OVERVIEW REPORT

DOE/NETL Clean Coal Research Program
Carbon Capture Program
FY2015 Peer Review Meeting

Pittsburgh, Pennsylvania
March 16-20, 2015

ASM INTERNATIONAL

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OVERVIEW REPORT
CLEAN COAL RESEARCH PROGRAM
CARBON CAPTURE PROGRAM
FY 2015 PEER REVIEW MEETING

Pittsburgh, Pennsylvania, USA
March 16-20, 2015

NETL Business Management Specialist and Peer Review Coordinator
Eric Bell
(412) 386-5802

Meeting Host Organization
Leonardo Technologies, Inc.
David Wildman
(412) 386-4791

Review Panel
Ravi Prasad, Chair, Peer Review Panel
Stan Theobald, Senior Director, Business Development
ASM International
(440) 338-5151 ext. 5502

Meeting Facilitator and Final Report
Ross Brindle, Nexight Group
(240) 667-7636

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DISCLAIMER

The work performed on this task/subtask was completed under Leonardo Technologies, Inc. (LTI), Prime Contract DE-FE0004002 (Subtask 300.02.03) for DOE-NETL.

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INTRODUCTION AND BACKGROUND

Carbon Capture Program Mission and Goals

The National Energy Technology Laboratory's (NETL) Carbon Capture research and development (R&D) effort is conducted under the Clean Coal Research Program's (CCRP) Carbon Capture and Storage (CCS) and Power Systems Program Area. The CCS and Power Systems Program conducts and supports long-term, high-risk R&D to significantly reduce fossil fuel power plant emissions (including carbon dioxide [CO_2]) and substantially improve efficiency, leading to viable, near-zero-emissions fossil fuel energy systems. The success of NETL research and related program activities will enable CCS technologies to overcome economic, social, and technical challenges, including cost-effective CO_2 capture, compression, transport, and storage through successful CCS integration with power generation systems.

The Office of Fossil Energy (FE) is investigating a broad portfolio of CO_2 capture research pathways in two general Technology Areas: Pre-Combustion Capture and Post-Combustion Capture. Pre-combustion capture is mainly applicable to integrated gasification combined cycle (IGCC) power plants and refers to the removal of CO_2 from synthesis gas (syngas) prior to its combustion for power production. Post-combustion systems are designed to separate CO_2 from the flue gas produced by fossil fuel combustion in air. These Technology Areas are focused on creating technological advances that provide step-change improvements in both cost and performance as compared to current state-of-the-art, solvent-based capture systems. Although efforts are focused on capturing CO_2 from the flue gas or syngas of coal-based power plants, the same capture technologies are also applicable to natural-gas- and oil-fired power plants, as well as other industrial CO_2 sources. Although commercially available solvent-based CO_2 capture technologies are being used in various industrial applications, their current state of development is such that they are not ready for widespread deployment in coal-based power plants. The net electrical output from a fossil-based power plant employing currently available 1st-Generation CO_2 capture and compression technologies will be significantly less than that of the same plant without capture. For the plant with capture, a portion of the energy (thermal and electrical) produced at the plant must be used to operate the CO_2 capture and compression processes. Steam usage decreases the gross electrical generation, while the additional auxiliary power usage decreases the net electrical output of the plant. Implementation of 1st-Generation CO_2 capture would generally result in a 7 to 10 percentage point decrease in net plant efficiency.

The goals of the Pre- and Post-Combustion Capture Programs support the energy goals established by the Administration and the U.S. Department of Energy (DOE). FE estimates that the expected cost to capture 1 metric tonne of CO_2 from a state-of-the-art, coal-based power plant with the most advanced system design is \$60. The goal for the technologies currently under development is \$40/tonne of CO_2 captured. Completion of R&D for these technologies is targeted for 2020, with commercial deployment anticipated after 2025.

Office of Management and Budget Requirements

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 fiscal year (FY) 2015 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. (LTI), ASM International convened a panel of five leading academic and industry experts on March 16–20, 2015, to conduct a five-day peer review of selected Carbon Capture Program research projects supported by NETL. One panelist, Bhadra Grover, became ill and could not travel to the review. Bhadra provided electronic comments for each project that were considered during panel deliberation.

Overview of Office of Fossil Energy Carbon Capture Program Research Funding

The total funding of the 12 projects reviewed, over the duration of the projects, is $43,734,510. The funding and duration of the 12 projects that were the subject of this peer review are provided in Table 1.

TABLE 1. CARBON CAPTURE PROGRAM PROJECTS REVIEWED

Reference Number	Project No.	Title	Lead Organization	Total Funding		Project Duration	
				DOE	Cost Share	From	To
1	FE0013118	Bench-Scale Development of a Hybrid Membrane-Absorption CO_2 Capture Process	Membrane Technology and Research, Inc.	$3,159,653	$789,914	10/1/2013	3/31/2017
2	FE0012926	An Advanced Catalytic Solvent for Lower Cost Post-Combustion CO_2 Capture in a Coal-Fired Power Plant	University of Kentucky	$2,966,957	$742,291	10/1/2013	9/30/2016
3	FE0013687	Bench-Scale Process for Low-Cost CO_2 Capture Using a Phase-Changing Absorbent	GE Global Research	$2,399,961	$599,990	1/1/2014	12/31/2016
4	FE0013122	Supersonic Post-Combustion Inertial CO_2 Extraction System	Alliant Techsystems Operations LLC	$2,999,951	$749,640	10/1/2013	12/31/2016
5	FE0012870	Sorbent-Based Post-Combustion CO_2 Slipstream Testing	TDA Research Inc.	$4,704,509	$1,175,869	2/3/2014	12/31/2017
6	FE0013127	Bench-Scale Development and Testing of Aerogel Sorbents for CO_2 Capture	Aspen Aerogels, Inc.	$2,990,267	$759,145	10/1/2013	9/30/2016
7	FWP-CC-FY14-T7	Post-Combustion Membranes	NETL Office of Research	$855,540	$0	TBD	TBD

