Carbon Capture Technology Research and Breakthrough Concepts

Overview and Project Summary

Last Updated:

January 2008

Sequestration Program Goals

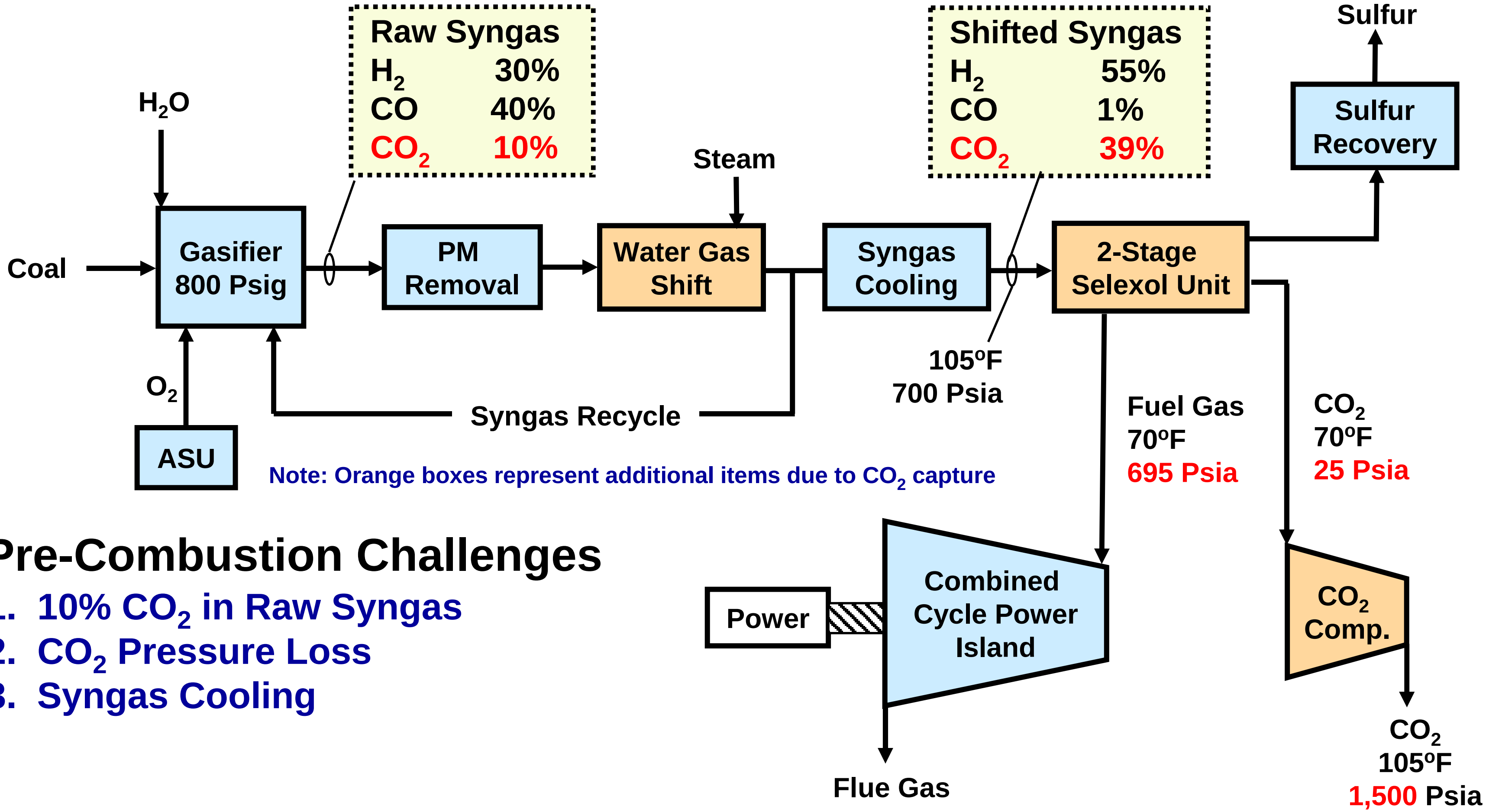
Develop Technology Options for GHG Management That...

- **Are safe and environmentally acceptable**
- **Separation and Capture R&D Goals**
  - **2007 have two technologies < 20% (45% PC based) increase in Cost of Energy *****
  - **2012 developed two technologies < 10% (20% PC based) increase Cost of Energy**
- **Sequestration/Storage R&D Goals**
  - **2012 predict CO_2 storage capacity with +/- 30% accuracy**
  - **Develop best practice reservoir management strategies that maximize CO_2 trapping**
- **Monitoring, Mitigation & Verification**
  - **2012 ability to verify 95% of stored CO_2 for credits (1605b)**
  - **CO_2 material balance to >99%**

*** **technologies identified and ready to move to demonstration (~ 4yrs) and then deployment (~4 yrs) – IGCC 20% and PC 45%**

Pre-Combustion Capture Pathway

IGCC Power Plant with CO_2 Scrubbing



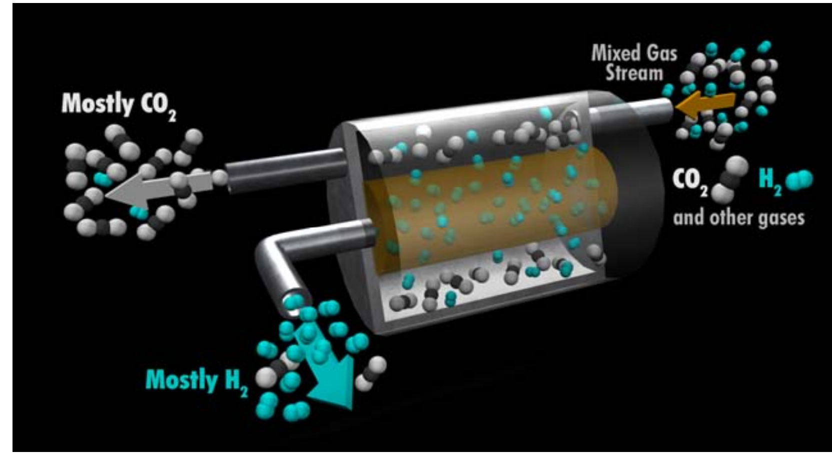
Pre-Combustion Challenges

1. 10% CO_2 in Raw Syngas
2. CO_2 Pressure Loss
3. Syngas Cooling

Source: *Evaluation of Innovative Fossil Fuel Power Plants with CO2 Removal,* DOE/EPRI, 1000316

