%
CO2 Produced (Million Metric Tons/Year)	3.26	3.64	3.82	3.68	4.31
CO2 Captured (Million Metric Tons/Year)	0	3.28	3.53	0	3.99
CO2 Emitted (Million Metric Tons/Year)	3.26	0.36	0.29	3.68	0.32

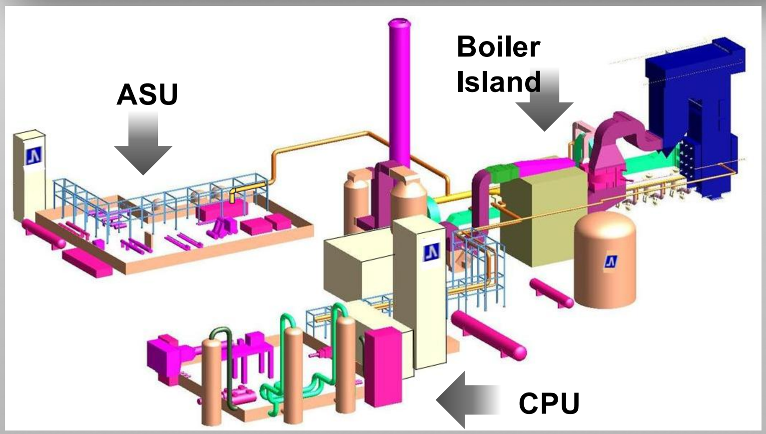
1) Oxy emissions are below practical measurement limits
2) IGCC from GE IGCC system w/CO2 Capture per DOE/NETL-2007/1281 Report, Case 2
3) Air-fired emissions based on 90% removal expected

Benefits of Oxy-Coal Combustion

- **Oxy-combustion is potentially the <u>highest efficiency and lowest cost</u> CO_2 capture technology for coal fired plants***
- **<u>Near Zero Emissions</u> of criteria air pollutants (NZEP)**
- **><u>90% CO_2 capture</u> at pipeline quality and purity specifications**
- **<u>Low technology risk</u> – plant components are primarily conventional equipment modified for operation in the oxy-mode. An oxy-plant will look and operate like a conventional power plant.**
- **<u>Can be retrofit</u> as easily as post combustion capture**
  - **Same existing plant equipment and space requirements**
  - **No LP steam requirement (output can be increased by heat integration)**
  - **No new chemicals or solvents**
- **<u>Unique operating options</u> can maximize output during the day**

* DOE/NETL 2007-1291 Rev. 2, August 2008, "Pulverized Coal Oxy-combustion Power plants"
DOE/NETL 2007-1281 Rev.1, August 2007 "Cost and Performance Baseline for Fossil Energy Plants"

FutureGen 2.0 – Oxy-Combustion Project



Project Structure

- Capture – Ameren Energy Resources (AER), teamed with B&W and Air Liquide
- Transport & Storage – FutureGen Alliance

