FY19 CROSSCUTTING (WATER MANAGEMENT R&D) PEER REVIEW OVERVIEW REPORT

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

DISCLAIMER

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INTRODUCTION AND BACKGROUND

The National Energy Technology Laboratory's (NETL) Crosscutting Program is unique in its ability to foster applications of a given technology across several fossil energy programs and efficiently leverage resources to accomplish common goals. Often, processes and materials that advance one technology platform may well have application in another with little to no modification.

Water Management Research and Development (R&D), a technology area within the Crosscutting Program portfolio, aims to reduce the amount of freshwater used by fossil-fueled power plants and to minimize the potential impacts of plant operations on water quality and availability. The vision for this program is to develop a 21st century America that can count on the nation's abundant, sustainable fossil energy and water resources to achieve the flexibility, efficiency, reliability, and environmental quality essential to continued economic health and national security.

Thermoelectric power generation accounts for more than 40% of freshwater withdrawals (143 billion gallons of water per day) and more than 3% of freshwater consumption (4 billion gallons per day) in the United States. As the cost associated with water consumption increases, so will the cost of water treatment, recovery, and reuse.

The Crosscutting Program leads a critical, national effort directed at removing barriers to sustainable, efficient water and energy use; developing technology solutions; and enhancing the understanding of the intimate relationship between energy and water resources.

The Water Management R&D Program addresses the competing needs for water consumption through research in three dynamic platforms:

- Increasing Water Efficiency and Reuse
- Treatment of Alternative Sources of Water
- Energy Water Analysis

Increasing Water Efficiency and Reuse

There is an inextricable link between water and energy; it is increasingly important to use water effectively through the power generation sector. This area aims to advance concepts for both new and existing plants to minimize water intake and use. Examining plant cycles and testing new, efficient processes can reduce water intake and lower overall operating costs.

Treatment of Alternative Sources of Water

Identifying and treating alternative sources of water, such as brackish and effluent streams, offers opportunities for scientists to address energy-water system challenges. This area focuses on furthering technology to utilize alternative water resources that span multiple facets of R&D, including capital costs, operating costs, and system integration.

Energy Water Analysis

The complex relationship between energy and water is constantly developing. The multiple components that impact the system can be modeled and analyzed to better inform decision makers and scientists alike. This area helps prioritize research objectives through analyses of the water-energy system behavior.

Office of Management and Budget Requirements

In compliance with requirements from the Office of Management and Budget, the U.S. Department of Energy (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 2019 (FY19) Crosscutting (Water Management R&D) 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 9-11, 2018, to conduct a peer review of six Crosscutting (Water Management R&D) Program research projects.

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

TABLE 1. CROSSCUTTING (WATER MANAGEMENT R&D) PEER REVIEW – PROJECTS REVIEWED

Project Number	Title	Lead Organization	Total Funding		Project Duration	
			DOE	Cost Share	From	To
FE0031556	Novel Patterned Surfaces for Improved Condenser Performance in Power Plants	Virginia Polytechnic Institute and State University	$749,898	$188,572	12/15/2017	12/14/2020
FWP-1022428	Treating Effluent Streams at Coal Power Plants Using Membranes	NETL Research & Innovation Center (RIC)	$1,100,000	$0	4/1/2018	3/31/2020
FE0031551	Energy Efficient Waste Heat Coupled Forward Osmosis for Effluent Water Management at Coal-Fired Power Plants	University of Illinois at Urbana-Champaign	$743,410	$186,207	12/19/2017	12/31/2020
FE0030456	Applying Anodic Stripping Voltammetry to Complex Wastewater Streams for Rapid Metal Detection	University of California – Los Angeles	$400,000	$0	8/1/2017	7/31/2020
FE0031555	Intensified Flue Gas Desulfurization Water Treatment for Reuse, Solidification, and Discharge	University of Kentucky Research Foundation	$738,921	$189,745	1/22/2018	1/21/2020
FE0031561	Application of Heat Transfer Enhancement (HTE) System for Improved Efficiency of Power Plant Condensers	Interphase Materials, Inc.	$745,915	$216,000	2/1/2018	1/31/2021
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.			$4,478,144	$780,524		
			$5,258,668			

OVERVIEW OF THE PEER REVIEW PROCESS

DOE and NETL are fully committed to improving the quality and results of their research projects. 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.

On October 9-11, 2018, KeyLogic convened a panel of four academic and industry experts to conduct a peer review of six research projects supported by the Crosscutting (Water Management R&D) 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.

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.