Polymer-Based High Temperature Membrane

Developing a high temperature polymer-based membrane and full-scale module for *pre-combustion capture*



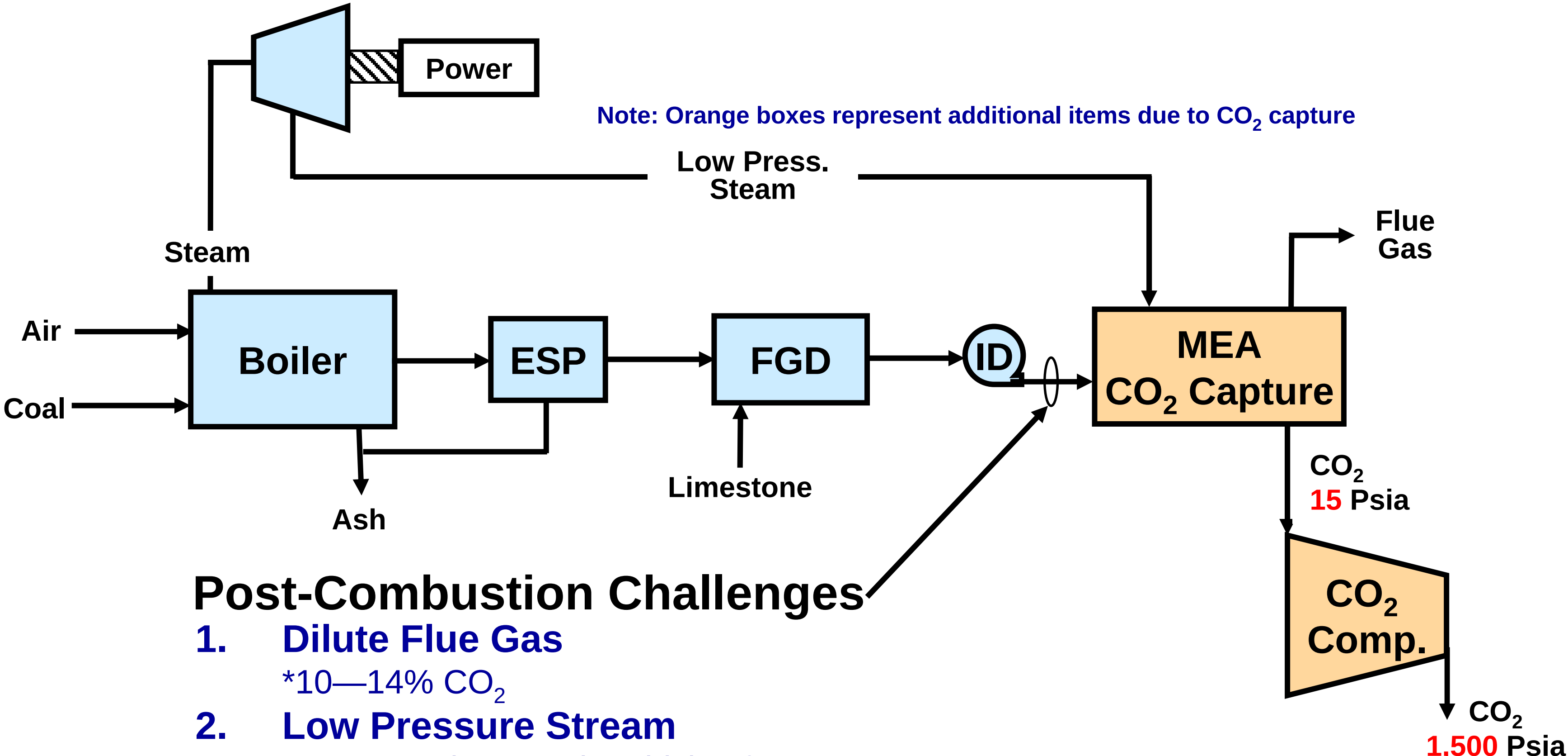
Accomplishments:

- Developed polybenzimidazole (PBI) – based membrane exhibits the *highest* operating temperature (400 °C) of a polymer-based membrane.
- Over 400 days of testing in simulated synthesis gas environments at temperatures exceeding 250 °C conducted while demonstrating:
  - permeabilities and selectivities of commercial interest
  - operation temperatures well matched to process temperatures
  - chemical stability to primary synthesis gas components
  - mechanical stability in the presence of process cycling and simulated upset conditions
- Successful independent testing (GTI) of the membrane at a NG fuel processor with a steam saturated, shifted reformate at temperatures up to 400 °C.

