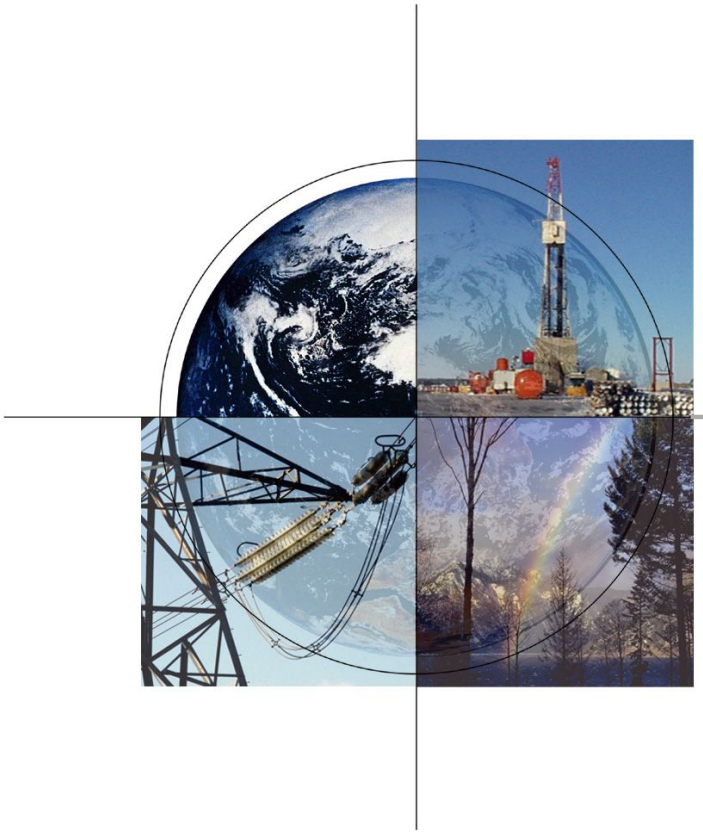
National Energy Technology Laboratory



Oxycombustion Technology Research through the DOE-NETL Carbon Sequestration Program

Alexandria, VA

May 9, 2006

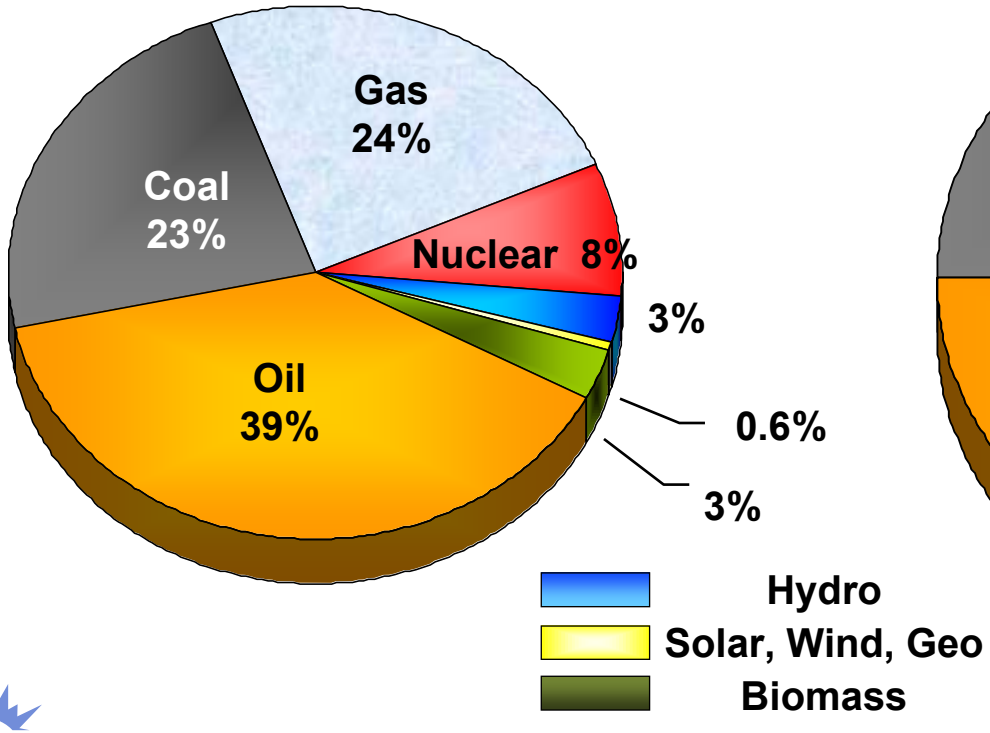
Timothy Fout*, Kanwal Mahajan – NETL Morgantown
Sean Plasynski, José Figueroa – NETL Pittsburgh

Outline for Presentation

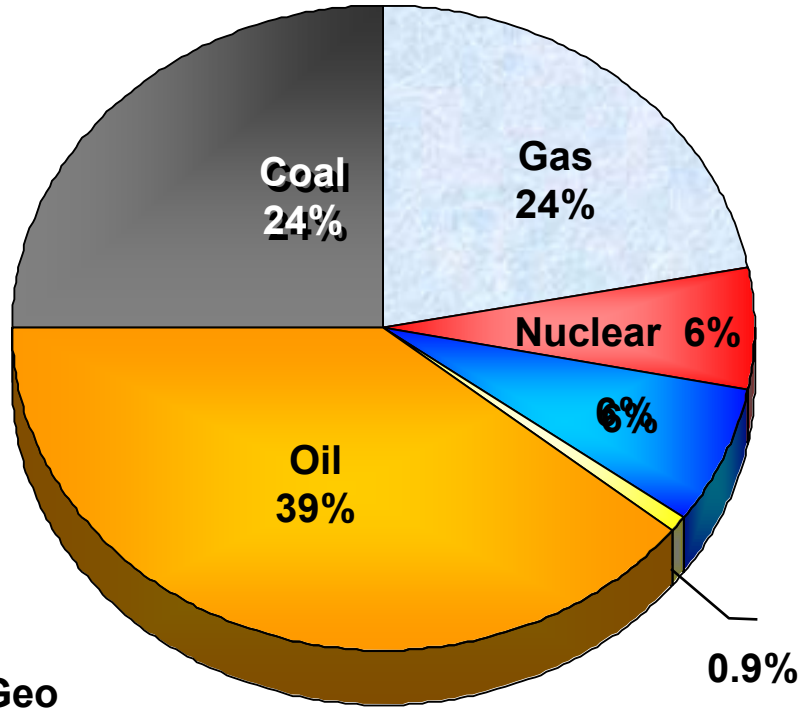
- **Drivers for Program**
- **Carbon Sequestration Program**
  - Overall Program
  - Capture Goals
- **Oxycombustion Overview**
  - Technical Challenges
  - Program Funded Research Efforts

