

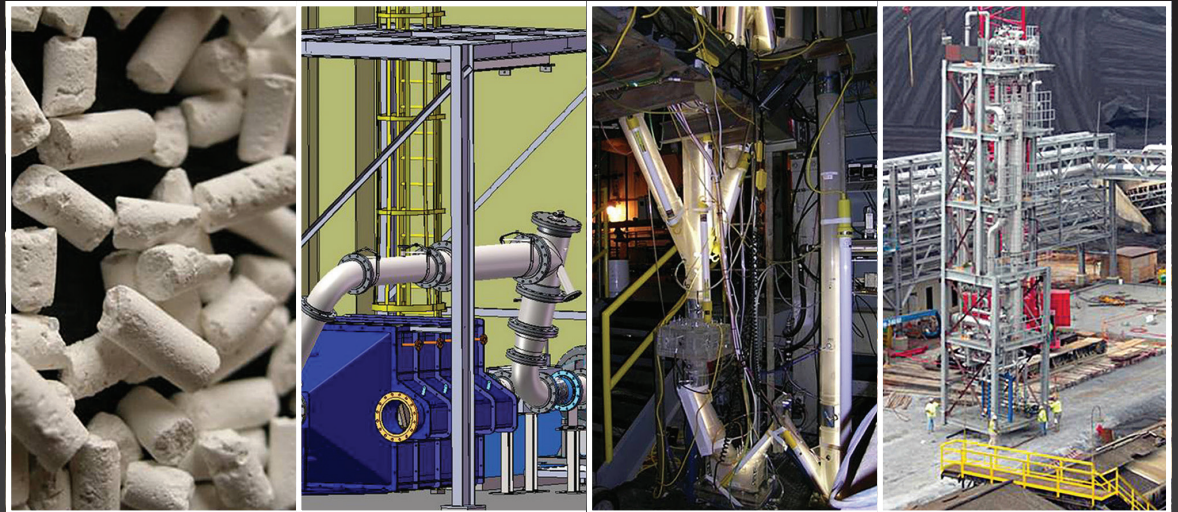
# AICHE<sup>®</sup>

## FINAL REPORT

Strategic Center for  
Coal Carbon Capture

FY 2013 Peer Review Meeting

2013  
Peer Review



**Meeting Summary and Recommendations Report**

Pittsburgh, Pennsylvania

March 11 – 15, 2013

U.S. DEPARTMENT OF ENERGY  
OFFICE OF FOSSIL ENERGY  
NATIONAL ENERGY TECHNOLOGY LABORATORY

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NATIONAL ENERGY TECHNOLOGY LABORATORY

**FINAL REPORT  
STRATEGIC CENTER FOR COAL  
CARBON CAPTURE  
FY 2013 PEER REVIEW MEETING**

Pittsburgh, Pennsylvania  
March 11-15, 2013

**MEETING SUMMARY AND RECOMMENDATIONS REPORT**

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Prime Contract DE-FE0004002 (Subtask 300.02.03)

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This report was prepared through the collaborative efforts of the members and staff of the American Institute of Chemical Engineers (AIChE, or “the Institute”). It is sincerely hoped that the information presented in this document will lead to insightful performance by the Peer Review panelists for NETL’s FY 13 Carbon Capture Peer Review. However, AIChE, its employees and consultants, its officers and directors, their employers’ officers and directors disclaim making or giving any warranties or representations, expressed or implied, including with respect to fitness, intended purpose, use or merchantability and/or correctness or accuracy of content of the information presented in this document. Company affiliations are shown for information only and do not imply approval by the companies listed. Reference to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the Institute or others involved in the preparation or review of this document. The views and opinions of authors, contributors, and reviewers do not necessarily reflect those of AIChE or others involved in the preparation or review of this report. As between (1) AIChE, its employees and consultants, its officers and directors, their employers, and their employers’ officers and directors, and (2) the user of this document, the user accepts any legal liability or responsibility for the consequences of its use or misuse.

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The work performed on this task/subtask was completed under Leonardo Technologies, Inc. (LTI), Prime Contract DE-FE-0004002 (Subtask 300.02.03) for DOE/NETL.

## MEETING SUMMARY AND RECOMMENDATIONS REPORT

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## EXECUTIVE SUMMARY

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The U.S. Department of Energy's (DOE's) Carbon Capture Program is conducted under the Clean Coal Research Program (CCRP). DOE's overarching mission is to increase the energy independence of the United States and to advance national and economic security. To that end, the DOE Office of Fossil Energy (FE) has been charged with ensuring the availability of ultraclean (near-zero emissions), abundant, low-cost domestic energy from coal to fuel economic prosperity, strengthen energy independence, and enhance environmental quality. As a component of that effort, the CCRP—administered by the Office of Fossil Energy and implemented by the National Energy Technology Laboratory (NETL)—is engaged in research, development, and demonstration (RD&D) activities to create technology and technology-based policy options for public benefit. The CCRP is designed to reduce and eliminate environmental concerns related to coal use by developing a portfolio of innovative technologies, including those for carbon capture and storage (CCS).

The Carbon Capture program consists of two core research Technology Areas: (1) Post-Combustion Capture and (2) Pre-Combustion Capture. Post-combustion capture is primarily applicable to conventional pulverized coal (PC)-fired power plants. Pre-combustion capture is applicable to integrated gasification combined cycle (IGCC) power plants. Although R&D efforts are focused on capturing carbon dioxide (CO<sub>2</sub>) from coal-based power plants, the same capture technologies are applicable to natural gas- and oil-fired power plants and other industrial CO<sub>2</sub> sources.

Current R&D efforts conducted within the Carbon Capture program include development of advanced solvents, sorbents, and membranes for both the Post- and Pre-Combustion Technology Areas. Under both Technology Areas, the program is developing second generation and transformational CO<sub>2</sub> capture technologies that have the potential to provide step-change reductions in both cost and energy penalty when compared to currently available first generation technologies. Success in developing these technologies will enable cost-effective implementation of CCS throughout the power-generation sector and ensure that the United States will continue to have access to safe, reliable, and affordable energy from fossil fuels.

The goals for the Carbon Capture Program call for the development of second generation technologies that are ready for demonstration-scale testing in 2020, and transformational technologies that are ready for demonstration-scale testing in 2030. For capture technologies applied to new power plants, the program goals are to contribute to a capture cost of less than \$40/tonne of CO<sub>2</sub> captured for second generation technologies and even lower costs for transformational technologies. However, post-combustion capture technologies can also be used to retrofit existing pulverized coal (PC) power plants. The competitive advantage for retrofit applications is that they leverage an existing infrastructure, reducing the need to recover the capital investment of a new power plant. This also reduces the resultant cost of electricity. .

### **Funding for the Carbon Capture Projects Reviewed**

DOE provided \$95,419,409 (79%) of the funding for the 16 projects evaluated for this Peer Review, while project partner cost-sharing contributed \$24,790,666 (21%). Total funding of the reviewed projects, for their duration, is \$120,210,075.

The 16 projects that were the subject of this Peer Review are summarized in Table ES-1 and in Section II of this report.

**TABLE ES-1 CARBON CAPTURE PROJECTS REVIEWED**

Project Order	Agreement Number	Performer	Project Title	Technology Category	Project Type	Start Date	Completion Date	Total Award Value	DOE Share	Performer Share
1	FE0007466	Battelle Memorial Institute	CO2 Binding Organic Liquids Gas Capture with Polarity Swing Assisted Regeneration	Post-Combustion Capture (Solvents)	Extramural	10/01/11	03/31/14	\$2,491,223	\$1,991,219	\$500,004
2	FE0005799	ION Engineering LLC	ION Novel Solvent System for CO2 Capture	Post-Combustion Capture (Solvents)	Extramural	10/01/10	04/30/13	\$6,454,759	\$4,836,424	\$1,618,335
3	FE0004228	Akermin, Inc.	Advanced Low Energy Enzyme Catalyzed Solvent for CO2 Capture	Post-Combustion Capture (Solvents)	Extramural	10/01/10	06/30/13	\$3,709,873	\$2,559,678	\$1,150,195
4	ORD-2012.01.00 Task 4	National Energy Technology Laboratory	Pre-Combustion Membranes	Pre-Combustion Capture (Membranes)	ORD	10/01/11	09/30/14	\$2,250,000	\$2,250,000	\$0
5	FE0007528	Neumann Systems Group, Inc.	Carbon Absorber Retrofit Equipment (CARE)	Post-Combustion Capture (Solvents)	Extramural	01/02/12	06/27/14	\$9,098,441	\$7,164,391	\$1,934,050
6	FE0007395	University of Kentucky	Application of a Heat Integrated Post-Combustion Carbon Dioxide Capture System with Hitachi Advanced Solvent into Existing Coal-Fired Power Plant	Post-Combustion Capture (Solvents)	Extramural	10/01/11	01/31/16	\$19,275,289	\$14,552,303	\$4,722,986
7	FE0007453	Linde LLC	Slipstream Pilot-Scale Demonstration of a Novel Amine Based Post-Combustion Process Technology for CO2 Capture from Coal-Fired Power Plant Flue Gas	Post-Combustion Capture (Solvents)	Extramural	12/01/11	11/30/15	\$18,490,456	\$14,792,365	\$3,698,091
8	FE0007948	Innosepra LLC	Novel Sorption-Based CO2 Capture Process	Post-Combustion Capture (Sorbents)	Extramural	10/01/11	03/31/14	\$3,185,240	\$2,529,885	\$655,355
9	FE0007603	University of North Dakota	Evaluation of Carbon Dioxide Capture from Existing Coal Fired Plants by Hybrid Sorption Using Solid Sorbents	Post-Combustion Capture (Sorbents)	Extramural	10/01/11	09/30/14	\$3,690,000	\$2,952,000	\$738,000
10	FE0007580	TDA Research, Inc.	Low Cost, High Capacity Regenerable Sorbent for Carbon Dioxide Capture from Existing Coal-Fired Power Plants	Post-Combustion Capture (Sorbents)	Extramural	10/01/11	09/30/14	\$3,375,000	\$2,700,000	\$675,000
11	FE0007707	Research Triangle Institute	Bench-Scale Development of an Advanced Solid Sorbent-Based Carbon Capture Process for Coal-Fired Power Plants	Post-Combustion Capture (Sorbents)	Extramural	10/01/11	09/30/14	\$3,847,161	\$2,997,038	\$850,123
12	FE0004343	ADA-ES Inc.	Recovery Act: Evaluation of Solid Sorbents as a Retrofit Technology for CO2 Capture	Post Combustion Capture (Sorbents)	Extramural	10/01/10	12/31/14	\$18,750,000	\$15,000,000	\$3,750,000
13	ORD-2012.01.00 Task 7	National Energy Technology Laboratory	Post-Combustion Membranes	Post-Combustion Capture (Membranes)	ORD	10/01/11	09/30/14	\$1,900,000	\$1,900,000	\$0
14	FE0007634	FuelCell Energy, Inc.	Electrochemical Membrane for Carbon Dioxide Capture and Power Generation	Post-Combustion Capture (Membranes)	Extramural	10/01/11	09/29/14	\$3,142,633	\$2,394,106	\$748,527
15	FE0005795	Membrane Technology & Research, Inc.	Recovery Act: Slipstream Testing of a Membrane CO2 Capture Process for Existing Coal-Fired Power Plants	Post-Combustion Capture (Membranes)	Extramural	10/01/10	09/30/15	\$18,750,000	\$15,000,000	\$3,750,000
16	FE-10-002	Los Alamos National Laboratory	High-Temperature Polymer-Based Membrane Systems for Pre-Combustion CO2 Capture	Pre-Combustion Capture (Membranes)	FWP	10/01/08	09/30/12	\$1,800,000	\$1,800,000	\$0
								<b>\$120,210,075</b>	<b>\$95,419,409</b>	<b>\$24,790,666</b>

\*Note: Funding amounts and project durations have been obtained from project summaries submitted by the principal investigator.

## NETL CARBON CAPTURE RESEARCH OVERVIEW

The DOE's Office of Fossil Energy's National Energy Technology Laboratory's (NETL's) Carbon Capture Program is developing second generation and transformational CO<sub>2</sub> capture technologies that have the potential to provide step-change reductions in both cost and energy penalty when compared to currently available first generation technologies. NETL's Carbon Capture Program consists of two core research Technology Areas: (1) Post-Combustion Capture; and (2) Pre-Combustion Capture. Post-combustion capture is primarily applicable to conventional pulverized coal (PC)-fired power plants, where the fuel is burned with air in a boiler to produce steam that drives a turbine/generator to produce electricity. The carbon is captured from the flue gas after fuel combustion. Pre-combustion capture is applicable to integrated gasification combined cycle (IGCC) power plants, where solid fuel is converted into gaseous components ("syngas") by applying heat under pressure in the presence of steam and oxygen. In this case, the carbon is captured from the syngas before combustion and power production occurs.

The successful development of advanced CO<sub>2</sub> capture technologies is critical to maintaining the cost-effectiveness of coal-based power generation while reducing emissions. Today, there are commercially available first generation CO<sub>2</sub> capture technologies that are being used in a variety of small-scale industrial applications. However, in their current state of development, these first generation technologies are not ready for widespread deployment on coal-based power plants. This is the case for three primary reasons:

- 1) They have not been demonstrated at a scale large enough for power plant application;
- 2) The energy required to support CO<sub>2</sub> capture would significantly decrease power generating capacity; and
- 3) Today's relevant markets are not anticipated to support broad deployment of current generation technologies.

A comprehensive, multi-pronged research and development (R&D) approach has been adopted, and the program is pursuing a portfolio of technologies along multiple technology paths to mitigate the risks inherent in new technology research efforts. The program encompasses R&D across a wide scale, integrating advances and lessons learned from fundamental research, technology development, and demonstration-scale testing. Within each Technology Area, specific challenges or uncertainties have been identified with research pathways constructed to address these challenges.

For both pre- and post-combustion, the Carbon Capture Program is pursuing three key areas of technology:

- Solvents – Solvent-based CO<sub>2</sub> capture involves chemical or physical absorption of CO<sub>2</sub> from syngas or flue gas into a liquid carrier. Research projects in this area are focused on the development of low-cost, non-corrosive solvents that have a high CO<sub>2</sub> loading capacity, improved reaction kinetics, low regeneration energy, and resistance to degradation. In addition, considerable effort is being applied to development of process design and integration that lead to decreased capital and operating costs and enhanced performance.



- Sorbents – Solid sorbents, including sodium and potassium oxides, zeolites, carbonates, amine-enriched sorbents, and metal organic frameworks (MOFs), are being explored for CO<sub>2</sub> capture. A temperature or pressure swing facilitates sorbent regeneration following chemical and/or physical adsorption. Possible configurations for sorbent contact include fixed, moving, and fluidized beds. Research projects in this area focus on the development of sorbents with the following characteristics: low-cost raw materials, thermally and chemically stable, low attrition rates, low heat capacity, high CO<sub>2</sub> adsorption capacity, and high CO<sub>2</sub> selectivity. Another important focus of this research is developing cost-effective process equipment designs that are tailored to the sorbent characteristics.
- Membranes – Membrane-based CO<sub>2</sub> capture uses permeable or semi-permeable materials that allow for the selective transport and separation of CO<sub>2</sub> from gases. Generally, gas separation is accomplished by some physical or chemical interaction between the membrane and the gas being separated, causing one component in the gas to permeate through the membrane faster than another. Research in this area focuses on development of low-cost, durable membranes that have improved permeability and selectivity, thermal and physical stability, and tolerance to contaminants.

### Overview of the Peer Review Process

NETL requested that the American Institute of Chemical Engineers (AIChE) assemble a Carbon Capture Peer Review Panel of recognized technical experts to provide recommendations on improving the management, performance, and overall results of each research project. Each project team prepared a detailed Project Information Form containing an overview of the project's purpose, objectives, and achievements; a Statement of Project Objectives containing project objectives, a description of the scope of the project, a detailed breakdown of project tasks and subtasks to be performed, and associated deliverables and presentations; and a presentation that was given at the Peer Review Meeting. The panel received the Project Information Forms, Statement of Project Objectives, and presentations prior to the Peer Review Meeting.

At the meeting, each research team made an uninterrupted 45-minute PowerPoint presentation that was followed by a 30-minute question-and-answer (Q&A) session with the panel. After the principal investigator (PI) and project team left the room, the panel held a 40-minute discussion about the strengths and weaknesses of each project, and developed recommendations and action items for addressing each project's weaknesses. To facilitate full and open exchange about project-related materials, all discussions after the Q&A sessions with the project teams were limited to the panel, AIChE team members, DOE personnel, and contract support staff.

After the group discussions, each Panel member individually evaluated the 16 projects, providing written comments based on a predetermined set of review criteria. These review criteria were:

- Scientific and Technical Merit
- Existence of Clear, Measurable Milestones
- Utilization of Government Resources

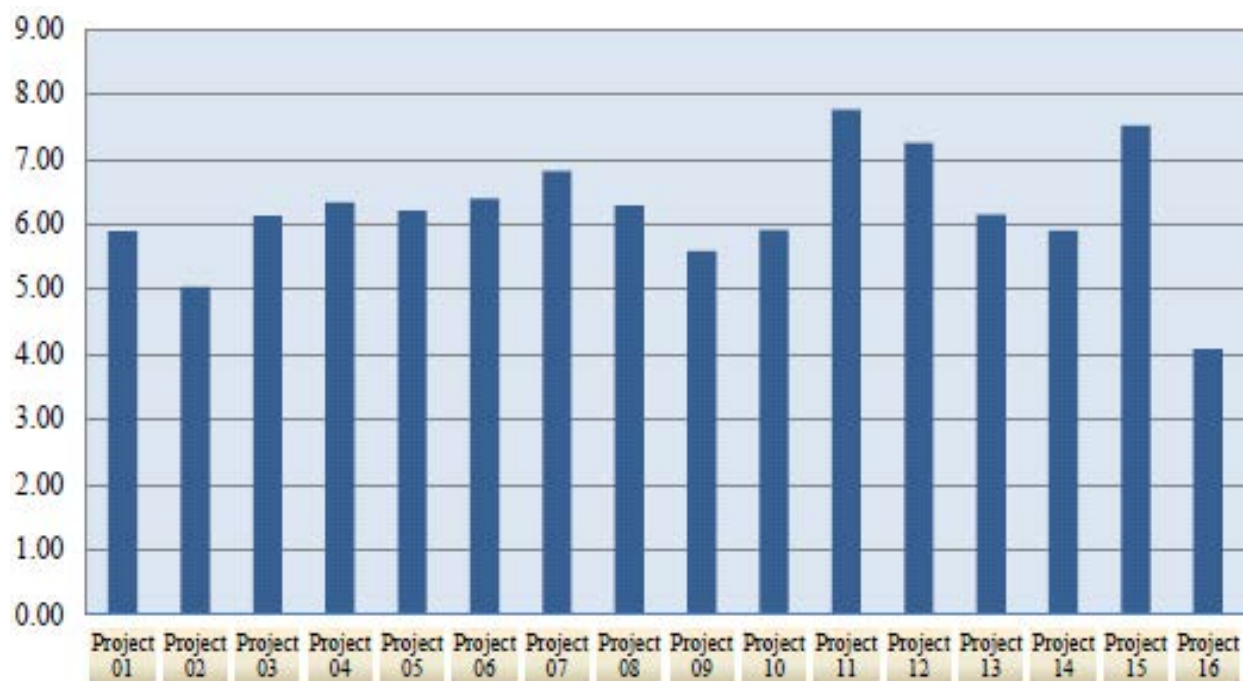
- Technical Approach
- Rate of Progress
- Potential Technology Risks Considered
- Performance and Economic Factors
- Anticipated Benefits, if Successful
- Technology Development Pathways

For each of the nine review criteria, the individual reviewer was asked to score the project as:

- Excellent (10)
- Highly Successful (8)
- Fair (5)
- Weak (2)
- Unacceptable (0)

Figure ES-1 shows the overall average score for each of the 16 projects, combining all 9 review criteria.

**FIGURE ES-1 AVERAGE SCORING, BY PROJECT**



The “Project Average” in Table ES-2, shows the score for each criterion averaged across all 16 projects. The “Highest Project Rating” and “Lowest Project Rating” columns portray the highest and lowest scores, respectively, received by an individual project in a given criterion.

**TABLE ES-2 AVERAGE SCORING, BY REVIEW CRITERION**

<b>Criterion</b>	<b>Project Average*</b>	<b>Highest Project Rating*</b>	<b>Lowest Project Rating*</b>
1. Scientific and Technical Merit	6.5	8.0	4.3
2. Existence of Clear, Measurable Milestones	6.6	8.9	4.3
3. Utilization of Government Resources	6.9	8.5	4.6
4. Technical Approach	6.3	8.3	3.9
5. Rate of Progress	6.3	7.9	4.3
6. Potential Technology Risks Considered	5.6	7.9	3.1
7. Performance and Economic Factors	5.5	7.3	4.3
8. Anticipated Benefits, if Successful	6.4	7.8	4.6
9. Technology Development Pathways	5.8	7.4	3.5

\* The score for each project in a given criterion is, by definition, the average of *all reviewer* ratings for that criterion.

Section III provides more on the overall evaluation process and the nine review criteria.

The Projects reviewed ranged from fundamental research to proof of concept and were also categorized based on their Technology Readiness Levels. By providing context, this categorization helped the panel appropriately rate the Economic Analysis and Technology Development Paths for projects at various stages of advancement. Table ES-3 gives definitions for Technology Readiness Levels developed by the Office of Fossil Energy to provide a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology.

**TABLE ES-3 TECHNOLOGY READINESS LEVELS (TRLs)**

Stage of Research	Description
TRL 1 - Basic Principles Observed and Reported	This is the lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples include paper studies of a technology's basic properties.
TRL 2 - Technology Concept and/or Application Formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies.
TRL 3 - Analytical and Experimental Critical Function and/or Characteristic Proof of Concept	Active R&D is initiated. This includes analytical and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology (e.g., individual technology components have undergone laboratory-scale testing using bottled gases to simulate major flue gas species at a scale of less than 1 scfm).
TRL 4 - Component and/or System Validation in a Laboratory Environment	Has the bench-scale prototype been developed and validated in the laboratory environment? Prototype is defined as less than 5% final scale (e.g., complete technology process has undergone bench-scale testing using synthetic flue gas composition at a scale of approximately 1-100 scfm).
TRL 5 – Laboratory-scale Similar-system Validation in a Relevant Environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. The prototype is defined as less than 5% final scale (e.g., a complete technology has undergone bench-scale testing using actual flue gas composition at a scale of approximately 1-100 scfm).
TRL 6 Engineering / Pilot-scale Prototypical System Demonstrated in a Relevant Environment	Engineering-scale models or prototypes are tested in a relevant environment. Pilot or process-development-unit scale is defined as being between 0 and 5% final scale (e.g., complete technology has undergone small pilot-scale testing using actual flue gas composition at a scale equivalent to approximately 1,250-12,500 scfm).
TRL 7 – System Prototype Demonstrated in a Plant Environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Final design is virtually complete. Pilot or process-development-unit demonstration of a 5-25% of final scale or design and development of a 200-600 MW plant (e.g., complete technology has undergone large-scale pilot testing using actual flue gas composition at a scale equivalent to approximately 25,000-62,500 scfm).
TRL 8 – Actual System Completed and Qualified Through Test and Demonstration in a Plant Environment <i>*Not relevant in this Peer Review</i>	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include startup, testing, and evaluation of the system within a 200-600 MW plant CCS/CCUS operation (e.g., complete and fully integrated technology has been initiated at full-scale demonstration including startup, testing, and evaluation of the system using actual flue gas composition at a scale equivalent to approximately 200 MW or greater).

TRL 9 – Actual System Operated Over the Full Range of Expected Conditions <i>*Not relevant in this Peer Review</i>	The technology is in its final form and operated under the full range of operating conditions. The scale of this technology is expected to be 200-600 MW plant CCS/CCUS operations (e.g., complete and fully integrated technology has undergone full-scale demonstration testing using actual flue gas composition at a scale equivalent to approximately 200 MW or greater).
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Section IV of this report provides a summary of key project findings. Section V covers process considerations and recommendations for future peer reviews.

**For More Information**

For more information concerning the contents of this report, contact the NETL Peer Review Coordinator, Eric Bell, at (412) 386-5802 or Eric.Bell@netl.doe.gov.

## I. INTRODUCTION

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In February 2013, the American Institute of Chemical Engineers (AIChE) was contracted to provide an independent, unbiased, and timely peer review of selected carbon capture projects within the U.S. Department of Energy (DOE) Office of Fossil Energy's (FE's) Carbon Capture Program administered by the National Energy Technology Laboratory (NETL). From March 11-15, 2013, AIChE convened a panel of eight leading academic, government, and industry experts to conduct a five-day peer review of selected carbon capture projects supported by NETL. This report summarizes the findings from that review.

### **Compliance with Office of Management and Budget Requirements**

DOE, FE, and NETL are fully committed to improving the quality and results of their projects. The peer review of selected carbon capture projects was designed to comply with requirements from the Office of Management and Budget (OMB).

### **AIChE Peer Review Advisory Board**

AIChE uses a Peer Review Advisory Board to determine the expertise needed for all peer reviews conducted and to identify experts with the proper backgrounds. The Advisory Board also makes sure that the panel is well-rounded and has sufficient technical knowledge of the various aspects of the projects selected for review. Upon notification of the projects to be reviewed, AIChE convened the Advisory Board to determine the required expertise and identify experts. The reviewer expertise needed was then balanced with potential reviewers. The Advisory Board used a scorecard to compare the required knowledge with the expertise of the reviewers to ensure that potential panelists covered the necessary skill sets and provided an appropriate balance of knowledge and expertise. In consultation with NETL, AIChE formulated the review meeting agenda, provided information advising the principal investigators (PIs) and their colleagues on how to prepare for the review, facilitated the review session, and prepared a summary of the results.

Appendix A provides a more extensive discussion of the AIChE peer review methodology used for the Carbon Capture Peer Review Meeting. Appendix B provides the meeting agenda, and Appendix C provides profiles of the panel members.

### **Overview of the Peer Review Process**

NETL selected AIChE as the independent organization to conduct a five-day peer review of 16 carbon capture projects. AIChE performed this project review work as a subcontractor to prime NETL contractor Leonardo Technologies, Inc. (LTI). NETL selected the 16 projects, while AIChE organized an independent review panel of 8 leading academic and industry experts. Prior to the meeting, project PIs submitted their PowerPoint presentations; a 15-page written summary (Project Information Form) of their project's purpose, objectives, and progress; and their Statement of Project Objectives containing project objectives, a description of the scope of the project, a detailed breakdown of projects tasks and subtasks to be performed, and associated deliverables and presentations. This project information was given to the panel before the meeting to allow the panel members to come to the meeting fully prepared with background information on each project. Before the meeting, the panel also requested additional information regarding several projects, which the PIs provided.

At the meeting, each research team made a 45-minute oral presentation, followed by a 30-minute question-and-answer (Q&A) session with the panel and a 40-minute panel discussion of each project. Both the PI presentations and Q&A sessions with the panel for the Carbon Capture Peer Review were closed sessions, limited to the project teams, the panel, AIChE team members, and DOE personnel and contractor support staff. The closed sessions ensured frank and open discussions between the PIs and the panel. Each member of the panel individually evaluated the project and provided written comments based on the predetermined set of review criteria. Panel members agreed to hold the discussions that took place during the Q&A session in confidence.

This publically available document, prepared by AIChE, provides a general overview of the Carbon Capture Peer Review and the projects reviewed therein.

### **Peer Review Criteria and Peer Review Criteria Forms**

A set of agreed-upon review criteria were applied to the projects reviewed at this meeting. AIChE provided the panel with these review criteria in advance of the Peer Review Meeting. Assessment sheets with the review criteria were pre-loaded (one for each project) onto laptop computers for each panel member. During the meeting, the panel members assessed the strengths and weaknesses of each project before providing both recommendations and action items to address identified weaknesses. Appendix D provides a more detailed explanation of this process and a sample Peer Review Criteria Form.

The following sections of this report summarize findings from the Carbon Capture Peer Review Meeting, organized as follows:

- II. *Summary of Projects Reviewed in FY 2011 Carbon Capture Peer Review:*  
A list of the 16 projects reviewed
- III. *An Overview of the Evaluation Scores:*  
Average scores and a summary of evaluations, including an analysis of strengths and weaknesses and recommendations and action items
- IV. *Summary of Key Project Findings:*  
An overview of key findings from project evaluations
- V. *Process Considerations for Future Peer Reviews:*  
Lessons learned in this review that may be applied to future reviews

## II. SUMMARY OF PROJECTS REVIEWED IN FY2013 CARBON CAPTURE PEER REVIEW

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NETL selected key projects within Carbon Capture Program, including projects being conducted at NETL, to be reviewed by the independent Peer Review panel. The selected projects are listed below along with the name of the organization leading the research. Appendix E presents short summaries of each of the 16 projects.

### PROJECTS REVIEWED

**01: FE000466**

CO<sub>2</sub> Binding Organic Liquids Gas Capture with Polarity Swing Assisted Regeneration  
*Battelle Memorial Institute*

**02: FE0005799**

Ion Novel Solvent System for CO<sub>2</sub> Capture  
*ION Engineering, LLC*

**03 : FE0004228**

Advanced Low Energy Enzyme Catalyzed Solvent for CO<sub>2</sub> Capture  
*Akermin, Inc.*

**04: ORD-2-12.01.00 Task 4**

Pre-Combustion Membranes  
*National Energy Technology Laboratory*

**05 : FE0007528**

Carbon Absorber Retrofit Equipment (CARE)  
*Neumann Systems Group, Inc.*

**06: FE0007395**

Application of a Heat Integrated Post-Combustion Carbon Dioxide Capture System with Hitachi Advanced Solvent into Existing Coal-Fired Power Plant  
*University of Kentucky*

**07 : FE0007453**

Slipstream Pilot-Scale Demonstration of a Novel Amine Based Post-Combustion Process Technology for CO<sub>2</sub> Capture from Coal-Fired Power Plant Flue Gas  
*Linde, LLC*

**08 : FE0007948**

Novel Sorption-Based CO<sub>2</sub> Capture Process  
*InnoSeptra, LLC*



**09 : FE0007603**

Evaluation of Carbon Dioxide Capture from Existing Coal-Fired Plants by Hybrid Sorption Using Solid Sorbents

*University of North Dakota*

**10 : FE0007580**

Low Cost, High Capacity Regenerable Sorbent for Carbon Dioxide Capture from Existing Coal-Fired Power Plants

*TDA Research, Inc.*

**11 : FE0007707**

Bench-Scale Development of an Advanced Solid Sorbent-Based Carbon Capture Process for Coal-Fired Power Plants

*Research Triangle Institute*

**12 : FE0004343**

Recovery Act: Evaluation of Solid Sorbent as a Retrofit Technology for CO<sub>2</sub> Capture

*ADA-ES, Inc.*

**13 : ORD-2012.01.00 Task 7**

Post-Combustion Membranes

*National Energy Technology Laboratory*

**14 : FE0007634**

Electrochemical Membrane for Carbon Dioxide Capture and Power Generation

*FuelCell Energy, Inc.*

**15: FE0005795**

Recovery Act: Slipstream Testing of a Membrane CO<sub>2</sub> Capture Process for Existing Coal-Fired Power Plants

*Membrane Technology & Research, Inc.*

**16 : FE-10-002**

High Temperature Polymer-Based Membrane Systems for Pre-Combustion CO<sub>2</sub> Capture

*Los Alamos National Laboratory*

### III. AN OVERVIEW OF THE EVALUATION SCORES

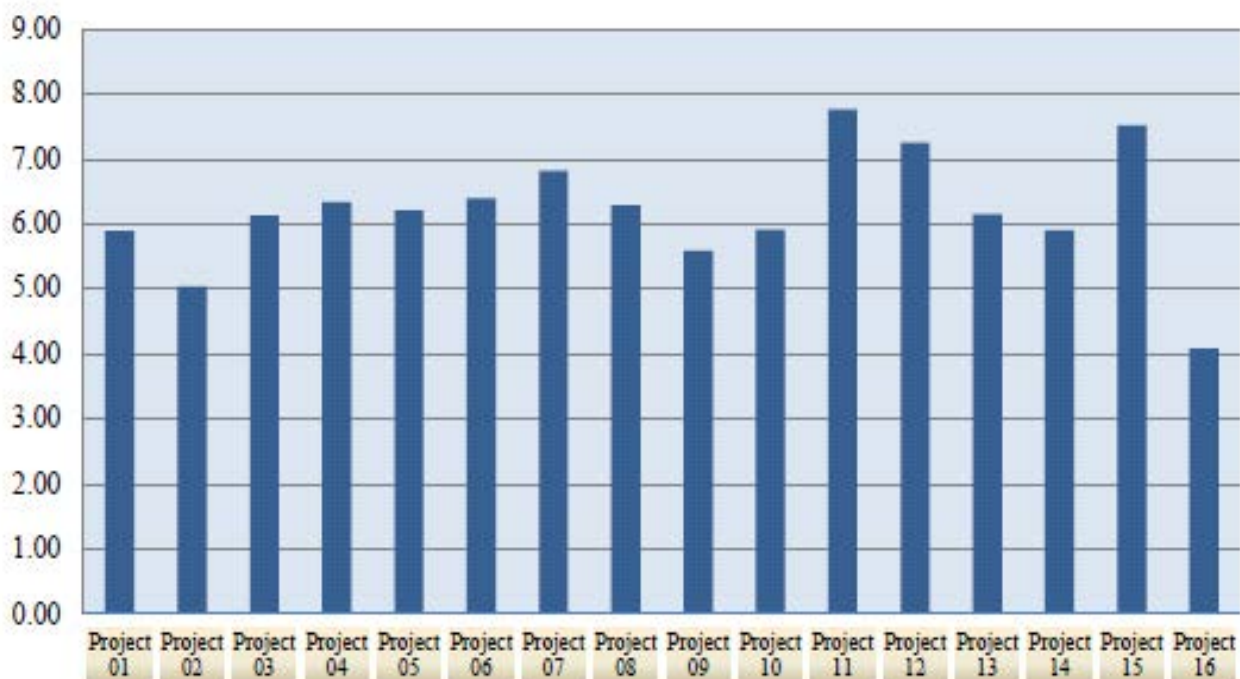
For each of the nine review criteria, individual reviewers were asked to score the project as one of the following:

- Excellent (10)
- Highly Successful (8)
- Fair (5)
- Weak (2)
- Unacceptable (0)

The average scores for all the projects and across each rating criterion indicate that, overall, the research being pursued by the Carbon Capture Program is more than adequate, but also has opportunities for improvement. The Program consists primarily of well-managed and well-staffed projects aimed at developing innovative, economically feasible, commercializable technologies that have considerable potential to advance carbon capture.