***Participant:** SRI International, LANL, Whitefox, Enerfex, Visage Energy, BP, Southern Company*

Post-Combustion Challenges

Pulverized Coal Power Plant with CO_2 Scrubbing



Post-Combustion Challenges

1. **Dilute Flue Gas**
   *10—14% CO_2
2. **Low Pressure Stream**
   *Decreased separation driving force
3. **Contaminants**
   *SO_2, Particulates, etc.
4. **Large Parasitic Load (regeneration steam)**

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Sodium Bicarbonate Regenerable Sorbent

- **Develop a CO_2 technology that is:**
  - A regenerable sorbent,
  - Applicable as a retrofit to existing and greenfield power plants,
  - Compatible with the operating conditions in current power plant configurations

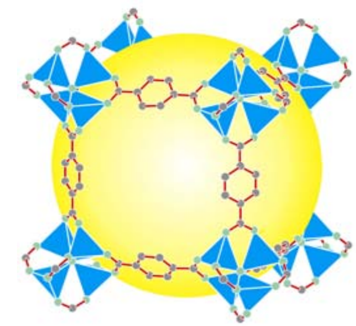
<u>Accomplishments:</u>

- Pilot Scale Testing at CANMET March 2005
- 90% CO_2 removal was achieved in flue gas with 10% and 15% [CO_2]
- Long-term (500 hr.) testing of integrated system at EPA Pilot facility with various coal ranks (2nd Qtr. FY2007)
- Next Phase to develop 1 TPD laboratory scale system

Participant: RTI, Sud-Chemie, Solvay Chemicals, EPRI/ Nexant,EPA/Arcadis, BOC Group, ADA-ES

Metal Organic Frameworks for CO_2 Capture

- Hybrid organic/inorganic structures that are highly porous and thermally stable
- Can be tailored to have specific sorption properties
- Key properties confirmed to date
  - High adsorption capacity
  - High selectivity
  - Good adsorption/desorption rates



- CO_2 capacity and selectivity – modeling and experiment match nicely
- Ongoing and future work
  - Evaluate hydrothermal stability
  - Optimize and validate material synthesis, forming, and scale-up
  - Develop process design and analyze economics

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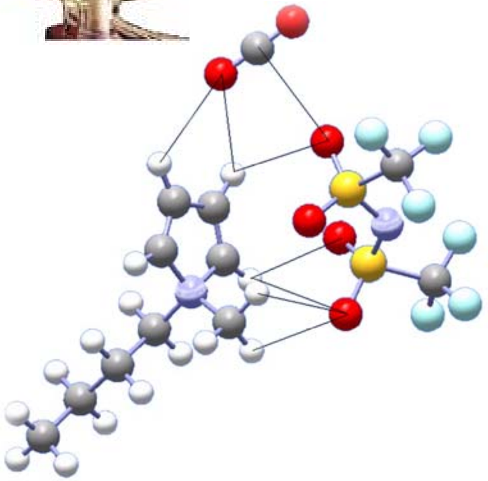
Participants: UOP LLC, Univ.of Michigan, Northwestern Univ. Vanderbilt Univ., Univ. of Edinburgh

Ionic Liquids as Novel Absorbents

Are salts that are liquid at room temperature which have high absorption potential and never evaporate.

Accomplishments:

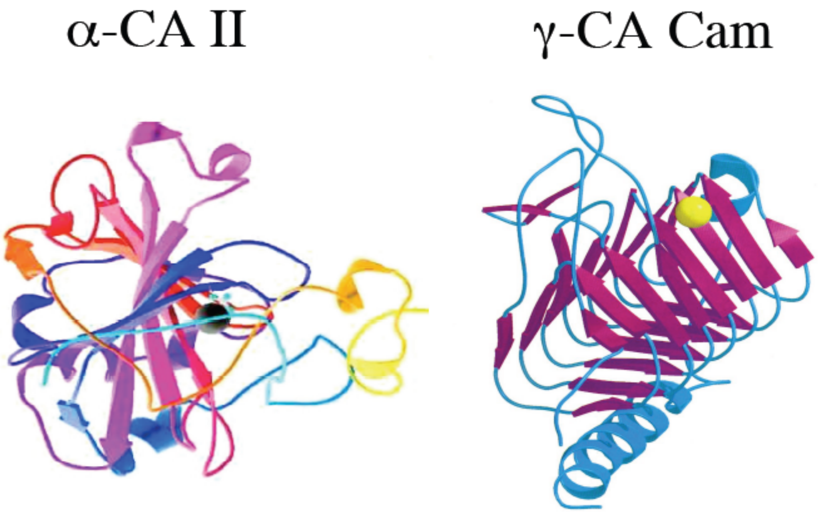
- Synthesized ILs have achieved the highest CO_2 solubility ever measured for an ionic liquid:
  - **over *19x increase* in CO_2 solubility for physical ILs and *40x increase* in CO_2 solubility for ILs with chemical complexation when compared to ILs available at the beginning of the project**
- Demonstrated[1] that *SO_2 is highly soluble in ILs*
  - **8 to 25 times more soluble than CO_2 depending upon pressure**
- NETL researchers prove that ILs can be used as the separating media in supported liquid membranes to separate CO_2 from H_2.



Participants: University of Notre Dame, DTE Energy, Babcock and Wilcox, Trimeric, Merck KGaA, NETL

[1] J. L. Anderson, J. K. Dixon, E. J. Maginn and J. F. Brennecke, "Measurement of SO2 solubility in ionic liquids", Journal of Physical Chemistry B, 2006, 110, 15059-15062.