Reference Number	Project No.	Title	Lead Organization	Total Funding		Project Duration	
				DOE	Cost Share	From	To
			and Development				
8	FWP-65872	Accelerating the Development of "Transformational" Solvents for CO_2 Separations	Pacific Northwest National Laboratory	$1,761,056	$0	4/1/2014	3/31/2016
9	FE0013105	Pilot Testing of a Highly Effective Pre-Combustion Sorbent-Based Carbon Capture System	TDA Research Inc.	$7,943,382	$1,985,846	10/1/2013	12/31/2017
10	FE0012965	Development of a Pre-combustion Carbon Dioxide Capture Process Using High-Temperature Polybenzimidazole Hollow-Fiber Membrane	SRI International	$2,249,997	$562,504	10/1/2013	10/31/2016
11	FE0012959	Development of Mixed-Salt Technology for Carbon Dioxide Capture from Coal Power Plants	SRI International	$1,838,009	$460,617	10/1/2013	3/31/2016
12	FE0013064	Robust and Energy Efficient Dual-Stage Membrane-Based Process for Enhanced CO_2 Recovery	Media and Process Technology Inc.	$2,000,023	$500,006	10/1/2013	9/30/2016
			TOTALS	$35,869,305	$7,865,205		

OVERVIEW OF THE PEER REVIEW PROCESS

The U.S. Department of Energy (DOE), Office of Fossil Energy (FE), and the National Energy Technology Laboratory (NETL) are fully committed to improving the quality and results of their research projects. To support this goal, in fiscal year (FY) 2015, ASM International was invited to provide an independent, unbiased, and timely peer review of selected projects within DOE FE's Carbon Capture Program. The peer review of selected projects within the Carbon Capture Program was designed to comply with requirements from the Office of Management and Budget.

On March 16–20, 2015, ASM International convened a panel of five leading academic and industry experts to conduct a five-day peer review of 12 research projects supported by the NETL Carbon Capture Program. Throughout the peer review meeting, these recognized technical experts provided recommendations on how to improve the management, performance, and overall results of each individual research project.

In consultation with NETL, who chose the 12 projects for review, ASM International selected an independent peer review panel, facilitated the peer review meeting, and prepared this report to summarize the results.

ASM International performed this project review work as a subcontractor to prime NETL contractor Leonardo Technologies, Inc.

Pre-Meeting Preparation

Several weeks before the peer review, each project team submitted a project technical summary. Additionally, the appropriate Federal Project Manager provided the project management plan and other relevant materials, including a project fact sheet, quarterly and annual reports, and published journal articles, that would help the peer review panel evaluate each project. Seven days before the review, each project team provided a PowerPoint slide deck they would present at the peer review meeting. The panel received all of these materials prior to the peer review meeting via a peer review SharePoint site, which enabled the panel members to come to the meeting fully prepared with the necessary project background information to thoroughly evaluate the projects.

To increase the efficiency of the peer review meeting, a WebEx meeting with the Technology Manager of the Carbon Capture Program was held approximately one month prior to the peer review meeting to provide an overview of the program goals and objectives.

Peer Review Meeting Proceedings

At the meeting, each research team made an uninterrupted 30-minute PowerPoint presentation that was followed by a 30-minute question-and-answer session with the panel and an extended panel discussion and evaluation of each project. The time allotted for the panel discussion was dependent on the individual project's complexity, duration, and breadth of scope. To facilitate a full and open discourse of project-related material between the project team and the panel, all sessions were limited to the panel, ASM International personnel, and DOE-NETL personnel and contractor support staff. Panel members were also instructed to hold the discussions that took place during the question-and-answer session as confidential.

The panel discussed each project to identify the project strengths, project weaknesses, and recommendations for project improvement. The panel designated all strengths and weaknesses as “major” or “minor,” and ranked recommendations from most to least important. The consensus strengths and weaknesses served as the basis for determining the overall project score in accordance with the Rating Definitions and Scoring Plan of the Peer Review Evaluation Criteria Form.

To facilitate the evaluation process, LTI provided the panel with laptop computers that were preloaded with Peer Review Evaluation Criteria Forms for each project, as well as the project materials that the panel members were able to access via SharePoint prior to the peer review meeting.

Peer Review Evaluation Criteria

At the end of the group discussion for each project, the panel came to consensus on an overall project score. The panel used the following rating values as a guide:

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

The Rating Definitions that informed scoring decisions are included in Appendix B of this report.

NETL completed a Technology Readiness Assessment (TRA) of its key technologies in 2014. The Technology Readiness Level (TRL) of projects assessed in 2014 was provided to the panel prior to the peer review meeting. These assessments enabled the panel to appropriately score the review criteria within the bounds of the established scope for each project. Appendix C describes the various levels of technology readiness used in 2014.

SUMMARY OF KEY FINDINGS

This section summarizes the overall key findings of the 12 projects evaluated at the FY 2015 Carbon Capture Program Peer Review.

