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

**Core R&D**
- Capture of CO₂
- Sequestration
  - Direct CO₂ storage
  - Enhanced natural sinks
- Measurement, Monitoring & Verification
- Non-CO₂ GHG Mitigation
- Breakthrough Concepts

**Integration**
- Power/Sequestration Complex
  - First-of-kind integrated project
  - Verify large-scale operation
  - Highlight best technology options
  - Verify performance & permanence
  - Develop accurate cost/performance data
  - International showcase

**Infrastructure**
- 7 Regional Partnerships
  - Engage regional, state, local governments
  - Determine regional sequestration benefits
  - Baseline region for sources and sinks
  - Establish monitoring and verification protocols
  - Address regulatory, environmental, & outreach issues
  - Test sequestration technology at small scale

- **Initiated FY 2003**
- **Initiated FY 2004**
Carbon Sequestration Projects

*Includes BP. Doesn’t include NETL.

LEGEND
- Capture of CO₂
- MMV
- Sequestration
- Breakthrough
- Non-CO₂
- SEQ/MMV
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 CO₂ 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

<table>
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<th>Year</th>
<th>COE Penalty IGCC Plants (% Increase)</th>
<th>COE Penalty PC Plants (% Increase)</th>
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<tr>
<td>2002</td>
<td>30</td>
<td>80</td>
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<tr>
<td>2007</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td>2012</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>2015</td>
<td>&lt;10</td>
<td>10</td>
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<tr>
<td>2018*</td>
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*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)

**Effect of CO₂ Capture on Capital Cost**

<table>
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<tr>
<th>Technology</th>
<th>Increase Resulting From CO₂ Capture</th>
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<tr>
<td>IGCC</td>
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<tr>
<td>PC</td>
<td>87%</td>
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<tr>
<td>NGCC</td>
<td>98%</td>
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**Effect of CO₂ Capture on Cost of Electricity**

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<th>Technology</th>
<th>Increase Resulting From CO₂ Capture</th>
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<tr>
<td>IGCC</td>
<td>25%</td>
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<tr>
<td>NGCC</td>
<td>60%</td>
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<tr>
<td>PC</td>
<td>72%</td>
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Separation and Capture Highlights
Many Advanced Integrated Schemes Emerging

**Coal Gasification**
- CO₂ 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

Outcomes

- Efficient low-cost electricity and hydrogen production with low GHG emissions
- Commercially viable options for retrofit of existing plants to reduce CO2 emissions

Technology Target

- <10% increase in COE for new plants by 2012
- <20% increase in COE for existing plants by 2012
- >90% CO2 Capture capability
- Safe and Effective

Commercialization

Open Category
- Carnegie Mellon Univ.—Modeling assessment tools
- Princeton Univ.—Conceptual CO2 capture designs
- ANL—Evaluation of CO2 Capture Options

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

- NEXANT—CO2 Hydrate
- NETL—Dry Sorbents
- MPTC—Ceramic Membranes
- BP—CO2 Capture Project
- Eltron—Membrane WGS
- Air Products—Enhanced WGS

Oxyfuel
- O2 Selective Membranes
- Advanced Cooling Cycles
- Compact Boilers

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

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

- 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 CO₂ Scrubbing**

- **Raw Syngas**
  - H₂: 30%
  - CO: 40%
  - CO₂: 10%

- **Shifted Syngas**
  - H₂: 55%
  - CO: 1%
  - CO₂: 39%

**Pre-Combustion Challenges**
1. 10% CO₂ in Raw Syngas
2. CO₂ 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 CO₂ capture
- Pressure-Swing Adsorbents
  - Improved adsorption capacity
- Temperature-Swing Adsorbents
  - Improved regeneration efficiency
  - Improved adsorption capacity
  - High syngas temperature (↑Efficiency)
  - Maintain CO₂ 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
Separation and Capture Highlights

**CO₂ Selective Ceramic Membrane**

- **Hydrotalcite/Ceramic membrane for selective CO₂ removal**
  - Continually shifts the equilibrium toward the production of H₂
  - Produces pure CO₂ stream for sequestration

- **Potential for high level of CO₂ capture at reduced cost while producing pure H₂**

- **Replaces WGS reactors and CO₂ capture unit**

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

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**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 CO₂ from syngas streams

- Functional sites added to the structure of a polymer chain to facilitate transfer of CO₂ through the membrane

- Membranes operate at temperatures of 100 to 400°C to take advantage of enhanced gas diffusion
  - “Tune” CO₂ permeability as a function of temperature