Carbonic Anhydrase Enzymatic Membrane

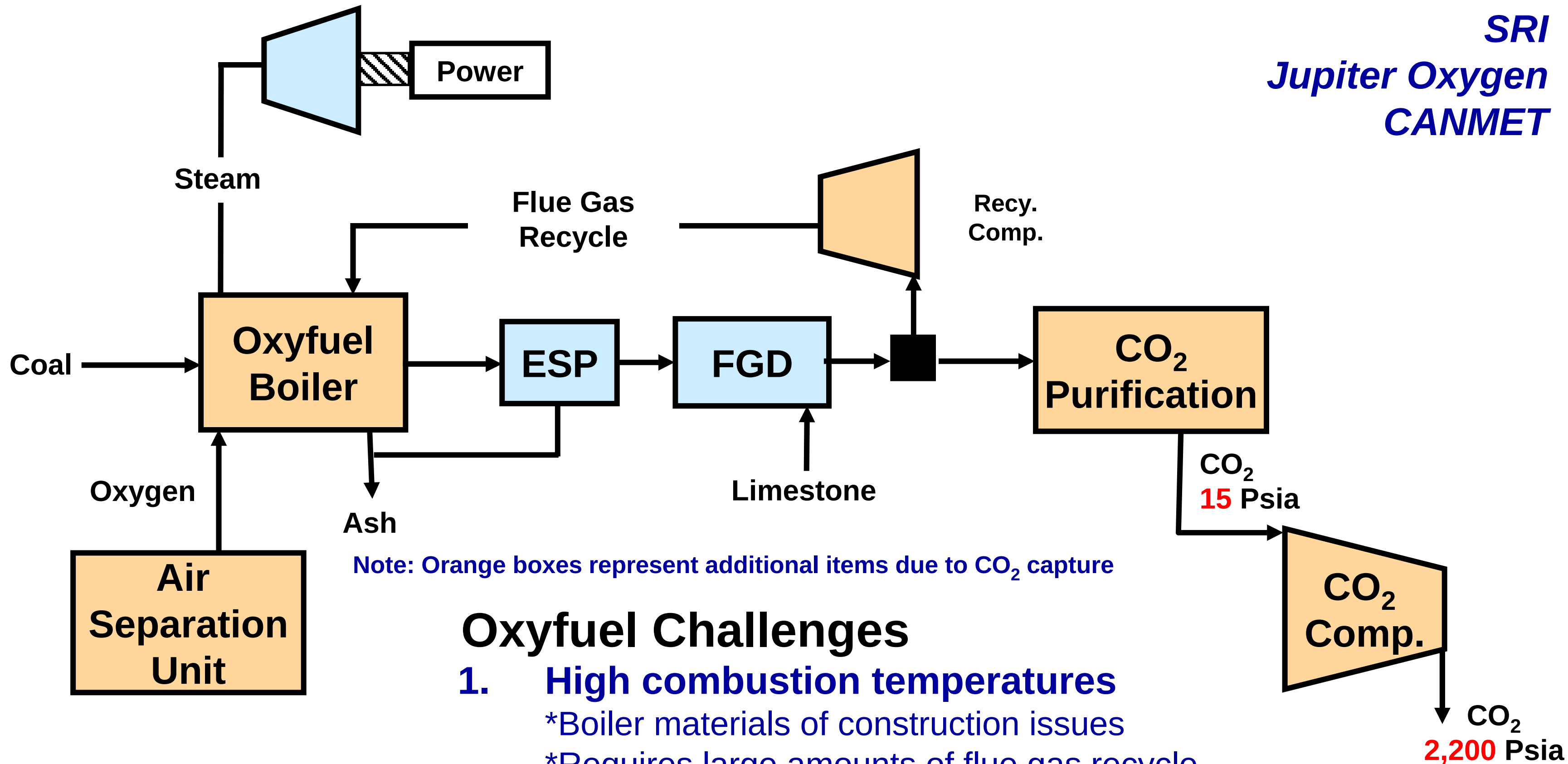


- **Enzyme-based hollow fiber contained liquid membrane technology (EB-HFCLM)**
- **Integration of Absorption and Stripping Processes into a Single Membrane Device**
- **Carbonic anhydrase is one of the fastest enzymes known with a turnover number of 600,000 katals.**

Participants: Carbozyme, Siemens, Novozymes, EERC, ElectroSep, ANL, SRI International, Visage Energy, KES Technologies, KSU, Cogentrix, Industrial Commission of North Dakota

Pulverized Coal Oxycombustion

PC Oxy-coal Projects:
B&W
SRI
Jupiter Oxygen
CANMET



Note: Orange boxes represent additional items due to CO_2 capture

Oxyfuel Challenges

1. **High combustion temperatures**
   *Boiler materials of construction issues
   *Requires large amounts of flue gas recycle
2. **Cryogenic oxygen production is expensive and energy intensive**
   *Opportunity for oxygen membranes

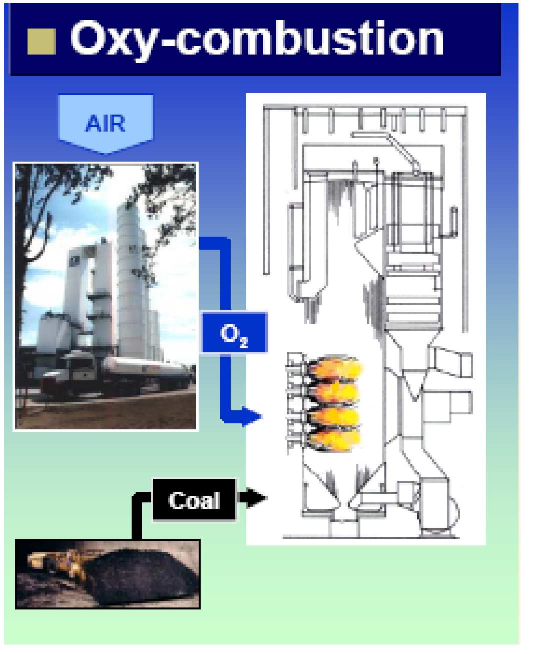
Development of Cost-Effective Oxy-Combustion Technology for Retrofitting Coal Fired Boilers

Project Description & Benefits

Pilot plant testing for commercial oxy-combustion retrofit application in existing wall-fired and cyclone boilers at B&W's 6 MMBtu Barberton, Ohio facility.

Project Objective

Assess CO_2 retrofit and greenfield control cost reductions via the integration of Air Separation Unit flue gas purification, compression, transportation, and sequestration.