Figure 1 shows the average overall project scores, combining the average scores for the nine review criteria for each of the 16 projects reviewed, providing an impression of how well the project performed. While it is not the intent of this review to compare one project with another, an average score exceeding 5.0 suggests that a specific project was viewed as adequate to effective by the panel. Fifteen of the 16 carbon capture projects reviewed met or exceeded this score. A project was viewed less favorably by the panel if the average score was below 5.0. Only 1 of the 16 projects fit in this category.

**FIGURE I AVERAGE SCORING, BY PROJECT**



General conclusions about NETL’s carbon capture research can also be drawn by looking at the average scores for each of the nine review criteria, which are shown in Table 1 below. All of the

criteria received average scores between 5.5 and 6.9, reflecting NETL’s efforts to fund and manage projects that are developing innovative and scientifically rigorous technologies. The lowest-ranking review criteria were Potential Technology Risks Considered and Performance and Economic Factors, indicating that some projects should place additional attention on understanding the risks involved in the technology’s development and providing adequate means to mitigate those risks. This also indicates that some projects have not yet provided cost estimates sufficient to assure their ability to achieve DOE’s technology cost goals.

The highest-ranking review criteria – Scientific and Technical Merit, Existence of Clear, Measurable Milestones, and Utilization of Government Resources, – earned average scores across all projects of 6.5 or greater, indicating that NETL is pursuing strong, relevant research and development (R&D), making good use of government resources, and clearly demonstrating progress in ensuring that ambitious R&D goals are achievable.

**TABLE I AVERAGE SCORING, BY REVIEW CRITERION**

Criterion	Project Average*	Highest Project Rating*	Lowest Project Rating*
1. Scientific and Technical Merit	6.5	8.0	4.3
2. Existence of Clear, Measurable Milestones	6.6	8.9	4.3
3. Utilization of Government Resources	6.9	8.5	4.6
4. Technical Approach	6.3	8.3	3.9
5. Rate of Progress	6.3	7.9	4.3
6. Potential Technology Risks Considered	5.6	7.9	3.1
7. Performance and Economic Factors	5.5	7.3	4.3
8. Anticipated Benefits, if Successful	6.4	7.8	4.6
9. Technology Development Pathways	5.8	7.4	3.5

\* The score for each project in a given criterion is by definition the average of *all reviewer* ratings for that criterion.

Appendix D provides a copy of the Peer Review Criteria Form and a detailed explanation of the review process.

## IV. SUMMARY OF KEY FINDINGS

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This section summarizes key findings across the 16 projects evaluated at the Carbon Capture Peer Review.

### General Project Strengths

The panel was impressed by the high-caliber of the projects it reviewed from NETL's carbon capture R&D effort. These projects have ambitious goals and significant potential to advance carbon capture technology. The panel found the carbon capture R&D projects to be essentially on track and to represent a well-balanced portfolio of fundamental science, national laboratory research, and large-scale projects. As reflected in Table I, the strongest-rated areas across the projects were:

- Scientific and Technical Merit
- Existence of Clear, Measurable Milestones
- Utilization of Government Resources
- Anticipated Benefits, if Successful

These rankings reflect the panel's perception that, overall, NETL's carbon capture R&D effort is addressing key research areas and technology challenges in the carbon capture field in a clear, technically rigorous, and cost-effective manner.

In general, the panel commended project management and leadership. It found nearly all of the PIs and project teams to be experienced, well-prepared experts who are passionate about their areas of research and technology development. The panel found that most projects are being fiscally prudent, achieving promising results, and producing valuable tools.

The highest-rated projects were Project 11, "Bench-scale Development of an Advanced Solid Sorbent-Based Carbon Capture Process for Coal-Fired Power Plants," conducted by the Research Triangle Institute (RTI); Project 15, "Slipstream Testing of a Membrane CO<sub>2</sub> Capture Process for Existing Coal-Fired Power Plants," conducted by Membrane Technology & Research (MTR), Inc; and Project 12, "Evaluation of Solid Sorbents as a Retrofit Technology for CO<sub>2</sub> Capture," conducted by the ADA-ES, Inc. These projects received, on average, outstanding ratings across the nine criteria of 7.3 or better out of 10.0. The panel cited the PIs and project teams and their sound technical approaches as strengths of these projects. All three projects were also judged very effective in their use of government resources. The RTI team was commended for pursuing a logical approach in developing credible process concepts, and then using them to scope out the criteria for a successful solid material to achieve credible interaction between material and process development. The MTR team was praised for its willingness and adaptability in exploring a new membrane (plate-and-frame) configuration to accommodate specific technical issues. The review panel noted that the ADA-ES team has demonstrated significant progress since the previous peer review.

Seven additional projects received scores that averaged higher than 6.0: Project 3, "Advanced Low Energy Enzyme Catalyzed Solvent for CO<sub>2</sub> Capture," conducted by Akermin, Inc; Project 4, "Pre-Combustion Membranes," conducted by the NETL's Office of Research and Development (ORD); Project 5, "Carbon Absorber Retrofit Equipment (CARE)" conducted by Neumann Systems Group, Inc.; Project 6, "Application of a Heat Integrated Post-Combustion Carbon Dioxide Capture System with Hitachi Advanced Solvent into Existing Coal-Fired Power Plant," conducted by the University of Kentucky; Project 7, "Slipstream Pilot-Scale Demonstration of a

Novel Amine Based Post-combustion Process Technology for CO<sub>2</sub> Capture from Coal-fired Power Plant Flue Gas,” conducted by the Linde, LLC; Project 8, “Novel Sorption-based CO<sub>2</sub> Capture Process,” conducted by the InnoSeptra, LLC; and Project 13, “Post-Combustion Membranes,” conducted by the NETL’s Office of Research and Development (ORD). These projects cover a wide range of developmental scales, but were all praised for the quality of their PIs and project teams, their innovative approaches, and their potential for significant progress in meeting DOE goals.

### **General Project Weaknesses**

The criteria of Performance and Economic Factors and Potential Technology Risks Considered had the lowest average scores (5.5 and 5.6 respectively). According to the rating definitions, these scores indicate, on average, that the projects are still more than adequate in these areas. However, while several projects performed well under these criteria, the low average scores indicate that a few projects underperformed relative to the standards of the evaluation criterion for their development stages. (See Appendix D.) Specifically, the panel found that some project teams should have addressed the impact of technical and market risks on the economic viability of their technology approaches more fully. In addition, there were concerns that economic analyses conducted as part of some projects did not sufficiently document the contribution of the technology toward meeting DOE’s cost and performance goals.

Another issue cited by the panel was the lack of defined pathways to achieving cost and performance goals. While gaps between current cost and performance and achieving DOE cost and performance goals were often acknowledged, some of the project teams did not detail plans for bridging these gaps. The lack of concrete plans for advancing technologies to the appropriate levels casts some doubt on the ability of some of the projects to meet cost and performance goals.

The panel also noted that some projects did not adequately address the impact of water and contaminants on process performance. Trace contaminants and water have the potential to degrade materials in the power plant, as well as the performance of solvents, sorbents, and membranes. The use of synthetic gases for testing provides useful information, but the movement of testing to actual gases should be accelerated.

For a few projects, the panel cited another area of concern--inattention to issues surrounding process scale-up and large-scale material manufacturing and utilization. For example, some of the technologies reviewed require high levels of vacuum for the capture process. These conditions can be easily achieved in a laboratory setting. However, their use at large scale is problematic. It was not always clear that the project teams had an appreciation for the risks associated with such scale-up issues. In addition, there were instances where the use of expensive materials in unusual configurations could make the possibility of large-scale adoption questionable. Finally, there were instances where the toxicity or flammability of materials could make their use at large-scale problematic. Those issues were inadequately addressed by the project team.

Lastly, while most projects performed well on the Existence of Clear, Measurable Milestones criterion, the panel noted that some milestones, even in projects that performed very well on other criteria, simply described particular tasks, rather than meaningful technical and economic performance metrics. Milestones lacking such measurability and rigor could result in prematurely advancing technologies to larger scales than would be advisable. The need for more meaningful milestones contributed to the panel’s conclusion that a few projects had given

insufficient consideration to the full economic and technical implications of their R&D approaches.

### **Issues for Future Consideration**

While most of the recommendations provided by the panel were technical in nature and specific to a particular project's technology, some overarching issues emerged. The first involves establishment of clear pathways toward meeting DOE cost and performance goals. The pathways developed need more detailed statements of project risks and mitigation strategies, documentation of further potential improvements that could move the technologies toward cost and performance goals, and clearer, expanded discussions of the benefits the project technologies can bring to NETL's overall program. Another key component of any path forward is an analysis of the impact of novel materials on scale ability, process and plant performance, and the environment.

The panel also recommended additional consideration of degradation of CO<sub>2</sub> capture materials. If process conditions lead to any form of degradation of CO<sub>2</sub> removal media over time, those media will require replacement. If estimated replacement costs would be unrealistically high, the advantage of a particular technology in the short term can be overstated. Therefore, testing that incorporates analyses of volatilization, attrition, and all forms of degradation under conditions appropriate for large-scale operations needs to be initiated for all of the projects not currently conducting them.

For some projects, the panel also suggested that prior R&D efforts be more thoroughly reviewed. Most projects were commended for their efforts in this regard, but a few were considered deficient. For these projects, the panel recommended a more complete literature search be conducted, so the project work can benefit from prior experience in the process industries involving the specific technologies/reagents under evaluation.

The panel recommended that some projects need to better assess technology risks. For a few projects, the technology risks listed were incomplete, failing to adequately factor in potential pitfalls and their possible impact on process performance and cost. The panel recommended that these project teams demonstrate a clearer understanding of what the technology risks are and develop strategies to better mitigate those risks.

Additionally, given that a few project milestone lists were weak and primarily task-oriented, the panel recommended that, as appropriate, project milestones be restated to better reflect desired outcomes. Creating measurable milestones of technical and economic factors will help projects stay on track, enhancing project performance and advancing program goals.

## V. PROCESS CONSIDERATIONS FOR FUTURE PEER REVIEWS

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The panel and NETL managers participating in the Carbon Capture Peer Review offered feedback on the review process and constructive comments for improving future peer reviews. These comments were provided at the conclusion of the Peer Review Meeting. The following is a brief summary of ideas for NETL's consideration when planning future peer review meetings.

### **General Process Comments**

Panelists agreed that the peer review process, as currently constituted, is effective and requires little modification. There was high praise for the frank and open nature of interaction with DOE personnel during the review, and consensus that their input added value to the process. Panel members indicated that the short overview comments provided by the Technology Manager prior to each project presentation were helpful and added valuable context to better understanding the presentations that followed.

The panel members appreciated having the project information documents prior to the Peer Review Meeting. They were impressed by the detail and scope of the information provided, although there was more information than they could readily absorb. There was some discussion regarding the potential value of providing pre-meeting questions to the PIs and having them address the questions during their presentations.

The panel indicated that there was some difficulty in providing comments concerning a few projects because PIs were not fully forthcoming about certain aspects of their technologies due to Intellectual Property (IP) concerns. It was suggested that NETL increase efforts to make PIs comfortable sharing such information and assure them of the confidentiality of the review process, so panelists can provide more knowledgeable input to project enhancements.

### **Meeting Agenda**

The panel indicated that the meeting agenda was well structured and provided adequate time for presentations, questioning, and subsequent Panel discussion. In general, the panel was pleased with the time given to each aspect of the Peer Review. However, it noted that allotting time for the presentation and question and answer session based on project technical readiness levels (TRLs) might be appropriate in subsequent peer reviews. The panel also suggested that the projects could be grouped on the agenda based on TRL levels, so projects at similar developmental stages follow one another. This arrangement would encourage questions appropriate to the particular TRL level being presented on a given day of the review.

The panelists also made suggestions related to the questions and answer session. There were times when the PIs engaged in lengthy monologues that insufficiently addressed the question and subsequently decreased the amount of time available for questions with greater relevance. Panelists indicated that they themselves along with the meeting facilitator and/or panel chair could be more forceful in cutting-off long-winded responses. In addition, PI's should be given instructions during their preparations which can be reinforced by the facilitator and chair that direct and succinct answers are recommended.

## **Presentations**

The panel recognized that the project presentations and the review process were enhanced by recent changes in the NETL presentation template and the Project Information Form. For example, setting limits on the number of slides, providing the summary slide, and moving boilerplate information to back-up slides were viewed as improvements. However, the panel did have some suggestions for further improvement.

The panelists thought that NETL should require PIs to add a slide that provides basic design information (e.g., pressures, temperatures, and composition of input and output streams) for their particular processes. This would clarify the conditions under which the process and material are relevant and where they might be applied in power generation. In addition, PIs should identify the target market for their technology – new plants, retrofits, or both. The panel also suggested that the information presented should be from the most recent budget period available. If results obtained during previous budget periods are presented, but information from work in a more recent budget period supersedes or invalidates that older information, presentation of the earlier data does not benefit the peer review process or project execution and success.

## **Evaluation Process**

While the panel noted that its introduction to the review process was quick and effective, there was some ambiguity regarding the context for evaluating certain criteria. First-time panelists indicated that grasping the rating definitions and scoring projects was difficult. They suggested more attention to the definitions and scoring in the overview presentations. It was also suggested that there be additional, more extensive orientation for first-time panelists.

The panel had discussions during the meeting to gain consensus on criteria interpretation. However, interpretation of Criterion 8, Anticipated Benefits, was specifically raised as an issue. Some panelists found it difficult to assess this criterion based on the information provided by the PIs. They felt that more guidance was needed regarding Criterion 8 and that coaching the PIs on what is expected for this criterion would be useful. They also suggested that the Technology Manager and the Division Director consider a pre-peer review meeting with the panel to discuss expectations.

Another suggestion regarding the evaluation process was to provide additional time for panel members to prepare comments by shortening the time for presentations. Finally, it was noted that panel comments should focus on project actions/remedies that could move each project to the next TRL.

## **Review Panel**

The panel valued this Peer Review as a unique opportunity to exchange insights with expert colleagues, and, most of all, as an important contribution to critical DOE research and development in carbon capture.



APPENDICES

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## APPENDIX A: AIChE PEER REVIEW METHODOLOGY

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Founded in 1908, the American Institute of Chemical Engineers (AIChE) has 45,000 members in 92 countries. These members provide a unique breadth and depth of resources and expertise. AIChE members join mechanical technologies with the chemical and biological sciences. Members have expertise in reacting systems coupled with complex thermodynamics and kinetics.

AIChE's unique industry and technology groups provide the Institute with core expertise in critical technology areas. For example, AIChE formed its Center for Chemical Process Safety in 1985 in response to the accident in Bhopal. Since then, the Institute has formed additional groups, including ones focused on energy, sustainability and biology. These Industry Technology Groups (ITGs) facilitate technology development and assessment, enabling validation and development of best practices and creating knowledge in each of the subject areas. The ITGs work with, and provide access to, world-renowned experts in these technology areas and provide a pool of expertise for the development of effective peer reviews.

### **AIChE's Center for Chemical Process Safety (CCPS)**

CCPS was formed when leaders of the chemical industry asked AIChE to lead a collaborative effort to reduce and eliminate catastrophic process incidents by advancing state of the art in technology and management practices. CCPS is the world's premier resource for information on process safety, supporting process safety in engineering, and promoting process safety as a key industry value. CCPS codified the critical elements of process safety and has provided critical tools for the continual improvement of process safety programs.

### **AIChE's Center for Energy Initiatives (CEI)**

Against the backdrop of growing global demand for energy and new energy legislation, AIChE and its members have launched a series of initiatives that apply chemical engineering expertise to helping meet our energy needs. To guide these endeavors, the AIChE Board of Directors organized CEI as a group of industry and academic experts and consultants representing a broad portfolio of energy technologies, as well as business and research interests. Among CEI's activities is the leadership of the Founder Society's Technologies for Carbon Management.

### **Founder Society's Technologies for Carbon Management**

AIChE is leading the Engineering Founder Societies (AIChE; American Institute of Mining, Metallurgical and Petroleum Engineers; American Society of Civil Engineers; American Society of Mechanical Engineers; and the Institute of Electrical and Electronics Engineers) in applying the joint expertise of their disciplines to climate change issues. The group has selected a scorecard approach as a tool for assessing the merit of various greenhouse gas management options. The scorecards developed so far focus on electric power and transportation systems (4-wheel passenger vehicles). Additional projects include the development of biofuels metrics, energy system boundaries, a carbon capture and sequestration network, a carbon management conference, greenhouse gas measurement, and gaps and barriers.

## Carbon Capture Peer Review Panel

For this project, AIChE was ultimately responsible for the identification and performance of the Peer Review panelists, including the chair and facilitator. NETL suggested candidates for AIChE's consideration. However, AIChE made the ultimate selection and was accountable for Panel composition and performance.

AIChE uses a Peer Review Advisory Board to determine the expertise needed for all the peer reviews to be conducted and then to identify experts with the proper background and domain experience. The Advisory Board makes sure that the panel is well-rounded and has sufficient technical knowledge of the various aspects of all of the projects selected for review. Upon notification of the projects to be reviewed, AIChE convened the Advisory Board to determine the necessary expertise and identify experts. The reviewer expertise needed was then balanced with the potential reviewers. A scorecard was used to ensure that potential panelists covered the necessary skill sets

AIChE determined that the expertise needed for the Carbon Capture Peer Review included the following:

- Post-combustion capture technology
- Pre-combustion capture technology
- Traditional and novel solvents
- Traditional and novel sorbents
- Membranes
- Polybenzimidazole (PBI) novel membranes
- Ionic liquids
- Alkanolamines
- Enzymes for CO<sub>2</sub> removal
- Absorber/adsorber design and regeneration
- Adsorber design, novel
- Heat integration
- Fluidized beds
- Combined fuel cell/membrane
- Integrated gasification combined cycle (IGCC)
- Gasification test bed
- Coal characterization and testing
- Utility industry
- Bench-scale parametric test design
- Bench-scale pilot plant design
- Integrated systems analysis
- Mass and heat transfer analysis
- Commercialization
- Risk assessment and management
- Pilot plant scale-up
- Field testing
- Economic analysis
- Solids handling and transport
- Environmental, health and safety systems analysis

Upon determining these scientific and technical areas of expertise and the skill sets required to assess the projects to be reviewed, AIChE carefully reviewed the résumés of all those who served on prior review panels for DOE (acknowledging the benefit of their previous experience in this form of Peer Review Meeting); a number of new submissions from DOE; and those resulting from discussions with AIChE members in its Divisions, Forums, and Industry Technology Groups with relevant experience. AIChE also recognized the importance of representing the different perspectives of academia, government, and industry to ensure a comprehensive technical review of the merits of each project. From these sources, the AIChE Peer Review Advisory Board selected an eight-member review panel, including six individuals who had served on prior Peer Review Panels, and agreed that the Panel members had the experience necessary to review the projects and did not present any conflicts of interest. Panel members and qualifications are described in Appendix C.

AIChE selected a meeting facilitator with knowledge in the subject area and facilitation experience, who assisted in preparation of the review team and helped to identify areas where additional detail is merited in discussions during the review process.

In addition, the AIChE writing team also had familiarity with the technology area, as well as many years of expertise in technical editing. These team members were also involved in meeting preparation.

### **Meeting Preparation and Logistics**

Prior to the meeting, the project team for each project to be reviewed was asked to submit a 15-page written summary (Project Information Form) of their project's purpose, objectives, and progress; a PowerPoint presentation per the template and guidelines provided; and their Statement of Project Objectives containing project objectives, a description of the scope of the project, a detailed breakdown of project tasks and subtasks to be performed, and associated deliverables and presentations. The Project Information Forms and Statement of Project Objectives were collected and provided to the panel well in advance of the meeting to help the panelists prepare for the review. The panel was also given hard-copy handouts of these PowerPoint slides prior to the meeting.

The meeting facilitator convened conference calls of the peer review team to orient them, along with writers prior to the meeting. This pre-review discussion covered the review process and the panelists' roles and responsibilities, as well as the roles of the chair and the facilitator. In addition, the calls allowed the panel to identify gaps in information provided by the project teams. In a few cases, project teams were asked for additional information that helped prepare the panel by providing additional details of the project under review. This clearer, more detailed information helped assure the overall quality and technical depth of the review.

### **Project Presentations, Evaluations, and Discussion**

At the Carbon Capture Peer Review Meeting, presenters were held to a 45-minute time limit to allow sufficient time for all presentations within the four-day meeting period. After each presentation, the project team participated in a 30-minute Q&A session with the panel.

The panel then spent 40 minutes evaluating the projects based on the presentation material. To start, each reviewer scored the project against a set of predetermined peer review criteria. The following nine criteria were used:

- Scientific and Technical Merit
- Existence of Clear, Measurable Milestones
- Utilization of Government Resources
- Technical Approach
- Rate of Progress
- Potential Technology Risks Considered
- Performance and Economic Factors
- Anticipated Benefits if Successful
- Technology Development Pathways.

For each of these review criteria, individual panel members scored each project as one of the following:

- Excellent (10)
- Highly Successful (8)
- Fair (5)
- Weak (2)
- Unacceptable (0).

To facilitate the evaluation process, Leonardo Technologies, Inc. (LTI) provided the panel with laptop computers that were preloaded with Peer Review Criteria Forms for each project. The panel jointly discussed the project for the purpose of defining project strengths, project weaknesses, recommendations, and action items that the team must address to address project deficiencies. After this discussion, each panel member scored the project against the nine criteria, documented project strengths and weaknesses, and recommendations and action items for addressing them, and provided written comments reiterating and expanding on the discussions.

During the review discussions, the facilitator prodded the panel to provide justification and documentation of both strengths and weaknesses and probed to assure depth in each recommendation and action item provided. The chair of the review panel helped clarify technical comments and assessments of the panel discussion.



## APPENDIX B: MEETING AGENDA

# FY13 Carbon Capture Peer Review



Sheraton Station Square  
Pittsburgh, PA  
March 11-15, 2013

### AGENDA

#### Monday, March 11, 2013 –

- 7:00 – 8:00 a.m.      **Registration –**
- 8:00 – 9:30 a.m.      **Peer Review Panel Kick Off Meeting**  
Open to National Energy Technology Laboratory (NETL) and American Institute of Chemical Engineers (AIChE) staff only
- Review of AIChE Process – June Wispelwey, AIChE
  - Role of Panel Chair – TBD, AIChE
  - Role of NETL – José Figueroa, NETL
  - Meeting logistics/completion of forms – Justin Strock/Nicole Ryan/Dave Wildman, LTI
- 9:30 – 10:15 a.m.      **Overview** Open to NETL and AIChE staff only
- Carbon Capture Technology Manager – Shailesh Vora, NETL
- 10:15 – 10:30 a.m.      **BREAK**
- 10:30 – 11:15 a.m.      **01 - Project # FE0007466** – CO<sub>2</sub> Binding Organic Liquids Gas Capture with Polarity Swing Assisted Regeneration –  
*David J. Heldebrant, Battelle Memorial Institute*
- 11:15 – 11:45 a.m.      Q&A
- 11:45 – 12:25 p.m.      Discussion
- 12:25 – 12:35 p.m.      Evaluation entry
- 12:35 – 1:35 p.m.      **Lunch (on your own)**
- 1:35 – 2:20 p.m.      **02 - Project # FE0005799** – Ion Novel Solvent System for CO<sub>2</sub> Capture –  
*Alfred (Buz) Brown, ION Engineering LLC*
- 2:20 – 2:50 p.m.      Q&A
- 2:50 – 3:30 p.m.      Discussion
- 3:30 – 3:40 p.m.      Evaluation entry
- 3:40 – 3:55 p.m.      **BREAK**

**Monday, March 11, 2013 –**

3:55 – 4:40 p.m.	<b>03 - Project # FE0004228</b> – Advanced Low Energy Enzyme Catalyzed Solvent for CO <sub>2</sub> Capture – <i>John Reardon and Alex Zaks, Akermin, Inc.</i>
4:40 – 5:10 p.m.	Q&A
5:10 – 5:50 p.m.	Discussion
5:50 – 6:00 p.m.	Evaluation entry

**Tuesday, March 12, 2013 –**

7:00 – 8:00 a.m.	<b>Registration –</b>
8:00 – 8:45 a.m.	<b>04 - Project # ORD-2012.01.00 Task 4</b> – Pre-Combustion Membranes – <i>David Hopkinson, National Energy Technology Laboratory</i>
8:45 – 9:15 a.m.	Q&A
9:15 – 9:55 a.m.	Discussion
9:55 – 10:05 a.m.	Evaluation entry
10:05 – 10:20 a.m.	<b>BREAK</b>
10:20 – 11:05 a.m.	<b>05 - Project # FE0007528</b> – Carbon Absorber Retrofit Equipment (CARE) – <i>Andy Awtry, Neumann Systems Group, Inc.</i>
11:05 – 11:35 a.m.	Q&A
11:35 – 12:15 p.m.	Discussion
12:15 – 12:25 p.m.	Evaluation entry
12:25 – 1:25 p.m.	<b>Lunch (on your own)</b>
1:25 – 2:10 p.m.	<b>06 - Project # FE0007395</b> – Application of a Heat Integrated Post-Combustion Carbon Dioxide Capture System with Hitachi Advanced Solvent into Existing Coal-Fired Power Plant – <i>Kunlei Liu, University of Kentucky</i>
2:10 – 2:40 p.m.	Q&A
2:40 – 3:20 p.m.	Discussion
3:20 – 3:30 p.m.	Evaluation entry
3:30 – 3:45 p.m.	<b>BREAK</b>
3:45 – 4:30 p.m.	<b>07 - Project # FE0007453</b> – Slipstream Pilot-Scale Demonstration of a Novel Amine Based Post- Combustion Process Technology for CO <sub>2</sub> Capture from Coal-Fired Power Plant Flue Gas – <i>Krish R. Krishnamurthy, Linde, LLC</i>
4:30 – 5:00 p.m.	Q&A
5:00 – 5:40 p.m.	Discussion
5:40 – 5:50 p.m.	Evaluation entry

**Wednesday, March 13, 2013 –**

7:00 – 8:00 a.m.	<b>Registration –</b>
8:00 – 8:45 a.m.	<b>08 - Project # FE0007948</b> – Novel Sorption-Based CO <sub>2</sub> Capture Process – <i>Ravi Jain, Innosepra Limited Liability Company</i>
8:45 – 9:15 a.m.	Q&A
9:15 – 9:55 a.m.	Discussion
9:55 – 10:05 a.m.	Evaluation entry
10:05 – 10:20 a.m.	<b>BREAK</b>
10:20 – 11:05 a.m.	<b>09 - Project # FE0007603</b> – Evaluation of Carbon Dioxide Capture from Existing Coal Fired Plants by Hybrid Sorption Using Solid Sorbents – <i>Steven A. Benson and Srivats Srinivasachar, University of North Dakota</i>
11:05 – 11:35 a.m.	Q&A
11:35 – 12:15 p.m.	Discussion
12:15 – 12:25 p.m.	Evaluation entry
12:25 – 1:25 p.m.	<b>Lunch (on your own)</b>
1:25 – 2:10 p.m.	<b>10 - Project # FE0007580</b> – Low Cost, High Capacity Regenerable Sorbent for Carbon Dioxide Capture from Existing Coal-Fired Power Plants – <i>Gökhan Alptekin, TDA Research, Inc.</i>
2:10 – 2:40 p.m.	Q&A
2:40 – 3:20 p.m.	Discussion
3:20 – 3:30 p.m.	Evaluation entry
3:30 – 3:45 p.m.	<b>BREAK</b>
3:45 – 4:30 p.m.	<b>11 - Project # FE0007707</b> – Bench-Scale Development of an Advanced Solid Sorbent-Based Carbon Capture Process for Coal-Fired Power Plants – <i>Thomas Nelson and Luke Coleman, Research Triangle Institute</i>
4:30 – 5:00 p.m.	Q&A
5:00 – 5:40 p.m.	Discussion
5:40 – 5:50 p.m.	Evaluation entry

**Thursday, March 14, 2013 –**

7:00 – 8:00 a.m.	<b>Registration –</b>
8:00 – 8:45 a.m.	<b>12 - Project # FE0004343</b> – Recovery Act: Evaluation of Solid Sorbents as a Retrofit Technology for CO <sub>2</sub> Capture – <i>Sharon Sjostrom, ADA-ES Inc.</i>
8:45 – 9:15 a.m.	Q&A
9:15 – 9:55 a.m.	Discussion
9:55 – 10:05 a.m.	Evaluation entry
10:05 – 10:20 a.m.	<b>BREAK</b>



**Thursday, March 14, 2013 –**

- 10:20 – 11:05 a.m.     **13 - Project # ORD-2012.01.00 Task 7** – Post-Combustion Membranes –  
*Erik Albenze, National Energy Technology Laboratory*
- 11:05 – 11:35 a.m.     Q&A
- 11:35 – 12:15 p.m.     Discussion
- 12:15 – 12:25 p.m.     Evaluation entry
- 12:25 – 1:25 p.m.     **Lunch (on your own)**
- 1:25 – 2:10 p.m.     **14 - Project # FE0007634** – Electrochemical Membrane for Carbon Dioxide Capture and Power  
Generation –  
*Hossein Ghezel-Ayagh, FuelCell Energy, Inc*
- 2:10 – 2:40 p.m.     Q&A
- 2:40 – 3:20 p.m.     Discussion
- 3:20 – 3:30 p.m.     Evaluation entry
- 3:30 – 3:45 p.m.     **BREAK**
- 3:45 – 4:30 p.m.     **15 - Project # FE0005795** – Recovery Act: Slipstream Testing of a Membrane CO<sub>2</sub> Capture  
Process for Existing Coal-Fired Power Plants –  
*Tim Merkel, Membrane Technology & Research, Inc.*
- 4:30 – 5:00 p.m.     Q&A
- 5:00 – 5:40 p.m.     Discussion
- 5:40 – 5:50 p.m.     Evaluation entry

**Friday, March 15, 2013 –**

- 7:00 – 8:00 a.m.     **Registration –**
- 8:00 – 8:45 a.m.     **16 - Project # FE-10-002** – High-Temperature Polymer-Based Membrane Systems for Pre-  
Combustion CO<sub>2</sub> Capture –  
*Kathryn A. Berchtold, Los Alamos National Laboratory*
- 8:45 – 9:15 a.m.     Q&A
- 9:15 – 9:55 a.m.     Discussion
- 9:55 – 10:05 a.m.     Evaluation entry
- 10:05 – 10:20 a.m.     **BREAK**
- 10:20 – 12:20 p.m.     **Meeting Wrap-up Session**



## APPENDIX C: PEER REVIEW PANEL MEMBERS

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AICHE had ultimate responsibility for the identification and performance of the Peer Review panelists, including the chair. NETL could suggest candidates for AICHE's consideration. However, AICHE made the ultimate selection and had accountability.

AICHE's Peer Review Advisory Board helps project personnel determine the expertise needed for reviews and identify experts with the proper backgrounds. This Advisory Board also makes sure that the panel is well-rounded and has sufficient technical knowledge of the various aspects of the projects for review.

When it received a list of the projects to be reviewed, AICHE convened its Advisory Board to determine the needed expertise and identify experts. Required reviewer expertise was then balanced with the potential reviewers. AICHE used a scorecard to ensure that potential panelists provided necessary skill sets.

With the input of its Advisory Board, AICHE determined that the expertise needed for the Carbon Capture Peer Review included these technical topics:

- Post-combustion capture technology
- Pre-combustion capture technology
- Traditional and novel solvents
- Traditional and novel sorbents
- Membranes
- Polybenzimidazole (PBI) novel membranes
- Ionic liquids
- Alkanolamines
- Enzymes for CO<sub>2</sub> removal
- Absorber/adsorber design and regeneration
- Adsorber design, novel
- Heat integration
- Fluidized beds
- Combined fuel cell/membrane
- Integrated gasification combined cycle (IGCC)
- Gasification test bed
- Coal characterization and testing
- Utility industry
- Bench-scale parametric test design
- Bench-scale pilot plant design
- Integrated systems analysis
- Mass and heat transfer analysis
- Commercialization
- Risk assessment and management
- Pilot plant scale-up
- Field testing
- Economic analysis
- Solids handling and transport
- Environmental, health and safety systems analysis

Upon determination of the scientific and technical areas, expertise, and skill sets required to assess these projects, AIChE carefully reviewed the résumés of all those who served on prior review panels for DOE (acknowledging the benefit of their previous experience in this form of Peer Review Meeting), a number of new submissions from DOE, and those resulting from discussions with AIChE members in its Divisions, Forums, and Industry Technology Groups with relevant experience. AIChE also recognized the importance of representing the different perspectives of academia, government, and industry to ensure a comprehensive technical review of the merits of each project. It was determined that six individuals who had served on prior Peer Review Panels were qualified to serve on the Carbon Capture Peer Review Panel.

