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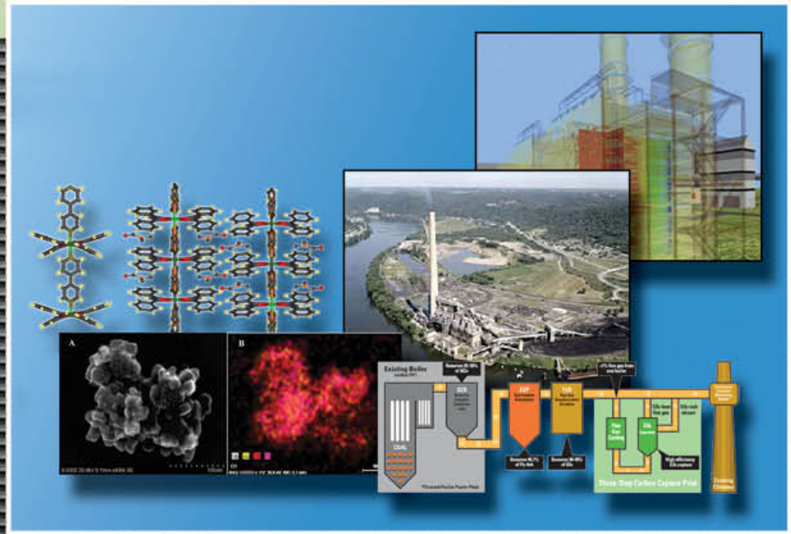
FINAL REPORT

Strategic Center for Coal Carbon Capture

FY 2011 Peer Review Meeting

2011

Peer Review



Meeting Summary and Recommendations

Pittsburgh, Pennsylvania

July 18-21, 2011

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

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FINAL REPORT
STRATEGIC CENTER FOR COAL
Carbon Capture
FY 2011 PEER REVIEW MEETING

Pittsburgh, Pennsylvania
July 18-21, 2011

MEETING SUMMARY AND RECOMMENDATIONS REPORT

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DISCLAIMER

The work performed on this task/subtask was completed under Leonardo Technologies, Inc. (LTI), Prime Contract DE-FE-0004002 (Subtask 300.01.05) for DOE/NETL.

MEETING SUMMARY AND RECOMMENDATIONS REPORT

EXECUTIVE SUMMARY

The mission of the U.S. Department of Energy's (DOE) Office of Clean Coal (OCC) is to ensure the availability of ultra-clean, near-zero emission, abundant, and low-cost domestic energy from coal in order to fuel economic prosperity, strengthen energy security, and enhance environmental quality.[1] OCC's research and development (R&D) effort is administered by the Office of Fossil Energy's (FE) National Energy Technology Laboratory (NETL) through eight technology areas. Two of these areas – the Innovations for Existing Plants (IEP) Program and the Carbon Sequestration (CS) Program – are engaged in carbon capture research, which is the subject of this report.

The IEP Program is focused on the development of low-cost, efficient technology to reduce carbon dioxide (CO_2) emissions from new and existing pulverized coal (PC) power plants. The focus on CO_2 emissions control technology – both post- and oxy-combustion – and related CO_2 compression is in direct response to the priority placed on advancing technology options for addressing greenhouse gas (GHG) emissions.

The IEP Program CO_2 capture goal is to:

> *Develop post- and oxy-combustion CO_2 capture technologies for new and existing coal-fired power plants that achieve 90 percent CO_2 capture at less than a 35 percent increase in cost of electricity and are available for commercial demonstration after 2020.*

The CS Program works to develop effective and economically viable technology options for carbon capture and storage (CCS). To accomplish this, the CS Program focuses on developing technologies to capture, separate, compress, transport, and store CO_2 to reduce GHG emissions from the energy and other industries without adversely affecting the supply of energy or hindering economic growth. Carbon dioxide capture research within the CS Program focuses on pre-combustion capture, which is mainly applicable to integrated gasification combined cycle (IGCC) power plants and refers to removal of the CO_2 from the synthesis gas (syngas) prior to its combustion for power production. The CS Program goal is to identify technologies that result in an increase of less than 10 percent in the cost of electricity for new gasification-based power plants

In compliance with requirements from the Office of Management and Budget (OMB), DOE and NETL are fully committed to improving the quality of research projects in their programs. To aid this effort, DOE and NETL conducted a FY 2011 Carbon Capture Peer Review Meeting with independent technical experts to assess ongoing research projects and, where applicable, to make recommendations for individual project improvement.

In cooperation with Leonardo Technologies, Inc., the American Institute of Chemical Engineers (AIChE) convened a panel of nine leading academic and industry experts on July 18-21, 2011, to conduct a four-day Peer Review of selected carbon capture research projects supported by NETL.

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1. U.S. Department of Energy, Office of Fossil Energy, Office of Clean Coal, Office of Clean Coal Strategic Plan (Washington D.C.: U.S. Department of Energy, September 2006), http://fossil.energy.gov/programs/powersystems/publications/OCC_Strategic_Plan_external_Sept06.pdf.

Funding for Carbon Capture Projects Reviewed

DOE provided $340,301,019 (74 percent) of the funding for these 16 projects, while project partner cost sharing contributed $119,957,948 (26 percent). Total funding of the reviewed projects, over their duration, is $460,258,967.

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

Reference Number	Project No.	Title	Lead Organization	Principal Investigator	Total Funding*		Project Duration*	
					DOE	Cost Share	From	To
01	410.01.16	Advancing Oxy-Combustion Technology for Bituminous Power Plants	NETL, National Energy Technology Lab	Michael Matuszewski	$185,000	$0	2/2/2009	4/29/2011 (sched)
02	NT0005286	Alstom's Chemical Looping Combustion Prototype for CO_2 Capture from Existing Pulverized Coal-Fired Power Plants	ALSTOM Power, Inc	Herbert E. Andrus	$6,895,624	$1,723,906	10/1/2008	9/30/2011
03	NT0000749	National Carbon Capture Center at Power Systems Development Facility	Southern Company Services, Inc	Kerry Bowers	$201,163,318	$50,290,830	10/1/2008	9/30/2013
04	NT0005290	Recovery Act: Oxy-Combustion Technology Development for Industrial-Scale Boiler Applications	ALSTOM Power, Inc	Armand A Levasseur	$15,000,000	$5,512,786	10/1/2008	9/30/2013
05	NT42811	Jupiter Oxy-Combustion and Integrated Pollutant Removal for the Existing Coal-Fired Power Generation Fleet	Jupiter Oxygen Cooperation	Manny Menendez	$6,519,516	$1,639,669	10/1/2006	9/30/2011
06	NT0005015	Clean and Secure Energy from Coal	University of Utah	Phillip Smith	$9,905,726	$2,476,427	10/1/2008	8/31/2013
07	NT43088	Recovery Act: Oxy-Combustion: Oxygen Transport Membrane Development	Praxair, Inc	Sean M. Kelly	$41,188,249	$23,939,957	3/30/2007	9/30/2015
08	NT0005498	Development and Evaluation of a Novel Integrated Vacuum Carbonate Absorption Process	University of Illinois	Yongqi Lu	$691,191	$339,259	10/1/2008	4/30/2012
09	FY11.611.CAP.1610241	Flue Gas Sorbent and Design Development	NETL, National Energy Technology Lab	Henry Pennline	$1,874,000	$0	10/1/2006	9/30/2011
10	NT0005649	Evaluation of Solid Sorbents as a Retrofit Technology for CO_2 Capture from Coal-Fired Plants	ADA-ES, Inc	Sharon M. Sjostrom	$2,291,845	$1,475,000	9/30/2008	7/31/2011
11	FE0000458	CO_2 Capture from Flue Gas Using Solid Molecular Basket Sorbents	Pennsylvania State University	Chunshan Song	$456,992	$114,299	9/1/2009	8/31/2011
12	FE0000493	Recovery Act: Ramgen Supersonic Shock Wave Compression and Engine Technology	Ramgen Power Systems	Pete Baldwin	$50,000,000	$29,737,997	8/1/2009	12/31/2016

Referenc e Number	Project No.	Title	Lead Organization	Principal Investigator	Total Funding*		Project Duration*	
					DOE	Cost Share	From	To
13	FY11.611.CAP.1610241	Sorbent Development for CO_2 Removal for Fuel Gas Applications	NETL, National Energy Technology Lab	Ranjani Siriwardane	$1,100,000	0	10/1/2008	9/30/2011
14	FE0000465	Evaluation of Dry Sorbent Technology for Pre-Combustion CO_2 Capture	URS Group Inc	Carl Richardson	$1,999,934	$684,462	1/1/2010	12/31/2012
15	FE0001124	Novel Polymer Membrane Process for Pre-Combustion CO_2 Capture from Coal-Fired Syngas	Membrane Technology & research, Inc	Tim Merkel	$952,764	$240,061	9/15/2009	9/14/2011
16	FE0000896	CO_2 Capture from IGCC Gas Stream Using the AC-ABC Process	SRI International	Gopala N. Krishnan	$3,421,404	$1,076,603	9/30/2009	9/30/2012
				TOTALS	$340,301,019	$119,957,948		

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

NETL CARBON CAPTURE RESEARCH OVERVIEW

Carbon capture research is a significant activity within NETL's Strategic Center for Coal (SCC). SCC IEP and CS programs support this carbon capture research.

The IEP Program is directed to the development of low-cost, efficient technology to reduce CO_2 emissions from new and existing PC power plants. The focus on CO_2 emissions control technology – both post- and oxy-combustion – and related CO_2 compression is in direct response to the priority placed on advancing technology options for addressing GHG emissions.

The IEP Program CO_2 capture goal is to:

> *Develop post- and oxy-combustion CO_2 capture technologies for new and existing coal-fired power plants that achieve 90 percent CO_2 capture at less than a 35 percent increase in cost of electricity and are available for commercial demonstration after 2020.*

The post- and oxy-combustion CO_2 capture portfolio includes both in-house research and development (R&D) and extramural projects. NETL in-house research develops new breakthrough concepts for CO_2 capture that could lead to dramatic improvements in cost and performance relative to today's technologies. Extramural projects have been funded through funding opportunity announcements (FOAs) in 2006, 2008, and 2010. Post-combustion CO_2 capture research is being conducted in three general areas: solvents, sorbents, and membranes. Oxy-combustion research includes investigations involving flame and burner characteristics, as well as oxygen production and chemical looping.

The CS Program works to develop effective and economically viable technology options for CCS. To accomplish this, the CS Program focuses on developing technologies to capture, separate, compress, transport, and store CO_2 to reduce GHG emissions from the energy and other industries without adversely affecting the supply of energy or hindering economic growth.

The CS Program has the following major goals, of which the first is particularly relevant to carbon capture:

- Develop technologies that can separate, capture, transport, and store CO_2, using either direct or indirect systems that result in a less than 10 percent increase in the cost of energy at pre-combustion power plants by 2015, relative to the 2003 technology baseline
- Develop technologies that will support industries' ability to predict CO_2 storage capacity in geologic formations to within ±30 percent by 2015
- Develop technologies to demonstrate that 99 percent of injected CO_2 remains in the injection zone by 2015
- Complete Best Practice Manuals (BPMs) for site selection, characterization, site operations, and closure practices by 2020

Carbon dioxide capture research within the CS Program focuses on pre-combustion capture, which is mainly applicable to IGCC power plants and refers to removal of the CO_2 from the syngas prior to its combustion for power production. The CS Program goal is to identify technologies that result in an increase of less than 10 percent in the cost of electricity for new gasification-based power plants by 2015. The program would then support projects to test the most promising technologies at pilot scale through 2020. Three technologies areas show significant promise and could be integrated into IGCC systems: physical solvents, solid sorbents, and membranes, which could also be integrated with advanced solvents. Each technology approach has a specific application, advantages over others, and challenges that are the focus of the current and future research.

Overview of the Peer Review Process

NETL requested that 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 that provided an overview of the project's purpose, objectives, and achievements. Each project team also prepared a presentation for delivery at the Peer Review Meeting. The Panel received these Project Information Forms 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

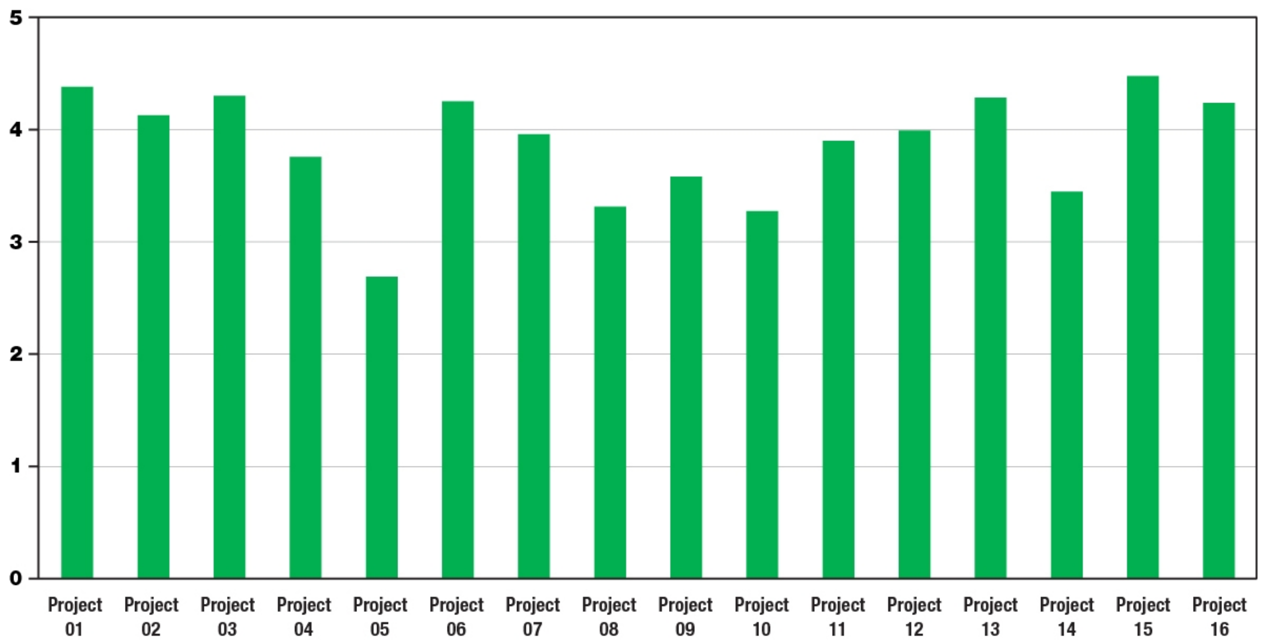
For each of the nine review criteria, the individual reviewer was asked to score the project as:

- Effective (5)
- Moderately Effective (4)
- Adequate (3)
- Ineffective (2)
- Results Not Demonstrated (1)

The Panel occasionally had divergent views of a project. In extreme cases, this divergence resulted in projects receiving ratings ranging from 2 to 5 on particular criteria. Such results should not be taken as an indication that the Panel was indecisive; rather, this reflects the varied backgrounds and differing perspectives of a diverse Panel. Such diversity is a strength, allowing the Panel, as a whole, to review a wide range of projects on varied topics with a comparable overall level of expertise.

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, below, 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

Criterion	Project Average	Highest Project Rating*	Lowest Project Rating
1. Scientific and Technical Merit	4.1	4.7	2.8
2. Existence of Clear, Measurable Milestones	4.1	4.7	3.6
3. Utilization of Government Resources	4.1	4.9	2.6
4. Technical Approach	4.0	4.8	2.7
5. Rate of Progress	4.1	4.7	2.7

6. Potential Technology Risks Considered	3.4	4.2	2.7
7. Performance and Economic Factors	3.4	4.4	2.3
8. Anticipated Benefits, if Successful	3.8	4.9	2.6
9. Technology Development Pathways	3.8	4.4	2.4

* 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.

Each project was categorized based on its stage of development, which ranged from fundamental research to proof-of-concept. Table ES-3 describes these development stages. This categorization provided context for interpreting the level of economic and development data for each project, enabling the Panel to appropriately score the Performance and Economic Factors and Technology Development Path criteria.

TABLE ES-3 DESCRIPTION OF DEVELOPMENT STAGES

Stage of Research	Description
Fundamental Research	The project explores and defines technical concepts or fundamental scientific knowledge. Projects are laboratory-scale and, traditionally but not exclusively, the province of academia.
Applied Research	The project presents a laboratory- or bench-scale proof of the feasibility of potential applications of a fundamental scientific discovery.
Prototype Testing	The project develops and tests a prototype technology or process in the laboratory or field, maintaining predictive modeling or simulation of performance and evaluating scalability.
Proof-of-Concept	The project develops and tests a pilot-scale technology or process for field testing and validation at full scale, but is not indicative of a long-term commercial installation.
Major Demonstration **not applicable in this peer review*	The project develops a commercial-scale demonstration of energy and energy-related environmental technologies, generally with the intent of becoming the initial representation of a long-term commercial installation.

Section IV of this report provides a summary of key project findings as they relate to individual projects. Section V covers process considerations and recommendations for future project reviews.

For More Information

For more information concerning the contents of this report, contact the NETL Federal Project Manager and Peer Review Coordinator, José D. Figueroa, at (412) 386-4966 or Jose.Figueroa@netl.doe.gov.

I. INTRODUCTION

In February 2011, 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) Innovation for Existing Plants (IEP) and Carbon Sequestration (CS) Programs (administered by the National Energy Technology Laboratory [NETL] Strategic Center for Coal [SCC]). On July 18-21, 2011, AIChE convened a panel of nine leading academic, government, and industry experts to conduct a four-day peer review of selected carbon capture research projects of the IEP and CS Programs 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 within the IEP and CS Programs 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 background. 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 four-day peer review of 16 carbon capture projects. AIChE performed this project review work as a subcontractor to prime NETL contractor Leonardo Technologies, Inc. NETL selected the 16 projects, while AIChE organized an independent review panel of 9 leading academic and industry experts. Prior to the meeting, project PIs submitted an 11-page written summary (Project Information Form) of their project's purpose, objectives, and progress. The PI's also submitted their PowerPoint presentations to the Panel prior to the meeting. This project information was given to the Panel prior to the meeting to allow the Panel members to come to the meeting fully prepared with necessary 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 held as closed sessions, limited to the Project Teams, the Panel, AIChE team members, and DOE personnel and contractor support staff. The closed sessions ensured 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

AIChE developed a set of agreed-upon review criteria to be applied to the projects reviewed at this meeting. AIChE provided the Panel and PIs 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. 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 FY2011 CARBON CAPTURE PEER REVIEW

NETL selected key projects within the IEP and CS Programs, 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: 410.01.16
Advancing Oxy-Combustion Technology for Bituminous Power Plants
National Energy Technology Laboratory

02: NT0005286
Alstom's Chemical Looping Combustion Protoype for CO_2 Capture from Existing Pulverized Coal-Fired Power Plants
ALSTOM Power, Inc

03 : NT0000749
National Carbon Capture Center at Power Systems Development Facility
Southern Company Services, Inc

04: NT0005290
Recovery Act: Oxy-Combustion Technology Development for Industrial-Scale Boiler Applications
ALSTOM Power, Inc

05 : NT42811
Jupiter Oxy-Combustion and Integrated Pollutant Removal for the Existing Coal-Fired Power Generation Fleet
Jupiter Oxygen Corporation

06: NT0005015
Clean and Secure Energy from Coal
University of Utah

07 : NT43088
Recovery Act: Oxy-Combustion: Oxygen Transport Membrane Development
Praxair, Inc.

08 : NT0005498
Development and Evaluation of a Novel Integrated Vacuum Carbonate Absorbtion Process
University of Illinois

09 : FY11.611.CAP.1610241
Flue Gas Sorbent and Design Development
National Energy Technology Laboratory

10 : NT0005649
Evaluation of Solid Sobents as a Retrofit Technology for CO_2 Capture from Coal-Fired Plants
ADA-ES, Inc

11 : FE0000458
CO_2 Capture from Flue Gas Using Solid Molecular Basket Sorbents
Pennsylvania State University

12 : FE0000493
Recovery Act: Design and Testing of CO_2 Compression Using Supersonic Shock Wave Technology
Ramgen Power Systems

13 : FY11.611.CAP.1610241
Sorbent Development for CO_2 Removal for Fuel Gas Applications
National Energy Technology Laboratory

14 : FE0000465
Evaluation of Dry Sorbent Technology for Pre-Combustion CO_2 Capture
URS Group, Inc

15: FE0001124
Novel Polymer Membrane Process for Pre-Combustion CO_2 Capture from Coal-Fired Syngas
Membrane Technology & Research, Inc

16 :FE0000896
CO_2 Capture from IGCC Gas Stream Using the AC-ABC Process
SRI International

III. AN OVERVIEW OF THE EVALUATION SCORES

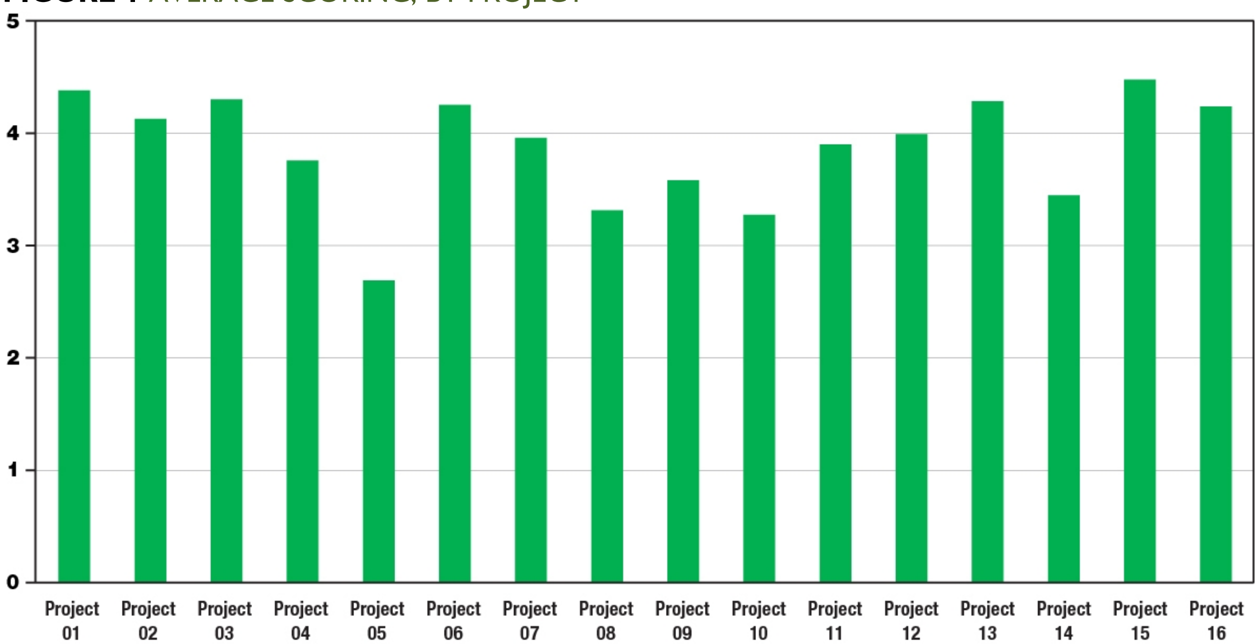
For each of the nine review criteria, individual reviewers were asked to score the project as one of the following:

- Effective (5)
- Moderately Effective (4)
- Adequate (3)
- Ineffective (2)
- Results Not Demonstrated (1)

The average scores for all the projects and across each rating criterion indicate that, overall, the carbon capture research being pursued by the IEP and CS Programs is more than adequate, but also has opportunities for improvement. The Programs consist 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. Figure 1 illustrates the scores for an individual project and provides 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 3.0 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 3.0. Only one of the 16 projects fit within this category.

FIGURE 1 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 3.4 and 4.1, 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 several 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 several 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, Utilization of Government Resources, and Rate of Progress – earned average scores across all projects of 4.1, 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 1 AVERAGE SCORING, BY REVIEW CRITERION

Criterion	Project Average	Highest Project Rating*	Lowest Project Rating
1. Scientific and Technical Merit	4.1	4.7	2.8
2. Existence of Clear, Measurable Milestones	4.1	4.7	3.6
3. Utilization of Government Resources	4.1	4.9	2.6
4. Technical Approach	4.0	4.8	2.7
5. Rate of Progress	4.1	4.7	2.7
6. Potential Technology Risks Considered	3.4	4.2	2.7
7. Performance and Economic Factors	3.4	4.4	2.3
8. Anticipated Benefits, if Successful	3.8	4.9	2.6
9. Technology Development Pathways	3.8	4.4	2.4

* 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

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-quality 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 industrial 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
- Rate of Progress

These rankings reflect the Panel's perception that, overall, NETL's carbon capture R&D effort is addressing the 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 the project management and leadership of the projects. 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 considered most projects cost-effective, to be achieving promising results, and producing valuable tools at reasonable expense.

The highest-rated projects were Project 15, "Novel Polymer Membrane Process for Pre-Combustion CO_2 Capture from Coal-Fired Syngas," conducted by Membrane Technology & Research (MTR), Inc; and Project 1, "Advancing Oxy-Combustion Technology for Bituminous Power Plants," conducted by NETL's Office of Program Planning and Analysis (OPPA). These projects received outstanding average ratings across the nine criteria of 4.5 and 4.4 out of 5.0 respectively. The Panel cited the PIs and project teams and their sound technical approaches as strengths of these projects. Both projects were also judged very effective uses of government resources. The MTR team was commended for effectively integrating process design and material development to take a new polymer, translate it into composite membranes, and fabricate modules in a relatively short time. The OPPA project was praised for identifying clear and credible priorities in R&D areas to help determine future carbon capture technology development.

Five additional projects received scores that averaged of 4.1 or higher: Project 3, "National Carbon Capture Center at Power Systems Development Facility," conducted by Southern Company Services, Inc; Project 13, "Sorbent Development for CO_2 Removal for Fuel Gas Applications," conducted by the NETL's Office of Research and Development (ORD); Project 6, "Clean and Secure Energy from Coal," conducted by the University of Utah; Project 2, "Alstom's Chemical Looping Combustion Protoype for CO_2 Capture from Existing Pulverized Coal-Fired Power Plants," conducted by ALSTOM Power, Inc; and Project 16, "CO_2 Capture from IGCC Gas Stream Using the AC-ABC Process," conducted by SRI International. These projects cover a wide range of developmental scales, but all were 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 (both at 3.4). According to the rating definitions, these scores indicate, on average, that the programs are more than Adequate in these areas. However, just as several projects performed well under these criteria, these low average scores also indicate that a few projects underperformed relative to the standards identified by the evaluation criterion for their development stages as noted in Appendix D. Specifically, the Panel found that some project teams did not adequately address the impact of technical and market risks on the economic viability of their technology. In addition, there was concern that economic analyses conducted as part of some projects lacked consistent bases and did not appropriately detail the contribution of the technology to meeting DOE's cost and performance goals.

Another issue cited by the Panel was the lack of uncertainty analyses. While uncertainties were often acknowledged, some of the analyses of cost and performance did not adequately factor them into their assessments. Failing to sufficiently assess uncertainties could lead to unrealistic expectations about the ability of a few technologies to perform at the necessary level.

The Panel also noted that some of the projects did not adequately address the impact of flue gas or syngas contaminants on process performance. Trace contaminants 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 efforts to move to actual gases needs to be accelerated.

For a few projects, another area of concern cited by the Panel was inattention to CO_2 purity requirements. The purity of the CO_2 exit stream can influence the choice of materials of construction for pipelines and the ability of the captured CO_2 to be used for enhanced oil recovery (EOR). Failing to consider CO_2 stream purity requirements can result in overly optimistic estimates of the cost of capture, because cleanup of that stream will add to the total cost of the process. Similarly, if cleanup of other output streams (solid, liquid, or gaseous) is required in order to meet environmental regulations, this cost must also be factored into estimates of capture cost.