Project Tasks

- Phase 1-Pilot-Scale Evaluation of Oxy-Combustion
  - Specification of Flue Gas Purification, Compression, Transportation, and Sequestration
  - Pilot-Scale Testing and Evaluation
- Phase 2- Techno-Economic Evaluations
  - Evaluate impact of oxy-combustion on net power production and COE.
  - Determine boiler population with close proximity between stationary CO_2 sources and candidate geologic sinks.

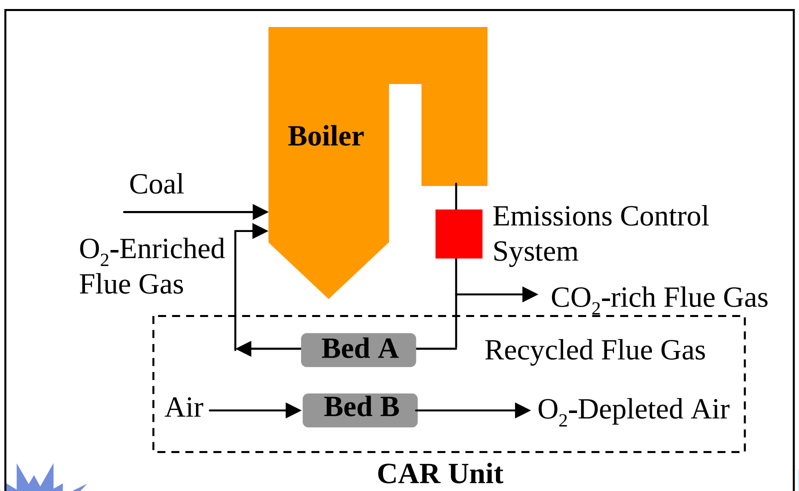
Results

- Determined process specifications, including CO_2 transportations and sequestration, flue gas purifications and storage.

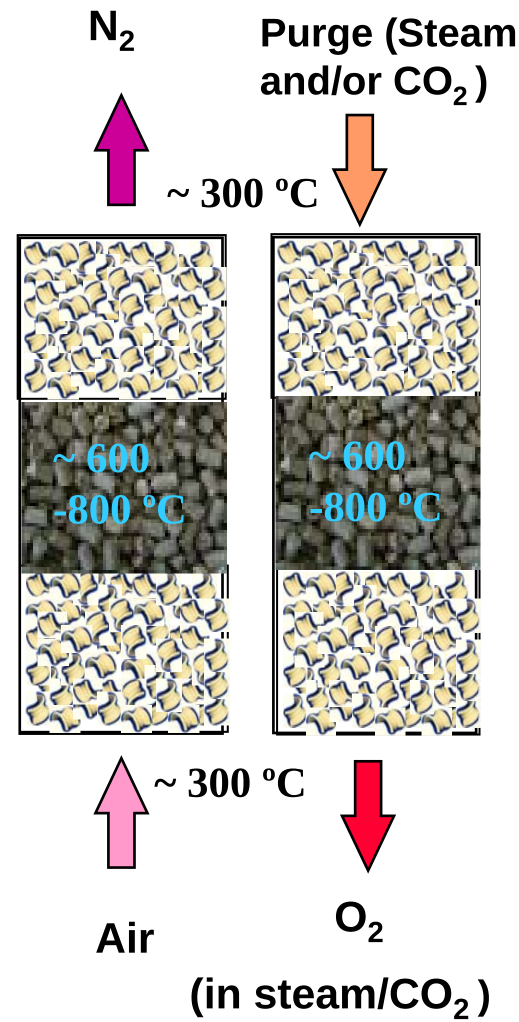
Participants: Babcock & Wilcox, Battelle, Air Liquide

CAR Technology

- High temperature (T > 550 ºC), Cyclic steady state process; uses perovskites pellets in a fixed-bed
- Flue gas recirculation system installation completed. System ready for CAR testing with recycled flue gas (June 2007)
- Oxygen-enriched product stream at high temperature: ~ 300 ºC; low purity O_2 (high N_2 rejection); high O_2 recovery



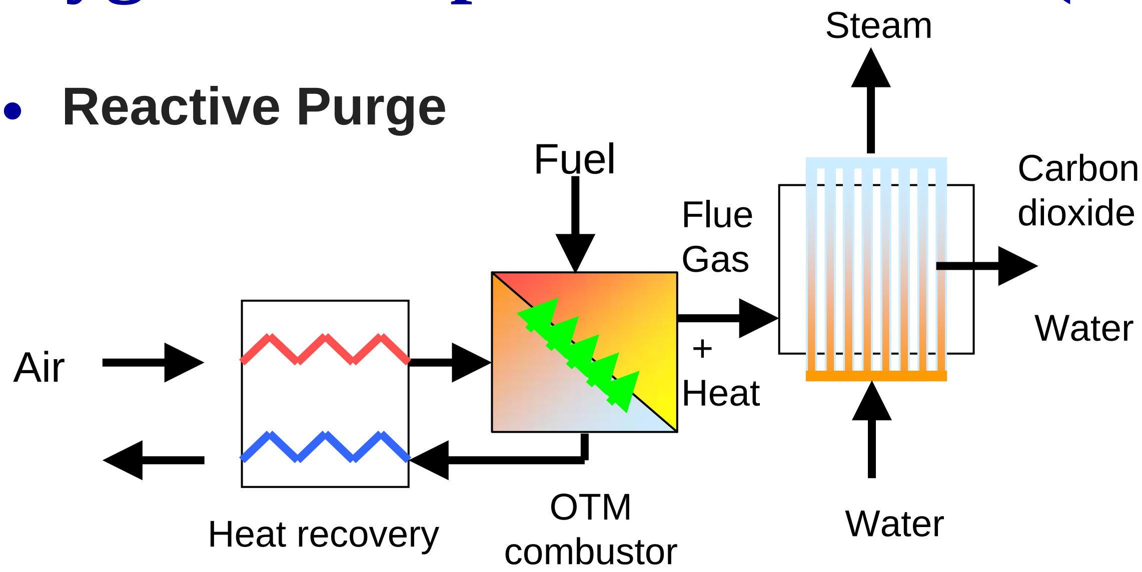
- Target ~25% savings compared to O_2 from cryogenic ASU