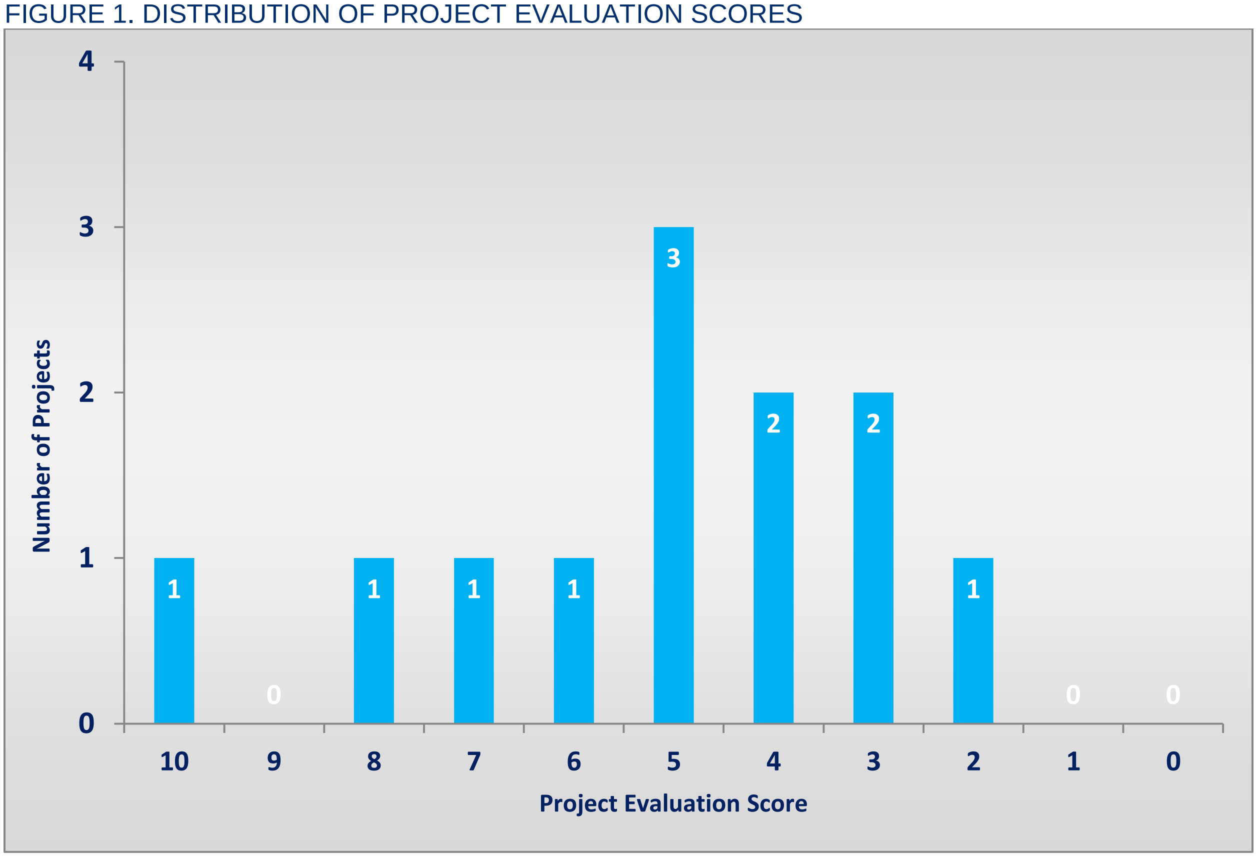
Overview of Project Evaluation Scores

The panel reached consensus on a score for each project using the following rating values as a guide:

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

While it is not the intent of this review to directly compare one project with another, a rating of five or higher indicates that a specific project was viewed as at least adequate by the panel. The distribution of project evaluation scores are shown in Figure 1.

FIGURE 1. DISTRIBUTION OF PROJECT EVALUATION SCORES



PROJECT SYNOPSES

For more information on the Carbon Capture Program and project portfolio, please visit the NETL website: http://www.netl.doe.gov/research/coal/carbon-capture.

01: FE0013118
BENCH-SCALE DEVELOPMENT OF A HYBRID MEMBRANE-ABSORPTION CO_2 CAPTURE PROCESS

Brice Freeman, Membrane Technology and Research, Inc.

Technology Readiness Level: 3	***DOE Funding:*** $3,159,653
Duration: 10/01/2013 – 03/31/2017	***Cost Share:*** $789,914

This project focuses on optimizing the configuration of a hybrid carbon dioxide capture system that combines amine absorption and membrane technology. Polaris™ membranes will be combined with an improved amine solvent-based capture system to increase efficiency and decrease capital and operating costs. Specifically, a bench-scale system will be constructed and two design variations will be tested.

02: FE0012926
AN ADVANCED CATALYTIC SOLVENT FOR LOWER COST POST-COMBUSTION CO_2 CAPTURE IN A COAL-FIRED POWER PLANT

Kunlei Liu, University of Kentucky

Technology Readiness Level: 3	***DOE Funding:*** $2,966,957
Duration: 10/01/2013 – 09/30/2016	***Cost Share:*** $742,291

This project focuses on testing two technologies to improve solvent-based capture: absorption catalyzation and membrane dewatering of CO_2-loaded solvent. Small-molecule organometallic carbonic anhydrase enzyme mimics enhanced absorber kinetics, and dewatering increases stripper driving force, yielding reductions in capital and operating costs. Specifically, impacts of these technologies will be evaluated through bench-scale parametric testing.

03: FE0013687
BENCH-SCALE PROCESS FOR LOW-COST CO_2 CAPTURE USING A PHASE-CHANGING ABSORBENT

Tiffany Westendorf, GE Global Research

Technology Readiness Level: 3	***DOE Funding:*** $2,399,961
Duration: 01/01/2014 – 12/31/2016	***Cost Share:*** $599,990

This project focuses on developing and testing an amino-silicone-based phase-change process for carbon dioxide (CO_2) capture. The solvent readily forms a solid in the presence of CO_2 in a thermally reversible reaction with no degradation of the solvent, which decreases operating cost. Specifically, bench-scale testing and analysis will be conducted to show the feasibility and scalability of the process.

