NATIONAL ENERGY TECHNOLOGY LABORATORY

FY19 CARBON CAPTURE PEER REVIEW OVERVIEW REPORT

December 6, 2018

U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY

DISCLAIMER

TABLE OF CONTENTS

INTRODUCTION AND BACKGROUND

The U.S. Department of Energy's (DOE) Fossil Energy (FE) Program has adopted a comprehensive, multi-pronged approach to the research and development (R&D) of advanced carbon dioxide (CO_2) capture technologies for coal-based power plants. The National Energy Technology Laboratory (NETL) is implementing the Carbon Capture R&D Program to develop the next generation of advanced CO_2 capture concepts.

The success of this research will enable cost-effective implementation of carbon capture and storage (CCS) technologies throughout the power-generation sector and ensure the United States will continue to have access to safe, reliable, and affordable energy from fossil fuels.

The Carbon Capture Program consists of two core research areas, Post-Combustion Capture and Pre-Combustion Capture, that are composed of approximately 60 projects with Technology Readiness Levels (TRLs) ranging from conceptual engineering and materials design (i.e., TRL 2) to 25 megawatt-electrical equivalent pilot testing (i.e., TRL 5-7). The core research areas are focused on creating technological improvements to provide a step-change in both cost and performance as compared to current state-of-the-art solvent-based capture systems.

Post-combustion systems separate CO_2 from the flue gas stream produced by conventional pulverized coal power plants after fuel combustion in air. In this approach, CO_2 is separated from nitrogen, the primary constituent of the flue gas. Pre-combustion systems are designed to separate CO_2 from hydrogen and other constituents in the syngas stream produced by the gasifier in integrated gasification combined cycle (IGCC) power plants. In both cases, R&D is underway to develop solvent-, sorbent-, membrane-, and novel concept-based capture technologies. Additionally, technologies are being investigated to increase the efficiency and reduce the cost of CO_2 compression. The four projects identified for evaluation at the Fiscal Year 2019 (FY19) Carbon Capture Peer Review are part of the Post-Combustion research area.

DOE's CCS R&D effort is implemented by NETL through contracted research activities and onsite research at NETL. Research projects are carried out under various award mechanisms—including partnerships, cooperative agreements, and financial assistance grants—with corporations, small businesses, universities, nonprofit organizations, and other national laboratories and government agencies.

Office of Management and Budget and DOE Requirements

In compliance with requirements from the Office of Management and Budget and in accordance with the DOE Strategic Plan, DOE and NETL are fully committed to improving the quality of research projects in their programs by conducting rigorous peer reviews. This report presents an overview of the peer review process, provides a synopsis of the projects reviewed, offers a summary of key findings, and identifies the panel members that conducted the project evaluations.

DOE and NETL held an FY19 Carbon Capture Peer Review Meeting with independent technical experts to offer recommendations to strengthen projects during the period of performance.

KeyLogic (NETL site-support contractor) convened a panel of four academic and industry experts[*] on October 15-16, 2018, to review four Carbon Capture Program research projects.

TABLE 1. CARBON CAPTURE PEER REVIEW – PROJECTS REVIEWED

Project Number	Title	Lead Organization	Total Funding		Project Duration	
			DOE	Cost Share	From	To
FE0031590	Engineering Scale Testing of Transformational Non-Aqueous Solvent-Based CO_2 Capture Process at Technology Centre Mongstad	Research Triangle Institute	$9,732,152	$13,045,000	8/8/2018	1/15/2021
FE0031591	Scale-Up and Testing of Advanced Polaris Membrane CO_2 Capture Technology	Membrane Technology and Research, Inc.	$7,427,258	$2,394,667	8/1/2018	7/31/2021
FE0031603	Membrane-Sorbent Hybrid System for Post-Combustion Carbon Capture	TDA Research, Inc.	$8,000,000	$2,000,025	8/15/2018	8/14/2021
FE0031588	Engineering Scale Demonstration of Mixed-Salt Process for CO_2 Capture	SRI International	$13,554,788	$3,388,697	7/1/2018	7/31/2021
The projects were subject to recommendations-based evaluations. During recommendations-based evaluations, the independent panel provides recommendations to strengthen the performance of projects during the period of performance.			$38,714,198	$20,828,389		
			$59,542,587			

---

[*] Please see "Appendix D: Peer Review Panel Members" for detailed panel member biographies.

OVERVIEW OF THE PEER REVIEW PROCESS

Peer reviews are conducted to help ensure that the Office of Fossil Energy's (FE) research program, implemented by NETL, is compliant with the DOE Strategic Plan and DOE guidance. Peer reviews improve the overall quality of the technical aspects of R&D activities, as well as overall project-related activities, such as utilization of resources, project and financial management, and commercialization.

KeyLogic convened a panel of four academic and industry experts to conduct a peer review of four research projects supported by the NETL Carbon Capture Program. Throughout the peer review meeting, these recognized technical experts offered recommendations to strengthen the projects during the remaining period of performance. In consultation with NETL representatives, who chose the projects for review, KeyLogic selected an independent Peer Review Panel, facilitated the peer review meeting, and prepared this report to summarize the results.