Appropriate résumés were then submitted to the Carbon Capture Peer Review Executive Committee for review. The following eight members were selected for the FY 2013 Carbon Capture Peer Review (\* indicates a prior Panel member):

- John C. Tao, PhD\*, Panel Chair
- Jon Gibbons, PhD
- Mark Golightley\*
- Daniel J. Kubek\*
- Alissa Park, PhD
- Ravi Prasad, PhD\*
- Veronika A. Rabl, PhD\*
- James C. Sorensen\*

AIChE selected a review panel chair who has participated in previous peer reviews and, therefore, has an understanding of the peer review process and the role of the panel members. The chair was selected before the panel was fully constituted, and he assisted AIChE in identifying candidates for the panel and in reviewing the credentials of these candidates. Other pre-review roles of the chair included assisting AIChE in finalizing the Peer Review Evaluation Criteria and Reviewer Guidance documents and developing, with AIChE, critical path milestones that defined process steps and schedule completion dates in order to ensure timely delivery of all final review panel documents to DOE/NETL.

When the review panel was fully constituted, the panel members were directed to a SharePoint site, created by NETL, which contained project and program-related information, such as the Project Information Forms, presentations, and the DOE Strategic Plan and Multi-Year Plan for the programs to be reviewed.

A conference call, consisting of the review panel, AIChE and its support staff, and the peer review facilitator, was conducted before the Peer Review meeting to discuss the following:

- Evaluation criteria
- Scoring criteria
- Peer review process (PI presentation, Q&A, and panel discussion)
- Goals/objectives of review (i.e., quality of reviewer comments, consistency of strengths and weaknesses)
- Scope and boundaries of the peer review
  - Programmatic and funding comments are outside the Panel's Review scope
  - Projects are reviewed based on their merit and not on a comparative basis
- Computerized evaluation criteria tool on a laptop network
- The separate, but interrelated, roles and responsibilities of the facilitator, chair, and reviewers

- What reviewers should be looking for as they review the Project Information Forms and listen to the Project Presentations
- How each project would be reviewed in terms of its Strengths, Weaknesses, Recommendations and Action Items

Panel members reviewed presentation materials prior to the meeting and spent five days at the meeting evaluating projects and providing comments. Panelists received an honorarium for their time as well as reimbursement of travel expenses. A brief summary of their qualifications follows.

## **FY 2013 Carbon Capture Peer Review Panel Members**

### ***John C. Tao, Panel Chair***

John Tao has a wealth of experience in gas separations, coal conversion and combustion technologies through 30-plus years at Air Products & Chemicals. Recently, he was vice president of open innovation at Weyerhaeuser, where he managed the corporate intellectual asset management process, technology partnering, and early business development. At Air Products, he was most recently corporate director of technology partnerships. He was responsible for worldwide external technology development, intellectual asset management, licensing and technology transfer with outside organizations, and government contracts. He is familiar with oxy-fuel combustion technology and advanced oxygen separation using ion transport membranes. During his career at Air Products, Dr. Tao was involved in engineering management, R&D management, commercial development, venture management, and planning and business development.

Tao is a Fellow of the American Institute of Chemical Engineers. He was a member of the Board of Directors for AIChE, Industrial Research Institute, Commercial Development and Marketing Association, and the Council for Chemical Research. He was chairman of Chemical Industry Environmental Technology Projects, a board member of the Pennsylvania State University Research Foundation, and the chairman of the Management Committee of the Air Products and Imperial College Strategic Alliance, the Air Products Alliance with the Georgia Institute of Technology, and the Air Products/Pennsylvania State University Research Alliance. He served as a member of the Visiting Committee of the department of chemical and petroleum engineering at the University of Pittsburgh and on the advisory council for the chemical engineering department of the University of Pennsylvania.

Tao has a BS and PhD in chemical engineering from Carnegie-Mellon University, and an MS in chemical engineering from the University of Delaware.

### ***Jon Gibbins***

Gibbins is currently professor of power plant engineering and carbon capture at the University of Edinburgh. He is also the Director of the United Kingdom's (UK's) Carbon Capture and Sequestration (CCS) Research Centre, which is supported by Research Councils UK in order to lead and coordinate a program of underpinning research on all aspects of CCS in support of basic science and UK government efforts on energy and climate change. Gibbins has worked on coal and biomass gasification and combustion for over 30 years, at Foster Wheeler, Imperial College and the University of Edinburgh and on CCS since 2002. He is involved in a number of other academic, industrial and government initiatives on CCS in the UK and abroad.

Currently he is working toward delivering the combination of technical, policy and economic advances that will move CCS rapidly to the stage where it can make an effective contribution to global climate change mitigation. Technical studies have been complemented by work on power plant economics and pathways for CCS implementation. Through his own group and by his involvement in the earlier UK CCS Consortium project, the UK CCS Community Network and the UK CCS Research Council, Gibbins has also worked to help develop the academic CCS capacity necessary to support rapid CCS development and deployment. Gibbins has authored over 50 papers and more than 100 articles and reports on CCS and related topics.

Gibbins graduated with a B.S. degree in mechanical engineering from Imperial College of London, where he also earned a Master of Philosophy and Ph.D. in chemical engineering and chemical technology.

### ***Mark Golightley***

Mark Golightley currently works for FirstEnergy Corp. (formerly Ohio Edison). He has worked in various capacities throughout his career in production at coal-fired power stations, in corporate engineering and in environmental departments. His current responsibilities include troubleshooting performance and environmental issues at the Sammis plant, including the start-up of baghouses and electrostatic precipitators.

During his tenure at FirstEnergy, he developed two patented processes for manufacturing gypsum and alpha plaster from flue-gas desulfurization calcium sulfite. He has been involved in pilot-level testing, development and demonstrating the patented processes. He also worked on designing and constructing a 30,000 ton per year alpha plaster plant and designing and constructing a 500,000 ton per year ex-situ gypsum plant, which supplies gypsum to a new wallboard plant adjacent to the power plant (which was the second largest recycle project in the U.S. at that time). He has supported corporate coal-fired plant environmental control technologies, including studying technologies addressing SO<sub>2</sub>, sulfur trioxide, mercury, nitrogen oxide, and CO<sub>2</sub>. Prior to working for FirstEnergy, Mark worked for Kaiser Aluminum.

Golightley received B.S. degrees in education and chemical engineering from the University of Toledo. He is a registered Professional Engineer in the State of Ohio.

### ***Daniel J. Kubek***

Daniel Kubek is a consultant specializing in synthesis gas and natural gas purification and separation. His clients include the Electric Power Research Institute – CoalFleet, for whom he provides technical guidance on integrated processes for gasification projects; and the Gasification Technologies Council, where he serves as an advisor on technical issues related to gasification, particularly in the areas of hydrogen sulfide removal and carbon capture.

Kubek was with UOP for 18 years as senior technology manager. His technical expertise is based in separations technology and engineering. His primary work was in solvent absorption, molecular sieve thermal-swing adsorption, membrane permeation, and pressure-swing absorption technologies, as applied to natural gas and synthesis gas processing. He was the process manager responsible for all process design packages for multiple gasification projects and served as development manager for UOP's gas processing business. Before joining UOP, he spent 17 years with Union Carbide. In 2005, Kubek was awarded UOP's Don Carlson Award for Career Technical Innovation. From 1996 to 2006, he served as UOP's representative to the Gasification Technologies Council's Board of Directors. He holds 8 patents and has co-authored 17 technical publications.

Kubek received a B.S. degree in chemical engineering from Rutgers University and holds an M.S. in chemical engineering from Purdue University.

### **Ah-Hyung (Alissa) Park**

Ah-Hyung (Alissa) Park is the Lenfest Junior Professor in Applied Climate Science of Earth and Environmental Engineering and Chemical Engineering at Columbia University. She is the Associate Director of the Lenfest Center for Sustainable Energy.

Her research interests include carbon capture and storage, sustainable energy conversion systems, particle technology and multiphase flows. The specific on-going research efforts of Park's group include:

1. The fundamental studies of novel organic-inorganic hybrid nanomaterials for application in CO<sub>2</sub> capture and storage.
2. Tailored synthesis of engineered carbon-neutral filler materials as a means of carbon sequestration (CS) and production of liquid fuels from biomass and solid municipal wastes with integrated carbon capture technology.
3. Production of hydrogen and liquid fuels from biomass and solid municipal wastes with integrated CS.

Park has received a number of awards and honors, including the National Science Foundation CAREER Award in 2009.

Park received her B.S. and M.S. degrees in chemical engineering from the University of British Columbia and a Ph.D. from Ohio State University.

### **Ravi Prasad**

Ravi Prasad of Helios-NRG, LLC, and formerly a corporate fellow of Praxair, Inc., holds 60 U.S. patents and broad industrial experience in developing and commercializing new technologies, launching technology programs (\$2–\$50 million), supporting business development, building cross-functional teams, and setting up joint development alliances. He was a founding member of an alliance involving Praxair, British Petroleum, Amoco, Phillips Petroleum, Statoil, and Sasol to develop ceramic membrane synthesis gas (syngas) technology for gas-to-liquid processes.

Prasad established and led programs for ceramic membrane oxygen technology; co-developed proposals to secure major DOE programs worth \$35 million in syngas and \$20 million in oxygen; identified novel, solid-state oxygen generation technology; and conceived and implemented a coherent corporate strategy in nanotechnology. He has championed many initiatives in India, including small onsite hydrogen plants, small gasifiers, and aerospace business opportunities; and developed implementation plans resulting in a new research and development center in Shanghai. Prasad is the director and a board member of the National Hydrogen Association, a member of the steering committee for Chemical Industry Vision 2020, and has been a recipient for Chairman's and Corporate Fellows' awards for technology leadership. He has authored or co-authored 30 publications, is co-author of a book on membrane gas separation, and has presented at more than 20 conferences and delivered invited lectures.

Prasad has a B.S. in mechanical engineering from the Indian Institute of Technology in Kanpur, India; and an M.S. and Ph.D. in mechanical engineering and chemical engineering from the State University of New York, Buffalo.

### ***Veronika A. Rabl***

Veronika Rabl is a recognized expert in energy efficiency, demand response, electric technologies, and energy industry issues. During her career, she has provided technical and business leadership for design, analysis, engineering, and implementation of energy technologies and programs in all sectors of the economy. She has authored numerous papers and has been an invited speaker and lecturer at many energy-related events in the U.S. and abroad.

Until 2001, Rabl served as director and general manager, retail energy products and services, at the Electric Power Research Institute (EPRI), leading the product portfolio strategy for retail and power markets. During her career at EPRI, she directed a range of technical and business areas, including strategic planning, market research, marketing, demand-side management, electric transportation, power quality, distribution systems, and metering. She joined EPRI in 1981 to create a demand response technology portfolio, developing thermal storage systems, energy management and distributed load control equipment, home automation, communication systems, and customer interface products.

Currently, Rabl is an independent consultant specializing in energy efficiency, demand response, and greenhouse gas mitigation, and the integration of these technologies into power system design and operation. Her recent work includes group leadership and preparation of demand management recommendations for the Virginia State Corporation Commission; a comprehensive examination of energy conservation effects of distribution voltage reduction; assessment of carbon tax and cap-and-trade impacts on markets for electric and hybrid vehicles; and leadership in organizing a workshop on knowledge gaps and implementation barriers to timely deployment of the most promising greenhouse gas management technologies.

Rabl is a member of IEEE-USA Energy Policy Committee and IEEE's lead representative on the Engineering Founder Societies' Technology for Carbon Management Initiative. She was also selected to serve as expert reviewer of the International Panel on Climate Change Working Group III Special Report on Renewable Energy Sources and Climate Change Mitigation. She is a recipient of the IEEE-USA Professional Achievement Award for Individuals.

Rabl received her undergraduate degree from Charles University, Prague, her MS from the Weizmann Institute of Science, and her PhD from Ohio State University.

### ***James C. Sorensen***

James Sorensen is a consultant with a primary focus on clean coal and natural gas conversion, including Integrated Gasification Combined Cycle (IGCC), oxyfuel combustion, CO<sub>2</sub> capture, coal-to-liquids, and supporting technologies. His assignments have included numerous peer reviews of DOE R&D programs and proposals to DOE, consulting to EPRI on the CoalFleet program and other studies and commercial projects. He is the former chief operating officer of, and now a senior advisor for, GTL petrol. Prior to founding Sorensenergy, LLC, he worked for Air Products & Chemicals, including positions as director of new markets with responsibility for Syngas Conversion Technology Development and Government Systems; and director of gasification and energy conversion, with responsibility for air separation plant sales for gasification applications. Earlier responsibilities included project management of Air Products' baseload LNG projects and commercial management of SNG production.



Sorensen is the founding chairman of the Gasification Technologies Council. He received BS and MS degrees in chemical engineering from California Institute of Technology and Washington State University, respectively, and an MBA from the Harvard Business School. He holds eight U.S. patents.

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**APPENDIX D: PEER REVIEW CRITERIA FORM**


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**PEER REVIEW CRITERIA FORM**
**U. S. DEPARTMENT OF ENERGY  
NATIONAL ENERGY TECHNOLOGY LABORATORY  
FY13 CARBON CAPTURE PEER REVIEW**
**March 11 – 15, 2013**


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<b>Project Title:</b>	
<b>Performer:</b>	
<b>Presenter:</b>	
<b>Name of Peer Reviewer:</b>	
<b>Date of Review:</b>	

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The following pages contain the criteria used to evaluate each project. The criteria have been grouped into three (3) major categories: (1) **Project Overview**; (2) **Technical Discussion**; and (3) **Technology Benefits**. Additionally, each criterion is accompanied by multiple characteristics to further define the topic.

The Reviewer is expected to provide a **rating** and **substantive comments** which support that rating for each criterion. Please note that if a rating of “0” is selected, **justifying comments must be included**. To assist with determining the criterion score, descriptions of those scores are provided below.

<b>RATING DEFINITIONS</b>	
<b>0</b>	<b>Unacceptable</b> – Project fails to meet all sub-criteria objectives. Significant weaknesses/deficiencies exist that are largely insurmountable.
<b>2</b>	<b>Weak</b> – Project fails to meet most sub-criteria objectives. Weaknesses outweigh strengths identified.
<b>5</b>	<b>Fair</b> – Projects meets sub-criteria objectives. Strengths and weaknesses are in balance.
<b>8</b>	<b>Highly Successful</b> – Project exceeds most sub-criteria objectives. Strengths are apparent and documented.
<b>10</b>	<b>Excellent</b> – Project exceeds all sub-criteria objectives. Strengths are apparent and documented. No weaknesses were identified.

Please evaluate the project against each of the nine (9) criteria listed below. For each criterion, select the appropriate rating by typing an "X" in the applicable cell. Definitions for the five ratings are provided on page 1. Reviewers need to identify the sub-criteria (i.e. 1.1, 1.2, 1.3) that are considered weak or unacceptable (see Comments section).

NOTE: If you rate any criterion as "0," a justification for this rating is required. Please include your justification in the box at the end of this table.

<b>PROJECT OVERVIEW</b>					
<b>1. Scientific and Technical Merit</b>	<b>0 *</b>	<b>2</b>	<b>5</b>	<b>8</b>	<b>10</b>
1.1 – Scientific feasibility of project concept 1.2 – Degree and likelihood of achieving planned technological advancements 1.3 – Degree of innovation evidenced					
<b>2. Existence of Clear, Measurable Milestones</b>	<b>0 *</b>	<b>2</b>	<b>5</b>	<b>8</b>	<b>10</b>
2.1 – Degree to which the number of milestones per budget period are appropriate 2.2 – Degree to which milestones are quantitative and show progression towards project goals 2.3 – Degree of completeness of milestones (title, completion date, success criterion)					
<b>3. Utilization of Government Resources</b>	<b>0 *</b>	<b>2</b>	<b>5</b>	<b>8</b>	<b>10</b>
3.1 – Degree of adequacy of the research team to address the project goal and objectives 3.2 – Feasibility of rationale presented for teaming or collaborative efforts 3.3 – Feasibility of equipment, materials, and facilities to meet the project goal and objectives					
<b>TECHNICAL DISCUSSION</b>					
<b>4. Technical Approach</b>	<b>0 *</b>	<b>2</b>	<b>5</b>	<b>8</b>	<b>10</b>
4.1 – Degree of adequacy of understanding of potential technical challenges and technical barriers 4.2 – Degree of adequacy of the mitigation strategy for the identified technical challenges and barriers 4.3 – Feasibility of technical approach to support stated project goal and objectives					
<b>5. Rate of Progress</b>	<b>0 *</b>	<b>2</b>	<b>5</b>	<b>8</b>	<b>10</b>
5.1 – Degree of adequacy of progress to date against stated project goal, objectives, milestones, and schedule 5.2 – Likelihood of achieving continued progress against technical barriers 5.3 – Feasibility of project goals, objectives, and expected outcomes and benefits being achieved 5.4 – Reasonableness of the cost performance to date and plan to achieve project goals and objectives					

<b>TECHNICAL DISCUSSION (continued)</b>					
<b>6. Potential Technology Risks Considered</b>	<b>0 *</b>	<b>2</b>	<b>5</b>	<b>8</b>	<b>10</b>
<p><b>6.1</b> – Degree to which potential risks to the environment or public associated with widespread technology deployment have been considered.</p> <p><b>6.2</b> – Degree to which project risks are identified and effective measures to address and mitigate these risks, including potential technical uncertainties and barriers, are presented.</p> <p><b>6.3</b> – Degree of recognition of scientific risks and plausibility of mitigation strategies presented.</p>					
<b>7. Performance and Economic Factors **</b>	<b>0 *</b>	<b>2</b>	<b>5</b>	<b>8</b>	<b>10</b>
<p><b>7.1</b> – Degree of adequacy of technology cost and performance assessments, given the level of technology development</p> <p><b>7.2</b> – Reasonableness of cost estimates for future technology development, if warranted, given uncertainties</p> <p><b>7.3</b> – Feasibility of meeting DOE Program cost and performance goals</p>					
<b>TECHNOLOGY BENEFITS</b>					
<b>8. Anticipated Benefits, if Successful</b>	<b>0 *</b>	<b>2</b>	<b>5</b>	<b>8</b>	<b>10</b>
<p><b>8.1</b> – Reasonableness of statements regarding potential benefits of the project’s research</p> <p><b>8.2</b> – Potential of technologies being developed benefitting other programs</p> <p><b>8.3</b> – Potential of technologies being developed to have a spin-off opportunity identified by the project team</p> <p><b>8.4</b> – Feasibility of the project to contribute to meeting near- and long-term program cost and performance goals</p>					
<b>9. Technology Development Pathways **</b>	<b>0 *</b>	<b>2</b>	<b>5</b>	<b>8</b>	<b>10</b>
<p><b>9.1</b> – Feasibility of the “real world” application described</p> <p><b>9.2</b> – Adequacy of the discussed requirements (additional research, potential partners, and resources) to advance to the next level of technology development</p> <p><b>9.3</b> – Feasibility of the development pathways provided for implementing the technology being developed (if research is successful)</p> <p><b>9.4</b> – Degree to which potential barriers to commercialization have been identified and addressed</p>					
<b>* Please explain why the project received a “0” for a particular criterion.</b>					

\*\* Additional details to be considered for Criterion 7 (Performance and Economic Factors) and 9 (Technology Development Pathways) for specific technology readiness levels are described on pages 5 and 6.

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**COMMENTS**

Please provide your comments for each of the areas in the blocks below. Reviewers need to identify the sub-criteria (i.e. 1.1, 1.2, 1.3) that are considered weak or unacceptable. Please substantiate your comments (i.e., facts on why you are making the statement). General statements without explanation (e.g., great project) are not sufficient. Please avoid any use of clichés, colloquialisms or slang.

**Strengths:**

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**Weaknesses:**

Please provide link from each Weakness to the corresponding Recommendation(s) and/or Action Item(s).

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**Recommendations:**

Please number.

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**Action Items:**

Please number.

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**General Comments:**

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## TECHNOLOGY READINESS LEVELS FOR ECONOMIC ANALYSIS & TECHNOLOGY DEVELOPMENT PATH

Research, Development, and Demonstration (RD&D) projects can be categorized based on the level of technology maturity. Listed below are nine (9) technology readiness levels (TRLs) of RD&D projects managed by the National Energy Technology Laboratory. These TRLs provide a basis for establishing a rational and structured approach to decision-making and identifying performance criteria that must be met before proceeding to the next level.

**TRL 1** - *Basic principles observed and reported.* This is the lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples include paper studies of a technology's basic properties.

**TRL 2** - *Technology concept and/or application formulated.* Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies.

**TRL 3** - *Analytical and experimental critical function and/or characteristic proof of concept.* Active R&D is initiated. This includes analytical and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology (e.g., individual technology components have undergone laboratory-scale testing using bottled gases to simulate major flue gas species at a scale of less than 1 scfm).

**TRL 4** - *Component and/or system validation in a laboratory environment.* Has the bench-scale prototype been developed and validated in the laboratory environment? Prototype is defined as less than 5% final scale (e.g., complete technology process has undergone bench-scale testing using synthetic flue gas composition at a scale of approximately 1–100 scfm).

**TRL 5** - *Laboratory-scale similar-system validation in a relevant environment.* The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Prototype is defined as less than 5% final scale (e.g., complete technology has undergone bench-scale testing using actual flue gas composition at a scale of approximately 1–100 scfm).

**TRL 6** - *Engineering/pilot-scale prototypical system demonstrated in a relevant environment.* Engineering-scale models or prototypes are tested in a relevant environment. Pilot or process-development-unit scale is defined as being between 0 and 5% final scale (e.g., complete technology has undergone small pilot-scale testing using actual flue gas composition at a scale equivalent to approximately 1,250–12,500 scfm).

**TRL 7** - *System prototype demonstrated in a plant environment.* This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Final design is virtually complete. Pilot or process-development-unit demonstration of a 5–25% final scale or design and development of a 200–600 MW plant (e.g., complete technology has undergone large pilot-scale testing using actual flue gas composition at a scale equivalent to approximately 25,000–62,500 scfm).

**TRL 8\*** - *Actual system completed and qualified through test and demonstration in a plant environment.* The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include startup, testing, and evaluation of the system within a 200–600 MW plant CCS/CCUS operation (e.g., complete and fully integrated technology has been initiated at full-scale demonstration including startup, testing, and evaluation of the system using actual flue gas composition at a scale equivalent to approximately 200 MW or greater).

**TRL 9\*** - *Actual system operated over the full range of expected conditions.* The technology is in its final form and operated under the full range of operating conditions. The scale of this technology is expected to be 200–600 MW plant CCS/CCUS operations (e.g., complete and fully integrated technology has undergone full-scale demonstration testing using actual flue gas composition at a scale equivalent to approximately 200 MW or greater).

\* Not relevant to this Peer Review.

Table 1 describes economic analysis and technology development for technology readiness levels. These bullets are examples of the types of information that is typically determined in technology research and development projects.

**Please note that the Economic Analysis and Technology Development Path are examples of the types of information that should be provided for the projects being reviewed. Projects are not expected to address all bullets for a given technology readiness level, but should address at least one of them. The Reviewer will rely on their experience and the guidance herein to assess each project.**

**Table 1. Economic Analysis and Technology Development**

Technology Readiness Level	Economics Analysis	Technology Development Path
1-3	<ul style="list-style-type: none"> <li>Material costs available</li> <li>Potential cost benefits over conventional systems identified</li> </ul>	<ul style="list-style-type: none"> <li>Scientific feasibility proven</li> <li>Application(s) considered</li> <li>Potential technology developers identified</li> </ul>
4-5	<ul style="list-style-type: none"> <li>Component or sub-system costs estimated</li> <li>First-order cost-benefit analysis available</li> <li>Material and energy balances calculated</li> </ul>	<ul style="list-style-type: none"> <li>Conceptual process proposed</li> <li>Potential applications well defined</li> <li>Process feasibility established</li> </ul>
6	<ul style="list-style-type: none"> <li>Conceptual process costs developed</li> <li>Market analysis completed</li> <li>Risk assessment completed</li> </ul>	<ul style="list-style-type: none"> <li>Process test data available</li> <li>Engineering scale-up data developed</li> <li>Optimum operating conditions identified</li> </ul>
7	<ul style="list-style-type: none"> <li>Process contingency costs identified</li> <li>Full-scale process costs, including O&amp;M calculated</li> <li>Full-scale installation costs developed</li> </ul>	<ul style="list-style-type: none"> <li>Major technology components thoroughly tested and evaluated</li> <li>Technology demonstration plans firmly established</li> <li>Major component optimization studies performed</li> </ul>
8-9*	<ul style="list-style-type: none"> <li>Installation costs determined</li> </ul>	<ul style="list-style-type: none"> <li>Business and commercialization plans developed</li> </ul>

\* Not relevant to this Peer Review.

## APPENDIX E: CARBON CAPTURE PROJECT SUMMARIES

Presentation ID Number	Project Number	Title
01	FE0007466	CO <sub>2</sub> Binding Organic Liquids Gas Capture with Polarity Swing Assisted Regeneration
02	FE0005799	Ion Novel Solvent System for CO <sub>2</sub> Capture
03	FE0004228	Advanced Low Energy Enzyme catalyzed Solvent for CO <sub>2</sub> Capture
04	ORD-2012.01.00 Task 4	Pre-Combustion Membranes
05	FE0007528	Carbon Absorber Retrofit Equipment (CARE)
06	FE0007395	Application of a Heat integrated Post Combustion Carbon Dioxide Capture System with Hitachi Advanced Solvent into Existing Coal-Fired Power Plant
07	FE0007453	Slipstream Pilot-Scale Demonstration of a Novel Amine Based Post-Combustion Process Technology for CO <sub>2</sub> Capture from Coal-Fired Power Plant Flue Gas
08	FE0007948	Novel Sorption-Based CO <sub>2</sub> Capture Process
09	FE0007603	Evaluation of Carbon Dioxide Capture from Existing Coal Fired Plants by Hybrid Sorption using Solid Sorbents
10	FE0007580	Low Cost, High Capacity Regenerable Sorbent for Carbon Dioxide Capture from Existing Coal-Fired Power Plants
11	FE0007707	Bench-Scale Development of an Advanced Solid Sorbent for Carbon Dioxide Capture from Existing Coal-Fired Power Plants
12	FE0004343	Recovery Act: Evaluation of Solid Sorbents as a Retrofit Technology for CO <sub>2</sub> Capture
13	ORD-2012.01.00 Task 7	Post-Combustion Membranes
14	FE0007634	Electrochemical Membrane for Carbon Dioxide Capture and Power Generation
15	FE0005795	Recovery Act: Slipstream Testing of a Membrane CO <sub>2</sub> Capture Process for Existing Coal-Fired Power Plants
16	FE-10-002	High-Temperature Polymer-Based Membrane Systems for Pre-Combustion CO <sub>2</sub> Capture

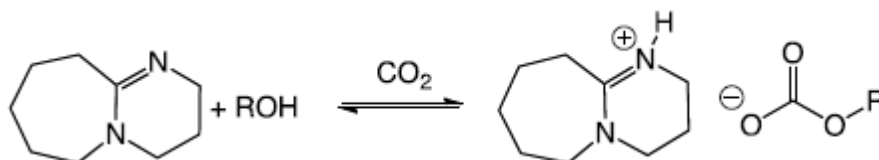


## 01: FE0007466

<b>Project Number</b> FE0007466	<b>Project Title</b> CO <sub>2</sub> Binding Organic Liquids Gas Capture with Polarity Swing Assisted Regeneration		
<b>Contacts</b> DOE/NETL Project Mgr.	<b>Name</b> I. Andrew Aurelio	<b>Organization</b> NETL – Existing Plants Division	<b>Email</b> Isaac.Aurelio@NETL.DOE.GOV
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<b>Partners</b>	Fluor Enterprises Inc. Queens University		
<b>Stage of Development</b>			
<input type="checkbox"/> Fundamental R&D	<input type="checkbox"/> Applied R&D	<input type="checkbox"/> Prototype Testing	<input checked="" type="checkbox"/> Proof of Concept
<input type="checkbox"/> Demonstration			

### Technical Background

The primary advantage of utilizing organic systems for CO<sub>2</sub> separating solvents to react with CO<sub>2</sub> is to exploit lower specific heats and high CO<sub>2</sub> weight capacities compared to water-based systems. Our CO<sub>2</sub>-binding organic liquid (CO<sub>2</sub>BOL) system was designed utilizing non-volatile single component derivatives of Philip Jessop's "switchable solvents.<sup>1</sup> CO<sub>2</sub>BOLs act like aqueous amines in that they utilize a base to chemically react with CO<sub>2</sub>. The key distinction between CO<sub>2</sub>BOLs and alkanolamines is that alcohol is used in place of water, and a non-nucleophilic base is used in place of nucleophilic primary and secondary amines. Chemically the base is not directly reacting with CO<sub>2</sub> (as is the case with primary and secondary amines forming carbamates) rather the alcohol reacts with CO<sub>2</sub> first forming an alkylcarbonic acid which then protonates the base component forming liquid alkylcarbonates. Some alkylcarbonate salts have been shown to have CO<sub>2</sub> capacities as high as 20 wt. % at 1 atm of CO<sub>2</sub> (Figure 1). Amidines and guanidines are necessary in the CO<sub>2</sub>BOL platform because of the reduced acidity of alkylcarbonic acids compared to carbonic and carbamaic acids utilized in 3° amines and 1° and 2° amines respectively. The polar ionic liquids can revert to the less-polar nonionic solvent by removing CO<sub>2</sub> thermally.

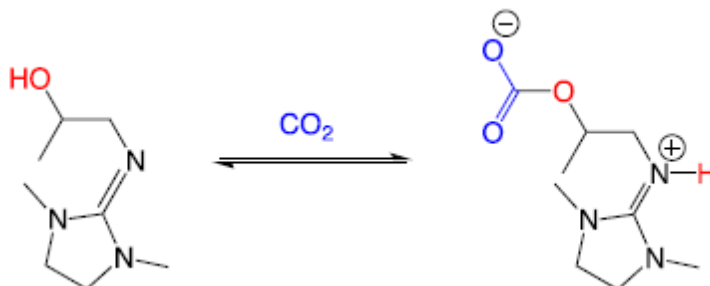


**Figure 1** Diazabicyclo[5.4.0]-undec-7-ene (DBU) and 1-Hexanol Binding of CO<sub>2</sub> as a CO<sub>2</sub>BOL Liquid Alkylcarbonate Salt

First-generation CO<sub>2</sub>BOLs were comprised of a combination of an individual base and alcohol. One drawback to the dual-component CO<sub>2</sub>BOL systems is the relatively high volatility of the constituents, which severely hinders the industrial applicability of these systems (Figure 2) due to high attrition rates of the solvent due to evaporation. We conjoined the alcohol and base moieties into a single molecule which reduced volatility to acceptable levels.<sup>2,3</sup> Similar to alkanolamines, the second-generation CO<sub>2</sub>BOLs were alkanolamidines and alkanolguanidines, which react with CO<sub>2</sub> to form zwitterionic liquids upon carboxylation. Such molecules, while non-

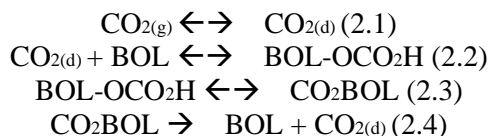
volatile, were inherently viscous prior to CO<sub>2</sub> uptake. After several variations of the CO<sub>2</sub>BOL molecules, we have designed and synthesized a low-viscosity alkanolguanidine based on a cyclic guanidine core derived from 1,3-dimethylimidazolidine (**3**).

**1.1 Mechanism of CO<sub>2</sub> Absorption** Our second-generation BOL reacts just as the first generation CO<sub>2</sub>BOLs, albeit as a zwitterionic (both charges on the same molecule) guanidinium alkylcarbonate ionic liquid (Figure 2). The CO<sub>2</sub> release is performed by thermal heating.

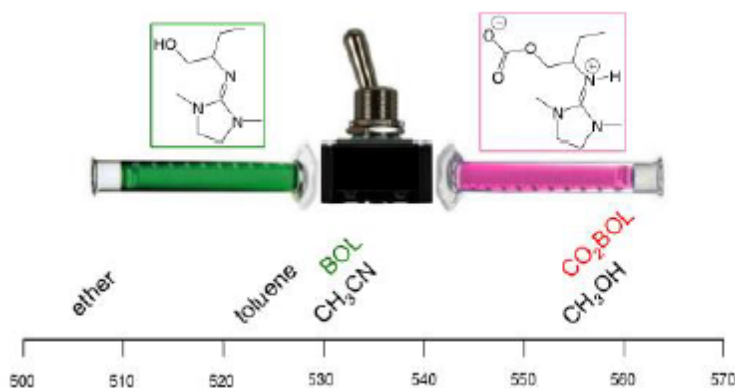


**Figure 2. Formation of the CO<sub>2</sub>BOL: CO<sub>2</sub> Uptake by the Alkanolguanidine**

We propose a reaction mechanism beginning with diffusion of CO<sub>2(g)</sub> into the BOL (Equation 2.1). The dissolved CO<sub>2(d)</sub> then inserts into the O-H bond of the alcohol moiety, producing an alkylcarbonic acid BOL-OCO<sub>2</sub>H (Equation 2.2). The alkylcarbonic acid then transfers a proton inter- or intramolecularly to the base component, forming the zwitterionic CO<sub>2</sub>BOL (Equation 2.3). Thermal release of CO<sub>2</sub> occurs via decarboxylation of the CO<sub>2</sub>BOL (Equation 2.4), producing the CO<sub>2</sub>-free BOL and dissolved CO<sub>2</sub>. Release of CO<sub>2(d)</sub> back into gas (reverse of Equation 2.1) completes the cycle.