- Chemical resistance of polymer will maximize membrane life

Participants: LANL, INEEL, Univ. Colorado, Pall Corp., Shell Oil
Post-Combustion Current Technology
_Pulverized Coal Power Plant with CO₂ Scrubbing_

Post-Combustion Challenges

1. **Dilute Flue Gas**
   *10—14% CO₂*
2. **Low Pressure Stream**
   *Decreased separation driving force*
3. **Contaminants**
   *SO₂, Particulates, etc.*
4. **Large Parasitic Load (regeneration steam)**
Separation and Capture Highlights

Dry Regenerable Sorbents

Sodium carbonate used as a dry regenerable sorbent to capture CO₂

Advantages
- Improved CO₂ Capacity
- Reduced Regeneration Energy
- Compatible with current power plant operating conditions (retrofit)

Barriers
- Continuous Solids Circulation
- Contaminants (SO₂, Particulates)

Project Status
- Bench-Scale Testing/Optimizing Designs

Participants: RTI, LSU, Church & Dwight

\[ \text{Na}_2\text{CO}_3 + \text{CO}_2 + \text{H}_2\text{O} \rightarrow 2\text{NaHCO}_3 \]

\[ 2\text{NaHCO}_3 \rightarrow \text{Na}_2\text{CO}_3 + \text{CO}_2 + \text{H}_2\text{O} \]
Separation and Capture Highlights
Advanced Liquid Sorbents—Potassium Carbonate

CO₂ Capture using potassium carbonate/piperazine (K₂CO₃/PZ) complex

Advantages (Compared to MEA)
• Greater CO₂ 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 CO₂ 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 CO₂ vs. 825 Btu/lb for MEA
- Multi-pollutant control with salable by-products
  - SO₂ → (NH₄)₂SO₄ (Ammonium Sulfate Fertilizer)
  - NOₓ → (NH₄)NO₃ (Ammonium Nitrate Fertilizer)
- Applicable to retrofit and new power plant applications

Project Status

- Technology proven at laboratory-scale

Participants: NETL

NH₃ + H₂O + CO₂ → NH₄HCO₃
2NH₃ + H₂O + CO₂ → (NH₄)₂CO₃
(NH₄)₂CO₃ + H₂O + CO₂ → 2NH₄HCO₃
Pulverized Coal Oxyfuel Combustion

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

O₂ Fired CFB Advantages
- Temperature controlled with solids
- Lower CO₂ recycle → Lower parasitic load
- Improved capital cost

Barriers
- Continuous solids circulation
- Cryogenic oxygen is expensive
  - Consider O₂ 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 $\text{O}_2$ combustion
- Significant reduction in power AND cost to generate $\text{O}_2$

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 Acceptor-Donor System
- Separation of CO₂ occurs during combustion
- Avoids direct contact of fuel and air and provides O₂ without air separation
- Pressurized 2-stage reactor system produces high pressure CO₂
- Low parasitic loads and cost benefits from no ASU

Project Status
- Conceptual design/bench scale

Principle of Chemical Looping

\[ \text{CH}_4 + 4\text{MeO} \rightarrow \text{CO}_2 + \text{H}_2\text{O} + 4\text{Me} \]

(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

**CO₂ Capture Project (CCP)**

- DOE has joined with eight major international energy companies
- Goal is to develop breakthrough technologies that reduce the cost of CO₂ 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 CO₂ 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 CO₂ Capture Facility

**Modular, flexible CO₂ 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 (SO₂, NOx, H₂S, 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

Plant Basis
- State-of-Art Technology
- Greenfield Plants
- ~ 350 to 450 MW<sub>e</sub> Plant Size
- > 90% CO<sub>2</sub> Removal
- ~ 80% Capacity Factor
- Coal Price = $1.24/10^6 Btu

Sources: Derived From NETL, EPRI, Alstom
Visit Our NETL Sequestration Website
www.netl.doe.gov/coalpower/sequestration/

Welcome to NETL's Carbon Sequestration Product webpage. We seek to define carbon sequestration's role in stabilizing atmospheric carbon dioxide levels by developing a scientific understanding and environmentally acceptable technologies. Our research areas include capture & storage, geologic, ocean, and terrestrial sequestration, advanced CO₂ conversion & reuse, and modeling & analysis.

Our site is designed to answer your questions about carbon sequestration—from the basics to specific technical information.

Carbon Sequestration Technology Roadmap [PDF-1025KB]
CO₂ Capture and Storage in Geologic Formations [PDF-226KB]
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