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 measurable technical and economic performance metrics. Milestones lacking such metrics and rigor can result in prematurely advancing technologies to larger scales than is advisable in light of actual performance. The issue of more meaningful milestones contributed to the Panel's conclusion that a few projects gave insufficient consideration to the full economic and technical implications of the chosen research approach.

Issues for Future Consideration

While many of the recommendations provided by the Panel were technical in nature and specific to the particular project's technology, several overarching issues emerged. The first involves technical-economic analyses. All of these analyses need to be conducted using consistent bases and with consideration of DOE cost and performance goals. Performing economic analyses on inconsistent bases makes realistic, “apples-to-apples” comparison of different technologies impossible. It undercuts the ability to reach informed decisions regarding program direction. The Panel suggested that NETL’s OPPA conduct performance and cost analyses of all carbon capture projects to ensure that consistent methods and bases are used. In addition, the economic analyses conducted should quantify the potential impact of technology risks. For example, if the technology being evaluated is dependent on some other enabling technology, the economic impact of the failure of that enabling technology needs to be evaluated and reported.

The Panel also suggested that more consideration be given to materials of construction and the durability of CO_2 removal media. For example, extreme temperature, pressure, and flow conditions, as well as the presence of corrosive chemicals, may necessitate the use of expensive materials of construction. If costs associated with these materials are not included in process cost and performance analyses, the ability of the technologies to meet DOE goals is compromised. Similarly, if process conditions lead to the degradation of CO_2 removal media over time, those media will require replacement. If estimated replacement costs are not realistic, the advantage of a particular technology can be overstated. Therefore, testing that incorporates analyses of erosion, corrosion, attrition, and all forms of degradation needs to be initiated for all projects that are not currently conducting them.

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

The Panel recommended that some projects needed better assessment of technology risks. For a few projects, technology risks listed were not complete, failing to accurately reflect potential pitfalls and their impact on process performance and cost. These project teams need to demonstrate a clearer understanding of what the technology risks are and develop strategies to better mitigate those risks.

Additionally, given that the Panel found that a few projects’ milestone lists were weak and consisted of tasks, it recommended that, as appropriate, project milestones be restated to better reflect 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

The Panel and NETL managers involved 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 recommended for consideration when planning future peer review meetings.

General Process Comments

Panelists unanimously agreed that the current peer review process requires little or no modification to remain effective. There was high praise both for the facilitation of the meeting and the work of the support staff. Panel members found the computerized score tabulation beneficial because it permitted quick display of a project's preliminary average score and allowed the Panel to record strengths, weaknesses, recommendations, and action items for individual projects in a timely manner. More time to write would have helped clarify comments, however.

The Panel members greatly appreciated having adequate time prior to the Peer Review Meeting to read through the project information documents, and noted the efficiency of the SharePoint site from which they could access and download all of the project documents. They were impressed by the openness and scope of the information provided, although there was more information than they could fully absorb.

The Panel also expressed appreciation for the Peer Review facilities. The room had sufficient space on the table, allowing easy access to notes, computers, etc.

The Panel noted that the Peer Review process provides a significant tool for determining which technologies are robust. The process was well organized and the level of scrutiny impressive. Panelists said that they hoped that other government programs receive the same time and effort that NETL has provided for serious and thorough evaluation of its projects. NETL's dedication to improving its programs was evident; one Panelist said he had not experienced this before with other organizations.

Meeting Agenda

The Panel indicated that the meeting agenda was well structured and provided adequate time for presentations, questioning, and subsequent Panel discussion. The Panel also indicated that NETL's Peer Reviews should start with NETL's systems projects, which can help set the stage for the other projects reviewed during the week. In general, the Panel was pleased with the time given to each aspect of the Peer Review. However, it noted that allotting additional time for the presentation and question and answer session for more complex projects would be appropriate in subsequent peer reviews. The Panel also suggested that the number of projects per day should be balanced to enable the daily evaluations to end by 6 p.m., allowing sufficient time for Panel members to revisit the day's evaluations, complete their review notes, and also prepare for the next day's projects.

The diverse areas of Panel members' expertise offered other members needed insight on various topics during discussion, providing more accurate and comprehensive ratings and comments. Panel members noted that the collective expertise assembled was remarkable and impressive. Having a facilitator with domain expertise, who understood the technical material and discussions, added value and streamlined the Peer Review meeting.

Presentations

The Panel recognized that the project presentations and the review process were enhanced by the NETL presentation template and NETL's efforts to familiarize the PIs with the peer review process. However, the Panel did have some suggestions for improvement.

The number of slides used for several presentations was deemed excessive. NETL should establish a limit for the maximum number of slides presented, with backup slides available if more detail is needed. For example, a 35-slide limit may be appropriate for a 45-minute presentation. (They considered it impossible to properly present 70 slides in the 45 minutes.) Presenters tended to rush through the last 10 to 20 slides, which resulted in longer Q&A sessions. Specifically, the Panel recommended that NETL inform the PIs that project management and administrative items (e.g. budget/cost progress, Gantt charts, and earned value analysis) should be omitted or placed at the end of the presentations. This information can be gleaned from the project information forms that the Panel reviews in advance of the presentations.

Evaluation Process

While the Panel noted that their introduction to the review process was quick and effective, there was some ambiguity on the context through which the Panel should evaluate certain criteria. The Panel had several discussions during the meeting to gain consensus on criteria interpretation. The ability to view preliminary project ratings during the Panel discussion session helped identify and mitigate differences in criteria interpretation among individual Panel members.

Specifically, the Use of Government Resources criterion was repeatedly raised as an issue. Sometimes Panelists found it difficult to assess this criterion with the information provided by the PIs. The Panel felt that coaching the PIs on what is expected for this criterion would be useful.

Review Panel

Each Panelist expressed great appreciation for being selected to serve on this Peer Review Panel, viewing it as a real privilege and honor. The Panel also appreciated the diversity of expertise that individual members brought, which enabled more comprehensive discussion and analysis. The Panel valued this Peer Review as a learning experience, and a unique opportunity to learn from other expert colleagues.

APPENDICES

APPENDIX A: AICHE PEER REVIEW METHODOLOGY

Founded in 1908, the American Institute of Chemical Engineers (AIChE) has 40,000 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 solve our energy problems. 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:

- Oxy-combustion technology
- Advanced flue gas treatment
- Coal-based power plants
- Molecular simulation
- Shock wave technology
- Compression technology
- Post-combustion capture technology
- Pre-combustion capture technology
- Solvents
- Sorbents
- Membranes
- Utility industry
- Integrated gasification combined cycle (IGCC)
- Gasification test bed
- Coal characterization and testing
- Computational fluid dynamics
- Integrated systems analysis
- Commercialization
- Risk assessment and management
- Pilot plant scale-up
- Demonstration plants
- Economic analysis
- Solids handling and transport
- Environmental regulations

Upon determining these scientific and technical areas of expertise and the skill sets required to assess the projects to be reviewed, AIChE combed the résumés of those who served on prior review panels for NETL (acknowledging the benefit of their previous experience in this form of Peer Review Meeting); a number of new submissions from NETL; 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 a nine-member review Panel and agreed that the Panel members had the experience necessary to review the broad range of projects and did not present any conflicts of interest. Panel members and qualifications are described in Appendix C.

AIChE selected a meeting facilitator with expertise in the subject areas. Based on previous assessments, employing a facilitator with knowledge in the subject area 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 an 11-page Project Information Form that detailed project objectives, purpose, and accomplishments to date. These Project Information Forms were collected and provided to the Panel well in advance of the meeting to help the Panelists prepare for the review. AIChE also gave the project teams a standard PowerPoint presentation template and set of instructions for the oral presentations they were to prepare for the Panel. 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 several 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:

- Effective (5)
- Moderately Effective (4)
- Adequate (3)
- Ineffective (2)
- Results Not Demonstrated (1).

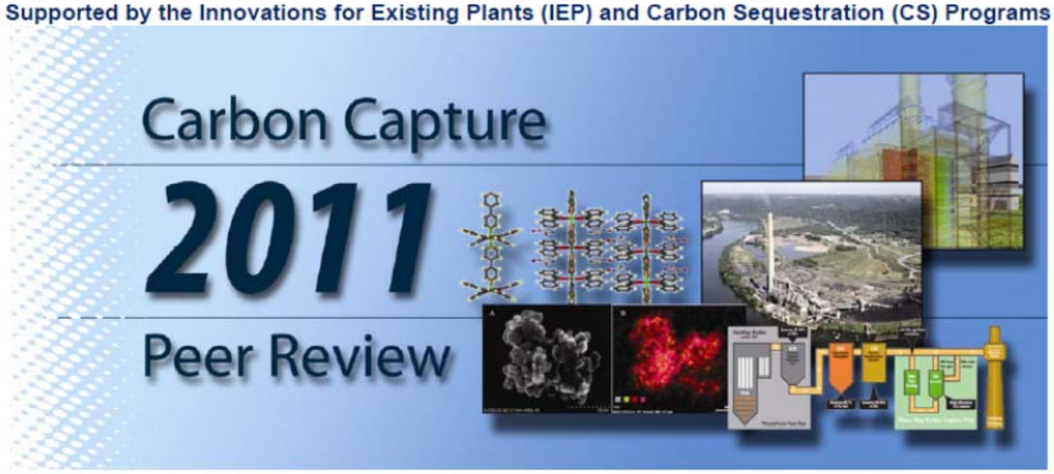
To facilitate the evaluation process, Leonardo Technologies, Inc. (LTI) provided the Panel with laptop computers that were preloaded with Peer Review Criteria Forms for each project. The Panel jointly discussed the project for the purpose of defining project strengths, project weaknesses, recommendations, 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

FY11 Carbon Capture Peer Review

Supported by the Innovations for Existing Plants (IEP) and Carbon Sequestration (CS) Programs



Sheraton Station Square
Pittsburgh, PA
July 18-21, 2011

AGENDA

Monday, July 18, 2011 – Waterfront Room

7:00 – 8:00 a.m. **Registration – Admiral Foyer**

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/Henry Kohlbrand, AIChE
- Role of Panel Chair – Ravi Prasad, AIChE
- Role of NETL – José Figueroa, NETL
- Scoring System Overview – Justin Strock/Nicole Ryan, Leonardo Technologies, Inc. (LTI)

9:30 – 10:15 a.m. **Overview** Open to NETL and AIChE staff only
- IEP Technology Manager – Jared Ciferno, NETL

10:15 – 10:30 a.m. **BREAK**

10:30 – 11:15 a.m. ***01 - Project # 410.01.16*** – Advancing Oxy-Combustion Technology for Bituminous Power Plants – *Michael Matuszewski*, **National Energy Technology Laboratory (NETL)**
11:15 – 11:45 a.m. Q&A
11:45 – 12:25 p.m. Discussion, evaluation, and written comments

12:25 – 1:25 p.m. **Lunch (on your own)**

1:25 – 2:10 p.m. ***02 - Project # NT0005286*** – Alstom's Chemical Looping Combustion Prototype for CO_2 Capture from Existing Pulverized Coal Fired Power Plants – *Herbert E. Andrus Jr.*, **ALSTOM Power, Inc.**
2:10 – 2:40 p.m. Q&A
2:40 – 3:20 p.m. Discussion, evaluation, and written comments

Monday, July 18, 2011 – Waterfront Room

3:20 – 3:35 p.m.	**BREAK**
3:35 – 4:20 p.m.	***03 - Project # NT0000749*** – National Carbon Capture Center at Power Systems Development Facility – *Kerry Bowers*, **Southern Company Services, Inc.**
4:20 – 4:50 p.m.	Q&A
4:50 – 5:30 p.m.	Discussion, evaluation, and written comments

Tuesday, July 19, 2011 – Waterfront Room

7:00 – 8:00 a.m.	**Registration – Admiral Foyer**
8:00 – 8:45 a.m.	***04 - Project # NT0005290*** – Recovery Act: Oxy-Combustion Technology Development for Industrial-Scale Boiler Applications – *Armand A. Levasseur*, **ALSTOM Power, Inc.**
8:45 – 9:15 a.m.	Q&A
9:15 – 9:55 a.m.	Discussion, evaluation, and written comments
9:55 – 10:10 a.m.	**BREAK**
10:10 – 10:55 a.m.	***05 - Project # NT42811*** – Jupiter Oxy-Combustion and Integrated Pollutant Removal for the Existing Coal Fired Power Generation Fleet – *Manny Menendez*, **Jupiter Oxygen Corporation**
10:55 – 11:25 a.m.	Q&A
11:25 – 12:05 p.m.	Discussion, evaluation, and written comments
12:05 – 1:05 p.m.	**Lunch (on your own)**
1:05 – 1:50 p.m.	***06 - Project # NT0005015*** – Clean and Secure Energy from Coal – *Adel Sarofim and Jost Wendt*, **University of Utah**
1:50 – 2:20 p.m.	Q&A
2:20 – 3:00 p.m.	Discussion, evaluation, and written comments
3:00 – 3:15 p.m.	**BREAK**
3:15 – 4:00 p.m.	***07 - Project # NT43088*** – Recovery Act: Oxy-Combustion: Oxygen Transport Membrane Development – *Sean M. Kelly*, **Praxair, Inc.**
4:00 – 4:30 p.m.	Q&A
4:30 – 5:10 p.m.	Discussion, evaluation, and written comments

Wednesday, July 20, 2011 – Waterfront Room

7:00 – 8:00 a.m.	**Registration – Admiral Foyer**
8:00 – 8:45 a.m.	***08 - Project # NT0005498*** – Development and Evaluation of a Novel Integrated Vacuum Carbonate Absorption Process – *Yongqi Lu*, **University of Illinois**
8:45 – 9:15 a.m.	Q&A
9:15 – 9:55 a.m.	Discussion, evaluation, and written comments

Wednesday, July 20, 2011 – Waterfront Room

9:55 – 10:10 a.m.	**BREAK**
10:10 – 10:55 a.m.	***09 - Project # FY11.611.CAP.1610241*** – Flue Gas Sorbent and Design Development – *Henry Pennline,* **National Energy Technology Laboratory (NETL)**
10:55 – 11:25 a.m.	Q&A
11:25 – 12:05 p.m.	Discussion, evaluation, and written comments
12:05 – 1:05 p.m.	**Lunch (on your own)**
1:05 – 1:50 p.m.	***10 - Project # NT0005649*** – Evaluation of Solid Sorbents as a Retrofit Technology for CO_2 Capture from Coal Fired Plants – *Sharon M. Sjostrom,* **ADA-ES, Inc.**
1:50 – 2:20 p.m.	Q&A
2:20 – 3:00 p.m.	Discussion, evaluation, and written comments
3:00 – 3:15 p.m.	**BREAK**
3:15 – 4:00 p.m.	***11 - Project # FE0000458*** – CO_2 Capture from Flue Gas Using Solid Molecular Basket Sorbents – *Chunshan Song,* **Pennsylvania State University**
4:00 – 4:30 p.m.	Q&A
4:30 – 5:10 p.m.	Discussion, evaluation, and written comments
5:10 – 5:25 p.m.	**BREAK**
5:25 – 6:10 p.m.	***12 - Project # FE0000493*** – Recovery Act: Ramgen Supersonic Shock Wave Compression and Engine Technology – *Joseph Williams,* **Ramgen Power Systems**
6:10 – 6:40 p.m.	Q&A
6:40 – 7:20 p.m.	Discussion, evaluation, and written comments

Thursday, July 21, 2011 – Waterfront Room

7:00 – 8:00 a.m.	**Registration – Admiral Foyer**
8:00 – 8:45 a.m.	***13 - Project # FY11.611.CAP.1610241*** – Sorbent Development for CO_2 Removal for Fuel Gas Applications – *Ranjani Siriwardane and James C. Fisher II,* **National Energy Technology Laboratory (NETL)**
8:45 – 9:15 a.m.	Q&A
9:15 – 9:55 a.m.	Discussion, evaluation, and written comments
9:55 – 10:10 a.m.	**BREAK**
10:10 – 10:55 a.m.	***14 - Project # FE0000465*** – Evaluation of Dry Sorbent Technology for Pre-Combustion CO_2 Capture – *Carl Richardson,* **URS Group Inc.**
10:55 – 11:25 a.m.	Q&A
11:25 – 12:05 p.m.	Discussion, evaluation, and written comments
12:05 – 1:05 p.m.	**Lunch (on your own)**

Thursday, July 21, 2011 – Waterfront Room

1:05 – 1:50 p.m.	***15 - Project # FE0001124*** – Novel Polymer Membrane Process for Pre-Combustion CO_2 Capture from Coal-Fired Syngas – *Tim Merkel*, **Membrane Technology & Research, Inc.**
1:50 – 2:20 p.m.	Q&A
2:20 – 3:00 p.m.	Discussion, evaluation, and written comments
3:00 – 3:15 p.m.	**BREAK**
3:15 – 4:00 p.m.	***16 - Project # FE0000896*** – CO_2 Capture from IGCC Gas Streams Using the AC-ABC Process – *Gopala N. Krishnan*, **SRI International**
4:00 – 4:30 p.m.	Q&A
4:30 – 5:10 p.m.	Discussion, evaluation, and written comments
5:10 – 5:25 p.m.	**BREAK**
5:25 – 7:25 p.m.	**Meeting Wrap-up Session**

APPENDIX C: PEER REVIEW PANEL MEMBERS

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:

- Oxy-combustion technology
- Advanced flue gas treatment
- Coal-based power plants
- Molecular simulation
- Shock wave technology
- Compression technology
- Post-combustion capture technology
- Pre-combustion capture technology
- Solvents
- Sorbents
- Membranes
- Utility industry
- Integrated gasification combined cycle
- Gasification test bed
- Coal characterization and testing
- Computational fluid dynamics
- Integrated systems analysis
- Commercialization
- Risk assessment and management
- Pilot plant scale-up
- Demonstration plants
- Economic analysis
- Solids handling and transport
- Environmental regulations

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 recognizes 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 nine members were selected for the FY 2011 Carbon Capture Peer Review (* indicates a prior Panel member):

- Ravi Prasad* – *Panel Chair*
- Mark Golightley
- Chris Higman*
- Daniel Kubek*
- Veronika Rabl
- Jim Sorenson*
- John Tao
- Michael von Spakovsky*
- Ron Wolk*

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 supporting 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 the merit of their work and not on a comparative basis
- Computerized evaluation criteria tool on a laptop network
- Discussion of 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 four 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 2011 Carbon Capture Peer Review Panel Members

Ravi Prasad, Chair

Ravi Prasad of Helios-NRG, LLC, and formerly a corporate fellow of Praxair, Inc., has 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.

Dr. Prasad also 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.

Dr. 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 of Chairman's & 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 papers at more than 20 conferences and delivered invited lectures.

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

R. Mark Golightley

Mark Golightley currently works for FirstEnergy Corp (formerly Ohio Edison). Throughout his career, he has worked in various capacities in production at coal-fired power stations, in corporate engineering, and in environmental departments.

Mr. Golightley's current responsibilities include troubleshooting performance and environmental issues at Sammis plant, including the start-up of baghouses and electrostatic precipitators. He has addressed flue gas desulfurization (FGD) problems of a large magnesium-lime wet scrubber concerning operations and by-product disposal. He developed two patented processes for manufacturing gypsum and alpha plaster from FGD calcium sulfite. He has operated pilot-level testing, developing and demonstrating the patented processes, designing and constructing a 30,000-ton/year alpha plaster plant, and designing and constructing a 500,000-ton/year ex-situ gypsum plant supplying gypsum to a new wallboard plant adjacent the power plant (the second largest recycle project in the United States at that time). He has also supported corporate coal-fired plant environmental control technologies, including studying technologies addressing SO_2, SO_3, Hg, NO_X, and CO_2.

Prior to working for FirstEnergy, Mr. Golightley worked for Kaiser Aluminum. He received bachelor's degrees in education and chemical engineering from the University of Toledo. He is a registered professional engineer in the State of Ohio.

Chris Higman

Chris Higman is currently an independent consultant for gasification and other syngas technologies. He is owner of Higman Consulting, GmbH, and has more than 40 years of experience in the sale, design, development, execution, and management of capital investment projects in the water supply, power, and chemical process industries around the world. His practice puts special emphasis on gas production, treatment, and synthesis processes. Past duties have included process and mechanical design and sales of process plants. His experience has included project management, construction, and start-up management of such projects in different countries. Recent activities (over the last five years) have included consulting to the gasification industry on various aspects of the technology, including acid gas removal and availability issues.

Mr. Higman began working on gasification projects when he commissioned a gas plant in South Africa. Nine years later, he joined Lurgi, where he spent the next 27 years, mostly involved with gasification and related technologies. At Lurgi, he held position of vice president of gas technology, vice president of corporate development, managing director of Lurgi India, and director of systems technology. Mr. Higman's responsibilities in these positions included a large number of ammonia, methanol, hydrogen, GTL, and other plants, mostly based on gasification. They also included all the associated gas treatment facilities, including acid gas removal. His projects covered locations in Germany, Portugal, China, India, and South Africa, among others. Responsibilities as vice president, corporate development, included technical and market due-diligence for an acquisition in the United States.

Mr. Higman co-authored the fundamentals book, *Gasification*. He is also author to various papers on gasification technology and is a contributor to *Ullmann's Encyclopedia of Industrial Chemistry*. He has been a visiting lecturer at the College of Petroleum and Energy Studies in Oxford. He has a number of patents in the field.

He received a BA in mathematics at Oxford and an MS in mechanical engineering at the University of Witwatersrand, Johannesburg. He is a member of AIChE.

Daniel J. Kubek

Daniel Kubek is a consultant specializing in synthesis gas and natural gas purification and separation. His clients include EPRI – CoalFleet, for whom he provides technical guidance on integrated processes for gasification projects, and the Gasification Technologies Council, for which he serves as an advisor on technical issues related to gasification, particularly in the areas of H_2S removal and carbon capture.

Mr. 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 TSA, membrane permeation, and PSA 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, Mr. 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 eight patents and has co-authored 17 technical publications.

Mr. Kubek received a BS degree in chemical engineering from Rutgers University and earned an MS in chemical engineering from Purdue University.

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 United States and abroad.

Until 2001, Dr. Rabl served as director and general manager, retail energy products and services, at 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, Dr. 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.

Dr. 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.

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

James C. Sorensen

James Sorensen is a consultant with a primary focus on clean coal and supporting technologies, including IGCC, oxy-fuel combustion, and coal-to-liquids. 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. In the latter position, he had commercial responsibility for numerous studies involving ASU/gas turbine integration for IGCC. Mr. Sorensen was responsible for the sale of the ASU for the Tampa Electric Polk County IGCC facility, which included the first commercial application of the Air Products cycle for nitrogen integration of the ASU with the gas turbine. He was also involved with gas turbine integration associated with Air Products' ITM Oxygen program. Prior responsibilities included project management of Air Products' baseload LNG projects, commercial management of SNG production, and general management of the Membrane Systems department.

Mr. Sorensen's technical interests include IGCC, oxy-fuel combustion, gas-to-liquids (GTL), and air separation and hydrogen/syngas technology. His programmatic interests include EPRI CoalFleet, Fossil Energy R&D, DOE's Clean Coal Power Initiative, DOE's FutureGen program, and commercial projects. His areas of expertise include project conception and development, consortium development and management, technology and government sales and contracting, R&D program management, technology consulting and training, commercial contract development, and intellectual property.

Mr. Sorensen is the founding chairman of the Gasification Technologies Council, and is vice chairman of both the Council on Alternate Fuels and Energy Futures International. He holds eight U.S. patents, one of which involves ASU/gas turbine integration for IGCC. He is also well published in the area of clean coal.

Mr. Sorensen 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.

John C. Tao

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 advances 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.

Dr. Tao is a Fellow of the AIChE. 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.

Dr. Tao has a BS and Ph.D. in chemical engineering from Carnegie Mellon University, and an MS in chemical engineering from the University of Delaware.

Michael von Spakovsky

Michael von Spakovsky has more than 18 years of teaching and research experience in academia and more than 17 years of industry experience in mechanical engineering, power utility systems, aerospace engineering, and software engineering. In January of 1997, Dr. von Spakovsky joined the mechanical engineering faculty at Virginia Polytechnic Institute and State University as professor and director of the Energy Management Institute (now the Center for Energy Systems Research). He teaches undergraduate and graduate level courses in thermodynamics, kinetic theory, fuel cell systems, and energy system design.

Before teaching at Virginia Poly, Dr. von Spakovsky worked at the National Aeronautics and Space Administration; in the power utility industry, first as an engineer and then as a consultant; and as both an educator and researcher at the Swiss Federal Institute of Technology in Lausanne, where he led a research team in the modeling and systems integration of complex energy systems and taught classes in the thermodynamics of indirect and direct energy conversion systems.

His research interests include computational methods for modeling and optimizing complex energy systems; methodological approaches for the integrated synthesis, design, operation, control, and diagnosis of such systems (stationary power as well as, for example, high performance aircraft systems); theoretical and applied thermodynamics with a focus on the unified quantum theory of mechanics and thermodynamics; and fuel cell applications for both transportation and distributed power generation.

Dr. von Spakovsky has been a contributing author of more than 170 publications, including articles in scholarly journals and conference proceedings, and has given talks, seminars, and short courses (e.g., on fuel cells) worldwide. Included among his professional activities and awards is membership in the American Institute of Aeronautics and Astronautics, Fellow of ASME, member of the Executive Committee for ASME's Advanced Energy Systems Division, elected member of Sigma Xi and Tau Beta Pi, associate editor of the *International Journal of Fuel Cell Science and Technology*, editor-in-chief of the *International Journal of Thermodynamics*, and chairman of the executive committee for the International Center of Applied Thermodynamics.

Dr. von Spakovsky holds a BS in aerospace engineering from Auburn University, and an MS and Ph.D. in mechanical engineering from the Georgia Institute of Technology.

Ronald H. Wolk

Ronald Wolk is a principal at Wolk Integrated Technical Services, which he formed in 1994. His previous positions included director of Advanced Fossil Power Systems at EPRI from 1980-1994, program manager of the Clean Liquid and Solid Fuels program at EPRI (1974-1980), and associate laboratory director at Hydrocarbon Research, Inc. He has extensive experience in assessing, developing, and commercializing advanced electricity generation and fuel conversion technologies, including fuel cell, gas turbine, distributed power generation, central station coal-fired power generation, and IGCC technology systems. His current work includes the evaluation of advanced fuel cells and CO_2 capture systems.

Mr. Wolk has served on the National Research Council's (NRC's) Committee on R&D Opportunities for Advanced Fossil Fuel Energy Complexes and has worked with the NRC on issues related to fuel cells and coal gasification. He has more than 200 published articles, papers, patents, and technical presentations.

Mr. Wolk holds BChE and MSChE degrees from the Polytechnic Institute of Brooklyn (now the Polytechnic Institute of New York University).

APPENDIX D: PEER REVIEW CRITERIA FORM

PEER REVIEW CRITERIA FORM

U. S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY
FY11 CARBON CAPTURE PEER REVIEW

SUPPORTED BY THE INNOVATIONS FOR EXISTING PLANTS (IEP) AND CARBON SEQUESTRATION (CS) PROGRAMS

July 18 – 21, 2011

Project Title:	
Performer:	
Presenter:	
Name of Peer Reviewer:	
Date of Review:	

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 ***"Results Not Demonstrated"*** is selected, **justifying comments must be included**. To assist with determining the criterion adjectival rating, descriptions of those ratings are provided below.

RATING DEFINITIONS	
Effective	**Effective** projects set ambitious goals, achieve results, are well-managed and enhance the likelihood of meeting program goals and objectives.
Moderately Effective	In general, a project rated **Moderately Effective** has set ambitious goals and is well-managed, and is achieving results. Better results could be realized by focusing on key technical issues, more efficient use of resources, and improvements in overall management.
Adequate	**Adequate** describes a project that needs to set more ambitious goals, achieve better results, improve accountability or strengthen its management practices.
Ineffective	**Ineffective** projects are unable to achieve results due to a lack of clarity regarding the project's purpose or goals, poor management, or some other significant weakness (e.g., technical problem).
Results Not Demonstrated	**Results Not Demonstrated** indicates that a project has not been able to develop acceptable performance goals or collect data to determine whether it is performing.