Pre-Meeting Preparation

Before the peer review, each project team submitted a Project Technical Summary (PTS) and project presentation. The appropriate Federal Project Manager (FPM) provided the project management plan (PMP), the latest quarterly report, and up to three technical papers as additional resources for the panel (as applicable). The panel received these materials prior to the peer review meeting, which enabled the panel members to fully prepare for the meeting with the necessary background information to thoroughly evaluate the projects.

To increase the efficiency of the peer review meeting, multiple pre-meeting orientation teleconference calls were held with NETL, the Review Panel, and KeyLogic staff to review the peer review process and procedures, evaluation criteria, and project documentation, as well as to allow for the Technology Manager to provide an overview of the program goals and objectives and NETL's Systems Analysis group to explain the cost of electricity goals.

Peer Review Meeting Proceedings

At the meeting, each project performer gave a presentation describing the project. The presentation was followed by a question-and-answer session with the panel and a closed panel discussion and evaluation. The time allotted for the presentation, the question-and-answer session, and the closed panel discussion was dependent on the project's complexity, duration, and breadth of scope.

During the closed sessions of the peer review meeting, the panel discussed each project to identify strengths, weaknesses, and recommendations in accordance with the Peer Review Evaluation Criteria. The panel offered a series of prioritized recommendations to strengthen the project during the remaining period of performance and assigned each project a score based on the NETL Peer Review Rating Definitions and Scoring Plan in the Peer Review Evaluation Criteria[†].

[†] Please see "Appendix A: Peer Review Evaluation Criteria Form" for more information.

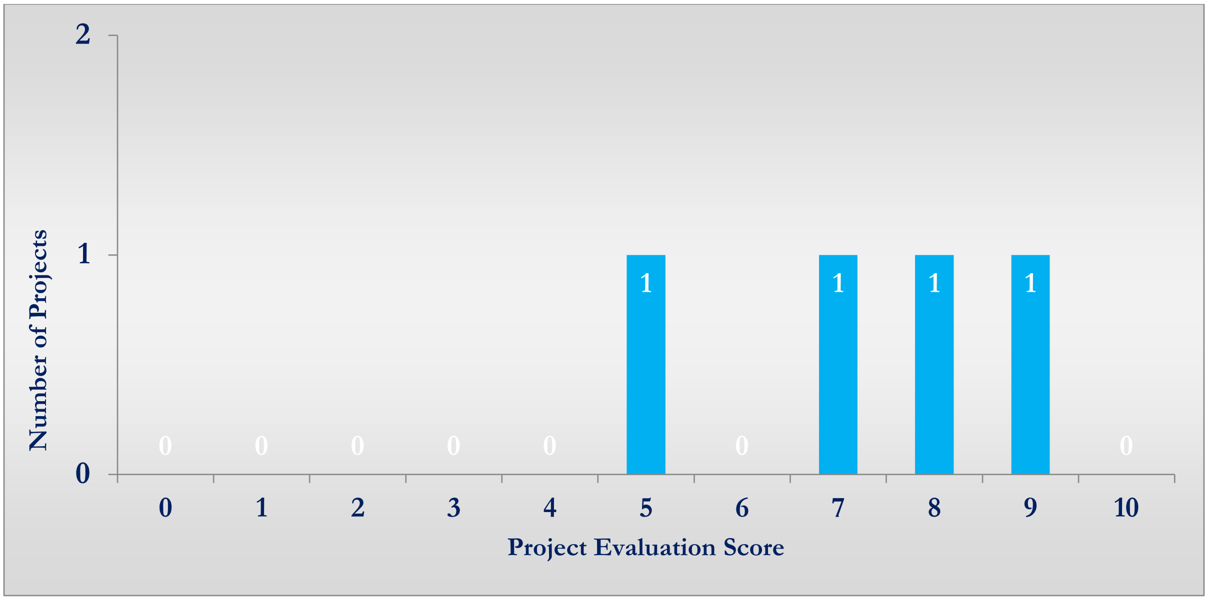
SUMMARY OF KEY FINDINGS

This section summarizes the overall key findings of the projects evaluated at the FY19 Carbon Capture Peer Review Meeting. The panel concluded that the peer review provided an excellent opportunity to comment on the relative strengths and weaknesses of each project. The presentations and question and answer sessions provided additional clarity to complement the pre-meeting documentation. The peer review has also provided an insight into the range of technology development and the relative progress that has been made by the project teams. The technical discussion enabled the panel to contribute to each project's development by identifying core issues and by making constructive recommendations to improve project outcomes. The panel generated 21 recommendations for NETL management to review and consider for incorporation into a project's Statement of Project Objectives or Statement of Work as a peer review milestone.

