NETL Carbon Sequestration Program

US Perspective on CO_2 Capture and Separation

Global Climate and Energy Project

April 27, 2004

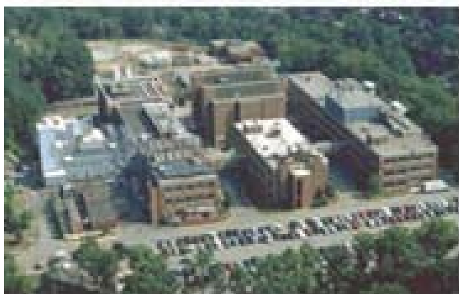
Stanford University

Jared P. Ciferno - National Energy Technology Laboratory

Presentation Outline

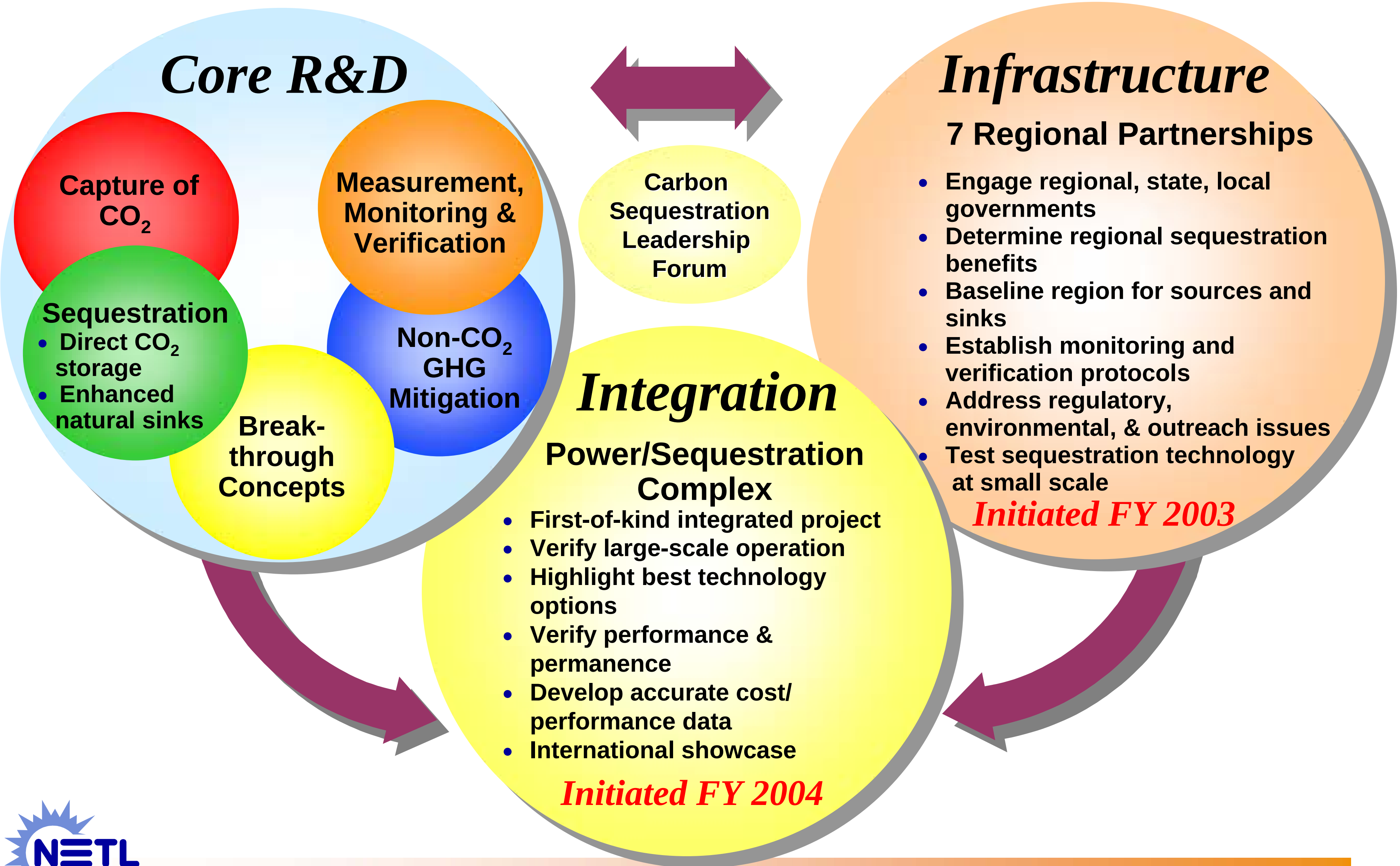
- Carbon Sequestration Program
- Pre-Combustion CO_2 Technologies
- Post-Combustion CO_2 Technologies
- Oxy-Fuel Technologies
- Modeling and Assessment Tools
- On-Site NETL R & D

National Energy Technology Laboratory



- **One of DOE's 17 national labs**
- **Government owned/operated**
- **Sites in Pennsylvania, West Virginia, Oklahoma, Alaska**
- **More than 1,100 federal and support contractor employees**
- **FY 03 budget of $750 million**