**1.2 Polarity Swing Assisted Regeneration (PSAR)** A unique property of CO<sub>2</sub>BOLs and other switchable ionic liquids is the fundamental polarity change that is observed when CO<sub>2</sub> is chemically bound or not. Unlike aqueous amine-based CO<sub>2</sub> capture solvents, CO<sub>2</sub>BOLs undergo unique changes in polarity as a function of CO<sub>2</sub> loading (Figure 3).<sup>2-4</sup> The equilibrium loading of CO<sub>2</sub> is influenced by temperature, but we hypothesized that loading could also be influenced by polarity.



**Figure 3. Conceptual “Switch” by CO<sub>2</sub> Loading (Polarity Scale Of Nile-Red Indicator dye, µM)**

Conceptually, the PSAR effect is self-accelerating. Mild heating induces CO<sub>2</sub> release from the CO<sub>2</sub>BOL making it less polar, but the increase of temperature also increases the miscibility between the antisolvent and the CO<sub>2</sub>-rich CO<sub>2</sub>BOL. As more CO<sub>2</sub> is released the CO<sub>2</sub>BOL becomes less polar, consequently antisolvent becomes more soluble, which forces more CO<sub>2</sub> release. One can envision the nonpolar antisolvent destabilizing the ionic form of a CO<sub>2</sub>BOL (the alkylcarbonate) and shifting the equilibrium to the left (Figure 3), in turn releasing CO<sub>2</sub>. While antisolvent is present, the CO<sub>2</sub> release is still equilibrium controlled at a given temperature, but the equilibrium favors lower CO<sub>2</sub> loading more so than it would in the absence of antisolvent. Thus, the antisolvent aids in CO<sub>2</sub> release from the CO<sub>2</sub>BOL, allowing nearly complete regeneration at temperatures 20-40°C lower than on a conventional thermal swing. Also, the presence of antisolvent induces a faster decrease in CO<sub>2</sub>BOL polarity, which results in faster CO<sub>2</sub> release.

The CO<sub>2</sub>BOL process with PSAR runs on the same architecture with the main difference being the introduction of an antisolvent circulation loop and separation unit off the desorber column. As in the thermal case, the incoming flue gas is dehydrated in a direct contact cooler using process cooling water with or without refrigeration. The CO<sub>2</sub> is absorbed at 40 C and the CO<sub>2</sub>-rich CO<sub>2</sub>BOL solvent is pumped to a regeneration column. Here, a nonpolar solvent, or “antisolvent” is added during regeneration to change the polarity of the CO<sub>2</sub>-rich CO<sub>2</sub>BOL solution. This change in polarity destabilizes the chemically bound CO<sub>2</sub> so that full release can be achieved at or below temperatures required for thermal regeneration without the antisolvent effect. After CO<sub>2</sub> release, the antisolvent can then be removed from the BOL solvent by cooling: when the mixture is cooled, the BOL and antisolvent form distinct liquid phases, which can be separated using a coalescing filter or similar physical separation process, and the antisolvent can be returned to the absorption column. The main differences between the PSAR and non-PSAR flowsheets is the lower regeneration temperature in the desorber column. Also, extra cooling water will be required in the PSAR process compared to the thermal case to counteract the exothermic phase separation of the antisolvent from the CO<sub>2</sub>-lean CO<sub>2</sub>BOL in the coalescing tank.

**1.3 Recycling Strategies for CO<sub>2</sub>BOL and Antisolvent** There are two strategies envisioned for removing the antisolvent from the CO<sub>2</sub>-lean CO<sub>2</sub>BOL. We envisioned liquid-liquid partitioning, or liquid-solid partitioning upon cooling in addition to carrying over the antisolvent into the absorber. We have performed studies on liquid and solid antisolvents and the potential of antisolvent carryover, but liquid-liquid separations are estimated to be the easiest to execute for the PSAR process.

### Relationship to Program

The PSAR could significantly improve the efficiency of CO<sub>2</sub> separations using a CO<sub>2</sub>BOL solvent. The reboiler heat duty for the CO<sub>2</sub>BOL process is 57% of NETL Case 10 (MEA) resulting in reduces parasitic power loads. Adding the PSAR to the CO<sub>2</sub>BOL process adds an estimated 20% increase in net electric power output over Case 10, with further opportunity for additional improvements. The addition of antisolvent lowers the temperature at which CO<sub>2</sub> is released from the rich CO<sub>2</sub>BOL and in turn lowers the temperature of the stripper reboiler and enables the use of innovative ways to extract more power from the steam cycle (*i.e.* from a let-down turbine). The lower temperature (~75 °C vs. 158 °C) in the reboiler also minimizes thermal degradation and evaporative losses of the CO<sub>2</sub>BOL solvent. The stripper may be operated at a higher pressure than the case without the antisolvent while keeping the temperature the same. Thermal compression of CO<sub>2</sub> with the PSAR can be as high as 6 ATM at 100°C at a lean solvent loading of 0.4 moles CO<sub>2</sub>/mole BOL. Higher CO<sub>2</sub> pressures are attractive as they can

reduce the mechanical CO<sub>2</sub> compression cost. Some combination of the above effects may prove to be the optimal configuration. The PSAR estimates for COE are nearly 17 points lower than the MEA baseline (68% versus 85%), with future potential for a 21-26 point gain.

### **Primary Project Goal**

Further develop and verify the performance of the process combining CO<sub>2</sub> binding organic liquids (CO<sub>2</sub>BOLS) with newly discovered polarity-swing-assisted regeneration (PSAR) process.

### **Objectives**

- Develop the CO<sub>2</sub>BOLS/ PSAR solvent and process configuration against DOE's carbon capture goals of 90% CO<sub>2</sub> capture and a Levelized-Cost of Electricity (LCOE) increase of <35%.
- Collect necessary additional thermodynamic and kinetic information to develop an optimized process configuration for the CO<sub>2</sub>BOLS/ PSAR concept that can be demonstrated at bench scale.
- Conduct a bench-scale demonstration of the technology that includes extended testing for quantifying solvent makeup requirements, by-product formation, and equipment corrosion, along with regeneration energy.
- Use bench-scale testing data to make robust energy and LCOE predictions for a full-scale system, using Aspen Plus™ to model the system.
- Quantify large-scale EH&S impacts for the technology.

## 02: FE0005799

<b>Project Number</b> FE0005799	<b>Project Title</b> Ion Novel Solvent System for CO <sub>2</sub> Capture			
<b>Contacts</b> DOE/NETL Project Mgr.	<b>Name</b> I. Andrew Aurelio	<b>Organization</b> NETL – Existing Plants Division	<b>Email</b> Isaac.Aurelio@NETL.DOE.GOV	
<b>Principal Investigator</b>	Alfred “Buz” Brown	ION Engineering, LLC	brown@ion-engineering.com	
<b>Partners</b>	ION, Nathan Brown University of Alabama, Department of Chemical Engineering, Jason Bara EERC, Brandon Pavlish			
<b>Stage of Development</b>				
<input type="checkbox"/> Fundamental R&D	<input type="checkbox"/> Applied R&D	<input type="checkbox"/> Prototype Testing	<input checked="" type="checkbox"/> Proof of Concept	<input type="checkbox"/> Demonstration

### Technical Background

Over the past decade, there has been significant interest in exploring the use of ionic liquids (ILs) and other novel solvents as alternative solvents for gas processing and CO<sub>2</sub> capture applications. The IL platform offers some unique opportunities with respect to controlling physical and chemical properties of the solvent. Furthermore, as ILs have essentially zero vapor pressure, there is little risk of their loss due to volatilization, which could theoretically eliminate the need for unit operations for solvent recovery such as condensers, water washes and chillers. Although there have been hundreds of different ILs explored in laboratory and small-scale tests for CO<sub>2</sub> capture, drawbacks to these solvents have become apparent. For the vast majority of ILs, physical solubility is the dominant mechanism of gas absorption. This renders the vast majority of ILs unsuitable for post-combustion CO<sub>2</sub> capture. Efforts had been made to develop amine-functionalized task-specific ionic liquids (TSILs) as a means of increasing CO<sub>2</sub> solubility for post-combustion applications. While TSILs were able to improve CO<sub>2</sub> uptake at low partial pressures, they suffered from high viscosities and prohibitively expensive synthetic procedures. A more straightforward, cost-effective approach to improving CO<sub>2</sub> solubility in IL solvents was reported in 2008 (Camper, Bara, et al. *Ind. Eng. Chem. Res.* **2008**). This approach involved simply blending the IL with a commodity amine (e.g. MEA) to achieve the benefits of IL non-volatility with the CO<sub>2</sub> capacity of amines which ideally would produce a low energy penalty solvent for post-combustion CO<sub>2</sub> capture. These IL-amine hybrid solvents were the premise upon which this project was originally funded. However, issues with this approach materialized during the first year of the project when it was found that, despite broad claims of IL stability in the literature, amines are capable of attacking and degrading ILs, resulting in loss of capacity of the solvent for CO<sub>2</sub> and undesirable changes in physical and chemical properties.

Around this time, Bara’s group at UA had become interested in the application of imidazoles as alternatives to ILs. Although many ILs are synthesized from imidazole precursors, virtually no attention had been given to imidazoles in gas processing applications. Like the ILs from which they are derived, imidazoles themselves have desirable and tunable chemical and physical properties, including very low vapor pressures and viscosities comparable to water. Bara’s group demonstrated in several publications that imidazole-amine blends could provide a stable, non-aqueous solvent with low volatility and high

capacity for CO<sub>2</sub>. Additionally, data indicate that imidazoles promote CO<sub>2</sub> capture, as stoichiometric expectations of amine loading were exceeded in the presence of the imidazole. Furthermore, the costs of imidazoles are already 1-2 orders of magnitude less than ILs, which indicates that they are much more likely to be commercially viable.

In 2010, ION licensed the imidazole-based solvents for gas treating from UA and in collaboration with Bara's group under a Sponsored Research Agreement (SRA) between ION and UA, as they are furthering the development of this technology in part funded by this Project. Using ION's in-house continuously operating absorber-regenerator unit, ION has determined a solvent composition that includes an imidazole, an amine and managed amount of water that is capable of >90% CO<sub>2</sub> capture under post-combustion conditions. Most recently, evaluations performed at EERC indicate Solvent C's performance is among the lowest energy penalties observed with regeneration energy of only 2.0-2.2 gigajoules per metric ton (GJ/tonne) of CO<sub>2</sub>.

### **Relationship to Program**

The solvents under development by ION and the University of Alabama offer a significant reduction in energy penalty compared to the MEA baseline and other advanced amine solvents.

- Reduced energy penalties are a key factor in limiting the process impact on COE.
- High solvent capacity for CO<sub>2</sub> reduces process CAPEX and OPEX, further limiting impact on COE.
- Utilizing water in the solvent has positive economic and technical benefits, while effective management of water content in the system minimizes make-up water requirements.
- Stability of imidazole-based solvents slows degradation pathways and minimizes need for solvent replacement.
- Overcomes earlier issues/limitations of ionic liquid-based solvents.
- Greater understanding of influence of molecular structure on physical and chemical properties providing rational guidelines for future improvements in solvent composition.

### **Collateral Benefits:**

- ION has completed a similar post-combustion CO<sub>2</sub> capture study using natural gas-fired flue gas at EERC with equally positive results as those reported here for coal-fired flue gas.
- ION and UA are examining the use of imidazoles in membranes for post-combustion CO<sub>2</sub> capture and have been awarded a Phase I STTR from DOE. NCCC has expressed interest in multiple aspects of this work and has obtained baseline data for imidazole-based solvents under pre-combustion CO<sub>2</sub> capture conditions.
- Bara has engaged collaborators in academia to undertake additional physical property studies and molecular simulations of imidazole-based solvents, already resulting in several peer-reviewed publications.
- A more thorough understanding of the synthesis, properties and applications of imidazoles can open new opportunities in fields unrelated to CO<sub>2</sub> capture including pharmaceuticals, biomaterials and stimuli-responsive polymers.
- This funding is supporting one Ph.D. student (Matthew S. Shannon) and has provided research opportunities for a number of undergraduate students.

### **Primary Project Goal**

Evaluate ION's solvent technology to determine if ION's technology can meet DOE's economic criteria for post-combustion CO<sub>2</sub> capture technologies (90% CO<sub>2</sub> Capture,  $\leq$  35% increase in COE at scale).

### **Objectives**

**Phase 1: Solvent Development, Process Design and Construction of Laboratory Test Unit** includes solvent performance analysis in the laboratory, process simulation modeling development using laboratory findings and solvent physical data, and testing of the solvent formulation in a laboratory scale continuous process test unit ("Lab Test Unit"). During Phase 1, a laboratory scale continuous process test unit will be designed, constructed and commissioned for solvent testing. The main objective of Phase 1 will be to develop the solvent and laboratory systems in order to develop solvent and process economic performance in Phase 2 sufficient to advance the solvent to field pilot (1.0 – 3.0 gpm scale) ready status.

**Phase 2: Economic Analysis of Solvent Performance at Scale** includes the development of an estimate for the potential impact on the cost of electricity (COE) metric for use in comparison to other technologies in use and under development. Pending outcome of solvent performance determined in Phase 1, additional solvent and performance optimization in the laboratory and lab test unit may be required in Phase 2.

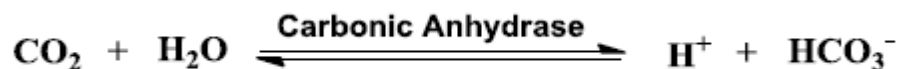
## 03: FE0004228

<b>Project Number</b> FE0004228	<b>Project Title</b> Advanced Low Energy Enzyme Catalyzed Solvent for CO <sub>2</sub> Capture			
<b>Contacts</b> DOE/NETL Project Mgr.	<b>Name</b> Andrew Jones	<b>Organization</b> NETL – Existing Plants Division	<b>Email</b> Andrew.Jones@NETL.DOE.GOV	
<b>Principal Investigator</b>	John Reardon	Akermin, Inc.	<a href="mailto:reardonj@akermin.com">reardonj@akermin.com</a>	
<b>Partners</b>	Battelle, Department L998 PNNL Pacific Northwest National Laboratory			
<b>Stage of Development</b>				
<input type="checkbox"/> Fundamental R&D	<input checked="" type="checkbox"/> Applied R&D	<input type="checkbox"/> Prototype Testing	<input type="checkbox"/> Proof of Concept	<input type="checkbox"/> Demonstration

### Technical Background

#### Enzymes as Biological Catalysts in Industrial Processes

Enzymes are proteins that catalyze chemical reactions by lowering the activation energy for reactions, thereby increasing the rate by many orders of magnitude. Enzymes are remarkably fast, selective, and environmentally-benign biocatalysts used in a variety of industries including the chemical, pharmaceutical, food, and textile sectors to increase process efficiency and lower production costs. Akermin has focused its research efforts on developing energy efficient, cost saving approaches to carbon dioxide (CO<sub>2</sub>) management using so called “low regeneration energy” solvents. As opposed to primary and secondary amines that directly react with CO<sub>2</sub> forming carbamates, the low-energy solvents, such as MDEA, other tertiary amines, aqueous solutions of potassium carbonate, etc., simply capture protons formed during the hydration of CO<sub>2</sub> with water. Since carbonates are significantly less stable than carbamates they require lower regeneration energy, thereby reducing the overall cost of CO<sub>2</sub> capture. Despite the fact that the energetic advantage of carbonate-forming solvents has been widely recognized, their widespread commercial application was negatively affected by their poor reactivity. To address the issues of inefficient CO<sub>2</sub> capture rates with low-energy solvents (a process that would otherwise demand extremely tall columns), Akermin has proposed to utilize biocatalysts that are specific for CO<sub>2</sub> and are highly-efficient in catalyzing CO<sub>2</sub> hydration (scheme below).



It should be emphasized that the enzymatic reaction is totally independent of the solvent other than water and therefore is expected to proceed in virtually any aqueous solution of compounds that can provide a proton sink, such as numerous tertiary amines, ammonia, carbonates of sodium, potassium, and other metals.

The biocatalyst amenable to this process is a ubiquitous enzyme, Carbonic anhydrases (CAs). Forms of the CA strain are now in various stages of development by the major enzyme producers for use in industrial settings for CO<sub>2</sub> removal. These include Novozymes, DuPont, and Codexis. Akermin has tested numerous enzyme strains and demonstrated that each worked well with its enzyme delivery approach. Akermin’s primary source of enzyme at this time is CA developed by Novozymes, which has demonstrated significant thermal stability in potassium carbonate/bicarbonate (K<sub>2</sub>CO<sub>3</sub>/KHCO<sub>3</sub>) solutions. Akermin is using developmental versions of recombinant, highly-active, and thermostable CAs available from Novozymes. The



enzyme is manufactured using a conventional fermentation process that demonstrates an excellent level of protein expression.

### **Enzyme Immobilization and Stabilization**

A key component of Akermin's technology solution is the approach that delivers the biocatalyst to the immediate vicinity of the gas-liquid interface in the absorber column. By concentrating the biocatalyst at the critical point in the CO<sub>2</sub> absorption process, the enzyme accelerates the CO<sub>2</sub> capture process while avoiding exposure to higher temperatures in the stripper column. Akermin's immobilization technology is based on physical encapsulation, or entrapment, of an enzyme within highly-CO<sub>2</sub> permeable thin polymeric structures. Immobilizing an enzyme within thin polymeric films serves several purposes: 1) permits the use of conventional contactor systems designed to maximize gas-liquid interface and CO<sub>2</sub> absorption efficiency; 2) minimizes internal diffusional limitations and maximizes enzyme utilization; 3) the cross-linked nature of the films prevents the protein from leaching; and 4) the multi-point interaction through hydrogen, ionic, and van-der-Waals bonding reduces the enzyme's susceptibility to denaturation and unfolding resulting in improved activity and longer operation lifetime. Indeed, Akermin's enzyme delivery method has demonstrated high rates of sustained CO<sub>2</sub> capture in a continuous flow reactor over the period of 270 days at 45°C. During this period of time, one molecule of enzyme hydrated more than 45,000,000 CO<sub>2</sub> molecules.

The current version of Akermin's enzyme delivery system is based on utilizing porous coatings containing entrapped CA to accelerate the conversion of CO<sub>2</sub> to bicarbonate. The coatings are deposited onto commercial contactors (Sulzer structured packing, for example), which are subsequently used in the absorber column. Akermin will begin testing this delivery system on a 500 standard liter per minute (SLPM) fully-integrated test unit at the National Carbon Capture Center starting in the first quarter of 2013. The next generation enzyme delivery systems will specifically focus on supporting commercial units and address issues associated with enzyme replenishment and maintenance with a minimal economic disruption for the customer. These commercial systems are expected to maximize the rate enhancement potential of the enzyme, extend the enzyme's lifetime, and reduce the amount of enzyme needed to support the desired process performance specifications for carbon capture.

### **Relationship to Program**

The main benefit of the proposed program is the development of a novel, easy to adapt, low-cost process to capturing CO<sub>2</sub> from flue gas with the goal of having less than a 35% increase in LCOE with post-combustion CO<sub>2</sub> capture. Specific benefits include simplification of the engineering design as the CO<sub>2</sub> capture unit based on Akermin's technology requires no polishing FGD, no reforming, and no wash columns. The approach is expected to minimize requirements for solution handling and storage, lower costs for solution replacement, lower cooling requirements and water consumption. The process is environmentally-friendly as it does not generate solvent emissions to the atmosphere and produces benign by-products with low disposal costs and opportunities for resale.

### **Primary Project Goal**

Akermin's primary goal is to demonstrate the novel technology capable of 90% CO<sub>2</sub> capture from flue gas in a 500 SLPM bench-scale unit using a solvent with significantly lower regeneration energy, such as K<sub>2</sub>CO<sub>3</sub>, at rates comparable to monoethanolamine (MEA). The secondary goal is to model and evaluate the capital and operational costs of a system at industrial scale for CO<sub>2</sub> capture from a coal-fired power plant, with an objective of approaching or achieving DOE's goal of less than a 35% increase in levelized cost of electricity (LCOE) with post-combustion CO<sub>2</sub> capture.

## Objectives

Akermin's objectives are as follows: 1) design immobilization approach to achieve high capture rates of CO<sub>2</sub> in low-energy solvents; 2) optimize the functional properties of immobilization material to minimize enzyme leaching during operation; 3) demonstrate enzyme-accelerated carbon capture process at bench-scale; 4) demonstrate enzyme life in excess of six months using simulated flue gas with greater than 50% retained activity; 5) evaluate the impact of common impurities present in coal-fired flue gas on enzyme performance; 6) demonstrate 90% CO<sub>2</sub> capture with the bench-scale unit using actual flue gas from a coal-fired power plant; 7) characterize the endurance performance of the biocatalyst delivery system in the bench unit with operation of up to six months; 8) evaluate impact of external process conditions on process performance; 9) generate data to validate or refine simulation models to confirm key advantages; and 10) perform necessary modeling and cost estimation to demonstrate how such a system would scale and cost-effectively integrate into an existing coal-fired power plant.

## 04: ORD-2012.01.00 Task 4

<b>Project Number</b> ORD-2012.01.00 Task 4	<b>Project Title</b> Pre-Combustion Membranes			
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<b>Partners</b>	URS Corporation Oak Ridge Institute for Science and Education (ORISE) Carnegie Mellon University (CMU)			
<b>Stage of Development</b>				
<input checked="" type="checkbox"/> Fundamental R&D	<input type="checkbox"/> Applied R&D	<input type="checkbox"/> Prototype Testing	<input type="checkbox"/> Proof of Concept	<input type="checkbox"/> Demonstration

### Technical Background

Integrated Gasification Combined Cycle (IGCC) plants are advanced coal-based power generation systems intended to improve the efficiency of power generation while facilitating carbon capture. Gasification produces a high pressure, high temperature fuel gas, which is a mixture of CO, H<sub>2</sub>, H<sub>2</sub>O, and CO<sub>2</sub> called syngas. This syngas is then combusted using a combustion turbine in primary power generation, and the heat produced is used to make steam, which is expanded in a steam turbine in secondary generation. Prior to combustion, the carbonaceous portion of the fuel gas may be converted to CO<sub>2</sub> through a process called water-gas shift, resulting in a CO<sub>2</sub> concentration of nearly 30%. Combined with the high total operating pressure, the result is a high CO<sub>2</sub> partial pressure (300+ psia) which provides excellent driving force. The IGCC process is then better suited for carbon capture and compression than conventional pulverized coal systems, particularly for membrane based technologies.

The current state of the art technology for IGCC pre-combustion capture is a physical solvent made from polyethyleneglycol dimethylether (PEGDME) that is known by the trade name Selexol. According to DOE/NETL's Cost and Performance Baseline for Fossil Energy Plants, Vol. 1 Rev. 2, an IGCC plant using a General Electric Energy gasifier with a two stage Selexol carbon capture process would result in a 38% increase in COE over an equivalent plant without carbon capture. DOE's programmatic goal is to develop advanced pre-combustion capture technologies that are capable of capturing 90% of CO<sub>2</sub> emissions with a less than 10% increase in cost of electricity (COE). DOE/NETL is currently funding numerous research efforts to produce advanced materials for reducing the cost of pre-combustion capture. Among them are advanced hydrophobic solvents such as high molecular weight polydimethyl siloxane (PDMS), carbon based physical sorbents, and hydrogen selective membranes such as polybenzimidazole (PBI) and palladium alloys.

One of the major challenges associated with pre-combustion carbon capture is the ability to capture CO<sub>2</sub> at high temperatures. High temperature gas cleanup is advantageous because syngas is produced at high temperature and also needs to be combusted at high temperature. Cooling the gas to capture CO<sub>2</sub> and then reheating it prior to combustion is energetically expensive. Unfortunately many capture materials suffer from low CO<sub>2</sub> solubility or instability at elevated temperatures.

The purpose of this task is to develop CO<sub>2</sub>-selective supported ionic liquid membranes (SILMs) that make use of advanced ionic liquid and polymer materials capable of functioning at high temperature. These technologies are composites comprised of an ionic liquid suspended within the pores of a glassy polymer support. Ionic liquids are a huge class of salt (as many as 10<sup>18</sup> possible substances) which are molten at room temperature, have very low vapor pressures, and tend toward thermal stability and high CO<sub>2</sub> solubility. Integrating ILs into a polymer membrane increases the selectivity and permeability of the membrane because of the superior gas transport properties of the IL. The proposed research will include ionic liquids (ILs) which form ring complexes upon interaction with CO<sub>2</sub>. 5-, 6-, and 7-membered cyclic molecules are naturally quite stable, and CO<sub>2</sub> complexes which include these ring structures should also be stable. Ionic liquids which form stable complexes with CO<sub>2</sub> may be used to create facilitated transport membranes which have good CO<sub>2</sub> selectivity at temperatures approaching those of the low temperature water gas shift reactor (roughly 260 °C). These ring-complexing SILMs will be tested at high temperature and high pressure to simulate pre-combustion capture conditions. Later, the SILMs will be converted into hollow fiber configurations, which have excellent gas transfer performance due to their high surface area per unit volume. The mechanical strength of the fibers will be optimized by choosing the best combination of IL, polymer material, and pore geometry to ensure the mechanical integrity of the hollow fibers under high pressure conditions. Computational property prediction and systems optimization techniques will be used to compliment the experimental approach.

The project goal is to develop, to the point of readiness for slipstream testing, supported ionic liquid membranes and designs for their integration into IGCC power systems which together are capable of capturing 90% of the CO<sub>2</sub> produced by those systems with an increase in COE of less than 10%.

### **Relationship to Program**

The following impacts and benefits are possible through this proposed research:

1. CO<sub>2</sub> capture technologies will be developed which decrease the cost of CO<sub>2</sub> removal from coal gasification facilities.
2. Structure property relationships for several classes of ILs will be discovered. Knowledge of these relationships will make it easier to tailor ILs for other applications outside carbon capture.
3. Methodologies will be developed for supporting ILs in hollow membrane fibers. ILs may be tailored for improved solubility of many gases. The ability to convert tailored ILs to membranes could enable more economic separation of many gas mixtures.
4. Process development for pre-combustion membrane systems will improve understanding of plant integration for CO<sub>2</sub> capture. This understanding will inform future technology development and help move toward future generations of CO<sub>2</sub> capture technology.
5. New processes will be designed which circumvent existing materials issues.

### **Primary Project Goal**

The project goal is to develop, to the point of readiness for slipstream testing, supported ionic liquid membranes and designs for their integration into IGCC power systems which together are capable of capturing 90% of the CO<sub>2</sub> produced by those systems with an increase in COE of less than 10%.

### **Objectives**

The objective of this research is to develop membrane materials and processes that are able to reduce the energy penalty and cost of CO<sub>2</sub> separation over conventional technologies for pre-

combustion CO<sub>2</sub> separation. In carrying out this work, several major challenges will be addressed: (1) Development of ionic liquids which form stable, diffusive complexes upon interaction with CO<sub>2</sub>. (2) Creation of polymer hollow fiber supports which can effectively contain the IL without interfering with gas transport and developing efficient means of impregnating these supports with the ILs. (3) Design and optimization of IGCC systems capable of meeting the programmatic cost goals based on CO<sub>2</sub>-selective membrane technologies. The approach to addressing each of these challenges is summarized below.

#### Ring-complexing Ionic Liquid Development Approach

In Year 1, a series of ILs were selected for synthesis based on their expected interaction with CO<sub>2</sub> to form stable ring structures. The CO<sub>2</sub> solubility of the ILs was then measured before they were used to prepare membranes for transport performance characterization. To date, numerous ring-complexing ILs have been successfully synthesized and characterized. The materials tended to show high solubility for CO<sub>2</sub> but poor membrane transport performance due to the slow diffusion of the CO<sub>2</sub>-containing complexes. The diffusion limitation was attributed to strong inter-complex binding, which increases the size and weight of the complex and hampers its movement.

In Year 2, ring-complexing ILs will be developed that reduce these inter-complex interactions by tuning the proton donor and acceptor interactions. Specifically, ILs that had featured a pair of primary amine groups will now have only one primary amine coupled with an alcohol group or a tertiary amine that can only act as a proton acceptor. In parallel, other ILs that have shown promise in this application will also be developed. For example, 1-ethyl-3-methylimidazolium acetate has a high selectivity for CO<sub>2</sub>/H<sub>2</sub> but suffers from competitive absorption of water. Efforts will be made to modify this IL with hydrophobic side groups.

#### Hollow Fiber Support Development Approach

The polymer hollow fiber support must be designed for excellent gas transport properties and mechanical stability. In an SILM configuration, the gas transport properties are a function of the pore structure and the thickness of the IL layer. In Year 1, the pore structure of hollow fiber supports was designed to maximize the IL content in order to increase both permeance and selectivity of the membranes. Fibers SILMs were prepared using an off-the-shelf ionic liquid, and the performance of the hollow fiber SILMs was compared with flat sheet SILMs. Also, molecular modeling was used to predict how the pore size and pore structure can be used to improve the transport properties of the ILs by inducing nano-scale structure. In Year 2, the method for loading the IL into the fiber will be refined in order to reduce the selective layer thickness, thereby increasing the membrane permeance. Also, the mechanical properties of the hollow fibers will be improved through the selection or synthesis of alternate polymer materials. Hollow fiber SILMs will then be prepared with advanced ILs. In Year 3, the module configuration will be refined and the hollow fiber SILMs based on advanced ILs will be tested under simulated fuel gas conditions.

#### Systems Optimization Approach

In the open literature, there have been no rigorous systems studies for pre-combustion CO<sub>2</sub> capture membranes used in IGCC power generation. The success of membrane separation approaches is highly dependent on the process that is used; yet, there are so many possible process combinations that it is difficult to definitively choose the most cost effective approach. In Year 1 of this effort, a superstructure based modeling approach was used to analyze over 2 million process configurations and then choose a single configuration that is the most cost effective given a membrane permeance and selectivity. Two membrane materials were simulated: one that is possible to produce today and another that is expected to be achievable

with additional research. The overall cost of electricity for each membrane was determined, and the results will be used to guide the performance targets in future materials development. In Year 2, the model will be improved by completely integrating the CO<sub>2</sub> capture system into the IGCC plant, rather than treating it as an independent entity. Additional model optimizations will also take place which will more fully evaluate the potential of the membranes in these systems and will be completed in Year 3.

## 05: FE0007528

<b>Project Number</b> FE0007528	<b>Project Title</b> Carbon Absorber Retrofit Equipment (CARE)			
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<b>Stage of Development</b>				
<input type="checkbox"/> Fundamental R&D	<input type="checkbox"/> Applied R&D	<input checked="" type="checkbox"/> Prototype Testing	<input type="checkbox"/> Proof of Concept	<input type="checkbox"/> Demonstration

### Technical Background

CARE is a slipstream project that will demonstrate a patented NeuStream™ absorber that will significantly reduce process equipment footprint and cost of full scale CO<sub>2</sub> capture systems. The patented NeuStream™ flat jet nozzle technology incorporated in a compact, modular absorber unit is already proven reliable and cost effective as employed in a \$25MM, 20 MW SOX pilot plant. The NeuStream™ absorber uses proprietary nozzle technology to produce an array of flat jets that are oriented in-line with the gas flow so that a gas contacts the CO<sub>2</sub> solvent with a high specific area needed for removal while minimizing the gas side pressure drop. The NeuStream™ absorber has been proven as an effective CO<sub>2</sub> absorber through laboratory scale testing (0.01 MWe) and small pilot scale testing (0.07 MWe) at the Energy and Environment Research Center (EERC) showing up to 90% capture depending on the solvent and solvent loading factors.

### Relationship to Program

The *NeuStream™* technology for CO<sub>2</sub> capture and purification is applicable to a variety of solvents and can be retrofitted to existing pulverized-coal power plants with reduced cost and footprint. Because of the modularity of the *NeuStream™* technology, it can be rapidly scaled to larger size systems and retrofitted into existing plants with little risk. This pilot-scale project advances the development of low cost, clean coal operations that could enable long-term use of coal in an environmentally constrained world. Other potential benefits include creation of jobs and a new industry.

### Primary Project Goal

The primary goal for Project CARE is to demonstrate 90% steady-state capture efficiency performance from a multi-stage NeuStream™ absorber unit traceable to commercial scale. The project will design, build, and operate a complete carbon capture system including a flue-gas desulfurization unit, carbon dioxide absorber, carbon dioxide stripper system, thermal reclaimer, and amine wash system. The system will be built and operated on a slipstream of flue gas from the Colorado Springs Utilities, Drake Power Plant, Boiler number 7. The system will be operated continuously for 2-months while monitoring all operating conditions.

## Objectives

The overall objective of the CARE project is to validate the NeuStream™ C absorber design points and processes required to successfully scale the technology to full plant operations with >90% CO<sub>2</sub> capture and <35% increase in Cost of Electricity (COE). To accomplish this, we must also identify and mitigate gaps or weaknesses in our current technical and economic concepts. The second objective is to identify and assess environmental, health, and safety issues so they can be eliminated or minimized during this project and any follow-on pilot scale project. While accomplishing these project objectives, CARE will also meet the eligibility objectives of maintaining at least 20% cost share during the entire project, using actual flue gas from an existing pulverized coal-fired power plant burning domestic (produced in the U.S.) coal; and, ensuring that greater than 75% of the project labor cost shall be incurred in the United States. The primary Budget Period I objective is to successfully complete a system critical design review. The sub-objectives required are to document system requirements, complete a preliminary and detailed design, and complete a Preliminary Environmental, Health, and Safety Analysis. During Budget Period II, the primary objective is to construct the system and prepare the system for testing. The sub-objectives are to fabricate, integrate, and prepare the CARE system for test which includes successfully completing system checkout and a test readiness review. The primary Budget Period III objective is to confirm that the NeuStream™-C absorber design and processes can be efficiently and safely scaled to full plant operations with >90% CO<sub>2</sub> capture and <35% increase in Cost of Electricity. Sub-objectives required to confirm the NeuStream™-C absorber design and processes readiness are to complete a Final Technical and Economic Analysis and an Assessment of Environmental, Health, and Safety Risks.