Fossil Fuels
World's Dominant Energy Source

United States
98 QBtu/yr; 86% Fossil Energy



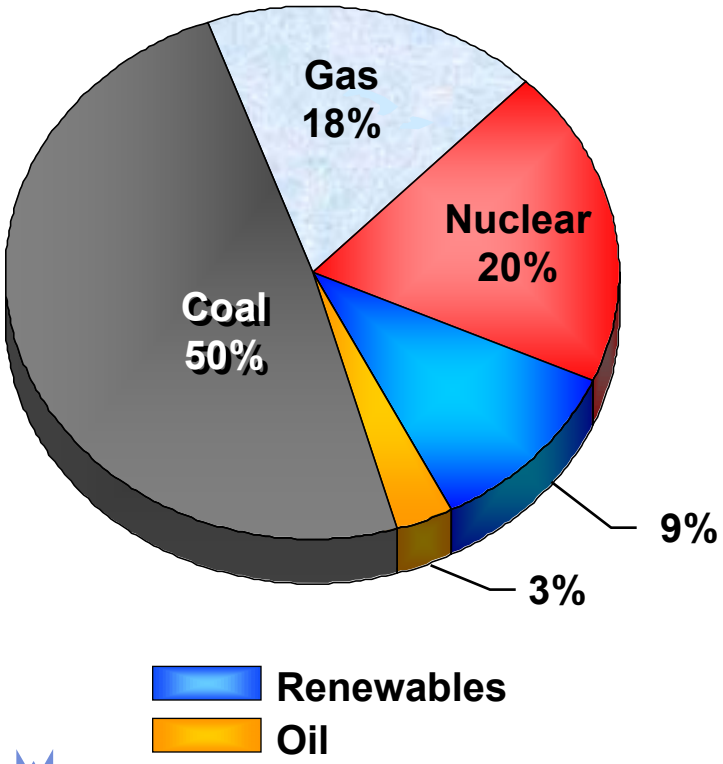
World
419 Quads/yr; 86% Fossil Energy



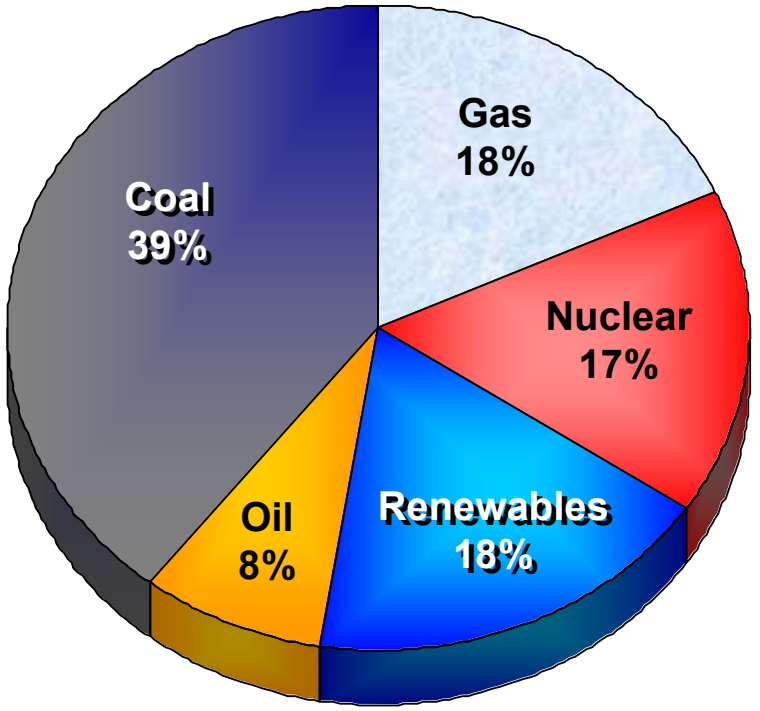
Source: EIA,International Energy Annual 2003
EIA Annual Energy Review 2004

Fossil Fuels
World's Dominant Electricity Source

United States - 2004
3.97 Trillion kWh - 71% Fossil Energy



World - 2002
14.3 Trillion kWh - 65% Fossil Energy

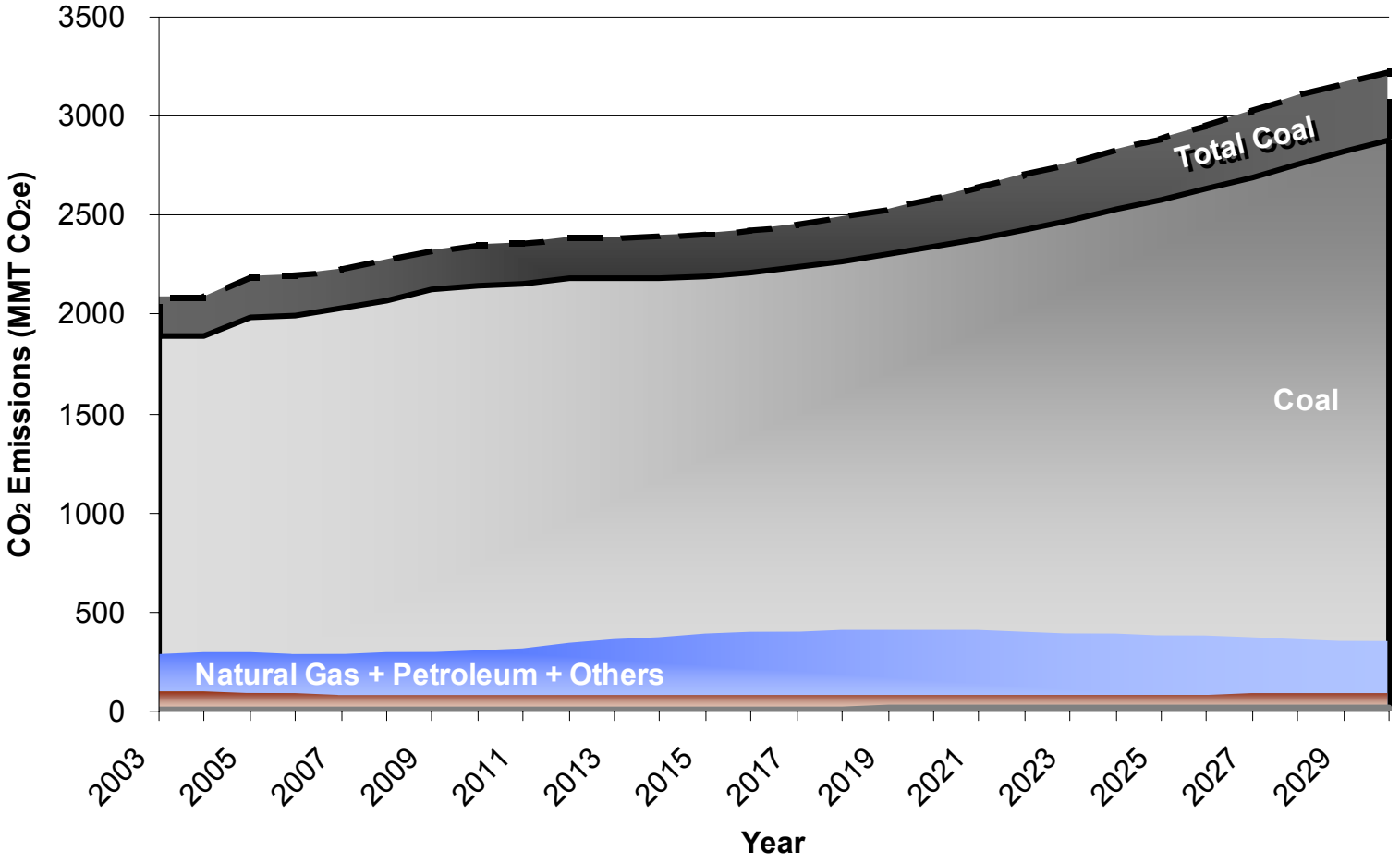


Source: EIA International Energy Outlook 2005

Fossil Fuels

CO_2 Emissions Breakdown

Emissions from Power Generation by Fuel Source



Source: Report #:DOE/EIA-0383(2006)