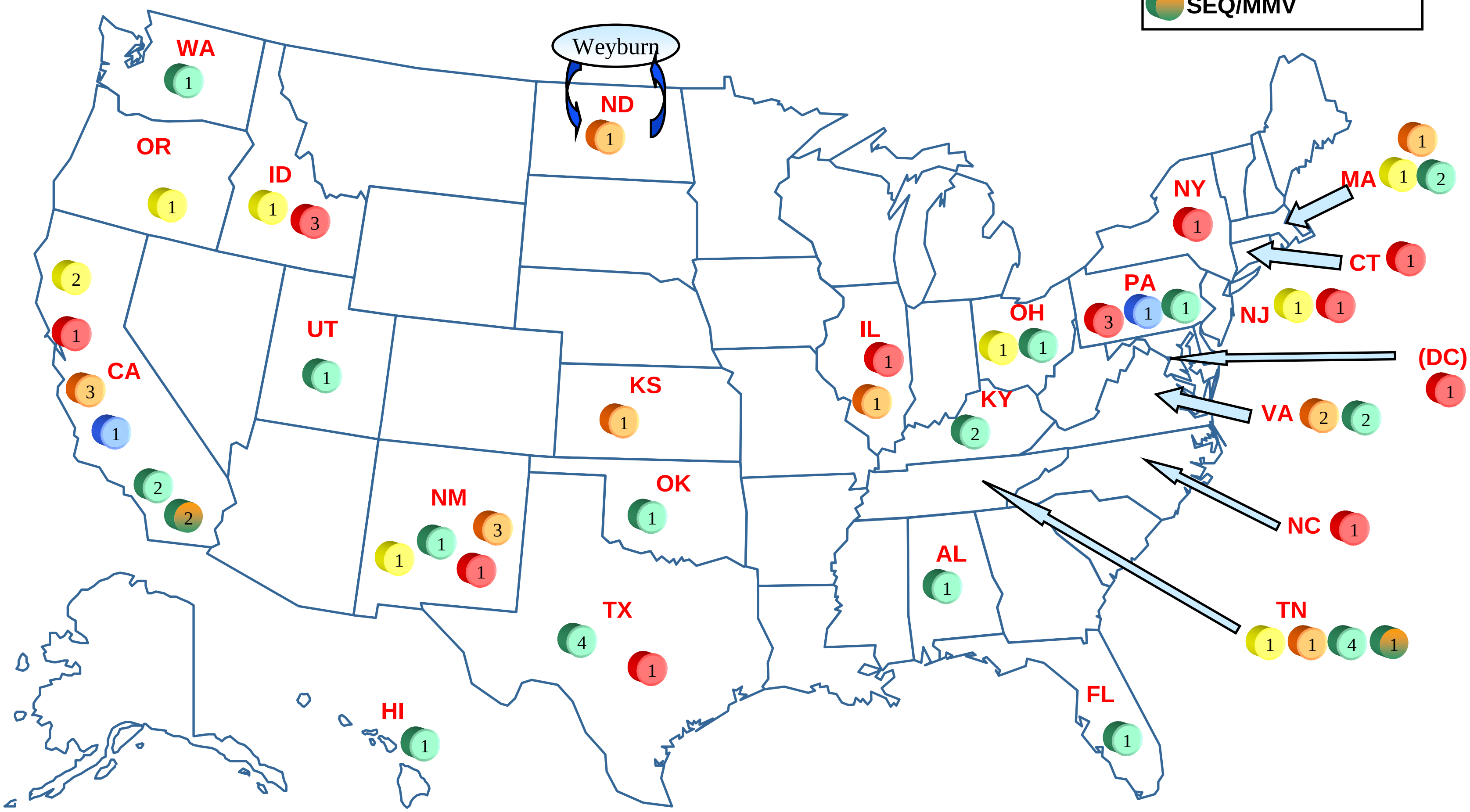
Carbon Sequestration Program Structure



Carbon Sequestration Projects

LEGEND

- Capture of CO_2
- MMV
- Sequestration
- Breakthrough
- Non-CO_2
- SEQ/MMV

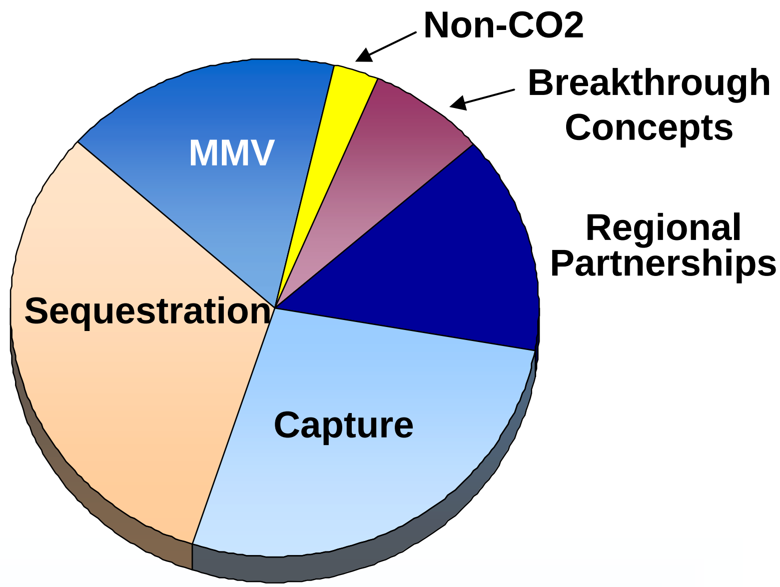


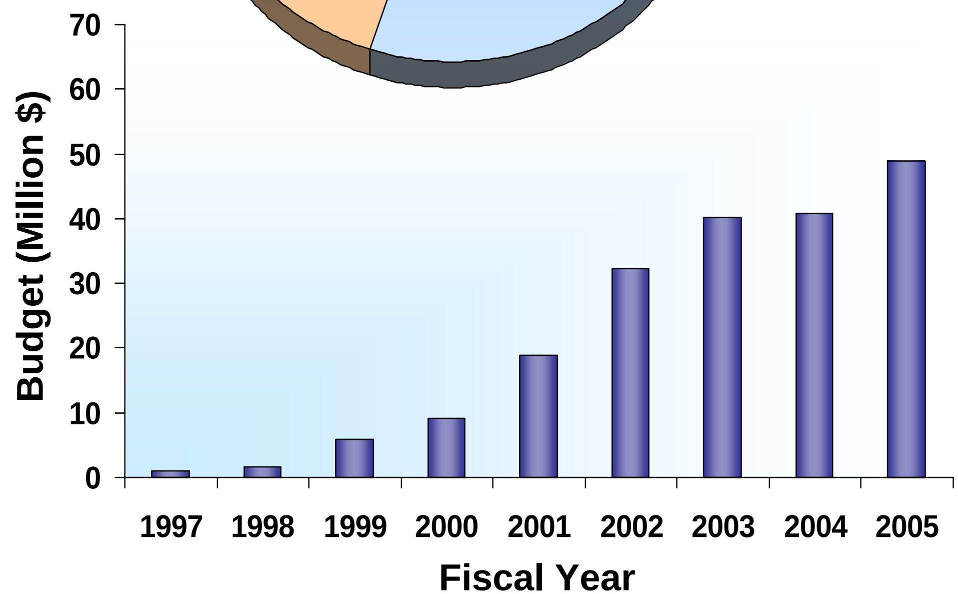
*Includes BP. Doesn't include NETL

Portfolio Overview – FY2004

Separation & Capture From Power Plants Plays Key Role

- **Diverse research portfolio**
  - 48 external projects
  - 16 focus area projects
  - BP & IEA consortia
- **Strong industry support**
  - ~ 36% cost share
- **Total portfolio ~ $140M**





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
- **Global Climate Change Initiative**
  - Contribute to reducing carbon intensity by 18% by 2012
  - Provide portfolio of commercially ready technologies for 2012