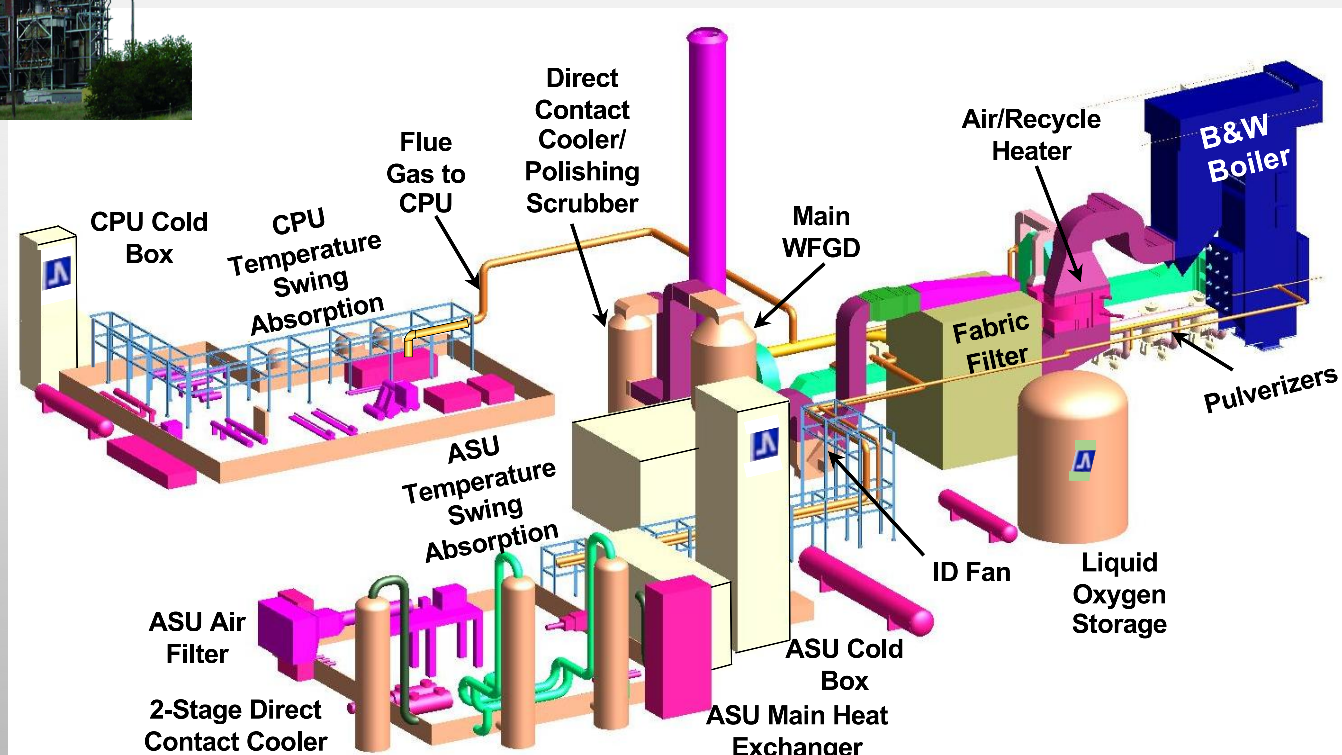
Meredosia Plant

- Meredosia, IL: Owned/operated by AER
- 3-coal fired units (2 retired)
- 1-oil-fired unit
- 200 MWe oil-fired Unit 4 built in 1975
- Repower Unit 4 steam-turbine
    - Purpose-built Oxy-PC boiler
- Illinois Coal, PRB or PRB blends