Technological Carbon Management Options

Reduce Carbon Intensity

- Renewables
- Nuclear
- Fuel Switching

Improve Efficiency

- Demand Side
- Supply Side

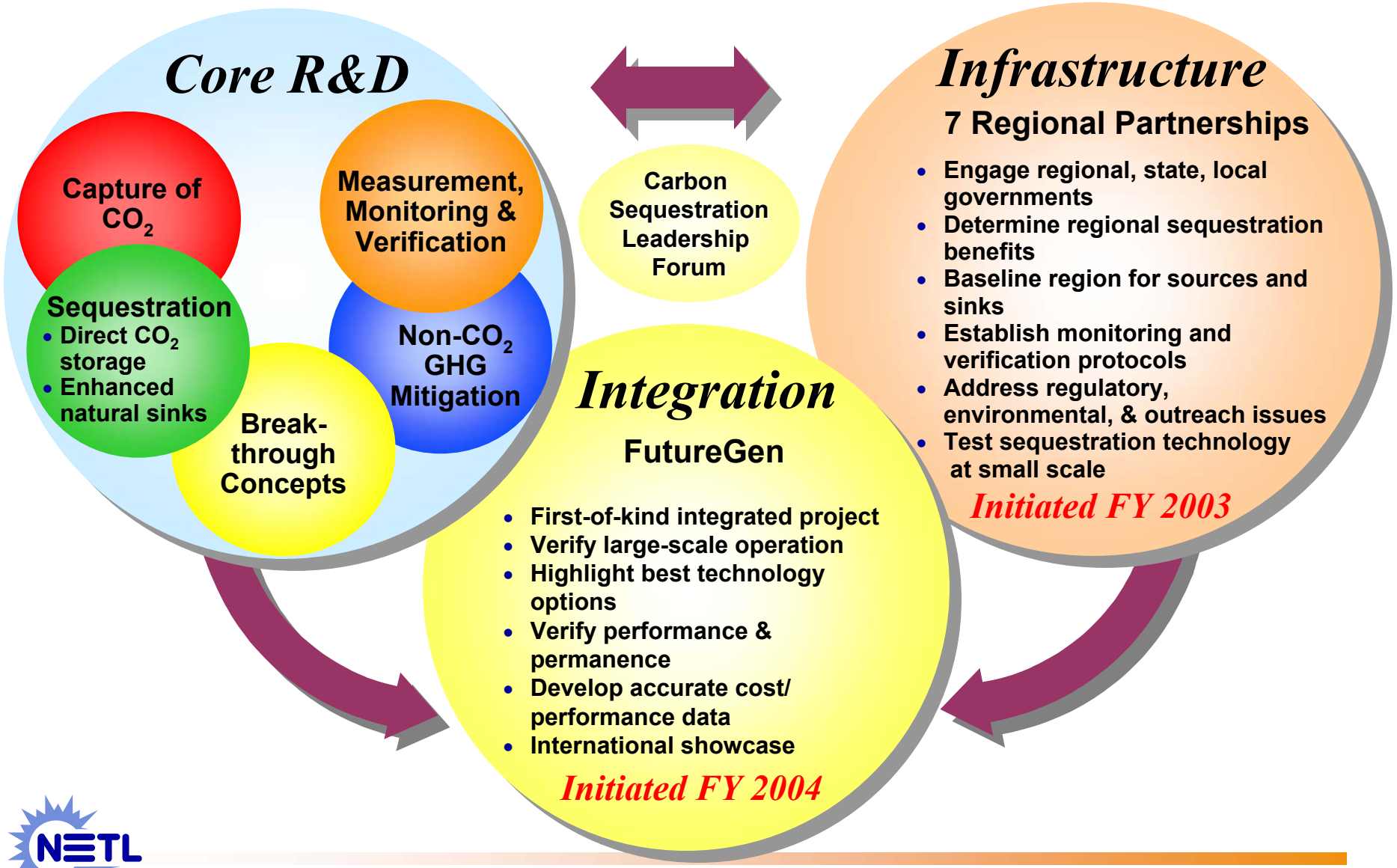
Sequester Carbon

- Capture & Store
- Enhance Natural Sinks

All options needed to:

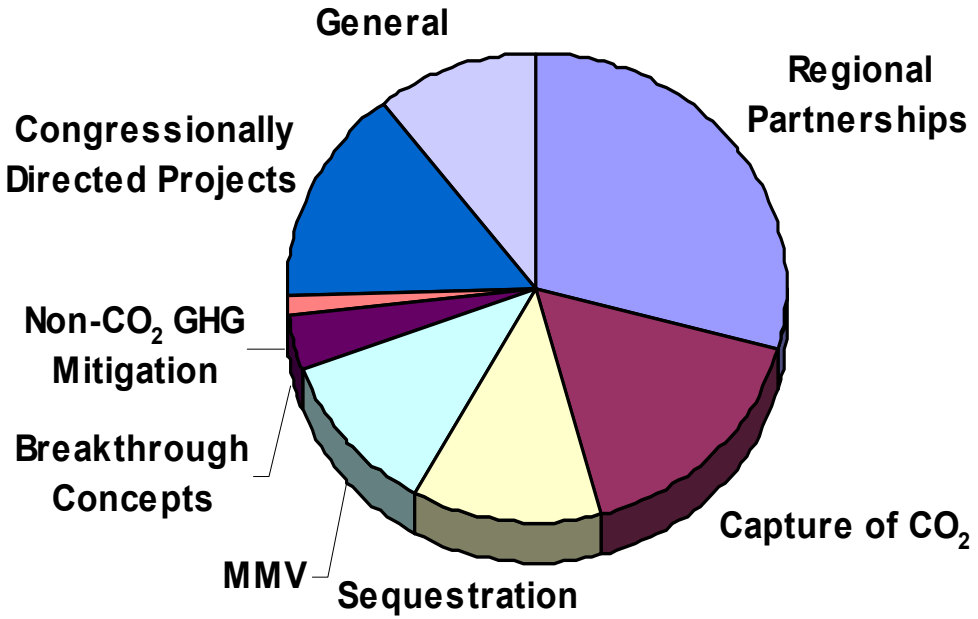
- Affordably meet energy demand
- Address environmental objectives

Carbon Sequestration Program Structure



Carbon Sequestration Portfolio Overview FY2006 - $67 million

- **Diverse research portfolio**
  - 76 external projects
  - 16 focus area projects
  - BP & IEA consortia
- **Strong industry support**
  - ~ 32% cost share
- **Total portfolio ~ $200M**



Sequestration Program Goals

Develop Technology Options for GHG Management

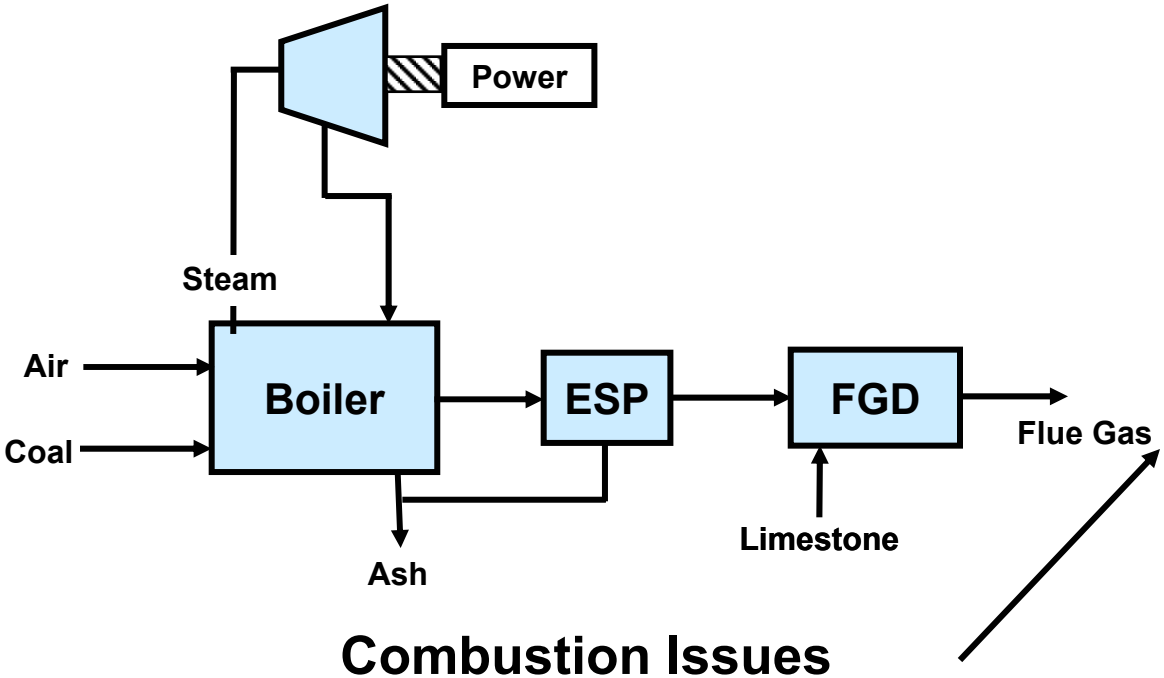
- **Safe and environmentally acceptable**
- **Result in**
  - < 10% increase in cost of energy (< $10/tonne CO_2 avoided for capture, transport, & storage)
  - Measurement, Monitoring & Verification protocols for assurance of permanent storage