## 06: FE0007395

<b>Project Number</b> FE0007395	<b>Project Title</b> Application of a Heat Integrated Post-Combustion Carbon Dioxide Capture System with Hitachi Advanced Solvent into Existing Coal-Fired Power Plant			
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<b>Partners</b>	Hitachi Power Systems America, Ltd., Sandhya Eswaran Electric Power Research Institute, Abhoyjit Bhowm Koch Modular Process Systems, Stan Lam Smith Management Group, Clay Whitney			
<b>Stage of Development</b>				
<input type="checkbox"/> Fundamental R&D	<input type="checkbox"/> Applied R&D	<input checked="" type="checkbox"/> Prototype Testing	<input type="checkbox"/> Proof of Concept	<input type="checkbox"/> Demonstration

### Technical Background

The mission of the U.S. Department of Energy/National Energy Technology Laboratory (DOE/NETL) Carbon Capture Research & Development (R&D) Program is to develop innovative environmental control technologies to enable full use of the nation's vast coal reserves, while at the same time allowing the current fleet of coal-fired power plants to comply with existing and emerging environmental regulations. The Carbon Capture R&D Program portfolio of carbon dioxide (CO<sub>2</sub>) emissions control technologies and CO<sub>2</sub> compression is focused on advancing technological options for the existing fleet of coal-fired power plants in the event of carbon constraints.

Pulverized coal (PC) plants burn coal in air to produce steam and comprise 99 percent of all coal-fired power plants in the United States. Carbon dioxide is exhausted in the flue gas at atmospheric pressure and a concentration of 10–15 percent by volume. Post-combustion separation and capture of CO<sub>2</sub> is a challenging application due to the low pressure and dilute concentration of CO<sub>2</sub> in the waste stream, trace impurities in the flue gas that affect removal processes, and the parasitic energy cost associated with the capture and compression of CO<sub>2</sub>. Solvent-based CO<sub>2</sub> capture involves chemical or physical sorption of CO<sub>2</sub> from flue gas into a liquid carrier. Although solvent-based systems are used commercially to remove CO<sub>2</sub> from industrial gases, they have not been applied to the removal of large volumes of gas, as in coal-fired power plant flue gas, due to significant cost and efficiency penalties.

The University of Kentucky Center for Applied Energy Research (UKy-CAER) Team developed a two megawatt thermal (0.7 megawatt electrical [MWe] equivalent) slipstream post-combustion CO<sub>2</sub> capture system for a coal-fired power plant using novel concepts coupled with Hitachi's proprietary advanced solvent (H3-1). An innovative heat integration method utilizes waste heat from the carbon capture system while improving steam turbine efficiency. A two-stage stripping concept has been developed to combine with the heat integration method to increase solvent capacity and capture rate in the CO<sub>2</sub> scrubber. The advanced solvent utilized by the process has several advantages over conventional amine solvents such as 30 weight percent (wt.%) monoethanolamine (MEA), including exhibiting lower heat of regeneration, higher capacity, and less solvent degradation and corrosion. Previous laboratory and pilot-scale tests of the CAER process and H3-1 solvent, as well as results from an initial techno-economic analysis of the

capture process, illustrate the potential of this CO<sub>2</sub> capture system. Key features of the project are a two-stage stripping process for solvent regeneration and a heat-integrated cooling tower system that recovers waste energy (low quality) if available from the carbon capture and main plant platform. The two-stage stripping process increases solvent working capacity by providing a secondary air stripping column following the conventional steam stripping column. The air stripping stream will be sent to the boiler as combustion air to increase the CO<sub>2</sub> content in the flue gas exiting the boiler. The integrated cooling tower system uses a liquid desiccant to dry the cooling tower air and low quality heat to dry the liquid desiccant. The working principle is that reducing the relative humidity of the cooling air lowers the turbine condenser cooling water temperature and thereby reduces the steam turbine back pressure for efficiency improvement. The overall effect will be improved power plant cooling tower and steam turbine efficiency.

### **Relationship to Program**

The novel concepts and advanced solvent used in this project show promise of improving the overall plant efficiency when integrated with a CO<sub>2</sub> capture system, and can be utilized to retrofit existing coal-fired power plants. The knowledge gained from this project on various aspects such as low quality heat utilization, material coatings, process simplification/optimization, system compatibility and operability, solvent degradation and secondary environmental impact, water management and potential heat integration can potentially be applied to future commercial applications directed toward achieving DOE's current goals for post-combustion CO<sub>2</sub> capture.

### **Primary Project Goal**

The project goal is to design, fabricate, install, and test a modular 0.7 MWe CO<sub>2</sub> capture system utilizing the advanced solvent with heat integration process on a slipstream of flue gas from a coal-fired power plant to show the potential pathway to meet DOE's target of no more than a 35 percent increase in the LCOE while capturing at least 90 percent of the CO<sub>2</sub> released during the combustion of fossil fuels in existing coal-fired power plants.

### **Objectives**

The project will be located at LG&E and KU Services Company's E.W. Brown Generating Station, located near Harrodsburg, Kentucky. The design, start-up, and commissioning of the test facility is performed with a generic 30 wt.% MEA solvent to obtain baseline data for comparison with other proprietary solvents to be tested in the program. Testing will be conducted on two proprietary solvents: Hitachi's H3-1solvent, and 30 wt.% MEA. Parametric testing and long-term verification campaigns will be conducted for each of the solvents. Corrosion evaluation and solvent degradation studies will be conducted concurrently with the verification runs. The potential modification of heat integration, solvent and water management, and CO<sub>2</sub> capture system stability and operability will be the main focal points for the test program in BP4. Process modeling has been and will continue to be performed to optimize the post-combustion CO<sub>2</sub> capture system, determine power plant integration strategies, and conduct sensitivity analyses. The results of the modeling studies are used to complete an economic analysis of the process to determine its capital and operating costs as well as to estimate the cost of electricity (COE) as compared to the reference MEA process.

The novel concepts and advanced solvent used in this study will be evaluated and tested in a 0.7 MWe slipstream facility, and should significantly improve the overall plant efficiency when integrated with the CO<sub>2</sub> capture system. The technologies and concepts being tested can be used to retrofit existing coal-fired power plants.

The objectives of the project are to (1) develop and deploy a novel heat integration scheme demonstrating the capability to integrate waste heat from the carbon capture platform to limit the reduction in overall power plant efficiency, (2) determine the performance of the H3-1 advanced solvent, and (3) collect the necessary information on mass and energy balances, solvent degradation (rate and products), and corrosion to provide a full techno-economic and environmental, health, and safety (EH&S) analysis at a 550 MWe commercial-scale level at the end of BP4.

### **Planned Activities**

- Perform a preliminary technical and economic feasibility analysis (TEA) of the final process design, based on a 550 MWe power plant. Project partner Electric Power Research Institute (EPRI) is leading the TEA activities.
- Design, fabricate, and install the 0.7 MWe modular slipstream facility. Project contractor Koch Modular Process Systems (KMPS) will complete the detailed engineering design, fabricate the 2 mega-watt thermal (MWth) slipstream facility in a modular-frame configuration at an off-site location, transport and install at Brown Station.
- Commission and shakedown the facility with a baseline 30 wt.% MEA solvent. The individual components and integrated system will be commissioned by KMPS and UKy-CAER researchers.
- Conduct parametric and verification investigations using two solvents.
- Conduct a system dynamics load-following study, a solvent degradation study, and a materials corrosion study.
- Perform system and economic analyses of the proposed technology using various steam extraction and heat recovery configurations, and compression technologies. EPRI will complete the system and economic analyses.

## 07: FE0007453

<b>Project Number</b> FE0007453	<b>Project Title</b> Slipstream Pilot-Scale Demonstration of a Novel Amine Based Post-Combustion Process Technology for CO <sub>2</sub> Capture from Coal-Fired Power Plant Flue Gas			
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<b>Partners</b>	BASF Linde Engineering Selas Fluid Processing Corporation EPRI Southern Company Services/National Carbon Capture Center			
<b>Stage of Development</b>				
<input type="checkbox"/> Fundamental R&D	<input type="checkbox"/> Applied R&D	<input type="checkbox"/> Prototype Testing	<input checked="" type="checkbox"/> Proof of Concept	<input type="checkbox"/> Demonstration

### Technical Background

Post-combustion carbon dioxide (CO<sub>2</sub>) capture technology offers flexibility to treat the flue gas from both existing and new coal-fired power plants. Solvent based technologies are today the leading option for post-combustion CO<sub>2</sub> capture from large coal-fired power plants as they have been applied in large scale in other applications. However, there are a number of challenges in the use of traditionally available solvent-based technologies, including need for implementation at very large scale, significant parasitic energy losses, and, solvent stability and degradation issues. Linde and BASF are working together to develop a post-combustion capture technology incorporating BASF's novel amine-based process, currently trademarked as OASE® blue. This technology offers significant benefits compared to other solvent-based processes as it aims to reduce the regeneration energy requirements using novel solvents that are stable under the coal-fired power plant feed gas conditions.

BASF's OASE® blue technology has been developed to address the key drawbacks in the large scale application of monoethanolamine (MEA) for flue gas carbon capture, including: (i) high specific energy for regeneration, (ii) lack of stability toward thermal and oxidative degradation, (iii) increased corrosiveness with increased CO<sub>2</sub> loading, and, (iv) lack of tolerance to impurities from coal combustion products. The specific proprietary solvent has been selected by, (i) screening approximately 400 chemical substances using vapor-liquid equilibrium measurements to determine approximate cyclic capacities, (ii) laboratory measurements of the key thermodynamic and kinetic properties of the 70 screened candidates and their mixtures to identify approximately 15 targets, (iii) testing of the targets to determine optimum circulation rate and specific energy consumption in a laboratory scale mini-plant to identify the leading candidates, and, (iv) pilot testing of three candidates with real power plant flue gas to identify the optimum solvent for the flue gas application. The CO<sub>2</sub> regeneration from the solvent is carried out by using low-pressure steam, typically from the power plant steam cycle. Testing using a 0.45 MWe pilot plant utilizing lignite-fired power plant flue gas has shown that the OASE® blue solvent is stable and little degradation was observed over 5000 hours, whereas the reference MEA solvent started to degrade appreciably under identical conditions after 2000 hours. The pretreatment requirement includes reducing oxides of sulfur (SO<sub>x</sub>) in the flue gas to 2-5 ppm in order to limit solvent degradation and is implemented in a direct contact cooler in

conjunction with flue gas cooling, typically by adding appropriate amount of sodium hydroxide corresponding to the SO<sub>x</sub> present in the flue gas. The main waste liquid stream is from the direct contact cooler where SO<sub>x</sub> is removed and this stream is typically handled in the power plant waste water treatment facility. A small amount of solid waste is removed using carbon filters that are replaced at regular intervals. Since the degradation observed in the pilot testing is small, no solvent reclamation unit is envisioned at large-scale.

**Technology Advantages:**

- Significant reduction in regeneration steam consumption (20 to 31% lower), electrical power (25 to 60% lower), and cooling water duty (26% lower), compared to a reference MEA plant
- Scalable to very large capacities with a single train system
- Lower post-combustion capture plant capital costs (30-35% compared to reference MEA at 550 MWe)

BASF is a producer of the solvent in addition to being the technology owner, thereby enabling application at scale by avoiding issues related to solvent manufacturing for large-scale commercial plants.

**R&D Challenges:**

- Proving the process enhancements at the 1 MWe and larger scale
- Validating the basis for scale-up of the advanced process features and the large single train capability

**Relationship to Program**

This project is aimed at the development of a carbon capture technology that can be rapidly commercialized at a very large scale. The technology development targets reducing the cost of electricity produced from a coal-fired power plant while capturing the CO<sub>2</sub> and using it in applications, such as enhanced oil recovery (EOR) or permanent sequestration. Carbon capture, utilization and storage is one of the essential approaches to reduce CO<sub>2</sub> emissions to required levels in order to mitigate climate change impact, while fossil fuels remain a dominant portion of the fuel mix used in energy generation.

The techno-economic analysis that has been performed to compare the novel amine-based technology currently in development against a reference amine-based solvent technology (MEA) clearly demonstrates how novel and advanced amine-based technologies can lead to significantly lower cost of carbon capture and identifies the key levers to continue the development in the cost reduction path. As part of the techno-economic analysis, some new and improved approaches to integrating the coal-fired power plant with the post-combustion capture facility that could result in increased energy efficiency and decreased cost of electricity have also been identified. Linde LLC, in conjunction with BASF, is initiating the commercial application of this technology by looking for current opportunities where the technology can be applied in large demonstration-scale with current state-of-development, while continuing further development and optimization for further cost reduction to meet long-term goals.

**Primary Project Goal**

The overall goal of the project is to demonstrate the Linde-BASF post-combustion capture technology by incorporating BASF's novel amine-based process in a 1 MW slipstream pilot plant and achieving at least 90% CO<sub>2</sub> removal from coal-derived flue gas while demonstrating significant progress toward achievement of the DOE target of less than a 35% increase in the

levelized cost of electricity (LCOE). To accomplish this, the project team, which includes Linde LLC, BASF, Selas Fluid Processing Corporation (SFPC), Linde Engineering Dresden GmbH (LEDD), the Electric Power Research Institute (EPRI), and Southern Company Services (SCS) through the National Carbon Capture Center (NCCC), will design, build and operate the pilot plant at a coal-fired power plant host site providing the flue gas as a slipstream.

### **Objectives**

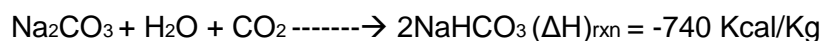
The objectives for Budget Period 1 are to perform a techno-economic assessment of a 550 MWe power plant incorporating the Linde-BASF post-combustion CO<sub>2</sub> capture technology to illustrate the benefits of the process, and to complete the process design optimization as well as the basic and detailed engineering and cost assessment of the 1 MW slipstream pilot plant. Based on the confirmation of the proposed new technology benefits through the techno-economic analysis and the slipstream pilot plant cost estimates as per the proposal, a decision will be made in conjunction with the DOE and the team will then proceed to Budget Period 2. The objectives for Budget Period 2 are to procure the equipment for the 1 MW slipstream pilot plant and to complete the system fabrication, site installation, and commissioning. Budget Period 3 will include the start-up and initial operations of the pilot plant and will be followed by the planning and implementation of parametric tests to demonstrate target performance based on data analysis. After the parametric testing, planning and implementation of long-duration tests (minimum 60 days) to demonstrate solvent stability will be completed and critical data required for scale-up and commercialization will be obtained. Finally, the techno-economic study will be refined by incorporating design information obtained from the 1 MW slipstream pilot testing to confirm the benefits, and a detailed commercialization plan will be developed.

## 08: FE0007948

<b>Project Number</b> FE0007948	<b>Project Title</b> Novel Sorption-Based CO <sub>2</sub> Capture Process			
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<b>Principal Investigator</b>	Ravi Jain	InnoSeptra LLC	Ravi.jain@innosepra.com	
<b>Partners</b>	Electric Power Research Institute New Mexico State University NRG Energy Adsorptech Inc. Pacific Northwest National Laboratory			
<b>Stage of Development</b>				
<input type="checkbox"/> Fundamental R&D	<input checked="" type="checkbox"/> Applied R&D	<input type="checkbox"/> Prototype Testing	<input type="checkbox"/> Proof of Concept	<input type="checkbox"/> Demonstration

### Technical Background

The most common technology for CO<sub>2</sub> capture from the power plant flue gas is based on aqueous amine absorption. These include MEA (monoethanolamine) technology from companies such as Fluor, and hindered amine technology from Mitsubishi and HTC. In addition to the heat of reaction that needs to be provided during regeneration a significant amount of energy also needs to be supplied for the evaporation of the solvent (water in most cases) for the amine-based absorption. The total energy requirement to produce >99% CO<sub>2</sub> at atmospheric pressure for the amine-based systems is >900 Kcal/Kg of CO<sub>2</sub>. The amine-based systems also suffer from high capital costs (most of the equipment needs to be fabricated in stainless steel, and a significant amount of on-site construction is needed). The amines are also degraded by SO<sub>x</sub>, O<sub>2</sub>, and NO<sub>x</sub> in the flue gas, and periodic amine replacement adds significantly to the CO<sub>2</sub> capture cost. The amine-based absorption increases the capital requirement with CO<sub>2</sub> capture by over 85% over the base case, and about 30% of power plant's output is needed for amine regeneration and CO<sub>2</sub> compression. Reactive adsorbents such as sodium carbonate and amines impregnated on a microporous support have been proposed as alternatives to amine-based absorption. An example is the sodium carbonate-sodium bicarbonate system.



While no water needs to be vaporized for reactive adsorbent systems, the total energy required is essentially the same as the amine-absorption systems once the energy required to heat the adsorbent and the adsorbent vessels is added. Figure

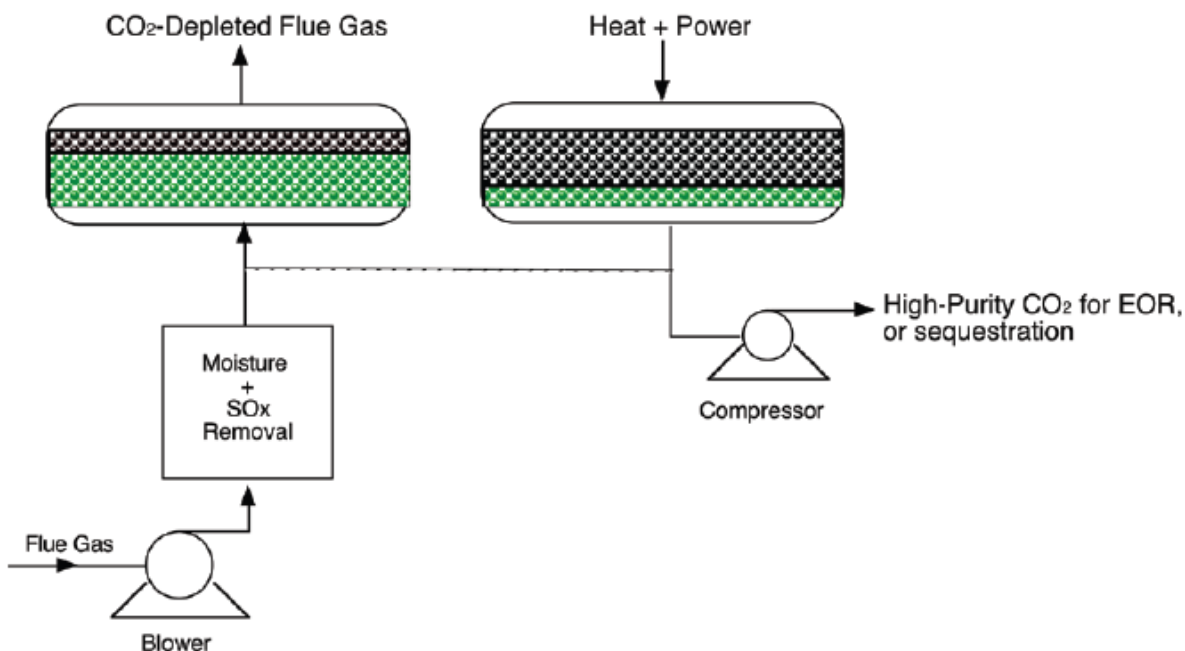


Figure 1: InnoSeptra CO<sub>2</sub> capture process schematic

The InnoSeptra technology is shown in the Figure 1. After the removal of moisture and SO<sub>x</sub> in a pretreatment system the CO<sub>2</sub> is adsorbed on InnoSeptra sorbents, and high purity CO<sub>2</sub> is produced during regeneration. The InnoSeptra process is based on physical sorbents that have significantly lower heats of adsorption compared to amine-based absorption or reactive sorbents. The heats of adsorption for InnoSeptra sorbents are around 200 Kcal/Kg, less than 25% of the total energy needed for amine-based systems. Even after adding the energy needed to heat the adsorbent and vessels, the total energy required is less than 50% of the energy needed for amine-based absorption and reactive sorbents. The InnoSeptra sorbents also have higher net CO<sub>2</sub> capacity than the reactive sorbents. Because of the non-corrosive and modular nature of the process most of the fabrication can be done off-site and in carbon steel. This leads to more than 50% reduction in the capital cost compared to amine-based absorption. The parasitic power for CO<sub>2</sub> capture (including compression) is also reduced by more than 40%. The combination of lower parasitic power and lower capital cost results in less than 45% increase in LCOE (levelized cost of electricity) with CO<sub>2</sub> capture compared to more than 85% increase in LCOE for amine-based absorption. If the costs for the InnoSeptra process were validated based on scale up testing we would be close to DOE's goal of less than 35% increase in LCOE within the next few years.

### Relationship to Program

The goal of DOE's CO<sub>2</sub> capture program is to develop and demonstrate a CO<sub>2</sub> capture process that has been demonstrated at a sufficiently large scale and can be deployed commercially by 2020. The process should result in less than 35% increase in the cost of electricity both for new plants as well as for the existing plants. A preliminary economic analysis of InnoSeptra's CO<sub>2</sub> capture technology indicates that the projected increase in LCOE for the InnoSeptra process is around 45%, and with some process optimization as well as with credits for the removal of additional contaminants it could allow the attainment of DOE program goals by 2020 or earlier. However, the process would need to be validated both at the bench-scale (~1 tons per day CO<sub>2</sub> product) and at the pilot scale (>20 tons per day CO<sub>2</sub> product), and the process economics would need to be validated by an independent evaluation.



The InnoSeptra technology has the potential for earlier commercialization compared to some other technologies as most of the materials and unit operations used in the InnoSeptra process are commercial or near commercial. The InnoSeptra process also offers additional benefits to the power plant operator such as the reduction in the water use for power generation as well as the removal of contaminants such as SO<sub>x</sub> and Hg at a lower cost than the current technologies. These could be pursued with or without CO<sub>2</sub> capture and can provide significantly more value than the project expenditure.

The InnoSeptra technology also has the potential for providing low-cost CO<sub>2</sub> (<\$40/ton) for enhanced oil recovery that has the dual benefit of energy independence (displacing imported oil with domestically produced oil) and greenhouse mitigation (storing CO<sub>2</sub> in oil fields). Widespread use of captured CO<sub>2</sub> for EOR can also make carbon capture commercially viable with or without climate legislation.

### **Primary Project Goal**

The Primary Project Goal is to demonstrate the effectiveness of an innovative post-combustion CO<sub>2</sub> capture technology utilizing a combination of novel microporous materials and process cycles that can remove at least 90% CO<sub>2</sub>, and can eventually lead to no more than a 35% increase in cost of electricity for commercial application as a retrofit to coal fired utility plants.

### **Objectives**

The overall project objective is to demonstrate the effectiveness of the InnoSeptra process to achieve at least 90% CO<sub>2</sub> removal with a potential pathway for no more than a 35% increase in LCOE for retrofit applications. This overall objective can be approached by meeting the following specific objectives for the DOE project:

- Confirm the design basis for bench-scale testing based on lab scale results and process modeling
- Design, build and test the bench scale unit in the lab
- Test the bench scale unit on actual coal-based flue gas
- Develop capital cost, operating cost, and LCOE for a commercial 550 MW power plant

Field testing of the process at one ton per day scale in an actual power plant, and independent verification of process economics will provide the firmer basis for the techno-economic evaluation in Budget Period 3 and indicate whether we are close to the ultimate project objective of less than 35% increase in LCOE. While we do want to target <35% increase in LCOE in the longer term we are also interested in capturing CO<sub>2</sub> for less than \$40/ton. This will make CO<sub>2</sub> capture very attractive for EOR applications in the near term and may make carbon capture economically viable even without any climate legislation. A preliminary techno-economic analysis indicates that this is achievable.

In addition to CO<sub>2</sub> capture, we are looking at synergies between CO<sub>2</sub> capture, and removal of other power plant contaminants such as SO<sub>x</sub>, and Hg. Certain combinations of CO<sub>2</sub> capture and contaminants removal can significantly reduce the cost and water use associated with the removal of SO<sub>x</sub>, and Hg. This can have significant beneficial effect on both the power plant operation and CO<sub>2</sub> capture.

## 09: FE0007603

<b>Project Number</b> FE0007603	<b>Project Title</b> Evaluation of Carbon Dioxide Capture from Existing Coal Fired Plants by Hybrid Sorption Using Solid Sorbents			
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<b>Partners</b>	Envergex ALLETE (Minnesota Power and BNI Coal Co.) North Dakota Industrial Commission (Lignite Energy Council) SaskPower Solex Thermal Sciences Barr Engineering			
<b>Stage of Development</b>				
<input type="checkbox"/> Fundamental R&D	<input type="checkbox"/> Applied R&D	<input type="checkbox"/> Prototype Testing	<input checked="" type="checkbox"/> Proof of Concept	<input type="checkbox"/> Demonstration

### Technical Background

The concept for the technology being evaluated in this project was developed in a Department of Energy Small Business Technology Transfer project (STTR). The STTR project was conducted by Envergex LLC and the University of North Dakota. The technology – Capture from Existing Coal-Fired Plants by Hybrid Sorption Using Solid Sorbents Capture (CACHYST™) – is a novel solid sorbent process based on the following principles:

- Reduction of energy for sorbent regeneration
- Utilization of novel process chemistry
- Contactor conditions that minimize sorbent-CO<sub>2</sub> heat of reaction and promote fast CO<sub>2</sub> capture
- Low-cost method of heat management Utilization of a low-cost sorbent

### Relationship to Program

The project will develop key information for the CACHYST™ process - sorbent performance, energy for sorbent regeneration, physical properties of the sorbent, the integration of process components, sizing of equipment, and overall capital and operational cost of the integrated CACHYST™ system. Through integrated bench-scale testing, this project aims to improve upon the current state-of-the-art by developing a novel sorbent-based, post-combustion technology, namely the CACHYST™ process, that can achieve at least 90% CO<sub>2</sub> removal from coal-fired power plants while demonstrating progress toward achievement of the DOE target of less than a 35% increase in the LCOE.

### Primary Project Goal

The University of North Dakota will be scaling-up and demonstrating a technology to capture CO<sub>2</sub> using hybrid sorption (CACHYST™) and separate the CO<sub>2</sub> from coal combustion-derived flue gas. The primary goal of this project is to improve upon the current state-of-the-art by developing a novel sorbent-based, post-combustion technology, namely the CACHYST™ process, that can achieve at least 90% CO<sub>2</sub> removal from coal-fired power plants while demonstrating progress toward achievement of the DOE target of less than a 35% increase in the levelized cost of electricity (LCOE).

## Objectives

The objective of this project is to scale-up and demonstrate a novel technology for CO<sub>2</sub> capture and separation from combustion-derived flue gas including coal combustion. The project involves the use of novel sorbents, and methods of use of these sorbents, to capture CO<sub>2</sub> with superior performance compared to solvent-based systems. The project will develop key information on the effectiveness of the sorbent to capture CO<sub>2</sub> from flue gas, energy required to regenerate the sorbent, physical properties of the sorbent, integration of process components, sizing of equipment, and overall capital and operational cost of the CACHYS™ system.

In Budget Period 1, the scope of the project includes an initial economic and technical feasibility study of the CACHYS™ concept. This study will provide the process scheme, design, and sizing of the equipment, and the projected capital and operating costs for the technology. The project team will then utilize laboratory-scale test methods to select and formulate sorbents, and test these sorbents to determine heat of sorption and capacity (CO<sub>2</sub> loading) over the range of process conditions identified for the technology. Testing will include the use of a TGA/DSC and a fixed-bed reactor. Multi-cycle adsorption-regeneration tests will be conducted for the preferred sorbents in the fixed-bed facility. Results will establish the optimum process conditions, preferred sorbent compositions, and updated bench-scale equipment design.

During Budget Period 2, the project team will design, procure, build, and conduct shakedown testing of a bench-scale CACHYS™ adsorption and desorption system designed for a flue gas flow of about 30 acfm. The flue gas will be obtained as a slipstream from a subbituminous coal-fired stoker boiler at the UND campus steam plant.

Integrated bench-scale testing of the CACHYS™ adsorption-desorption unit will be performed during Budget Period 3. The overall rate of CO<sub>2</sub> capture, sorbent CO<sub>2</sub> loading, and sorbent utilization will be determined for different adsorber operating conditions. Regeneration testing will include the performance of an overall heat balance and the determination of optimum operating conditions. Based on the results of integrated bench-scale testing, the technical and economic feasibility analysis performed from prior tasks will be updated and an environmental, health and safety (EH&S) risk assessment performed.

## 10: FE0007580

<b>Project Number</b> FE0007580	<b>Project Title</b> Low Cost, High Capacity Regenerable Sorbent for Carbon Dioxide Capture from Existing Coal-Fired Power Plants			
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<b>Principal Investigator</b>	Gökhan Alptekin	TDA Research, Inc.	galptekin@tda.com	
<b>Partners</b>	Gas Technology Institute, Dr. Chakravarthy Shistla The Babcock & Wilcox Company (B&W), Dr. Barteve Sakadjian University of California (UCI), Dr. Ashok Rao MeadWestvaco (MWV), Ms. Paula Walmet			
<b>Stage of Development</b>				
<input type="checkbox"/> _Fundamental R&D	<input type="checkbox"/> _Applied R&D	<input type="checkbox"/> _Prototype Testing	<input checked="" type="checkbox"/> _X_Proof of Concept	<input type="checkbox"/> _Demonstration

### Technical Background

Coal currently accounts for 56% of U.S. electric power generation. With a projected 50% increase (from 300 GW to 450 GW) in electricity demand by 2030 (Annual Energy Outlook 2007) and having 25% of world's coal reserves, the U.S. will continue to produce the bulk of its electricity from coal (Tonks 2007). CO<sub>2</sub> is a major greenhouse gas and plays a significant role in global climate change, and roughly one third of the U.S. carbon emissions come from coal-fired power plants. Because future regulations are expected to require CO<sub>2</sub> capture, these plants will need to be retrofitted with a low cost CO<sub>2</sub> capture technology.

For the existing pulverized coal (PC) plants, the CO<sub>2</sub> capture and separation will most likely be carried out by post-combustion CO<sub>2</sub> scrubbing/capture or oxy-combustion. In both approaches, the challenge is to carry out the separation while increasing the cost of electricity as little as possible. The fundamental reason that CO<sub>2</sub> removal, compression and sequestration is expensive (e.g., consumes a large amount of energy and capital) is that the power plant exhaust is at ambient pressure and the CO<sub>2</sub> is diluted with N<sub>2</sub> (10 to 15% vol. CO<sub>2</sub> in the flue gas). Any carbon capture method must essentially concentrate the CO<sub>2</sub> and compress it through a pressure ratio of 100 to 1,000. There is minimum theoretical energy requirement to recover 90% of the dilute CO<sub>2</sub> in the flue gas (i.e. concentrate it from 1% to 100%) and then to compress it to 2,200 psig. TDA calculated theoretical energy requirement as 9.46% (the minimum plant power loss to concentrate the CO<sub>2</sub> in flue gas to a pure stream at 1 atm is 3.05% and compressing the CO<sub>2</sub> to 2,200 psia requires another 6.41%). Assuming an additional 4% penalty for transportation and sequestration, CO<sub>2</sub> capture will reduce the plant output by a minimum of 13.46%. Any inefficiency in the CO<sub>2</sub> removal system itself will further increase this energy penalty. Obviously, it is essential that the CO<sub>2</sub> capture process is as efficient as possible.

Currently, many post-combustion CO<sub>2</sub> capture methods are being investigated, including aqueous solvents (e.g., amines like monoethanolamine, carbonates), physical adsorbents (e.g. molecular sieves), cryogenic coolers and membranes. For any sorbent or solvent-based post-combustion capture system, a key contributor to energy consumption is the heat input needed for the regeneration step. Because the regeneration of most solvents or sorbents is carried out at low temperatures (either to avoid a large temperature swing or because of the instability of the getter material at elevated temperatures), the recovery of this energy input is usually not

worthwhile and the heat input for the regeneration is likely to be wasted. The chemical solvents and chemical sorbents that remove CO<sub>2</sub> by forming a covalent bond suffer from a particularly large efficiency penalty because of the large heat input required to release the CO<sub>2</sub>. For example, RTI is developing a process using an alkali-based chemical absorbent to remove CO<sub>2</sub> (NaHCO<sub>3</sub> is used as an example to illustrate the point):  $2\text{NaHCO}_3(\text{s}) = \text{Na}_2\text{CO}_3(\text{s}) + \text{CO}_2(\text{g}) + \text{H}_2\text{O}(\text{g})$  The regeneration of this sorbent produces a gas stream containing only CO<sub>2</sub> and water. Condensation separates the water out, leaving a pure CO<sub>2</sub> stream for compression and sequestration. The heat of decomposition of sodium bicarbonate phase is 29.9 kcal per mole of CO<sub>2</sub> removed.

This regeneration energy requirement alone is 27 to 37% of the plant output (obviously they are working on system integration to recover some of this energy and avoid a prohibitive penalty). The amine solvents have a similar disadvantage. As shown by NETL (Klara 2007), using amines raises the cost of electricity for a newly built supercritical PC plant by 84%, from 4.9 to 9.0 cents/kWh, resulting in a very high CO<sub>2</sub> capture cost (\$68/ton of CO<sub>2</sub> avoided). Thus, there is a need for advanced sorbents or solvents that can be regenerated relatively easily (without a large energy input) to minimize the increase in cost of electricity.

