The U.S. Department of Energy/NETL Carbon Dioxide Capture R&D Program

Regina, Saskatchewan
September 5, 2012
Pulverized Coal Power Plant System

*Post-combustion CO₂ Scrubbing*

**Post-combustion advantages:**
- Back-end retrofit
- Slip-stream (0 to 90% capture)

**Amine scrubbing Advantages:**
- Proven Technology (Petroleum refining, NG purification)
- Chemical solvent → High loadings at low CO₂ partial pressure
- Relatively cheap chemical ($2-3/lb)

**Key Challenges:**
- Dilute flue gas (12-15 volume %)
- 2-3 MM acfm for a 500-600 Mwe plant
- ~50% currently scrubbed for SOx/NOx
- Increased cooling requirements
IGCC Power Plant System

Pre-combustion CO$_2$ Scrubbing

IGCC CO$_2$ Capture Advantages:
- High chemical potential (Temp, P$_{CO2}$)
- Low Volume Syngas Stream

Selexol™ CO$_2$ Capture Advantages:
- 30+ years of commercial operation (55 worldwide plants)
- Physical Liquid Sorbent
- Highly selective for H$_2$S and CO$_2$
- CO$_2$ is produced at “some” pressure

Key Challenges:
- Complex, integrated power process
- Additional process (WGS) to get high capture rates
- Current technology (Selexol) requires cooling and reheating
Pulverized Coal Oxyfuel Combustion
Technology Opportunities

Cheap Oxygen
Oxygen Membranes

Coal + O₂ → CO₂ + H₂O

Advanced MOC*
Reduce CO₂ Recycle
Handle High Sulfur Con.

ASU
Steam
95-99% O₂
Power

PC Boiler (No SCR)
Bag Filter
ID Fans

Advanced Compression
Ramgen, SwRI

Oxyfuel Boilers
Compact Boiler Designs
Adv. Materials (USC)
Advanced Burners

Advanced Materials (USC)

Co-Sequestration
Multi-pollutant capture

*Materials of Construction
Stages of Energy RD&D

DOE Research Programs

Research Phases

Basic Research

Applied Research

Process & Engineering Development

Demonstration & Commercialization

Office of Science Research

Fossil Energy Advanced Research

Fossil Energy Core Programs

CCPI, ICCS, FutureGen
DOE/NREL CO₂ Capture RD&D

R&D Programs
- Carbon Capture
  - Post-Combustion
  - Pre-Combustion
- Advanced Energy Systems
  - Advanced Combustion
  - Gasification
  - Fuels
  - Fuel Cells
  - Turbines
- Carbon Storage
- Cross-Cutting Research
- Office of Research & Development
- Office of Program Planning & Analyses

NETL’s Carbon Capture R&D

Demonstration Programs
- Clean Coal Power Initiative
- FutureGen 2.0
- Industrial Carbon Capture and Storage
CO₂ Solvents

**R&D Focus**
- High CO₂ working capacity, **optimal** ΔHrxn, low heat capacity, non-volatile
- Fast kinetics (enzymes)
- Improved mass transfer systems
- Thermally and chemically stable
- Non-corrosive, environmentally safe
- Low cost solvent
- Match process to solvent (MOC)

**Solvent Technologies**
- High capacity oligomers
- Ionic liquids
- Phase change solvents
- Amino Acids
- Carbonates

**Partners:**
1. GE Research Corporation (Polymers)
2. Akermin (Enzymes)
3. Ion Engineering (IL/Amine mixtures)
4. Siemens Energy (Amino Acids)
5. University of Notre Dame (IL)
6. Georgia Tech. (IL)
7. Illinois St. Geological Survey (Carbonate)
8. 3H (Phase change)
9. University of Illinois (Carbonate)
10. URS Group
11. Southwest Research Institute (Carbonate)*
12. LBNL (Bicarbonate, Membrane ILs)
13. NETL (ILs, Phase change, Molecular simulations)