Cost Performance Goals

Year	COE Penalty IGCC Plants (% Increase)	COE Penalty PC Plants (% Increase)
2002	30	80
2007	20	45
2012	10	20
2015	<10	10
2018*	0	0

*Cost/Energy offset from sequestering CO2 with criteria pollutants NOX, SOx, H2S (gasification)

Typical Power Plant Configuration

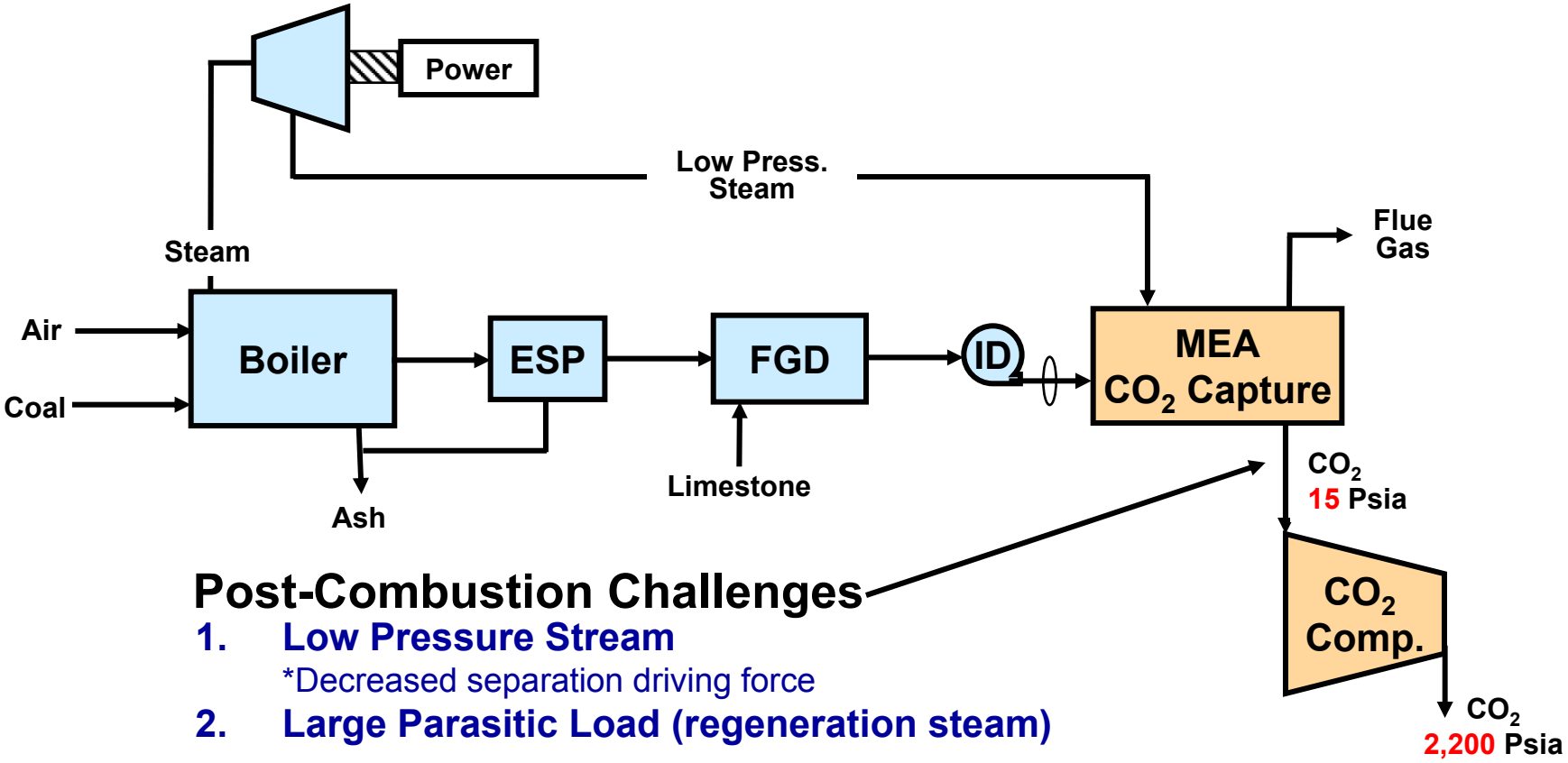


Combustion Issues

1. **Dilute Flue Gas**
   *10—14% CO_2
2. **Contaminants**
   *SO_2, Particulates, etc.

Post-Combustion Current Technology

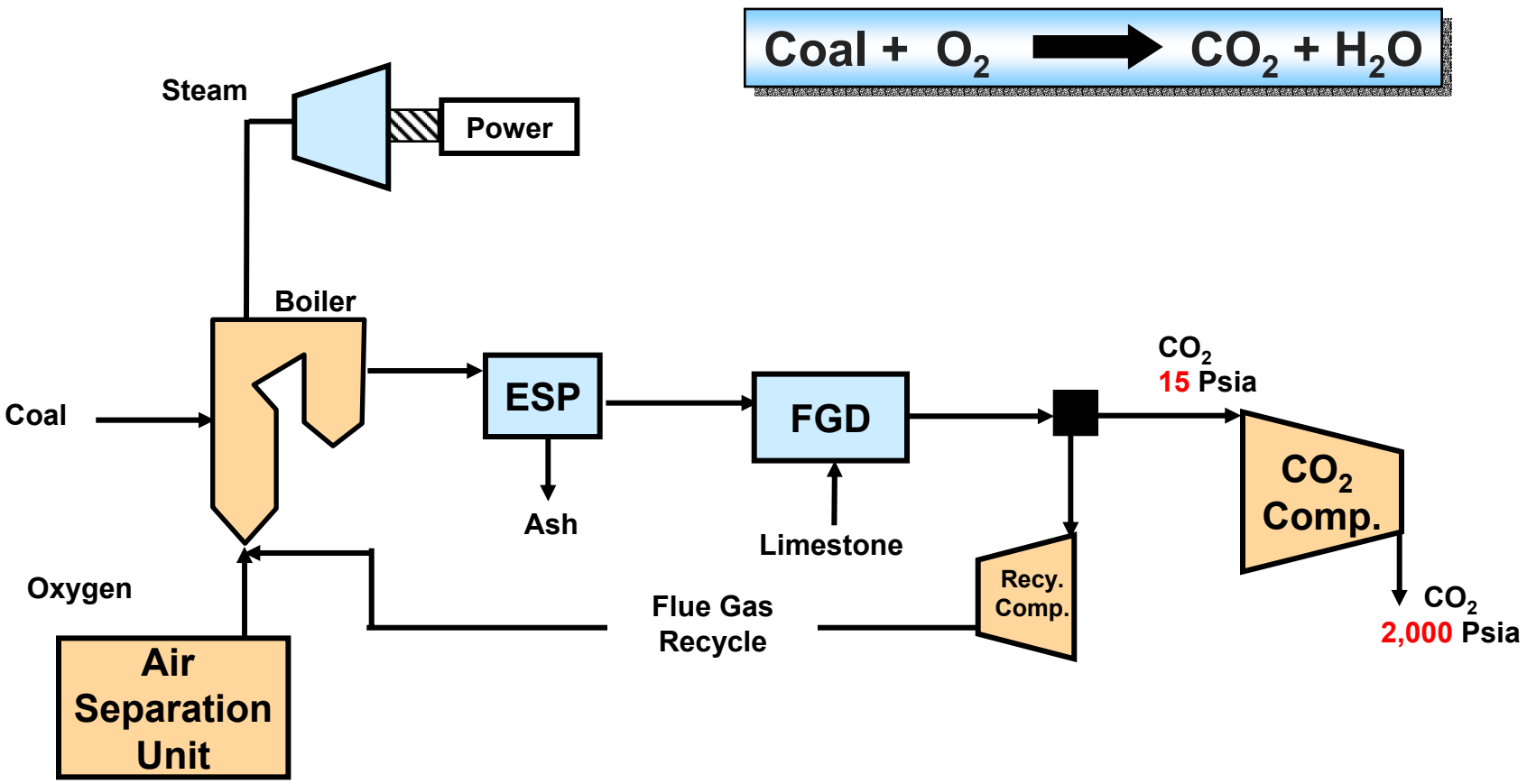
Pulverized Coal Power Plant with CO_2 Scrubbing