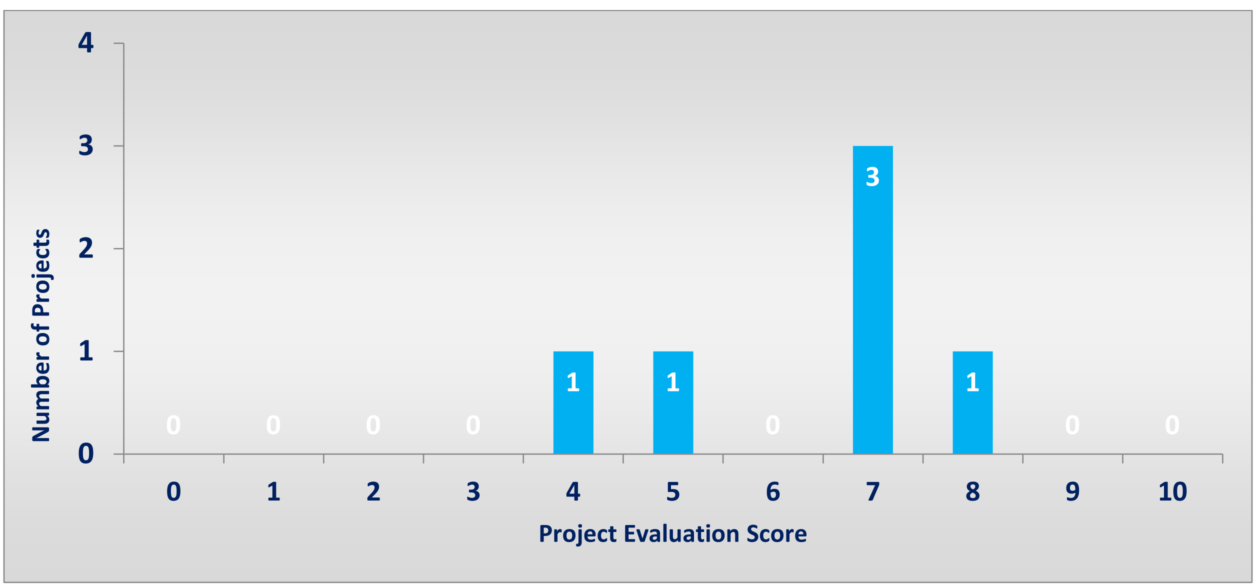
SUMMARY OF KEY FINDINGS

This section summarizes the overall key findings of the projects evaluated at the FY19 Crosscutting (Water Management R&D) 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 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 40 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 four to eight.

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



FY19 Crosscutting (Water Management R&D) Peer Review Project Evaluation Scores

General Project Strengths

The panel was impressed by the quality of the Crosscutting (Water Management R&D) Program projects they reviewed. They indicated that the projects represent a diverse set of technologies with ambitious goals and significant potential to improve condenser efficiency or effluent water management at coal-fired power plants. Based on the progress made to date by the projects reviewed, the panel was optimistic about the potential for these projects to further progress toward achieving DOE's challenging goals and continue along the pathway to commercialization. The following are noteworthy project strengths from the panel members that relate to one or more projects:

- Research is focused on critical parameters regarding fouling and corrosion of the coated surface. Numerous upcoming issues and possible barriers to continued development have been examined.
- The technology has a potentially lower capital cost and energy footprint than a thermal evaporator. There are currently no commercial technologies available for this application other than a thermal evaporator, so there is a need to develop technologies that are lower cost and less energy intensive.
- The economic analysis considers numerous factors that are known for forward osmosis (FO). The economic analysis has been compared to that of numerous other membrane technologies, such as reverse osmosis (RO), membrane distillation, and nano-filtration.
- The ability to detect metals while the power plant is online in near real-time is important. This method does not exist elsewhere.
- The system does not have the inherent weaknesses that standard biological treatment has with selenium removal. Temperature, chloride concentration, nutrients, and solids are not concerns, making this technology more robust than standard biological treatment.
- The technology allows for ease of application and can be used to retrofit existing power plants.

General Project Weaknesses

Observations that panel members noted as project weaknesses included:

- There is a lack of clear test results regarding the effects of scaling, fouling, corrosion, vibration, and chemical interactions on the coated surface at design temperatures.
- Zero Liquid Discharge (ZLD) is not currently a regulation for coal-fired power plants in the United States, so there is no driver for the technology.
- The level of effluent water pretreatment was inadequately addressed.
- The sensing method does not appear to account for all the metals of interest.
- The project lacks cost and energy data.
- The chemical and mechanical stability of the technology is unknown.