Overview of Project Evaluation Scores

The panel assigned a score for each project, based on the following definitions. A rating of five or higher indicates that a specific project was viewed as at least adequate by the panel. The panel was permitted to assign any integer value ranging from 0 to 10. For the various projects subject to review, the panel assigned scores ranging from five to nine.

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



FY19 Carbon Capture Peer Review Project Evaluation Scores

General Project Strengths

The panel was impressed by the quality of the Carbon Capture Program projects they reviewed. They indicated that the projects have significant potential to test transformational solvent-based CO_2 capture technologies at engineering scales using existing infrastructure, or membrane-based approaches that, due to their modular nature, can be built and tested at a relevant scale. The panel was optimistic about the potential for these projects to further progress toward achieving DOE's challenging goals. The following are noteworthy project strengths from the panel members that relate to one or more projects:

- The test program is focused on examining core solvent challenges, such as degradation, corrosion, and emissions.
- There is advantageous modularity (facilitating scale-up of the process) and adaptability (ability to be easily modified) of the technology.
- The project examined opportunities to enhance the process performance by improving the balance of plant.
- There is a process concept with high-performance credibility because it potentially leverages the benefits of membranes and the benefits of a sorbent.
- There is an understanding of the goals of the test program, a good plan to market the technology, and a respectable track record with publications and data dissemination.

General Project Weaknesses

Observations that panel members noted as project weaknesses included:

- The techno-economic analysis (TEA) is lacking aspects such as a sensitivity analysis.
- Not stating the volume of solvent necessary.
- Not clearly stating the route and timeline to market (e.g., commercialization plan, proforma, first customers).
- Inadequately addressing the balance of plant or scale-up of the sorbent bed design.
- Not considering the restart of the testing facility.

General Project Observations and Recommendations

The panel members offered recommendations that were technical in nature and specific to each particular project's technology or approach. The panel's recommendations addressed the weaknesses and offered suggestions to further improve the project plan. Panel recommendations included:

- Developing a solvent degradation and management program.
- Developing a model with a TEA based on a process flow diagram developed for the solvent in addition to a conventional solvent system.
- Presenting an uncertainty quantification (e.g., Monte Carlo) analysis to NETL on the impact of membrane lifetime and cost.
- Evaluating how balance of plant performance can improve overall system flexibility and performance.
- Completing a proper evaluation of sulfur oxide (SO_X) and other reactive contaminants and mitigation measures.
- Developing a test program contingency plan for major equipment failures.

PROJECT SYNOPSES

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

FE0031590

ENGINEERING SCALE TESTING OF TRANSFORMATIONAL NON-AQUEOUS SOLVENT-BASED CO_2 CAPTURE PROCESS AT TECHNOLOGY CENTRE MONGSTAD

Shaojun James Zhou – Research Triangle Institute

Project Description: RTI International will advance its nonaqueous (water-lean) solvent-based carbon dioxide (CO_2) capture technology and tests will be performed using the existing large-scale pilot infrastructure at the Technology Centre Mongstad (TCM) in Norway. This project expands on work conducted with the U.S. Department of Energy (DOE) in both the Office of Fossil Energy's (FE) and the Advanced Research Projects Agency-Energy's (ARPA-E) portfolios.

FE0031591

SCALE-UP AND TESTING OF ADVANCED POLARIS MEMBRANE CO_2 CAPTURE TECHNOLOGY

Tim Merkel – Membrane Technology and Research, Inc.

Project Description: Membrane Technology and Research, Inc. will scale up next-generation Polaris^{TM} membranes and modules to a final form for commercial use and validate their potential in an engineering-scale field test at the Technology Centre Mongstad (TCM) in Norway.

FE0031603

MEMBRANE-SORBENT HYBRID SYSTEM FOR POST-COMBUSTION CARBON CAPTURE

Gokhan Alptekin – TDA Research, Inc.

Project Description: TDA Research, Inc. will design, construct, and operate an engineering-scale, 1-megawatt-electric post-combustion hybrid carbon capture system. This system consists of a polymeric membrane and a low-temperature physical adsorbent to remove carbon dioxide (CO_2) from the flue gases generated by coal-fired power plants. The membrane, developed by Membrane Technology and Research, Inc., will be responsible for bulk CO_2 removal, while the TDA-developed sorbent will extract additional levels to achieve an overall 90 percent system removal.

FE0031588

ENGINEERING SCALE DEMONSTRATION OF MIXED-SALT PROCESS FOR CO_2 CAPTURE

Indira Jayaweera – SRI International

Project Description: SRI International will demonstrate its mixed-salt process at engineering-scale, using the existing infrastructure at the Technology Centre Mongstad (TCM) in Norway. The objectives are to address concerns related to scale-up and integration of the technology in coal-based power plants.