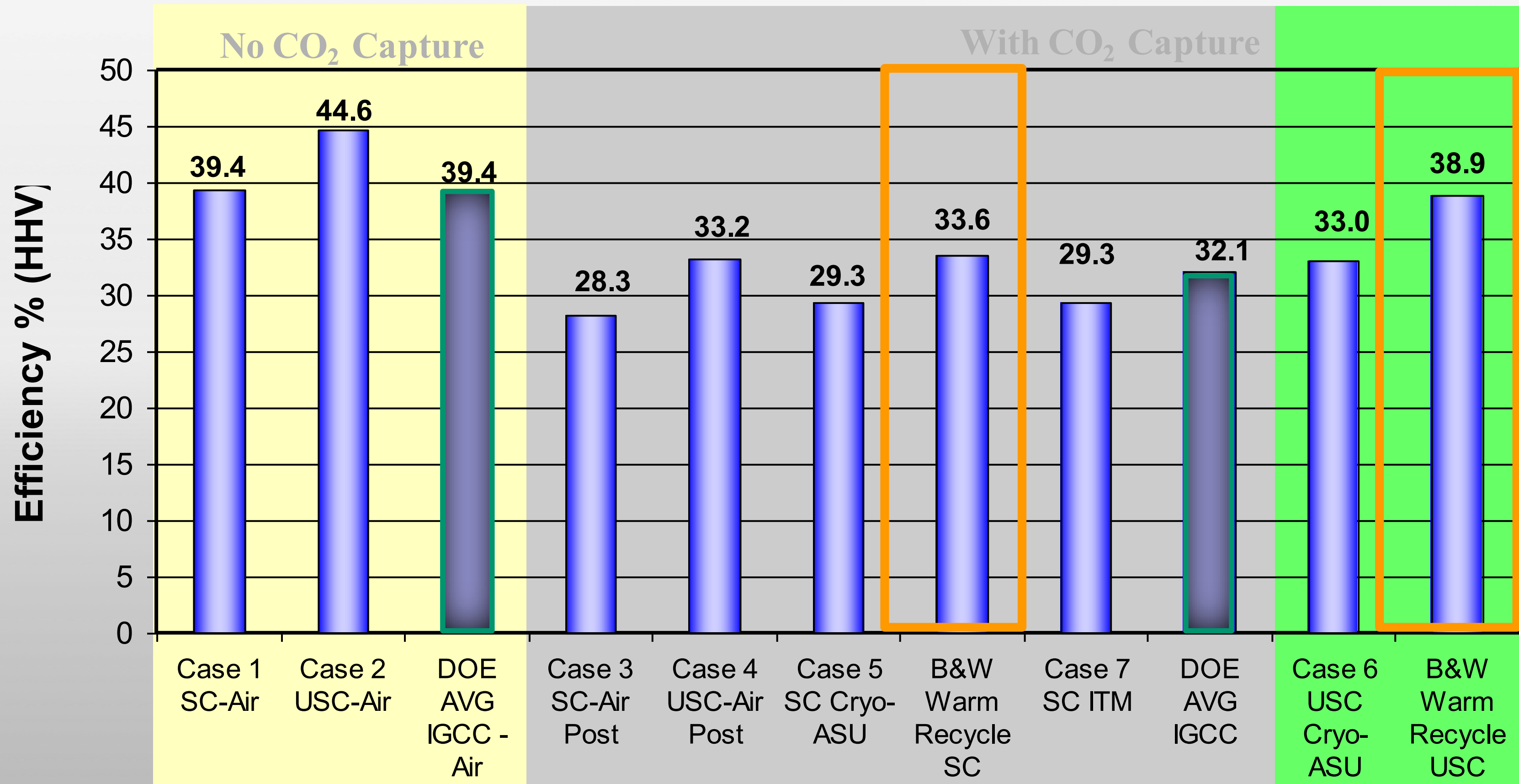
Project Timeline

- Expect project award by Sept. 30, 2010
- Phased approach to develop project
- Commission by end of 2015