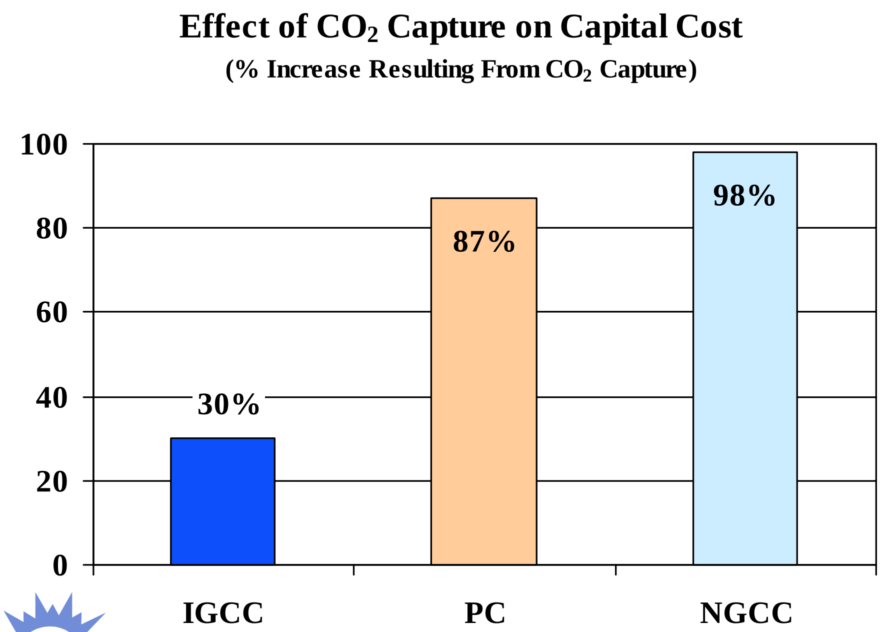
Cost Performance Goals

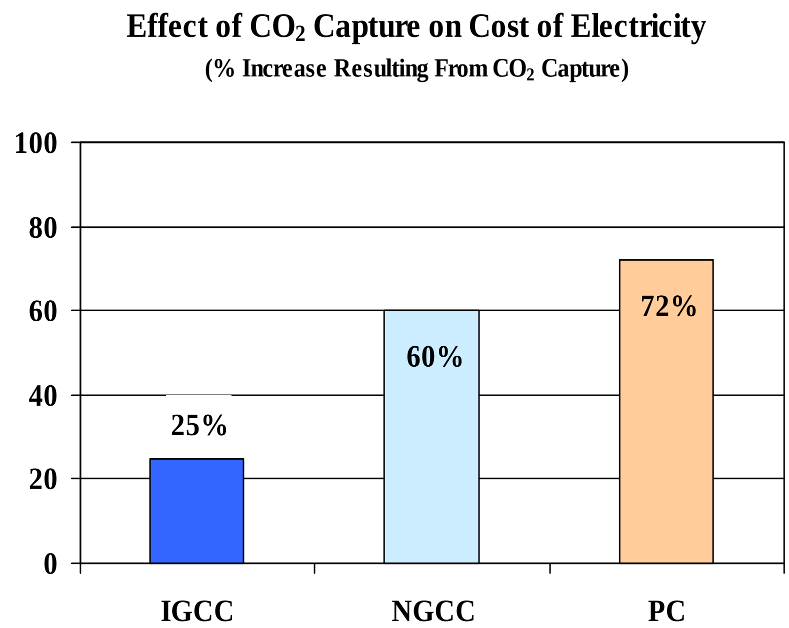
Year	COE Penalty IGCC Plants (% Increase)	COE Penalty PC Plants (% Increase)
2002	30	80
2007	20	45
2012	10	20
2015	<10	10
2018*	0	0

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

Status of Current "Best Case" Technologies
Using State-of-the-Art Scrubbing Technologies

- Significant capital cost (30% to 100% increase)
- Increased operating cost (25% to 100% increase)
- Parasitic power load ranges from 5% to 30%
- Decreased plant efficiencies (up to 30% decrease)





Separation and Capture Highlights

Many Advanced Integrated Schemes Emerging

Coal Gasification

CO_2 Hydrates
Membranes
Advanced Scrubbers
Inexpensive Oxygen
Chemical Looping

Pulverized Coal

Oxygen Combustion
Membranes
Advanced Scrubbers
New Sorbents
Mineral Carbonation
Chemical Looping

Pathways to Zero Emissions

Separation and Capture Overview

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

Technology Target
- **<10% increase in COE for new plants by 2012**
- **<20% increase in COE for existing 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**

- **NEXANT—CO_2 Hydrate**
- **NETL—Dry Sorbents**
- **MPTC—Ceramic Membranes**
- **BP—CO_2 Capture Project**
  Eltron—Membrane WGS
  Air Products—Enhanced WGS

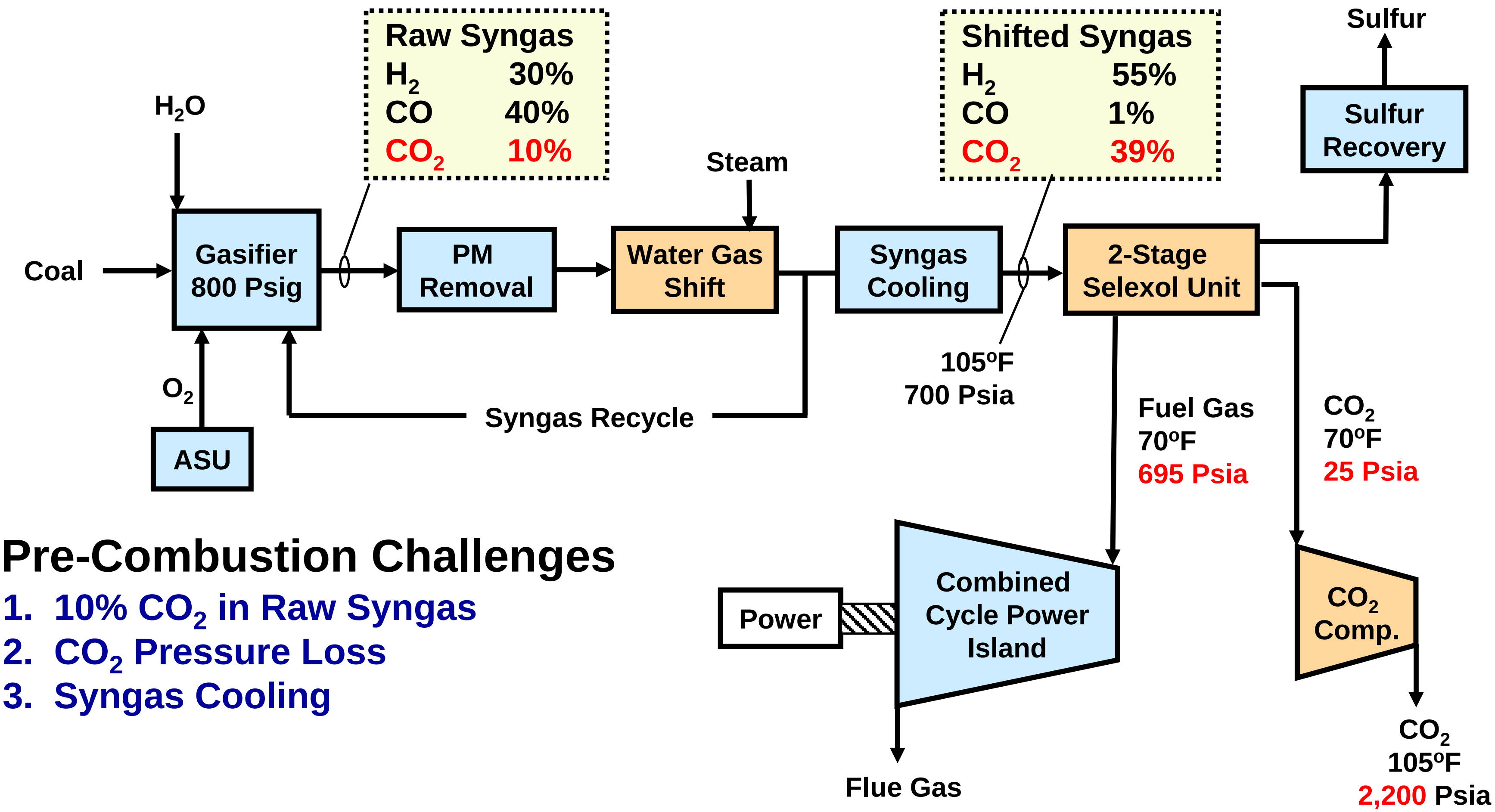
- **Praxair**—Oxyfuel boilers and process heaters
- **Alstom Power**—O_2 Fired CFB
- **Foster-Wheeler**—Technical/Economic viability of O2 enriched PC-Fired system

---

- **RTI**—Dry Regenerable Sorbents
- **NETL**—Regenerable Sorbents
- **NETL**—Amine Enriched Sorbents
- **UT Austin**—K2CO2/Piperazine adsorption
- **INEEL, LANL**—High Temperature polymer membrane