**Status:**
- 2011: Bench scale → 2.5 MWe slipstream design
- 2016: 10–25 MWe Pilot Scale
- 2020: 50 MWe — **ready for demonstration**

*Pre-combustion Applications
CO$_2$ Sorbents

R&D Focus

- **Optimal** CO$_2$ working capacity, low heat capacity, fast kinetics (enzymes)
- Durability: thermally, chemically and physically stable
- Non-corrosive, environmentally safe
- Low cost sorbent and process MOC
- Match process to sorbent (system)
- Hybrid (Shift + Capture) for IGCC

Project Types

- Supported amines (silica, clay)
- MOFs
- Carbon-based
- Alumina
- Water-gas shift (IGCC)
- Sorbent systems development

Partners:

1. University of Akron (amine functionalized metal zeolites)
2. ADA-ES (amine, zeolites, process design)
3. SRI International (Carbon-based)
4. TDA (Carbon, alumina)*
5. URS Group (IGCC WGS sorbent)
6. NETL ORD (Supported amines, MOFs)

Status:

- 2011: Bench scale $\rightarrow$ 1 MWe slipstream design (ADA-ES)
- 2016: 10 – 25 MWe Pilot Scale
- 2020: 50 MWe – ready for demonstration
Advanced Separation Membranes

Membrane Advantages
• Simple operation; no chemical reactions, no moving parts
• Tolerance to acid gases & O₂
• Compact, modular → small footprint
• Builds on existing technology at similar scale (NG purification)

Membrane Approaches
• Spiral wound & hollow fiber
• Cryogenic membrane separation
• Membrane/solvent hybrid
• Integrated water-gas shift*
• H₂ Selective zeolite*
• High Temperature Polymer*
• Nanoporous*
• PSA/Membrane Hybrid*
• Palladium Alloy*

Partners:
1. Membrane Technology Research (MTR)
2. RTI International
3. Air Liquide
4. Gas Technology Institute
5. Univ. of Minnesota*
6. Pall Corporation*
7. Arizona State University*
8. Gas Tech. Institute*
9. Membrane Technology*
10. New Jersey Institute of Technology*
11. LANL/SRI*

Status:
2011: Bench scale → 1 MWe slipstream design (MTR)
2015: 5 – 25 MWe Pilot Scale
2020: 50 MWe – ready for demonstration

* Pre-combustion Applications
Pulverized Coal Oxy-combustion

R&D Focus
- Oxygen Separation
- Air infiltration (new and existing boilers)
- Corrosion and process control
- Boiler Designs, heat transfer
- Excess O₂ and inerts (N₂, Ar..)
- Pressurized Systems

Project Types
- O₂ membrane
- “2nd Gen” oxyboiler designs
  - Adv. Materials and burners
- Existing boiler retrofits
  - Air leakage, heat transfer, corrosion, process control
- CO₂ purification
- Chemical Looping

Partners:
1. Praxair (O₂ Membrane, CO₂ Purification)
2. Air Products (CO₂ Purification)
3. Jupiter Oxygen (Burners)
4. Alstom (Pilot plant)
5. B&W (Cyclone pilot test)
6. Foster Wheeler (Corrosion)
7. Reaction Engineering Int. (Retrofit)
8. Southern Research Institute (Retrofit)
9. NETL ORD (Modeling, CO₂ Purification)

Status:
2011: 10 MWe wall-fired test (B&W)
  5 MWe T-fired pilot (Alstom)
  5 MWe burner pilot (Jupiter)
2015: 1st Gen (Cryogenic) demo.
2020: 2nd Gen* demonstration

Advanced CO₂ Compression

Challenges
- Scale-up (550 MWe plant = 15,000 TPD)
- Parasitic load
- Contaminants (O₂, SOx, NOx, …)
- Cost

R&D Objectives
- Increase compression efficiency
- Reduce footprint and capital cost
- Power plant integration/heat recovery