04: FE0013122
SUPERSONIC POST-COMBUSTION INERTIAL CO_2 EXTRACTION SYSTEM

Anthony Castrogiovanni, ACENT Laboratories; and Vladimir Balepin, Alliant Techsystems Operations LLC

Technology Readiness Level: 3	***DOE Funding:*** $2,999,951
Duration: 10/01/2013 – 12/31/2016	***Cost Share:*** $749,640

This project focuses on utilizing a unique aero-thermodynamic inertial separation device derived from aerospace applications to capture carbon dioxide (CO_2). The inertial CO_2 extraction system converts vapor-phase CO_2 to solid CO_2 via supersonic expansion followed by inertial separation, resulting in decreased capital and operating costs. Specifically, bench-scale testing will be conducted to confirm the feasibility of the process.

05: FE0012870
SORBENT-BASED POST-COMBUSTION CO_2 SLIPSTREAM TESTING

Jeannine Elliott, TDA Research, Inc.

Technology Readiness Level: N/A	***DOE Funding:*** $4,704,509
Duration: 02/03/2014 – 12/31/2017	***Cost Share:*** $1,175,869

This project focuses on the scale-up of an alkalized alumina adsorbent capture system. The effectiveness of the system has been established through laboratory, bench-scale, and field testing. Specifically, a 0.5-MWe slipstream pilot plant will be designed, built, and operated at the National Carbon Capture Center (NCCC).

06: FE0013127
BENCH-SCALE DEVELOPMENT AND TESTING OF AEROGEL ABSORBENTS FOR CO_2 CAPTURE

George Gould, Aspen Aerogels

Technology Readiness Level: 3	***DOE Funding:*** $2,990,267
Duration: 10/01/2013 – 09/30/2016	***Cost Share:*** $759,145

This project focuses on scale-up and testing of an advanced aerogel sorbent-based capture technology. The aerogels have high surface area and porosity and excellent hydrophobicity for resisting performance degradation from moisture and flue gas contaminants, resulting in reduced operating costs. Specifically, the performance of amine-functionalized powdered and pelletized aerogel formulations will be assessed at the bench scale.

07: FWP-CC-FY14-T7

POST-COMBUSTION MEMBRANES

Surendar Venna, National Energy Technology Laboratory (NETL)

Technology Readiness Level: 3	***DOE Funding:*** $1,886,168
Duration: TBD – TBD	***Cost Share:*** $0

The focus of this project is to evaluate mixed-matrix membranes (MMM) that contain metal organic frameworks (MOFs). Integrating MOFs into a polymer membrane increases the selectivity and permeance of the membrane, lowering capital costs and energy requirements. Specifically, multiple techniques will be employed to improve polymer/MOF compatibility, including creation of strongly MOF-interactive polymers, layer-by-layer polymer encapsulation of MOF nanocrystals, and emulsion-based fabrication techniques.

08: FWP-65872
ACCELERATING THE DEVELOPMENT OF "TRANSFORMATIONAL" SOLVENTS FOR CO_2 SEPARATIONS

David Heldebrant and Vassiliki-Alexandra Glezakou, Pacific Northwest National Laboratory (PNNL)

Technology Readiness Level: N/A	***DOE Funding:*** $1,761,056
Duration: 04/01/2014 – 03/31/2016	***Cost Share:*** $0

This project focuses on the advancement of the CO_2 binding organic liquid (CO_2BOLs) solvent platform-based capture system. Cost reduction and improved transport properties of loaded solvents (less than 50 cP) will be emphasized. Specifically, CO_2BOL solvents will be optimized, synthesized, and characterized to identify candidates with acceptable cost and transport properties.

09: FE0013105
PILOT TESTING OF A HIGHLY EFFECTIVE PRE-COMBUSTION SORBENT-BASED CARBON CAPTURE SYSTEM

Gokhan Alptekin, TDA Research, Inc.

Technology Readiness Level: 5	***DOE Funding:*** $7,943,382
Duration: 10/01/2013 – 12/31/2017	***Cost Share:*** $1,985,846

This project focuses on scaling up a novel carbon sorbent-based pre-combustion capture technology. Carbon dioxide is captured above the dew point and at a pressure that significantly improves net plant efficiency and decreases operating costs. Specifically, this project involves designing and fabricating a 0.1-MWe pilot-scale carbon dioxide (CO_2) separation system and testing this system on actual synthesis gas (syngas) at the National Carbon Capture Center (NCCC) and at a Sinopec gasification facility.

10: FE0012965
DEVELOPMENT OF A PRE-COMBUSTION CARBON DIOXIDE CAPTURE PROCESS USING HIGH-TEMPERATURE POLYBENZIMIDAZOLE HOLLOW-FIBER MEMBRANE

Indira Jayaweera, SRI International

Technology Readiness Level: 3	***DOE Funding:*** $2,249,997
Duration: 10/01/2013 – 10/31/2016	***Cost Share:*** $562,504

This project focuses on the evaluation of a polybenzimidazole (PBI) membrane-based process for separation of hydrogen and carbon dioxide (CO_2). The membrane consists of hollow-fiber PBI, which is intrinsically chemically and thermally stable at temperatures up to 450°C (but due to temperature constraints of associated materials will be operated in the 200°C to 250°C range) and pressures up to 55 atmospheres, negating the need for cooling after water-gas shift, increasing efficiency, and reducing operating costs. Specifically, asymmetric hollow-fiber membranes will be fabricated and tested at 50-kWth scale using actual synthesis gas.

11: FE0012959
DEVELOPMENT OF MIXED-SALT TECHNOLOGY FOR CARBON DIOXIDE CAPTURE FROM COAL POWER PLANTS

Indira Jayaweera, SRI International

Technology Readiness Level: 3	***DOE Funding:*** $1,697,647
Duration: 10/01/2013 – 03/31/2016	***Cost Share:*** $424,095

This project focuses on testing a low-cost, ammonia-based, mixed-salt solvent capture technology. The mixed-salt technology combines existing ammonium and potassium carbonate technologies with improved absorption steps for rate enhancement and a novel selective regeneration process to reduce capital and operating costs. Specifically, this project will demonstrate the absorber and regenerator processes individually through bench-scale testing.