Pre-Combustion Current Technology

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

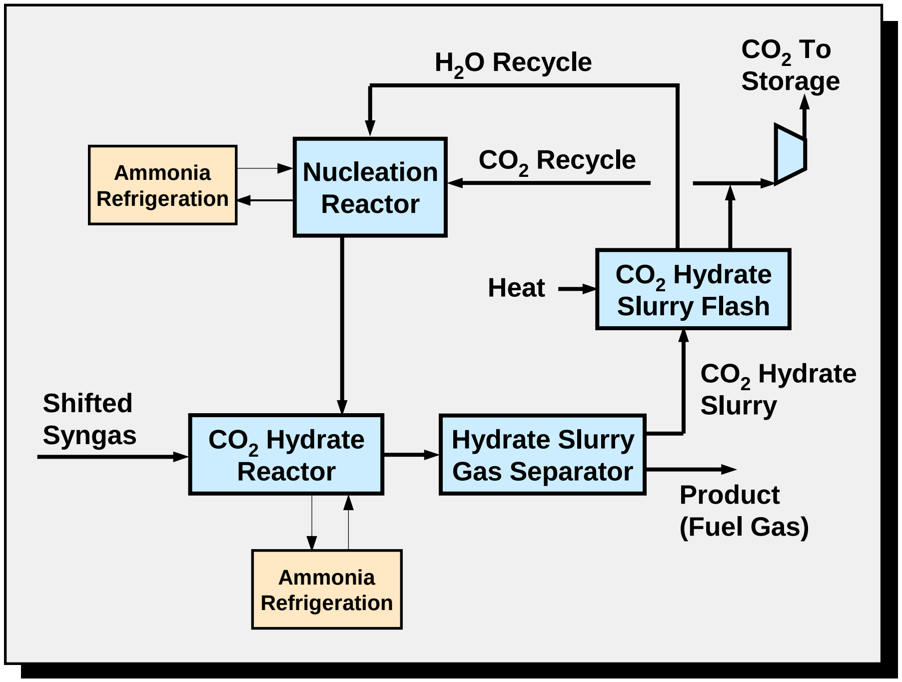
Source: *Evaluation of Innovative Fossil Fuel Power Plants with CO2 Removal*, DOE/EPRI, 1000316

Separation and Capture Highlights

CO_2 Hydrates

High Pressure Pre-Combustion CO_2 Capture Process

- **CO_2 capture by forming CO_2 Hydrates**
- **Maintains CO_2 Pressure**
  - Low CO_2 Compression Load
- **Promising preliminary economics**
- **Barriers**
  - Currently captures <60% of CO_2
  - High refrigeration load
  - Maintaining continuous hydrate formation
- **Project Status**
  - Very early development stage
  - Developing a continuous pilot plant



Participants: Nexant, SIMETECHE, LANL

Separation and Capture Highlights
Pressure/Temperature Swing Adsorption

- **Pre-Combustion CO_2 capture**
- **Pressure-Swing Adsorbents**
  – Improved adsorption capacity
- **Temperature-Swing Adsorbents**
  – Improved regeneration efficiency
  – Improved adsorption capacity
  – High syngas temperature (↑ Efficiency)
  – Maintain CO_2 pressure
- **Barriers**
  – Solid Transport, Attrition, Regeneration penalty, Capacity
- **Project Status**
  – Bench scale testing → preparing for pilot scale

Natural Zeolites
Synthetic Zeolites
NETL Sorbents

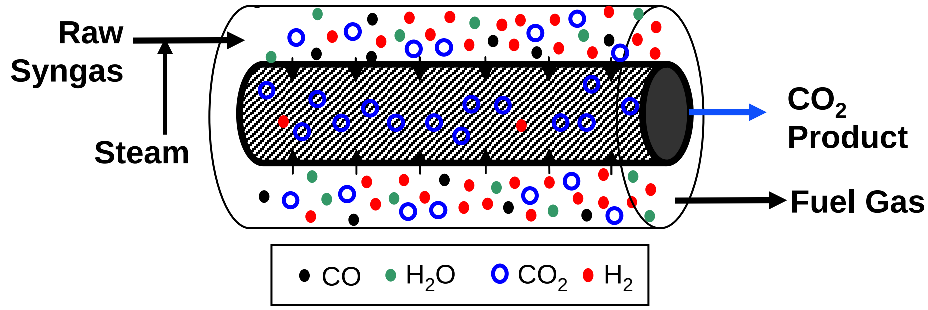
Participants: NETL, Carnegie Mellon University, Sud Chemie

NETL

Separation and Capture Highlights

CO_2 Selective Ceramic Membrane

$$CO + H_2O \Leftrightarrow CO_2 + H_2$$



- **Hydrotalcite/Ceramic membrane for selective CO_2 removal**
  - Continually shifts the equilibrium toward the production of H_2
  - Produces pure CO_2 stream for sequestration

- **Potential for high level of CO_2 capture at reduced cost while producing pure H_2**

- **Replaces WGS reactors and CO_2 capture unit**

- **Barriers**
  - Membrane durability, product is at reduced pressure, selectivity, permeability, contamination (particulates, sulfur)

Participants: Media and Process Technology & University of Southern California

Separation and Capture Highlights
Thermally Optimized Membrane

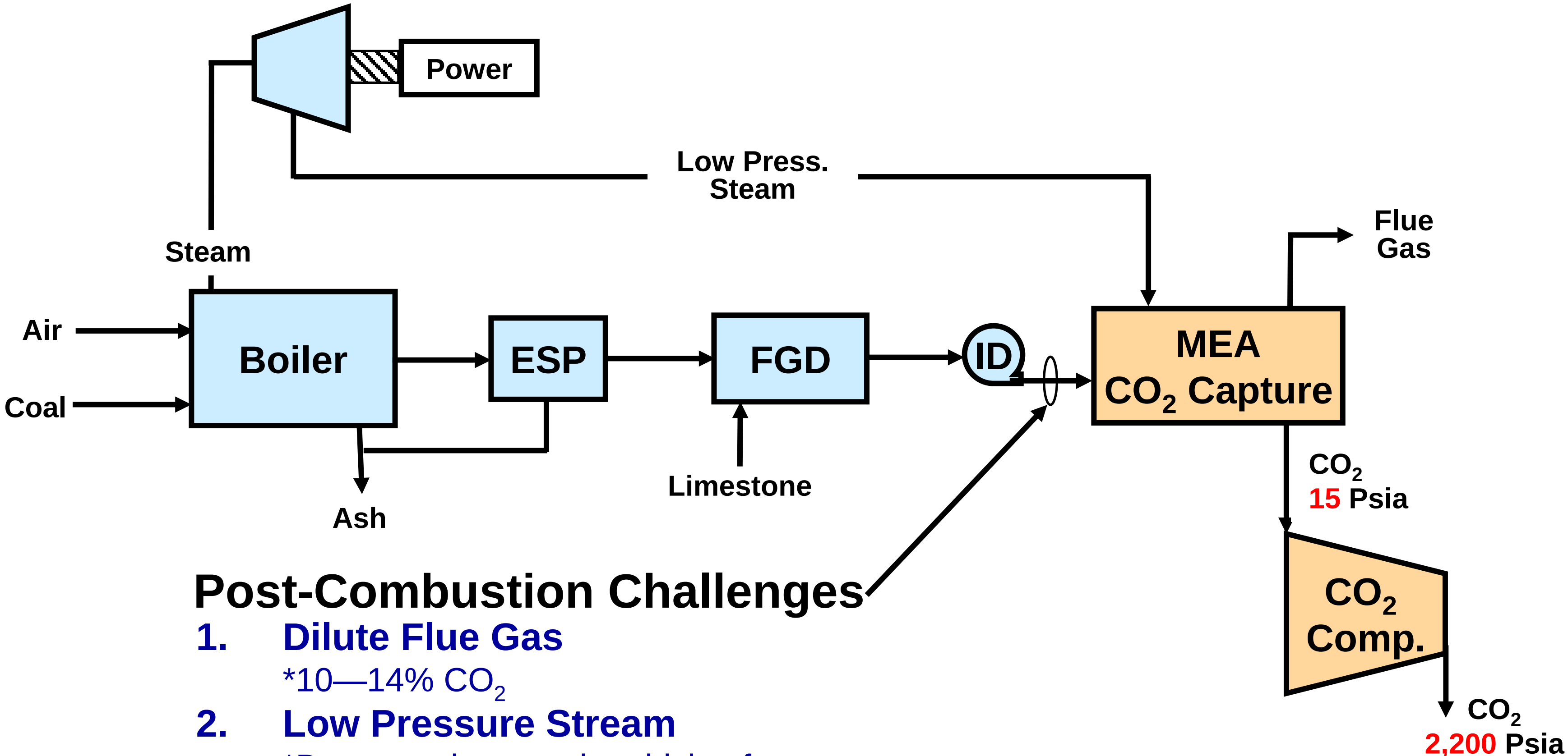
- **Develop high-temperature polymer membranes for more efficient separation of CO_2 from syngas streams**
- **Functional sites added to the structure of a polymer chain to facilitate transfer of CO_2 through the membrane**
- **Membranes operate at temperatures of 100 to 400ºC to take advantage of enhanced gas diffusion**
  - "Tune" CO_2 permeability as a function of temperature
- **Chemical resistance of polymer will maximize membrane life**