Page 1 of 5

PEER REVIEW RATING CRITERIA

Please evaluate the project against each of the 9 criterion listed below. Definitions for these 9 criteria are provided on page 4. For each criterion, select the appropriate rating by typing an "X" in the applicable cell. Definitions for the five ratings criteria are provided on page 1.

NOTE: If you rate any criterion as "Results Not Demonstrated," a justification for this rating is required. Please include your justification in the box at the end of this table.

CRITERION		RATING CRITERIA				
(Criterion Definitions, refer to Page 4)		(Rating Criteria Definitions, refer to Page 1)				
		Effective	Moderately Effective	Adequate	Ineffective	Results Not Demonstrated*
PROJECT OVERVIEW						
1	**Scientific and Technical Merit**					
2	**Existence of Clear, Measurable Milestones**					
3	**Utilization of Government Resources**					
TECHNICAL DISCUSSION						
4	**Technical Approach**					
5	**Rate of Progress**					
6	**Potential Technology Risks Considered**					
7	**Performance and Economic Factors**					
TECHNOLOGY BENEFITS						
8	**Anticipated Benefits, if Successful**					
9	**Technology Development Pathways**					
*Please explain why the project was rated "Results Not Demonstrated" for a particular criterion.						

Page 2 of 5

COMMENTS

Please provide your comments for each of the areas in the blocks below. 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:

Weaknesses:

Recommendations:

Action Items:

General Comments:

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CRITERION DEFINITIONS

PROJECT OVERVIEW

1: Scientific and Technical Merit

- The underlying project concept is scientifically sound.
- Substantial progress or even a breakthrough is possible.
- A high degree of innovation is evident.

2: Existence of Clear, Measurable Milestones

- At least two measureable milestones per budget period exist.
- Milestones are quantitative and clearly show progression towards project goals.
- Each milestone has a title, planned completion date and a description of the method/process/measure used to verify completion.

3: Utilization of Government Resources

- Research team is adequate to address project goal and objectives.
- Sound rationale presented for teaming or collaborative efforts.
- Equipment, materials, and facilities are adequate to meet goals.

TECHNICAL DISCUSSION

4: Technical Approach

- Technical approach is sound and supports stated project goal and objectives.
- A thorough understanding of potential technical challenges and technical barriers is evident.

5: Rate of Progress

- Progress to date against stated project goal, objectives, milestones, and schedule is reasonable.
- Continued progress against possible technical barriers is likely.
- There is a high likelihood project goal, objectives, and expected outcomes and benefits will be achieved.
- The budget is on track to achieve project goal and objectives.

6: Potential Technology Risks Considered

- Potential risks to the environment or public associated with widespread technology deployment have been considered.
- Project risks are identified and effective measures to address and mitigate these risks, including potential technical uncertainties and barriers, are presented.
- Scientific risks are within reasonable limits.

7: Performance and Economic Factors *

- Appropriate technology cost and performance assessments are conducted consistent with the level of technology development.
- Implementation cost estimates, if warranted, are sensible given uncertainties.
- There is a high likelihood of meeting ultimate DOE cost and performance goals.

TECHNOLOGY BENEFITS

8: Anticipated Benefits, if Successful

- There exist clear statements of potential benefits if research is successful.
- Technologies being developed can benefit other programs.
- Project will make a significant contribution towards meeting near- and long-term program cost and performance goals.

9: Technology Development Pathways *

- Researchers know and can describe a "real world" application and adequately discuss requirements (additional research, potential partners, and resources) for the next level of technology development.
- Market analyses, if appropriate, indicate the technology being developed is likely to be implemented if research is successful.
- Potential barriers to commercialization have been identified and addressed, if appropriate.

* Additional details to be considered for Criterion 7 (Performance and Economic Factors) and 9 (Technology Development Pathways) for specific Technology Development Stages are described on the next page.

TECHNOLOGY DEVELOPMENT STAGES FOR ECONOMIC ANALYSIS & TECHNOLOGY DEVELOPMENT PATH

In past Peer Reviews, Peer Review Panelists have had difficulty scoring the "Economic Analysis" and "Technology Development Path" criterions, because the rating criteria were not specific to the stage of technology development. Research, Development, and Demonstration (RD&D) projects can be categorized based on the level of technology maturity. Listed below are five (5) technology development categories of RD&D projects managed by the National Energy Technology Laboratory. These technology maturation categories are often termed "stages," which provide a basis for establishing a rational and structured approach to decision-making and identifying performance criteria that must be met before proceeding to a subsequent stage of development.

Fundamental Research—Explores and defines technical concepts or fundamental scientific knowledge; laboratory-scale; traditionally but not exclusively the province of academia.

Applied Research—Laboratory- or bench-scale proof of the feasibility of multiple potential applications of a given fundamental scientific discovery.

Prototype Testing—Prototype technology development and testing, either in the laboratory or field; predictive modeling or simulation of performance; evaluation of scalability.

Proof-of-Concept—Pilot-scale development and testing of technology or process; field testing and validation of technology at full-scale, but in a manner that is not designed or intended to represent a long-term commercial installation.

Major Demonstration*—Commercial-scale demonstration of energy and energy-related environmental technologies; generally a first-of-a-kind representation of a long-term commercial installation.

Table 1 describes economic analysis and technology development sub-criteria for each of the five technology development stages. These sub-criteria 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 sub-criteria for a given Technology Development Stage, but should address at least one of them.

Table 1. Economic Analysis and Technology Development Sub-Criteria

Technology Development Stage	Economics Analysis Sub-Criteria	Technology Development Path Sub-Criteria
Fundamental Research	• Material costs available • Potential cost benefits over conventional systems identified	• Scientific feasibility proven • Application(s) considered • Potential technology developers identified
Applied Research	• Component or sub-system costs estimated • First-order cost-benefit analysis available • Material and energy balances calculated	• Conceptual process proposed • Potential applications well defined • Process feasibility established
Prototype Testing	• Conceptual process costs developed • Market analysis completed • Risk assessment completed	• Process test data available • Engineering scale-up data developed • Optimum operating conditions identified
Proof-of-Concept	• Process contingency costs identified • Full-scale process costs, including O&M calculated • Full-scale installation costs developed	• Major technology components thoroughly tested and evaluated • Technology demonstration plans firmly established • Major component optimization studies performed
Major Demonstration*	• Installation costs determined	• Business and commercialization plans developed

* Not relevant to this Peer Review.

Page 5 of 5

APPENDIX E: CARBON CAPTURE PROJECT SUMMARIES

Presentation ID Number	Project Number	Title
01	410.01.16	Advancing Oxy-Combustion Technology for Bituminous Power Plants
02	NT0005286	Alstom's Chemical Looping Combustion Prototype for CO_2 Capture from Existing Pulverized Coal-Fired Power Plants
03	NT0000749	National Carbon Capture Center at Power Systems Development
04	NT0005290	Recovery Act: Oxy-Combustion Technology Development for Industrial-Scale Boiler Applications
05	NT42811	Jupiter Oxy-Combustion and Integrated Pollutant Removal for the Existing Coal-Fired Power Generation Fleet
06	NT0005015	Clean and Secure Energy from Coal
07	NT43088	Recovery Act: Oxy-Combustion: Oxygen Transport Membrane Development
08	NT0005498	Development and Evaluation of a Novel Integrated Vacuum Carbonate Absorption Process
09	FY11.611.CAP.1610241	Flue Gas Sorbent and Design Development
10	NT0005649	Evaluation of Solid Sorbents as a Retrofit Technology for CO_2 Capture from Coal-Fired Plants
11	FE0000458	CO_2 Capture from Flue Gas Using Solid Molecular Basket Sorbents
12	FE0000493	Recovery Act Design and Testing of CO_2 Compression Using Supersonic Shock Wave Technology
13	FY11.611.CAP.1610241	Sorbent Development for CO_2 Removal for Fuel Gas Applications
14	FE0000465	Evaluation of Dry Sorbent Technology for Pre-Combustion CO_2 Capture
15	FE0001124	Novel Polymer Membrane Process for Pre-Combustion CO_2 Capture from Coal-Fired Syngas
16	FE0000896	CO_2 Capture from IGCC Gas Streams Using the AC-ABC Process

01:410.01.16

Project Number	Project Title			
410.01.16	Advancing Oxy-Combustion Technology for Bituminous Coal Power Plants			
Contacts	**Name**	**Organization**	**Email**	
DOE/NETL Project Mgr.	Michael Matuszewski	NETL OPPA	Michael.Matuszewski@NETL.DOE.GOV	
Principal Investigator	Michael Matuszewski	NETL OPPA	Michael.Matuszewski@NETL.DOE.GOV	
Partners	Robert Brasington			
Stage of Development				
__Fundamental R&D	_X_Applied R&D	__Prototype Testing	__Proof of Concept	__Demonstration

Technical Background

DOE has adopted a goal of developing technology capable of capturing and sequestering 90 percent of the CO_2 produced in a pulverized coal (PC)-fired power plant with an increase in the cost of electricity (COE) of no more than 35 percent over that for a non-capture base plant. Oxy-combustion is one of the pathways to implement CO_2 capture on coal-fired power plants. In an oxy-combustion process, a pure or enriched oxygen gas stream is used instead of air as the oxidant for combustion. In this process, almost all of the nitrogen is removed from the air yielding a concentrated stream of oxygen (typically ~95 percent O_2). Oxy-combustion technology generally involves three components: an oxygen production unit, a combustion (fuel conversion) unit, and a CO_2 purification and compression unit.

Compared to traditional air-fired plants, oxy-combustion has many potential advantages. The main benefits of oxy-combustion technology as a CO_2 capture and sequestration solution are:

1. Due to the removal of nitrogen in air, oxy-combustion produces approximately 75 percent or less flue gas than air-fired combustion, and produces exhaust consisting of typically more than 70 vol % CO_2. Due to lower flue gas volumes, plant equipment sizes, and thus the capital cost, have the potential to be significantly reduced.
2. Oxy-combustion produces high purity, near-sequestration-ready CO_2, which requires minimal purification.
3. As a result of the lower nitrogen levels in the oxidant, 60 to 70 percent reduction of NO_X versus air-fired combustion is possible. Some nitrogen is still available from the coal and from air infiltration, however, which may still contribute to NO_X formation.
4. Increased mercury ionization. With oxy-combustion, there is potential for enhancement of Hg removal in the baghouse and FGD unit based on Babcock & Wilcox (B&W) data during Small Boiler Simulator (~5 MMBtu/hr) tests, which showed an increase in the oxidized Hg/elemental Hg ratio during oxy-combustion with bituminous coal. Oxidized Hg is more efficiently captured in the baghouse and FGD unit.
5. Oxy-combustion technology can readily be applied to new and existing coal-fired power plants.
6. Current oxy-combustion technology uses conventional equipment already proven in the power generation industry; however, it has not yet been demonstrated as a fully integrated system at commercial scale.

The above benefits position oxy-combustion as a viable alternative to other CO_2 removal technologies for conventional air-fired boilers. Like other technologies, however, the appeal of oxy-combustion is tempered by some challenges, as described below:

1. Since pure or enriched oxygen is used, oxygen separation is required, which is an energy- and capital-intensive process.
2. Air infiltration into the boiler is an issue, as it dilutes the resulting flue gases. Various options are being investigated to minimize infiltration.
3. Single-pass combustion of coal in pure oxygen would occur at temperatures too high for existing burner designs and would have lower mass flows that would reduce convective heat transfer and create heat transfer problems in existing boiler designs. This issue is mitigated by diluting the oxygen with a cooled flue gas recycle (FGR) stream; however, this results in an increase of the parasitic power load.
4. Because of the oxygen separation, FGR, and CO_2 compression, an oxy-combustion power plant is much less efficient than a traditional air-fired power plant without CO_2 removal.

Recent analyses carried out by ALSTOM Power; Air Liquide; IEA GHG; and NETL's Office of Systems, Analyses, and Planning (OSAP) have shown that even with its disadvantages, oxy-combustion with CO_2 capture is competitive with conventional air-based combustion utilizing amine scrubbing for CO_2 control. To advance oxy-combustion technology, this study identified potential areas for oxy-combustion process improvements that have the potential to significantly decrease CO_2 mitigation costs and to approach the DOE carbon capture goal.

Relationship to Program

This project will support important advances within the oxy-combustion activities of the IEP Program. It provides a defensible pathway for advancing oxy-combustion technology with prudent expenditure of R&D funding. The results of this study suggest that both cost and performance improvements need to be made in multiple technologies applicable to the oxy-combustion pathway for CO_2 capture in order to meet DOE's CO_2 capture goals. Not all of the advanced technologies were found to have a positive cost or performance impact as significant as some others.

The major conclusions of this study uncover how future R&D should focus on developing oxy-combustion-specific technologies for the most beneficial improvements in performance and cost. Based on the results of this study, improvements in the following technologies should have the largest positive impact on oxy-combustion:

- **Oxygen Supply**: Advanced ITM air separation technology shows promise due to its high-temperature and high-pressure operation, which allows for a relatively high amount of heat and power recovery. ITM system integration, membrane performance enhancements, and capital cost reduction should be the main areas of focus based on the results of this study.
- **Sulfur-Tolerant Materials**: Research should be conducted to develop sulfur-tolerant materials to handle the recycled flue gas in systems with reduced FGD. It is understood that completely eliminating the FGD may not be possible in the near-term because of materials constraints; however, if continual progress is made in this area, system efficiency will continue to increase in proportion.
- **Oxy-Combustion Boilers**: As sulfur-tolerant materials are developed, smaller oxy-combustion-based boiler designs with enhanced heat transfer may become more effective. Sulfur-tolerant materials will allow less recycle, less FGD requirements, and

therefore higher efficiencies, all while decreasing the boiler size, and potentially the cost, depending on the premium for exotic material.

- **Advanced Steam Conditions**: While not specific to oxy-combustion, raising steam conditions in the Rankine cycle also has a beneficial effect on oxy-combustion systems, as might be expected. The oxy-combustion cycle appears to impose no direct limitations on the steam conditions that can be applied. However, advanced steam conditions should be taken into consideration when designing advanced oxy-combustion-specific boiler designs.

This study provides a diverse portfolio of oxy-combustion-based technologies that should be included in RD&D plans for government, industrial, and academic entities as a means to drive down costs and improve the performance of CCS.

Primary Project Goal

NETL is funding research aimed at improving the performance and reducing the cost of oxy-combustion in order to meet the challenges of reducing GHG emissions.

DOE/NETL has established program-wide CCS goals for the "Existing Plants, Emissions & Capture" Program. By 2020, advanced technologies will be demonstrated and best practices will be implemented to achieve the following goals:

- 90 percent CO_2 capture.
- 99+ percent storage permanence.
- For post- and oxy-combustion carbon capture, the increase in COE should be less than 35 percent above that of an equivalent plant without carbon capture.

The advanced oxy-combustion technologies studied were evaluated to determine if they could meet the DOE carbon capture goal. The levelized costs of electricity (LCOE) of the advanced technology cases were compared to the LCOE of an air-fired, supercritical boiler with no carbon capture.

Objectives

The objective of this study is to guide oxy-combustion research in areas that can provide the largest benefits in electricity cost and plant performance. The advanced oxy-combustion technologies evaluated in this study are categorized into four major areas: advanced boiler design, advanced oxygen production, advanced flue gas treatment, and innovative CO_2 compression concepts. Improvements in these technology areas were both individually evaluated and evaluated in a cumulative manner to determine if advancing oxy-combustion technology has potential for meeting DOE's carbon capture goals.

02: NT0005286

<table>
<tr><td>Project Number
NT0005286</td><td colspan="4">Project Title
ALSTOM's Chemical Looping Combustion Prototypes for CO_2 Capture from Existing Pulverized Coal-Fired Power Plants</td></tr>
<tr><td>Contacts
DOE/NETL Project Mgr.</td><td>Name
Bruce Lani</td><td>Organization
NETL – Existing Plants Division</td><td colspan="2">Email
Bruce.Lani@netl.doe.gov</td></tr>
<tr><td>Principal Investigator</td><td>Herbert E. Andrus</td><td>ALSTOM Power, Inc</td><td colspan="2">Herberte.andrus@power.alston.com</td></tr>
<tr><td>Partners</td><td colspan="4">PEMM Corp, Dr. Frederic A. Zenz
University of British Columbia, Dr. John R Grace</td></tr>
<tr><td colspan="5">Stage of Development</td></tr>
<tr><td>__Fundamental R&D</td><td>__Applied R&D</td><td>_X_Prototype Testing</td><td>__Proof of Concept</td><td>__Demonstration</td></tr>
</table>

Technical Background

Alstom has more than 100 years of experience in successfully developing and commercializing advanced combustion and gasification processes for the world-wide coal-fired power generation market. More than 40 percent of the world's electric utility boilers are of Alstom design. This background provides a firm basis for Alstom's Chemical Looping process. In particular, three of Alstom's earlier technical developments provide the technical and commercial basis for Alstom's Chemical Looping process:

- Alstom's Air-blown, Entrained-flow, Slagging Coal Gasification process.
- Alstom's Circulating Fluidized Bed (CFB) boiler technology.
- Alstom's Hot Solids Coal Gasification process.

Alstom's Chemical Looping process uses air, carbon-based fuel, limestone, and steam to produce hydrogen and capture CO_2. Heat and product gas produced by the process can be directly used to produce electricity via Rankine cycle, Brayton/Rankin cycle, fuel cell cycles, etc. Alstom's process can also produce hydrogen, syngas (CO/H_2) and transportation fuels (via Fischer-Tropsch, etc.) using any carbon-based fuel (e.g., all types of coal, biomass, petcoke, etc.). More than 95 percent of the carbon in the fuel is captured as a nearly pure CO_2 stream (for use or sequestration).

The chemical looping process uses solids transport principles similar to those used in Alstom's CFB boilers. A schematic of the process is shown in Figure 1; operation is as described for Figure 1; and major reactions are shown in Table 1.

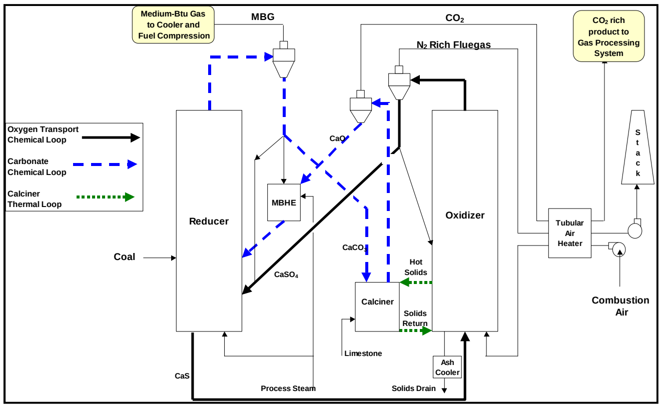

Figure 1: Chemical Looping Gasification with Hydrogen Production and CO_2 Capture

Table 1: Overall Reactions in Chemical Looping Gasification

Reducer	**Oxidizer**
<u>Gasification Reactions</u>	
4C (Coal) + $CaSO_4$ + Heat → 4CO + CaS	CaS + $2O_2$ → $CaSO_4$ + Heat
8H (Coal) + $CaSO_4$ + Heat → CaS + $4H_2O$	
H_2O + C (Coal) + Heat → H_2 + CO	
<u>Water-Gas Shift Reaction</u>	**Calciner**
CO + H_2O → H_2 + CO_2	
<u>Carbonation Reaction</u>	$CaCO_3$ + Heat → CaO + CO_2
CaO + CO_2 → $CaCO_3$ + Heat	

This concept has the following advantages:

- Avoids the large investment costs and parasitic power associated with either cryogenic ASUs or oxygen transport membranes.
- Captures and calcines CO_2 using CaO at temperatures higher than the power cycle temperatures, without additional external energy, thus eliminating the thermodynamic penalty normally associated with CO_2 capture.
- Fast chemical reactions allow for small equipment and low capital cost.
- Conventional material of construction and fabrication techniques.

Because of these factors, Alstom's chemical looping concept provides the lowest cost method of capturing CO_2, from coal-based power, found to-date.
The process has been peer reviewed both internally and externally by Dr Janos Beer, Mr. Eric Reichle, Dr. Fred Zenz, and the DOE/ASME third-party review in 2007.

Alstom's process (Figure 2) consists of the oxidation, reduction, carbonation, and calcination of limestone-based compounds, which chemically react with coal, biomass, or opportunity fuels. Limestone makeup calcines to produce CaO (Calciner); CaO captures the sulfur in the fuel to produce CaS (Reducer), which is burned to produce hot $CaSO_4$ (Oxidizer). Hot $CaSO_4$ gasifies coal (Reducer) and produces CO_2 and H_2O or syngas (carbon monoxide [CO] and H_2) and CaS for reuse. Steam shifts CO to H_2 and CO_2 (Reducer). CaO Captures CO_2 (Reducer) forming $CaCO_3$ and producing hydrogen product gas. $CaCO_3$ is calcined (Calciner) using energy from hot solids from the Oxidizer producing near-pure CO_2 for use or sequestration and CaO for reuse. Coal ash and sulfur (as $CaSO_4$) are purged. Product gas (H_2 or syngas) and steam are used for power, etc.

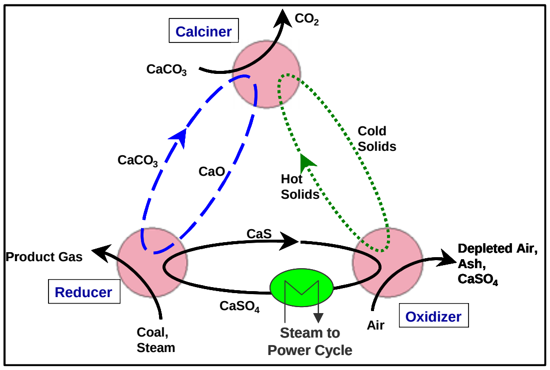

Figure 2: Chemical Looping Gasification with Hydrogen Production and CO_2 Capture

Relationship to Program

This project will support important advances within the pre- and post-combustion carbon capture activities of the CS and IEP Programs. The technology can be employed in several ways, as follows:

- As a combustion-based steam power plant with CO_2 capture.
- As a hybrid combustion-gasification process producing a syngas for gas turbines or fuel cells or other industrial uses.
- As an integrated hybrid combustion-gasification process producing hydrogen for gas turbines, fuel cells, or other hydrogen-based applications, while also producing a separate stream of CO_2 for use or sequestration.
- As a process using any carbon-based fuel such as all coal types, biomass, and opportunity fuels (e.g., petcoke, coal waste, etc.).
- As a means to retrofit existing power plants for CO_2 capture at a low capital cost.

Economic studies have shown that calcium-based chemical looping has the **lowest capital costs and cost of electricity** of any competing advanced power generating technology capable of capturing CO_2. The details of these studies are shown in the references.

Primary Project Goal

The primary project goal is to develop and commercialize a chemical looping combustion process that is well suited for capturing at least 90 percent of the CO_2, at a 20 percent or less increase in the cost of energy services from existing or new PC and CFB power plants.

Objectives

The objectives of the project include the following:

- More than 90 percent CO_2 capture from coal.
- Less than $20/ton, avoided cost of CO_2 capture.
- Capital cost (standalone) – 20 percent lower than Conventional Boiler Island (without CO_2 liquification).
- Capital Cost (Retrofit) – Less than 20 percent increase over conventional plant.
- Beat Steam Power and IGCC performance and economics, world-wide.
- Medium-Btu gas or Hydrogen without an Oxygen Plant.
- To construct and learn how to operate the prototype. This includes initial testing of non-reactive solids transport and 40 hour auto-thermal operation of the Prototype.

- To complete the Prototype design and cost estimate in Budget Period 1.
- To complete the Prototype EPC and perform initial testing, analyze performance data, and develop a technical and cost plan to continue the development program under a separate future project, during Budget Period 2.

03: NT0000749

Project Number	Project Title			
NT0000749	National Carbon Capture Center at Power System Development Facility			
Contacts	**Name**	**Organization**	**Email**	
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Partners	Electric Power Research Institute AEP Luminant NRG Arch Coal Peabody Coal Company Rio Tinto Coal Company			
Stage of Development				
__Fundamental R&D	_X_Applied R&D	_X_Prototype Testing	_X_Proof of Concept	__Demonstration

Technical Background

In cooperation with Southern Company, DOE established the National Carbon Capture Center (NCCC) in 2009 at the Power Systems Development Facility (PSDF) in Wilsonville, Alabama. The center will support national efforts to reduce GHG emissions by collaborating with technology developers in accelerating their CO_2 capture technology development for application to coal-fueled power plants. NCCC offers a flexible test facility which provides commercially representative flue gas and syngas and the necessary infrastructure in which developers' technologies are installed and tested to generate data for performance verification under industrially realistic operating conditions.

PSDF was launched in late 1990, funded by DOE and industrial partners and managed by Southern Company. Since completion of the facility in 1996, it has been a center for national efforts to develop high-efficiency, coal-based power generation technologies that are reliable, environmentally acceptable, and cost-effective. Two significant achievements in this time period were in (1) hot gas filtration to improve energy efficiency, and (2) a gasifier suitable for use with low-rank fuels. These two technologies have progressed to commercialization with IGCC power plants being built at Kemper County, Mississippi, and DongGuan, China. Building on this success, PSDF has now refocused its mission on supporting the development and scale-up of cost-effective, commercially viable carbon capture technologies for coal-fueled power plants through collaboration with DOE and third-party technology developers. Most of the current CO_2 capture technologies are being developed at laboratory- or bench-scale under ideal conditions. Continued R&D under realistic field conditions are needed to validate laboratory results and identify technical issues that are not present under ideal conditions. In collaboration with technology developers, NCCC makes available coal-derived syngas and flue gas to carry out applied R&D on components or small pilot-scale systems to bridge gaps between fundamental R&D and large-scale commercial demonstration and provides for a seamless transition for promising technologies to migrate from laboratory into commercial applications.

NCCC is a unique test facility that consists of two major sets of infrastructure to support CO_2 capture technology development. One is the existing pilot-scale coal gasification facility that produces syngas for pre-combustion CO_2 capture technology evaluation and the other is the newly constructed Post-Combustion Carbon Capture Center (PC4) located at an adjacent PC power plant, Alabama Power's E.C. Gaston. Both are readily adapted to test a variety of technologies at multiple scales, providing data for scale-up to commercial applications. This flexibility in conjunction with real-world operating conditions allows NCCC to support developers in advancing the CO_2 capture technologies that are critical to continued use of coal for power generation.

NCCC is also evaluating the potential benefits of oxy-combustion CO_2 capture approach using the pressurized transport reactor operating in oxygen combustion mode. Preliminary screening studies have been conducted with favorable results. Detailed system studies, modeling, and additional economic analysis will be used to evaluate the commercial feasibility of the technology.

Relationship to Program

This project will support important advances within the carbon capture focus of the CS and IEP Programs. Few test facilities in existence today have the scale, test duration, flexibility, and/or operational expertise to fully test emerging technologies. Lack of such a flexible test facility results in a gap between laboratory works and commercial-scale demonstrations, and therefore hinders technology progression. NCCC addresses these issues by providing a flexible test facility to match individual technology testing requirements (gas quality, temperature, pressure, test duration, etc.) at various scales. Such flexibility cannot be matched by any other facilities in the United States or the world.

Data collected at NCCC will be used to support technology scale-up and possible commercial demonstration. Success in these demonstrations eventually paves the way for commercial deployment for cost-effective CO_2 capture. Such economic benefits will preserve the continuous use of domestic, abundant coal in an environmentally responsible manner. NCCC plays a crucial role in facilitating and accelerating such technology progression and streamlining the commercialization efforts.