12: FE0013064
ROBUST AND ENERGY EFFICIENT DUAL-STAGE MEMBRANE-BASED PROCESS FOR ENHANCED CO_2 RECOVERY

Richard Cicora Jr., Media and Process Technology Inc.

Technology Readiness Level: 3	***DOE Funding:*** $2,000,023
Duration: 10/01/2013 – 09/30/2016	***Cost Share:*** $500,006

This project focuses on developing a dual-stage membrane process that couples a hydrogen-selective carbon molecular sieve (CMS) membrane in a water-gas-shift membrane reactor with a palladium (Pd)-based membrane for residual hydrogen recovery. The dual-stage membrane process achieves high hydrogen recovery and carbon dioxide (CO_2) capture efficiency with minimal or no parasitic energy consumption, thereby decreasing operating costs. Specifically, this project involves bench-scale testing with real synthesis gas.

APPENDIX A: ACRONYMS AND ABBREVIATIONS

Acronym or Abbreviation	Definition
AIChE	American Institute of Chemical Engineers
CCC	Copyright Clearance Center
CCRP	Clean Coal Research Program
CCS	carbon capture and storage
CCUS	carbon capture, utilization, and storage
cP	centipoise
CMS	carbon molecular sieve
CO_2	carbon dioxide
CO_2BOL	CO_2-binding organic liquid
DOE	U.S. Department of Energy
FE	Office of Fossil Energy
FY	fiscal year
IGCC	integrated gasification combined cycle
IPO	Independent Professional Organization
kWth	kilowatt thermal
LTI	Leonardo Technologies, Inc.
MMM	mixed-matrix membranes
MOF	metal organic framework
MW	megawatt
MWe	megawatt-electric
NCCC	National Carbon Capture Center
NETL	National Energy Technology Laboratory
OMB	Office of Management and Budget
PBI	polybenzimidazole
Pd	palladium
PI	principal investigator
PNNL	Pacific Northwest National Laboratory
R&D	research and development
RD&D	research, development, and demonstration
scfm	standard cubic feet per minute
syngas	synthesis gas
TRA	Technology Readiness Assessment
TRL	Technology Readiness Level

APPENDIX B: PEER REVIEW EVALUATION CRITERIA FORM

U.S. DEPARTMENT OF ENERGY (DOE)
NATIONAL ENERGY TECHNOLOGY LABORATORY (NETL)

FY 2015 CARBON CAPTURE PEER REVIEW

MARCH 16-20, 2015

Project Title:	
Performer:	
Name of Peer Reviewer:	

The following pages contain the criteria used to evaluate each project. Each criterion is accompanied by multiple characteristics to further define the topic. Each Reviewer is expected to independently assess the provided material for each project, considering the Evaluation Criteria on the following page. Prior to the meeting, the Reviewers will independently create a list of strengths and weaknesses for each project based on the materials provided.

At the meeting, the Facilitator and/or Panel Chairperson will lead the Peer Review Panel in identifying consensus strengths, weaknesses, overall score, and prioritized recommendations for each project. The consensus strengths and weaknesses shall serve as a basis for the determination of the overall project score in accordance with the Rating Definitions and Scoring Plan detailed on the following page.

A **strength** is an aspect of the project that, when compared to the evaluation criterion, reflects positively on the probability of successful accomplishment of the project's goals and objectives.

A **weakness** is an aspect of the project that, when compared to the evaluation criterion, reflects negatively on the probability of successful accomplishment of the project's goals and objectives.

Consensus strengths and weaknesses shall be characterized as either "major" or "minor." For example, a weakness that presents a significant threat to the likelihood of achieving the project's stated technical goals and supporting objectives should be considered "major," whereas relatively less significant opportunities for improvement are considered "minor."

A **recommendation** shall emphasize an action that will be considered by the project team and/or DOE to be included as a milestone for the project to correct or mitigate the impact of weaknesses, or expand upon a project's strengths. A recommendation should have as its basis one or more strength or weakness. Recommendations shall be *ranked* from most important to least, based on the major/minor strengths/weaknesses.

Per the Independent Professional Organization (IPO) request, Reviewers are to record their individual strengths, weaknesses, recommendations, and general comments under the

Reviewer Comments section of this form (page 3). However, only the panel's consensus remarks/scores will be used in the IPO-generated reports.

EVALUATION CRITERIA	
1	**Degree to which the project, if successful, supports the program's near- and/or long-term goals.** • Clear project performance and/or cost/economic* objectives are present, appropriate for the maturity of the technology, and support the program goals. • Technology is ultimately technically and/or economically viable for the intended application.
2	**Degree of project plan technical feasibility.** • Technical gaps, barriers, and risks to achieving the project performance and/or cost objectives* are clearly identified. • Scientific/engineering approaches have been designed to overcome the identified technical gaps, barriers, and risks to achieve the project performance and/or cost/economic objectives*.
3	**Degree to which progress has been made towards the stated project performance and cost/economic* objectives.** • Milestones and reports effectively enable progress to be tracked. • Reasonable progress has been made relative to the established project schedule and budget.
4	**Degree to which the project plan-to-complete assures success.** • Remaining technical work planned is appropriate, in light of progress to date, and remaining schedule and budget. • Appropriate risk mitigation plans exist, including Decision Points if appropriate.
5	**Degree to which there are sufficient resources to successfully complete the project.** • There is adequate funding, facilities, and equipment. • Project team includes personnel with needed technical and project management expertise. • The project team is engaged in effective teaming and collaborative efforts, as appropriate.