Participants: LANL, INEEL, Univ. Colorado, Pall Corp., Shell Oil

NETL

Post-Combustion Current Technology

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)**

NETL

Separation and Capture Highlights
Dry Regenerable Sorbents

Sodium carbonate used as a dry regenerable sorbent to capture CO_2

Advantages

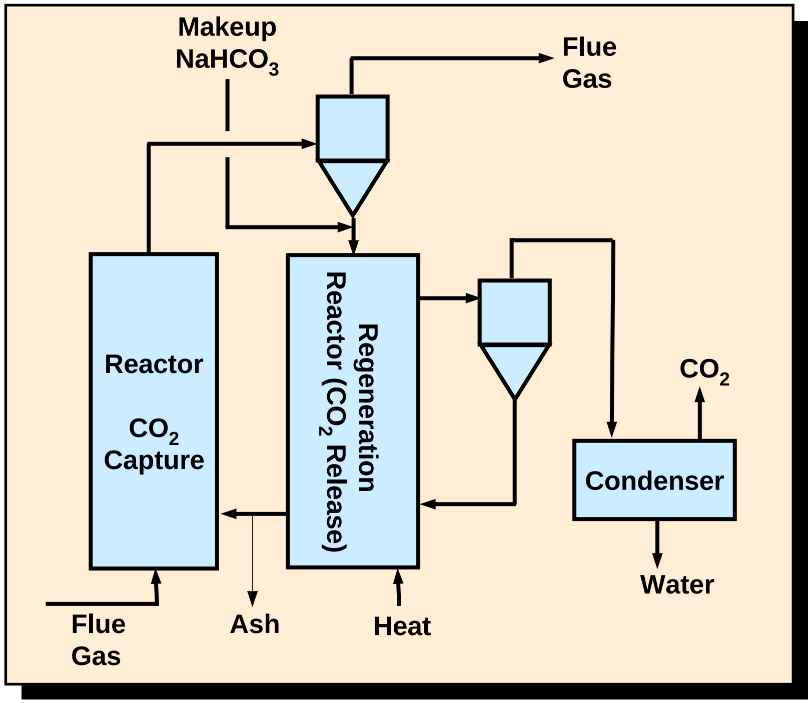
- Improved CO_2 Capacity
- Reduced Regeneration Energy
- Compatible with current power plant operating conditions (retrofit)

Barriers

- Continuous Solids Circulation
- Contaminants (SO_2, Particulates)

Project Status

- Bench-Scale Testing/Optimizing Designs



$$Na_2CO_3 + CO_2 + H_2O \Rightarrow 2NaHCO_3$$

$$2NaHCO_3 \Rightarrow Na_2CO_3 + CO_2 + H_2O$$

Participants: RTI, LSU, Church & Dwight

Separation and Capture Highlights

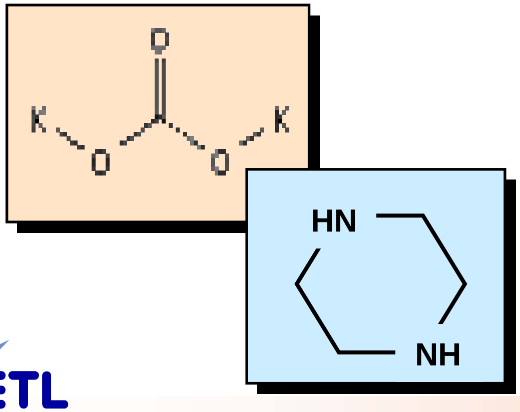
Advanced Liquid Sorbents—Potassium Carbonate

CO_2 Capture using potassium carbonate/piperazine
(K_2CO_3/PZ) complex

Pilot Plant

Advantages (Compared to MEA)

- **Greater CO_2 Capacity**
- **2-3 times faster absorption rate**
- **Improved Regeneration Energy**
  - 20 - 40% less energy
- **Target existing coal-fired power plants**



Project Status

- **Rigorous thermodynamic models complete (applicable to other CO_2 solvents)**
- **Pilot plant testing stage**

Participants: University of Texas at Austin

Separation and Capture Highlights

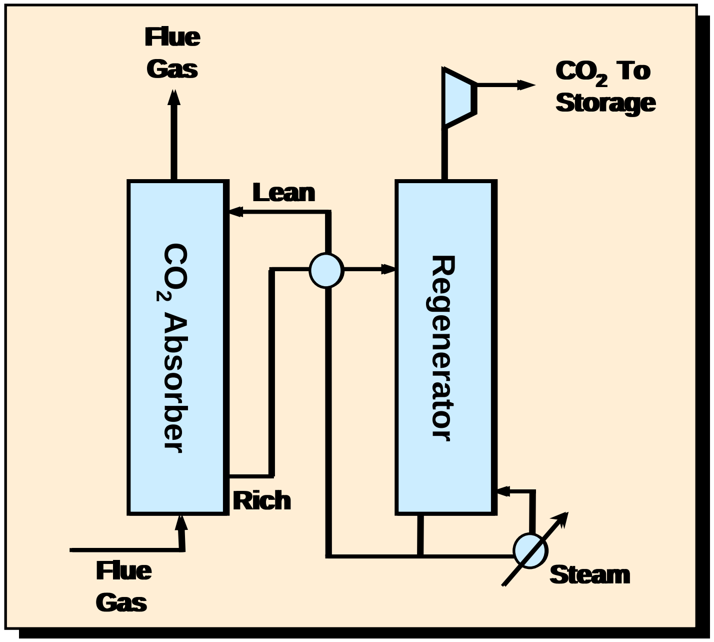
Advanced Liquid Sorbents—Aqueous Ammonia

Advantages

- Low theoretical heat of regeneration
  - 286 Btu/lb CO_2 vs. 825 Btu/lb for MEA
- Multi-pollutant control with salable by-products
  - $SO_2 \rightarrow (NH_4)_2SO_4$ (Ammonium Sulfate Fertilizer)
  - $NOx \rightarrow (NH_4)NO_3$ (Ammonium Nitrate Fertilizer)
- Applicable to retrofit and new power plant applications