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 upon project accomplishments. Panel recommendations included:

- Test for the effects of scaling, fouling, corrosion, vibration, and chemical interactions on the coated surface at design temperatures.
- Obtain flue-gas desulfurization (FGD) wastewater samples and test to determine an accurate chemistry of the water that needs to be treated.
- Define pretreatment requirements for the system, such as solids separation and softening.
- Investigate sensor materials for all inorganics of interest, including: mercury, arsenic, selenium, and copper.
- Develop preliminary cost and energy estimates for the system. The costs should be compared to other treatment systems.
- Identify any chemical interactions with conditioning chemicals, such as biocides, chlorine, and inhibitors.

PROJECT SYNOPSES

For more information on the Crosscutting (Water Management R&D) Program and project portfolio, please visit the NETL website: https://www.netl.doe.gov/coal/water-management.

FE0031556

NOVEL PATTERNED SURFACES FOR IMPROVED CONDENSER PERFORMANCE IN POWER PLANTS

Ranga Pitchumani – Virginia Polytechnic Institute and State University

Project Description: The project aims to improve thermoelectric power plant performance through engineered superhydrophobic/slippery liquid infused porous surfaces (SLIPS) for condenser tube designs fabricated by a patented two-step electrodeposition technique. The electrodeposition process is a widely used industrial process that is applicable to a variety of shapes, materials, and sizes. The project will demonstrate and characterize a variety of SLIPS coatings based on copper, nickel, copper/nickel, zinc, tungstite, and other materials on commonly used condenser tube surfaces, namely copper, copper/nickel, stainless steel, and titanium alloys through a facile and cost-effective electrodeposition process. The goal is to demonstrate overall condenser heat exchanger effectiveness that is at least 50% higher than that of current systems while reducing condenser pressure and improving power plant efficiency.

FWP-1022428

TREATING EFFLUENT STREAMS AT COAL POWER PLANTS USING MEMBRANES

Nick Siefert – NETL-RIC

Task Description: There are a number of different effluent streams generated at coal-fired power plants that require onsite treatment. One option for treating these effluent streams is called Zero Liquid Discharge (ZLD), which effectively concentrates the dissolved ionic species while separating out freshwater. Currently, ZLD is an expensive option for treating these effluent streams because of the high energy and capital cost associated with the brine concentration step in the ZLD process. As such, the objective of National Energy Technology Laboratory Research & Innovation Center (NETL RIC) research is to demonstrate advanced technologies that can concentrate effluent streams to high concentrate while reducing both the energy and capital cost of the brine concentration step by 50%. The goal is to demonstrate at an existing coal power plant by 2020. A side benefit of ZLD is the generation of freshwater for local use. The main area of research within this task is to demonstrate experimentally and to numerically simulate a novel membrane process for concentrating effluent streams which can significantly reduce the energy consumed compared against commercially available, non-membrane technologies, such as mechanical vapor recompression (MVR).

FE0031551

ENERGY EFFICIENT WASTE HEAT COUPLED FORWARD OSMOSIS FOR EFFLUENT WATER MANAGEMENT AT COAL-FIRED POWER PLANTS

Nandakishore Rajagopalan – University of Illinois at Urbana-Champaign

Project Description: This project will evaluate a transformational low energy (less than 200 kilojoules/kilogram water) waste heat coupled forward osmosis (FO)-based water treatment system (the Aquapod©), adapted to meet the complex and unique environment of a power plant, to manage effluents, meet cooling water demands, and achieve water conservation. The target is to enable recovery of at least 50% of the water from highly degraded water sources without extensive pretreatment in a cost-effective manner.

FE0030456

APPLYING ANODIC STRIPPING VOLTAMMETRY TO COMPLEX WASTEWATER STREAMS FOR RAPID METAL DETECTION

David Jassby – University of California – Los Angeles

Project Description: This project's objective is to develop a lab-on-a-chip (LOC) electrochemical sensor capable of accurately measuring heavy metal concentrations, including lead (Pb), cadmium (Cd), and arsenic (As), in complex aqueous streams such as wastewater. The sensor technology relies on anodic stripping voltammetry (ASV), which has been demonstrated to detect extremely low (sub parts per million [ppm]) concentrations of these metals. The technology will be capable of autonomously conducting metal measurements and reporting the findings remotely via cellular technology. Furthermore, using open-source hardware and software tools, the project team will construct sensor technology that operates with minimal human intervention and be capable of autonomously performing all of the pretreatment steps needed to perform metal measurement activities. To accomplish this objective, the project team will concentrate on characterizing metal speciation in wastewater, develop appropriate pretreatment methods that will allow analysis of this complex matrix on an LOC device, fabricate a range of electrodes specifically tailored to enhance the detection of the target metals, and construct and test an autonomous LOC device that incorporates the pretreatment steps and specialized electrodes for the detection of heavy metals in wastewater.