* Projects that do not have cost/economic objectives should be evaluated on performance objectives only.

RATINGS DEFINITIONS AND SCORING PLAN

The panel will be required to assign a consensus score to the project, after strengths and weaknesses have been agreed upon. Intermediate scores are *not* acceptable. The overall project score must be justified by, and consistent with, the identified strengths and weaknesses.

RATING DEFINITIONS	
10	**Excellent –** Several major strengths; no major weaknesses; few, if any, minor weaknesses. Strengths are apparent and documented.
8	**Highly Successful –** Some major strengths; few (if any) major weaknesses; few minor weaknesses. Strengths are apparent and documented, and outweigh identified weaknesses.
5	**Adequate –** Strengths and weaknesses are about equal in significance.
2	**Weak –** Some major weaknesses; many minor weaknesses; few (if any) major strengths; few minor strengths. Weaknesses are apparent and documented, and outweigh strengths identified.
0	**Unacceptable –** No major strengths; many major weaknesses. Significant weaknesses/deficiencies exist that are largely insurmountable.

APPENDIX C: TECHNOLOGY READINESS LEVEL DESCRIPTIONS

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

TRL	DOE-FE Definition	DOE-FE Description
1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies.
3	Analytical and experimental critical function and/or characteristic proof of concept	Active R&D is initiated. This includes analytical and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology (e.g., individual technology components have undergone laboratory-scale testing using bottled gases to simulate major flue gas species at a scale of less than 1 scfm).
4	Component and/or system validation in a laboratory environment	A bench-scale prototype has been developed and validated in the laboratory environment. Prototype is defined as less than 5% final scale (e.g., complete technology process has undergone bench-scale testing using synthetic flue gas composition at a scale of approximately 1–100 scfm).
5	Laboratory-scale similar-system validation in a relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Prototype is defined as less than 5% final scale (e.g., complete technology has undergone bench-scale testing using actual flue gas composition at a scale of approximately 1–100 scfm).
6	Engineering/pilot-scale prototypical system demonstrated in a relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. Pilot or process-development-unit scale is defined as being between 0 and 5% final scale (e.g., complete technology has undergone small pilot-scale testing using actual flue gas composition at a scale equivalent to approximately 1,250–12,500 scfm).
7	System prototype demonstrated in a plant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Final design is virtually complete. Pilot or process- development-unit demonstration of a 5–25% final scale or design and development of a 200–600 MW plant (e.g., complete technology has undergone large pilot-scale testing using actual flue gas composition at a scale equivalent to approximately 25,000–62,500 scfm).
8	Actual system completed and qualified through test and demonstration in a plant environment	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include startup, testing, and evaluation of the system within a 200–600 MW plant CCS/CCUS operation (e.g., complete and fully integrated technology has been initiated at full-scale demonstration including startup, testing, and evaluation of the system using actual flue gas composition at a scale equivalent to approximately 200 MW or greater).
9	Actual system operated over the full range of expected conditions	The technology is in its final form and operated under the full range of operating conditions. The scale of this technology is expected to be 200–600 MW plant CCS/CCUS operations (e.g., complete and fully integrated technology has undergone full-scale demonstration testing using actual flue gas composition at a scale equivalent to approximately 200 MW or greater).

APPENDIX D: MEETING AGENDA

AGENDA

FY15 Carbon Capture Peer Review
March 16 – 20, 2015
Sheraton Station Square
Pittsburgh, PA

Monday, March 16, 2015 – Ellwood Room

7:00 – 8:00 a.m.	**Registration – 2nd Floor Foyer**
8:00 – 8:45 a.m.	**Peer Review Panel Kick-Off Meeting** Open to National Energy Technology Laboratory (NETL) and ASM International staff only - NETL and ASM International Welcome - Role of Panel Chair - Peer Review Process Overview - Meeting Logistics
8:45 – 9:15 a.m.	**Technology Manager/Office of Performance & Benefits (OPPB) and Panel Q&A** Open to NETL and ASM International staff only - Carbon Capture Technology Manager – Lynn Brickett, NETL - OPPB
9:15 – 9:30 a.m.	**BREAK**
9:30 – 10:00 a.m.	**01 – Project # FE0013118** – Bench-Scale Development of a Hybrid Membrane Absorption CO_2 Capture Process *Brice Freeman* - **Membrane Technology and Research Inc.**
10:00 – 10:30 a.m.	Q&A
10:30 – 12:00 p.m.	Discussion
12:00 – 1:00 p.m.	**Lunch (on your own)**
1:00 – 1:30 p.m.	**02 – Project # FE0012926**- – An Advanced Catalytic Solvent for Lower Cost Post-Combustion CO_2 Capture in a Coal-fired Power Plant *Kunlei Liu* - **University of Kentucky**
1:30 – 2:00 p.m.	Q&A
2:00 – 3:30 p.m.	Discussion

Tuesday, March 17, 2015 – Ellwood Room

7:00 – 8:00 a.m.	**Registration – 2nd Floor Foyer**
8:00 – 8:30 a.m.	**03 – Project # FE0013687** – Bench-Scale Process for Low-Cost Carbon Dioxide (CO_2) Capture Using a Phase-Changing Absorbent *Tiffany Westendorf* - **GE Global Research**
8:30 – 9:00 a.m.	Q&A
9:00 – 10:15 a.m.	Discussion
10:15 – 10:30 a.m.	**BREAK**
10:30 – 11:00 a.m.	**04 – Project # FE0013122** – Supersonic Post-Combustion Inertial CO_2 Extraction System *Vladimir Balepin* - **Alliant Techsystems Operations LLC**
11:00 – 11:30 a.m.	Q&A
11:30 – 12:45 p.m.	Discussion
12:45 – 1:45 p.m.	**Lunch (on your own)**
1:45 – 2:15 p.m.	**05 – Project # FE0012870** – Sorbent Based Post-Combustion CO_2 Slipstream Testing *Jeannine Elliott* - **TDA Research Inc.**
2:15 – 2:45 p.m.	Q&A
2:45 – 4:00 p.m.	Discussion