APPENDIX A: PEER REVIEW EVALUATION CRITERIA

PEER REVIEW EVALUATION CRITERIA AND GUIDELINES

Peer reviews are conducted to ensure that the Office of Fossil Energy's (FE) research program, implemented by the National Energy Technology Laboratory (NETL), is compliant with the U.S. Department of Energy (DOE) Strategic Plan and DOE guidance. Peer reviews improve the overall quality of the technical aspects of research and development (R&D) activities, as well as overall project-related activities, such as utilization of resources, project and financial management, and commercialization.

In the upcoming NETL peer review, a significant amount of information about the projects within its portfolio will be covered in a short period. For that reason, NETL has established a set of rules for governing the meeting so that everyone has an equal chance to accurately present their project accomplishments, issues, recent progress, and expected results for the remainder of the performance period (if applicable).

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 all the provided material for each project prior to the meeting and engage in discussion to generate feedback for each project during the meeting.

Technology Readiness Level (TRL)-Based Evaluation

At the meeting, the Facilitator and/or Panel Chairperson will lead the Peer Review Panel in assessing a project's readiness to start work towards the next TRL based on a project's strengths[‡], weaknesses[§], recommendations, issues, and concerns. NETL identifies key technology development gates as passing from (1) laboratory research to relevant environment research (Technology Readiness Level [TRL] 4 to 5), (2) relevant environment research to operational system testing (TRL 6 to 7), and (3) operational system testing to successfully commissioned in an operating to commercial system (TRL 7 to 8). NETL TRL definitions are included below.

Recommendations-Based Evaluation

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 (see below).

[‡] 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 goal(s) 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 goal(s) and objectives.

Under a recommendation-based evaluation, consensus strengths and weaknesses shall be characterized as either “major” or “minor” during the Review Panel’s consensus discussion at the meeting. For example, a weakness that presents a significant threat to the likelihood of achieving the project’s stated technical goal(s) 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 strengths or weaknesses. Recommendations shall be ranked from most important to least, based on the major/minor strengths/weaknesses.

NETL Peer Review Evaluation Criteria
1. Degree to which the project, if successful, supports the DOE Program's near- and/or long-term goals.
• Program goals are clearly and accurately stated. • Performance requirements[1] support the program goals. • The intended commercial application is clearly defined. • The technology is ultimately technically and economically viable for the intended commercial application.
2. Degree to which there are sufficient resources to successfully complete the project.
• There is adequate funding, facilities, and equipment. • Project team includes personnel with the needed technical and project management expertise. • The project team is engaged in effective teaming and collaborative efforts, as appropriate.
3. Degree of project plan technical feasibility.
• Technical gaps, barriers, and risks to achieving the performance requirements are clearly identified. • Scientific/engineering approaches have been designed to overcome the identified technical gaps, barriers, and risks to achieve the performance requirements. • Remaining technical work planned is appropriate considering progress to date and remaining schedule and budget. • Appropriate risk mitigation plans exist, including Decision Points when applicable.
4. Degree to which progress has been made towards achieving the stated performance requirements.
• The project has tested (or is testing) those attributes appropriate for the next TRL. The level of technology integration and nature of the test environment are consistent with the aforementioned TRL definition. • Project progress, with emphasis on experimental results, shows that the technology has, or is likely to, achieve the stated performance requirements for the next TRL (including those pertaining to capital cost, if applicable). • Milestones and reports effectively enable progress to be tracked. • Reasonable progress has been made relative to the established project schedule and budget.
5. Degree to which an appropriate basis exists for the technology’s performance attributes and requirements.
• The Technology Readiness Level (TRL) to be achieved by the end of the project is clearly stated[2]. • Performance attributes for the technology are defined[2]. • Performance requirements for each performance attribute are, to the maximum extent practical, quantitative, clearly defined, and appropriate for and consistent with the DOE goals as well as technical and economic viability in the intended commercial application.
[1] If it is appropriate for a project to not have cost/economic-related performance requirements, then the project will be evaluated on technical performance requirements only. [2] Supported by systems analyses appropriate to the targeted TRL. See Systems Analysis Best Practices.

Rating Definitions and Scoring Plan (not applicable to TRL-based evaluation)

The Review Panel will be required to assign a consensus score to the project, after strengths and weaknesses have been agreed upon. Intermediate whole number scores are acceptable if the Review Panel feels it is appropriate. The overall project score must be justified by, and consistent with, the identified strengths and weaknesses.

NETL Peer Review Rating Definitions and Scoring Plan	
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 B: NETL TECHNOLOGY READINESS LEVELS

NETL Technology Readiness Levels

NETL supports a wide range of R&D projects, from small, short-duration materials development and property characterization projects up to large-scale power plant demonstrations. The nature and complexity of the technology under development will have implications for the application of the Technology Readiness concept, particularly with respect to supporting systems analysis requirements.