NCCC's flexibility in carrying out various scales of testing offers different degrees of benefits to technology development and produces engineering data about technology performance and integration issues at different stages in the R&D process under realistic conditions. Such technical data are needed before one can move technologies from laboratory into commercial deployment. For example:

- A simple exposure test of technology components in real gas conditions for extended test duration allows developers to refine their search for better and more robust materials and chemistry earlier in the developmental cycle (e.g., palladium-based hydrogen membranes from several developers).
- Testing of technology components or integrated systems at small bench scale generates performance data that helps developers to redesign their processes for scale-up assessments (e.g., MTR's polymeric CO_2 membranes).
- Testing scale-up of technology proves technologies' readiness for commercial-scale demonstration (e.g., PSTU solvent evaluation).

NCCC serves as a central test facility for third-party technology developers. This avoids the need for multiple test sites that each technology developer may have to pursue were NCCC not available. Significant benefits are realized from cost and schedule perspectives. Since its establishment in 2008, NCCC, in the pre-combustion CO_2 capture area, has worked with three chemical solvents, two physical solvents, three membrane technologies, three WGS catalysts, one fuel cell technology, and will be working with two CO_2 sorbents, a new membrane, a new WGS catalyst, and a physical solvent in the near future. In addition, three technologies are being scaled up based on the results and findings from their initial demonstration scales and one has successfully deployed into commercial use. These demonstrate NCCC's capability to streamline and facilitate technology testing and advance technologies in an accelerated pace for scale-up and eventually to commercialization. It is anticipated that similar progression will be realized in the post-combustion CO_2 capture area once test results are available.

NCCC provides not only a test facility that makes available realistic syngas and flue gas to multiple technology developers for performance verification, but also an infrastructure sufficiently flexible to interface with various advanced technologies with short turnaround time. Staff members at NCCC are highly trained and experienced in process integration, design, operation, and maintenance areas and offer testing and data analysis expertise to help technology developers validate their test results. Since multiple technology tests are carried out in the same environment, comparison of performance results between different technologies are more direct and effective.

To accelerate the development of the carbon capture technologies from inception to full-scale deployment, DOE has launched the Carbon Capture Simulation Initiative (CCSI). Its goal is to develop advanced modeling and simulation tools based on basic science. However, to validate the model and gain confidence in the simulation, actual field test data will be needed. NCCC will play a key role in providing such needed field test data from testing of multiple technologies. NCCC will collaborate with CCSI to design experiments based on key parameters identified in the simulation and feed the test results back to the model for validation. Initial discussions are underway for a solvent-based and a solid sorbent-based technology.

NCCC's industrial sponsors include utility and coal companies as well as EPRI. These sponsors have direct access to performance and cost information generated through the test program and provide feedback to the technology developers from the end-users' point of view. Such collaboration allows interactions between the technology developers and end users early in the development stage, which will streamline commercial demonstration once it is proven at NCCC.

Primary Project Goal

To support developers in accelerating development and commercialization of cost-effective CO_2 capture technologies by building and operating flexible test facilities for post- and pre-combustion capture from coal-derived flue gas and syngas.

Objectives

A. Modify the existing gasification infrastructure to increase the facility's ability to accommodate testing of a wide range of capture technologies at different syngas flow rates, temperatures, pressures, and composition.

A portion of particulate-free syngas produced in the gasifier is piped to a syngas slipstream test facility (SSTF) to be processed and conditioned for downstream technology testing. With anticipation of more technologies to come and future scale-up tests, SSTF was upgraded with a new syngas header to increase the syngas flow rate available to SSTF. Three fixed-bed pressurized reactors are available to process syngas for testing technologies, such as water-gas shift (WGS) and hydrocarbon cracker catalysts and high-temperature sulfur and mercury sorbents. Depending on the requirements for syngas conditioning by technology developers, a wide range of additional gas processing equipment can be installed in order to meet testing objectives. For example, in recent tests, a syngas cooling system and water knockout tank were installed to deliver syngas at close to 100°F for a polymeric CO_2-selective membrane test. In another test, sulfur will be removed to deliver near-zero sulfur syngas to a metallic hydrogen-selective membrane test that operates at 750°F.

Larger slipstream facilities have been conceptually designed, but will be implemented in the future if justified by demand.

B. <u>Build a new test facility</u>, PC4, at adjacent Alabama Power's Gaston PC power plant to accommodate tests of a wide range of capture technologies from flue gas.

PC4 was designed to provide several parallel paths to test candidate technologies at appropriate scales. A flue gas slipstream is extracted downstream of Plant Gaston's Unit 5 FGD process. A little more than half of the flue gas is used for testing and the remainder helps maintain the flue gas temperature and limit the condensation in the delivery duct. The test facility includes three major test areas: (1) a pilot solvent test unit (PSTU) to test developers' next generation CO_2 absorption solvents; (2) a second test bay to support evaluation of fully integrated test systems supplied by technology developers; and (3) a bench-scale test area to accommodate up to four small test skids of emerging, advanced technologies such as sorbents or membrane systems. The facility has been designed and constructed so that multiple tests can proceed simultaneously.

Design and construction of the PSTU is one major endeavor at the PC4. It is a conventional packed-bed absorption column designed for solvent-based capture technology evaluation. It consists of a pre-scrubber for deep removal of sulfur, a condenser for water removal, an absorber for gas-liquid contacting of solvents with flue gas, a stripper to regenerate the solvent, reboilers, heat exchangers, pumps, gas analyzers, and associated piping, instrumentation. It was designed to be highly flexible to allow rapid modification of absorption and regeneration systems to match the physical and chemical properties of emerging solvents as they are developed and brought to the site by development entities. The unit was designed to achieve a 90 percent overall CO_2 removal efficiency using a 30 percent monoethanolamine (MEA) aqueous solution, which is being used as a reference solvent to obtain baseline performance against which other solvents will be compared.

The PSTU is designed and built to be flexible in testing various advanced solvents such as hindered amines, amino acid salts, and ionic liquids, as well as any additives that enhance CO_2 capture performances such as enzymes. All vessels are spaced to allow for modifications to existing equipment or installation of additional equipment. The absorber and regenerator design allows alternative packing and other gas-liquid contacting arrangements to be readily installed. The regenerator is designed for a maximum of 200 pounds per square inch gauge (psig) to allow solvents to be regenerated at elevated pressure. Appropriate instruments and controllers are provided to control and maintain system process conditions. Data collected are verified through appropriate QA/QC procedures, cross-checks using alternative test and calculation procedures, and achieving good heat and mass balance closures.

PC4 was designed and constructed on an accelerated pace so that evaluation of capture technologies could proceed as quickly as possible. It took about 18 months from the beginning of the design phase to construction completion. Commissioning of the PSTU is currently underway. Planned tests at PC4 for 2011 include chemical solvents, CO_2 membrane, and CO_2

sorbent technologies. Contracts are either in place or in progress with technology developers to carry out the above tests.

C. <u>Support developers in testing advanced CO_2 capture technologies</u> that provide improved efficiency and cost effectiveness over those currently considered commercially available. In addition to individual component testing, components of the CO_2 capture process will be integrated and optimized to provide data needed for scale-up.

For pre-combustion CO_2 capture, a portfolio of emerging technologies is being tested or plans to be tested. Those include chemical and physical solvents, WGS catalysts, various hydrogen and CO_2 membranes and CO_2 sorbents. Scale of these technologies ranges from 1 lb/hr to 80 lb/hr of syngas. Tests have produced valuable information for technology developers to make further improvements on materials and process configurations. Based on the promising test results obtained at NCCC, one technology vendor is planning to scale-up the design from 50 lb/hr to 500 lb/hr syngas capacity. In another test, WGS catalyst test results reveal that steam-to-CO ratio could be reduced, which in turn increases the net power output of an IGCC plant and reduces COE with CO_2 capture. This finding is being implemented at the Mississippi Power's Plant Ratcliffe IGCC plant currently under construction at Kemper County, Mississippi. The results have been supplied to WGS catalyst vendors and are available for use by other IGCC technologies that may be considering adding CO_2 capture to their plants.

For post-combustion CO_2 capture, tests of advanced technologies will commence in 2011. These include two to three chemical solvents to be tested in the PSTU, one solvent skid from a developer, one CO_2 membrane test, and one solid sorbent test in the bench-scale area. The scale of these tests ranges from 1 kW to 0.5 MW equivalent of electric output.

To effectively utilize the NCCC facility and bring the most promising technologies to the market as quickly as possible, a systematic process is necessary to identify the best candidate technologies based on a set of appropriate criteria including cost reduction, technology competency, and organizational strength. Jointly with DOE, NCCC has developed a Technology Screening Process (TSP) which is a key evaluation tool to assess and prioritize technologies for testing. The TSP also ensures that final technology selection will form a balanced portfolio that promotes the advancement of both near- and long-term candidate technologies.

Key elements of the TSP include a comprehensive inventory of candidate technologies, quantitative scoring criteria, and a qualitative best value assessment. The TSP inventory currently has more than 300 technologies related to CO_2 capture in the area of pre-, post-, and oxy-combustion; gas treatment and purification; CO_2 compression; power generation; etc. Four confidential TSP reports on candidate technologies have been completed with two more in progress.

D. <u>Test, develop, and optimize components</u> to enable the deployment of carbon capture with minimal increase in the cost of electricity. These components include gas contaminant clean-up, gas separations, coal/biomass gasification or combustion technologies, fuel cell technology, materials, sensor technology, and others.

Although NCCC's primary focus is on CO_2 capture technologies, other power plant components could influence the design and performance of these technologies. For example, a warm-gas clean-up process coupled with high-temperature CO_2 capture processes (e.g., hydrogen membrane or solid sorbents) may enable a more efficient process configuration that achieves higher overall plant generating efficiency and lower COE. One of the warm-gas cleanup technologies, high-temperature mercury capture sorbents, is currently being tested at NCCC with excellent results. NCCC also supports solid oxide fuel cell testing that evaluates the impact of various contaminants in the coal-derived gas on fuel cell degradation.

Another area of interest is fuel flexibility for coal-fueled power plant; specifically, gasification of coal and biomass co-feed. Current commercial systems are high-cost with low reliability and have never been demonstrated using biomass as a portion of the total feed to an advanced coal-generation system. Ongoing development of high-pressure feed systems will identify ways to decrease capital and operating cost, improve reliability and controllability of feed systems, and address the added challenges of feeding different types of fuel mixes into a pressurized environment.

04: NT0005290

Project Number	Project Title			
NT0005290	Recovery Act: Oxy-Combustion Technology Development for Industrial-Scale Boiler Applications			
Contacts	**Name**	**Organization**	**Email**	
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Partners	Illinois Clean Coal Institute North Dakota Industrial Commission			
Stage of Development				
__Fundamental R&D	__Applied R&D	__Prototype Testing	_x_Proof of Concept	_Demonstration

Technical Background

Oxy-combustion is one of the most promising near-term technologies for CCS from PC-fired boilers for power or industrial applications. The basic concept of oxy-combustion is to replace combustion air with a mixture of oxygen and recycled flue gas, thereby creating a high-CO_2 content flue gas stream that can be more simply processed for sequestration or high-purity product. Oxy-combustion technology builds upon proven commercial technologies and is complementary with conventional boiler and steam power plant technology.

Alstom is a world-leading supplier for the power industry and has more than 100 years of experience in successfully developing and commercializing advanced combustion processes. More than 40 percent of the world's electric utility boilers are of Alstom tangentially-fired (T-fired) design. Alstom has been developing oxy-combustion technology for more than a decade and is aggressively pursuing a roadmap for its commercialization in industrial and utility boiler applications. Alstom's efforts address all major components of an oxy-fired steam plant, including their design and integrated operation.

This project focuses on development and commercialization of oxy-fired tangential boiler systems. The oxy-firing boiler is the heart of an oxy-combustion plant and essential to overall plant performance and economics. T-fired boilers differ from wall-fired boilers in the design and operation of the combustion system, which impacts the design and control of nearly all of the boiler sub-systems. Global boiler aerodynamics and mixing is much more important to the combustion process during T-firing compared to wall-firing where fuel and air/oxygen mixing occurs in or near the burners. Development and optimization of an oxy-fired tangential boiler must address these differences. This project builds upon Alstom's deep experience, existing test facilities and methodologies, and the knowledge gained from other Alstom oxy-combustion developments to develop and design oxy-fired boiler systems for industrial and utility applications.

Relationship to Program

This project will support important advances within the oxy-combustion focus of the IEP Program. Oxy-combustion is a cost-competitive, near-term solution for CO_2 capture that offers a relatively low technical risk due to use of conventional components. It can be used in new and retrofit applications, and has the potential for greater than 90 percent CO_2 capture. It can achieve near-zero emissions of typical coal-firing pollutants and does not create new emission sources. This technology can also provide a CO_2 Capture Ready design option for current new plants that can be implemented in the future.

This project addresses development of an oxy-fired system for tangential boilers, which represent a major share of the boiler existing fleet and future market. T-fired boilers have unique features that will be optimized for oxy-combustion. Results will reduce risk for oxy-fired demonstration and help to accelerate demonstration and commercialization of this technology.

Primary Project Goal

The overall project goal is to develop and test oxy-combustion T-fired boiler technology to provide commercially attractive CO_2 capture solutions and to accelerate commercialization for retrofit of existing boilers and installation of new boilers.

Objectives

Major objectives of this project include:

- Design and develop an innovative oxy-combustion firing system for existing T-fired boilers that minimizes overall capital investment and operating costs.
- Evaluate the performance of oxy-combustion T-fired boilers in pilot-scale tests at Alstom's 15-MWth Boiler Simulation Facility (BSF).
- Determine the boiler design and performance impacts for oxy-combustion.
- Evaluate and improve engineering and computational fluid dynamic (CFD) modeling tools for oxy-combustion.
- Develop the design, performance, and costs for a demonstration-scale oxy-fuel boiler and auxiliary systems.
- Develop the design and costs for both industrial and utility commercial-scale reference oxy-fuel boilers and auxiliary systems, which are optimized for overall plant performance and cost.

The primary objectives of the early phases of this project address the generation of the detailed information and understanding necessary to design and demonstrate commercial-scale oxy-fired boilers at an acceptably low risk. Oxy–combustion impacts nearly all aspects of boiler operation. Key aspects are shown in Figure 1 and are being investigated under this project.

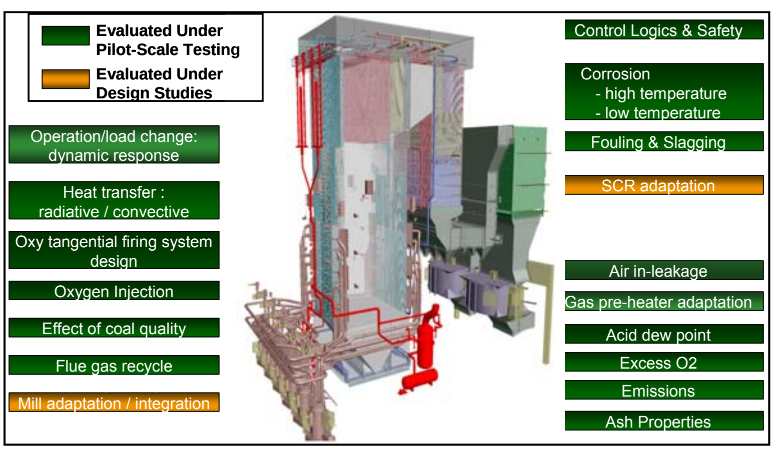

Figure 1: Aspects of Boiler Operation Requiring Assessment

The 15 MWth testing focuses on control of furnace heat release rates and heat transfer for boiler thermal performance during oxy-combustion, while obtaining good fuel burnout and control of emissions. Measurements are conducted to assess ash deposition and fireside corrosion, as well as SO_3 formation and behavior of trace metals such as mercury.

To date, four test campaigns have been successfully completed firing sub-bituminous, low-sulfur bituminous, high-sulfur bituminous, and North Dakota lignite. Pilot test results are very positive, demonstrating that furnace temperatures and heat flux profile during oxy-fired can be controlled, by adjusting gas recycle rates and oxy-firing system parameters, to values comparable with those during air firing. Results also show good combustion performance with low NO_X and CO emissions during oxy-firing. Two additional test campaigns are planned. The objective of Campaign 5 is to assess new design concepts based on current findings that could provide cost and performance benefits for new and future oxy-combustion systems. The objective of Campaign 6 is to establish a link with the comprehensive test program being conducted at the 30 MWth Oxy Pilot Plant at Vattenfall's Schwarze Pumpe station. This link will aid in interpretation of test results from both pilots as well as provide additional information for tool development.

Test measurements from both pilots, including detailed furnace mapping of furnace heat flux, temperature, and gas species, are used to refine and validate CFD models and other boiler design tools that will be used in the design of the demonstration and commercial-scale boilers. Tests and validation results will be used to develop oxy-combustion design guidelines and procedures.

The design guidelines and validated tools will be applied to develop comprehensive design packages including performance, operational control, and costing data for a commercial-scale design for demonstration and to develop design packages for reference commercial utility and industrial designs.

05: NT42811

Project Number	Project Title			
NT42811	Jupiter Oxy-Combustion and Integrated Pollutant Removal for the Existing Coal Fired Power Generation Fleet			
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Partners	SNC Lavalin America, Inc Consortium for Clean Coal Utilization Peabody Energy CoalTeck Evansville University, Professor Stamps EPRI NETL Doosan Babcock			
Stage of Development				
__Fundamental R&D	__Applied R&D	__Prototype Testing	_x_Proof of Concept	_ Demonstration

JOC High Flame Temperature Oxy-Combustion

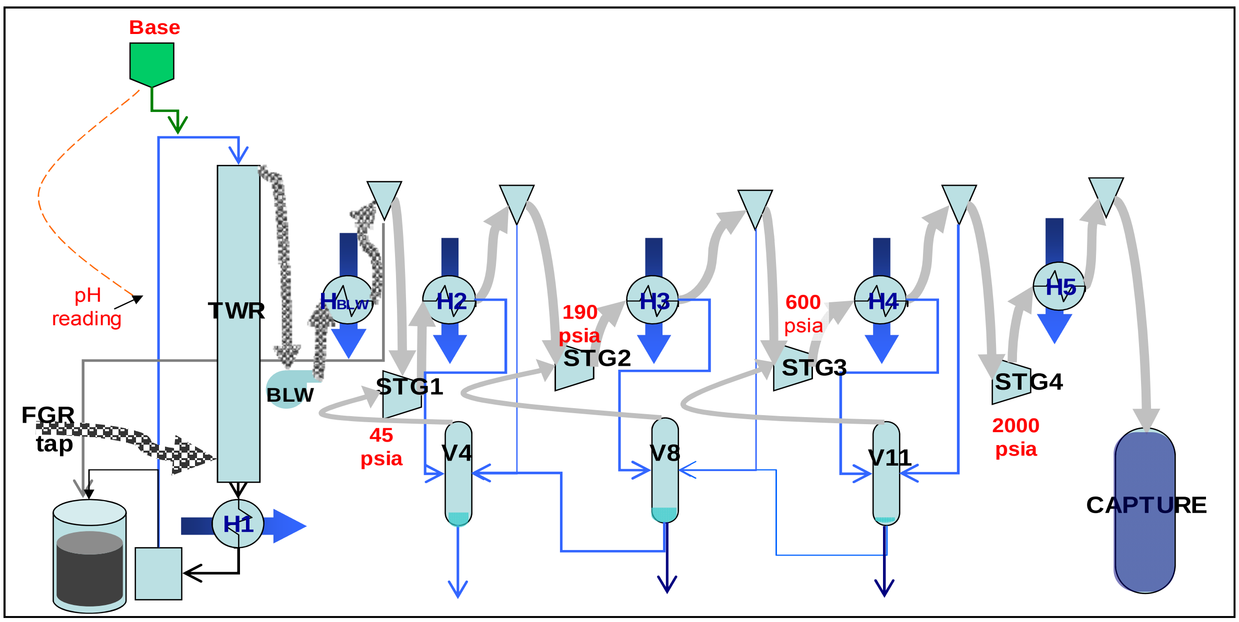
- Development of oxy-combustion technology for Jupiter Aluminum facility in Hammond, Indiana
  - An oxy-combustion process has been in use by Jupiter since 1997 in an aluminum furnace; this prior experience is being leveraged for the new application to utility and industrial boilers.
- Jupiter Oxygen as a CRADA partner with the NETL (2003)
  - Successful retrofit of 0.5 MWe equivalent boiler with JOC high flame temperature oxy-combustion.
  - Produced saturated steam while maintaining boiler interior temperature profile the same as with air firing by making changes to mass flow rates and the use of recycled flue gas.
  - Boiler efficiency gains resulted.
- Jupiter Oxygen/NETL project funded by DOE (2006)
- Key characteristics
  - Eliminate air from the combustion system.
  - Fuel and oxygen mixed at the burner undiluted with flue gas recycle except to motivate coal to the boiler (unlike low-temperature oxy-combustion, which dilutes oxygen with flue gas recycle prior to combustion).
  - Results in a high-flame temperature to enhance heat transfer in the radiant zone.
  - Flue gas produced is primarily CO_2 and water (little or no nitrogen).
  - Flue gas recycle introduced around the flame/combustion zone to adjust the total flue gas volume flow and transfer heat duty to the convective zone, as required.
  - Additional FGR does not lower flame temperature.
- Benefits
  - Significantly reduce NO_X emissions at combustion.
  - Enhanced radiant heat transfer increases boiler efficiency, which results in boiler fuel savings.

- Less fuel results in lower carbon generation, reduced capture costs, and lower oxygen demand.
- Reduced volume of flue gas and concentrated CO_2 in flue gas also reduces the cost of carbon capture.

• Challenges
- Burner stability and performance.
- Balancing heat duty in radiant and convective zones for retrofit projects or conventional new build projects.
- Minimizing air in-leakage to boiler.

NETL Integrated Pollutant Removal (IPR®) System

• Key Characteristics
- Coal-fired flue gas is cooled and scrubbed via a direct contact wet heat exchanger.
- Condensed water from the flue gas is separated and recovered for power plant use.
- Balance of flue gas is compressed in multiple stages to required pressure for CO_2 processing or sequestration.
- Heat of compression is recovered for power plant use.



Schematic illustration of the Integrated Pollutant Removal (IPR®) System

• Advantages
- Integration of IPR® with the power plant thermal cycle minimizes parasitic load for the work required to remove pollutants and capture/process CO_2.
- Condensed water captured from the combustion flue gas is sufficient to supply 100 percent of the boiler feed water makeup or up to seven percent of the cooling water makeup for the plant.
- IPR® uses “off-the-shelf” technology.

• Challenges
- Optimizing material selection costs while minimizing corrosion concerns.

– Minimization of energy use of integrated oxy-combustion/IPR system.
– Treatment of captured water for release and/or use in the plant water supply.

Relationship to Program

This project will support important advances within the oxy-combustion area of the IEP Program. Combined Jupiter Oxygen high-flame temperature oxy-combustion technology and NETL IPR® pollution control and carbon capture system for coal-fired power plants provide the following benefits:

- Technologies provide a means to retrofit existing power plants and build new ones.
- Boiler system fuel savings can be expected from high-flame temperature oxy-combustion technology compared to other carbon capture approaches.
- 95-100 percent carbon capture is feasible.
- Technologies allow fully carbon capture-ready power plants to exist today which can be completely compliant with clean air regulatory requirements.
- Water recovery will exceed boiler feed water makeup requirements or partial cooling water makeup requirements.
- Heat integration from cryogenic oxygen plant and IPR® compressors can provide additional benefits and lower fuel costs.

Primary Project Goal

The primary goal of this project is the demonstration of Jupiter's high-flame temperature oxy-combustion process combined with NETL's IPR® system with a full-scale retrofit to a 50-MMBtu/hr boiler utilizing commercially available coal and equipment.

Objectives

- Design, construct, and operate a 5-MWe equivalent test facility for oxy-coal combustion research based on a 50-MMBtu/hr burner.
- Support the design, construction, and operation of a 20-kWe equivalent bench-scale facility that treats 100 to 140 lb/hr flue gas for research of the IPR® component development testing that will utilize a slipstream of flue gas from the 5-MWe equivalent test facility.
- Operate the test facility with a coal that is expected to be used in larger-scale testing of the oxy-coal combustion technology in a coal-fired boiler at an electricity-generating facility. Perform parametric studies and operate the facility at steady state optimum oxy-coal combustion conditions for three weeks of continuous 24-hour per day operation.
- Demonstrate during the steady state optimum conditions testing that the single oxy-coal burner firing at its design rate up of 50 MMBtu per hour, maintains a stable flame, and produces NO_X levels no higher than 0.15 lb/MMBtu before other controls.
- Demonstrate that the combination of oxy-coal combustion and the IPR® process can produce a CO_2 by-product that meets the specifications for deep saline aquifer sequestration and/or EOR as defined by DOE's CS Program.
- Evaluate the retrofit impact of oxy-coal combustion and the IPR® process on balance-of-plant issues including, but not limited to, flame stability, steam generation, unburned carbon levels, tube wastage, slagging and fouling, recycle duct and boiler corrosion, pollutant emissions, and discharge streams, including by-products, and parasitic energy requirements during the operation of the facilities.
- Generate the necessary technical data (including, but not limited to, equipment requirements for the boiler island, including flue gas purification, and CO_2 compression) required as inputs into a systems analysis so as to demonstrate the technologies are viable for technical and economic scale-up, either in combination or individually with

generic counterparts, and conform to DOE's CS Program goals of 90 percent CO_2 capture and subsequent storage at an increase in the cost of electricity of no more than 20 percent by 2012.

06: DE-NT0005015

Project Number	Project Title			
DE-NT0005015	Clean and Secure Energy from Coal			
Contacts	**Name**	**Organization**	**Email**	
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Principal Investigator	Philip Smith	University of Utah	Philip.smith@utah.edu	
Partners				
Stage of Development				
X_Fundamental R&D	__Applied R&D	__Prototype Testing	__Proof of Concept	__Demonstration

Technical Background

DOE/NETL's Advanced Research (AR) Program is engaged in the development of innovative, cost-effective technologies for improving the efficiency and environmental performance of advanced coal and power systems. AR's Coal Utilization Science (CUS) Program performs crosscutting R&D to expand the basic understanding of the underlying chemical and physical processes involved in utilizing coal, and to directly benefit developers, designers, manufacturers, and operators in their efforts to improve the efficiency and environmental performance of advanced power systems.

The University of Utah, via their Institute for Clean and Secure Energy (ICSE), is pursuing research to utilize the vast energy stored in our domestic coal resources and to do so in a manner that will capture CO_2 from combustion from stationary power generation. The research is organized around the theme of validation and uncertainty quantification through tightly coupled simulation and experimental designs. The results of the research will be embodied in the computer simulation tools which predict performance with quantified uncertainty, thus transferring the results of the research to practitioners to predict the effect of energy alternatives using these technologies for their specific future application. Overarching project objectives are focused in three research areas and include: clean coal utilization for power generation "retrofit"; secure fuel production by in-situ substitute natural gas production from deep coal seams; and environmental, legal, and policy issues.

This program review focuses on two of the power generation "retrofit" areas:

Oxy-Coal Combustion

The ultimate objective of this task is to produce predictive capability with quantified uncertainty bounds for pilot-scale, single-burner, oxy-coal operation. This validation research brings together multi-scale experimental measurements and computer simulations. This predictive tool forms the basis for application to full-scale, industrial burner operations. Particular attention is focused on ignition, coal flame stability, ash partitioning, and ash deposition under pulverized oxy-coal conditions, with a smaller companion effort on application of circulating fluidized beds to oxy-coal combustion conditions. Additional detail on the work being performed follows:

Oxy-Coal Combustion Large Eddy Simulations: The University of Utah is expanding its high-performance simulation tools coupled with direct quadrature method of moments (DQMOM) to quantitatively predict oxy-coal conditions. This work is being performed using experimental data from the University of Utah's 100-kW oxy-fuel combustor (OFC) and is identifying mechanisms important to the operation of oxy-coal retrofit options. To date, the research has focused on predicting flame stability at the 100-kW scale; although the final scope is being developed, the University of Utah is planning to partner with industry on the simulation of heat flux in a larger scale oxy-coal combustion system.