Project Status

- Technology proven at laboratory-scale



$$NH_3 + H_2O + CO_2 \Longrightarrow NH_4HCO_3$$

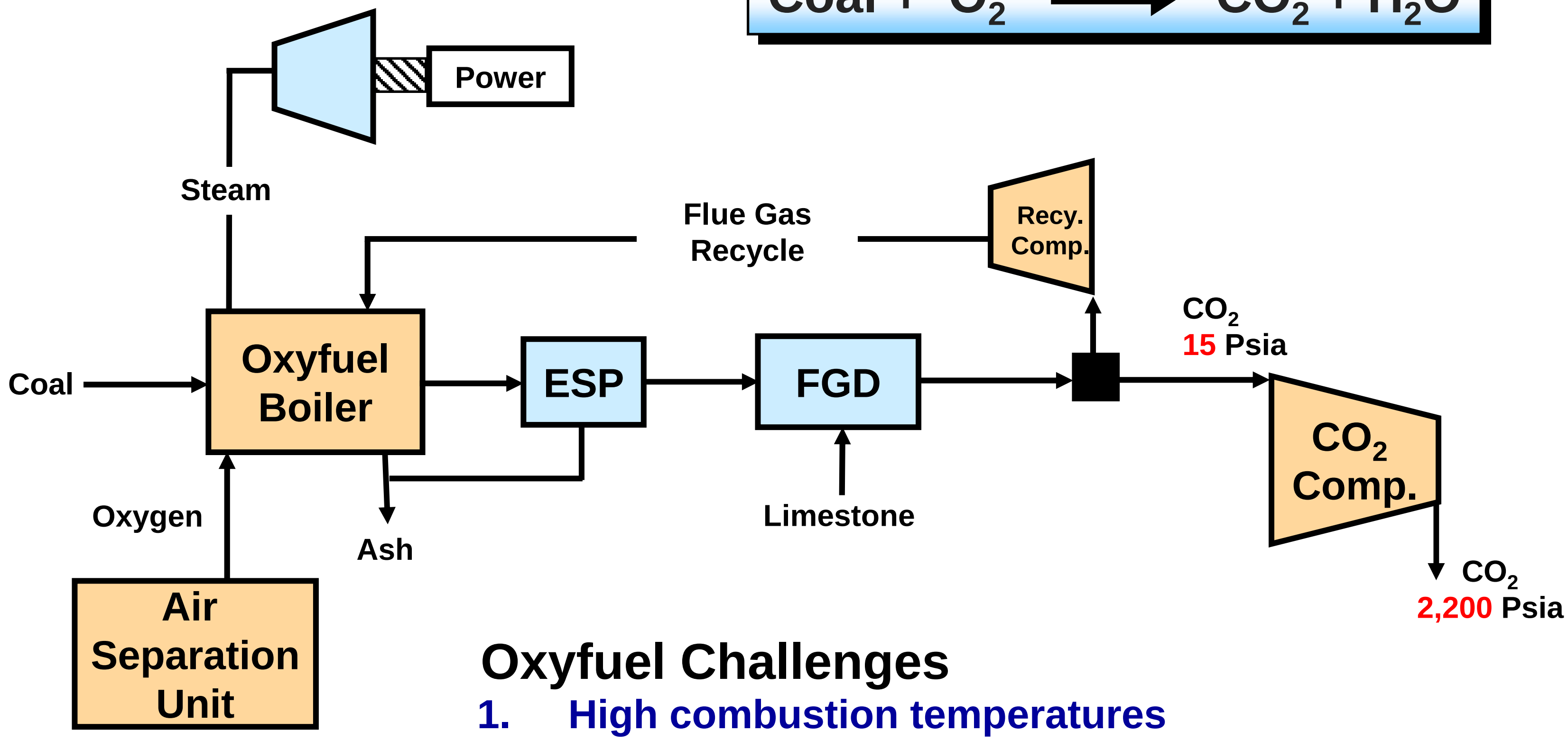
$$2NH_3 + H_2O + CO_2 \Longrightarrow (NH_4)_2CO_3$$

$$(NH_4)_2CO_3 + H_2O + CO_2 \Longrightarrow 2NH_4HCO_3$$

Participants: NETL

Pulverized Coal Oxyfuel Combustion

Coal + O_2 → $CO_2 + H_2O$



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

Separation and Capture Highlights

Oxygen Firing in Circulating Fluidized Bed Boilers

O_2 Fired CFB Advantages

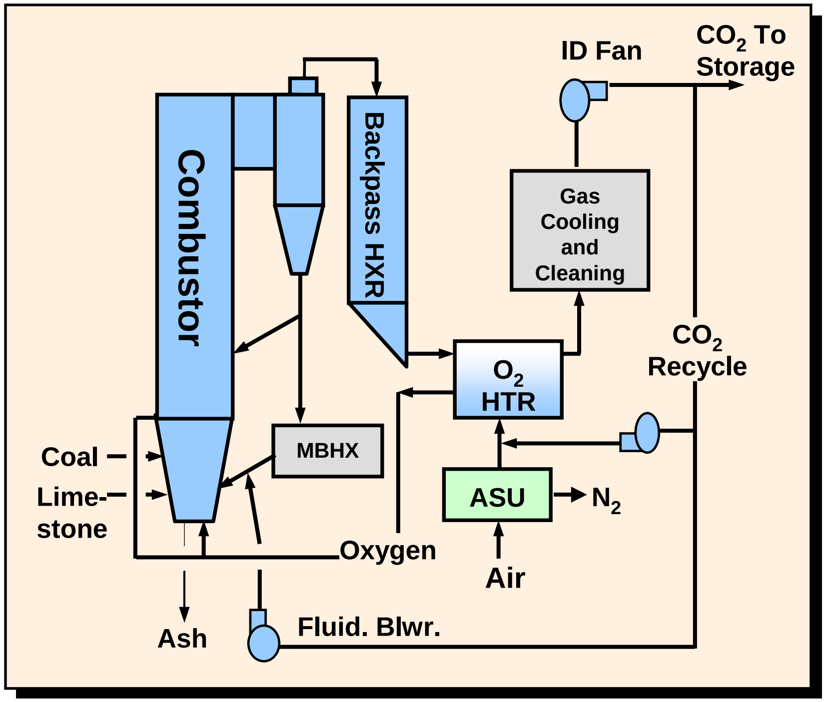
- **Temperature controlled with solids**
- **Lower CO_2 recycle→ Lower parasitic load**
- **Improved capital cost**

Barriers

- **Continuous solids circulation**
- **Cryogenic oxygen is expensive**
  - Consider O_2 membranes

Project Status

- **Proof-of-concept completed in 4-inch laboratory scale CFB**
- **Starting a large pilot facility in May 2004**



Participants: Alstom Power, ABB Lummus Global, Praxair, Parsons Energy

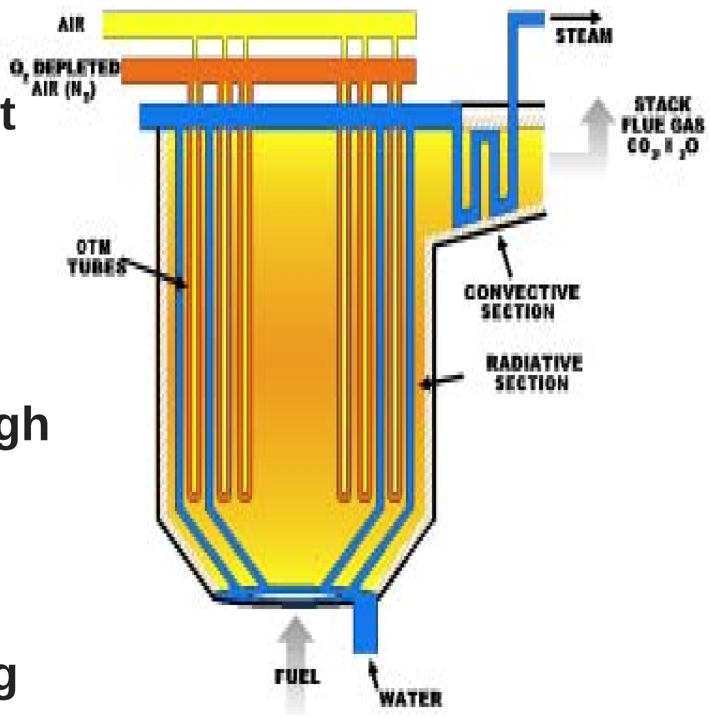
Separation and Capture Highlights
Oxyfuel Technology & Oxygen Transport Membrane

Ceramic oxygen transport membrane (OTM) incorporated into boiler

Advantages
- **Integrates high temperature oxygen transport membrane and O_2 combustion**
- **Significant reduction in power AND cost to generate O_2**