Post-Combustion Challenges

1. **Low Pressure Stream**
   *Decreased separation driving force
2. **Large Parasitic Load (regeneration steam)**

Basic Oxycombustion System



Technical Issues

- **Advantages**
  - No steam use
  - Greater than 90% CO_2 capture
  - Oxygen infrastructure in place for future use
  - Greater thermal efficiency

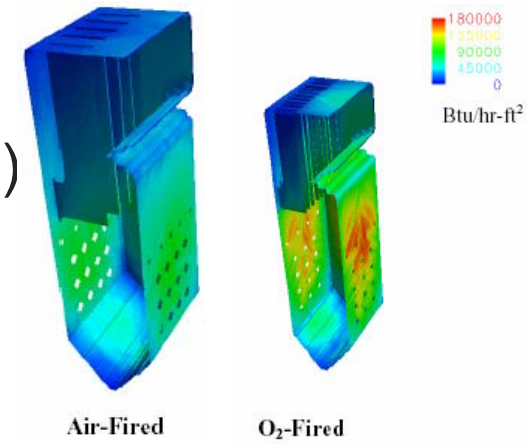
- **Hurdles & Questions**
  - Cost of air separation
  - Recycle or not to recycle?
  - Air leakage
  - Corrosion
  - Performance / Optimization

NETL Funded Oxygen-based Combustion Projects

- Systems Studies – Foster Wheeler, ANL, NETL
- Circulating Fluidized Bed Boilers – Alstom
- Advanced OTM integrated Boilers – Praxair
- Oxygen-Based PC Boiler Testing – Southern Research Institute
- Oxygen-Based PC Boiler Testing – B&W
- CAR integrated Boilers – BOC

Conceptual Design of Oxygen-Based PC Boiler
Foster Wheeler

- **Sub-Critical Pulverized Coal System (460 MWe gross)**
  - System Design and Analysis in Aspen Plus
  - 30.6% efficiency (36.7% for air-fired reference)
  - Furnace has reduced surface area and volume compared to air-fired
  - Mitigation Cost $21.4 / ton CO_2
  - 6.41 ¢/kWh (39% increase in COE)

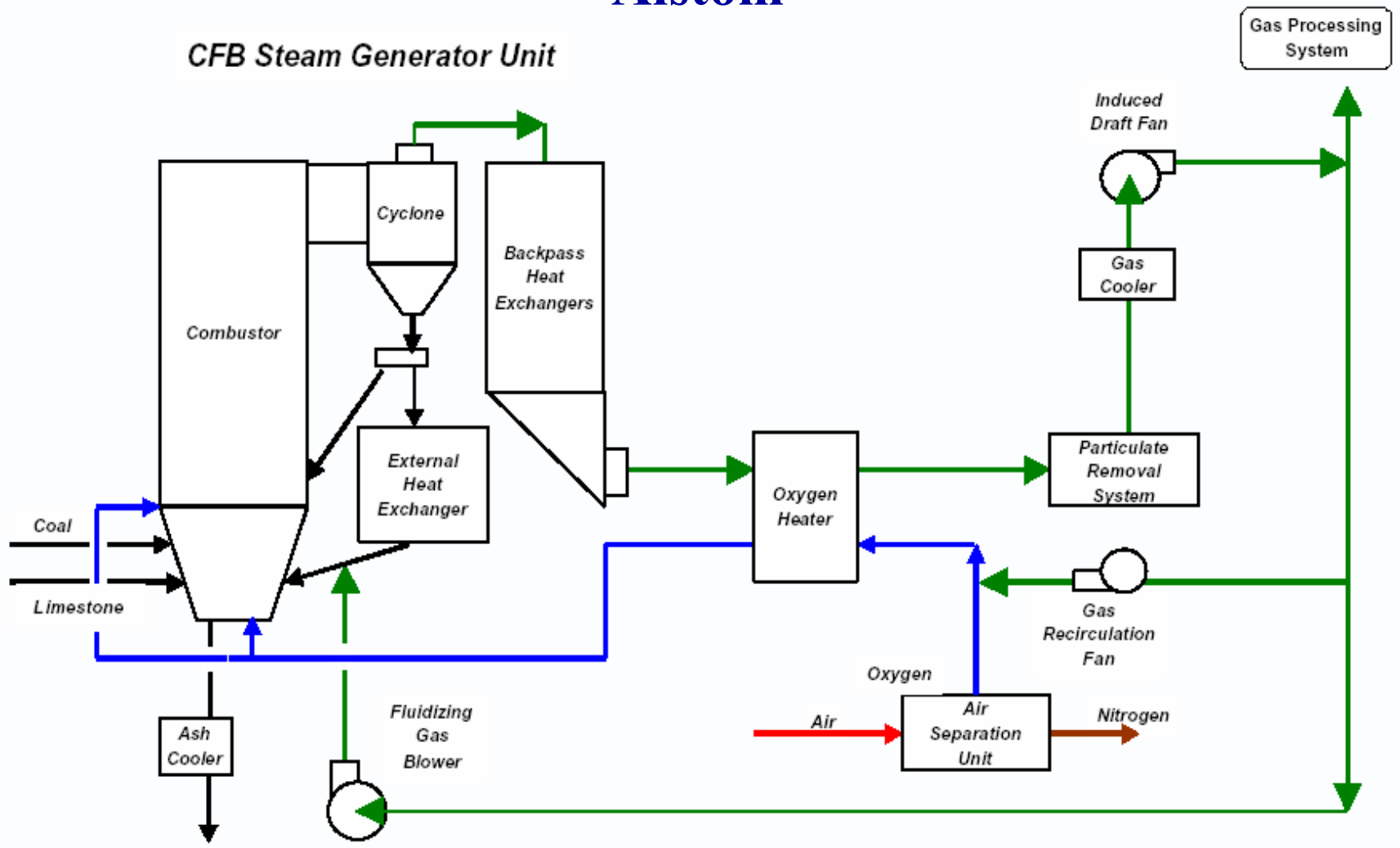


Conceptual Design of Oxygen-Based PC Boiler

Foster Wheeler

- **Super-Critical Pulverized Coal System (460 MWe gross)**
  - System Design and Analysis in Aspen Plus
  - 32.9% efficiency (39.5% for air-fired reference)
  - Currently working on
    - Integration with advanced oxygen production technologies
    - Furnace and HRA design
    - Cost Estimation

Oxygen Firing in Circulating Fluidized Bed Boilers
Alstom



Source: **Nsakala** , ***Greenhouse Gas Emissions Control Studies,*** Presentation to NETL at Alstom Facilities, Windsor, CT, August 24, 2004

Project Highlights
Alstom

- **Results**
  - Phase I (Systems Analyses)
    - Oxygen-Fired CFB is the Most Near Term Solution
    - Significant Boiler Cost Savings Compared to O_2 fired PC or Stoker Boilers
    - Preliminary Economics Look Viable For Commercial EOR Applications
  - Phase II (MTF Testing)
    - No bed agglomeration in furnace with up to 70% O_2
    - Recarbonation of limestone observed in sealpot and cyclone (should not be a problem in commercial units)
    - NO_x emissions lower than air firing
    - SO_2 and CO emissions slightly greater than air firing
    - Little or no difference in heat transfer to waterwalls
    - Plant design updated
      - Efficiency of 26%
      - 7.9¢/kWh COE
      - $2382/kW Capital Cost
      - $37/ton CO_2 avoided