TDA Research, Inc (TDA) proposes to develop a low cost, high capacity CO<sub>2</sub> adsorbent and demonstrate its technical and economic viability for post-combustion CO<sub>2</sub> capture at existing pulverized coal-fired power plants. TDA uses an advanced physical adsorbent to selectively remove CO<sub>2</sub> from the flue gas. The sorbent consists of a mesoporous carbon with surface functional groups to remove CO<sub>2</sub>. As documented in representative bench-scale experiments (e.g., T=50-120°C, 0.1-0.15 atm CO<sub>2</sub> partial pressure), the sorbent exhibits a much higher affinity for CO<sub>2</sub> than N<sub>2</sub>, H<sub>2</sub>O or O<sub>2</sub>, enabling effective separation of CO<sub>2</sub> from the flue gas. The sorbent binds CO<sub>2</sub> more strongly than common carbon adsorbents, providing the chemical potential needed for the separation. However, because CO<sub>2</sub> does not form a true covalent bond with the surface sites (as it does in chemical absorbents), the regeneration can be carried out with only a very small energy input. The heat input to regenerate our sorbent is only 4.9 kcal per mol of CO<sub>2</sub>, which is much lower than that for chemical absorbents (e.g., 29.9 kcal/mol CO<sub>2</sub> for sodium carbonate) or amine-based solvents (e.g., 14.2 kcal/mol CO<sub>2</sub> for mono-ethanolamine).

The mesoporous carbon sorbent has been previously developed with DOE funding (Contract No. DE-FE-0000469) for pre-combustion CO<sub>2</sub> capture, where stable sorbent capacity has been demonstrated for over 11,650 cycles with simulated coal-derived synthesis gas. A process analysis carried out by University of California, Irvine showed that the efficiency is 2-3% percentage points better than an Integrated Gasification Combined Cycle (IGCC) plant equipped with Selexol to capture CO<sub>2</sub>. Two field demonstrations of our sorbent in removing CO<sub>2</sub> from gasification streams have been carried out in 2011 and 2012 at the National Carbon Capture Center and the Wabash River IGCC plant. We also showed that our sorbent could successfully separate CO<sub>2</sub>/CH<sub>4</sub> to remove CO<sub>2</sub> from biogas (in a project funded by Metawater Japan, we are designing a pilot-scale unit) and for multi-contaminant control from refinery flue gas to remove CO<sub>2</sub> along with mercury and arsenic impurities (EPA Contract No. EP-D-11-047).

We proved sorbent's efficacy in removing CO<sub>2</sub> from coal flue gas under conditions simulating the downstream of a wet flue gas desulfurization unit. We showed stable CO<sub>2</sub> capacity for over 220 cycles with no sign of degradation. The presence of acid gases such as SO<sub>2</sub> and NO<sub>x</sub> (80 and 200 ppmv, respectively), and water vapor up to 15% vol. did not cause any adverse effect on the CO<sub>2</sub> capacity. The regeneration of the sorbent and the CO<sub>2</sub> recovery and pressurization can be achieved by several approaches, including temperature swing and vacuum swing. Our

preliminary analysis based on using a mild vacuum swing/low pressure steam sweep combination showed that the proposed CO<sub>2</sub> capture process will reduce plant efficiency only by 7.76% (as opposed to a 11.9% reduction by the amine scrubbers) while providing 90% capture. In the proposed effort TDA Research will work with Babcock & Wilcox (B&W), MeadWestvaco Corporation (MWV), the University of California, Irvine (UCI), and the Gas Technology Institute (GTI) to advance the technology by improving the material capabilities and process design, and to carry out an evaluation with a fully-equipped prototype unit using coal derived flue gas to demonstrate the technical viability of the concept. All our results will feed into a techno-economic analysis using Aspen Plus™ software to estimate the impact of CO<sub>2</sub> capture system on plant efficiency and cost of electricity (all analyses will be consistent with DOE/NETL's Cost Estimation Guidelines).

### **Relationship to Program**

- TDA's technology improves the net plant efficiency of a pulverized coal fired plant equipped with CO<sub>2</sub> capture by 20% over the current amines based technologies
- TDA's technology will provide a cost effective CO<sub>2</sub> capture option compared to current amines based technology by reducing the levelized COE and cost of CO<sub>2</sub> avoided by 20%

### **Primary Project Goal**

The objective of this project is to develop a low cost, high capacity CO<sub>2</sub> sorbent and demonstrate its technical and economic viability for CO<sub>2</sub> capture from existing coal-fired power plants.

### **Objectives**

The project tasks will be completed in three years. Our first year goals are to optimize the chemical and physical properties of the sorbent and develop methodologies for production scale-up using high throughput equipment and low-cost raw materials. We will estimate the large-volume production cost of the sorbent in collaboration with MWV, a leading supplier of specialty carbon products in the U.S. We will also carry out parametric tests to identify the optimum operating conditions for the sorbent. We will work with UCI and B&W to carry out detailed design of the CO<sub>2</sub> capture process. In Year 2, we will demonstrate the long life and durability of the sorbent (running over 5,000 cycles) and assess the impact of criteria pollutants and other contaminants on its performance. In these experiments we will also investigate the multi-contaminant removal capability of the sorbent. TDA will design and build a skid-mounted unit, capable of demonstrating sorbent's operation throughout the full-cycle. We will work with B&W to design all critical system components, particularly the gas-solid contactors used in the adsorption and regeneration processes, and the ancillary equipment, including heat exchangers, gas and solid movers. The process simulation will be revised based on the results of the multiple-cycle experiments and a sensitivity analysis will be carried out to improve the process design. In Year 3, we will run the prototype unit using actual coal flue gas to fully assess and demonstrate technical viability of the process. We will work with GTI and ICCI to demonstrate the operation of the unit and optimize its operation using the flue gas generated by a pilot-scale coal combustor. In Year 3, based on the field test results and reactor and sorbent cost estimates, we will complete an economic evaluation to accurately estimate the cost of removal of CO<sub>2</sub> based on DOE/NETL's Cost Estimation Guidelines, and complete an Environmental, Health and Safety (EHS) assessment.

# II: FE0007707

<b>Project Number</b> FE0007707	<b>Project Title</b> Bench-Scale Development of an Advanced Solid Sorbent-Based Carbon Capture Process for Coal-Fired Power Plants			
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<b>Partners</b>	Pennsylvania State University – EMS Energy Institute Masdar – Masdar Carbon and Masdar Institute Foster Wheeler USA Clariant (formerly SCI) – BU Catalysis & Energy UNC-CH – Energy Services Dept.			
<b>Stage of Development</b>				
<input type="checkbox"/> Fundamental R&D	<input checked="" type="checkbox"/> Applied R&D	<input type="checkbox"/> Prototype Testing	<input type="checkbox"/> Proof of Concept	<input type="checkbox"/> Demonstration

## Technical Background

The significant reduction of carbon dioxide (CO<sub>2</sub>) emissions from existing and future coal-fired power plants presents an enormous opportunity for mitigating greenhouse gas emissions and ultimately global climate change. State-of-the-art (SOTA) CO<sub>2</sub> capture technologies are prohibitively expensive and if implemented could result in a 75 to 100% increase in the cost of electricity (ICOE) for consumers.<sup>1</sup> The primary contributor to this high ICOE is the high parasitic power load associated with solvent regeneration and the high capital costs associated with the scale and materials of construction of process equipment<sup>2</sup>. Although these technologies have been evaluated and demonstrated at reasonably large scale, they are at least an order of magnitude smaller than required for a commercial coal-fired boiler utility, and current, optimistic cost and performance analysis of these technologies indicate that none of these technologies meet the US DOE's programmatic goals of >90% CO<sub>2</sub> capture with a ICOE <35%.

One promising alternative to the conventional, liquid solvent-based CO<sub>2</sub> capture processes is the solid, absorbent-based process. Solid sorbents are considered promising CO<sub>2</sub> capture materials because they:

- exhibit high CO<sub>2</sub> loadings (in excess of 8 wt.% CO<sub>2</sub>),
- have low heat capacities (1-1.5 kJ/kg·K),
- are able to generate high partial pressure CO<sub>2</sub> during regeneration without vaporizing the solvent,
- are typically less corrosive and allow for the use of low cost materials of construction, and
- often avoid the toxicity and volatility issues associated with liquid solvent systems.

Under a previous DOE\NETL-funded project (DE-FC26-07NT43089), we performed an extensive engineering evaluation of potential reactor designs and process configurations for solid sorbent-based CO<sub>2</sub> capture processes. To summarize the outcome, we proposed a process that closely resembles conventional gas-liquid absorption processes: a cyclic, thermal-swing process design based on continuous sorbent circulation through dual fluidized, moving-bed reactors (FMBRs), the CO<sub>2</sub> Absorber and Sorbent Regenerator. The selection of a

fluidized-bed reactor design was based on the necessity for efficient heat management in the CO<sub>2</sub> Absorber (removal) and Sorbent Regenerator (addition). Heat management is extremely critical in sorbent-based CO<sub>2</sub> capture processes, especially in the CO<sub>2</sub> Absorber, since CO<sub>2</sub> absorption is an exothermic, self-extinguishing reaction.

The proposed circulating FMBR process concept addresses the major process-related challenges associated with solid sorbent-based CO<sub>2</sub> capture and achieves the following:

- process intensification by minimizing the number of process vessels and sorbent load,
- minimizing the total thermal regeneration energy by enabling the use of solid sorbents with high CO<sub>2</sub> loadings and eliminating the cyclic thermal load of associated process equipment
- providing a heat integration strategy similar to the crossover heat exchanger in solvent processes,
- providing superior gas-solid heat and mass transfer characteristics compared to fixed-bed reactors
- providing an effective means of ensuring counter-current flow of gas and solids via bed staging
- utilizing equipment that are commercially available at the scale required.

Furthermore, the engineering analysis revealed a set of CO<sub>2</sub> absorbent properties and performance characteristics that must be met to realize the benefits of the circulating FMBR CO<sub>2</sub> capture process configuration that can compete with SOTA solvent processes. A suitable CO<sub>2</sub> absorbent must:

- be a fluidizable and attrition-resistant material
- achieve dynamic CO<sub>2</sub> loadings in excess of 8 wt.% under flue gas conditions
- exhibit a heat of CO<sub>2</sub> adsorption <80 kJ/mol of CO<sub>2</sub>
- be inexpensive (preferably < \$10/kg)

Currently no CO<sub>2</sub> absorbing materials have been sufficiently developed to meet all of the property and performance requirements that came out of our engineering analysis. Several next-generation CO<sub>2</sub> absorbents appear to be very promising in that they achieve the performance targets of high CO<sub>2</sub> loading and have low heats of absorption, are capable of utilizing low-cost sorbent materials, and have the potential to be converted to a fluidizable, attrition-resistant material.

In the field of amine-supported sorbents, one of the most-promising had been developed by Dr. Chunshan Song's group at Pennsylvania State University (PSU), which was made possible through funding by DOE/NETL. PSU's "molecular basket sorbent" (MBS) is an impregnated-amine absorbent that is a composite material consisting of a CO<sub>2</sub>-philic polymer, polyethyleneimine (PEI), and a high surface area material for dispersion. PEI is a polymeric amine consisting of primary, secondary, and tertiary amines which react with CO<sub>2</sub> via the reaction pathways given below. Over several years of development, PSU has demonstrated that the MBS materials is capable of achieving high CO<sub>2</sub> loadings (<14 wt.% CO<sub>2</sub>), high CO<sub>2</sub>/N<sub>2</sub> selectivity (> 1000), exhibits a reasonable heat of absorption (65 kJ/mol CO<sub>2</sub>), and that it can be prepared from inexpensive high surface area materials while retaining CO<sub>2</sub> capture performance.

Although, PSU's MBS material exhibited many desirable CO<sub>2</sub> capture performance characteristics, several challenges remain and include:

- improving the thermal stability of the MBS chemistry to release CO<sub>2</sub> at elevated CO<sub>2</sub> pressures by regenerating at higher temperatures



- converting the MBS chemistry to a fluidizable and attrition-resistant material
- continue materials cost reduction by utilizing low-cost, commercially-available support materials and utilizing scalable manufacturing practices.

The rationale for improving the stability of the MBS material, and essentially all polymeric amine sorbents, is provided in the figures below. The benefit of a thermal-swing absorption process is based on increasing the working capacity of the absorbent and pressure of the released gas by increasing the regeneration temperature. However, the stability of the CO<sub>2</sub> loading capacity is adversely affected at elevated temperatures. Therefore, improving the stability of MBS material under proposed regeneration conditions will enable the benefits of the proposed thermal-swing process to be realized in a cost-effective manner.

Ultimately, the partnership of RTI and PSU represents a strategic combining of expertise gained on two separate past DOE/NETL projects in order to move forward with a single objective of developing a sorbent-based process capable of achieving DOE's CO<sub>2</sub> capture cost and performance targets.

### **Relationship to Program**

At the conclusion of the this project, and the bench-scale prototype phase of development, this advanced solid sorbent CO<sub>2</sub> capture process will have addressed many of the technical and economic challenges facing any solid sorbent-based CO<sub>2</sub> capture processes. If successful, it will also have demonstrated its potential for achieving an ICOE of <35% increase and it will have demonstrated sufficient technology readiness for the next-stage of development. We believe that the advancements made in developing a viable fluidized-bed process and sorbent formulation pathways will be applicable to most solid sorbent CO<sub>2</sub> capture technologies. Success in this project will put the technology on the pathway to meet or exceed DOE/NETL program goals and maintain a high probability to be available for large-scale demonstration by 2020 (as is one of the goals of DOE's CO<sub>2</sub> Capture R&D Program).

### **Primary Project Goal**

The goal of this project is to address the technical and economic hurdles to developing a sorbent-based CO<sub>2</sub> capture process by transitioning a promising sorbent chemistry based on PSU's MBS material to a low-cost sorbent suitable for use in a fluidized-bed process and developing a scalable circulating fluidized-bed process arrangement. Addressing these hurdles will transition sorbent-based CO<sub>2</sub> capture from the lab (TRL1-3) to bench-scale field testing in a representative process at realistic process conditions (TRL4-5). Ultimately, the overall goal is to demonstrate the technical feasibility and economic competitiveness of an advanced sorbent CO<sub>2</sub> capture process and its potential to achieve DOE's programmatic goals of >90% CO<sub>2</sub> capture from a coal-fired power plant with an ICOE < 35%.

### **Objectives**

The overall objective of this R&D project is to thoroughly evaluate and demonstrate the potential that an advanced, solid sorbent-based CO<sub>2</sub> capture process, utilizing PSU's very promising "Molecular Basket Sorbent" (MBS), has for achieving the DOE's CO<sub>2</sub> capture process performance target of >90% CO<sub>2</sub> capture with <35% increase in cost of electricity (ICOE) through reducing not only the energy penalty related to the capture of CO<sub>2</sub> from coal-derived flue gas but also the associated capital and operating costs. More specific goals and objectives of this proposed project include the following:

Budget Period 1:

- Improve the thermal stability and contaminant stability of the base PEI reactant to further improve critical CO<sub>2</sub> capture and regeneration performance parameters.
- Transition PSU's fixed-bed MBS materials into a fluidizable form with a retention of most physical, chemical, and CO<sub>2</sub> capture performance properties.
- Determine how critical process elements such as reactor geometries, heat transfer tubes, gas velocities, and gas-solid flow ratios influence reactor temperature profiles, heat and mass transfer rates, and solids flow dynamics.
- Establish design and cost performance baselines for a large-scale CO<sub>2</sub> capture process based on MBS materials: preliminary estimates of energy penalty, levelized cost of electricity increase, capital costs, operating costs, and overall CO<sub>2</sub> capture cost.

Budget Period 2:

- Produce an advanced, third generation fluidized-bed MBS material exhibiting significant improvements in critical properties (thermal stability, CO<sub>2</sub> capture performance, scalability, physical properties) as compared to first and second generation sorbents produced in Budget Period 1.
- Utilize critical process engineering data (heat transfer coefficients, hydrodynamic measurements, pressure drop, etc.) collected with a laboratory CO<sub>2</sub> capture contactor to design a fully integrated, bench-scale CO<sub>2</sub> capture prototype based on the advanced, fluidized-bed MBS material.

Budget Period 3:

- Utilize pilot manufacturing equipment to scale-up production of the fluidized-bed MBS material to 1,000 lbs., with this sorbent having similar or superior properties as compared to the same lab-produced sorbent.
- Demonstrate, on a bench-scale, effective and continuous CO<sub>2</sub> capture from coal-fired flue gas using the MBS-based prototype designed in BP2. Effective CO<sub>2</sub> capture implies that the CO<sub>2</sub> capture sorbent is chemically, thermally, and physically stable over multiple absorption/regeneration cycles and shows significant potential to meet the DOE program targets for CO<sub>2</sub> capture.
- Substantially prove the technical and economic competitiveness of the MBS-based CO<sub>2</sub> capture process through a detailed update of the technical feasibility study conducted in BP1 and through an environmental analysis of the process technology.

## I2: FE0004343

<b>Project Number</b> FE0004343	<b>Project Title</b> Recovery Act: Evaluation of Solid Sorbents as a Retrofit Technology for CO <sub>2</sub> Capture		
<b>Contacts</b> DOE/NETL Project Mgr.	<b>Name</b> Bruce Lani	<b>Organization</b> NETL – Existing Plants Division	<b>Email</b> Bruce.Lani@NETL.DOE.GOV
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<b>Partners</b>	Technip Stone & Webster Process Technology Stantec Consulting, Ltd. EPRI Southern Company Luminant		
<b>Stage of Development</b>			
<input type="checkbox"/> Fundamental R&D	<input type="checkbox"/> Applied R&D	<input checked="" type="checkbox"/> Prototype Testing	<input type="checkbox"/> Proof of Concept
		<input type="checkbox"/> Demonstration	

### Technical Background

Solid sorbents are being developed and hundreds have been characterized for CO<sub>2</sub> capture effectiveness in gas representative of a post-combustion CO<sub>2</sub> control application. ADA is focused on solid sorbents used in a temperature swing process. Originally, solid sorbents were considered promising for post-combustion CO<sub>2</sub> capture because the specific heat capacity of these materials is approximately 25 to 30% that of water, so the energy input required to change the temperature of these materials (i.e. sensible heat) was much less than that for aqueous MEA. Recently, cross heat exchangers have been developed for the aqueous amine CO<sub>2</sub> capture systems that can reduce the sensible heat requirements up to 85 to 90%, however, several other benefits have been demonstrated by solid sorbents that could significantly reduce the energy penalty, water usage, wastewater generation, and environmental impacts of CO<sub>2</sub> capture compared to aqueous amine systems. ADA has developed a process that can take advantage of beneficial sorbent properties, and is building a pilot designed to treat an equivalent of 1 MWe of flue gas to demonstrate effectiveness of the process and advance the technology readiness level of solid sorbents for post-combustion CO<sub>2</sub> capture.

The general process developed by ADA is applicable to a range of sorbents. The 1 MWe pilot was designed based on the physical and chemical properties of a single sorbent, a commercially produced ion exchange resin functionalized with a primary amine. This material has been extensively evaluated in the laboratory with regards to CO<sub>2</sub> capture, H<sub>2</sub>O uptake, and other properties critical to overall success in a post-combustion CO<sub>2</sub> control application. Specific properties that have been measured include:

- CO<sub>2</sub> capacity (Measurements at CO<sub>2</sub> partial pressures of 0.04, 0.081, 0.15, 0.30, 0.81 bar, temperatures between 30 and 170°C)
- H<sub>2</sub>O loading (H<sub>2</sub>O partial pressures 0 to 0.081 bar at sorbent temperatures of 40, 80, 100, and 120°C)
- Specific heat capacity
- Thermal stability
- Cyclic stability
- Chemical stability when exposed to SO<sub>2</sub>, NO<sub>2</sub>, or NO
- Crush strength
- Jet cup attrition

- Particle density
- Hydrodynamics of fluidized material (using multiple particle size distributions)

One of the most important sorbent properties for post-combustion CO<sub>2</sub> capture is the CO<sub>2</sub> working capacity. Isotherms were generated using experimental data and the Langmuir isotherm model, which are provided in Figure 1. To calculate the CO<sub>2</sub> working capacity of this sorbent, the adsorption conditions are assumed to be 40°C and P<sub>CO<sub>2</sub></sub> = 0.15 bar while the regeneration conditions are assumed to be 120°C and 0.81 bar (note that the CO<sub>2</sub> in the regenerator exhaust will be slightly diluted with desorbing moisture). Using the isotherms provided in Figure 1 the CO<sub>2</sub> loading under adsorption conditions is approximately 10.5 g CO<sub>2</sub>/100 g fresh sorbent while the CO<sub>2</sub> loading under the regeneration conditions is approximately 3.5 g CO<sub>2</sub>/100 g fresh sorbent; the CO<sub>2</sub> working capacity is approximately 7 g CO<sub>2</sub>/100 g fresh sorbent, which is nearly an 80% improvement versus the working capacity of aqueous MEA provided in the 2010 version DOE Baseline Report (Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 2, November 2010, [www.netl.doe.gov](http://www.netl.doe.gov)).

In addition to the larger working capacity, and lower specific heat capacity, this sorbent also demonstrates a small (~0.9 g H<sub>2</sub>O/100 g fresh sorbent under expected 1 MWe pilot operating conditions) H<sub>2</sub>O working capacity. Therefore, the energy penalty for vaporizing H<sub>2</sub>O in the regenerator is less than that of aqueous amines. All this leads to an improvement in the energy penalty associated with CO<sub>2</sub> capture, which is described in more detail later. It is also important to note that this particular sorbent was actually optimized for another application. We expect that with the large amount of research and development of solid sorbents currently being completed worldwide, the advanced sorbents will further improve the energy penalty and economics of a solid sorbent-based CO<sub>2</sub> capture process.

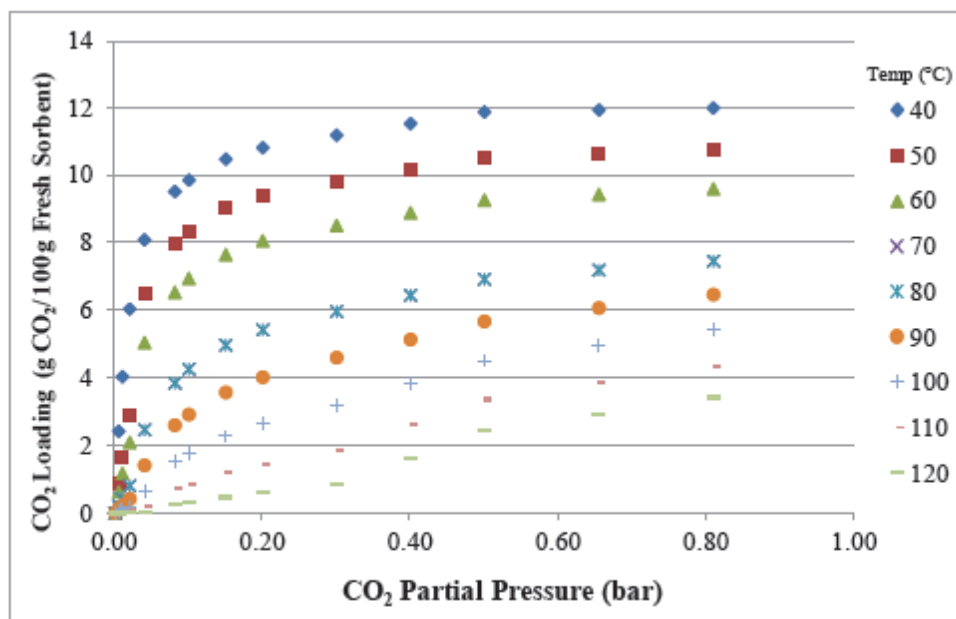


Figure 1: Sorbent Isotherms

It is imperative that the capture process is designed to leverage beneficial sorbent properties to achieve lower energy penalties and overall costs compared to other CO<sub>2</sub> capture options. Under this program, several reactor types were evaluated (i.e. entrained reactors, moving beds, trickle down reactors, fluidized beds, etc.). The key considerations for the process included:

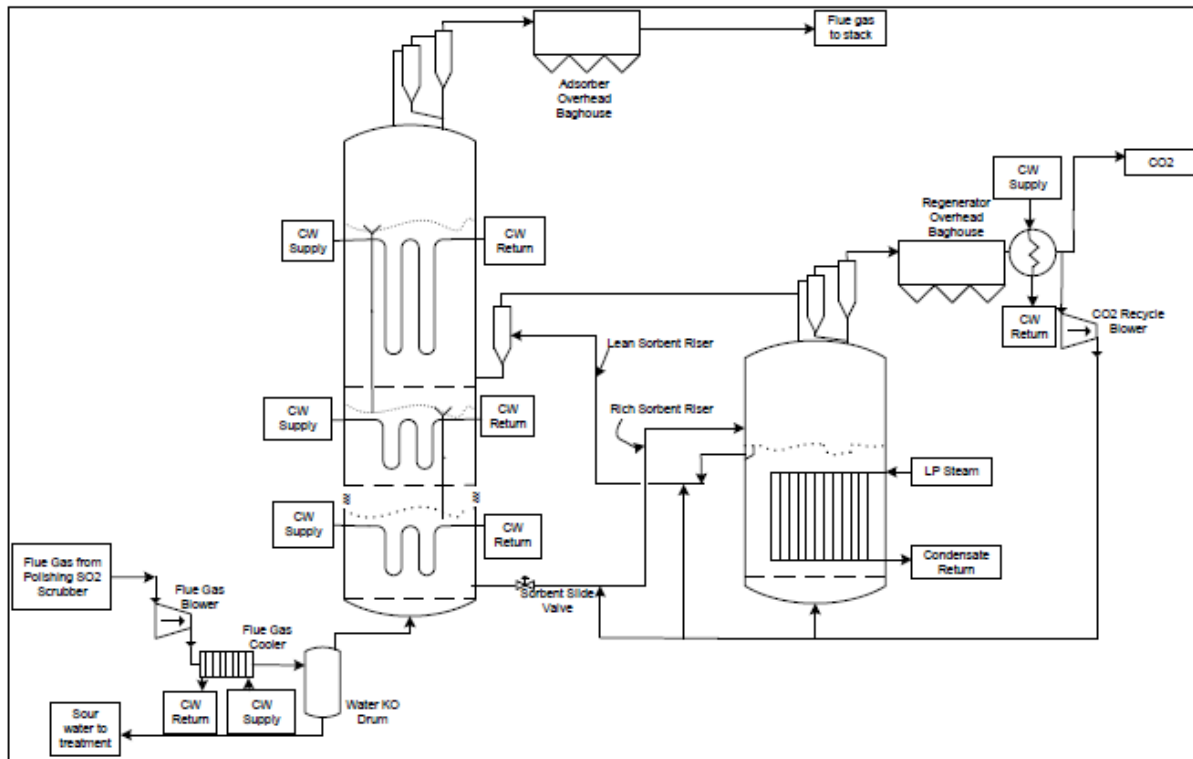
Must Haves:

- Effective gas/solids mixing
- High heat transfer coefficient (to maintain isothermal operation)

Wants:

- Lowest possible capital costs
- Low pressure drop
- Reliable operation
- Minimize sorbent attrition
- Demonstrated commercial

Some reactor designs could quickly and easily be removed from consideration based on the stated assumptions and the sorbent CO<sub>2</sub> isotherms. For example, an entrained reactor cannot be effectively used to attain acceptable CO<sub>2</sub> loadings for the selected supported amine sorbent (see Figure 1 – the rapid decrease in CO<sub>2</sub> loading at lower CO<sub>2</sub> partial pressures). A dilute phase trickle down reactor was also considered briefly. However, novel packing structures would be required to maintain good sorbent distribution and effective gas/solids mixing. In the midst of the packing for distribution, heat transfer surface area would be required, which would further complicate the reactor design and increase capital costs. Optimally the system would become a fluidized bed or moving bed system, which were already under consideration, so the trickle down reactor concept was removed from consideration. For the adsorption unit operation, moving beds and staged fluidized beds were evaluated in depth based on technical and financial merits. Similarly, a moving bed and a single fluidized bed were evaluated in depth based on technical and financial merits. The design selected is shown in Figure 2, which consists of a staged fluidized bed adsorber, a single fluidized bed regenerator, and pneumatic conveyance between the process vessels.



**Figure 2: Schematic of the CO<sub>2</sub> Capture Process**

The proposed process meets the requirements defined at the onset of the project for post-combustion CO<sub>2</sub> capture. Because the sorbent and flue gas are contacted in a system that approaches counter current flow, CO<sub>2</sub> working capacity can be maximized. In addition, the heat transfer coefficient has been maximized through the use of bubbling fluidized beds; note that the capital costs were lower than the moving beds because the heat transfer coefficient dictated the equipment size, and was larger for the bubbling fluidized bed versus the moving bed. The optimal mixing that is characteristic of bubbling fluidized beds also translates into effective gas/solids contacting. The process employs many established methods and principles used for gas-solid systems, such as in-bed heat transfer, risers, standpipes, cyclones and diplegs. Large-scale two-stage fluidized beds have been used commercially for fluid catalytic cracking processes. However, not all aspects of the design are commercially available. Wherever necessary novel and innovative components, such as the trays used to support the fluidized beds, have been developed.

When comparing different CO<sub>2</sub> capture processes, one of the most important criteria for comparison is the levelized cost of electricity (LCOE). A key cost driver is the energy penalty associated with regeneration and compression. To calculate these energy penalties equations (1) and (2) can be used (these equations and the information for the compressor work are from Berger, A. Bhowan, A., Optimizing Solid Sorbents for CO<sub>2</sub> Capture, *Energy Procedia*, 2013 – also presented at the GHGT11 Conference).

$$Q = \frac{C_p \Delta T + \Delta h_{CO_2} \Delta q_{CO_2} + \Delta h_{H_2O} \Delta q_{H_2O}}{CO_{2\_produced}} \quad (1)$$

$$E_p = 0.75 Q \eta_{Carnot} + W_{Compression} \quad (2)$$

Where  $Q$  regeneration heat duty, kJ/kg CO<sub>2</sub>  
 $C_p$  specific heat capacity, kJ/kg<sub>sorbent/solvent</sub>·K  
 $\Delta T$  difference in temperature between adsorption and regeneration – this is reduced in the table for the cases where heat recovery is employed, K  
 $\Delta h_{CO_2}$  enthalpy of adsorption of CO<sub>2</sub>, kJ/kg CO<sub>2</sub>  
 $\Delta q_{CO_2}$  working capacity of CO<sub>2</sub>, kg CO<sub>2</sub>/kg sorbent or solvent  
 $\Delta h_{H_2O}$  enthalpy of adsorption of H<sub>2</sub>O, kJ/kg H<sub>2</sub>O  
 $\Delta q_{H_2O}$  working capacity of H<sub>2</sub>O, kg H<sub>2</sub>O/kg sorbent or solvent  
 $E_p$  energy penalty, kJ/kg CO<sub>2</sub>  
 $\eta_{Carnot}$  Carnot efficiency  
 $W_{Compression}$  work due to compression, kJ/ kg CO<sub>2</sub>

Table 1: Energy Penalty Calculation

Inputs	Term	Units	ADA - Dry Sorbents	ADA - Dry Sorbents - 50% Heat Recovery	Aqueous MEA*	Aq. MEA + 90% Heat Recovery*
Enthalpy of Reaction with CO <sub>2</sub>	$\square h_{CO_2}$	kJ/mol	75	75	75	75
Working CO <sub>2</sub> Capacity	$q_{CO_2}$	kgCO <sub>2</sub> /kg <sub>sorb/solv</sub>	0.07	0.07	0.045	0.045
Enthalpy of Reaction with H <sub>2</sub> O	$\square h_{CO_2}$	kJ/mol	40.7	40.7	40.7	40.7
Working H <sub>2</sub> O Capacity	$q_{H_2O}$	kgH <sub>2</sub> O/kg <sub>sorb/solv</sub>	0.009	0.009	0.03915	0.03915
Specific Heat Capacity	$C_p$	kJ/kg·K	1.05	1.05	4.182	4.182
Temperature Swing	$\square T$	K	80	40	63	6.3
Carnot Efficiency at Steam Extraction Location	$\eta_{Carnot}$		0.27	0.27	0.23	0.23
Work due to compression	$W_{Compression}$	kJ/kg CO <sub>2</sub>	353	353	300	300
<b>Energy Penalty</b>	$E_p$	<b>kJ/kg CO<sub>2</sub></b>	<b>991</b>	<b>871</b>	<b>1978</b>	<b>1050</b>

\*The working CO<sub>2</sub> capacity for MEA was calculated using the 2010 DOE Baseline Report. The temperatures for aqueous MEA was calculated using information from Ziaii et al., IECR, 2009, 48, 6105-6111; this information was also used to calculate the amount of water evaporated at the total energy penalty and agrees with the 2010 DOE Baseline Report.

Even without any heat recovery or integration, which will be evaluated under the project, the solid sorbent-based process demonstrates a lower energy penalty than the MEA process with 90% heat recovery. If 50% heat recovery can be achieved with ADA's solid sorbent process, then the energy penalty savings compared to MEA are significant. In addition, as was already

stated the sorbent being utilized for the 1 MW pilot test (the basis for the comparison in Table 1) may not be the final sorbent, therefore additional improvements are likely as sorbents with improved properties are developed.

ADA has already evaluated other materials that have demonstrated the following promising properties:

- Larger CO<sub>2</sub> working capacities
- Higher adsorption temperature
- Smaller temperature change required
- Lower specific heat capacities

It is theorized that through a combination of process development (i.e. heat recovery and integration) and sorbent development, solid sorbents for CO<sub>2</sub> capture have the ability to significantly lower the energy penalty and costs associated with CO<sub>2</sub> capture. It should be noted that under the project a techno-economic analysis will be completed that will include these potential improvements as well as capital cost calculations.