Meredosia Clean Coal Facility

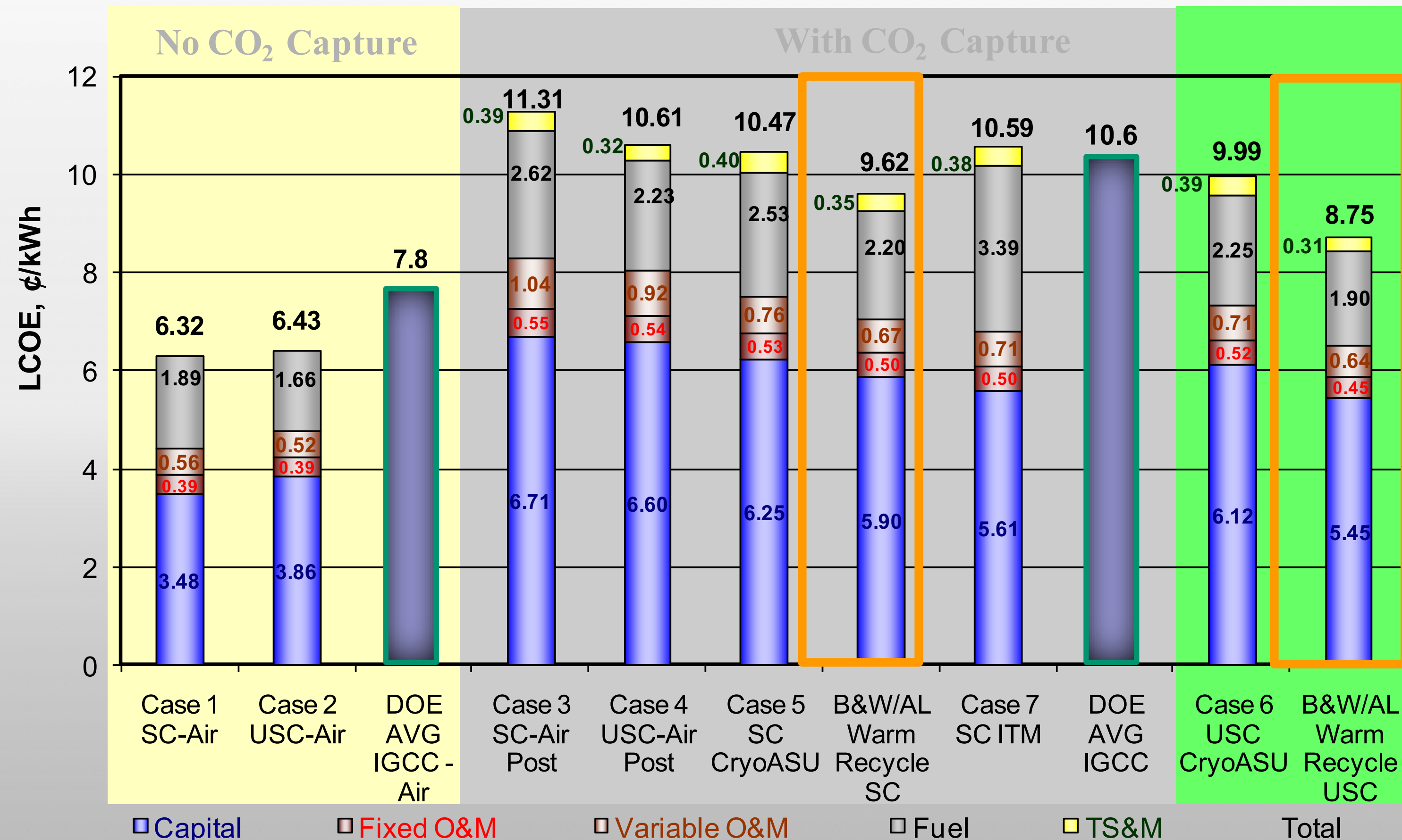


Comparison of Net Plant Efficiency for Carbon Capture Technologies



Per DOE/NETL 2007 - 1291 Rev. 2 Oxy Coal Study and B&W/AL Integration Study

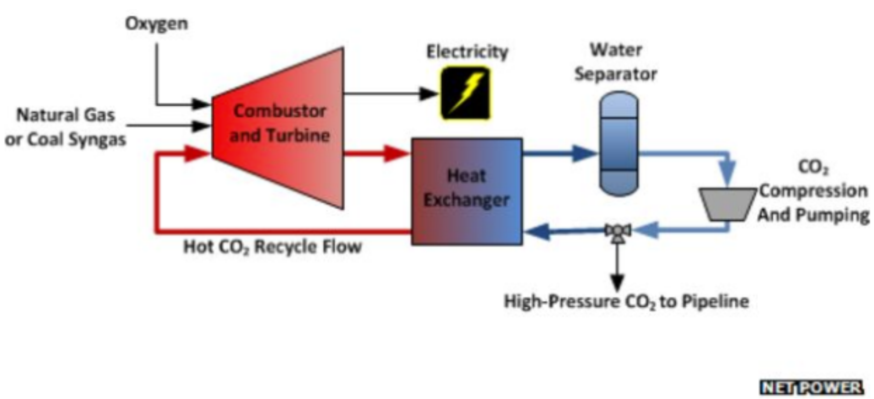
Comparison of Levelized COE for Carbon Capture Technologies