Approach 1:
High PR 2-Stage
Inter-stage Heat Recovery

Approach 2:
Compression → Cool → Pump
National Carbon Capture Center at the Power Systems Development Facility (PSDF)

Goal
Develop technologies under realistic conditions that will reduce the cost of advanced coal-fueled power plants with CO₂ capture

Post-combustion Carbon Capture Center

- Plant Gaston
  - 880 MWe
  - 12,000 tpd CO₂
  - ID Fan
  - FGD

- 3 MWe
  - 60 tpd CO₂

- 1 MWe
  - 20 tpd CO₂

- < 0.1 MWe
  - < 2 tpd CO₂

Bench Scale Units

- 1
- 2
- 3
- 4

Pilot Test Unit #1

Pilot Test Unit #2

Pilot Solvent Test Unit (PSTU)

0.5 MWe
(10 tpd CO₂)
0.5 MWe Slipstream: Carbon Absorber Retrofit Equipment (CARE)
Neumann Systems Group

- Design and construct a module of the NeuStream-C absorber technology that is highly compact and operates with a high mass transfer solvent on Colorado Springs Utilities Drake #7 coal-fired power plant.

Flat Jet Gas/Liquid Contactor

- High specific surface area flat jet nozzle technology engineered in a modular, scalable, efficient, cross-flow, gas liquid contactor
CO₂ Capture Program Goals

By 2020, have ready for demonstration, 2\textsuperscript{nd} generation technologies that achieve:

<table>
<thead>
<tr>
<th>Post- and Oxy-combustion</th>
<th>Pre-combustion (IGCC)</th>
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<tbody>
<tr>
<td>90% CO₂ capture</td>
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<tr>
<td>Compression, transport, storage</td>
<td>Compression, transport, storage</td>
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<tr>
<td>&lt; 35% increase in COE</td>
<td>&lt; 10% increase in COE</td>
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Market-Based Approach

Putting CO₂ to Work – Carbon Utilization for Enhanced Oil Recovery
Carbon Capture Utilization and Storage (CCUS)

- \textit{2\textsuperscript{nd} Generation} CCUS technology will result in capture cost of <$40/tonne
  - Satisfy strong EOR market opportunities
  - Meet broad acceptance
  - Enable a significant increase in domestic oil production.

- \textit{Transformational} CCUS technology will result in capture cost of <$10/tonne
  - Open greater domestic EOR opportunities
  - Expand beneficial utilization opportunities such as conversion of CO₂ to higher value chemicals
  - Deliver advanced higher performance coal-fueled energy systems that can compete with NGCC
NETL Pathway Study

• Pathway begins with 1st generation supercritical PC plant with today’s post-combustion capture technology
• Extend the pathway to include emerging technologies and estimate their performances at a mature stage of development (i.e., 15-20 years), thus simulating “nth-of-a-kind” plant performance (low risk financial structure)
• Technologies included:
  – Next generation post-combustion CO₂ capture
  – A-USC steam conditions (5000/1350/1400)
  – Advanced CO₂ compression
BFD for PC with CO\textsubscript{2} Capture
MTR CO$_2$ Capture Membrane Process (Case 5)

1. Flue gas
2. CO$_2$ - enriched permeate
3. CO$_2$ - depleted residue
4. Air sweep
5. Air sweep to boiler
6. Treated flue gas
7. CO$_2$ recycle

Coal feed to boiler

Vacuum pump
Compressor
Condenser

Recycle to flue gas feed

H$_2$O
H$_2$O
H$_2$O

Liquid CO$_2$ for sequestration
Design Basis: Case 5 MTR Membrane Process
Enhanced Performance Relative to Literature
Key Parameter Assumptions