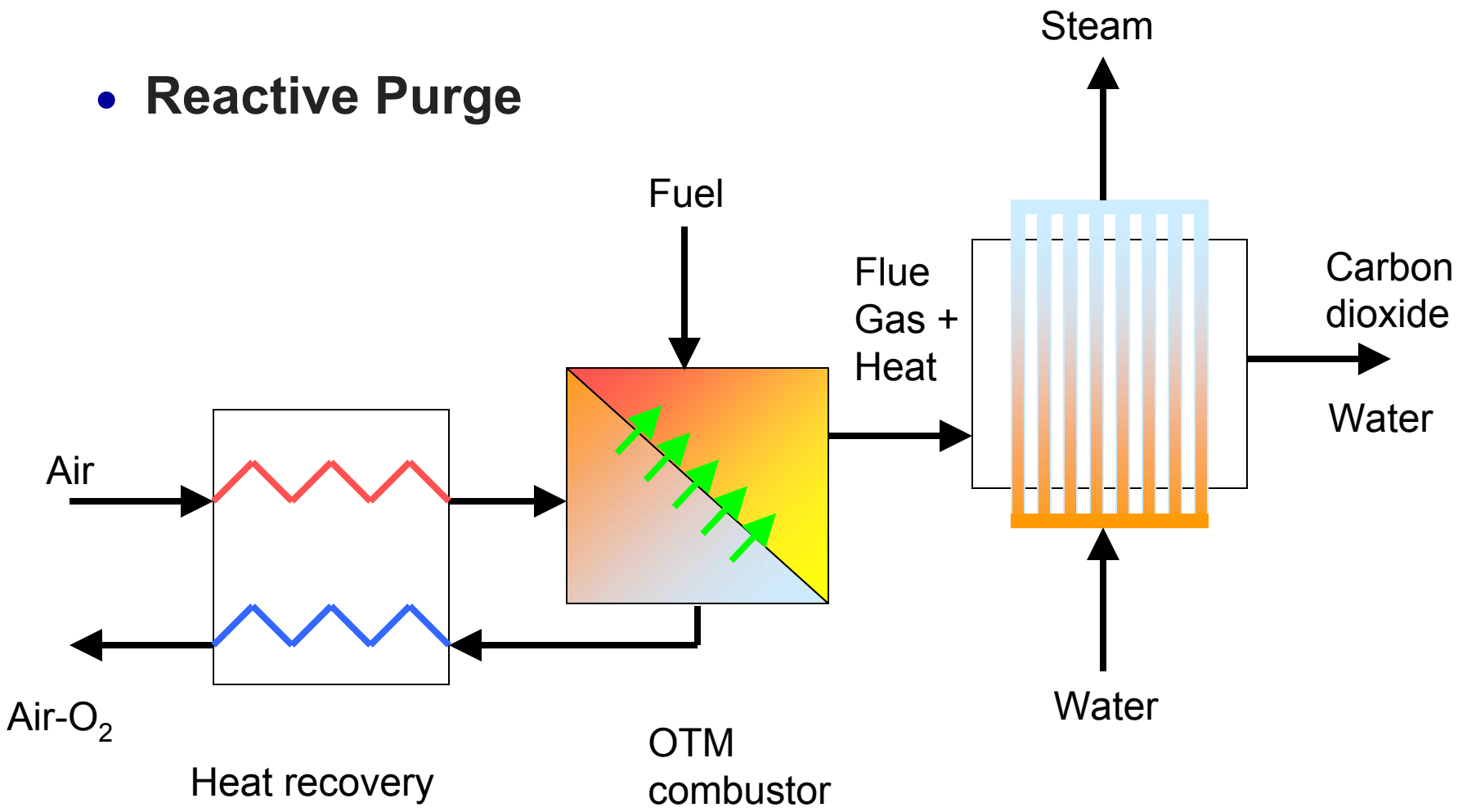
Preliminary Results
Alstom

- **Testing**
  - FDA similar % sulfur reduction with O_2 firing and air
  - Lower NOx emissions achieved with ammonia addition (slip issues)
  - Higher CO emissions
  - Low N_2O and VOC emissions
  - MBHE performed well under oxyfiring conditions
- **Economic Study**
  - Retrofit analysis performed on 90 MW facility
  - 94% CO_2 capture (3.1¢/kWh incremental COE)
- **Currently conducting New "capture-ready" plant study**

Advanced Boiler Concept

Praxair

- **Reactive Purge**



Project Highlights
Praxair

Results

- Reactive purge configuration found optimal
- Oxygen flux measurement commenced
- Preliminary Economic Analysis
  - Less than $10 ton CO_2 avoided
  - Capital Cost savings of ~ 60% compared to conventional boiler

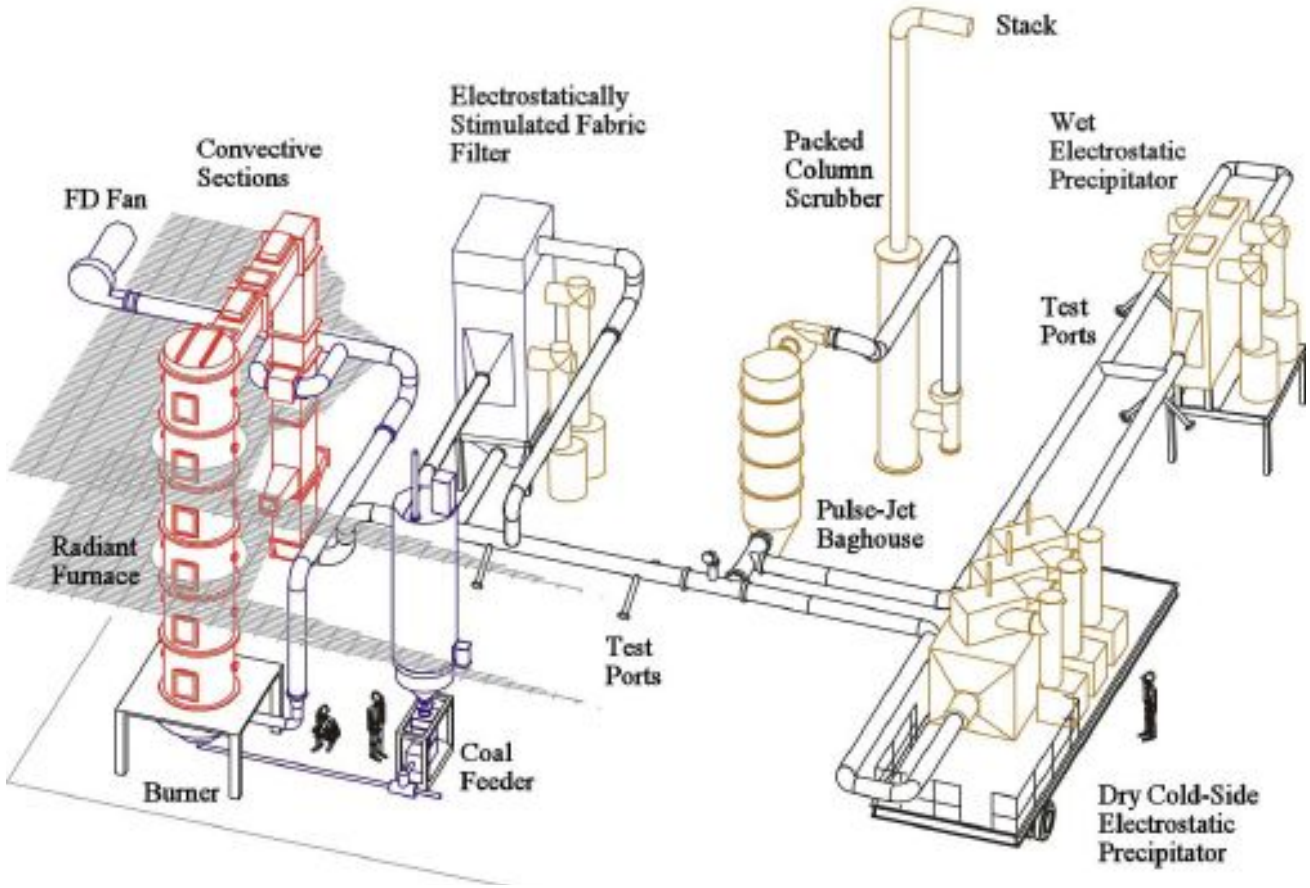
Oxygen-Fired CO_2 Recycle for Application to Direct CO_2 Capture from Coal-Fired Power Plants