Accompanying the TRL definitions and descriptions provided in the table below are Systems Analysis Best Practices. These Best Practices serve as a critical resource to guide the identification of performance attributes and to establish corresponding performance requirements for a given technology which are, in turn, tied to the intended commercial application and higher-level goals (e.g., program goals). A systems analysis is carried out to estimate the performance and cost of the technology based on the information (e.g., experimental data) that is expected to be available at a particular TRL. The results, when compared with conventional technology, are used to inform the next stage of development and provide specific experimental and analysis success criteria (the performance requirements). The performance requirements that may be appropriately tested at a particular TRL must be substantially met, thereby supporting the feasibility of commercial success/goal achievement, prior to proceeding to the subsequent TRL. Note that, as with the TRL descriptions, these Systems Analysis Best Practices are “gate-in;” that is, prerequisites to achieving the associated TRL.

TRL	Definition	Description	Systems Analysis Best Practices
1	**Basic principles observed and reported**	Core Technology Identified. Scientific research and/or principles exist and have been assessed. Translation into a new idea, concept, and/or application has begun.	Assessment: Perform an assessment of the core technology resulting in (qualitative) projected benefits of the technology, a summary of necessary R&D needed to develop it into the actual technology, and principles that support of the viability of the technology to achieve the projected benefits.
2	**Technology concept and/or application formulated**	Invention Initiated. Analysis has been conducted on the core technology for practical use. Detailed analysis to support the assumptions has been initiated. Initial performance attributes have been established.	White Paper: A white paper describing the intended commercial application, the anticipated environment the actual technology will operate in, and the results from the initiation of a detailed analysis (that will at least qualitatively justify expenditure of resources versus the expected benefits and identify initial performance attributes).
3	**Analytical and experimental critical function and/or characteristic proof-of-concept validated**	Proof-of-Concept Validated. Performance requirements that can be tested in the laboratory environment have been analytically and physically validated. The core technology should not fundamentally change beyond this point. Performance attributes have been updated and initial performance requirements have been established.	Performance Model and Initial Cost Assessment: This performance model is a basic model of the technology concept, incorporating relevant process boundary conditions, that provides insight into critical performance attributes and serves to establish initial performance requirements. These may be empirically- or theoretically-based models represented in Excel or other suitable platforms. In addition, an initial assessment and determination of performance requirements related to cost is completed.
4	**Basic technology components integrated and validated in a laboratory environment**	Technology Validated in a Laboratory Environment. The basic technology components have been integrated to the extent practical (a relatively low-fidelity integration) to establish that key pieces will work together, and validated in a laboratory environment. Performance attributes and requirements have been updated.	System Simulation and Economic Analysis: These models incorporate a performance model of the technology (may be a simple model as developed for TRL 3, or something more detailed – either should be validated against empirical data gathered in the laboratory) into a model of the intended commercial system (e.g., power plant). In addition, an economic analysis (e.g., cost-of-electricity) of the technology is performed, assessing the impact of capital costs, operating and maintenance costs, and life on the impact of the technology and its contributions to the viability of the overall system in a commercial environment. These analyses serve to assess the relative impact of known performance attributes (through sensitivity analyses) and refine performance requirements in the context of established higher-level technical and economic goals (e.g., programmatic or DOE R&D goals). These models are typically created in process simulation software (e.g., ASPEN Plus) or other suitable platforms. DOE maintains guidance on the execution of techno-economic analyses [1].

TRL	Definition	Description	Systems Analysis Best Practices
5	**Basic technology components integrated and validated in a relevant environment**	Technology Validated in a Relevant Environment. Basic technology component configurations have been validated in a relevant environment. Component integration is similar to the final application in many respects. Data sufficient to support planning and design of the next TRL test phase have been obtained. Performance attributes and requirements have been updated.	System Simulation and Economic Analysis Refinement: A more detailed process model for the technology, validated against empirical data gathered in the laboratory, will be developed and incorporated into system simulations. This provides greater fidelity in the performance and cost estimation for the technology, facilitating updates to performance attributes and requirements (including updates to the economic analysis). This also allows greater evaluation of other process synergy claims (e.g., state-of-the-art technology is improved by the use of the new technology). Cost estimation should be either vendor-based or bottom-up costing approaches for novel equipment.
6	**Prototype validated in a relevant environment**	Prototype Validated in Relevant Environment. A prototype has been validated in a relevant environment. Component integration is similar to the final application in most respects and input and output parameters resemble the target commercial application to the extent practical. Data sufficient to support planning and design of the next TRL test phase have been obtained. Performance attributes and requirements have been updated.	System Simulation and Economic Analysis Refinement: Performance and cost models are refined based upon relevant environment laboratory results, leading to updated performance attributes and requirements. Preliminary steady-state and dynamic (if appropriate for the technology) modeling of all critical process parameters (i.e., upper and lower operating limits) of the system prototype is completed. Cost estimation should be either vendor-based or bottom-up costing approaches for novel equipment. Key process equipment should be specified to the extent that allows for bottom-up estimating to support a feasibility study of the integrated system.
7	**System prototype validated in an operational system**	System Prototype Validated in Operational Environment. A high-fidelity prototype, which addresses all scaling issues practical at pre-demonstration scale, has been built and tested in an operational environment. All necessary development work has been completed to support Actual Technology testing. Performance attributes and requirements have been updated.	System Simulation and Economic Analysis Refinement: Performance and cost models are refined based upon relevant environment and system prototype R&D results. The refined process, system and cost models are used to project updated system performance and cost to determine if the technology has the potential to meet the project goals. Performance attributes and requirements are updated as necessary. Steady-state and dynamic modeling all critical process parameters of the system prototype covering the anticipated full operation envelope (i.e., upper and lower operating limits) is completed. Cost models should be based on vendor quotes and traditional equipment estimates should be minimal.
8	**Actual technology successfully commissioned in an operational system**	Actual Technology Commissioned. The actual technology has been successfully commissioned for its target commercial application, at full commercial scale. In almost all cases, this TRL represents the end of true system development.	System Simulation and Economic Analysis Validation: The technology/system process models are validated by operational data from the demonstration. Economic models are updated accordingly.