Near-Field Aerodynamics of Oxy-Coal Flames: Under this project, the University of Utah has built a 100-kW OFC for studying the effect of various operating parameters on flame stability under oxy-combustion conditions. The reactor is equipped with quartz and sapphire windows optical access; heated or cooled walls; flue gas recycle; and a coaxial, zero swirl burner. The entire system is controlled by Opto22 commercial software with automated data logging of temperature at multiple locations, pressure, and gas concentrations. The investigators also developed a photographic method to quantify flame stability for thousands of flame images and reported results in the form of probability density functions for flame stand-off distance, which can be compared quantitatively to simulation results.

Using the OFC, the University of Utah has investigated the effect of the partial pressure of oxygen in the primary (transport stream with coal) and secondary stream as well as the nature of the inert (N_2 or CO_2) on flame stability. The work also includes investigation of strategies for directed oxygen injection with minimum CO_2 recycle and the effect of different types of coals. Although the scope is currently being developed, Phase 3 of this project is expected to focus on the resultant effects on heat flux, both in the burner near field and in the far field. The investigators are continuing to work closely with the simulation and advanced diagnostics group to develop an understanding of the most important mechanisms governing both flame stability and resultant heat flux.

Advanced Diagnostics for Oxy-Coal Combustion: The advanced diagnostics team developed the capability for applying particle image velocimetry to laboratory coal burners and has begun to apply this to the 100-kW OFC for the measurement of planar velocity fields in turbulent oxy-coal flames. Initial data from a simple bench-top pulverized coal burner demonstrated that the data and image-processing techniques have been appropriately adapted for oxy-coal flames. Although the scope is currently being developed for Phase 3, the investigators plan to employ an infrared camera to measure temperatures in the OFC in a non-intrusive manner.

Oxy-Coal Combustion in Circulating Fluidized Beds: This work is aimed at developing an understanding of the process dynamics, and the impact of key process variables on bed temperature, bed agglomeration, solids recycle rate, and sulfur capture. The recently modified oxy-fired, pilot-scale CFB is being used to study operational impacts of variations in oxygen concentration, in-bed heat removal, and external heat removal (from the solids recycle stream). In addition, the formation of SO_3 in the high CO_2 and O_2 environment of the CFB is being evaluated to develop an understanding of its potential for sulfuric acid condensation and corrosion. The investigators are working with DOE/NETL MFIX model staff to provide necessary input on the types of measurements and measurement locations that will assist in the development and validation efforts of both modeling teams.

Single-Particle Oxy-CO_2 Combustion: This subtask will focus on both PC and fluidized-bed systems, with two objectives: (1) for PC systems, single-particle kinetics for oxy-CO_2 combustion are being developed from the literature in conjunction with Sandia National Laboratories; (2) for fluidized-bed conditions, the impact of an O_2/CO_2 environment on carbon, nitrogen, and sulfur release from coal and coal char is being explored in a bench-scale, single-particle fluidized-bed reactor. Measurements focus on both rate determination with detailed uncertainty quantification for use in model development, as well as the identification of the influence on major operating variables such as oxygen concentration and bed temperature on the release of nitrogen and sulfur impurities.

Ash Partitioning Mechanisms for Oxy-Coal Combustion: The University of Utah is focused on understanding ash partitioning under oxy-coal combustion conditions by considering experiments on two scales: (1) at the bench-scale using a drop tube reactor with coal flow rates of ~1-4 g/h, to determine fundamental ash partitioning mechanisms using simulated flue gases; and (2) at 100-kW self sustained combustor scale (coal flow rates of ~ 10kg/h) where the focus is on how the amount of recycled flue gas affects ash partitioning mechanisms. In both experiments, ash aerosol particle size distributions and size segregated ash compositions are obtained using aerosol mobility and impaction techniques. To date, investigators have studied effects coal type, oxygen concentration, and flue gas recirculation rates on ash partitioning behavior.

Chemical Looping Combustion

The ultimate objectives of this task are to develop a new, low-cost carbon capture technology for coal through chemical-looping combustion (CLC) and to transfer this technology to industry through a numerical simulation tool with quantified uncertainty bounds. The research will primarily focus on CuO/Cu_2O, but include iron-based carriers for some of the modeling studies using data from the literature for kinetics and verification. It will also include chemical looping with gasification products. The specific research targets for these tasks are to quantitatively identify reaction mechanisms and rates, explore operating options with a laboratory-scale bubbling bed reactor, identify process modeling economics, and demonstrate and validate simulation tools for a pilot-scale fluidized bed as described below.

CLC Kinetics: The CLC Team is using TGA experiments to elucidate the chemical kinetics of the copper metal/copper oxides CLC oxygen carrier system with a single gas and with gas mixtures that simulate fuels such as syngas as well as the kinetics of CuO decomposition to yield O_2 for carbon oxidation and the kinetics of the oxidation of the resulting Cu_2O. The goal is to extract reaction kinetics for the process modeling studies. To date, the investigators have investigated the ability of CuO/Cu_2O for hundreds of hours and have fitted a preliminary first-order reaction rate to the data.

Laboratory-Scale CLC Studies: The CLC Team is studying the performance of oxygen carriers in an environment having characteristics in a fluidized bed-based system. The research focuses on the performance of the oxygen carriers, including carrier capacity and rates of oxidation and combustion as the system is cycled between oxidizing conditions and fuel combustion conditions. This will include development of simple reaction kinetic expressions. In addition, the investigators are studying the extent and rates of oxygen release (uncoupling) in a nitrogen environment and comparing these to the fundamental information being obtained through thermogravimetric studies. Thus far, the investigators have designed and constructed a laboratory-scale, bubbling fluidized bed reactor and completed a preliminary characterization of one iron-based and one copper-based carrier.

LES-DQMOM Simulation of a Pilot-Scale Fluidized Bed: The University of Utah is expanding the DQMOM models and their high-performance simulation tools to dense-particle regimes. Their current work is focused on CLC particles under non-reacting conditions. They are beginning to perform validation studies using data from NETL's cold-flow CLC fluidized bed to quantify and potentially reduce the uncertainty in the fluidized bed models.

Process Modeling and Economics: The investigators are developing simplified process models of the CLC process, which include simple material and energy balances and utilize the Aspen® process modeling suite. The process models will allow us to estimate how a full-scale chemical looping system will perform and will help guide the research by identifying information gaps. Where possible, the model will help ascertain the key operational and reactor volume differences between the different metals under consideration (copper versus iron). To date, the investigators have completed a preliminary estimation of flows, reactor sizing, and operating conditions based on consideration of the kinetics as well as material and energy balances. Parameters estimated include the temperatures of the fuel and air reactors, the minimum oxygen carrier loading, the carbon loading in the fuel reactor, and the rate of circulation of the oxygen carrier between fuel and air reactor.

Relationship to Program

This project will support important advances within the oxy-combustion and chemical looping activities of the IEP Program. The entire project will provide experimental results and simulation tools to aid in the development, production, and utilization of coal for power generation in a carbon-constrained world. The strength of the tool-set is the inclusion and quantification of uncertainty associated with the individual options in order to better enable informed energy futures decisions.

If the oxy-coal project is successful, it will provide enabling technologies that promote the deployment of oxy-coal combustion as a cost-effective carbon capture technology for retrofit power applications. The predictive tool will form the basis for application to full-scale, industrial burner operations. The experimental and simulation work will improve our understanding critical operating parameters that effect performance, safety, and environmental impacts. The integrated experimental and simulation work on flame stability has begun to identify key factors (i.e., inert composition, temperature, oxygen partial pressure, wall temperature) governing flame stability under oxy-coal combustion conditions. For example, the ability to achieve flame stability without employing oxygen in the transport stream is important for maintaining safe operation. Furthermore, the ability to minimize or even eliminate flue gas recycle has important boiler design implications and could lead to reductions in capital cost. The work on flame stability and heat flux is critical to optimize optimal boiler design and performance, reduce equipment downtime, and develop cost-effective retrofit and boiler design strategies.

If successful, the CLC project will lead to the development a new, low-cost carbon capture technology and accelerate industry adoption of the technology through a numerical simulation tool with quantified uncertainty bounds. The primarily focus is on CuO/Cu_2O because of its suitability for coal combustion. In order for this highly promising work to be deployed, optimal oxygen carriers (and supports) must be identified and tested. This project will contribute to the knowledge base for CLC and facilitate its deployment.

Primary Project Goal

Through tightly coupled simulation and experimental designs, the development of computer simulation tools which predict performance with quantified uncertainty of oxy-coal combustion and CLC systems; thus transferring the results of the research to practitioners to predict the effect of energy alternatives using these technologies.

Objectives

Oxy-Coal Combustion – To ultimately produce predictive capability with quantified uncertainty bounds for pilot-scale, single-burner, oxy-coal operation. The work focuses on ignition, coal-flame stability, and ash partitioning under oxy-coal conditions. This predictive tool developed under this effort will form the basis for application to full-scale, industrial burner operations.

Chemical Looping Combustion – To develop a new carbon capture technology for coal through CLC and to transfer this technology to industry through a numerical simulation tool with quantified uncertainty bounds. The specific research target for this project is to quantitatively identify reaction mechanisms and rates, explore operating options with a laboratory-scale bubbling bed reactor, develop process models and economics, and demonstrate and validate simulation tools for a pilot-scale fluidized bed. This task will focus primarily on CuO/Cu_2O.

07: NT43088

Project Number	Project Title			
NT43088	Recovery Act: Oxy-Combustion: Oxygen Transport Membrane Development			
Contacts	**Name**	**Organization**	**Email**	
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Partners	EnrG Inc University of Utah Shaw Energy & Chemical Group Saint Gobain			
Stage of Development				
__Fundamental R&D	_Applied R&D	_X_Prototype Testing	__Proof of Concept	__Demonstration

Technical Background

As oxy-combustion is currently practiced, a pure stream of oxygen is separated in an ASU and then delivered to a boiler for combustion. OTM technology integrates oxygen separation and combustion in one unit. An OTM consists of an inert porous support coated with a dense gas separation layer, as illustrated in Figure 1. Air contacts the separation layer where molecular oxygen reacts with oxygen vacancies and electrons on the membrane surface to form oxygen ions, which are transported through oxygen vacancies in the separation layer using a chemical potential difference as the driving force. Fuel species (CO, H_2, methane [CH_4] etc.) located on the porous support side diffuse through the support and react with oxygen ions at the membrane surface to form oxidation products (H_2O, CO_2) and release electrons which are transported back through the separation layer.

Several process concepts incorporating ceramic OTM are being explored to understand their impact on process economics. One process concept under development is shown in Figure 2. In this process, coal is first gasified in an oxygen-blown gasifier to generate syngas. The syngas is optionally reacted in an OTM partial oxidation reactor to raise its temperature.

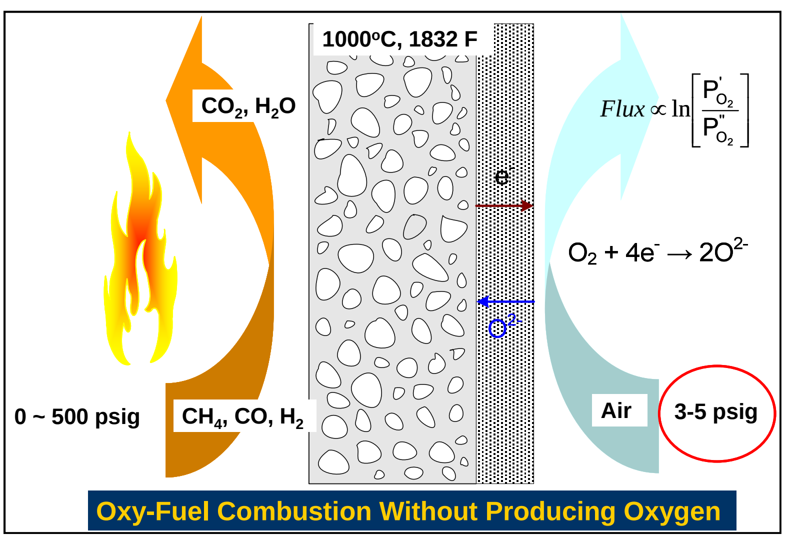

Figure 1: Schematic of Ceramic OTM

The hot syngas is expanded to recover power. After the syngas is expanded to ambient pressure, it is sent to the OTM boiler. Within the OTM boiler, syngas is first passed over an array of OTM tubes. Air is preheated by heat exchange with the oxygen-depleted air and then passed on to the feed side of the OTM tubes. Oxygen from the air transports across the membrane and reacts with the syngas. Since the rate of oxygen transport is limited by the availability of the membrane area, the oxidation of syngas will take place over a large area (the OTM zone) within the boiler. As the syngas gets oxidized, the driving force for oxygen transport will decrease and the required membrane area will increase. For practical reasons, the OTM will be used to supply oxygen to the fuel side until 80 to 90 percent fuel utilization is achieved. The remainder of fuel will be combusted using oxygen supplied from the cryogenic ASU.

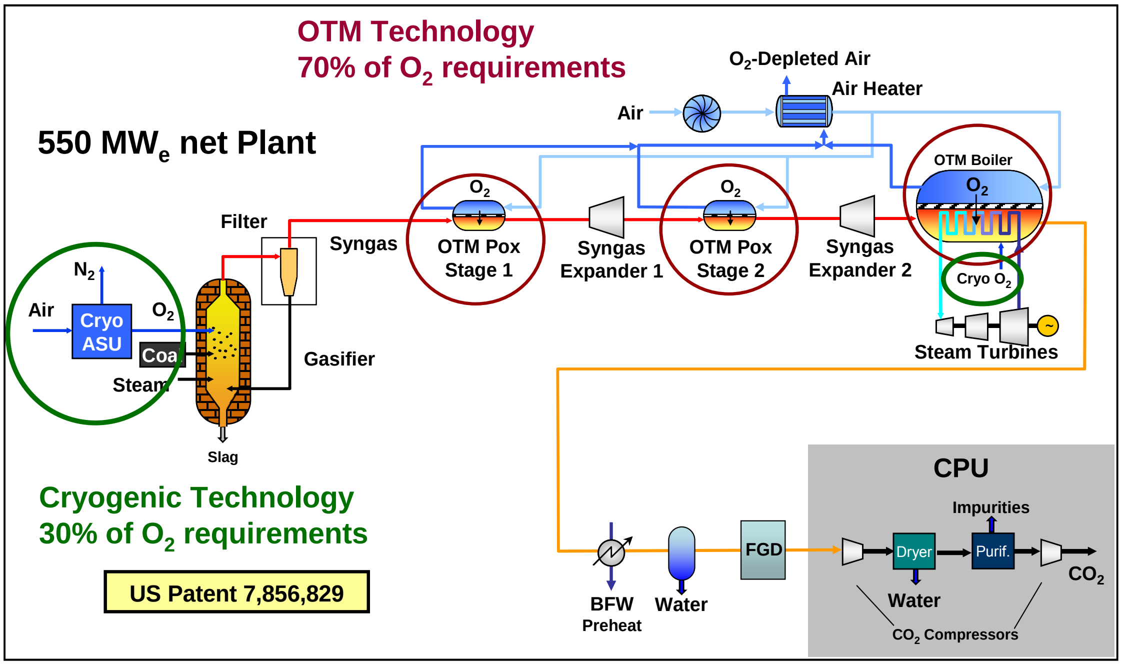

Figure 2: OTM-Based Process for Power Generation with CO_2 Capture

The thermal energy released within the boiler is used for steam generation. In the OTM zone, steam tubes will be interspersed with the OTM tubes such that the temperature is maintained at the optimum level for membrane performance. After the fuel is completely oxidized with externally supplied O_2, the flue gas will pass through a convective section of the boiler for further steam generation and boiler feed water preheating. The flue gas exiting the boiler is processed according to a purification process proposed for a conventional oxy-fuel technology.

The demonstration of reactively driven OTM devices in both syngas mode and combustion is a critical step in the commercialization of this technology. The technology roadmap targets applications in the industrial space to help accelerate the commercialization of OTM technology and facilitate the subsequent demonstration of the Advanced Power Cycle (APC). Focusing on industrial-scale applications will enable the development and rapid commercialization of smaller scale (relative to utility scale) OTM devices. These commercial installations of the reactively driven OTM devices will provide real world experience related to their operability, maintenance requirements, and robustness that will better position all parties for the investment required to build a power plant utilizing this technology. With the commercialization of reactively driven OTM devices in a number of industrial applications, a fleet of operating sites will serve as testimonials for the robustness and reliability of the core components of the OTM technology, thereby reducing the risk associated with a first-of-a-kind utility-scale demonstration of the technology.

A technology can be considered to be transformational if it has the ability to drive significant economic benefits in a wide range of industrial processes and applications. OTM creates a new paradigm in the way that oxygen (O_2) can be supplied to combustion or partial oxidation processes. Oxygen is never collected and stored; it is separated via the membrane using a partial pressure gradient and immediately consumed in the process. There can be few technology platforms that have the potential to significantly impact as many energy-related applications as OTM. OTM technology creates an entirely new oxygen supply mode to combustion and partial oxidation applications in which oxygen is never actually separated and stored.

Both OTM combustion and OTM syngas also support the DOE program on "Carbon Capture and Sequestration from Industrial Sources and Innovative Concepts for Beneficial CO_2 Use" (ICCS). Combustion processes in cement plants, chemical plants, refineries, steel and aluminum plants, other manufacturing facilities, and opportunity-fueled power plants can benefit in a similar manner as described above. In addition to the power savings as compared to cryogenically provided oxygen for oxy-combustion, OTM also has the advantage of a wider range of scale for deployment.

This program would also deliver benefits to industrial processes used to produce syngas for subsequent processing into a variety of chemical and/or petrochemical end products. Many industrial chemical processes utilize partial oxidation (POx) reactors and/or autothermal reformers (ATR) to produce a syngas with a desired H_2/CO ratio. Many of these units utilize oxygen from a cryogenic ASU. A significant amount of the net CO_2 emissions from these plants is associated with the power required to produce the oxygen. The OTM Syngas Unit would reduce the effective CO_2 footprint of these processes by dramatically reducing the power requirements of the plant. The end result would be an industrial chemical plant with a lower net CO_2 footprint.

There is a large available source of hydrocarbons contained in domestic natural gas resources. DOE estimates for United States proven dry natural gas reserves in 2007 were 237 trillion cubic feet (equivalent to 36 billion barrels of oil). If a greater portion of these natural gas resources can be economically converted to liquid fuels and hydrogen, the Nation's dependence on imported oil will be significantly reduced. OTM Technology can integrate oxygen separation with methane partial oxidation, thereby substantially reducing the cost of producing syngas as compared to the conventional conversion processes (i.e., cryogenic air separation and auto-thermal reforming). The breakdown of capital costs associated with the individual steps in conventional GTL processing is 60 percent for syngas generation (ASU plus ATR), 25 percent for syngas processing, and 15 percent for separation and upgrading. OTM technology is expected to lead to a 30 to 40 percent reduction in capital investment when compared to conventional GTL fuels conversion technologies. Commercial deployment of a new natural GTL fuels technology with a step change capital cost reduction will greatly expand the domestic energy supply of the United States.

One task within Phase III of the project will focus on the design and construction of a skidded syngas system with oxygen supplied from OTM membranes capable of producing approximately 1 MM scfd of syngas at full capacity. It is anticipated that this system will incorporate a second-generation OTM module that improves on the performance and cost of the initial module. This system will be commissioned and tested at the Praxair Technology Center in Tonawanda, New York. After it is commissioned it could be shipped to another facility for a field demonstration in which it is integrated with a downstream industrial chemical process to demonstrate the performance of the system when integrated with another process (this testing is outside the scope of this program). Another task within Phase III of the project will focus on demonstrating the oxy-combustion of a syngas using reactively driven OTM modules operating with high fuel utilization and transferring energy to a thermal load. The unit will be designed to demonstrate heat transfer from the OTM modules to a process stream. This process stream could be water, oil, or any other fluid that allows a range of heat flux regimes to be evaluated. Efforts will focus on the radiative and convective heat transfer mechanisms occurring in the high-temperature region of the furnace where the OTM modules and process tubes are located. CFD models will be developed to predict the heat transfer between the OTM devices and the thermal load. These models will be used to design the distribution of OTM surface area vs. thermal load surface area for target heat flux conditions. Once the system is commissioned, the models will be validated with data from the operating system. As with the Pilot-Scale Syngas System, this system will be used to prove out all required startup and shutdown processes as well as the overall performance and design guidelines for larger scale systems. This task will provide the required information for designing larger scale systems with an understanding of design requirements for different heat flux regimes characteristic of process heaters (typ. 25,000 – 47,000 W/m2) to boilers (typ. 125,000 – 290,000 W/m2).

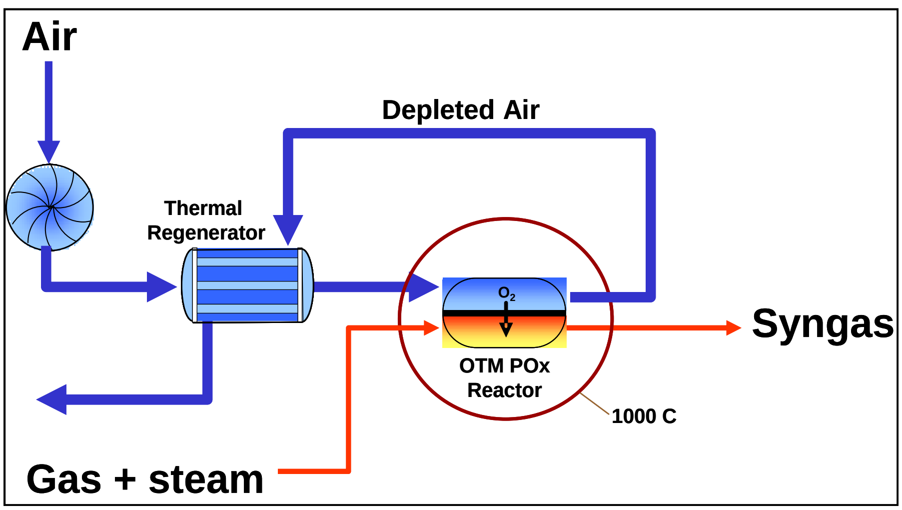

Figure 3: Phase III OTM Syngas System Concept

Relationship to Program

This project will support important advances within the oxy-combustion area of the IEP Program. The development of an OTM-based coal-fired power generation process will aid in attaining the DOE program goals of advanced power generation that can achieve 90 percent CO_2 capture at less than a 35 percent increase in COE. The OTM oxy-combustion system can provide a highly concentrated, sequestration-ready stream of CO_2 without costly cryogenic oxygen production or CO_2 separation processes. The use of reactively driven OTMs is expected to reduce the power associated with oxygen production by 70 to 80 percent. This represents a step change in the cost and related CO_2 emissions and will enable a variety of oxy-combustion technologies, as well as other combustion applications, where CO_2 capture may be required.

Reactively-driven OTMs that utilize oxygen ion and electron-conducting ceramic materials are a breakthrough technology for providing low-cost oxygen to high-temperature industrial processes. Processes that are under consideration for integration of OTM can be classified into three categories: (i) gas reformers; (ii) partial oxidation reactors; and (iii) process heaters. Many industrial chemical processes utilize POx reactors and/or ATRs to produce a syngas with a desired H_2/CO ratio. Large-scale industrial processes that require a syngas with an H_2/CO ratio of two or less typically utilize an oxygen-based process to produce the syngas. As these processes typically require thousands of tons of oxygen per day, they necessitate the use of cryogenic ASUs. Air compression is one of the largest operating expenses in a cryogenic air separation facility. Based on the required syngas pressure and the projected power savings identified in section 2.0 above, the net CO_2 emissions for syngas production using an OTM-based ATR over a conventional ASU/ATR are expected to be on the same order as the power savings of a high-pressure cryogenic ASU (~85 percent).

Another application that is well suited for OTM integration is POx reactors. Figure 3 illustrates the integration of an OTM POx with a gasifier. In these reactors, oxygen is mixed with hydrocarbon feed streams to convert the hydrocarbons to H_2 and CO. Processes that are particularly attractive for OTM are those in which a gasifier is utilized to convert a solid feedstock into syngas for subsequent conversion to chemicals or fuels. In this situation, gaseous components other than H_2 and CO are typically inert to the downstream conversion processes. Utilization of an OTM POx can convert these residual hydrocarbons to H_2 and CO, thereby increasing the overall yield of the downstream conversion process. Increasing the yield of the process is expected to reduce the CO_2 emissions of the process as a higher percentage of the carbon in the feedstock is in the product rather than the tail gas, which is typically burned to produce power and/or steam. These gasifiers can be fed with biomass to produce biofuels or coal to produce liquid fuels and/or chemicals.

In addition to the integration of OTMs into boilers used to produce steam, OTMs may also be integrated into process heaters in refineries as well as cracking furnaces in chemical plants. In each of these cases, the traditional air-fired furnace would be replaced with a furnace that has OTMs interspersed among the process tubes. Heat liberated from the OTM surfaces based on the combustion of the fuel on the surface of the membrane with the oxygen from the separation process is radiated to the process tubes to affect the reactions that take place within the tubes. As with the boilers, the flue gas streams exiting these furnaces are more amenable to CCS than air-based processes as the CO_2 is present in higher concentrations. One additional benefit associated with an OTM-fired furnace over an air-fired furnace is the ability to control the heat flux profile to the process tubes. Tailoring the heat flux profile to the tubes based on the endothermic reactions that are occurring within the tubes can allow extended run times and reduced downtime for maintenance and decoking operations. Maximizing run time can have a significant impact on the profitability of a particular furnace.

The optimization and testing of OTM systems for both syngas and combustion is a critical step toward the commercialization of OTM technology. The development and commercialization of reactively driven OTM devices in a number of industrial applications will result in a fleet of operating sites that will serve as testimonials for the robustness and reliability of the core components of the OTM technology, thereby reducing the risk associated with a first-of-a-kind utility-scale demonstration of the technology.

Primary Project Goal

The primary project goal is to develop a new method of producing oxygen for high-temperature reactions that optimizes performance, reliability, and cost, thereby enabling oxy-fuel combustion for CCS as well as the use of oxygen in other industrial processes that have heretofore been too costly to meet financial decision metrics.

Objectives

Phase I:

- Develop more detailed OTM cost and performance estimates based on experiments.
- Develop a preliminary conceptual design and cost models for a pilot plant utilizing OTM technology.
- Identify the rate limiting steps for oxygen separation through the OTM and address kinetic or mass transport limitations by appropriate materials selection and membrane architecture.
- Develop procedures to manufacture one-third pilot-size OTM tubes; test them for oxygen flux and durability in CO, H_2, CO_2, and H_2O fuel streams with the presence of sulfur impurities.
- Test OTM membranes in a coal gas OTM reactor.

Phase II:

- Demonstrate ability to produce OTM tubes with the appropriate dimensions and manufacturing yield required to proceed with pilot demonstration.
- Deliver preliminary engineering cost estimate for OTM pilot plant system (OTM POx and Boiler).

Phase III:

- Demonstrate conversion of natural gas to 1 MM scfd of syngas in a skidded OTM integrated pilot-scale system.
- Demonstrate OTM oxy-combustion and heat transfer at high rates of fuel utilization in a developmental-scale 1 MWth system.

08: NT0005498

Project Number	Project Title			
NT0005498	Development and Evaluation of a Novel Integrated Vacuum Carbonate Absorption Process			
Contacts	**Name**	**Organization**	**Email**	
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Principal Investigator	Yongqi Lu	University of Illinois at Urbana-Champaign	lu@isgs.illinois.edu	
Partners	Illinois Clean Coal Institute Calgon Carbon Corporation			
Stage of Development				
__Fundamental R&D	_x_Applied R&D	__Prototype Testing	__Proof of Concept	__Demonstration

Technical Background

MEA-based absorption processes are the best available, but very expensive (~$70/ton CO_2 avoided), technologies. The major part of the cost, amounting to about 60 percent, is the parasitic power loss due to extraction of power plant steam to provide the heat required for CO_2 stripping.