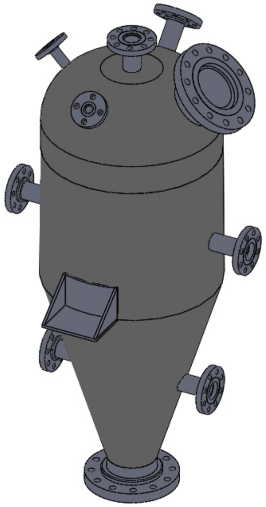
Per DOE/NETL 2007 - 1291 Rev. 2 Oxy Coal Study and B&W/AL Integration Study

REI Current Oxy-coal Efforts

- Impact of High Temperatures and Pressures in Oxy-coal Combustion
- Dry Coal Feeding for High Pressure Oxy-coal Combustion
- Oxy-combustion of Coal Syngas for Allam Cycle
- JOC High Temperature Combustion Retrofit for Power and ECBM
- JOC High Temperature Combustion Retrofit for Power and EOR



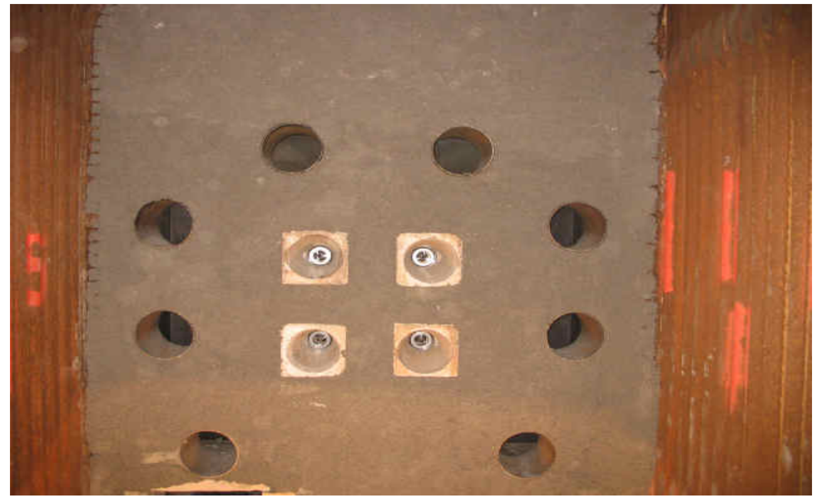
1st Generation Oxy-coal Burner



JUPITER OXYGEN CORPORATION

- Jupiter's testing and development of a patented oxy-fuel process began in the mid-1990's as a way to cut fuel costs and lower emissions in aluminum recycling and manufacturing
- Their patented concept for oxy-coal firing with minimal FGR promises:
  - Highly effective heat transfer
  - Higher boiler efficiencies
  - Substantial reductions in flue gas volume
  - High purity CO2 exhaust stream