9	**Actual technology operated over the full range of expected operational conditions**	Commercially Operated. The actual technology has been successfully operated long-term and has been demonstrated in an operational system, including (as applicable) shutdowns, startups, system upsets, weather ranges, and turndown conditions. Technology risk has been reduced so that it is similar to the risk of a commercial technology if used in another identical plant.	Commercial Use: Models are used for commercial scaling parameters.

[1] *Performing a Techno-economic Analysis for Power Generation Plants, DOE/NETL-2015/1726, July 2015.*

Glossary of Terms

Actual Technology: The final product of technology development that is of sufficient size, performance, and reliability—ready for use at the target commercial application. The technology is at Technology Readiness Levels (TRLs) 8–9.

Basic Technological Components Integrated: A test apparatus that ranges from (1) the largest, most integrated and/or most realistic technology model that can reasonably be tested in a laboratory environment, to (2) the lowest-cost technology model that can be used to obtain useful data in a relevant environment.

Commissioning/Commission: The actual system has become operational at target commercial conditions and is ready for commercial operations.

Concept and/or Application: The initial idea for a new technology or a new application for an existing technology. The technology is at TRLs 1–3.

Core Technology: The idea, new concept, and/or new application that started the research and development (R&D) effort. Examples include: (1) a new membrane material, sorbent, or solvent; (2) new software code; (3) a new turbine component; (4) the use of a commercial sensor technology in more durable housing; or (5) the use of a commercial enhanced oil recovery technology to store CO_2. Typically this is a project's intellectual property.

Economic Analysis: The process of estimating and assigning costs to equipment, subsystems, and systems, corresponding to models of and specifications for the commercial embodiment of the technology. Such analyses include the estimation of capital costs, as well as operating and maintenance costs. Component service life and corresponding replacement costs are often a crucial aspect of these analyses. See *Performing a Techno-economic Analysis for Power Generation Plants, DOE/NETL-2015/1726, July 2015,* for further guidance.

Fidelity: The extent to which a technology and its operating environment/conditions resemble that of the target commercial application.

Integrated: The functional state of a system resulting from the process of bringing together one or more technologies or subsystems and ensuring that each function together as a system.

Laboratory Environment: An environment isolated from the commercial environment in which lower-cost testing is performed to obtain high-quality, fundamental data at earlier TRLs. For software development, this is a small-scale, simplified domain for a software mockup.

Operational System: The environment in which the technology will be tested as part of the target commercial application.

Performance Attributes: All aspects of the technology (e.g., flux, selectivity, life, durability, cost, etc.) that must be tested or otherwise evaluated to ensure that the technology will function in the target commercial application, including all needed support systems. Systems analysis may assist in the identification of relevant performance attributes. It is likely that the performance attributes list will increase as the technology matures. Performance attributes must be updated as new information is received and formally reviewed at each TRL transition.

Performance Requirements: Criteria that must be met for each performance attribute before the actual system can be used at its target commercial application. These will be determined – typically via systems analysis - in consideration of program goals, requirements for market competitiveness for the target commercial application, etc. Performance requirements may change over time, and it is unlikely that all of them will be known at a low TRL.

Program: The funding program. The program goals will be used to judge project value and, in concert with systems analysis, will support acceptable performance requirements for the project. The funding program will also determine whether the system will be tested under one or several sets of target commercial applications.

Project: The funding mechanism for technology development, which often spans only part of the technology development arc. Some projects may contain aspects that lack dependence; these may have different TRL scores, but this must be fully justified.

Proof-of-Concept: Reasonable conclusions drawn through the use of low-fidelity experimentation and analysis to validate that the new idea—and resulting new component and/or application—has the potential to lead to the creation of an actual system.

Prototype: A test apparatus necessary to thoroughly test the technology, integrated and realistic as much as practical, in the applicable TRL test environment.

Relevant Environment: More realistic than a laboratory environment, but less costly to create and maintain than an operational environment. This is a relatively flexible term that must be consistently defined by each program (e.g., in software development, this would be "beta testing").