SRI

- Retrofit Combustion Research Facility to Oxyfuel Configuration
- Maxon Corp. – Oxyfuel Burner Design
- BOC – Oxygen skid, associated safety systems, use fireside simulator developed by REI
- REI – Create fireside simulator from updated version of CFD

Combustion Research Facility Schematic

SRI 42430



Test Parameters
SRI

- **Firing Configuration**
  - Wall vs Tangential
  - Extent of Furnace Staging
  - Extent of Burner Staging
  - Extent of secondary burner swirl
  - Furnace exit oxygen
- **Oxygen Purity**
  - 90% to 99.5% Purity
- **Furnace and Flame Inputs**
  - Level of CO2 Recycle
  - Flame Oxygen Concentration
- **Coal Type**
  - Several different Hv-bituminous coals
  - PRB sub-bituminous coal
  - Anthracite or semi-anthracite
  - Possibly a lignite

Development Of Cost-effective Oxy-combustion Technology For Retrofitting Coal-fired Boilers

Babcock & Wilcox

- B&W, Air Liquide, Battelle
- 5 million Btu per hour pilot-scale tests
- Parametric testing of wall-fired and cyclone boiler
- Eastern bituminous coal, Power River Basin pulverized coal, sub-bituminous coal, and lignite coal.
- 2 year project

Pilot Modifications for Oxy-combustion

B&W's Small Boiler Simulator (SBS)
5 million Btu/hr - 1.5MW$_{th}$

Oxygen Supply System

Flue gases to stack

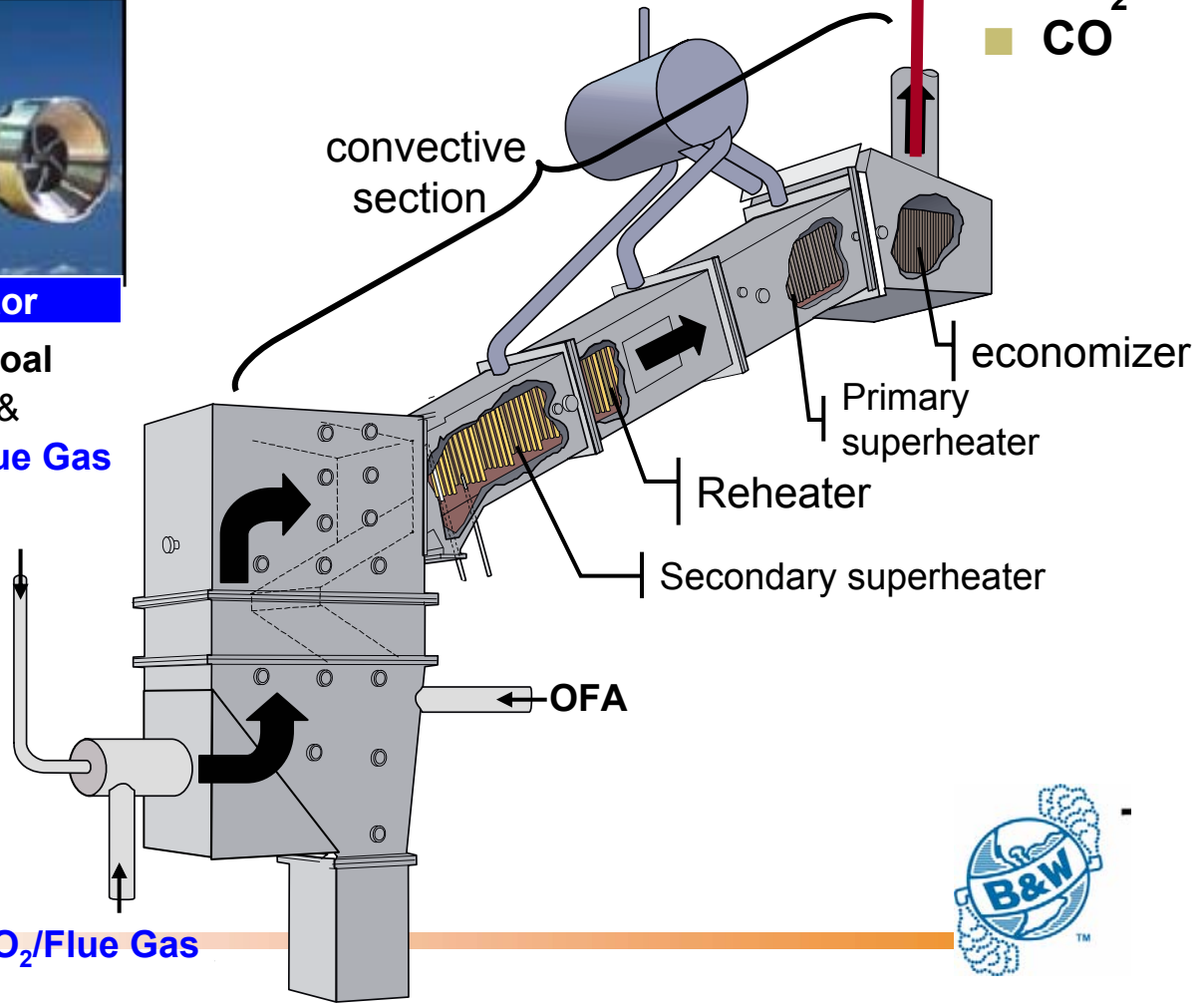
- CO_2
- O_2
- NO_x
- SO_2
- CO

Recycled Flue Gas

Oxynator

Coal & O_2/Flue Gas

furnace



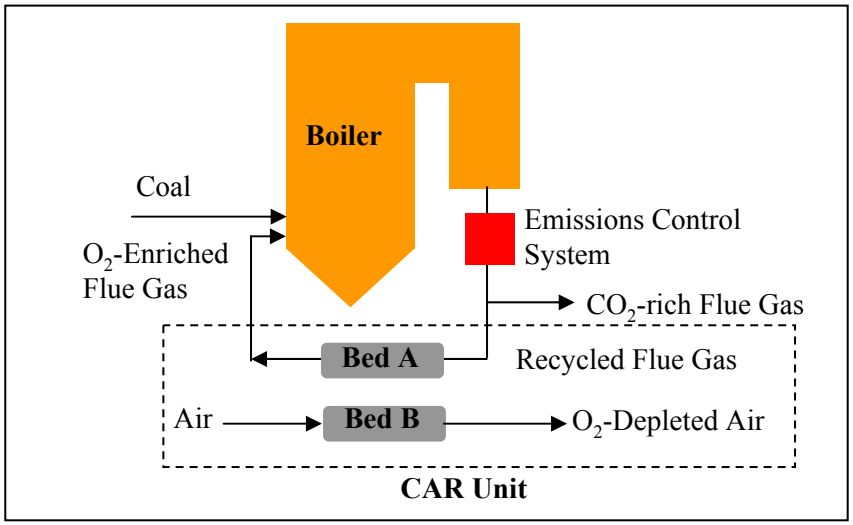
O_2/Flue Gas

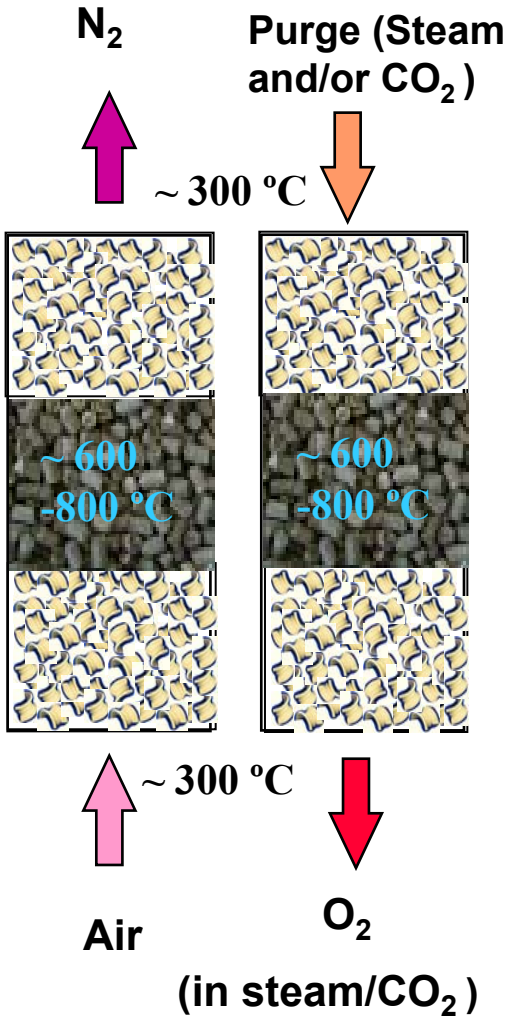
Pilot-Scale Demonstration of a Novel, Low-Cost Oxygen Supply Process and its Integration with Oxy-Fuel Coal-Fired Boilers
BOC