Participants: BOC, Alstom, WRI

Oxygen Transport Membranes (OTM)

- Reactive Purge



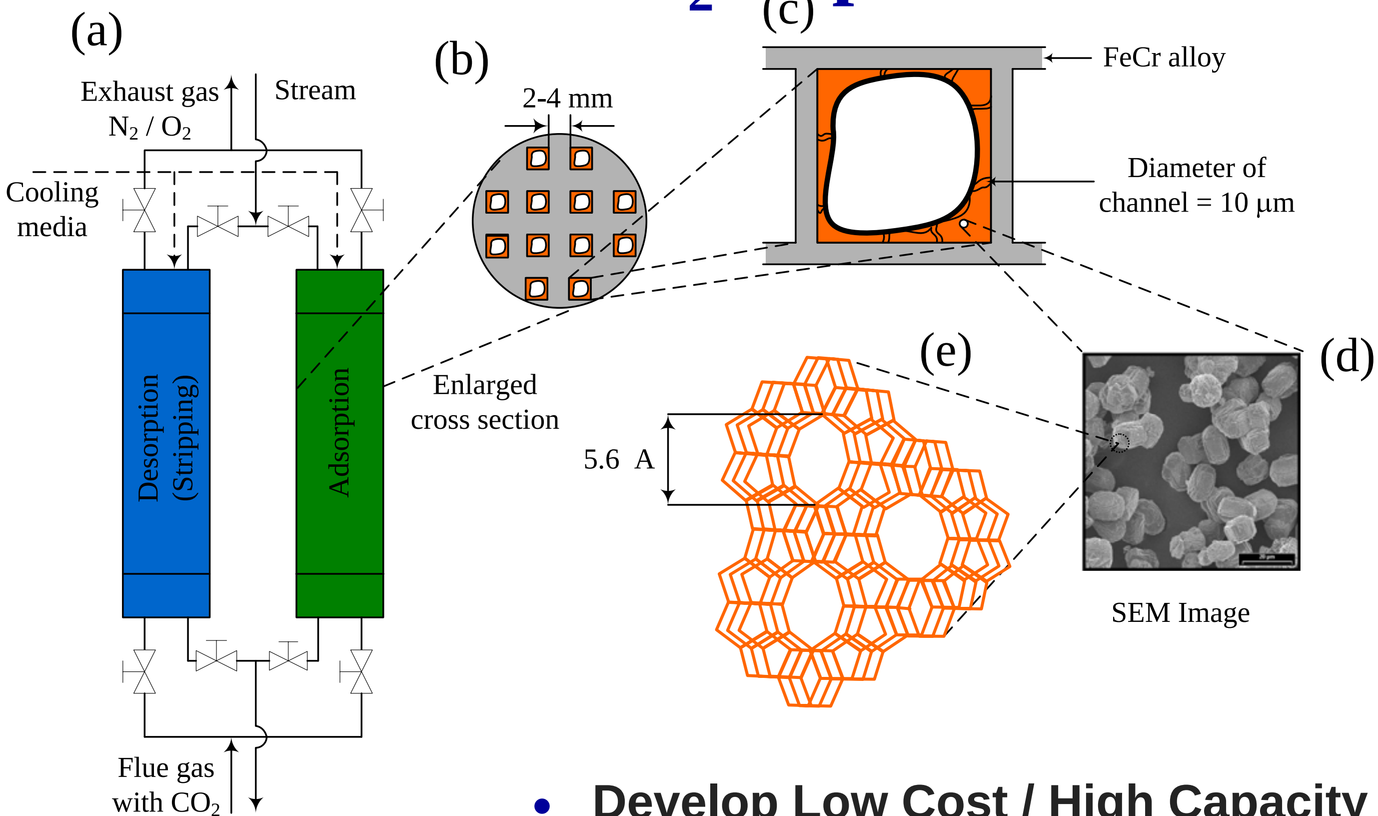
- **Oxy-fuel combustion technology. Natural Gas approach depicted. Coal based concepts under development.**
- **Increase in thermal efficiency from ~87 % to ~95% (HHV)**
- **CO_2 product ready for sequestration**
- **Ultra Low NO_x emissions**
- **1/10th the power consumption for oxygen separation from air compared to a cryogenic ASU.**

Participants: Praxair, University of Utah

Graphic from Praxair Presentation, 2/15/06 NETL Pittsburgh

Breakthrough Concepts

Metal Monolithic Amine-grafted Zeolites for CO_2 Capture



- **Develop Low Cost / High Capacity Sorbent**
  - Metal monoliths add ability to handle heat quickly
  - Can be designed to absorb both SO_2 and CO_2