Systems Analysis: The analytic process used to evaluate the behavior and performance of processes, equipment, subsystems, and systems. Such analyses serve to characterize the relationships between independent (e.g., design parameters and configurations, material properties, etc.) and dependent variables (e.g., thermodynamic state points, output, etc.) through the creation of models representative of the envisioned process, equipment, subsystem, or system. These analyses are used to determine the variables important to desired function in the target commercial application (i.e., performance attributes) and the associated targets that must be achieved through R&D and testing to realize program and/or commercial goals (i.e., performance requirements). Models and simulations may use a variety of tools, such as Excel, Aspen Plus, Aspen Plus Dynamics, etc., depending upon the scope of the development effort and the stage of development. See *Performing a Techno-economic Analysis for Power Generation Plants, DOE/NETL-2015/1726, July 2015,* for further guidance.

Systems Analysis Best Practices: These best practices serve as a guide for the level of systems and economic analysis rigor and level of effort appropriate for each TRL. The scope of the project – the subject and nature the technology under development - must be considered when applying these best practices. For example, the analytical effort associated with the development of a thermal barrier coating is quite different than that appropriate to the development of a post-combustion CO_2 capture system.

Target Commercial Application: This refers to one specific use for the actual system, at full commercial scale, which supports the goals of the funding program. A project may include more than one set of target commercial applications. Examples are:

1. Technologies that reduce the cost of gasification may be useful for both liquid fuels and power production.
2. Technologies that may be useful to monitor CO_2 storage in more than one type of storage site.

Technology: The idea, new concept, and/or new application that started the research and development (R&D) effort plus other R&D work that must be done for the project's core technology to translate into an actual system.

Technology Aspects: Different R&D efforts, both within and external to any given project. Examples include material development, process development, process simulation, contaminant removal/control, and thermal management.

Validated: The proving of all known performance requirements that can reasonably be tested using the test apparatus of the applicable TRL.

APPENDIX C: MEETING AGENDA

Carbon Capture Peer Review
October 15-16, 2018
NETL-Pittsburgh Building 922 Room 106A

Monday, October 15, 2018

8:00 a.m.	*Visitors Arrive at the NETL-Pittsburgh Entrance Gate for Security Check*
8:15 – 8:30 a.m.	*Escort Visitors to NETL-Pittsburgh Building 922 Room 106A*
8:30 – 9:00 a.m.	Peer Review Panel Kickoff Session - Facilitator Opening, Review Panel Introductions, Technology Manager Welcome, Peer Review Process and Meeting Logistics Presentation
9:00 – 9:45 a.m.	Project FE0031590 – Engineering Scale Testing of Transformational Non-Aqueous Solvent-Based CO_2 Capture Process at Technology Centre Mongstad *Shaojun James Zhou* – Research Triangle Institute
9:45 – 10:30 a.m.	Question and Answer Session
10:30 – 10:45 a.m.	BREAK
10:45 – 12:00 p.m.	Closed Discussion (Recommendation-Based Evaluation; Review Panel) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
12:00 – 1:00 p.m.	Lunch (*onsite cafeteria; cash only, orders will be placed in the morning*)
1:00 – 1:45 p.m.	Project FE0031591 – Scale-Up and Testing of Advanced Polaris Membrane CO_2 Capture Technology *Tim Merkel* – Membrane Technology and Research, Inc.
1:45 – 2:30 p.m.	Question and Answer Session
2:30 – 2:45 p.m.	BREAK
2:45 – 4:00 p.m.	Closed Discussion (Recommendation-Based Evaluation; Review Panel) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
4:00 p.m.	Adjourn

Tuesday, October 16, 2018

8:00 a.m.	*Visitors Arrive at the NETL-Pittsburgh Entrance Gate for Security Check*
8:15 – 8:30 a.m.	*Escort Visitors to NETL-Pittsburgh Building 922 Room 106A*
8:30 – 9:15 a.m.	Project FE0031603 – Membrane-Sorbent Hybrid System for Post-Combustion Carbon Capture *Gokhan Alptekin* – TDA Research, Inc.
9:15 – 10:00 a.m.	Question and Answer Session
10:00 – 10:15 a.m.	BREAK
10:15 – 11:30 a.m.	Closed Discussion (Recommendation-Based Evaluation; Review Panel) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
11:30 – 12:30 p.m.	Lunch (*onsite cafeteria; cash only, orders will be placed in the morning*)
12:30 – 1:15 p.m.	Project FE0031588 – Engineering Scale Demonstration of Mixed-Salt Process for CO_2 Capture *Indira Jayaweera* – SRI International
1:15 – 2:00 p.m.	Question and Answer Session
2:00 – 2:15 p.m.	BREAK
2:15 – 3:30 p.m.	Closed Discussion (Recommendation-Based Evaluation; Review Panel) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
3:30 – 4:00 p.m.	Peer Review Panel Wrap-Up Session
4:00 p.m.	Adjourn

APPENDIX D: PEER REVIEW PANEL MEMBERS

Carbon Capture Peer Review
October 15-16, 2018
NETL-Pittsburgh Building 922 Room 106A

Dane Boysen, Ph.D.