The proposed patent-pending Integrated Vacuum Carbonate Absorption Process (IVCAP) employs a potassium carbonate (PC, K_2CO_3) aqueous solution for CO_2 absorption. The heat of reaction between CO_2 and K_2CO_3 is low compared to that between CO_2 with the amine solvents (Table 1). The weak affinity of CO_2 with K_2CO_3 allows CO_2 to be stripped from the CO_2-rich solution at a low temperature (50-70°C) and pressure (2-8 pounds per square inch absolute [psia]) in the stripper. Such a temperate/pressure condition enables the use of either the waste steam or a low-quality steam from the power plant's steam cycle to provide the heat for the CO_2 stripping. The schematic diagram of the IVCAP integrated with the power plant steam cycle is shown in Figure 1.

Table 1: A Comparison of Heats of Absorption for Three CO_2 Solvents

Solvent	Main Reaction	Heat of Absorption
Primary/secondary amines	$2RR'NH + CO_2 = RR'NCOO^- + RR'NH_2^+$	MEA: 1,900 kJ/kg
Tertiary amines	$RR'R''N + CO_2 + H_2O = HCO_3- + RR'R''NH^+$	MDEA: 1,200 kJ/kg
Carbonate	$CO_3^{2-} + CO_2 + H_2O = 2\ HCO_3-$	600 kJ/kg

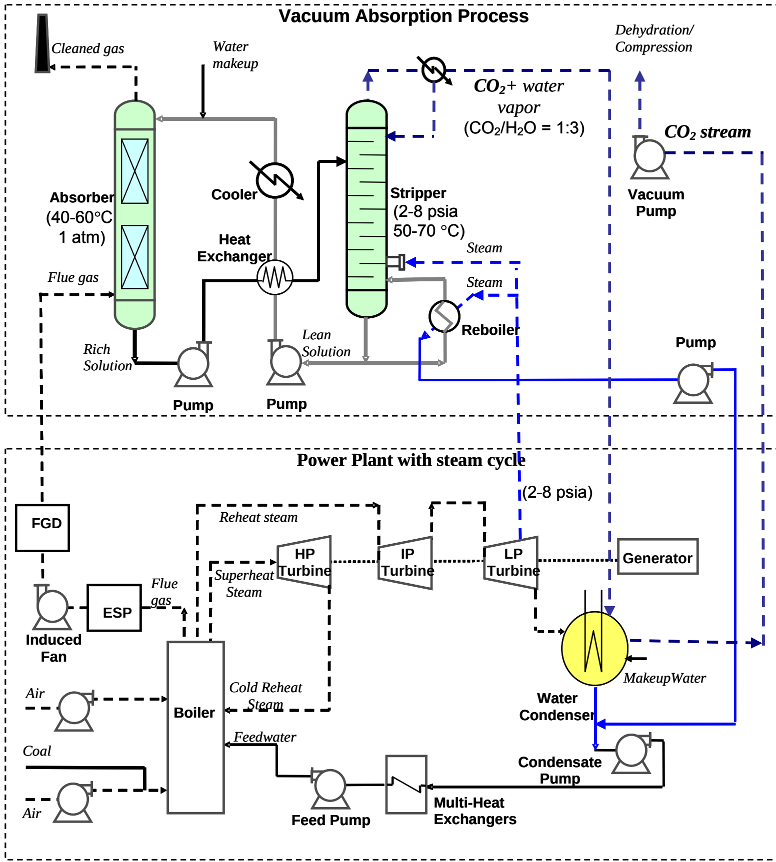

Figure 1: Schematic Diagram of the Proposed IVCAP Process

The heat quality of the steam in the power plant steam cycle varies with its pressure and temperature. The efficiency of heat conversion to electricity decreases with decreasing steam pressure (Figure 2). The MEA-based processes extract a superheated steam of about 60 psia for CO_2 stripping, in which about 18 percent of the heat can be used for generating electricity. In comparison, the IVCAP withdraws a low-quality steam (2-9 psia) with <10 percent heat-to-electricity conversion efficiency. As a result, the parasitic power loss due to the steam extraction can be significantly lowered in the IVCAP (Note: the blue curve provided in Figure 2 refers to the heat-to-electricity conversion efficiency).

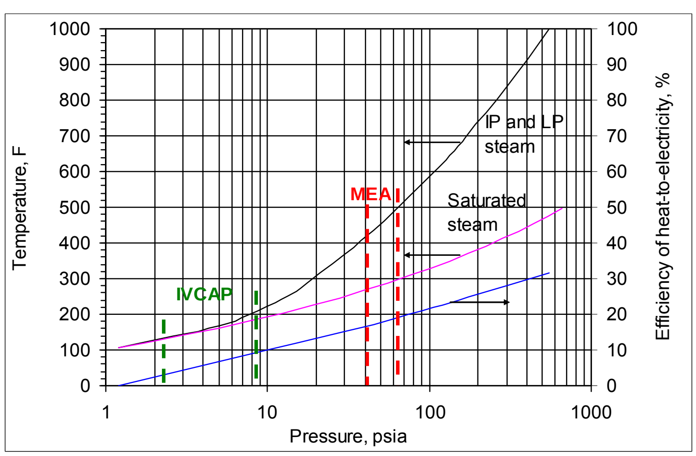

Figure 2: Steam Properties During Expansion in Intermediate (IP) and Low-Pressure (LP) Turbines

Potassium carbonate (K_2CO_3) is weakly alkaline and a K_2CO_3-based system has a much slower CO_2 absorption rate compared with MEA. Therefore, a key technical issue in the IVCAP is to enhance the absorption rate to a level comparable to the MEA process. The conventional approach for promoting the CO_2 absorption rate into a weak solvent is to mix one or more solvents with stronger CO_2 affinity into the prime solvent. This approach, however, will increase the heat of absorption and thus consume more energy for solvent regeneration. By contrast, the IVCAP employs the *carbonic anhydrase* (CA) enzyme to accelerate the absorption rate without changing the heat of absorption. This enzyme catalyst has the potential to offer unparalleled CO_2 hydration rates.

In the IVCAP, a significant part (70 to 80 percent) of the heat required for CO_2 stripping is consumed by water vaporization, resulting in the gas stream exiting the stripper containing a large amount of water vapor (water vapor: CO_2 = ~3:1). Employing an additive that can effectively lower the water vapor pressure over the potassium carbonate solution will further reduce the heat use in the IVCAP.

Another advantage of the IVCAP is that the SO_2 removal can be potentially integrated with the CO_2 capture process. In the amine-based or amine-promoted absorption processes, SO_2 and other acidic gases react with the amines to form heat-stable salts that are difficult to reclaim. Therefore, the flue gas must be treated by removing these acidic gases to a very low level (<20 parts per million [ppm]). In the IVCAP, however, this is not a concern. A high SO_2 removal efficiency (>99 percent) can be potentially achieved since SO_2 strongly reacts with K_2CO_3 to form potassium sulfate (K_2SO_4). The solvent consumed by SO_2 can be continuously reclaimed using a novel, lime-based process proposed in this project. In this process, lime is added into the SO_2-rich solution (from the absorber) to convert K_2SO_4 to $KHCO_3$ and produce a gypsum ($CaSO_4{\cdot}2H_2O$) by-product. The uniqueness of the process is the use of a high-pressure CO_2 stream available in the IVCAP to control the degree of conversions between CO_3^{2-} and HCO_3^-, thus lowering the CO_3^{2-}concentration in the solution. A much lower concentration of CO_3^{2-} compared to that of SO_4^{2-} kinetically favors Ca^{2+} to precipitate from the solution as $CaSO_4$ rather than $CaCO_3$.

Relationship to Program

This project will support advances within the post-combustion carbon capture area of the IEP Program. The IVCAP has several advantages over the conventional amine-based technologies:

- Lower-quality steam is used for CO_2 stripping. Consequently, the IVCAP can reduce the parasitic power loss by 25 to 35 percent compared to the conventional MEA-based processes.
- A large portion of the steam is directly introduced into the stripper. Direct heat exchange between the steam and the solvent improves the efficiency of heat transfer in the stripper. In addition, the size of the reboiler in the stripper can be significantly reduced.
- The SO_2 removal can be potentially integrated into the CO_2 capture process. A separate FGD unit can thus be downsized or eliminated in the IVCAP.

The IVCAP employs the K_2CO_3 aqueous solution as a solvent. There are no concerns associated with solvent degradation and corrosion.

Primary Project Goal

The primary goal of this project is to reduce energy consumption and cost through the development of a successful post-combustion CO_2 capture process. The IVCAP could achieve 90 percent CO_2 removal, reduce the parasitic power loss by 25 to 35 percent compared to the conventional MEA-based processes, and significantly contribute to reducing the overall capture and storage cost to correspond to a 35 percent increase in COE compared to a non-capture power plant.

Objectives

This project is aimed at testing the proof-of-concept of the IVCAP and obtaining process engineering data to advance the technology development. The specific objectives are to:

- Identify an effective catalyst to accelerate the absorption rate of CO_2.
- Identify an effective additive to reduce the stripping heat.
- Evaluate a modified IVCAP as a multi-pollutant control process for combined SO_2 and CO_2 capture.

09: FY11.611.CAP.1610241

Project Number	Project Title			
FY11.611.CAP.16102 41	Flue Gas Sorbent and Design Development			
Contacts	**Name**	**Organization**	**Email**	
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Partners	McMahan Gray – NETL-ORD Ranjani Siriwardane – NETL-ORD James Hoffman – NETL –ORD Larry Shadle – NETL-ORD ADA-Environmental Solutions			
Stage of Development				
__Fundamental R&D	X Applied R&D	X Prototype Testing	__Proof of Concept	__Demonstration

Technical Background

The sorbent-based research efforts in the post-combustion carbon capture area began during the infancy of the overall CS Program within NETL-ORD. Various sorbent systems were investigated, but most were ruled out because of inherent deficiencies. An effort was devoted to zeolites, specifically 13X and others, but because of their strong attraction to moisture, a component in most gas streams of interest that contain CO_2, the work was abandoned. Alkali/alkaline earth compounds were also investigated, but poor energetics, such as high heats of reaction and large temperature differences between absorption and regeneration conditions, eliminated them from further investigation. Activated carbons, although relatively cheap, are typically not selective to only CO_2, since other components in the gas to be decarbonated will also be readily adsorbed. More recent work with MOFs and ZIFs has been reported. For post-combustion applications, these sorbents have very low CO_2 capacities at ambient pressures and can be sensitive to moisture. Pre-combustion application could be more relevant. Although there can be some candidates from these families of sorbents that could be serious contenders as post-combustion sorbents, the recent sorbent development work at NETL-ORD has concentrated on amine-enriched sorbents. Preliminary systems analysis indicated that these type of sorbents could meet the overall programmatic goal for the carbon sequestration scenario (of which carbon capture is the key step): to develop fossil fuel conversion systems that achieve 90 percent CO_2 capture with 99 percent storage permanence at less than a 35 percent increase in the cost of energy services for post-combustion capture at new and existing PC-fired power plants.

A concerted effort began in FY 2007 with two routes of sorbent investigation. One technique of sorbent development dealt with the immobilization of amines onto a solid substrate, and the second encompassed the encapsulation of an organic material into a clay-based substrate. Information pertaining to the working capacities for these regenerable sorbents and overall performance in flue gas surroundings has led to varying process concepts. During these sorbent development studies, concerns about how the sorbents would fit into reactor schemes and into the overall power plant, in general, led to an outside study with a reactor design organization. Performance targets were established and critical information that is needed to assess the sorbents in a power plant scenario was defined. In addition, a more recent thrust has been to specify and develop information that will be required in the actual design of a reacting system. Technology transfer with outside organizations has been an ongoing effort in this project.

Relationship to Program

This project will support advances within the post-combustion carbon capture area of the IEP Program. CCS holds the promise of continued fossil fuel usage while addressing global climate change concerns. The separation/capture step is the dominant cost in a CO_2 mitigation strategy of CCS. Existing MEA wet scrubbing is energy intensive with respect to regeneration heat duty, and dry sorbent scrubbing holds the potential to lower the regeneration heat duty. Once a sorbent-based dry scrubbing process is fully investigated and any uncertainty is resolved, the technology will provide a CO_2 capture technique that is applicable to the existing fleet as well as to new coal-fired power generators. Thus, a CO_2 removal process will be available to the electric power industry that addresses capturing CO_2 for eventual storage.

Primary Project Goal

R&D in the capture/separation area is aimed at developing sorbent-based systems that are low in capital cost, have low parasitic load, can reduce CO_2 emissions significantly, and can be integrated within the power generation scheme. With the exception of membranes and oxy-firing systems, most technologies require a material (solvent or sorbent) that can absorb the CO_2 and then be regenerated. This project provides chemical and engineering support and reactor design oversight for the development of CO_2 removal processes utilizing amine-enriched solid sorbents for flue gas application currently under development by NETL in-house researchers. The activities support the overall DOE CO_2 program goal of limiting the increase in cost of energy service for CCS from large point sources.

Objectives

The key objective is to develop sorbent-based post-combustion CO_2 capture systems for both existing plants and advanced power generating facilities that lower the energy penalty and costs associated with capturing CO_2 from large point sources. In the Existing Plants, Emissions, and Capture (EPEC) Program, the overall programmatic goal for the carbon sequestration scenario (of which carbon capture is the key step) is to develop fossil fuel conversion systems that achieve 90 percent CO_2 capture with 99 percent storage permanence at less than a 35 percent increase in the cost of energy services for post- and oxy-combustion capture at new and existing PC-fired power plants. Sorbent-based capture techniques have the potential to meet this programmatic goal.

10: NT0005649

Project Number	Project Title			
NT0005649	Evaluation of Solid Sorbents as a Retrofit Technology for CO_2 Capture from Coal Fired Plants			
Contacts	**Name**	**Organization**	**Email**	
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Partners	EPRI Southern Company Stantec Consulting, Ltd			
Stage of Development				
__Fundamental R&D	_x_Applied R&D	__Prototype Testing	__Proof of Concept	__Demonstration

Technical Background

State-of-the-art aqueous amine systems utilize a temperature swing to capture CO_2 (low temperature) and then release a purified CO_2 stream. Such temperature swing processes are effective, but the process required to regenerate the solution and release the CO_2 has been demonstrated to be highly energy intensive. Solid sorbents used in a similar temperature swing process, often referred to as temperature swing adsorption (TSA), have the potential to significantly reduce the energy penalty associated with CO_2 capture. This energy penalty reduction can be attributed to: (1) the heat capacity of solids is significantly lower than that of water (i.e., by approximately a factor of four), which dramatically reduces the sensible heat input required to accomplish the temperature swing; and 2) the moisture content during regeneration will be significantly lower for solids compared to solvents, so less evaporation will occur. Although CO_2 capture by solid sorbents has yet to be demonstrated on the scale necessary to reduce emissions from power plants, this is not a new technology.

ADA-ES proposed a two-pronged approach to assess the viability and accelerate development of solid sorbents for post-combustion CO_2 capture. One aspect of the project involves assessing sorbent properties through laboratory and pre-pilot evaluations. In a parallel effort potential equipment and process options and their related costs are also being evaluated. A short technical background on the sorbents and the equipment is discussed in the subsequent paragraphs.

For many sorbents, an increase in temperature results in the release of CO_2; the relationship between CO_2 capacity and temperature is the foundation of TSA. Two families of sorbents designed for TSA CO_2 capture are supported reactants and physisorbents. Supported reactants take advantage of a chemical reaction with CO_2 that can be reversed (regeneration) with an increase in temperature. Supported reactants consist of chemicals, usually amines or carbonates, immobilized on a high surface area support. Supports are necessary to improve the contact by increasing surface area and to limit system pressure drop and corrosion effects from the liquid amines, which are viscous and caustic.

Physisorbents are characterized by physical, rather than chemical, adsorption of the CO_2. Examples of physisorbents include zeolites and activated carbon. Most research for CO_2 capture with solids has been directed towards improved sorbent development. However, finding effective means to accomplish gas/solids contacting, heat exchanging, and conveying on the scale required for post-combustion CO_2 capture is also non-trivial. Numerous gas-solid contactor technologies and thermal regeneration processes are used commercially for other purposes within the power generation industry, as well as chemical and mineral processing industries. Examples include: moving-bed, multi-air pollutant control technologies utilizing the Bergbau-Forschung (marketed by Mitsui, Sumitomo, and J-power ReACT); radial-flow contactors like those being developed by Energetics; and fluidized-bed reactors such as those marketed by Lurgi, GSA, and Wulf.

Equipment and operational experience from these and other technologies has been evaluated individually and/or in combination for application to TSA CO_2 capture with the most promising solid sorbents from this program. These technologies have been evaluated for capital cost, O&M, materials of construction, parasitic power, solids attrition, plant footprint requirements, and other technical and economic criteria. The most promising of these technologies have been evaluated more thoroughly for conceptual scale-up and economics to determine the best technology for commercial application.

Relationship to Program

This project will support advances within the post-combustion carbon capture area of the IEP Program. It provides the following benefits:

- Development of an additional technology option for post-combustion CO_2 capture.
- Achieve significant cost reductions for post-combustion CO_2 capture versus state-of-the-art advanced amine systems.
- Development of collaborations to help assess the state of the technology in general.

Primary Project Goal

The primary goal of this project is to collect the data necessary and perform analysis of such data to determine whether solid sorbents have the realistic potential to reduce the costs associated with CO_2 capture compared to a state-of-the-art aqueous amine system.

Objectives

The primary objectives of the project are to assess the viability and accelerate development of solid sorbent-based CO_2 capture technologies that can be retrofit to conventional coal-fired power plants. This will be accomplished by bringing together a multi-disciplinary team of experts to advance the understanding of the technology. Technology issues and critical hurdles will be identified and addressed. The specific objectives are as follows:

- Identify the most promising sorbents from multiple developers.
- Determine whether 90 percent CO_2 capture is achievable long term on actual flue gas.
- Determine whether CO_2 capture can be implemented with <35 percent increase in LCOE.
- Complete a conceptual design for integration of CO_2 capture process into a commercial-scale power plant.

11: FE0000458

Project Number	**Project Title**			
FE0000458	CO_2 Capture from Flue Gas Using Solid Molecular Basket Sorbents			
Contacts	**Name**	**Organization**	**Email**	
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Principal Investigator	Chunshan Song	Pennsylvania State University	csong@psu.edu	
Partners				
Stage of Development				
X Fundamental R&D	__Applied R&D	__Prototype Testing	__Proof of Concept	__Demonstration

Technical Background

According to DOE, the mission of IEP Program is to develop innovative environmental control technologies that will 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 IEP Program portfolio of post- and oxy-combustion CO_2 emissions control technologies and CO_2 compression and reuse is focused on advancing technological options for the existing fleet of coal-fired power plants for addressing climate change.

The current state-of-the-art post-combustion capture technology – aqueous amine scrubbing – is a highly energy-intensive process which is estimated to increase COE by about 75 to 85 percent, while the goal of IEP Program is to achieve 90 percent CO_2 capture with an increase in COE less than 35 percent. Therefore, it is important to develop inexpensive, effective, and robust materials and technologies that can reduce CO_2 emission and are suitable for installation in power plants to maintain the cost-effectiveness of U.S. coal-fired power plants.

Recently, Pennsylvania State University has developed a new sorbent concept for CO_2 capture from flue gas, termed molecular basket sorbent. The idea of molecular basket sorbent development is to load CO_2-philic polymers, such as polyethylenimine, onto high-surface-area mesoporous materials to prepare the molecular basket sorbent, as illustrated in Figure 1.

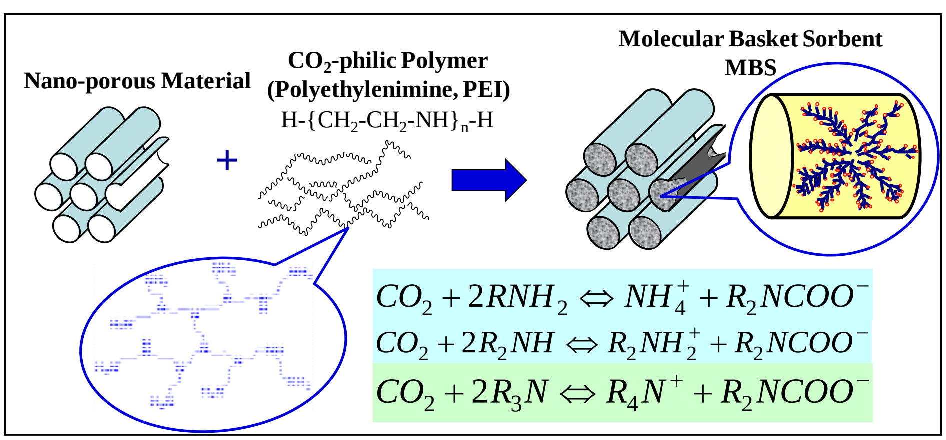

Figure 1: Concept of Molecular Basket Sorbent (MBS) for CO_2 Capture

With this sorbent configuration, the accessible number of sorption sites on/in the sorbent can be greatly increased, and the sorption-desorption rate can be significantly enhanced by increasing the gas-sorbent contacting interfacial area and by improving the mass transfer in the sorption-desorption process. The sorption-desorption performance of the developed molecular basket sorbents has been evaluated in a fixed-bed sorption system in the laboratory scale, including sorption capacity, selectivity, regenerability and stability. The effect of moisture on CO_2 sorption performance of developed molecular basket sorbents has also been examined. Our early studies have indicated that molecular basket sorbent has some potential advantages, including a high sorption capacity (90-140 mg-CO_2/g-sorbent at a CO_2 partial pressure of 15 kPa) with fast sorption-desorption rate, high selectivity (CO_2/N_2 > 1,000, CO_2/O_2 = 180), less or even no corrosion compared to liquid amine, easy regeneration (at 80 to 100°C) with much lower regeneration energy penalty compared to aqueous amine, and promotion effect of moisture on sorption capacity.

In support of the DOE IEP Program mission, the present project focuses on developing a new generation of solid and regenerable low-cost sorbent on the basis of the molecular basket concept for more efficient and cost-effective capture and separation of CO_2 from flue gas of coal-fired power plants, especially to align with the IEP Program goal of 90 percent CO_2 capture at an increase of COE less than 35 percent. To lower the cost of CO_2 capture and storage, an effective CO_2 capture sorbent should possess following key features: (1) high CO_2 working capacity and long-term regeneration capacity; (2) fast sorption-desorption rates; (3) low regeneration energy requirement; (4) high thermal and chemical stability; and (5) low cost for materials. Although the early generation of molecular basket sorbents (using MCM-41 and SBA-15) has shown the potential, the use of MCM-41 and SBA-15 could significantly increase the cost for the sorbent preparation. The preliminary estimation on the cost for MCM-14 and SBA-15-based molecular basket sorbent material shows a base value of ~$800/kg. In order to support the program and align with the program goal, it has become necessary and important for us to identify much cheaper materials for molecular basket sorbent preparation. At the same time, we need to maintain the other advantages of MBS, including high capacity, fast sorption-desorption rate, easy regeneration, and high thermal and chemical stability, which are the main efforts of this project. The basic knowledge and fundamental understanding on CO_2 sorption over molecular basket sorbent materials including effect of porosity of nanoporous substrates, effect of sorption conditions (e.g., temperature, pressure, etc.), effect of polymer loading, the interaction between polymer and inorganic nanoporous substrate, the interaction between CO_2 molecules and polymeric sorption sites, the relationship between the sorbent structure and the sorption performance, and CO_2 sorption mechanism, will be necessary for further development of new sorbents with improved sorption capacity. With the aid of a computational approach, a deeper insight into the CO_2 sorption mechanism and the interactions between CO_2 and polymeric sorption sites, polymer and inorganic nanoporous substrate can be attained, which can facilitate the project work for development of new molecular basket sorbent for efficient and cost-effective CO_2 capture from flue gas of coal-fired power plants.

Relationship to Program

This project will support advances within the post-combustion carbon capture area of the IEP Program. The use of low-cost raw materials for the preparation of a new generation of molecular basket sorbent while maintaining the merits of early generation of high-cost molecular basket sorbents, including high sorption capacity and selectivity, fast sorption-desorption rate, low energy for regeneration, and good thermal and chemical stability, may provide a promising type of solid sorbent materials which could meet the IEP Program goal of higher than 90 percent CO_2 capture with a COE increase less than 35 percent. In addition, combined with the fundamental understanding on the physical and chemical properties of molecular basket sorbent, the interactions between polymer and nanoporous substrate, CO_2 and polymeric amine sites, and CO_2 sorption mechanism, the current project work has the potential to lead to a breakthrough technology for the efficient and cost-effective capture of CO_2 from flue gas of coal-fired power plants.

Primary Project Goal

The primary goal of this project is to develop a new generation of low-cost, solid and regenerable polymeric molecular basket sorbent for more efficient capture and separation of CO_2 from flue gas of coal-fired power plants.

Objectives

In support of the project primary objective, there are two specific goals for this project, including: (1) to develop a new generation of molecular basket sorbent, which have a regenerable working sorption capacity higher than 70 mg-CO_2/g-sorbent; and (2) to lower the cost for the sorbent preparation compared to the early generation of molecular basket sorbent including MBS-1 and MBS-2 (the first and second generation of molecular basket sorbent, i.e., MCM-41 and SBA-15 based molecular basket sorbent, respectively). To achieve the project objectives, the following approaches have been proposed:

1) Optimizing the combination of CO_2-philic polymers and nanoporous materials to further enhance CO_2 sorption capacity.
2) Searching inexpensive and commercially-available nanoporous materials, such as fused silica and silica gel as well as porous carbon materials to replace mesoporous molecular sieves such as MCM-41 and SBA-15, for preparation of the new generation of molecular basket sorbent to significantly reduce the cost for the sorbent.
3) Evaluating the sorption performance of the developed new generation molecular basket sorbents in a laboratory-scale, fixed-bed sorption system, including the sorption capacity, selectivity, regenerability, and stability, and determining the best conditions for CO_2 sorption and desorption.
4) Conducting a computational chemistry approach to estimate the heats of sorption of CO_2 on different molecular basket sorbents and the kinetics barriers for the diffusion of CO_2 sorbate in the bulk of the sorbent to gain a fundamental understanding of the sorption mechanism, which can ultimately benefit the development, design, and modification of the sorbents and the process.
5) On the basis of the experimental data, conducting a preliminary technical and economic analysis of the developed sorbent and the corresponding process using molecular basket sorbent material.

12: FE0000493

Project Number FE0000493	**Project Title** Recovery Act: Design and Testing of CO_2 Compression Using Supersonic Shock Wave Technology			
Contacts DOE/NETL Project Mgr.	**Name** Timothy Fout	**Organization** NETL – Existing Plants Division	**Email** Timothy.Fout@NETL.DOE.GOV	
Principal Investigator	Aaron Koopman	Ramgen Power Systems	akoopman@ramgen.com	
Partners	Dresser Rand Company			
Stage of Development				
__Fundamental R&D	__Applied R&D	__Prototype Testing	_x_Proof of Concept	__Demonstration

Technical Background

The mission of DOE's EPEC 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 EPEC R&D Program portfolio of post- and oxy-combustion CO_2 emissions control technologies and CO_2 compression is focused on advancing technological options for the existing fleet of coal-fired power plants in the event of carbon constraints. These projects will accelerate carbon capture R&D for industrial sources toward the goal of cost-effective CCS within 10 years.

Studies conducted by DOE have revealed the high cost and energy requirements that exist for CO_2 compression. The CO_2 captured from a power plant will need to be compressed to 1,500 to 2,200 psia to be effectively transported via pipeline and injected into an underground sequestration site. The energy requirement for compression can be as much as 9 to 10 percent of the electrical output of a subcritical pressure, coal-fired power plant, which represents a potentially large auxiliary power load on the overall power plant system. Reduction of the compression cost and energy requirements will be beneficial to the overall efficiency of CCS for both utility and industrial applications.