Pilot-scale Demonstration



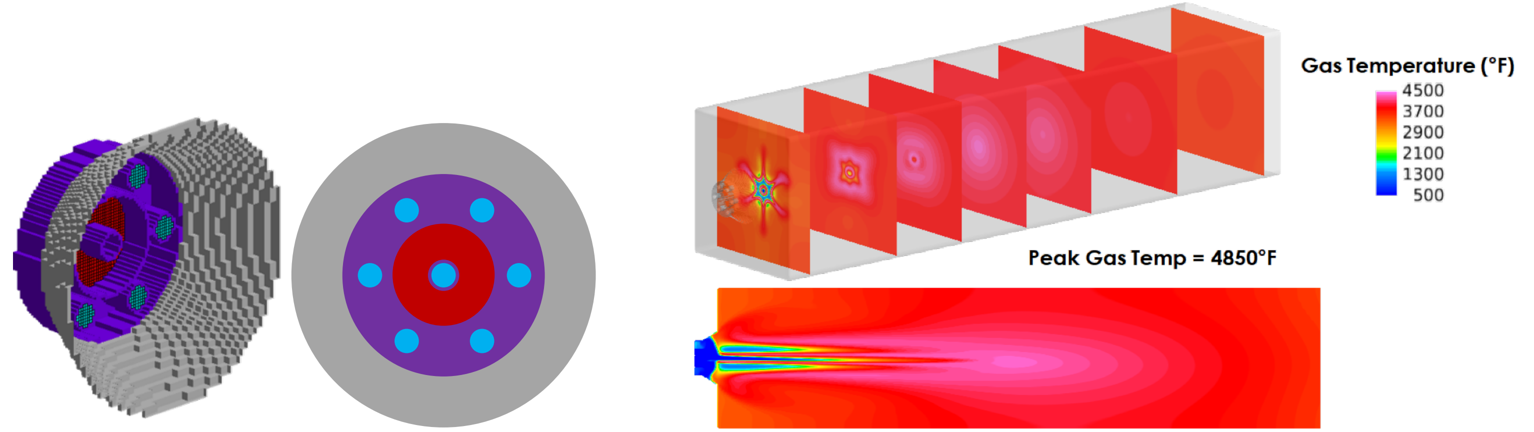
- JOC/DOE Albany Keeler Boiler demonstration
- Patented process results in flame temperatures >4500°F
- Design, construction, and operation of a 5 MWe equivalent boiler and a 20 KWe equivalent integrated pollutant removal facility

220 TPH Pulverized Coal Boiler

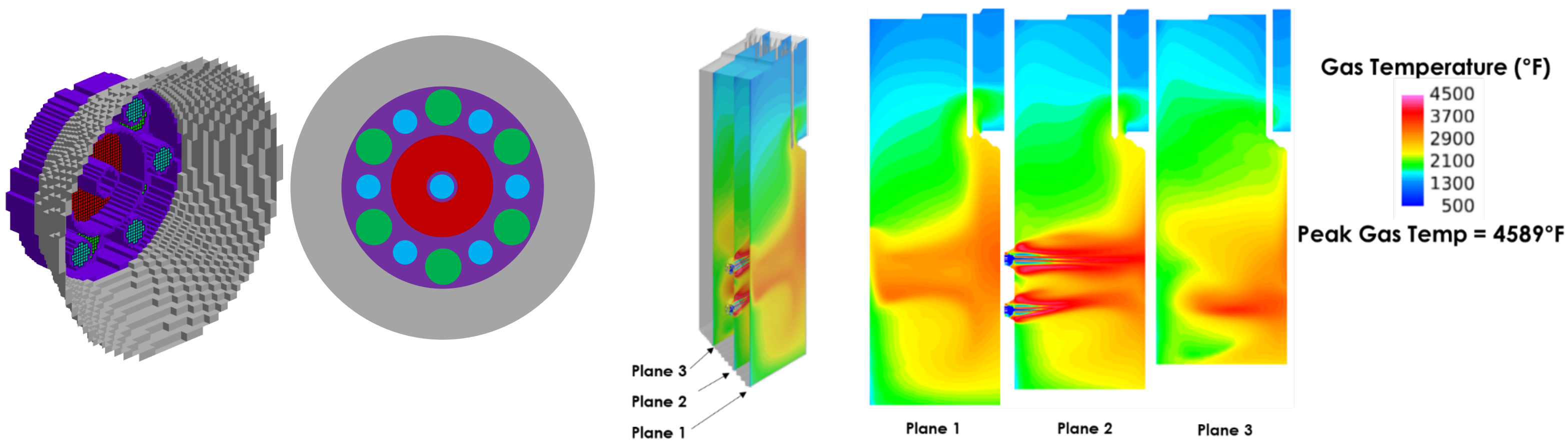
- Objective: Evaluate the feasibility of retrofitting a 220 tph steam pulverized coal-fired boiler with a JOC oxy-coal firing system including minimum flue gas recycle
- Approach
  - CFD modeling and SteamGen Expert process modeling performed to provide guidance in the preparation of a conceptual design
  - A detailed CFD model of the new oxy burner performed to optimize burner performance
  - The oxy burner conceptual design integrated into a full furnace model for evaluation of furnace performance
  - Performance metrics include
    - Peak and average surface heat flux, ash deposition/slagging/sintering, tube and burner part temperature, tube corrosion
    - Heat balance and potential impacts on boiler tuning and load limitations
    - Emissions including NOx, SOx, CO, and flyash carry-over
    - Carbon-in-flyash