Participants: University of Akron

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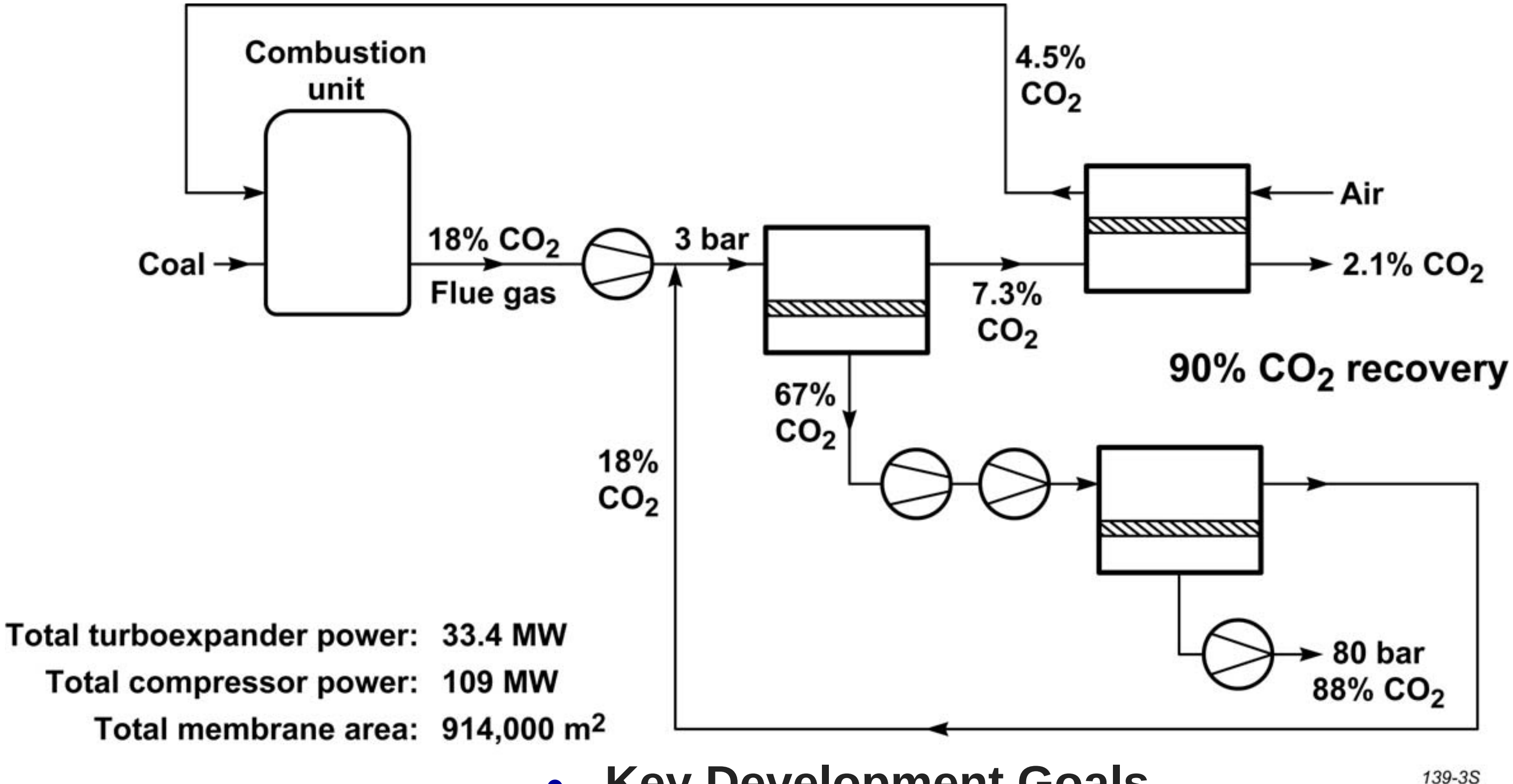
Membrane Process to Sequester CO_2 from Power Plant Flue Gas



- **Key Development Goals**
  - Optimization of high performance membranes
  - Fabrication of these membranes into robust, low-cost modules that demonstrate effective counter flow

Participants: Membrane Technology & Research

RD&D Challenges

Pre-combustion
(Synthesis Gas)

- Loss of CO_2 pressure due to flash regeneration
- Cooling / refrigeration of syngas to accommodate low operating temperatures; reheating prior to combustion
- H_2 losses, particularly in membranes
- Sulfur-tolerant materials / membranes

Post-combustion
(Flue Gas)

- Low-pressure flue gas dilute in CO_2
- Steam requirement for thermal regeneration (amines)
- High compression costs and large loads due to CO_2 produced at low pressure
- Flue gas contaminants

Oxygen Combustion
(OxyFuel)

- Cost of O_2 production and materials
- Cooled CO_2 recycled to mitigate combustion temperatures

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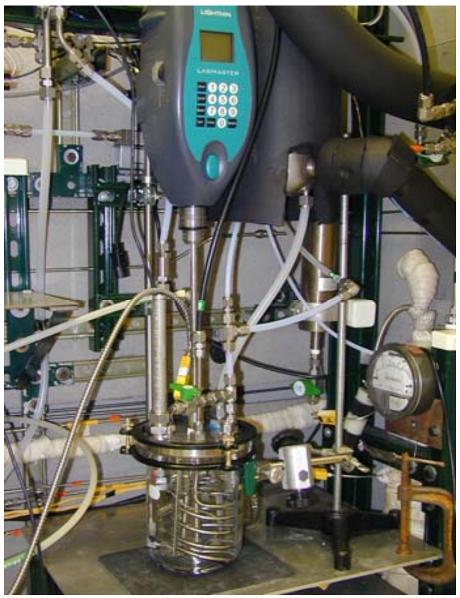
Key Issues: Cost & Scale-Up

Laboratory Scale



Technically Possible?

Scale-up

Economically Feasible?