The basis for improvements regarding energy penalty have been explained. However, the environmental impact of CO<sub>2</sub> capture may also be reduced by using dry sorbents. For example, compared to an aqueous amine system:

- No corrosion inhibitors are required
- Less water waste will be generated
- No process makeup water will be required
- Amine volatilization will be reduced (indicated during laboratory testing and will be evaluated during 1 MWe pilot testing)

Under this project the selected supported amine sorbent will be used to capture CO<sub>2</sub> from the equivalent of 1 MWe of flue gas using the described design. The observations collected from 1 MWe pilot testing will be used to identify potential improvements in the process as well as refine the energy penalty and cost estimates. This 1 MWe pilot project represents an important step in the development of solid sorbents.

### **Relationship to Program**

- Demonstrate an alternative CO<sub>2</sub> capture technology.
- Demonstrate a CO<sub>2</sub> capture technology that can be carried out with lower energy requirements compared to the benchmark aqueous MEA CO<sub>2</sub> capture process
- Minimize water make-up and aqueous waste for CO<sub>2</sub> capture
- Develop a roadmap to make significant progress towards the DOE's goal of achieving CO<sub>2</sub> capture at less than a 35% increase in the LCOE

### **Primary Project Goal**

The project goal is to demonstrate 90 percent CO<sub>2</sub> capture at the 1 MWe pilot scale and, based on a techno-economic assessment, demonstrate progress towards limiting the increase in the LCOE to less than 35 percent after commercial deployment.

### **Objectives**

Specific objectives for this project include

1. Demonstrate the technical, economic, and energy benefits of a promising CO<sub>2</sub> capture technology.
2. Develop performance data through the operation of the system on flue gas, including



temperature control and optimized system heat recovery.

3. Measure process conditions, including sorbent heat of reaction, sorbent working capacity, sorbent attrition, system pressure drop, and CO<sub>2</sub> capture
4. Assess sorbent performance sensitivity to flue gas constituents
5. Operate continuously for at least 2 months to identify operating and maintenance issues and system reliability.
6. Remove at least 90% of the incoming CO<sub>2</sub> from the flue gas.
7. Produce high purity CO<sub>2</sub> that will be capable of meeting pipeline standards.
8. Conduct a techno-economic analysis of the commercial design developed by the commercial EPC.

## 13: ORD-2012.01.00 Task 7

<b>Project Number</b> ORD-2012.01.00 Task 7	<b>Project Title</b> Post-Combustion Membranes			
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<b>Partners</b>	Oak Ridge Institute for Science and Education University of Pittsburgh Carnegie Mellon University URS Corporation			
<b>Stage of Development</b>				
<input checked="" type="checkbox"/> Fundamental R&D	<input type="checkbox"/> Applied R&D	<input type="checkbox"/> Prototype Testing	<input type="checkbox"/> Proof of Concept	<input type="checkbox"/> Demonstration

### Technical Background

Capturing CO<sub>2</sub> is a critical step in reducing greenhouse gas emissions from fossil fuel-based processes. Carbon dioxide capture from coal combustion is currently at the research and development stage with very few large-scale demonstrations. Liquid solvents are the most mature technology, with monoethanolamine (MEA) being preferred for post-combustion flue gas. Although MEA is a good performer for CO<sub>2</sub> gas separation, NETL's Cost and Performance Baseline for Fossil Energy Plants found that the use of MEA to capture 90% of CO<sub>2</sub> in a pulverized coal power plant would impose a 30% energy penalty and ultimately result in an 85% increase in cost of electricity. Most of this energy loss is due to solvent regeneration. MEA is also corrosive and environmentally toxic.

Other capture technologies, such as membranes and solid sorbents are at less advanced stages of development. DOE/NETL is currently funding efforts by MTR and ADA to develop pilot scale post-combustion capture demonstrations of membranes and sorbents, respectively. MTR is developing a spiral wound polymer membrane system for CO<sub>2</sub>/N<sub>2</sub> separation that has been slipstream tested at the National Carbon Capture Center (NCCC). They are now working to scale up this effort to pilot scale. ADA has slipstream tested several supported amine solid sorbents and is now working to scale up that effort to a 1 MW slipstream. These projects represent next generation capture technologies that will be valuable proof-of-concept demonstrations of membranes and sorbents. It is expected that further fundamental materials development by NETL will drive down the energy penalty associated with carbon capture. The ability to test materials using real flue gas at sites such as the NCCC will be the key to moving these enhanced capture materials into large-scale demonstration and commercialization.

Mixed matrix membranes<sup>1</sup> (MMMs) are a membrane technology which could potentially achieve superior performance for coal-based gas streams. MMMs are a composite structure that makes use of a polymer support and a gas transport medium. Metal organic frameworks (MOFs) are proposed as the gas transport medium because of their potentially high CO<sub>2</sub> uptake and the tunability of their pores. Integrating MOFs into a polymer membrane increases the selectivity and permeance of the membrane, making the system more capable of dealing with a low partial pressure driving force than conventional polymers.

Mixed matrix membranes often suffer from poor contact between the polymer matrix and MOF crystallites<sup>1</sup>. This phenomenon, known as the sieve-in-a-cage effect, can cause gas streams to bypass the MOFs without separation, thus dramatically reducing selectivity. Overcoming this problem and identifying a polymer-MOF pair with the capability to form a highly permeable and selective membrane is the focus of this project. Using the integrated materials development approach described below, NETL has developed new MOFs, polymers, and fabrication techniques designed to address this issue. These techniques and materials have yet to be optimized. In doing so, NETL researchers expect not only to generate new, highly efficient capture devices, but also to revolutionize understanding of this class of membranes.

<sup>1</sup> Noble R, "Perspectives on Mixed Matrix Membranes", *J. Membrane Science*, 378 (2011) 393-397.

### **Relationship to Program**

The following impacts and benefits are possible through this proposed research:

1. Carbon dioxide capture technologies will be developed which decrease the cost of CO<sub>2</sub> removal from coal combustion facilities.
2. Techniques will be invented for creating polymer/MOF composites with intimate contact between the two materials. In addition to enabling mixed matrix membrane separations for a variety of gases based on the use of tailored MOFs, this technology could also allow MOFs to be incorporated into other varieties of functional composites.
3. Process development for this technology will improve understanding of plant integration of CO<sub>2</sub> capture. This understanding will inform future technology development and help move toward future generations of CO<sub>2</sub> capture technology.

### **Primary Project Goal**

The planned research is aimed at accelerating the development of efficient, cost-effective technologies that drive towards the post-combustion programmatic goal of capture of 90% of the CO<sub>2</sub> produced by an existing coal-fired power plant with less than a 35% increase in the COE. Specifically, this work aims to develop at least one candidate membrane and corresponding process integration scheme to the point of readiness for bench-scale testing in a slipstream of actual flue gas.

### **Objectives**

Capturing CO<sub>2</sub> is a critical step in reducing greenhouse gas emissions from fossil fuel-based processes. The research is aimed at accelerating the development of efficient, cost-effective membrane technologies that drive towards the post-combustion programmatic goal of 90% capture of CO<sub>2</sub> produced by an existing coal-fired power plant with less than a 35% increase in the cost of electricity (COE). The specific objective of this FWP is to develop membrane based post-combustion carbon capture technologies to the point of readiness for testing in a slipstream of actual flue gas.

## I 4: FE0007634

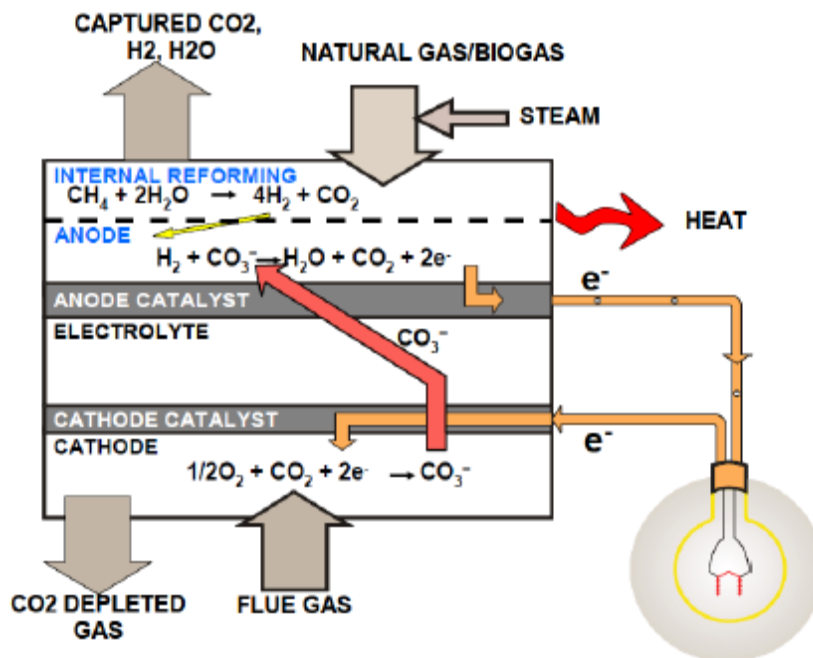
<b>Project Number</b> FE0007634	<b>Project Title</b> Electrochemical Membrane for Carbon Dioxide Capture and Power Generation			
<b>Contacts</b> DOE/NETL Project Mgr.	<b>Name</b> José Figueroa	<b>Organization</b> NETL – Existing Plants Division	<b>Email</b> Jose.Figueroa@NETL.DOE.GOV	
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<b>Partners</b>	URS Corporation Pacific Northwest National Laboratory			
<b>Stage of Development</b>				
<input type="checkbox"/> Fundamental R&D	<input checked="" type="checkbox"/> Applied R&D	<input type="checkbox"/> Prototype Testing	<input type="checkbox"/> Proof of Concept	<input type="checkbox"/> Demonstration

### Technical Background

This project is focused on development of an Electro-chemical Membrane (ECM) for separation of carbon dioxide from flue gas of coal-fired power plants. The most intriguing feature of the ECM is the generation of electricity (using a fuel) while capturing carbon dioxide from the coal plant's flue gas. This unique feature results in a very attractive proposition for carbon dioxide capture from the existing plants. Unlike most other CO<sub>2</sub> capture technologies, ECM is a net power producer.

The operating principle of the ECM is shown in Figure 1, along with the electrochemical reactions involved. The ECM membrane is fabricated by lamination of three thin layers (anode, electrolyte matrix, cathode) composed of ceramic materials (Lithium Aluminate and NiO) and metal particles (Ni/Al or Ni/Cr alloys), similar to a fuel cell (in this case, Molten Carbonate Fuel Cell [ref 1]). The ECM tri-layers are impregnated with a mixture of alkali metal (Li/Na/K) carbonate electrolyte which constitutes a molten phase immobilized in the ECM pores at the operating temperature of 550-650 °C. The anode and cathode are porous to allow gas diffusion. The inner matrix layer is completely filled with electrolyte and is impervious to gas transport while providing a path for ionic transfer across the membrane. Carbon dioxide and oxygen present in the flue gas of a coal power plant are used as reactants at the cathode. The ECM utilizes H<sub>2</sub> at the anode. The hydrogen is made available to the anode by a mixture of a fuel (such as natural gas, syngas or biogas) and steam. The hydrocarbon content of the fuel is internally steam reformed to produce hydrogen in the anode chamber.

The electrochemical reactions (Figure 1) involve the formation of carbonate ions (CO<sub>3</sub><sup>2-</sup>) at the cathode by the combination of O<sub>2</sub>, CO<sub>2</sub>, and two electrons; transport of the carbonate ions to the anode through electrolyte; and finally, reaction of the carbonate ion with H<sub>2</sub> at the anode, producing H<sub>2</sub>O, CO<sub>2</sub>, and two electrons. The internal transport of carbonate ions in an ECM assembly (or cell) and the flow of electrons in the external circuit results in electric power generation as a consequence of the electrochemical CO<sub>2</sub> separation process. DC power produced is converted to AC power using an inverter. Overall, the operating mechanism of the ECM cell results in the separation (from flue gas) and transfer of CO<sub>2</sub> into the anode exhaust stream which has a much reduced volumetric flow rate (resulting in a CO<sub>2</sub>-rich stream) compared to the original flue gas stream.

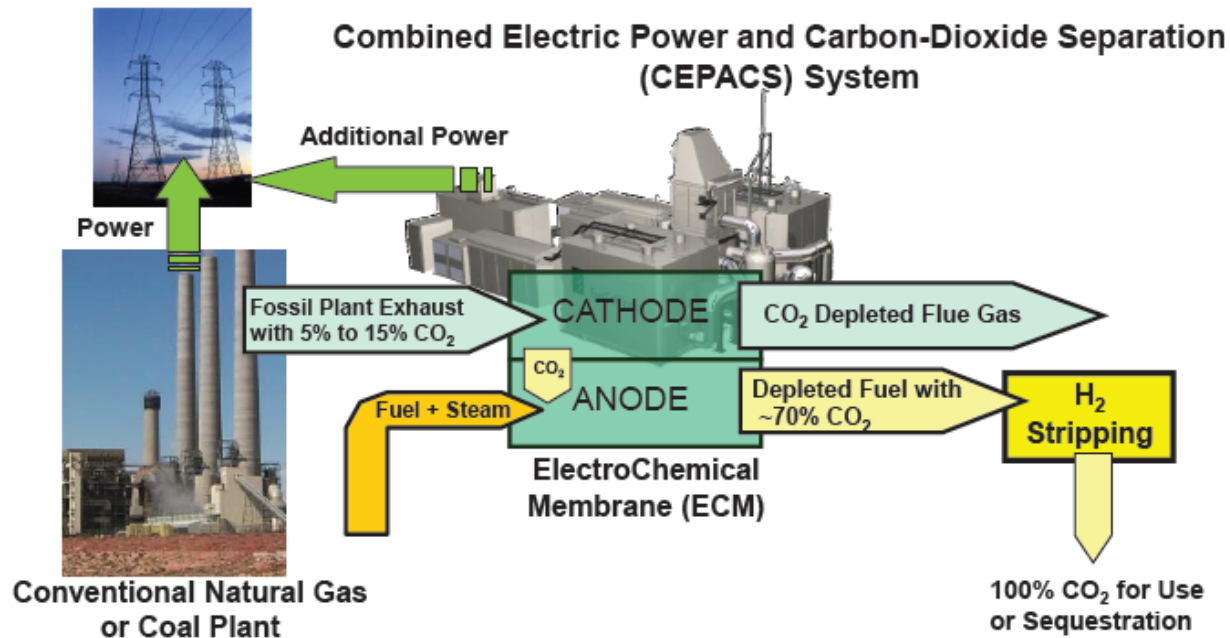


**Figure 1. Separation of CO<sub>2</sub> in the Electrochemical Membrane Cell:**

CO<sub>2</sub> is used at cathode as an oxidant and transferred to anode via carbonate electrolyte

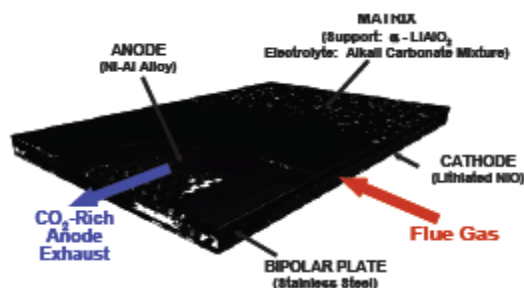
Based on the ECM technology, FuelCell Energy (FCE) has developed the Combined Electric Power and Carbon-dioxide Separation (CEPACS) system concept (US Patent 7,396,603 B2, [ref 2 - 6]) as a novel solution for greenhouse gas emission reduction. To illustrate how the system works, a simplified diagram of the CEPACS system concept is shown in Figure 2. CO<sub>2</sub>-containing flue gas from a coal-fired (combustion-based) power plant, such as the exhaust from a Pulverized Coal (PC) power plant or other industrial source, is utilized as the oxidant for the ECM cathode. A supplementary fuel such as natural gas, coal-derived syngas, or biogas is reformed with steam internal to the ECM to provide the hydrogen needed to complete the electrochemical power generation cycle. The ECM utilizes the CO<sub>2</sub> of the flue gas as a reactant for the electrochemical reaction to produce power, while synergistically transferring CO<sub>2</sub> from the flue gas to the anode exhaust stream.

The H<sub>2</sub>O (product of ECM anode-side electrochemical reaction) is removed by simple condensation during downstream processing. There is also some unused fuel (mainly H<sub>2</sub> and some carbon monoxide, CO) in the CO<sub>2</sub>-rich anode exhaust stream. This remaining H<sub>2</sub> (and CO) is separated and recycled to provide additional preheat in the system and for use as part of the supplementary fuel, thereby reducing the consumption of the fuel to ECM anode. After the water has been condensed out and the H<sub>2</sub> removed, the resulting high-purity CO<sub>2</sub>-capture stream (99.7%+ CO<sub>2</sub>) is ready for compression and sequestration/use. Water condensed during post-processing of the CO<sub>2</sub>-rich anode exhaust stream is used to provide water (steam) needed for internal reforming of CH<sub>4</sub> in the supplementary fuel, eliminating the need for external process water. The CO<sub>2</sub>-lean cathode exhaust (flue gas after CO<sub>2</sub> removal) is vented to atmosphere after recovering the heat for process use (e. g. preheating of feed streams and generation of steam).



The ECM cell operates at atmospheric pressure. Unlike conventional membrane technologies that rely on pressure (partial pressure) differentials and permeability properties, the ECM separates CO<sub>2</sub> at a rate dependent on the electrical current drawn. The flue gas does not need to be pressurized and vacuum operation is not required on the permeate side. The ECM separates CO<sub>2</sub> from the flue gas with complete selectivity over the nitrogen present in the gas. ECM is capable of producing 3000-3500 KJ of gross direct current electricity per Kilogram of CO<sub>2</sub> transferred from the flue gas to the anode gas. With the benefit of generating power, the ECM technology is anticipated to offer a cost-effective solution for carbon capture from exhaust of coal power plants. Because of fast electrode kinetics, the ECM does not require high CO<sub>2</sub> concentration in the feed gas. The CO<sub>2</sub> concentration of <15% normally found in the PC plant flue gas is suitable.

Although the application of ECM in CEPACS is a novel concept for CO<sub>2</sub> capture, the electrochemical membrane is based on a mature technology developed by FCE for use as fuel cells in standalone stationary power systems. It has been deployed in MW-scale power plants as a commercial product. The ECM assembly, as shown in Figure 3, is planar for ease of fabrication and scale-up. The membrane assemblies are sandwiched between stainless steel bipolar plates in a unitized cell package. The corrugated flow channels are inserted adjacent to the electrodes (cathode and anode), providing a cross-flow arrangement, similar to a plate-and-frame heat exchanger. The ECM cell packages can be assembled into tall stacks of cells similar to the stacking of fuel cells as shown Figure 4. The planar geometry of ECM offers ease of scalability to large sizes suitable for deployment in PC plants. Based on large gas flow channels, ECM can process large gas volumes without significant back pressure (2-3 inches of water).



**Figure 3. ECM Cell Package Configuration**



**Figure 4. Full-height Assembled Stack**

The anodes and cathodes are manufactured by standard processing techniques such as tape casting or powder doctoring followed by sintering. Cell matrix manufacturing by tape casting is also well developed. Standard sheet metal forming, bending, and welding operations are involved in the manufacture of cell hardware components. Currently the fuel cells about 9000 cm<sup>2</sup> in size (suitable for large-scale applications) are being mass-produced at FCE's Torrington, CT manufacturing facility (Figure 5). This facility is equipped with commercial size tape caster, sintering furnace, sheet metal forming machines, and other necessary production equipment. Fuel cell matrices and anodes are fabricated by high-speed tape casting machines.

The membrane has been tested at the laboratory scale verifying the feasibility of the technology for CO<sub>2</sub> separation from simulated flue gases of PC plants as well as Combined Cycle power plants and other industrial facilities. Also, in the past, ECM based CO<sub>2</sub> capture system studies have been performed for a variety of applications including natural gas fueled Combined Cycle power plants [ref 7] and industrial sites such as refineries and cement factories [ref 8].

This project will further advance the CEPACS technology to a maturity level suitable for adaptation by the coal fired plants. The project is intended to resolve the issues related to inadequate information on the effects of flue gas trace contaminants on ECM and to demonstrate the viability of the technology to PC plants, leading to pilot scale demonstration and subsequent commercial deployment.

(7) Campanari, S., Chiesa, P., Manzolini G., "CO<sub>2</sub> capture from combined cycles integrated with Molten Carbonate Fuel Cells", *International Journal of Greenhouse Gas Control*, 4, (2010) 441–451.

(8) Hunt, J., Willman, C., Ghezal-Ayagh, H., Singh, P., "Carbon Capture from the Industrial Sites Using a High Temperature Ionic Membrane", *11th Annual Conference on Carbon Capture Utilization & Sequestration*, Pittsburgh, PA, April 30 - May 3, 2012.

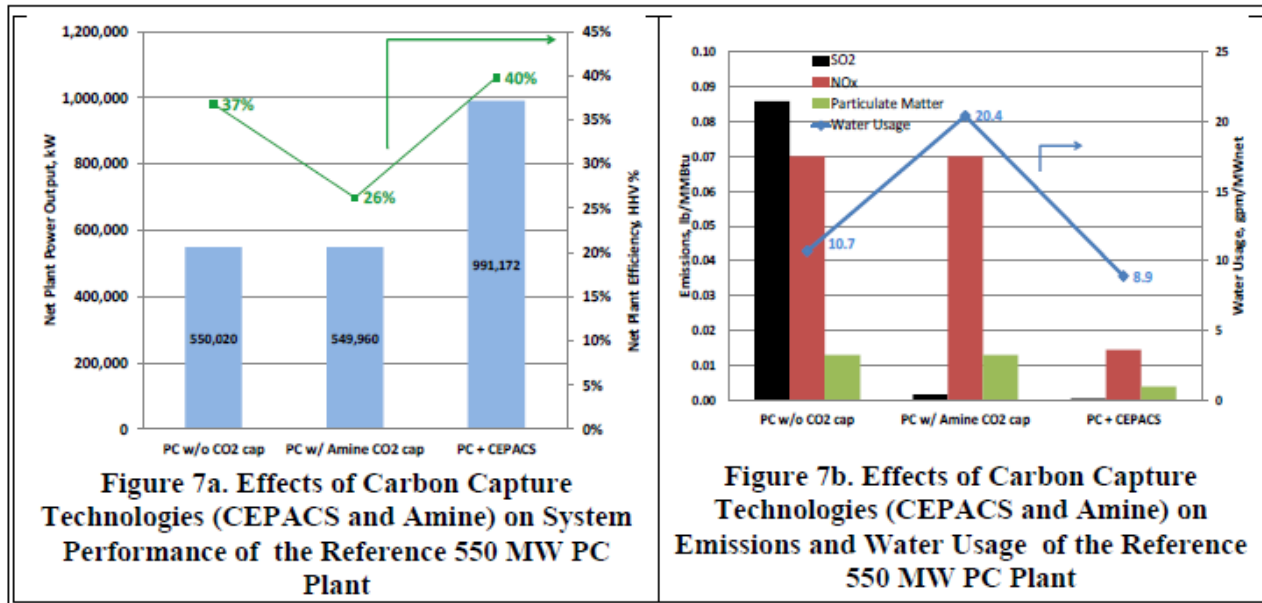
### Relationship to Program

The ECM-based CO<sub>2</sub> capture technology (CEPACS system) is anticipated to have a significant impact by advancing the application of CO<sub>2</sub> capture technology to both existing (retrofitting) and new PC power plants. Operation of the CEPACS system is set apart from other CO<sub>2</sub> capture technologies by generation of electric power rather than consuming it, resulting in an increase in the power output of the retrofitted PC power plant. For example, Monoethanolamine (MEA) based scrubbing technology is considered to be the state-of-the-art for separating CO<sub>2</sub>. However, the energy and efficiency penalties of using amines for CO<sub>2</sub> capture in PC plants are substantial. About 22-30% of plant gross power is used up by the amine system, dropping the plant efficiency to <30% [ref 11]. The PT&EFS has shown that CEPACS increases the Net power output of the Reference 550 MW PC plant by approximately 80% and its efficiency by 3% while capturing 90% of the carbon dioxide as shown in Figure 7a.

The key benefits of the CEPACS system include:

- ECM allows for separation of at least 90% of carbon dioxide from the greenhouse gases generated by coal fired power plants.
- US Department of Energy's (DOE's) target of <35% increase in cost-of-electricity (COE) for post-combustion CO<sub>2</sub> capture is achievable by commercial ECM-based CEPACS system units.
- ECM technology is modular; suitable for incremental applications to many types of plants (allowing for phased addition of CO<sub>2</sub> capture capacity over time).
- Unlike other CO<sub>2</sub> capture technologies (scrubber or membrane-based), the ECM-based CEPACS system produces additional electric power (using a supplemental fuel), rather than consuming power, thereby increasing net electric power generated by the existing fossil-fueled plants.
- The net plant efficiency of a CEPACS-equipped PC plant with CO<sub>2</sub> capture is estimated to be ~8% higher than the net plant efficiency of a baseline PC plant without CO<sub>2</sub> capture.
- The CEPACS system generates excess clean water as part of the electrochemical separation process, an important feature where water is scarce. Figure 7b shows the significance of the water usage reduction by the CEPACS carbon capture applied to the Reference PC plant as compared to the Amine Scrubber technology which increases the water demand.
- ECM technology is anticipated to reduce flue gas NO<sub>x</sub> emissions (produced by the older plants) by 60-70%. PC plant retrofitted with CEPACS system has lower emissions of NO<sub>x</sub>, SO<sub>x</sub>, and Hg than a PC plant retrofitted with Amine scrubber for CO<sub>2</sub> capture (Figure 7b).





### Primary Project Goal

The primary project goal is to successfully demonstrate the ability of Combined Electric Power and Carbon-Dioxide Separation (CEPACS) system technology to separate (capture) at least 90% CO<sub>2</sub> from flue gas of an existing Pulverized Coal (PC) Rankine cycle power plant and to compress the captured CO<sub>2</sub> to a state that can be easily transported for sequestration or beneficial use, and to show, through a techno-economic feasibility study, that it can meet DOE's objective of no more than 35% increase in the cost of electricity (COE) for post-combustion CO<sub>2</sub> capture.

### Objectives

The project objectives [ref 9] are mainly focused on completing the analyses and tests to ascertain the achievements of the cost and performance targets as specified in the Primary Project Goal. The specific objectives include:

- Perform a Preliminary Technical and Economic Feasibility Study (PT&EFS) to gauge the performance and cost of the CEPACS system.
- Perform contaminant effect testing to establish maximum permissible concentrations of impurities in flue gas, which will limit performance degradation of the electrochemical membrane to an acceptable level.
- Establish that ECM has an added benefit of destroying a significant amount of NO<sub>x</sub> from the flue gas of the PC plant.
- Specify and incorporate appropriate flue-gas pre-treatment and pollution control technologies, based on the results of the contaminant tests.
- Develop the design of Balance-of-Plant (BOP) components and perform a gap analysis to identify the technical/cost improvements that are required to achieve the primary project goal.
- Perform an Environmental, Health & Safety (EH&S) study of the system to ensure compliance with all environmental and safety regulations.
- Perform bench-scale membrane tests using clean simulated PC plant flue gas to demonstrate the feasibility of pure CO<sub>2</sub> capture.

This project consists of three budget periods to demonstrate the technology, complete the feasibility studies, and complete risk assessments and mitigations. FCE has successfully completed Budget Period 1 (BP1) [ref 10] activities and is currently in BP2.

Budget Period 1 (BP1):

The specific objective for BP1 was to complete the Preliminary Technical and Economic Feasibility Study (PT&EFS) on the ECM technology-based CEPACS system, for capturing CO<sub>2</sub> from a PC plant flue-gas stream. This study was based on the current state of ECM technology, scaled up to a carbon capture system size suitable for a Reference 550 MW PC power plant. The study was conducted in accordance with the U.S. Department of Energy/National Energy Technology Laboratory (DOE/NETL) report entitled “Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 2” [ref 11], and specifically focused on developing technical and economic comparisons to Cases 9 and 10 of the report.

Budget Period 2 (BP2):

The specific objectives for BP2 are to perform evaluation tests of the flue gas contaminant effects on ECM performance and endurance, small area membrane tests using clean simulated flue gas, design of the flue gas pretreatment system for processing of the flue gas prior to ECM feed, and update the Technical & Economic Feasibility Study incorporating results of contaminant effect tests and small area membrane tests. Electrochemical membranes in 250 cm<sub>2</sub> size will be tested for carbon capture performance under the coal gas compositions representing the Reference PC plant. The results will be utilized in updating the system models. Also, ECMs will be tested for their effectiveness in destruction of NO<sub>x</sub> in the coal gas. Additionally, a Technology Gap Analysis is planned to identify the improvements in equipment and materials which are needed to achieve the primary goals of cost and performance. Preparation of test facility for bench scale testing (to be conducted in BP3) is also included in BP2.

Budget Period 3 (BP3):

The main objective of the BP3 is to verify the performance and characteristics of the ECM in a bench-scale facility setup prototypical of a CEPACS system. The bench-scale test facility will include approximately 11.7 m<sup>2</sup> of electrochemical membrane for CO<sub>2</sub> capture, and will be equipped for final purification, and compression of the separated CO<sub>2</sub> from a contaminant-free simulated coal gas. Bench-scale testing will include parametric testing of the ECM as well as long duration testing in excess of six months. Additionally, a Technical Environmental Health and Safety (EH&S) Review will be conducted for the CEPACS systems to evaluate emission types (gas, liquid, solid), emission levels, emission properties, regulatory compliance and implications, and safe handling and storage procedures for raw materials, products and by-products. The success criterion for this task is to illustrate that there are no environmental or safety concerns which would delay commercialization efforts.

The flue gas contaminant studies are performed under a Cooperative Research and Development Agreement between FCE and Pacific Northwest National Laboratory (PNNL). In addition to availability of advanced and sophisticated analytical laboratory equipment, the PNNL team has capabilities and established facilities to test ECM with trace species in a gaseous stream. The PNNL team’s experience in characterizing the effects of the coal gas trace contaminants on Solid Oxide Fuel Cells (SOFC) [ref 12 and 13] will be extended to quantification of the ECM tolerance limits to contaminants including SO<sub>2</sub>, Cl, Se, and Hg.

FCE is also collaborating with URS Corporation (URS) in the Technical and Economic Feasibility Study for application of the CEPACS to capture CO<sub>2</sub> from the flue-gas of the Reference 550 MW PC power plant. URS is a premier technology company that adds expertise in systems engineering and technical assistance; construction and construction management; operations and maintenance; and EH&S evaluation. URS will support the system design and economic analysis of ECM-based CO<sub>2</sub> capture system for retrofitting the existing PC plants.

The results of this project are expected to demonstrate that the ECM is an advanced technology, fabricated from inexpensive materials, based on proven operational track records, modular, scalable to large sizes, and a viable candidate for >90% carbon capture from the existing PC plants.

(9) <http://www.netl.doe.gov/technologies/coalpower/ewr/co2/post-combustion/membrane-fuelcell-energy.html> , General project information available on DOE/NETL website.

(10) Ghezel-Ayagh, H., "Electrochemical Membrane for CO<sub>2</sub> Capture and Power Generation No. DE-FE0007634 FuelCell Energy, Inc.", 2012 NETL CO<sub>2</sub> Capture Technology Meeting July 9, 2012 Pittsburgh, PA.

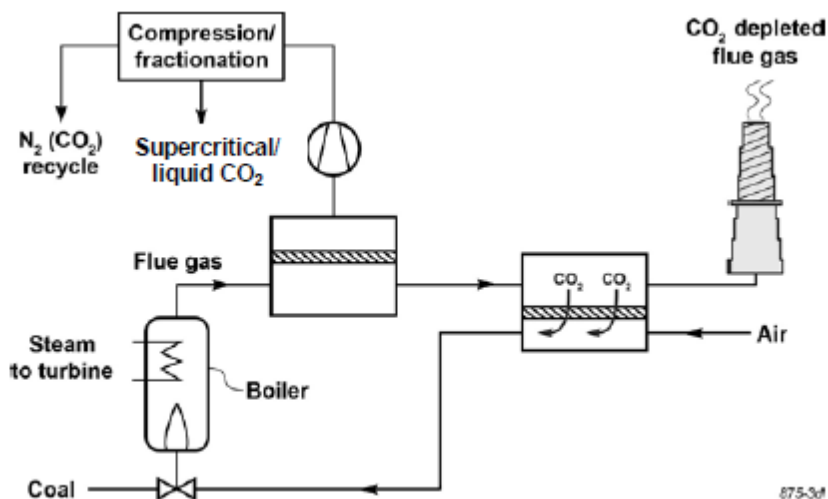
(11) Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 2, DOE/NETL-2010/1397, November 2010. (12) Marina, O. A., Pederson, L. R., Coyle, C. A., Thomsen, E. C., and Edwards,

## 15: FE0005795

<b>Project Number</b> FE0005795	<b>Project Title</b> Recovery Act: Slipstream Testing of a Membrane CO <sub>2</sub> Capture Process for Existing Coal-Fired Power Plants			
<b>Contacts</b> DOE/NETL Project Mgr.	<b>Name</b> José Figueroa	<b>Organization</b> NETL – Existing Plants Division	<b>Email</b> Jose.Figueroa@NETL.DOE.GOV	
<b>Principal Investigator</b>	Tim Merkel	Membrane Technology & Research, Inc.	Tim.merkel@mtrinc.com	
<b>Partners</b>	Electric Power Research Institute, Inc. Babcock & Wilcox Power Generation Group National Carbon Capture Center Vectren Corporation			
<b>Stage of Development</b>				
<input type="checkbox"/> Fundamental R&D	<input type="checkbox"/> Applied R&D	<input checked="" type="checkbox"/> Prototype Testing	<input type="checkbox"/> Proof of Concept	<input type="checkbox"/> Demonstration

### Technical Background

Some time ago, MTR conceived the idea of a CO<sub>2</sub> capture process using combustion air as a sweep gas on the permeate side of a membrane to create driving force for CO<sub>2</sub> removal with minimal energy input. A block diagram illustrating the application of this membrane process to CO<sub>2</sub> capture in a coal-fired power plant is shown in Figure 1. A first membrane unit using a vacuum on the permeate side to generate driving force removes a portion of the CO<sub>2</sub> from flue gas and sends the CO<sub>2</sub> to a compression and purification unit. The flue gas, still containing some CO<sub>2</sub>, is then sent to a second membrane unit where air passing countercurrent to the flue gas strips CO<sub>2</sub> out of the gas. The CO<sub>2</sub>-laden sweep air is then used to burn coal in the power plant boiler, while the CO<sub>2</sub>-depleted flue gas is sent to the stack. By recycling CO<sub>2</sub> to the boiler, the CO<sub>2</sub> concentration in the flue gas can be enriched by up to a factor of two (to 20- 25% CO<sub>2</sub>). The increased CO<sub>2</sub> concentration in the flue gas makes subsequent capture of the CO<sub>2</sub> by the first membrane unit easier (lower cost and energy requirements).