Wednesday, March 18, 2015 – Ellwood Room

7:00 – 8:00 a.m.	**Registration – 2nd Floor Foyer**
8:00 – 8:30 a.m.	**06 – Project # FE0013127** - Bench-Scale Development and Testing of Aerogel Sorbents for CO_2 Capture *Redouane Begag and George Gould* - **Aspen Aerogels Inc.**
8:30 – 9:00 a.m.	Q&A
9:00 – 10:15 a.m.	Discussion
10:15 – 10:30 a.m.	**BREAK**
10:30 – 11:00 a.m.	**07 – Project # FWP-CC-FY14-T7** – Post-Combustion Membranes *Surendar Venna* - **National Energy Technology Laboratory (NETL)**
11:00 – 11:30 a.m.	Q&A
11:30 – 12:45 p.m.	Discussion
12:45 – 1:45 p.m.	**Lunch (on your own)**
1:45 – 2:15 p.m.	**08 – Project # FWP-65872** – Accelerating the Development of "Transformation" Solvents for CO_2 Separations *David Heldebrant and Vassiliki-Alexandra Glezakou* - **Pacific Northwest National Laboratory (PNNL)**
2:15 – 2:45 p.m.	Q&A
2:45 – 4:00 p.m.	Discussion

Thursday, March 19, 2015 – Ellwood Room

7:00 – 8:00 a.m.	**Registration – 2nd Floor Foyer**
8:00 – 8:30 a.m.	**09 – Project # FE0013105** – Pilot Testing of a Highly Effective Pre-Combustion Sorbent-Based Carbon Capture System *Gokhan Alptekin* - **TDA Research Inc.**
8:30 – 9:00 a.m.	Q&A
9:00 – 10:15 a.m.	Discussion
10:15 – 10:30 a.m.	**BREAK**
10:30 – 11:00 a.m.	**10 – Project # FE0012965** – Development of a Pre-Combustion Carbon Dioxide Capture Process Using High Temperature Polybenzimidazole Hollow-Fiber Membrane *Indira Jayaweera* - **SRI International**
11:00 – 11:30 a.m.	Q&A
11:30 – 12:45 p.m.	Discussion
12:45 – 1:45 p.m.	**Lunch (on your own)**
1:45 – 2:15 p.m.	**11 – Project # FE0012959** – Development of Mixed-Salt Technology for Carbon Dioxide Capture from Coal Power Plants *Indira Jayaweera* - **SRI International** *and Prodip Kundu*- **OLI Systems**
2:15 – 2:45 p.m.	Q&A
2:45 – 4:00 p.m.	Discussion

Friday, March 20, 2015 – Ellwood Room

7:00 – 8:00 a.m.	**Registration – 2nd Floor Foyer**
8:00 – 8:30 a.m.	**12 – Project # FE0013064** – Robust and Energy Efficient Dual-Stage Membrane-Based Process for Enhanced Carbon Dioxide Recovery *Richard J. Ciora Jr.* - **Media and Process Technology Inc.**
8:30 – 9:00 a.m.	Q&A
9:00 – 10:15 a.m.	Discussion
10:15 – 10:30 a.m.	**BREAK**
10:30 – 11:30 a.m.	**Wrap-up Session**

APPENDIX E: PEER REVIEW PANEL MEMBERS

Ravi Prasad, Ph.D. – Panel Chair

- Principal investigator (PI) of DOE Small Business Technology Transfer Phase II project developing step-change technology to recover helium from low-purity sources using a new separation technology in a hybrid process.
- PI of new algae technology for carbon dioxide (CO_2) mitigation, bio-fuel production, and water remediation applications.
- Consulted with the U.S. Department of Energy (DOE) in application reviews for "CCS from Industrial Sources and Innovative Concepts for Beneficial CO_2 Use," "Clean Coal Power Initiative–Round 3," and "Large-Scale Industrial CCS Projects."
- Panelist in 11 National Energy Technology Laboratory (NETL) peer reviews and Chair of five peer reviews.
- Consultant to Praxair on sustainability initiative.
- Provided consultation services to industrial clients in clean energy, natural gas processing, CO_2, helium recovery, membrane technology, cryogenic, and other gas-separation processes.

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 million to $50 million), supporting business development, building cross-functional teams, and setting up joint development alliances. Dr. Prasad established more than 25 alliances for development and commercialization; recruited, mentored, and led a world-class team of 35 scientists and engineers; and established and managed Praxair's polymeric membrane process skill center and helped assess and later integrate new acquisition. He is a founding member of a major international alliance involving Praxair and five Fortune 500 companies to develop step-change synthesis gas (syngas) technology for gas-to-liquids.

Dr. Prasad also established and led programs for ceramic membrane oxygen technology; co-developed proposals to secure major DOE programs in syngas, worth $35 million, and in oxygen, worth $20 million; identified novel, solid-state oxygen generation technology; and conceived and implemented a coherent corporate strategy in nanotechnology. He developed Praxair's skill center in ceramic ion transport membranes, and led programs in integrated gasification combined cycle (IGCC), combustion, oxygen, and solid oxide fuel cell (SOFC) afterburner.

Dr. Prasad's technical areas of expertise include membranes and separations, hydrogen and helium, industrial gas production and application, ceramic membranes and SOFCs, new technology development, technology road mapping, intellectual property strategy development, technology due diligence, combustion, nanotechnology, gas-to-liquids, coal-to-liquids, and silane pyrolysis reactors.