• Membrane Process
  – CO₂ and SO₂ Permeance: 3,500 gpu
  – N₂, O₂, Ar Permeance: 100 gpu
  – H₂O Permeance: 5,000 gpu
  – Pressure drop: 1.0 psi (flue gas and sweep sides)
  – Vacuum pump achieves 0.2 bar pressure
  – Membrane replacement time 5 years
  – Membrane surface area: 1,500,000 m²
  – Membrane installed cost $80/m²
  – Membrane replacement cost $15/m²

• CO₂ Shockwave Compressor (Cases 5D & 5E)
  – Increased polytropic efficiency: 93%
Membrane Pathway Plant Efficiency

NOTES:
• Fluor-based cases are consistent with NETL Bituminous Baseline Report (2010)
• All MTR- and TDA-based cases utilize enhanced performance and cost parameters
First-Year Cost of Electricity – Membrane

NOTES:
• Fluor-based cases are consistent with NETL Bituminous Baseline Report (2010)
• All MTR- and TDA-based cases utilize enhanced performance and cost parameters
TDA Sorbent CO₂ Capture Process
Design Basis: Case 6 TDA Sorbent Process
Enhanced Performance Relative to Literature
Key Parameter Assumptions

• **TDA Sorbent Process**
  – Adsorbent: alkalized alumina; 3/8 inch diameter spheres
  – Adsorbent cost: $5/lb
  – **Sorbent CO\(_2\)** loading: 3.0%
  – Adsorber and regenerator temperature: 140°C
  – Adsorber and regenerator pressure drop: 0.4 psi
  – Adsorbent entrains 1.0 wt% of inlet N\(_2\), O\(_2\) and water vapor to the regenerator
  – **Regenerator off-gas**: 50 mole % CO\(_2\)
  – Adsorber-regenerator type: Moving bed
  – Adsorbent transport: Bucket conveyor-elevators

• **CO\(_2\)** Shockwave Compressor
  – Increased polytropic efficiency: 93%
First-Year Cost of Electricity – Sorbent

NOTES:
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For More Information About the NETL Carbon Capture Program

- NETL website:  
  - www.netl.doe.gov

- Office of Fossil Energy website:  
  - www.fe.doe.gov

Reference Shelf

- Annual CO2 Capture Meeting

Innovations for Existing Plants

CO₂ Emissions Control

Welcome to the Innovations for Existing Plants (IEP) Program's CO₂ emissions control R&D website. In FY08, the IEP Program redirected its focus to include CO₂ emissions control for existing coal combustion-based plants, e.g., conventional powerplants with CO₂ emissions control technology—both post-combustion and pre-combustion—and related areas of CO₂ compression and CO₂ beneficial reuse as a direct result of the priority placed on advancing technological options for the existing fleet of coal-fired power plants for addressing climate change. In addition to funding R&D projects conducted externally, DOE/NETL also conducts in-house research to develop new breakthroughs for carbon capture that would benefit existing improvements in cost and performance relative to today's technologies. The IEP CO₂ emissions control R&D activity also sponsors systems analysis studies of the cost and performance of various carbon capture technologies. The program goal is to develop advanced CO₂ capture and separation technologies for existing power plants that can achieve at least 85% CO₂ removal at no more than a 35% increase in cost of energy services.

For More Information About the NETL Carbon Capture Program

- Program Goals and Targets
- Post-Combustion CO₂ Control
- Pre-Combustion CO₂ Control
- CO₂ Compression
- CO₂ Beneficial Use
- Systems Analysis
- CO₂ Emissions Control Reference Shelf

Prior to FY08, DOE/NETL's CO₂ emissions control R&D effort was conducted under the Carbon Sequestration Program. With responsibility for existing plant CO₂ emissions control R&D now being conducted under the IEP Program, the Carbon Sequestration Program continues to focus on pre-combustion CO₂ emissions control and geological sequestration. Since its inception in 1997, the Carbon Sequestration Program has been developing both core and enabling technologies that will enable efficient carbon capture and storage (CCS) at grid-scale power plants. Staged and R&D will enable CCS.