Ramgen Power Systems (Ramgen) has developed an advanced CO_2 compression technology utilizing supersonic shock waves that can lower the cost of CCS and reduce GHG emissions. Integrated with the development of the CO_2 compressor, a novel concept engine for power generation will be developed that combines shock wave compression and advanced vortex combustion (AVC) to offer significant cost savings over conventional designs. This innovative engine shows potential as an important tool for load leveling with renewable power generation operations, further reducing emissions of GHGs, as well as generating power with fugitive methane emissions from coal mines.

The Innovation of the Ramgen Compressor

Historically, the most important breakthroughs in technology result from new combinations of well-known technologies from diverse fields. The Ramgen compressor combines Aero-based shock wave compression with Turbomachinery technology to create a revolutionary compressor product that has enormous advantages, particularly with heavier gases such as CO_2. Dresser-

Rand, the leading compressor manufacturer in the world, recently described this Ramgen technology as “game changing.”

This innovation is particularly important because of the fundamental limitations which conventional compressors have when applied on CO_2. A revolutionary breakthrough of the significance promised by the Ramgen technology is required to reduce the cost of compressing CO_2 to achieve affordable CCS.

A principal advantage of Ramgen’s shock compression is that it can achieve exceptionally high compression efficiency at very high single-stage compression ratios, resulting in a product simplicity and size that will lower both manufacturing and operating costs.

Unique
To the best of our knowledge, Ramgen is the only company in the world which is developing a fundamentally new approach to the compression of heavy molecular weight gases such as CO_2. Additionally, shock wave-based compression appears to be the only way to provide heat of compression at a high enough temperature to integrate into the power plant and/or CCS processes.

In addition to the cost advantages and as a direct result of the Rampressor being able to achieve single-stage compression ratios of 10:1, stage discharge temperatures are estimated to range between 450 to 500°F, depending on inlet gas and cooling water temperatures. This temperature level offers the potential for significant heat integration, without compromising compressor performance. The combined compressor and heat recovery creates an energy-efficiency advantage by recovering 70 to 80 percent of the electrical input energy in the form of useful heat. Potential uses for the available heat are to regenerate capture process solvents or pre-heat boiler feedwater.

Relationship to Program
This project will support advances within the carbon capture area of the IEP Program. The project provides the following benefits:

a) Lower energy consumption
b) Fuel cost savings
c) Electricity cost savings
d) Emissions reduction
e) U.S. equipment exports
f) Re-powering of older fossil plants
g) Use of coal, our Nation’s most abundant fossil fuel
h) Creation of U.S. jobs
i) Keeping U.S. businesses competitive

The major benefit of the proposed work will be a significantly lower capital, space, and maintenance costs, and significantly lower power requirement for CO_2 compression in support of Clean Coal, FutureGen, and CCS. The successful development of the Ramgen CO_2 Compressor will also serve to save and expand a compressor manufacturing and technology base in the United States, creating economic opportunity and jobs. Today, there are no large-scale integrally geared CO_2 turbo-compressors manufactured in the United States.

In addition to meeting the basic objective of CO_2 compression at lower capital and operating costs with higher system efficiencies, the development of the Ramgen CO_2 compressor will also provide an advanced technology platform to support other IGCC and FutureGen needs as follows:

ISC Engine – Unique Capability to Use Dilute Fuels to Generate Electricity

The ISC Engine will have the capability to generate electricity efficiently and cost-effectively using dilute methane gases released during coal mining operations and from landfills. This unique opportunity is based on the combustion of the air/methane mix occurring virtually instantaneously following its supersonic compression, thereby eliminating the possibility of premature ignition, combustion, or detonation.

Importance of Reducing Methane Emissions

Methane is the second largest anthropogenic GHGs contributor, after CO_2, to global warming. Methane traps 21 times more heat in the atmosphere, per volume, than CO_2. Eliminating 1 ton of methane equals 21 tons of CO_2. The estimated volumes of methane released into the atmosphere annually by mining coal worldwide ranges from 462 to 756 $MMTCO_2E$.

Because methane remains in the atmosphere for approximately 10 years, compared to 100 years for CO_2, cutting methane emissions produces results in a shorter time frame and is critical to a realistic GHG strategy over the next 20 years. Experts, including Dr. James Hansen at NASA, have proposed that a comprehensive multi-gas strategy would be immediately effective in mitigating climate change.

Direct ingestion of the dilute methane/air mixtures by gas turbines is highly problematic. Methane becomes explosive at atmospheric pressure and normal temperatures in concentrations of approximately 15 percent. As the pressure increases, the gas becomes explosive at lower concentrations. By the time the methane is compressed sufficiently to enter a turbine engine (approximately 6 to 10 atmospheres), it can be explosive down to one to two percent of the volume. Thus, while a small percentage of methane is non-flammable at atmospheric conditions, it becomes explosive as it progresses through the compressor stage of the gas turbine and its pressure and temperature are increased. As a result, dilute methane becomes susceptible to flash-back. With reciprocating engines, the detonation of the dilute methane/air mixtures prior to the completion of the compression stroke of the pistons prevents the engine from working properly.

Market Driven Application of the Ramgen Engine with Dilute Methane

In the ISC Engine, the combustion air and the fuel are pre-mixed, compressed, and burned nearly instantaneously; as a result, the explosion takes place where it is needed, in the combustor, and methane in the combustion air directly contributes to the total system fuel requirement. The capability of the Ramgen ISC Engine to operate at partial loads without losing significant efficiency is also a major advantage as the methane coming off the mines varies for reasons ranging from mine operations to air pressure changes caused by weather systems.

Engineers from the Jim Walter Resources mining company and Ramgen staff developed an approach that can use up to 75 percent of the methane worldwide now being emitted into the atmosphere as fuel to generate electricity. Currently, approximately 90 percent of this methane is vented directly into the atmosphere.

Multiple General Applications for the ISC Engine

Uniting high efficiency with low capital and operating costs and very low emissions of NO_X, even when being throttled down by as much as 50 percent, this engine will be used in multiple applications. The low capital and operating costs are based on system studies done for this technology. By recovering and using the exhaust heat through combined cycle applications, system efficiencies on the order of 50 percent are projected and one possibility for widespread application is this engine sparking new interest in "distributed generation."

The ISC Engine as Back Up to Burn High Flame Speed Fuels

A unique feature of the ISC Engine is its very high combustor inflow velocity. The fuel/air premix velocity entering the combustor is so high that even fuels with very high flame speeds can be premixed, ingested and burned by the ISC Engine without danger of combustion flash-back.

The fuel streams generated by many of the coal gasification projects currently under consideration have high hydrogen concentration levels. Since hydrogen has a flame speed almost eight times that of natural gas (methane), the ISC Engine system could accommodate these high flame speed fuels with little or no modification. The ISC Engine is a flexible and cost-effective backup to work being done with other technologies to burn hydrogen in coal gasification projects.

Primary Project Goal

The project goal is the integrated development of high-efficiency, low-cost CO_2 compression using supersonic shock wave technology to significantly reduce capital and operating costs associated with CCS, and of the ISC engine to lower capital and operating costs and increase cogen efficiencies to 80+ percent. The heat power ratio would approach 1:1.

Objectives

The project objectives are detailed in five Phases. Phase 1 objectives are to show the feasibility of high-pressure shock wave compression by testing a high-pressure ratio air compressor rotor and evaluating a number of candidate conceptual configurations. Phase 2 objectives are to identify and reduce technical risk areas through the execution of a critical success factors/risk reduction validation and test program, and to complete the 13,000 hp proof-of-concept supersonic shock wave CO_2 compressor preliminary and final designs. The Phase 3 objective is to operate the proof-of-concept supersonic shock wave CO_2 compressor producing supercritical CO_2 at approximately 1,500 psia. Phase 4 objectives are to expand the CO_2 key aerodynamic scaling algorithms and shock compression flow-path refinements for the proof-of-concept ISC engine power wheel and apply them to the optimization and efficiency improvement of the CO_2 compressor rotor. Phase 5 objectives are to scale the ISC engine power wheel up to a 5-MW size, which will provide further design rules and refine performance scaling algorithms that can be directly applied to support the design refinement and optimization of the shock compression section of the CO_2 compressor rotor.

13: FY11.611.CAP.1610241

Project Number	Project Title			
FY11.611.CAP.1610241	Sorbent Development for CO_2 Removal for Fuel Gas Applications			
Contacts	**Name**	**Organization**	**Email**	
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Partners	Air Liquide			
Stage of Development				
__Fundamental R&D	__x Applied R&D	__Prototype Testing	__Proof of Concept	__Demonstration

Technical Background

IGCC is an efficient power generation system and coal gasification will become an important technique for power generation in the future. The coal gas produced in an IGCC plant consists mainly of H_2 and CO, which can be converted to CO_2 and additional H_2 by the WGS reaction. Removal of CO_2 after the WGS reactor will produce a gas stream containing a large percentage of hydrogen. Carbon dioxide removal process systems would be more energy efficient for IGCC systems if the sorbents were operational at warm gas temperatures (150 to 350°C).

A novel magnesium hydroxide-based sorbent that can capture CO_2 from 200 to 315°C and 280 psi was developed and patented by NETL researchers. The sorbent is also regenerable at 375 to 400°C. The capture process with these novel warm gas CO_2 removal sorbents involves a chemical reaction, as shown in Reaction 1 below. The novel sorbent has a CO_2 sorption capacity near 4 mol/kg of sorbent at 200 to 315°C, which is a considerably higher capacity than that of the commercial Selexol process.

$$Mg(OH)_2\ (s) + CO_2\ (g) \rightarrow MgCO_3\ (s) + H_2O \qquad (1)$$

The carbonate formed during the reaction can be thermally decomposed to release CO_2 and regenerate according to the reaction as described in Reaction 2 at 375 to 400°C.

$$MgCO_3\ (s) + H_2O \rightarrow Mg(OH)_2\ (s) + CO_2 \qquad (2)$$

Reaction 2 may also occur in two reaction steps as shown in Reactions 3 and 4:

$$MgCO_3\ (s) \rightarrow MgO\ (s) + CO_2\ (g) \qquad (3)$$
$$MgO\ (s) + H_2O\ (g) \rightarrow Mg(OH)_2\ (s) \qquad (4)$$

In order to have an economical process, the feasibility of these reactions and heat integration of these reactions have to be considered.

Sorbent development and process analysis work with the $Mg(OH)_2$-based sorbent will be presented. The sorbent was tested in both fixed-bed and fluidized-bed flow reactors at zero to 280 psig with gas streams containing CO_2 (simulated gas steam from WGS reactor outlet). The CO_2 sorption experiments were conducted at 200°C and regeneration was conducted at 350 to 425°C. High CO_2 capture capacities (4 moles/kg) were obtained during the reactor tests. Rehydroxylation process (Reaction 4) prior to CO_2 capture was critical for the process. High pressure appeared to be favorable for the CO_2 capture process with the sorbent. It was also possible to regenerate the material at high pressure, which will contribute to lower the compression costs associated with CO_2 sequestration.

Process analysis was conducted with the sorbent combined with thermodynamic predictions to evaluate the sorbent integration into an IGCC power plant using a previous NETL study as the baseline (Cost and Performance Baseline for Fossil Energy Plants-DOE/NETL-2007/1281). The energy analysis consisted of designing a three-reactor system consisting of an absorber, regenerator, and hydroxylator that could be implemented in an IGCC power plant with a GEE gasifier. The results of the energy and thermodynamic analysis indicate that the steam usage was a significant source of energy consumption. Steam usage was minimized by recycling the CO_2 free fuel gas from the WGS reactor to hydroxylate the sorbent. Further investigation showed the decomposition of the carbonate, Reaction (3), consumed the most energy while the hydroxylation, Reaction (4), released a similar amount of energy. Combining these reactions would greatly minimize the overall energy consumption of the capture system. It was estimated that approximately 50 percent of the sorbent could be hydroxylated in the decomposition reactor when steam was applied directly to the decomposition reactor. Flow reactor test data demonstrated that both regeneration and hydroxylation can be combined into a single-step regeneration conducted in a single reactor. When energy analysis was conducted using the single step regeneration as applied to the GEE IGCC power plant, the energy requirements for CO_2 removal are lower than that of the current commercial Selexol CO_2 removal process.

During the process analysis, a unique feature of the $Mg(OH)_2$ sorbent was utilized. Reaction (3) shows that for every mole of CO_2 captured a mole of H_2O is released. This feature was utilized to reduce the amount of shift steam required for the WGS reactor. The addition of the pre-WGS CO_2 capture made the energy requirements for $Mg(OH)_2$ highly favorable over the Selexol process.

Relationship to Program

This project will support advances within the pre-combustion, carbon capture area of the CS Program. The project provides the following benefits:

- Cooling of the fuel gas for CO_2 removal with the $Mg(OH)_2$ sorbent from IGCC-based systems is not required as with the Selexol process.
- The sorbent is insensitive to the steam content in the fuel gas stream.
- Currently there are no CO_2 removal sorbents for warm gas temperature and if the project is successful it can be applied to IGCC systems and to enhance WGS reaction for production of H_2.
- The sorbent has a higher CO_2 capture capacity than that with Selexol.
- Other warm gas clean up technologies for sulfur, HCl, and ammonia removal can be used if there is a warm gas temperature CO_2 removal process available.
- Energy analysis data for the process showed improved efficiency compared to that with Selexol.

Primary Project Goal

Develop commercial systems that result in a less than 10 percent increase in the cost of energy services.

Objectives

- To develop a warm-gas CO_2 capture sorbent that is more energy efficient than the existing capture technologies, such as Selexol.
- Conduct experiments to evaluate the sorbents capture, regeneration, and hydroxylation reactions to obtain a more economical process than the current commercial processes.
- Minimize energy for regeneration.
- Conduct a complete system analysis incorporating the sorbent and minimize the energy required to remove the CO_2 from the exhaust gas.
- Work with external partner to commercialize the sorbent.

14: FE0000465

Project Number	Project Title			
FE0000465	Evaluation of Dry Sorbent Technology for Pre-Combustion CO_2 Capture			
Contacts	**Name**	**Organization**	**Email**	
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Partners	University of Illinois Urbana-Champaign/Illinois State Geological Survey (UIUC/ISGS) Illinois Clean Coal Institute			
Stage of Development				
__Fundamental R&D	X Applied R&D	__Prototype Testing	__Proof of Concept	__Demonstration

Technical Background

URS Group, Inc. is leading an R&D effort focused on the development of a dry sorbent process that combines the WGS reaction with CO_2 removal for coal gasification systems. The result will be a sorption-enhanced water-gas shift (SEWGS) process. A conventional method to produce a high purity hydrogen gas stream from a coal gasification syngas involves a catalytic WGS reaction to convert CO and H_2O to H_2 and CO_2 and then remove the CO_2 in a separate downstream unit, as shown in Figure 1. The SEWGS process combines the WGS reaction with CO_2 capture in one reactor unit, also shown in the Figure 1. The process concept includes *in situ* capture of CO_2 on a solid sorbent bed, thus reducing or even eliminating the need for a WGS catalyst. Additional benefits of this process would include eliminating the need for a separate CO_2 capture system and, subsequently, the need for gas cooling and reheating. As a result, overall process power requirements would be lower.

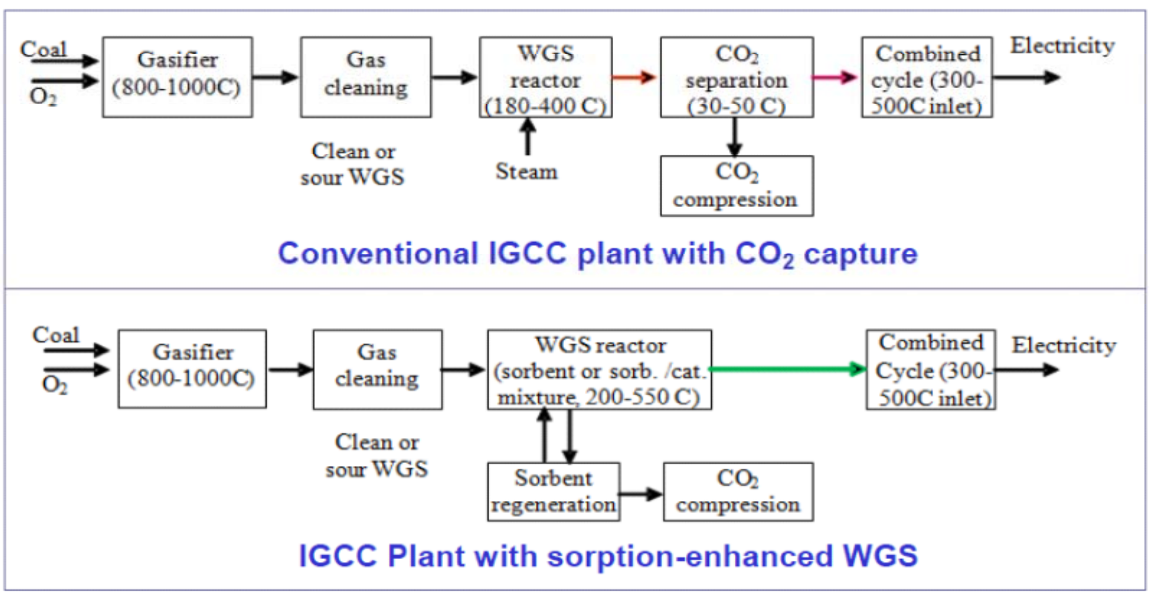

Figure 1: IGCC with SEWGS vs. Conventional IGCC

The WGS reaction is equilibrium limited, which implies that CO conversion increases with decreasing reaction temperature. In practice, however, both a high- (300 to 500°C) and low-temperature (180 to 300°C) shift catalyst are operated in series to convert most of the CO at high temperature and then achieve near complete CO conversion at a lower temperature. For CO_2 removal, the WGS effluent gas is typically further cooled before entering an absorption unit. The proposed CO_2 SEWGS process has a number of significant advantages compared to conventional processes for H_2 production and CO_2 capture, including:

(1) Complete conversion of CO to CO_2 can be achieved at high temperatures (550 to 800°C). This can be illustrated by a SEWGS equilibrium analysis using a CaO sorbent ($CO_2 + CaO = CaCO_3$, $\Delta H = -183\ kJ / mol$), as shown in Figure 2.[2] At temperatures below 750°C, SEWGS achieves complete CO conversion at 25 atm compared to only 40 percent conversion without sorption-enhanced CO_2 removal. A SEWGS process employing an efficient sorbent could significantly reduce the amount of WGS catalyst necessary for a given CO conversion, or even eliminate the need for catalyst at high enough temperatures.

(2) WGS steam requirements could be reduced by shifting the CO conversion equilibrium through the immediate removal of CO_2 produced in the reaction; this would subsequently increase plant efficiency and enhance operational flexibility of an IGCC system, including the CO_2 capture process.

(3) Removing CO_2 from the WGS gas, at a temperature close to the gas turbine inlet temperature, will eliminate the need for gas cooling/heating, thus improving thermal and economic performance of an IGCC plant.

(4) The SEWGS process enables direct production of a CO/CO_2-free H_2 gas stream at the feed gas pressure and eliminates the need for a separate CO_2 separation process. A high purity H_2 product gas can therefore be produced. The key technical issue for advancement of the SEWGS technology is the identification of high-performance, high-efficiency sorbents. This project aims to either identify appropriate commercial sorbents or to engineer sorbents with tailored properties for superior CO_2 capture.

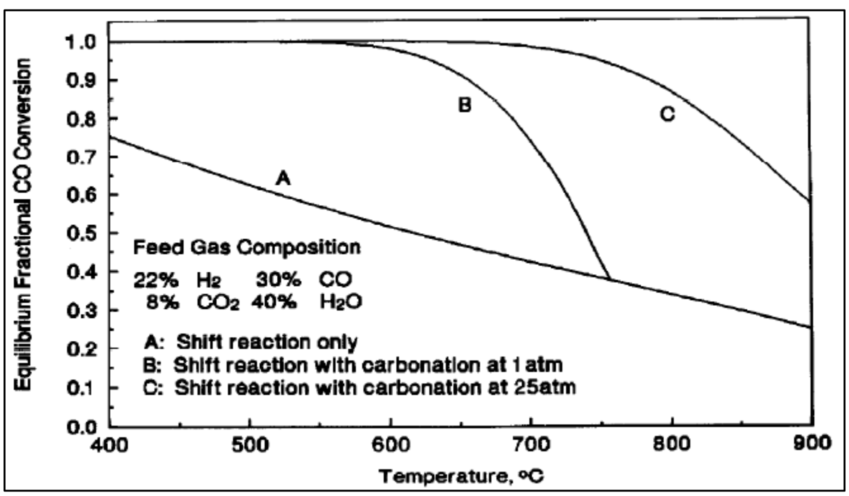

Figure 2: Thermodynamic Equilibrium Analysis: WGS and Sorption-Enhanced WGS

The objective of this program is to enhance the current state-of-the-art for dry CO_2 sorbent technology by developing a means to predict and then fabricate sorbent materials with the reactivities and capacities required for success in this application. In addition, this project will provide important information pertaining to optimal process conditions for CO_2 sorbent adsorption and regeneration at conditions applicable to WGS reactors. A logical approach will

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[2] C. Han and D. P. Harrison, “Simultaneous Shift Reaction and Carbon Dioxide Separation for the Direct Production of Hydrogen.” *Chemical Engineering Science* 1994, 49(248):5875-5883.

be taken to achieve these objectives involving use of several computational studies, including a combination of thermodynamic, process, and molecular modeling integrated with sorbent synthesis activities to identify key sorbent properties and operating conditions needed for effective performance. The resulting information will be used to identify and synthesize sorbents with optimal CO_2 adsorption properties. Sorbents will be evaluated in laboratory screening and parametric tests, designed to validate model predictions and determine optimal process conditions for sorbent adsorption and regeneration performance. A phased testing approach will be taken in which a large number of identified or synthesized sorbents will first be evaluated in a series of screening tests conducted in a high temperature and pressure reactor (HTPR). Screening test results will be used to guide additional sorbent preparation activities, as well as to down-select the number of sorbents evaluated in subsequent laboratory tests focused on evaluating the impacts of syngas impurities, such as H_2S and COS, and performance over multiple adsorption-regeneration cycles. The planned outcome of this program will be the identification of high-performance sorbents, capable of achieving 90 percent CO_2 removal in syngas at operating conditions (temperature [T] and pressure [P]) favorable for energy-efficient WGS operation.

Relationship to Program

This project will support advances within the pre-combustion carbon capture area of the CS Program. Successful completion of this project will demonstrate the feasibility of the sorption-enhanced WGS concept for removing CO_2 from syngas. The separation of CO_2 across a WGS reactor with dry sorbents would reduce or eliminate the need for WGS catalysts and would eliminate the need for a separate downstream CO_2 control process. It would result in a purified CO_2 stream at an appreciably higher temperature and pressure than obtained with existing capture processes, thus reducing the energy required for preparing the stream for subsequent pipeline transport. Specific benefits of a successful SEWGS process would include:

- A 50 to 80 percent decrease in compression costs relative to existing CO_2 capture processes (such as Selexol).
- Decreased steam requirements associated with syngas cooling/reheating (for downstream CO_2 capture).
- Elimination of capital and O&M costs associated with downstream CO_2 capture.

It is acknowledged that capital costs associated with the WGS process will increase as a result of implementing this technology, due primarily to additional vessels and mechanical equipment associated with the dry sorbents. The extent of this increase will be impacted by the properties and performance of the developed sorbents and is expected to be considerably lower than the potential cost reductions described above. Sorbent optimization is an objective of this program and subsequent impacts on WGS capital and O&M costs will be a focus of the techno-economic evaluation.

Primary Project Goal

The DOE CS Program goals include the development of fossil fuel conversion systems that offer 90 percent CO_2 capture with 99 percent storage permanence at less than a 10 percent increase in COE services. This program focuses on the development of a novel CO_2 capture technology that, if successful, will help meet these goals through the use of customized sorbent materials that will enhance the WGS reaction. The project team aims to develop a dry sorbent process that combines CO_2 capture with the WGS reaction by developing and optimizing sorbents to perform in syngas at high pressure and high temperature. The primary project goal is the development dry CO_2 sorbent materials, through the coupling of thermodynamic, molecular simulation, and process simulation modeling with novel synthesis methods, that possess superior adsorption and regeneration properties at conditions applicable to WGS systems. If successful, this project will demonstrate that one or more sorbent materials are able to remove greater than 90 percent of the CO_2 from a simulated syngas at conditions applicable to a WGS reactor, thus meeting a key DOE program objective. Furthermore, a successful project will demonstrate through a detailed techno-economic analysis that DOE COE objectives can be met with SEWGS technology through the development of effective sorbents with superior adsorption-regeneration properties, appropriate reactor design and integration, resulting process enhancements to the WGS reaction (associated with lower steam requirements), and expected future process improvements to IGCC technology. Successful demonstration of DOE performance and cost objectives will validate the feasibility of subsequent scale-up prototype testing of the SEWGS technology.

Objectives

This project is being conducted under DOE's CS Program. A key objective of the DOE program is the removal of the carbon content of a fuel, before it is burned, thereby converting a fossil resource to a nearly carbon-free energy carrier. This project will develop novel sorbents that will operate as part of a SEWGS process capable of achieving greater than 98 percent CO conversion and greater than 90 percent CO_2 removal from simulated syngas at conditions applicable to WGS reactors. If successful, the developed process will enhance the overall CO_2 separation efficiency of a typical IGCC plant configured with a Selexol carbon capture process, while lowering capital and operating costs, thus enabling the DOE target of 10 percent increase in COE to be met.

Specific technical objectives of this project include:

- Determination of optimal CO_2 sorbent properties and process operating conditions for CO_2 removal and subsequent WGS CO conversion in simulated syngas, as well as sorbent regeneration, using a combination of computational and experimental methods. Through thermodynamic and process modeling, determine required sorbent adsorption and regeneration performance specifications for given process operating conditions in order to achieve cost-feasibility for the SEWGS process.
- Development of one or more sorbents that demonstrate high adsorption capacity, provide a means for a properly-designed SEWGS process to recover high-quality heat during CO_2 adsorption, achieve effective sorbent regenerate at elevated pressure, demonstrate minimal sorbent deactivation over multiple cycles, have high selectivity at high temperatures, and display superior thermal stability and mechanical integrity (demonstrated over multiple adsorption/regeneration cycles). This will result in sorbents capable of 90 percent CO_2 removal with high loading capacities and able to operate at the high temperatures and pressures typically encountered upstream of a WGS reactor. If successful, the sorbents developed in this program will augment or replace the CO conversion catalysts currently used in WGS reactors and improve overall WGS thermal efficiency.
- Determine the techno-economic feasibility of the SEWGS process for removing CO_2. Results from the computational and experimental work will be used to estimate the configuration, size, performance, and balance of plant impacts of a SEWGS process. The study will include an assessment of heat and energy requirements and sorbent usage for a permanent system. Capital and operating costs will be projected and compared to those of a standard IGCC plant configured with a Selexol carbon capture process. The study will include estimated costs for compressing the CO_2 product stream for pipeline transport.

Project objectives will be achieved through the execution of five primary tasks: Project Management and Planning; Sorbent Engineering Analysis and Selection; Sorbent Preparation;

Sorbent Evaluation Testing; and Engineering Feasibility Study. The project work breakdown structure (WBS) is listed in Table 1. A flowchart outlining the project path is shown in Figure 3. Project logic flow for decision making ensures that tests are conducted in a logical order with appropriate samples and conditions.