500 MW Commercial Power Plant

- 0.1 ft^3 Reactor Volume
- 0.27 scf per minute

- 57,000 ft^3 Reactor Volume
- 1,800,000 scf per minute

Separation and Capture Summary

Open Category
- **Carnegie Mellon Univ.**—Modeling assessment tools
- **ANL**—Evaluation of CO_2 Capture Options

Technology Target
- **<10% increase in COE for Pre-Combustion plants by 2012**
- **<20% increase in COE for Post-Combustion plants by 2012**
- **>90% CO_2 Capture capability**
- **Safe and Effective**

Commercialization

Outcomes
- Efficient low-cost electricity and hydrogen production with low GHG emissions
- Commercially viable options for retrofit of existing plants to reduce CO_2 emissions

Pre-Combustion
- **Decarbonization**
- **Advanced Sorbents**
- **Hybrid Sorbent/Membranes**

Oxyfuel
- **O_2 Selective Membranes**
- **Advanced Cooling Cycles**
- **Compact Boilers**

Post Combustion
- **Chemical and Physical Sorbents**
- **Hybrid Sorbent/Membranes**
- **Gas/Liquid Contactors**

- **NETL**—Dry Sorbents, Membranes
- **U. Minn**—Hydrogen Selective Silica Membranes
- **UOP** —MOFs*
- **SRI/LANL**—High Temperature polymer membrane

- **Praxair**—OTM boilers and process heaters
- **Alstom Power**—O_2 Fired CFB
- **B&W**—PC-Fired with ASU Pilot
- **BOC**—PC-Fired with CAR Pilot
- **SRI** — O_2 Retrofit

- **NETL**—Aqueous Ammonia
- **NETL**—Amine Enriched Sorbents
- **UT Austin**—K_2CO_3/Piperazine absorption
- **U New Mexico**—Membranes
- **Notre Dame**—Ionic Liquids
- **RTI**—Dry Regenerable Sorbent
- **Carbozyme**—Carbonic Anhydrase
- **UOP**—MOFs *
- **MTR**- Membrane Process
- **U Akron** - Metal Monolithic Amine Grafted Zeolites

Note: Other significant research performed in Gasification and Hydrogen & Fuels Programs.

* Single project

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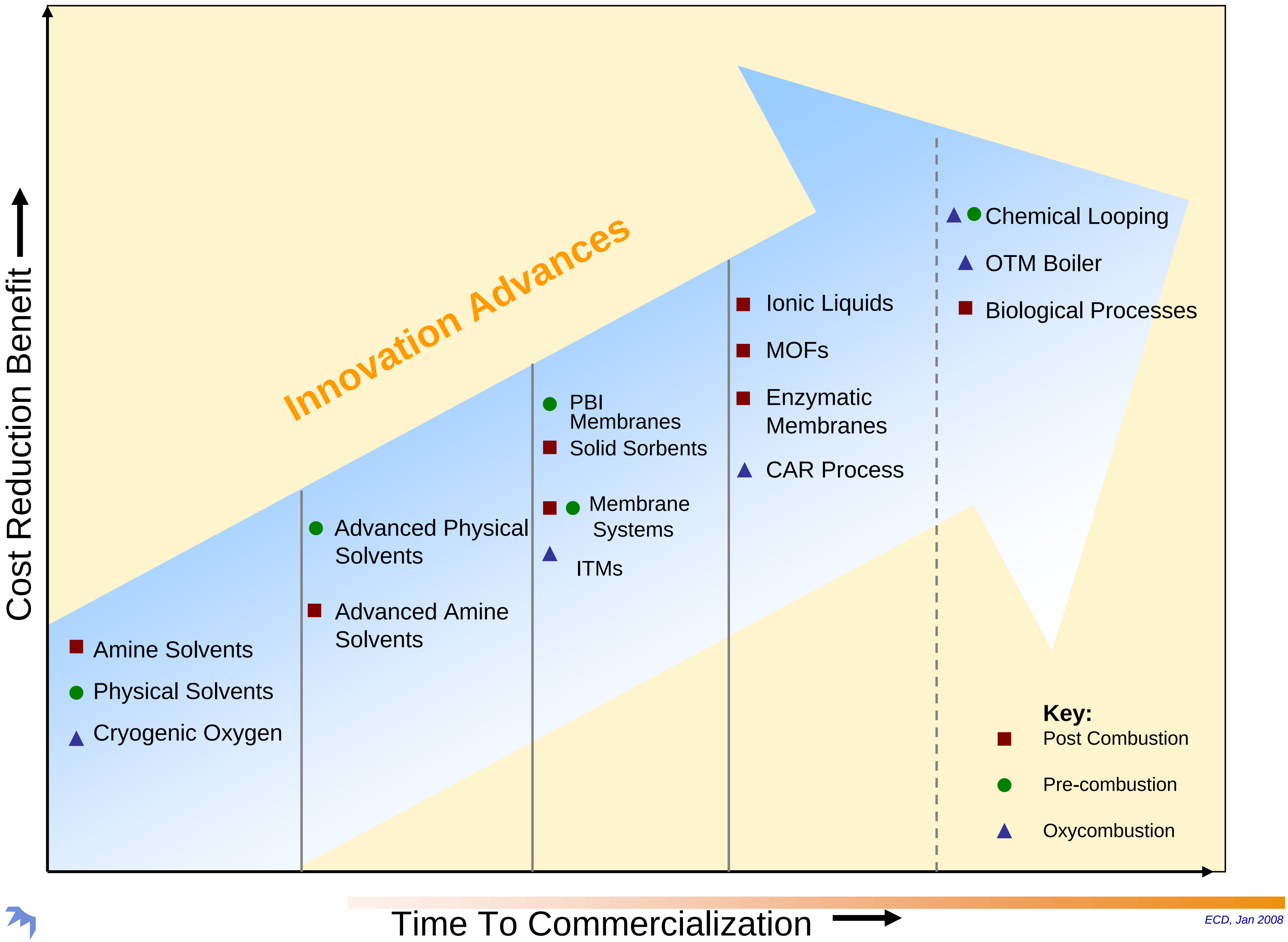
Cost Reduction Benefit
Innovation Advances
Amine Solvents
Physical Solvents
Cryogenic Oxygen
Advanced Physical Solvents
Advanced Amine Solvents
PBI Membranes
Solid Sorbents
Membrane Systems
ITMs
Ionic Liquids
MOFs
Enzymatic Membranes
CAR Process
Chemical Looping
OTM Boiler
Biological Processes
Key:
Post Combustion
Pre-combustion
Oxycombustion
Time To Commercialization
ECD, Jan 2008