Utility Scale Modeling

1) 30 MW



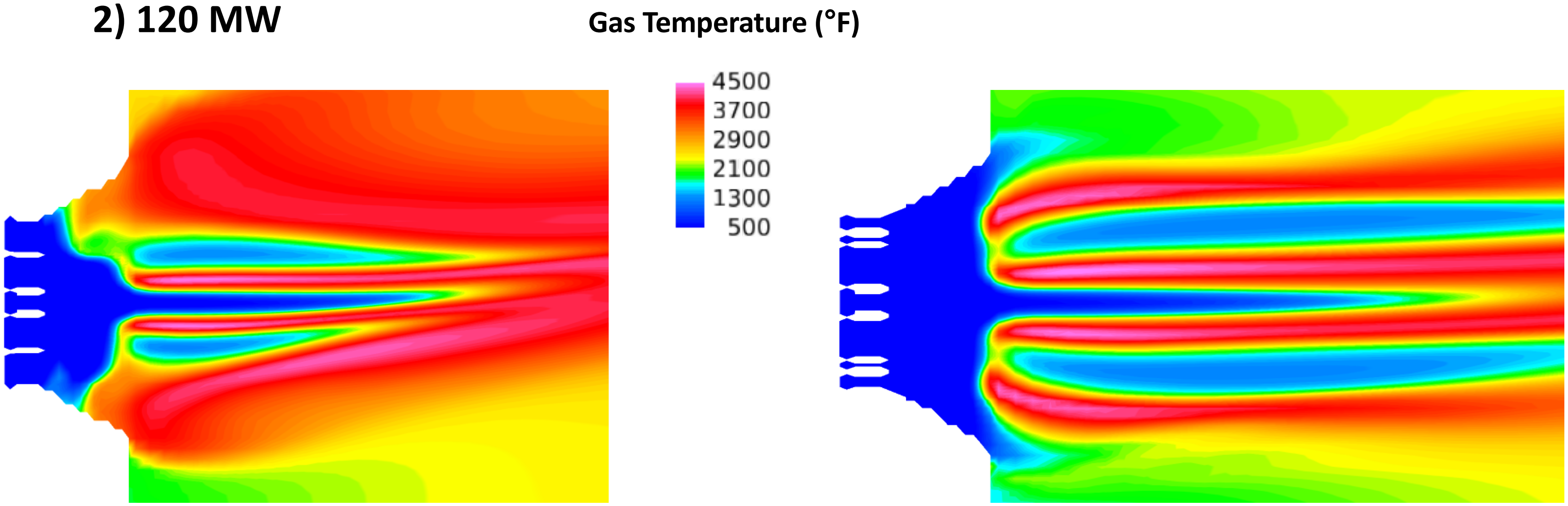
2) 120 MW



Burner Optimization

Moderating High Radiant Flux

2) 120 MW



Discrete Ports Burner
Peak: 4581°F

Optimized Burner
Peak: 4572°F

Summary

- Post-combustion CCUS demonstrations using CO_2 from pulverized coal power plants have established the technical feasibility of existing technology
- Recent enhancements of Section 45Q tax credits improve the economics of future CCUS projects
- Pilot-scale demonstrations and modeling of full-scale oxy-coal retrofits illustrate the feasibility and potential advantages of oxy-coal combustion for CCUS in reducing emissions, increasing efficiency, reducing capital and operating costs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