Prior to founding Modular Chemical Inc. in October 2017, Dr. Dane Boysen served as the Chief Technologist at Cyclotron Road, and has many years of experience developing and commercializing hard energy technology. Previous to Cyclotron Road, he was Executive Director of Research Operations at the Gas Technology Institute and Program Director at the Advanced Research Projects Agency-Energy (ARPA-E), where he managed more than $100 million spread over 30 of the nation's most cutting-edge energy technology research and development projects. Prior to joining ARPA-E, Dr. Boysen led an $11 million project to develop liquid metal batteries for grid-scale energy storage under Professor Donald Sadoway at the Massachusetts Institute of Technology. This work led to the founding of the venture-backed liquid battery startup company Ambri. In 2004, Dr. Boysen co-founded Superprotonic Inc., a venture capital-backed startup company developing solid acid electrolyte-based fuel cells. Dr. Boysen received his M.S. and Ph.D. in materials science at Caltech.

Jon Gibbins, Ph.D.

Dr. Jon Gibbins has worked in the carbon capture and storage (CCS) field since 2002, but has worked on coal and biomass gasification and combustion for more than 30 years at Foster Wheeler, Imperial College of London, and the University of Edinburgh. He is a professor of power plant engineering and carbon capture at the University of Sheffield, as well as the Director of the UK Carbon Capture and Storage Research Centre (UK CCS), a member of the UK CCS Coordination Group, and the Research Area Champion for Solvent Post-Combustion. Dr. Gibbins is involved in a number of other academic, industrial, and government initiatives on CCS in the UK and overseas, including the SaskPower CCS Global Consortium Advisory Committee. He was also a member of SaskPower's Clean Coal Project Advisory Panel for their 400-megawatt oxyfuel plant study in 2006 and 2007, has participated in reports and inquiries on CCS for a range of UK government and other organizations, and has contributed to a number of media pieces and outreach activities on CCS. He also takes an interest in broader energy system issues as a previous member of the UK Department of Energy and Climate Change (DECC) Scientific Advisory Group (from 2010 to 2014) and through participation in ongoing work on electricity system balancing, economics, and regulation.

Through his own group and by his involvement in the earlier UK CCS Consortium project, the UK CCS Community Network, and the UK CCS Research Council, Dr. Gibbins has also worked to help develop the academic CCS capacity necessary to support rapid CCS development and deployment. Dr. Gibbins has authored more than 50 papers and more than 100 articles and reports on CCS and related topics.

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

Niall MacDowell, Ph.D.

Dr. Niall MacDowell leads the Clean Fossil and Bioenergy Research Group at Imperial College of London, where he is a lecturer in energy and environmental technology and policy. In addition, Dr. MacDowell is a member of the Centre for Process Systems Engineering and the Centre for Environmental Policy, and is a Chartered Engineer with the Institution of Chemical Engineers and a Member of the Royal Society of Chemistry.

Dr. MacDowell is a member of the Technical Working Group on Industrial CCS of the Zero Emissions Platform and the Carbon Capture and Storage Association and is also a member of the Executive Committee of the Institute of Chemical Engineers' (IChemE) Energy Centre.

Dr. MacDowell's research interests are highly interdisciplinary and are focused on integrated multi-scale modelling of low-carbon energy systems, with an emphasis on their dynamic interactions across varying length and time scales.

In addition to his research work, Dr. MacDowell acts as a consultant for companies involved in power generation and has given advice to the UK Department of Energy and Climate Change, the International Energy Agency, the Joint Research Centre, and the Energy Technologies Institute. He has travelled on behalf of the Foreign Office to China and Korea to promote low-carbon power generation, was part of the Imperial College Delegation to the UN Framework Convention on Climate Change COP18 event in Doha, Qatar, and has been invited to provide written evidence to members of the Select Committee on Energy and Climate Change.

John Shinn, Ph.D.

Dr. John Shinn holds a Ph.D. in Chemical Engineering from University of California, Berkeley and has spent his career dedicated to improving the world's energy systems from an environmental and social perspective. Dr. Shinn served 35 years guiding Chevron and the oil industry developing new environmentally-improved process technology and on effective approaches to improve the environmental and social value of their operations. He formed his own private advisory group (SynPatEco LLC) advising clients that include the World Bank, U.S. Department of Energy, Pacific Northwest National Laboratory, Lawrence Berkeley National Laboratory and others on the environmentally- and socially-effective use of fossil fuels and biofuels and has been involved in a number of green venture capital startups seeking to create businesses that profit both the owners and the world.

Dr. Shinn has served on numerous advisory boards and similar roles to engineering, environmental and social institutes at the Massachusetts Institute of Technology, Caltech, Stanford, Sandia, Kyushu University, Penn State and others. He served on the Governing Board of Engineers Without Borders USA for 10 years during its key formative development period.