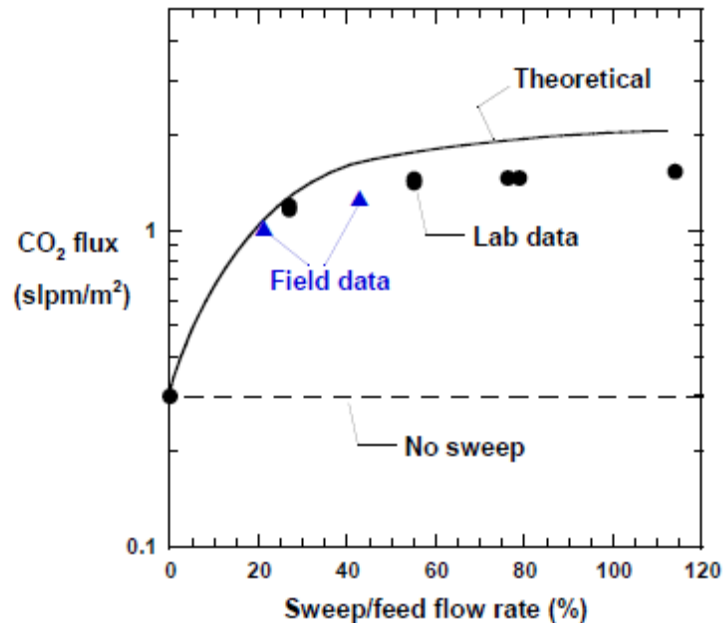


**Figure 1.** A simplified diagram of the MTR flue gas CO<sub>2</sub> capture process.

The process design shown in Figure 1 is useful for lowering CO<sub>2</sub> capture costs with membranes. However, in addition to this innovative design patented by MTR, very special membranes are required to make CO<sub>2</sub> capture affordable. Because of the large flow rate and low pressure of power plant flue gas, enormous membrane area is required for separation unless extremely permeable membranes are used. In previous DOE NETL-funded work, MTR developed new membranes – designated Polaris™ – with ten times the CO<sub>2</sub> permeance of conventional gas separation membranes. A tenfold increase in permeance leads to a tenfold decrease in the required membrane area, and reduces the capital cost and footprint of a CO<sub>2</sub> capture system substantially. These process and materials innovations offer the potential for a membrane process to capture CO<sub>2</sub> from flue gas in a cost-effective manner. Moreover, membrane processes offer a number of other advantages when applied to flue gas CO<sub>2</sub> capture, including tolerance to flue gas contaminants (SO<sub>x</sub>, NO<sub>x</sub>, etc.), no use of harmful chemicals with emissions or disposal issues, recovery of flue gas water, and – because they use only electric power – no modifications to existing boilers and steam turbines.

In previous DOE NETL-funded work (DE-FE0005312), MTR successfully took the Figure 1 process to the small field demonstration stage. A 1 TPD CO<sub>2</sub> capture membrane test skid was built and installed at the Arizona Public Service (APS) Cholla coal-fired power plant in northeastern Arizona, near Holbrook; that plant has a total capacity of 995 MWe, fueled by bituminous and sub-bituminous coal. The flue gas delivered to the MTR test skid was taken downstream of a wet lime flue gas desulfurization (FGD) system and contained 50 ppm SO<sub>2</sub>. The 1 TPD system ran for approximately three months. During this period, 8-inch diameter Polaris cross-flow and countercurrent/sweep spiral-wound modules were tested, and both types of modules showed stable performance. The CO<sub>2</sub> permeance and CO<sub>2</sub>/N<sub>2</sub> selectivity of the membrane modules were unaffected by exposure to post-FGD flue gas and rust particle deposition, demonstrating the robustness of the modules when exposed to coal-derived flue gas containing 50 ppm SO<sub>2</sub> for up to 3 months.

The other key finding from our initial tests with the 1 TPD system confirmed that CO<sub>2</sub> capture using air as a sweep stream to generate permeation driving force is effective in commercial-sized spiral-wound Polaris modules. This finding is demonstrated in Figure 2, which compares the measured CO<sub>2</sub> module flux with the maximum theoretical countercurrent performance and the no sweep case. Field data confirm that using air as a sweep gas dramatically increases the CO<sub>2</sub> flux through the module.

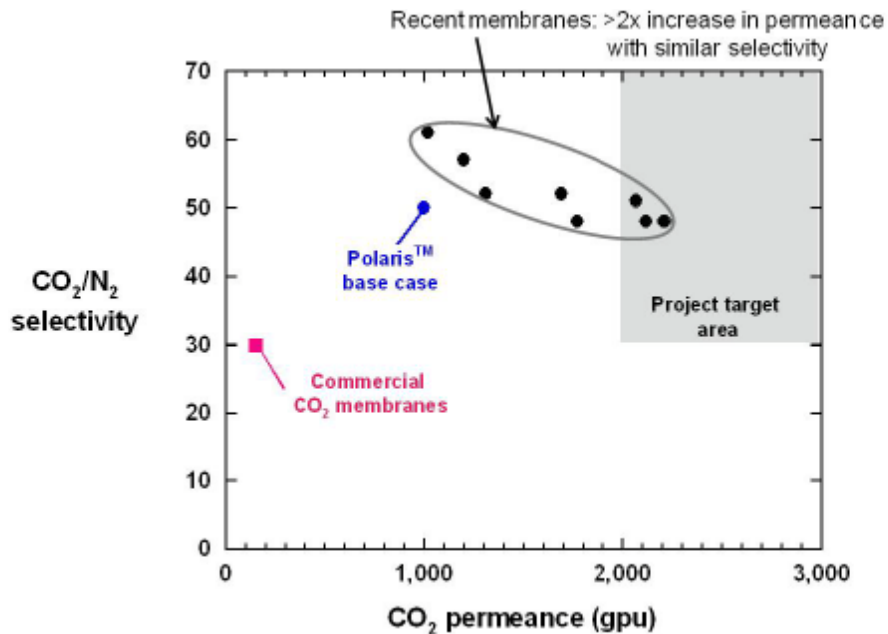


**Figure 2.** CO<sub>2</sub> flux as a function of sweep-to-feed flow rate ratio for countercurrent sweep spiral wound modules. The field data are for 8-inch diameter modules tested on the 1 TPD system at APS Cholla and the lab data are for 4-inch diameter modules tested at MTR. The theoretical curve is calculated using a custom simulation package that assumes ideal countercurrent operation. A full scale system would operate with a sweep/feed ratio of 50-70%.

As part of our current project (DE-FE0005795), the membrane CO<sub>2</sub> capture process is being scaled up, from a 1 TPD field test system to a 20 TPD unit. The design for the larger unit was completed in budget period 1 (BP1), and the skid is currently being fabricated, with installation at NCCC scheduled for the last quarter of 2013. The 1 TPD system was moved to NCCC during BP1 and will continue to operate throughout this project as a test vehicle for membrane improvement and lifetime studies.

In addition to the successful completion of the 20 TPD design work and initial runs of the 1 TPD unit at NCCC, other key work completed in BP1 of the current project includes the following items:

- The performance of the Polaris CO<sub>2</sub> capture membrane was further optimized. During BP1, the MTR research team improved the CO<sub>2</sub> permeance of Polaris membrane by more than 100% to >2,000 gpu, while maintaining the CO<sub>2</sub>/N<sub>2</sub> selectivity. This result is shown in the form of a selectivity-permeance tradeoff plot in Figure 3.



**Figure 3.** A tradeoff plot showing CO<sub>2</sub>/N<sub>2</sub> selectivity as a function of CO<sub>2</sub> permeance. Data for the base case Polaris membrane and recently developed laboratory membranes are shown. The highlighted project target area is the original performance goal by the end of budget period 3.

The current membrane performance already meets the BP3 target. Nevertheless, we believe further improvements are possible, and the economic analysis shows that such effort is worthwhile.

- A new module design was tested and shown to reduce pressure drop by half compared to the base design used previously. This advance will produce large energy savings in the blowers required to push gases through the membrane system.
- Four topical reports were completed in BP1, including:
  - A report by Babcock & Wilcox on “Effect of Secondary Synthetic Air on Boiler Performance,” based on the B&W COMO modeling software. The preliminary B&W evaluation suggests it is possible to recycle CO<sub>2</sub> to a coal boiler without significantly affecting the efficiency of the boiler and steam cycle. Testing on a pilot-scale boiler at B&W in BP2 will seek to validate this finding. – A preliminary evaluation of the use of Polaris membranes for use in industrial CO<sub>2</sub> operations, using process design simulations. This analysis shows that modified Polaris membranes lab tested in BP1 can be a cost-effective means of CO<sub>2</sub> capture from refineries. During BP2 we will investigate options for conducting a small field test of industrial CO<sub>2</sub> capture in BP3.
  - A progress report on plate-and-frame module development activities at MTR, pertinent to the pressure drop issues encountered in separation of the massive gas quantities involved in CO<sub>2</sub> separation from power plant flue gas.
  - A systems design and economic analysis of the MTR membrane process for post-combustion CO<sub>2</sub> capture. This analysis – discussed in more detail in Section 12 of this document – showed that the MTR CO<sub>2</sub> capture process can achieve an increase in COE of 40-45% at 90% CO<sub>2</sub> capture from a subcritical PC power plant.

Currently, we are continuing to test membranes on the 1 TPD system at NCCC to validate lab membrane/module improvements and to evaluate membrane lifetime when treating real flue

gas. Key upcoming BP2 tasks include boiler testing at B&W with CO<sub>2</sub>-laden combustion air and installation of the 20 TPD test system at NCCC.

### **Relationship to Program**

If successful, the project will provide the following benefits to the DOE NETL CO<sub>2</sub> capture effort:

- Field demonstration of a 20-fold scale-up of emerging membrane CO<sub>2</sub> capture technology that numerous studies have shown has potential to approach DOE target post-combustion CO<sub>2</sub> capture targets.
- Evaluation of boiler operation at B&W with combustion air containing recycled CO<sub>2</sub>; effective boiler operation with recycled CO<sub>2</sub> is key to the MTR CO<sub>2</sub> capture process and variations of this process scheme are being considered by a number of technology developers in addition to MTR.
- Continued performance improvement of the industry-leading CO<sub>2</sub> capture membrane. Polaris is the standard by which other CO<sub>2</sub> membranes are judged and performance has already been doubled in this project.
- Preliminary investigation of novel membrane designs for CO<sub>2</sub> capture from industrial processes and natural gas-fired power generation. Several patents in these areas have already been filed.
- As a collateral benefit, the Polaris membrane developed in the DOE program has been commercialized for use in polar gas removal from natural gas and syngas. These applications are not dependent on CO<sub>2</sub> emissions regulation/legislation because the polar species, including CO<sub>2</sub>, must be removed to increase the value of a product (e.g., natural gas). Thus, even without CO<sub>2</sub> emission controls, we believe there is a significant market for the technology developed in this program.

### **Primary Project Goal**

The overall goal of this project is to demonstrate a cost-effective membrane process to separate carbon dioxide from coal-fired power plant flue gas at the 1 MWe (20 metric ton CO<sub>2</sub>/day) scale, that shows potential to meet the DOE target of <35% increase in LCOE for coal-fired plants at a 90% CO<sub>2</sub> capture rate.

### **Objectives**

This project will scale up the MTR membrane technology to a 20 metric ton CO<sub>2</sub>/day (20 TPD or 1 MWe) slipstream test with coal-fired flue gas using commercial-scale membrane components. Concurrently, laboratory work will continue to improve membrane and module performance, and these components will be incorporated into the field test to allow iterative performance optimization under real operating conditions. Field testing will be conducted at the National Carbon Capture Center (NCCC) run by Southern Company. In addition, collaborative work with Babcock & Wilcox (B&W) will aim to clarify the impact on boiler performance of CO<sub>2</sub> recycle by sweep.

The key project objectives by budget period as established in the project SOPO are:

#### **BP1**

Modification and testing of the 0.05 MWe (1 ton CO<sub>2</sub>/day or 1 TPD) CO<sub>2</sub> membrane field system at a coal-fired power plant will be conducted. In addition, optimization of membrane materials, identification of the best low-pressure-drop module designs, and determination of the membrane pretreatment requirements will be performed. A preliminary computer modeling study will be conducted to evaluate the impact of CO<sub>2</sub> recycle to the boiler on boiler performance. Membrane manufacturing improvements will be assessed to reduce overall membrane fabrication costs. Technical, systems, and economic analyses based on pilot test data will be performed to assess



the performance of the base-case membrane capture process applied to a full-scale power plant. The 20 TPD membrane CO<sub>2</sub> capture system will be designed. Bench-scale membrane research, development, and analysis of: (1) the Polaris membrane used for industrial CO<sub>2</sub> capture at a refinery and (2) plate-and-frame module configuration research for increased energy efficient CO<sub>2</sub> capture system performance will be conducted. A preliminary design study of membranes for industrial CO<sub>2</sub> capture at a refinery will be performed.

### BP2

Testing of the 1 TPD CO<sub>2</sub> membrane field system to continue the membrane and module optimization work started in BP1 will be performed. Optimized module configurations, including a plate-and-frame design with low-pressure drop and small footprint, will be tested on this system. Power plant integration studies to identify potential lower energy process designs will be completed. The 20 TPD CO<sub>2</sub> membrane system will be fabricated and installed at a coal-fired power plant. Pilot scale boiler testing with CO<sub>2</sub>-enriched air will be conducted at B&W to simulate the sweep gas membrane effects on a wall-fired boiler configuration; these experimental results will be compared to the computer modeling performed in BP1.

### BP3

Continued testing of the 1 TPD CO<sub>2</sub> field system to assess the durability of the CO<sub>2</sub> membrane will be performed. The 20 TPD membrane system will be operated for 6 months of parametric and continuous testing at a coal-fired power plant. The pilot test results from the 1 TPD and 20 TPD membrane systems will be analyzed and a technical/economic evaluation of the membrane process will be prepared. A case study of a 20 MW<sub>e</sub> (400 TPD) membrane CO<sub>2</sub> capture system at a coal-fired power plant will be completed. Industrial membrane field testing and an updated techno-economic study to ascertain the suitability of the CO<sub>2</sub> membrane system for industrial application in a refinery will be performed. Testing of a 500 m<sup>2</sup> prototype plate-and-frame module as an alternative to a spiral-wound sweep gas module on the 20 TPD membrane system will be completed.

## 16: FE-10-002

<b>Project Number</b> FE-10-002	<b>Project Title</b> High-Temperature Polymer-Based Membrane Systems for Pre-Combustion CO <sub>2</sub> Capture			
<b>Contacts</b> DOE/NETL Project Mgr.	<b>Name</b> Elaine Everitt	<b>Organization</b> NETL – Existing Plants Division	<b>Email</b> Elaine.Everitt@NETL.DOE.GOV	
<b>Principal Investigator</b>	Kathryn A. Berchtold	LANL	berchtold@lanl.gov	
<b>Partners</b>	Great Point Energy EIG, Inc.			
<b>Stage of Development</b>				
<input type="checkbox"/> Fundamental R&D	<input checked="" type="checkbox"/> Applied R&D	<input type="checkbox"/> Prototype Testing	<input type="checkbox"/> Proof of Concept	<input type="checkbox"/> Demonstration

### Technical Background

Los Alamos National Laboratory performs applied research and development in carbon dioxide (CO<sub>2</sub>) capture in support of the U.S. DOE National Energy Technology Laboratory Strategic Center for Coal – Carbon Capture R&D Program. The goal of this work is to execute the enabling science that will help lead to large-scale deployment of CO<sub>2</sub> capture technology as part of DOE's program to mitigate anthropogenic emission of CO<sub>2</sub> with a focus on the utility sector. This project is aimed at the continued development and demonstration of LANL developed membrane-based pre-combustion hydrogen purification/carbon capture materials, technologies, and separation schemes.

Capturing carbon dioxide from mixed-gas streams is a first and critical step in carbon sequestration. To be technically and economically viable, a successful separation method must be applicable to industrially relevant gas streams at realistic temperatures, and be compatible with large gas volumes. While the separation of CO<sub>2</sub> from process streams is readily accomplished via standard separation techniques such as solvent scrubbing and pressure-swing adsorption, the effectiveness of these current technologies for separating CO<sub>2</sub> is limited. These techniques require low temperatures and produce a low-pressure CO<sub>2</sub> stream, resulting in a significant energy penalty for separating CO<sub>2</sub>. In contrast, polymer-based membrane separations are less energy intensive, requiring no phase change in the process, and typically provide low-maintenance operations. Polymer membranes have been used successfully in a number of industrial applications, including the production of high-purity nitrogen, gas dehydration, removal of acid gases, and recovery of hydrogen from process streams for recycle. However, successful use of a polymer membrane in a syngas separation requires a membrane that is thermally, chemically, and mechanically stable at high temperature and high pressure in the presence of the chemically challenging syngas components. Unfortunately, the commercially available polymeric materials currently employed in separation applications are not stable in these demanding environments to the degree required. Current membrane materials are often subject to chemical degradation by minor components in the process stream, a problem that is exacerbated by elevated temperature. Additionally, as the glass transition temperature of the polymer is approached, membrane selectivity is significantly reduced and flux declines due to membrane compaction. Consequently, there is a compelling need for membrane materials and subsequent capture systems based on those materials that can operate under more extreme environmental conditions for extended periods of time while providing a level of performance that is economically sustainable by the end user.

Alternatives to polymer membranes are the inorganic membranes, which include zeolites, carbon molecular sieves, and selective surface-flow membranes. These membranes currently suffer from lack of reproducibility, densification due to humidity and elevated temperatures, and high-cost fabrication. Given these limitations, mixed matrix membranes and cross-linked membranes have been suggested as viable development pathways of the future. Mixed matrix membranes are composed of a filler material, often inorganic, e.g., carbon molecular sieves or zeolites, embedded in a polymer matrix. Although permeabilities and selectivities have been increased above the traditional upper bound for polymers, application temperatures are still limited by the polymer matrix. Alternatively, cross-linked membranes can reduce the plasticization effects at elevated pressures as well as increase membrane selectivity; however, permeability is often adversely affected. Hence, the development of high-performance polymer membranes and matrix materials remains a very attractive and viable engineering approach to filling the critical need for high-temperature membrane separations.

Development and demonstration of high  $T_g$  materials to address the aforementioned limitations of the current state of the art and the corresponding separations needs of industry including the utility sector has been the focus of much work at LANL. Benzimidazole-based polymer chemistries have been identified, by our team, as exceptional candidates for the capture of CO<sub>2</sub> and purification of hydrogen from these coal derived synthesis gas streams. These materials possess excellent chemical resistance, very high glass transition temperatures (ca. 450 °C), good mechanical properties, and an appropriate level of processability. Much of our initial work, inclusive of project FE-10-002, involving this class of selective barrier materials has focused on understanding the permselectivity character and durability of these materials under industrially relevant conditions. These efforts have led to the realization of polybenzimidazole (PBI)-based membrane chemistries, structures, deployment platforms, and sealing technologies that achieve the aforementioned critical combination of high permselectivity and durability at elevated temperatures (up to 400°C, the highest ever reported viable operating temperature of a polymer based membrane). Our results also indicate that the developed materials not only function at significantly higher temperatures (>400°C) than current commercially available polymeric membranes (<150°C) but also provide improved performance while exhibiting long-term temperature stability, sulfur tolerance, and overall durability over a broad range of industrially relevant operating conditions.

Systems and economic analyses combined with in- and out-of-laboratory testing established the technical viability of these materials and indicated the strong potential for our membrane based capture technology to meet and exceed in step-change fashion the U.S. DOE National Energy Technology Laboratory Strategic Center for Coal – Carbon Capture Program goals of 90% CO<sub>2</sub> capture at less than a 10% increase in the cost of energy services. *However, these analyses also made clear the need to minimize the membrane support costs, maximize membrane flux, and increase the area density realized by the ultimate module design in order to realize the desired step-change in both performance and cost of CO<sub>2</sub> capture associated with the use of this membrane based capture technology.* One promising option for achieving a substantial increase in active membrane area density and mitigate the cost of a inorganic-based support is the use of a hollow fiber membrane platform. A hollow fiber module is the membrane configuration with the highest achievable packing density, i.e., the highest membrane selective area density. Hollow fiber modules have been fabricated to obtain as high as 30,000 m<sup>2</sup>/m<sup>3</sup>. Realization of such a step change in area density with the materials previously developed by this team would lead to **substantial** technoeconomic benefits.

To that end, the primary objectives of the current and out-year work of the follow-on project to FE-10- 002, FE-308-13 are to develop and demonstrate polymer-based membrane structures,

deployment platforms, and sealing technologies that achieve the critical combination of high selectivity, high permeability, chemical stability, and mechanical stability - all at elevated temperatures (>150 °C) - all amenable for packaging in a scalable, economically viable, high area density system for incorporation into an IGCC plant for pre-combustion CO<sub>2</sub> capture. Stability requirements are focused on tolerance to the primary synthesis gas components, impurities, and process pressures and temperatures. Since the process stream compositions and conditions (temperature and pressure) vary throughout the IGCC process, the project is focused on the optimization of a technology that could be positioned upstream or downstream of one or more of the water-gas-shift reactors (WGSRs) or integrated with a WGSR.

Specifically, the project FE-308-13 effort is aimed at translation of the previously developed membrane materials chemistries into a high area density hollow fiber membrane platform via commercially viable hollow fiber membrane manufacturing methods, developing defect-mitigation strategies for optimizing membrane performance and durability, and demonstrating the produced membranes in simulated and ultimately real process environments with the overarching goal of technology progression towards commercialization. The end year deliverable of this project includes technology demonstration at the National Carbon Capture Center (NCCC) comprising capture from a coal derived IGCC synthesis gas feed.

As the original developers of this technology (materials & membranes), our project team possesses expertise in all aspects of the materials synthesis, development, and deployment related to this technology and correspondingly, the capability to successfully execute the FE-308-13 project plan with the end goal of developing the materials, methods, and process schemes required to ultimately realize the production, demonstration, and commercialization of this technology.

### Relationship to Program

The ultimate achievement in the area of CO<sub>2</sub> capture is the production of a CO<sub>2</sub>-rich stream at pressure using methods compatible with the overall Program research goals of 90% CO<sub>2</sub> capture at less than a 10% increase in the cost of energy services. The RD&D that our project team is pursuing is aligned directly with these capture goals and utilizes a pre-combustion capture approach focused on the integration of high-temperature polymer-based membranes into an advanced IGCC process. The materials and membranes that have been developed and continue to be optimized as part of this project outperform any polymer-based membrane available commercially or reported in the literature for separations involving hydrogen. This achievement is validated via membrane productivity (separation factor and flux) comparisons. The improved performance of this technology in an application such as IGCC-integrated capture is further substantiated by the accessible operating temperature range (up to 400°C), long-term hydrothermal stability, sulfur tolerance, and overall durability of the composite membrane materials in these challenging pre-combustion environments. Additionally, the modular, low-maintenance, and flexible design of our membrane technology combined with the technology achievements anticipated over the course of the life of this project make it an exceptional candidate for use for pre-combustion capture of CO<sub>2</sub>. **The achievement of the objectives set forth by our highly skilled team will result in a non-incremental improvement in the combined economics and performance achievable by a pre-combustion capture technology and correspondingly the development and demonstration of a new separations tool that soundly addresses the DOE goals for carbon capture.**

Collateral Benefits: The realization of this class of benzimidazole-based materials in a truly gas separation quality, high permeance, hollow fiber platform would lead to opportunities for

potential use of this materials class for other national gas separation needs beyond the utility sector.

### **Primary Project Goal**

This project entails the development and demonstration of an innovative membrane technology for pre-combustion capture of carbon dioxide that operates over a broad range of conditions relevant to the power industry while meeting the U.S. DOE FE / NETL Strategic Center for Coal – Carbon Capture Program goals of 90% CO<sub>2</sub> capture at less than a 10% increase in the cost of energy services.

The primary objectives of the current and out-year work outlined here are to develop and demonstrate polymer-based membrane structures, deployment platforms, and sealing technologies that achieve the critical combination of high selectivity, high permeability, chemical stability, and mechanical stability all at elevated temperatures all packaged in a scalable, economically viable, high area density system amenable to incorporation into an IGCC plant for pre-combustion CO<sub>2</sub> capture. The end year deliverable (and primary project goal) of this project (FE-308-13) includes technology demonstration at the NCCC comprising capture from a coal derived IGCC shifted synthesis gas feedstock and achievement of membrane performance characteristics at the NCCC that mimic those achieved during laboratory demonstrations in simulated syn-gas environments.

### **Objectives**

Previous work by the LANL team has demonstrated that PBI-based chemistries show promise as membrane materials for pre-combustion capture of CO<sub>2</sub>. The primary goals of this project are: to continue to develop and demonstrate PBI-based materials and morphologies as a separation media for hydrogen purification and carbon capture, to demonstrate the performance of those materials in industrially relevant process streams, and to further develop fabrication methodologies and separation schemes to support the technically and economically viable integration of a pre-combustion CO<sub>2</sub> capture system based on these materials into an advanced IGCC plant.

The ultimate achievement in the area of CO<sub>2</sub> capture is the production of a CO<sub>2</sub>-rich stream at pressure using methods compatible with the overall Program research goals of 90% CO<sub>2</sub> capture at less than a 10% increase in the cost of energy services. The RD&D that our project team is pursuing is aligned directly with these capture goals and utilizes a pre-combustion capture approach focused on the integration of high-temperature polymer-based membranes into an advanced IGCC process. The materials and membranes that have been developed and continue to be optimized as part of this project outperform any polymer-based membrane available commercially or reported in the literature for separations involving hydrogen. This achievement is validated via membrane productivity (separation factor and flux) comparisons. The improved performance of this technology in an application such as IGCC-integrated capture is further substantiated by the accessible operating temperature range (up to 400°C), long-term hydrothermal stability, sulfur tolerance, and overall durability of the proposed membrane materials in these challenging pre-combustion environments. To-date these achievements and material/membrane property validations have been largely conducted on flat sheet and tubular platform membranes.

The work being conducted as part of this continuing development and demonstration effort includes the non-trivial advancement of realizing these exceptional materials in a commercially viable, all polymeric, hollow-fiber membrane platform. Hollow fiber membranes provide numerous opportunities for realization of the desired performance and economic enhancements

associated with the use of this membrane based capture technology for pre-combustion capture. Hollow fibers represent a high area density membrane platform, which will reduce the size requirement of the costly, high-temperature-tolerant membrane module housings, will minimize membrane support costs thru their all polymeric design, and will facilitate membrane flux maximization thru processing facilitated selective layer thickness minimization. We will explore the synergies that derive from combining these advantageous hollow fiber characteristics to produce a high-flux, high area density membrane platform that meets or exceeds DOE system performance and economic goals.

Specifically, the effort outlined here is aimed at translation of the previously developed membrane materials chemistries into a high area density hollow fiber membrane platform via commercially viable hollow fiber membrane manufacturing methods, developing and deploying defect-mitigation strategies for optimizing membrane performance and durability, and demonstrating the produced membranes in simulated and ultimately real process environments with the overarching goal of technology progression towards commercialization.

Thus, the work to be conducted under this FWP is focused on materials and membrane design and demonstration and includes the following tasks: •) Hollow Fiber Fabrication; •) Sealing Layer Development & Process Integration; •) Module Fabrication; and •) Demonstration and Validation of Developed Materials and Methods. The end year deliverable of this FWP includes technology demonstration at the National Carbon Capture Center (NCCC) comprising capture from a coal derived IGCC synthesis gas feed.

## APPENDIX F: LIST OF ACRONYMS AND ABBREVIATIONS

Acronym/Abbreviation	Definition
Å	Angstroms
ACS	American Chemical Society
ADA	Advancing Cleaner Energy, Inc.
AEP	American Electric Power Company
AIChE	American Institute of Chemical Engineers
ASU	Air Separations Unit
BASF	Baden Aniline and Soda Factory
BOC	British Oxygen Company
BOLs	Binder Organic Liquids
BPI	Budget Period I
BS	Bachelor of Science
Btu	British thermal unit
Btu/lb	British thermal unit per pound
B&W	The Babcock & Wilcox Company
CA	Carbonic Anhydrase
CACHYSTM	Capture of CO <sub>2</sub> by Hybrid Sorption
CARE	Carbon Absorber Retrofit Equipment
CCS	Carbon Capture and Sequestration
CFD	Computation Fluids Dynamics
CCUS	Carbon Capture, Use and Storage
cm <sup>2</sup>	Squared Centimeters
CO <sub>2</sub>	Carbon Dioxide
CO <sub>2</sub> BOLs	Carbon Dioxide Binder Organic Liquids
COE	Cost of Electricity
cP	Centipoise
CPU	Central Processing Unit
CS	Carbon Sequestration
DOE	Department of Energy
ECM	Electrochemical Membrane
EERC	Energy & Environmental Research Center

EFRC	Energy Frontier Research Center
EHS	Environmental Health and Safety
EOR	Enhanced Oil Recovery
EPC	Engineering, Procurement, and Construction
EPRI	Electric Power Research Institute
FCE	FuelCell Energy, Inc.
FE	Fossil Energy
FGD	Flue Gas Desulfurization
GPU	Graphics Processing Unit
GTI	Gas Technology Institute
GTL	Gas-to-Liquids
H <sub>2</sub>	Hydrogen
HFM	Hollow Fiber Membrane
H <sub>2</sub> S	Hydrogen Sulfide
HAZOP	Hazard and Operability Analysis
HSS	Heat Stable Salts
HTS	High-Throughput Screening
ICCS	Integrated Carbon Capture and Sequestration
ICOE	Increased Cost of Electricity
IEEE	Institute of Electrical and Electronics Engineers
IGCC	Integrated Gasification Combined Cycle
IL	Ionic Liquid
IP	Intellectual Property
IPCC	Intergovernmental Panel on Climate Change
IPO	Independent Professional Organization
ITM	Iron Transport Membrane
KBR	Kellogg Brown & Root
K <sub>2</sub> CO <sub>3</sub>	Potassium Carbonate
kJ/kg	Kilojoules per Kilogram
KNO <sub>3</sub>	Potassium Nitrate
kW	Kilowatts
LANL	Los Alamos National Laboratory
LCOE	Levelized Cost of Electricity



L/G	Liquid-to-Gas Ratio
LNG	Liquefied Natural Gas
LTI	Leonardo Technologies, Inc.
m	Meters
MBA	Master of Business Administration
MBS	Molecular Basket Sorbent
MCFC	Molten Carbonate Fuel Cell
MEA	Monoethanolamine
MOFs	Metal Organic Frameworks
Mole	SI Unit of Amount of Substance
m <sup>2</sup> /g	Meters Squared per Gram
mm	Millimeter
MMM	Mixed Matrix Membrane
m/s	Meters per Second
MS	Master of Science
MTR	Membrane Technology Research, Inc.
MW	Megawatt
MWe	Megawatt Electric
MWth	Megawatt Thermal
MWV	MeadWestvaco
N <sub>2</sub>	Nitrogen
NCCC	National Carbon Capture Center
NETL	National Energy Technology Laboratory
NETL-RUA	NETL Regional University Alliance
NSG	Neumann Systems Group
nm	Nanometers
NO <sub>x</sub>	Nitrogen Oxides
O <sub>2</sub>	Oxygen
OEM	Original Equipment Manufacturer
O&M	Operations and Management
OMB	Office of Management and Budget
ORD	Office of Research and Development
PBI	Polybenzimidazole

PC	Pulverized Coal
PEI	Princeton Environmental Institute
PhD	Doctor of Philosophy
PI	Principal Investigator
PIF	Project Information Form
PIP	Piperzine
PNNL	Pacific Northwest National Laboratory
PP	Parts-Per
ppm	Parts Per Million
ppmv	Parts Per Million by Volume
PSAR	Polarity-swing Assisted Regeneration
PSIA	Pounds per Square Inch Absolute
PSIG	Pound-force per Square Inch Gauge
PSU	The Pennsylvania State University
R&D	Research and Development
RTI	Research Triangle Institute
SCC	Strategic Center for Coal
scfm	Standard Cubic Feet per Minute
SILM	Supported Ionic Liquid Membrane
SNG	Synthetic Natural Gas
SO <sub>2</sub>	Sulfur Dioxide
SO <sub>x</sub>	Sulfur Oxides
SOFC	Solid Oxide Fuel Cells
T <sub>g</sub>	Glass Transition Temperature
TPD	Tons Per Day
TRL	Technology Readiness Level
TSA	Tyramide Signaling Amplification
µm	Micrometers
UND	University of North Dakota
URS	United Research Services
UK	United Kingdom
VLE	Vapor-Liquid-Equilibrium