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

Bhadra S. Grover
Bhadra Grover is a chemical engineer and a recognized expert in various technologies for chemical production and gas purification. He has industrial experience in engineering, research and development (R&D), business development, application development, and operation of the following processes and plants. He is the inventor of more than 12 patents.

Education
MS in Chemical Engineering (1978), Manhattan College, NY. B.Tech in Chemical Engineering (1967), Indian Institute of Technology, New Delhi, India.

Professional Experience
Air Liquide America, Houston, TX Senior Corporate Expert, Engineering and Development MW Kellogg (Now KBR), Houston, TX. Process Manager, responsible for process design, and proposal preparation for various ammonia, methanol, and LNG plants. UOP (formally Union Carbide), Tarrytown, NY.

CO_2 Abatement, Capture, and Storage.

- CO_2 capture by Solvents (amines, K2CO_3, rectisol, selexol), Cryogenics, Adsorbents, and Membranes (Polymeric and Inorganic). CO_2 capture from coal gasification, natural gas processing plants, ammonia production, steel mills, and other chemical plants.
- Pre- and post-combustion for CO_2 capture for power generation. Integration of O_2 production with power production.
- Integration of ion transport membranes for boilers, syngas generation, steel mill; producing CO_2-rich flue gas.
- Development of chemical looping for combustion and hydrogen production.
- CO_2 abatement by process optimization, and use of renewable fuels.
- CO_2 compression and transport for enhance oil recovery (EOR) and sequestration.

Daniel J. Kubek

Daniel Kubek is a consultant specializing in synthesis gas and natural gas purification and separation. His clients include the Electric Power Research Institute – Coal Fleet Consortium, for whom he provides technical guidance on integrated processes for gasification projects; UOP LLC, for whom he conducts investigations on emerging gas processing technologies; DOE/NETL, for whom he has conducted numerous R&D peer reviews and solicitation review; and others.

Mr. Kubek was with UOP LLC for 18 years as senior technology manager. His technical expertise is based in separations technology and engineering. His primary work was in solvent absorption, molecular sieve thermal-swing adsorption, membrane permeation, and pressure-swing adsorption 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 LNG projects, and served as development manager for UOP's gas processing business. Before joining UOP LLC, he spent 17 years with their parent company 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 is the holder of 8 patents and has co-authored 17 technical publications. Mr. Kubek received a B.S. degree in chemical engineering from Rutgers University and earned an M.S. in chemical engineering from Purdue University.

Michael R. von Spakovsky, Ph.D.

Dr. Michael von Spakovsky has more than 28 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. He received his B.S. in aerospace engineering in 1974 from Auburn University and his M.S and Ph.D. in mechanical engineering in 1980 and 1986, respectively, from the Georgia Institute of Technology. While at Auburn he worked for 3.5 years at NASA in Huntsville, Alabama, and from 1974 to 1984 and from 1987 to 1989 he worked in the power utility industry, first as an engineer and then as a consultant. From 1989 to 1996, Dr. von Spakovsky worked as both an educator and researcher at the Swiss Federal Institute of Technology in Lausanne, Switzerland, 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 (including fuel cells).

In January 1997, Dr. von Spakovsky joined the Mechanical Engineering faculty at Virginia Tech 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 and intrinsic quantum thermodynamics, kinetic theory and the Boltzmann equation, fuel cell systems, and energy system design. His research interests include computational methods for modeling and optimizing complex energy systems; methodological approaches (with and without sustainability and uncertainty considerations) for the integrated synthesis, design, operation, and control of such systems (e.g., stationary power systems, grid/microgrid/producer/storage and district heating/cooling networks, high performance aircraft systems); theoretical and applied thermodynamics with a focus on intrinsic quantum thermodynamics applied to nanoscale and microscale reactive and non-reactive systems; and fuel cell applications for both transportation and centralized, distributed, and portable power generation and cogeneration. He has been published widely (in scholarly journals, conference proceedings, etc. [more than 215 publications]), and has given talks, keynote lectures, seminars, and short courses (e.g., on fuel cells and intrinsic quantum thermodynamics) worldwide. Included among his various professional activities and awards is *Senior member of the AIAA*; *Fellow of the ASME*; the *2014 ASME James Harry Potter Gold Medal*; the *2012 ASME Edward F. Obert Award*; the *ASME AESD Lifetime Achievement Award*; former Chair of the *Executive Committee* for the ASME AESD; elected member of Sigma Xi and Tau Beta Pi; Associate Editor of the *ASME Journal of Fuel Cell Science and Technology*; and former Editor-in-Chief (11-year tenure) and now Honorary Editor of the *International Journal of Thermodynamics*.

John C. Tao, Ph.D.

Dr. John Tao has a wealth of experience in gas separations, coal conversion, and combustion technologies through more than 30 years at Air Products and Chemicals. He is currently President of O-Innovation Advisors, a management consulting company that offers partnering, licensing, and government contract services to startups as well as Fortune 500 companies worldwide. Prior to starting O-Innovation Advisors, 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, Dr. Tau served as 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 oxyfuel combustion technology and advanced oxygen separation using ion transport membranes. During his career at Air Products, Dr. Tao was involved in engineering management, R&D management, commercial development, venture management, and planning and business development.

Dr. Tao is a Fellow of the American Institute of Chemical Engineers (AIChE). He was a member of the Board of Directors for AIChE, the Industrial Research Institute, the Commercial Development and Marketing Association, and the Council of Chemical Research. He was the 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 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 presented and published more than 90 papers and holds 9 patents.

Dr. Tao received his B.S. and Ph.D. in chemical engineering from Carnegie-Mellon University, and an M.S. in chemical engineering from the University of Delaware.