Table 1: Project Work Breakdown Structure

Task	Description	Task	Description
1	**Project Management and Planning**	**3**	**Sorbent Preparation**
1.1	Project Management Plan	3.1	Sorbent Synthesis
1.2	Recipient Project Management	3.2	Analytical Characterization
1.3	Project Kickoff Meeting	**4**	**Sorbent Evaluation Testing**
1.4	Test Plan, QA/QC Plan	4.1	HTPR Parametric Testing
1.5	Laboratory Mobilization	4.2	Syngas Impurity Testing
2	**Sorbent Engineering Analysis & Selection**	4.3	Sorbent Regeneration Testing
2.1	Sorbent Thermodynamic Analysis	4.4	Analytical Characterization
2.2	Process Simulation Analysis	4.5	Sorbent Model Development
2.3	Molecular Simulation	**5**	**Engineering Feasibility Study**
2.4	Sorbent Identification and Procurement	5.1	Techno-economic Analysis
		5.2	Scale-up Test Design

Process simulation modeling and sorbent molecular and thermodynamic analyses are being performed to predict optimal sorbent properties (adsorption capacity, multi-cycle stability, composition, heat of reaction, specific heat capacity, specific surface area, density) and identify optimal operating properties (temperature, pressure, space velocity) to maximize the energy efficiency of the combined WGS and CO_2 capture processes. The thermodynamic study includes developing phase equilibrium diagrams for potential sorbents, identifying operating conditions for CO_2 capture, and assessing the impacts of syngas impurities. Molecular simulation studies are used to predict CO_2 adsorption isotherms, thermodynamic properties of sorbents, adsorption kinetics, and sorbent bed dynamics, and identify sorbents with desired properties (i.e., best combination of capacity, kinetics, adsorption and desorption temperature and pressure, stability, etc.) using grand canonical Monte Carlo (GCMC) simulation and integrated Kinetic Monte Carlo (KMC) and Molecular Dynamics (MD) simulation. Process simulation analyses are analyzing various process scenarios for heat integration between SEWGS and IGCC and process energy performance for individual sorbents.
All sorbent development work is being conducted by the University of Illinois at Urbana-Champaign (UIUC). Sorbents are being synthesized with desired pore structure, surface functionality, and composition guided by the combined modeling and bench-scale testing efforts. Sorbents will be synthesized using a variety of precursors, including calcium and magnesium aluminates, clay-based materials, metal oxides and salts, and adsorbent-shift catalyst hybrids. Novel preparation methods, including ultrasonic spray pyrolysis (USP) and mechanical alloying, are being used to synthesis and optimize CO_2 sorbents. Sorbent down-selection will proceed according to the decision tree shown below.

A high temperature and pressure reactor (HTPR) system, capable of operating at 20 bar and 950°C, will be used for screening sorbents for CO_2 removal. Ultimately, promising sorbents will be tested for adsorption and regeneration under simulated WGS conditions in an integrated test reactor. Short-term initial screening tests, however, will involve sorbent evaluation in a reactor exposed to a gas stream containing CO_2 and nitrogen (N_2) over typical CO_2 partial pressure ranges. Nitrogen (N_2) will be used in the mixture to minimize the change in the total flow rate due to the CO_2 removal. An in-line gas chromatograph (GC) will be used to measure the CO_2 concentration in the inlet and effluent gas streams. Tests will be conducted over a range of temperatures (200 to 800°C) and CO_2 partial pressures (up to 15 bar) to obtain CO_2 adsorption isotherms and breakthrough curves; the former will be used to calculate sorbent CO_2 capacity. Breakthrough curves will be used to interpret the dynamics and kinetics of CO_2 adsorption. To evaluate the impact of the WGS reaction on CO_2 adsorption, selected sorbents will be tested using simulated syngas mixtures to identify optimum process conditions to achieve a high level of CO conversion in the syngas. Sorbent tests will be performed both in the presence and absence of a commercial high-temperature WGS catalyst material (e.g., Fe_3O_4/Cr_2O_3 or sulfided Co/Mo) both for comparison and to determine an optimal ratio of sorbent versus catalyst; an optimal ratio will be one that provides high CO conversion rates (>98 percent) using the lowest possible amount of catalyst material and energy. Slurry-fed gasification processes will be simulated in the CO_2 capture tests. Steam to CO volume ratios will be adjusted to 1-3 to simulate the syngas conditioning by steam addition prior to the WGS reaction. A mathematical model will be developed and will include bulk mass and heat balances, the intra-particle mass transfer (using a linear driving force model), and surface reaction kinetics. The model will be used to fit the breakthrough data to determine the dynamics of the sorbent bed and kinetics of CO_2 adsorption and/or WGS conversion reactions.

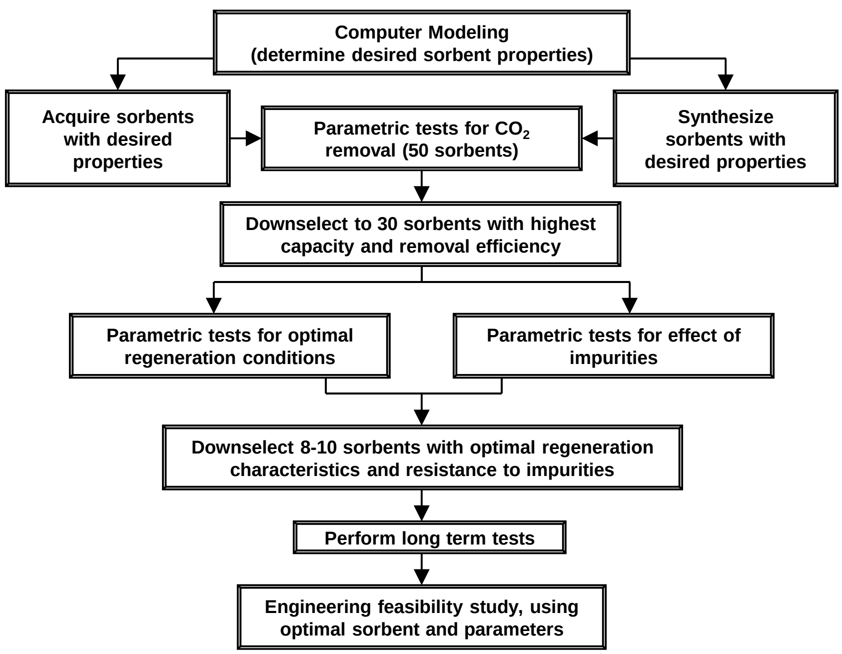

Figure 3. Project Path Flowsheet

URS will construct an HTPR system, capable of integrated adsorption-regeneration testing, to evaluate sorbent adsorption performance in the presence of syngas impurities, such as reduced sulfur species (H_2S, COS), methane, and ammonia. Approximately 30 down-selected sorbents will be tested for sorbent resistance to these syngas impurities. Tests will be conducted in a similar manner as described above to determine the impurity impact on sorbent CO_2 removal and loading capacity but in a gas stream more closely resembling WGS conditions.

Regeneration tests will evaluate the ability to remove captured CO_2 from the sorbents. Following CO_2 adsorption, the simulated WGS reactor gas will be replaced with steam and the reactor will be subjected to the appropriate temperature and/or pressure swing to promote CO_2 desorption. Parametric tests will be used to determine optimal regeneration conditions. It is anticipated that the swing temperature and pressure will be within 250°C and 10 bar, respectively, of the sorbent adsorption conditions. A GC unit will monitor the reactor effluent to acquire information about CO_2 desorption extent and kinetics. Regeneration temperature and pressure will be the primary variables evaluated to identify the optimum conditions for minimum energy use. Current process simulations have identified combustion gas as the most efficient heat source. Regeneration parametric test results will be used to select eight to 10 sorbents for long-term testing, where selected sorbents will be subjected to adsorption/regeneration cycles for a period of one to two weeks. These tests will evaluate sorbent removal performance, regeneration efficiency, and sorbent integrity over multiple cycles.

Laboratory results will be used as the basis for a preliminary engineering study to evaluate the feasibility of the SEWGS process as compared to base WGS operation with other CO_2 removal strategies. The study will evaluate costs for achieving >90 percent CO_2 removal and will include estimates for sorbent costs (initial and operating costs based on anticipated lifetime, i.e., replacement rate, savings because a WGS catalyst is not needed, estimated future market costs of precursor materials, and handling equipment). Process modeling will be used to quantify sorbent regeneration costs, heat/energy integration, compression costs with SEWGS, unit footprint, capital costs, and scalability as compared to conventional removal techniques. Estimated COE costs associated with the SEWGS process will be included. Results from the techno-economic analysis will be used to determine the feasibility of conducting further development of this process.

15: FE0001124

Project Number	Project Title			
FE0001124	Novel Polymer Membrane Process for Pre-Combustion CO_2 Capture from Coal-Fired Syngas			
Contacts	**Name**	**Organization**	**Email**	
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Principal Investigator	Tim Merkel	Membrane Technology & Research, Inc.	Tim.merkel@mtrinc.com	
Partners	Tetramer Technologies, LLC Power System Development Facility at Southern Company			
Stage of Development				
__Fundamental R&D	X Applied R&D	__Prototype Testing	__Proof of Concept	__Demonstration

Technical Background

Three pathways are being considered by DOE for CO_2 capture from fossil fuel power production: post-combustion CO_2 capture from flue gas, pre-combustion capture from syngas, and oxy-combustion, which produces a nearly sequestration-ready CO_2 effluent. This project is directed toward improving the cost and efficiency of CO_2 capture from pre-combustion syngas.

The separation of hydrogen from CO_2 in future IGCC power plants has been the subject of various studies. Current absorption technologies used for this separation are costly, energy intensive, and unlikely to meet DOE CO_2 capture targets. Membrane processes have also been considered for these applications. Key membrane challenges include high membrane cost, low flux, and stability in a challenging thermal and chemical environment; device reproducibility; scale-up issues; and poor understanding of membrane system design. For an IGCC membrane process to be successfully implemented, innovations in the membranes and membrane process designs that address these issues are required.

In this research project, novel gas separation membranes based on newly discovered low-cost polymers are being developed. These membranes can be fabricated into robust, inexpensive modules of the type currently used commercially in the refinery and natural gas industries to separate gas mixtures at high pressures. The target properties of the membranes (hydrogen permeance of 200 gpu and H_2/CO_2 selectivity of 10 at 100 to 200°C), when combined with innovative process schemes, produce membrane systems with significant cost savings over conventional acid gas removal technologies. With further improvements in their separation properties, these polymer membranes show potential to approach the DOE pre-combustion goal of <10 percent increase in the LCOE at 90 percent CO_2 capture.

Relationship to Program

This project will support advances within the pre-combustion carbon capture area of the CS Program. The successful development of proposed membrane technology will provide the following benefits:

- Significantly lower the cost of capturing CO_2 in IGCC power plants. Using the developed membrane process, the increase in the LCOE at 90 percent CO_2 capture is about 16 percent, which is half of the value obtained when using current absorption technologies, such as Selexol.

- Help enable the use of coal, of which the United States has the world's largest reserves, as an environmentally responsible future source of energy and chemical production.

Primary Project Goal

The goal of this project is to develop a cost-effective membrane process that can be used in the relatively near term to capture CO_2 from shifted syngas generated by a coal-fired IGCC power plant

Objectives

A 24-month development program is proposed to evaluate the potential of this low-cost, relatively near-term membrane approach. The specific objectives of the program are to:

- Investigate novel, stable high-temperature polymers identified by Tetramer for use in H_2/CO_2-selective membranes.
- Prepare composite polymer membranes and bench-scale modules that have H_2/CO_2-selectivities of 10 or higher and hydrogen permeances of greater than 200 gpu at desired syngas cleanup temperatures (100 to 200°C).
- Optimize membrane process designs, investigate the sensitivity of different proposed processes to membrane performance, and assess the optimal integration of a membrane system into the syngas cleanup train.
- Conduct bench-scale testing of optimized membranes at MTR's laboratories with simulated WGS syngas mixtures to evaluate membrane performance and lifetime under expected operating conditions.
- Prepare a comparative evaluation of the cost of the polymer membrane-based separation process versus current cleanup technologies (Rectisol, Selexol, and PSA) and proposed future membrane reactors.

16: FE0000896

Project Number	Project Title			
FE0000896	CO_2 Capture from IGCC Gas Streams Using the AC-ABC Process			
Contacts	**Name**	**Organization**	**Email**	
DOE/NETL Project Mgr.	Meghan Napoli	NETL – Gasification Division	Meghan.Napoli@NETL.DOE.GOV	
Principal Investigator	Gopala Krishnan	SRI International	Gopala.Krishnan@sri.com	
Partners	Great Point Energy EIG, Inc.			
Stage of Development				
__ Fundamental R&D	__ Applied R&D	_x_ Prototype Testing	__Proof of Concept	__Demonstration

Technical Background

Capturing CO_2 from coal-fired power plants is a critical step in carbon sequestration. In the IGCC process, which generates electricity more efficiently than do PC combustion power plants, coal is reacted with steam and O_2 under pressure in the range of 300 to 1,000 psi to form a fuel gas containing mainly CO, H_2, H_2S, CO_2, and residual steam. The CO in the gas stream is converted to CO_2 and H_2 by using the WGS reaction at about 200 to 285°C. The gas stream leaving the WGS reactor contains mainly H_2, CO_2, H_2S, and H_2O. An H_2-rich fuel gas suitable for combustion in a gas turbine is produced by condensing the steam and removing the CO_2 and H_2S. The current "best-case" option for carbon capture is using a liquid solvent such as Selexol or Rectisol to absorb CO_2 and H_2S at elevated pressures.

The AC-ABC process for capture of CO_2 and H_2S in the pre-combustion gas stream offers many advantages over other solvent-based technology. The process relies on the simple chemistry of the NH_3-CO_2-H_2O-H_2S system, and on the ability of the aqueous ammoniated solution to absorb CO_2 at near ambient temperatures and to release it as a high-pressure gas at a moderately elevated temperature.

The well-known reaction mechanism between CO_2 and aqueous ammonia is as follows:

$$NH_4OH+CO_2 \Leftrightarrow NH_4HCO_3$$
$$(NH4)_2CO_3+CO_2 + H_2O \Leftrightarrow 2NH_4HCO_3$$
$$NH_4(NH_2CO_2)+CO_2 +2H_2O \Leftrightarrow 2NH_4HCO_3$$
$$NH_4HCO_3 \Leftrightarrow NH_4HCO_3 \text{ (precipitate)}$$

All the reactions are reversible and they go from left to right in the absorber (lower temperature) and from right to left in the stripper (higher temperature). Heat of reaction is in the 300 to 600 Btu/lb of CO_2 range and it depends on temperature and the CO_2/NH_3 ratio of the solution. A similar set of reactions occur between H_2S and ammoniated solution:

$$2NH_4OH + H_2S \Leftrightarrow 2NH_4HS + H_2O$$
$$(NH_4)_2CO_3 + H_2S \Leftrightarrow NH_4HS + NH_4HCO_3$$
$$NH_4HCO_3 + H_2S \Leftrightarrow NH_4HS + H_2O + CO_2$$

Under conditions of interest, the precipitation of sulfide salts does not occur. The release of H_2S can be performed at elevated temperature and at medium pressure in the range of 50 to 150 psi.

The AC-ABC process differs significantly from the Chilled Ammonia Process that is in demonstration level testing at Mountaineer, West Virginia. In the AC-ABC process, the absorption of CO_2 and H_2S is performed at ~50°C at high pressures without the need to chill the gas or the solution below ambient temperature.

The net CO_2 loading in the AC-ABC is in the range 100 to 200 g/liter or three to four times greater than that of the Selexol process. The stripping of CO_2 is accomplished at high pressure comparable to that of the absorber. The combination of low pressure drop and high loading (low solution flow rate) results in dramatically lower power consumption for pumping. The H_2S loading of the AC-ABC 10-20 g/liter is also greater than that of the Selexol process, by about 50 to 100 percent. Due to the higher CO_2 and H_2S loading, the pumping of the solutions between the absorbers and the strippers requires significantly smaller pumps, resulting in greatly reduced pumping power consumption. Also, the AC-ABC process can achieve very low CO_2 and H_2S emission at ambient temperature with no need for chilling.

The solubility of H_2, CO, and CH_4 is very low in the aqueous solution used in the AC-ABC process compared to the Selexol process. Very high recovery of these fuel gas components can be achieved during CO_2 absorption eliminating the need for flash release of these gases at reduced pressures and compressing them back to the feed gas pressure.

In brief, concentrated ammoniated solution is used to capture CO_2 and H_2S from syngas at a high pressure. No refrigeration is needed because absorber operates at or above ambient temperature. High net CO_2 loading up to 20 percent by weight can be achieved, reducing the pumping requirements. The size of the CO_2 stripper and the electric power consumption of the final CO_2 compression are reduced by high-pressure operation. Hydrogen sulfide can be released during solvent regeneration at conditions suitable for sulfur recovery.
These features demonstrates that the AC-ABC process has the potential to meet the DOE objectives of developing a cost-effective CO_2 and H_2S capture process from IGCC gas streams.

Relationship to Program

This project will support advances within the pre-combustion carbon capture area of the CS Program. The successful completion of this project will provide the following benefits:

- Low cost and readily available reagent: Ammonia and ammonium carbonate solutions are easily available commodities at a relatively low cost.
- Reagents are chemically stable under the operating conditions: In contrast to organic solvents, ammoniated solutions do not degrade at high temperatures and hence the solvent make-up requirements are relatively small.
- Low heat consumption for CO_2 stripping: The thermal energy required for CO_2 stripping is about half that of required for amines. This energy consumption results in the generation of CO_2 at elevated pressures off-setting the electrical energy requirement for CO_2 compression.
- Extremely low solubility of H_2, CO and CH_4 in the aqueous absorber solution: This characteristic allows recovery of nearly all such fuel components in the absorber exit gas at near feed gas pressures. In contrast, the organic solvents such as Selexol have a significant solubility for these fuel species at the absorber operating pressures,

necessitating the use of a flash chamber to recover these gases and pumping them back to the gas turbine inlet pressures which has a negative impact on the COE.
- Absorber and regenerator can operate at a similar pressure: Hence, there is no need to pump the solution across pressure boundaries, which results in low energy consumption for pumping and simplifying process operation.

The above cited benefits result in a cost-effective and technically viable process that will allow CO_2 capture from IGCC gas stream commensurate with DOE goals.

Primary Project Goal

DOE's CS Program has a major goal to develop technologies that can separate, capture, transport, and store CO_2 using either direct or indirect systems that result in <10 percent increase in the cost of energy at pre-combustion power plants by 2015. Pre-combustion CO_2 capture has the advantage in that CO_2 can be captured at high temperatures, as compared to cooler conventional scrubbing temperatures, thus providing a thermal efficiency advantage and potentially resulting in lower parasitic power load. This project is funded under the Funding Opportunity DE-PS26-08NT00699-00: Pre-combustion carbon capture technologies for coal-based gasification plants; Topic Area 2: High Efficiency Solvents. The solicitation aimed to identify the most favorable high-efficiency solvents, absorption device designs, solvent recovery, technology validation, and conceptual integration schemes with appropriate components of future IGCC-CCS power production systems.

The project aims to meet the CS Program goal by developing an innovative, low-cost CO_2 capture technology based on CO_2 absorption on a high-capacity and low-cost aqueous ammoniated solution. In this process, the low heat consumption for CO_2 stripping from the solution increases the power plant efficiency. The ammoniated solution is thermally stable reducing solvent replacement operating costs. The CO_2 absorber and stripper units can operate at a similar pressure with no need to pump the solution across pressure boundaries, which results in low energy consumption for pumping and simplifying process operation.

Objectives

The project objectives are to: (1) test the technology on a bench-scale batch reactor to validate the concept and to determine the optimum operating conditions for a pilot-scale reactor; (2) design, construct, and perform tests using a pilot-scale reactor capable of continuous integrated operation; and (3) perform a technical and economic evaluation on the technology. The program will consist of two phases: Phase I – Bench-Scale Testing, and Phase II – Pilot-Scale testing. Both experimental testing, process modeling, and economic analysis will be conducted in each phase, thus providing reliable information for process analysis to meet the DOE goals. The experimental program will consist of three tasks:

The project tasks are:

1. Bench-scale Batch Tests: In this task, a bench-scale test unit will be modified to conduct both absorption and regeneration experiments (Sub task 1.1) and a test plan will be created (Sub task 1.2). The unit will be operated to determine the rate and efficiency of CO_2 and H_2S absorption (Sub task 1.3) and desorption (Sub task 1.4) in an ammoniated solution as a function of temperature, pressure, gas flow rate, solution composition, and other relevant process variables. The data will be analyzed to determine the optimum operating conditions (Sub task 1.5). An ASPEN model will be used to develop a process flow sheet of an IGCC system based on the data from the bench-scale absorber and regenerator tests (Sub task 1.6). The energy required to the capture CO_2 and H_2S will

be estimated. A preliminary economic analysis will be made using DOE guidelines (Sub task 1.7).

2. Pilot-Scale Integrated, Continuous Tests: On approval by DOE, we will proceed to (1) design a pilot-scale system (capable of handling a gas stream of 1 ton/day coal equivalent); (2) construct the system; (3) develop test plans; (4) perform tests using a gas stream from an operating gasifier; (5) perform process modeling; and (6) update the economic analysis to determine the process potential to meet DOE goals.
3. Project Management: We will provide quarterly technical and management reports, present annual briefings, and participate in technical review meeting.

We have made significant progress in Task 1 and on schedule in Task 3. Task 2 will be conducted in Budget Period 2. We demonstrated the operation of a bench-scale system at high pressure (20 bar) and high temperatures (up to 160°C). We achieved very high levels (>90 percent) of CO_2 and H_2S capture efficiency. Regeneration of solution and release of CO_2 and H_2S at high pressures were also demonstrated. Preliminary analysis shows a significant cost improvement over the Selexol case.

APPENDIX F: LIST OF ACRONYMS AND ABBREVIATIONS

Acronym/ Abbreviation	Definition
ABC	Ammonium Bicarbonate
AC	Ammonium Carbonate
AC-ABC	Ammonium Carbonate-Ammonium Bicarbonate
ADA-ES	ADA-ES, Inc., a Company
A/E	Architectural/Engineering
AEP	American Electric Power Company
AIChE	American Institute of Chemical Engineers
APPCD	Air Pollution Prevention Control Division
As	Arsenic
ASME	American Society of Mechanical Engineers
ASU	Air Separations Unit
BA	Bachelor of Arts
BChE	Bachelor in Chemical Engineering
BIAS	Basic Immobilized Amine Sorbent
BOD	Board of Directors
BS	Bachelor of Science
BSF	Boiler Simulation Facility
Btu	British thermal unit
°C	Degree Celsius
CA	Carbonic Anhydrase
$CaCO_3$	Calcium Carbonate
CaO	Calcium Oxide
CaS	Calcium Sulfide
$CaSO_4$	Calcium Sulfate
CCS	Carbon Capture and Sequestration
CDR	Conceptual Design Review
CFB	Circulating Fluidized Beds
CFD	Computational Fluid Dynamic
CH_4	Methane
CIGRE	Conseil International des Grands Electriques
CLC	Chemical Looping Combustion
CLOU	Chemical Looping with Oxygen Uncoupling
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COE	Cost of Electricity
COS/OCS	Carbonyl Sulfide

Acronym/ Abbreviation	**Definition**
Cr_2O_3	Cromium (III) Oxide
CRADA	Competitive Research and Development Agreement
CS	Carbon Sequestration
Cu	Copper
CuO	Cupric Oxide
D-B	Doosan Babcock
DOE	U.S. Department of Energy
EC	Encapsulated Clay
EIA	Energy Information Administration
EPC	Engineering Procurement and Construction (Firm)
EOR	Enhanced Oil Recovery
EPRI	Electric Power Research Institute
FDR	Final Design Review
FE	DOE's Office of Fossil Energy
FGD	Flue Gas Desulfurization
Fe_3O_4	Iron (III) Oxide
FOA	Funding Opportunity Announcement
FY	Fiscal Year
g	Gram
GC	Gas Chromatograph
GHG	Greenhouse Gas
GmbH	Gesselschaft mit beschranker Haftung, legal entity for corporation in Germany and European Union
GTL	Gas-to-Liquids
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen Sulfide
Hg	Mercury
hp	Horsepower
hr	Hour
HTPR	High-Temperature Pressure Reactor
IEEE	Institute of Electrical and Electronics Engineers
IEP	Innovations for Existing Plants
IGCC	Integrated Gasification Combined Cycle
IP	Intellectual Property
IPO	Independent Professional Organization
IPR®	Integrated Pollutant Removal

Acronym/ Abbreviation	**Definition**
ISC	Idle Speed Control
ISO-NE	ISO New England
ITG	Industry Technology Group (an entity within AIChE)
ITM	Ion Transport Membrane
IVCAP	Integrated Vacuum Carbonate Absorption Process
JOC	Jupiter Oxygen Corporation
K_2CO_3	Potassium Carbonate
K_2SO_4	Potassium Sulfate
KBR	Kellogg Brown & Root
Kg	Kilogram
kW	Kilowatt
kWe	Kilowatt Electrical
kWh	Kilowatt Hour
lb	Pound
LES	Large Eddy Simulation
LCOE	Levelized Cost of Electricity
LOI	Loss on Ignition
LTI	Leonardo Technologies, Inc.
MATRIC	Mid-Atlantic Technology, Research & Innovation Center, a company
MBA	Master's Degree in Business Administration
MBS	Molecular Basket Sorbent
MEA	Monoethanolamine
mg	Milligram
$MgCO_3$	Magnesium Carbonate
MgO	Magnesium Oxide
$Mg(OH)_2$	Magnesium Hydroxide
MMBtu	One Million British Thermal Units
MS	Master of Science
MSChE	Master of Science in Chemical Engineering
MTR	Membrane Technology & Research, Inc.
MW	Megawatt
MWe	Megawatt Electrical
MWth	Megawatt Thermal
N_2	Nitrogen
NH_4OH	Ammonia Hydroxide
NH_4HCO_3	Ammonium Bicarbonate

Acronym/ Abbreviation	Definition
$NH_4(NH_2CO_2)$	Ammonium Carbamate
$(NH_4)_2CO_3$	Ammonium Carbonate
NCCC	National Carbon Capture Center
NEMS	National Energy Modeling System
NERC	North American Electric Reliability Corporation
NETL	National Energy Technology Laboratory
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NO_X	Nitrogen Oxide
NRC	National Research Council
O_2	Oxygen
O&M	Operation and Maintenance
OCC	DOE's Office of Clean Coal
OEM	Original Equipment Manufacturer
OMB	Office of Management and Budget
OPPA	Office of Policy and Program Analysis
ORD	Office of Research and Development
OTM	Oxygen Transport Membranes
PC	Pulverized Coal
PC4	Post-Combustion Carbon Capture Center
PDR	Preliminary Design Review
PEI	Princeton Environmental Institute
Ph.D.	Doctor of Philosophy
PI	Principal Investigator
PM	Project Manager
POX	Partial Oxidation
ppm	Parts per million
PSA	Pressure Swing Adsorption
PSDF	Power Systems Development Facility
psia	Pounds Per Square Inch Absolute
psig	Pounds Per Square Inch Gauge
PSTU	Pilot Solvent Test Unit
PSU	The Pennsylvania State University
QA/QC	Quality Assurance/Quality Control
R&D	Research and Development
RD&D	Research, Development and Demonstration
RAM	Reliability, Availability, and Maintainability

Acronym/ Abbreviation	**Definition**
RTI	Research Triangle Institute
SCC	NETL'S Strategic Center for Coal
SCFH	Standard Cubic Foot per Hour
Sec	Second(s)
SEWGS	Sorption Enhanced Water Gas Shift
SMR	Steam Methanol Reformer
SNG	Synthetic Natural Gas
SO_2	Sulfur Dioxide
SO_X	Sulfur Oxide
SRI	SRI International, a Company (formerly Stanford Research Institute)
SSTF	Slip Stream Test Facility
Syngas	Synthetic Gas
T-fired	Tangentially-Fired
TGA	Thermogravimetric Analyzer
TROC™	Transport Oxy-Combustion
TSA	Temperature Swing Adsorption
TSP	Technology Screening Process
UIUC	University of Illinois, Urbana-Champaign
UOP	UOP LLC, a Honeywell Company
USP	Ultrasonic Spray Pyrolysis
VLE	Vapor Liquid Equilibrium
WFGD	Wet Flue Gas Desulfurization
WGS	Water Gas Shift
WGSR	Water Gas Shift Reactor