- Project Team
  - **BOC Group Inc.**
  - **Western Research Institute**
  - **Alstom Power**
  - **Advisory Board:**
    - **ATCO Power**
    - **Nova Scotia Power**
    - **East Kentucky Power**
    - **SaskPower**

CAR Technology
BOC

- **High temperature (T > 550 ºC), Cyclic steady state process; uses perovskites pellets in a fixed-bed**
- **Oxygen-enriched product stream at high temperature: ~ 300 ºC; low purity O_2 (high N_2 rejection); high O_2 recovery**
- **Oxy-fuel combustion for power production**
  - Main Driver: CO_2 sequestration
  - Target ~25% savings compared to O_2 from cryogenic ASU





CAR Process Development Unit
BOC

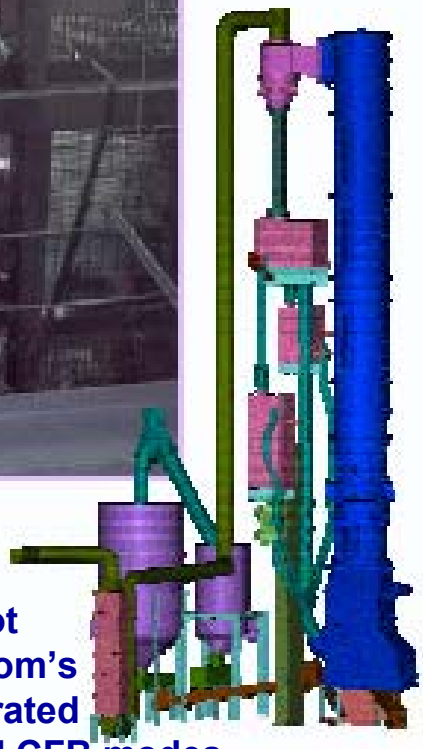
- **30 kg/hr (0.7 TPD) O_2 PDU**
- **Procurement, fabrication and assembly completed as part of a jointly sponsored research (JSR) project with WRI**
- **Start-up initiated (Jan. 2006) and intial testing is in process**
- **2-Bed Unit; 200 mm ID**
  - Internally insulated vessels
  - High temperature valves
  - Provision for both CO_2 and/or Steam as sweep gas
  - Steam rinse provision for reducing N_2 in O_2-rich stream

CAR PDU-CTF Integrated Testing with Flue Gas Recycle BOC

- Integrated testing of CAR Unit with CTF
  - Flue gas for CAR regeneration
  - Optimization of process conditions
  - Evaluation of contaminant effect on CAR material

250,000 BTU/hr balanced-draft system designed to closely replicate pulverized coal-fired utility boiler

CAR Pilot Plant Integration with Multi-Use Test Facility
BOC



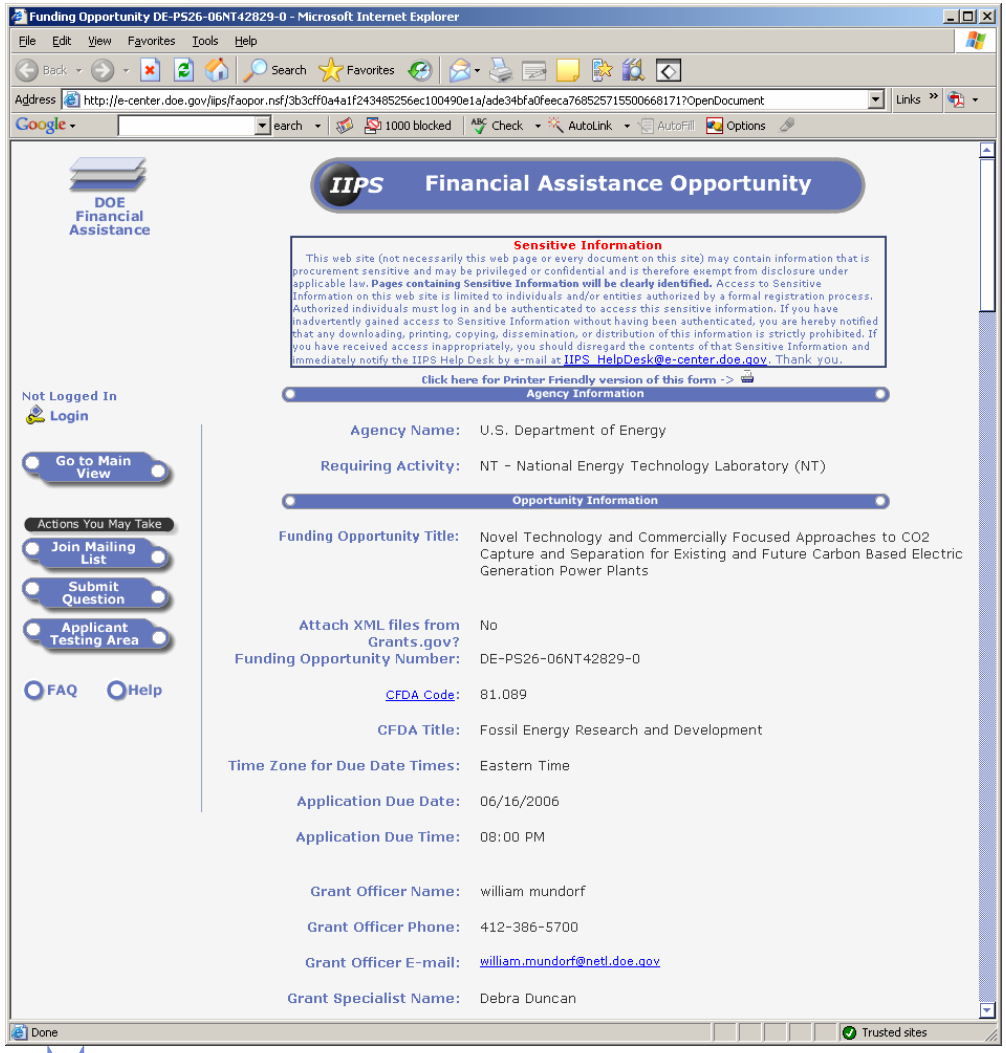
- Small-pilot scale vertical test furnace
- 9.9 MMBtu/hr (3 MWt) maximum firing rate
- Coal, oil, natural gas, biomass, and pet coke (etc) capable
- Tangential, wall fired, CFB, BFB and gasifier (etc) configurations

In Task 6, a 10 tons/day CAR Pilot Plant will be integrated with Alstom's Multi-Use Test Facility and integrated testing performed in both PF and CFB modes.

ALSTOM

NETL

Solicitation Released



Website:

http://www.netl.doe.gov/business/solicitations/index.html

Closing Date: June 16, 2006

Area of Interest 1 - Breakthrough Approaches to Carbon Dioxide and Separation

Areas of Interest 2 - Continued Development of Direct CO_2 Capture and Separation Technologies

Area of Interest 3 - Field-testing of CO_2 Capture and Separation Technologies