FE0031555

INTENSIFIED FLUE GAS DESULFURIZATION WATER TREATMENT FOR REUSE, SOLIDIFICATION, AND DISCHARGE

Xin Gao – University of Kentucky Research Foundation

Project Description: This project will develop a process that is able to treat, for reuse, wastewater resulting from wet flue-gas desulfurization (FGD) scrubbing systems, leading to significant reductions in footprint and chemical consumption compared to the state-of-the-art water treatment technologies. To achieve this goal, the project will (1) evaluate the effectiveness of electrocoagulation (EC) with air-dissolved flotation on removing regulated species through design, construction, and testing of a one liter per hour sub-pilot unit; (2) examine a nanofiltration unit to achieve greater than 80% monovalent salt rejection; (3) conduct long-term operation of membrane-based filtration for FGD wastewater aimed at determining performance degradation (e.g., membrane fouling); (4) determine a practical salt concentration for solidification, resulting in an acceptable leachate; and (5) apply continuous capacitive deionization as a polishing step to remove any remaining government-regulated species below the effluent limitation guidelines requirements for recycling or discharge.

FE0031561

APPLICATION OF HEAT TRANSFER ENHANCEMENT (HTE) SYSTEM FOR IMPROVED EFFICIENCY OF POWER PLANT CONDENSERS

Kasey Catt – Interphase Materials, Inc.

Project Description: The objective of this project is to determine the condenser efficiency improvements and the reduction of continuous feed water treatment that coal-fired plants could realize by utilizing Interphase's heat transfer enhancement technology (HTE system). Previous lab-scale work has demonstrated that the HTE system can inhibit biofouling, microbiologically induced corrosion, and scale buildup, as well as improve baseline heat transfer efficiency of cooling systems in laboratory-scale testing. By applying the HTE system first to field test rigs at the Longview site, and subsequently the condenser at the Longview plant, Interphase and Longview will collect field data on the HTE system's potential to increase heat transfer efficiency in the condenser cooling systems of coal-fired 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.
6. The project Technology Maturation Plan (TMP) represents a viable path for technology development beyond the end of the current project, with respect to scope, timeline, and cost.
[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

Crosscutting (Water Management R&D) Peer Review
October 9-11, 2018
NETL-Pittsburgh Building 922 Room 106A

Tuesday, October 9, 2018

8:00 a.m.	*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 FE0031556 – Novel Patterned Surfaces for Improved Condenser Performance in Power Plants *Ranga Pitchumani* – Virginia Polytechnic Institute and State University
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 (Recommendations-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 FWP-1022428 – Treating Effluent Streams at Coal Power Plants Using Membranes *Nick Siefert* – NETL-RIC
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 (Recommendations-Based Evaluation; Review Panel) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
4:00 p.m.	Adjourn

Wednesday, October 10, 2018

8:00 a.m.	*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 FE0031551 – Energy Efficient Waste Heat Coupled Forward Osmosis for Effluent Water Management at Coal-Fired Power Plants *Nandakishore Rajagopalan* – University of Illinois at Urbana-Champaign
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 (Recommendations-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 FE0030456 – Applying Anodic Stripping Voltammetry to Complex Wastewater Streams for Rapid Metal Detection *Ashok Mulchandani* – University of California – Los Angeles
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 (Recommendations-Based Evaluation; Review Panel) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
3:30 p.m.	Adjourn

Thursday, October 11, 2018

8:00 a.m.	*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 FE0031555 – Intensified Flue Gas Desulfurization Water Treatment for Reuse, Solidification, and Discharge *Xin Gao* – University of Kentucky Research Foundation
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 (Recommendations-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 FE0031561 – Application of Heat Transfer Enhancement (HTE) System for Improved Efficiency of Power Plant Condensers *Kasey Catt* – Interphase Materials, Inc.
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 (Recommendations-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

Crosscutting (Water Management R&D) Peer Review
October 9-11, 2018
NETL-Pittsburgh Building 922 Room 106A

Young Chul Choi, Ph.D.

Dr. Young Chul Choi serves as the Associate Director of Southern Research's (SR) Industrial Water Practice, focusing on creating clean water technologies through engineering services, development, and analytical testing. Before coming to SR, he launched a water program at RTI International in Research Triangle Park, North Carolina, developing technical solutions in the water-energy nexus. He also worked for CH2M Hill as a regional technology leader and at Doosan Hydro Technology as the founder of a research and development group. His expertise includes water and wastewater treatment using membranes and biological treatment, particularly desalination, nutrient removal, and industrial treatment.