Barriers
- **Materials and system integration barriers (High Temperature Environment)**
- **Membrane durability**

Project Status
- **Modeling studies and laboratory scale testing**



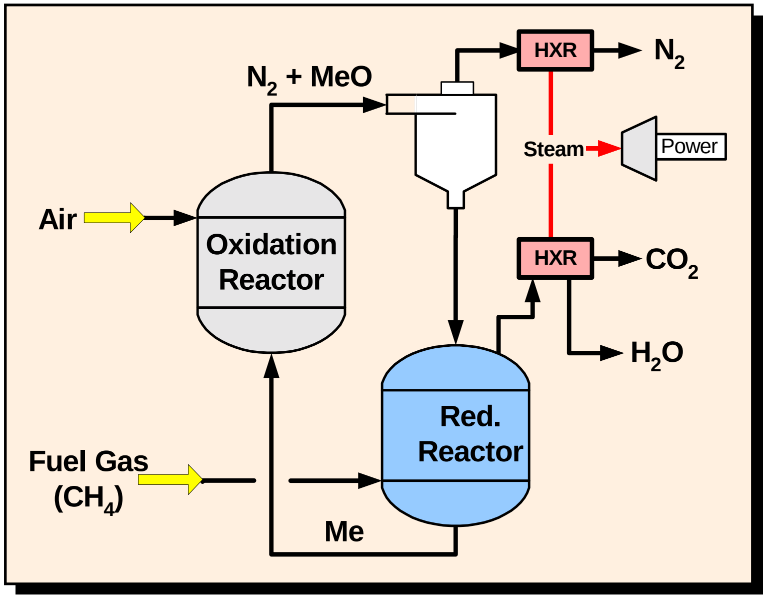
Participants: Praxair and Alstom Power

Separation and Capture Highlights
Chemical Looping

- Sorbent Energy Transfer System (SETS) or Accepter-Donor System
- Separation of CO_2 occurs during combustion
- Avoids direct contact of fuel and air and provides O_2 without air separation
- Pressurized 2-stage reactor system produces high pressure CO_2
- Low parasitic loads and cost benefits from no ASU

Project Status

- Conceptual design/bench scale



Principle of Chemical Looping

$$CH_4 + 4MeO \Longrightarrow CO_2 + H_2O + 4Me$$

(Me: Cu, Fe, CaS)

Participants: TDA Research, Alstom Power

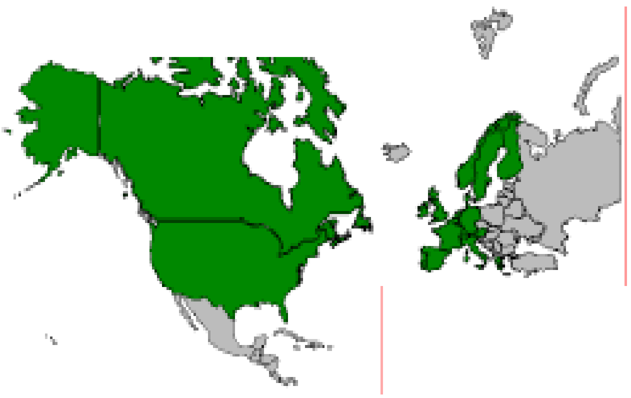
Separation and Capture Highlights
Breakthrough Concepts

- **Many terrestrial sequestration concepts being pursued (algae and enhanced photosynthesis)**
- **Photoreductive sequestration to form carbon products & fuel - SRI International**
- **Sequestration by mineral carbonation using a continuous flow reactor - Albany RC**
- **Chemical dissolution approaches to mineral sequestration – LANL**
- **8 New capture projects recently selected with support from NRC/NAS**

Separation and Capture Highlights

CO_2 Capture Project (CCP)

- **DOE has joined with eight major international energy companies**
- **Goal is to develop breakthrough technologies that reduce the cost of CO_2 capture and geologic storage**
  - Perform bench-scale R &D to prove feasibility
  - Develop guidelines for safe geologic sequestration
  - Develop promising technologies to proof-of-concept stage
  - Develop at least one large-scale application by 2010
- **CCP team represents a large market for new technologies**
  - New technologies could reduce worldwide emissions by 150 millions tons/year



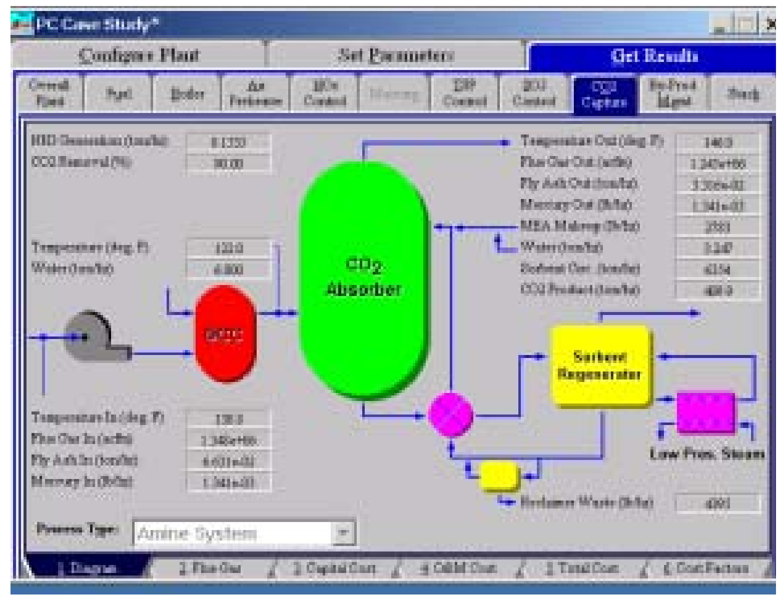
Participants: BP, ChevronTexaco, ENI, Norsk Hydro, Panfansdian, Shell, Statoil, Suncor

Separation and Capture Highlights

Modeling and Systems Analysis

- **Develop modeling and assessment tools to evaluate and compare the overall effectiveness, costs, and sequestration potential of alternative carbon management methods.**
- **Tools needed to help identify and prioritize the most promising R&D efforts.**

- **An easy-to-use, state-of-the-art computer model is being developed**
  - Allow systematic evaluation of CO_2 capture and storage technologies
  - Uncertainties and technological risks can be characterized
- **Result is a computer model called IECM-CS**
  - Publicly available at no cost
  - http://www.iecm-online.com/



Participants: CMU

NETL CO_2 Capture Facility

Modular, flexible CO_2 capture test facility developed at NETL

- Pilot scale
- Used to accelerate the development of low-cost capture and separation technologies
- Side-by-side comparison of advanced capture and separation concepts can be conducted (internal and external technology assessments)
- Used to investigate the impact of gaseous components (SO_2, NOx, H_2S, particulates and/or air toxics emissions)