Dr. Choi received a B.S. degree in civil engineering and an M.S. in environmental engineering from Seoul National University. He completed his doctorate in environmental engineering at the University of Illinois at Urbana-Champaign. He is also a registered professional engineer with two U.S. patents and serves as Editor-in-Chief for the technical journal, Membrane Water Treatment.

Bryan Hansen, PE

Mr. Bryan Hansen is a chemical engineer specializing in air pollution control, water and wastewater treatment systems, and water chemistry studies. Throughout his 25-year career, Mr. Hansen has provided various engineering services, including consulting, studies, reports, conceptual design, detailed design, procurement, and construction. Mr. Hansen has also functioned as the project manager on numerous studies, reports, and projects.

In his current role at Burns & McDonnell, Mr. Hansen works primarily on projects involving water and wastewater treatment process design and air pollution control equipment process design for electric utilities and industrial clients. Mr. Hansen also regularly conducts studies to evaluate technologies for regulatory compliance and has extensive experience related to effluent limitation guidelines (ELG) compliance. Mr. Hansen regularly writes papers and delivers presentations at technical conferences such as Electric-Power, Coal-Gen, Power-Gen, the International Water Conference, and the MEGA Symposium. Mr. Hansen received a B.S. degree in chemical engineering from the University of Missouri-Columbia and is certified as a professional engineer in New Mexico, Nevada, and Kansas.

Andrew Shaw, Ph.D.

Dr. Andrew Shaw is a Global Practice and Technology Leader in Sustainability and Wastewater for Black & Veatch. He has more than 20 years of experience in wastewater treatment design projects in the United Kingdom (UK), Australia, Asia, and North America. His expertise includes nutrient removal, computer modeling, instrumentation, process optimization, and life-cycle assessments – this includes planning, design, and operations of treatment facilities; advancing the use of process modeling; and development of wastewater technologies. He serves as chair of the Water Environment Federation's Municipal Resource Recovery Design Committee, which is involved in programs and technical information on the advancement of municipal wastewater treatment design practices. Dr. Shaw is also chair of several International Water Association task groups and committees in areas such as computer modeling and water life-cycle assessments.

Dr. Shaw served as Process Lead for the city of Raleigh, North Carolina, Wastewater Master Plan, which included selection of the most appropriate technology and investigating future treatment requirements, including nutrient removal in conjunction with the collection system for the city across multiple sites. He also served as process specialist in implementing phosphorus recovery at the Stickney Water Reclamation Plant in Chicago, Illinois, which is the largest wastewater treatment plant in the world and serves 2.3 million people. Dr. Shaw also has significant international experience, including his role as the lead wastewater process engineer for the iconic Deep Tunnel Sewerage System Phase 2 in Singapore. In this project, pump stations and treatment plants are being consolidated into a deep tunnel collection system, single pump station, and a new state-of-the-art membrane bioreactor plant treating more than 200 million gallons per day of "used water" in order to produce "NEWater" for reuse. Dr. Shaw earned a B.S. degree in chemical engineering with environmental protection from Loughborough University in the UK and a Ph.D. in environmental engineering from the Illinois Institute of Technology.

Paul Ziemkiewicz, Ph.D.

Paul Ziemkiewicz is the Director of the West Virginia Water Research Institute (WVWRI). The WVWRI works with the faculty of WVU and other universities to manage programs that range from local, regional, national, to international in scope. Major programs include mine drainage, watershed management, biofuels, industrial site restoration, and treatment of drilling brines.

Dr. Ziemkiewicz's responsibilities focus on addressing high priority environmental issues by developing research opportunities, assembling and managing research teams and responding to the needs of sponsors. In addition to his research roles, Dr. Ziemkiewicz serves on both state and federal policy advisory committees focusing on energy and water. Dr. Ziemkiewicz is a member of the West Virginia Acid Mine Drainage Task Force, the Eastern Mine Drainage Federal Consortium, the West Virginia Special Reclamation Trust Fund Advisory Council and the Ohio River Basin Water Availability and Management Work Group.

Dr. Ziemkiewicz received the E.M. Watkin Award in 1985 for Outstanding Contribution to the Betterment of Land Reclamation in Canada, presented by the Canadian Reclamation Association. In 2005, he received the Environmental Conservation Distinguished Service Award, presented by the Society for Mining, Metallurgy and Exploration. In 2017, he received the Pioneers in Reclamation Award presented by the American Society of Mining and Reclamation. He holds a Bachelor's in Biology and a Master's in Range Ecology from Utah State University, and Doctorate in Forest Ecology from the University of British Columbia.