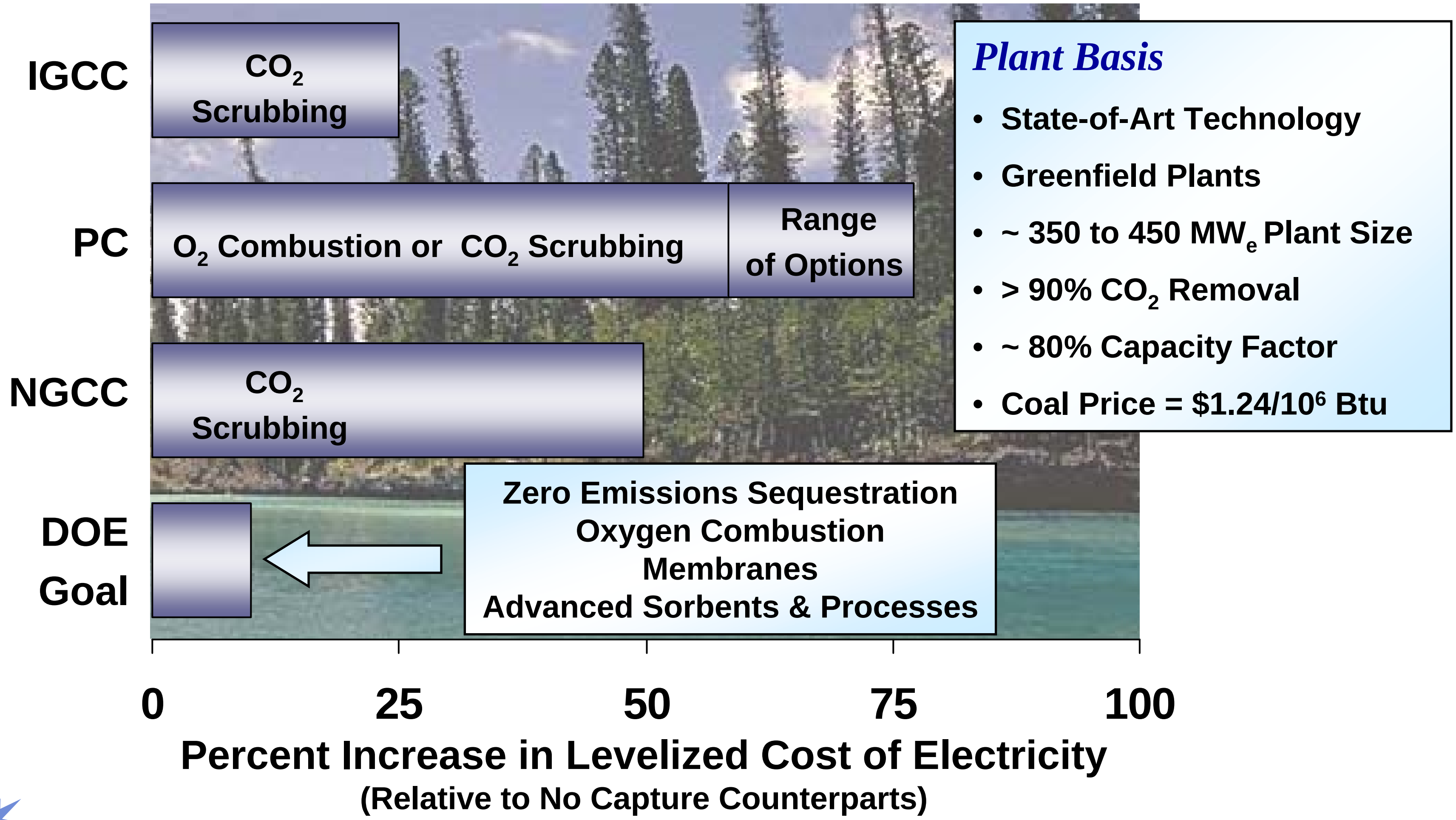
Capabilities

- Combustor can be fired with natural gas, coal or a combination
- Up to 40 lbs per hour of pulverized coal (110 scfm flue gas)
- In the fuel gas mode, the system blends various high pressure gases to simulate the gas composition found in gasification processes

Participants: NETL

Separation and Capture

A Challenging Task Ahead

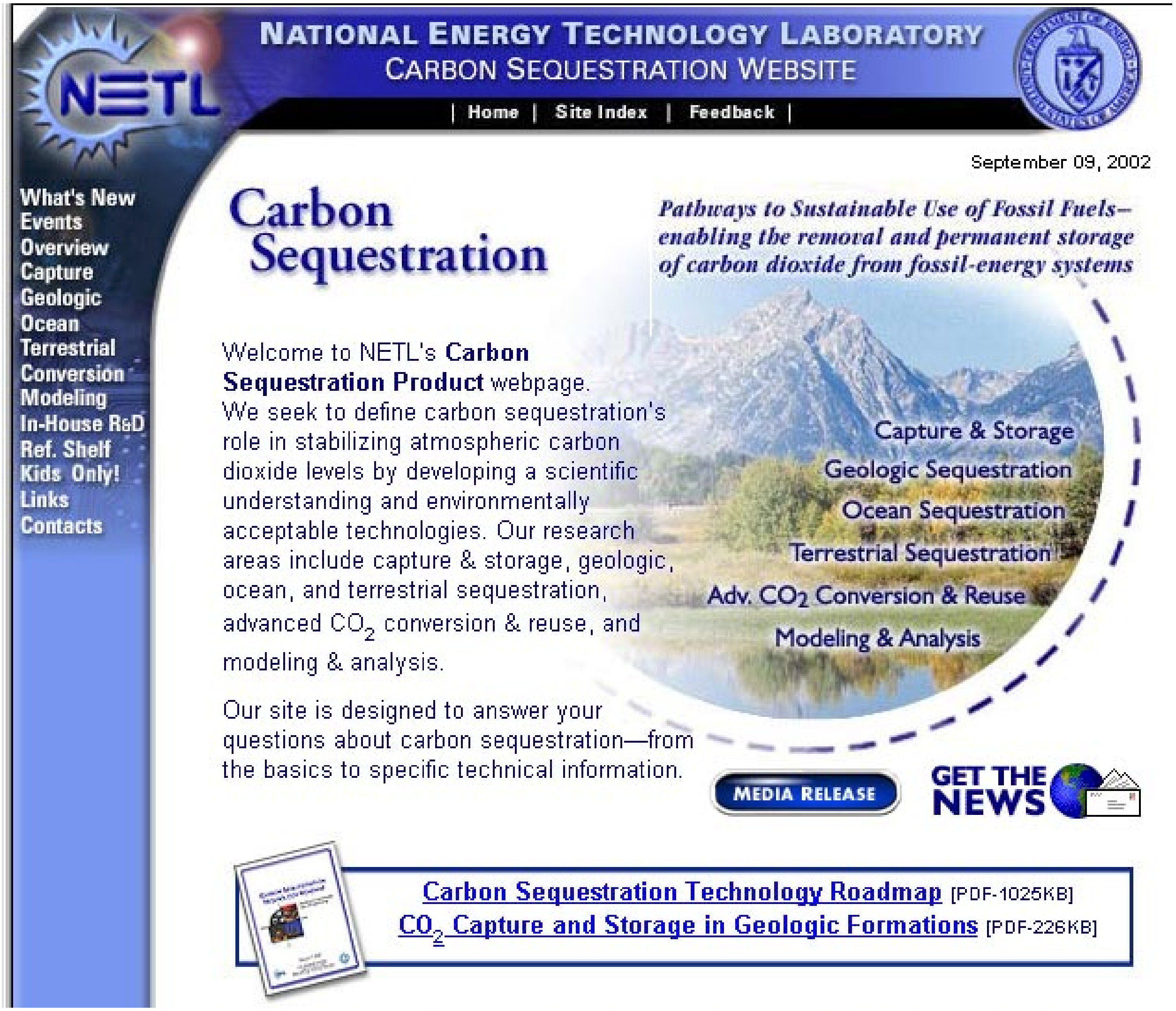


NETL

Sources: Derived From NETL, EPRI, Alstom

Visit Our NETL Sequestration Website

www.netl.doe.gov/coalpower/sequestration/



Carbon Sequestration E-mail Newsletter

Subscribe for The Carbon Sequestration Newsletter

Each month, NETL publishes a short newsletter describing significant events related to carbon sequestration that have taken place over the past month. This newsletter is posted here on our website's Reference Shelf and distributed by e-mail. If you'd like to join the e-mail distribution list, please refer to the Subscription Directions page for more information as to "Subscribing" and "Unsubscribing" to our mailing list.