NATIONAL ENERGY TECHNOLOGY LABORATORY

FY20 TRANSFORMATIVE POWER GENERATION PEER REVIEW OVERVIEW REPORT

December 5, 2019

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

DISCLAIMER

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INTRODUCTION AND BACKGROUND

The Transformative Power Generation Program aims to advance science, engineering, and technology by inventing, integrating, maturing, and commercializing coal combustion power technologies and systems to enhance the nation's energy production and protect the environment for future generations. The program develops technologies to improve performance and extend the life of existing power plants. Research also focuses on next generation modular coal-fired power plants providing stable power generation with operational flexibility and high efficiency, as well as advanced combustion technologies (e.g., oxy-combustion and chemical looping combustion [CLC]) that provide options for coal-fired power generation in a carbon-constrained future. The program uses a multipronged and coordinated approach to identify and perform research through in-house research and development (R&D), as well as cost-shared R&D with external partners in academia, industry, and other national laboratories. Transformative power generation technologies will be market-driven with the best technologies, growing deployment opportunities in an increasingly challenging power generation market.

The Transformative Power Generation Program has three primary R&D areas: Coal FIRST (Flexible, Innovative, Resilient, Small, Transformative) – Coal Plant of the Future, Improvements for Existing Coal Plants, and Advanced Combustion.

The Coal FIRST Initiative will develop the coal-based power plant of the future that is needed to provide secure, stable, and reliable power. This R&D will underpin coal-fired power plants that are capable of flexible operations to meet the needs of the grid, use innovative and cutting-edge components that improve efficiency and reduce emissions, provide resilient power to Americans, small compared to today's conventional utility-scale coal, and transform how coal technologies are designed and manufactured.

The existing coal power generation fleet plays a critical role in providing reliable power generation required for power grid stability. It is important that these existing units continue to operate in an efficient and reliable manner. Under the current energy landscape, power plants are often required to operate at low and/or variable loads. Since the plants are not designed to operate below baseload, operation at low-load results in lowered efficiency and increased wear on the plant components. Operation at variable loads requires ramping of the plant capacity, which adds to the lowered efficiency and increased wear on plant components. As a result, there is a need for rapid commercialization of technologies to improve the efficiency, reliability, and flexibility of existing coal-based power plants. Existing plant combustion technologies R&D focuses on the identification of impactful, near-term opportunities applicable to the needs of the existing fleet.

Advanced combustion power generation combusts coal in an oxygen-rich environment rather than air. This eliminates most of the nitrogen found in air from the combustion process, resulting in flue gas composed largely of carbon dioxide (CO_2) and water. The high concentration of CO_2 and absence of nitrogen simplify separation of CO_2 from the flue gas for storage or beneficial use. Thus, oxygen-fired combustion is an alternative approach for carbon capture and storage (CCS) for coal-fired systems.

Advanced combustion has several challenges, including capital cost, energy consumption, air infiltration that dilutes the flue gas with nitrogen, and energy-efficient purification processes to remove pollutants and excess oxygen from the concentrated CO_2 stream. Cost-shared R&D is being performed both externally (by industry, research organizations, and academic institutions) and internally (through the National Energy Technology Laboratory's [NETL] Research and Innovation Center [RIC]) to develop oxy-combustion and CLC technologies to overcome these challenges. The projects selected for this peer review focus on CLC technologies.

Transformative power generation technologies provide the following benefits: performance upgrades to existing coal-fired plants; accelerated deployment of advanced technologies to improve the reliability, availability, and maintainability of coal-fired generation; modular system designs that can be adapted by industry for smaller, more reliable and efficient facilities that increase deployment opportunities; and environmental stewardship through long-term development of near-zero emissions coal combustion technologies.

Office of Management and Budget Requirements and DOE Requirements

In compliance with requirements from the Office of Management and Budget and in accordance with the U.S. Department of Energy (DOE) Strategic Plan, DOE and NETL are fully committed to improving the quality of research projects in their programs by conducting rigorous peer reviews. DOE and NETL conducted a Fiscal Year 2020 (FY20) Transformative Power Generation Peer Review Meeting with independent technical experts to offer each project prioritized recommendations and assess two projects' Technology Readiness Level (TRL) progression. KeyLogic (NETL site-support contractor) convened a panel of four academic and industry experts[*] on October 22-24, 2019, to conduct a peer review of three Transformative Power Generation Program research projects.

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

TABLE 1. TRANSFORMATIVE POWER GENERATION PEER REVIEW – PROJECTS REVIEWED

Project Number	Title	Lead Organization	Total Funding		Project Duration	
			DOE	Cost Share	From	To
FWP-1022461	Task 12.1: Oxygen Carrier Development and Task 13.2: Bench Scale Reactor Testing * Task 12.2.1: Fundamental Particle Degradation * Task 12.2.3: High Fidelity Attrition Models * Task 13.1: Lab-Scale Testing *	National Energy Technology Laboratory	$5,957,000^	$0	04/01/2018	03/31/2020
FE0029160	Development of Enabling Technologies for Chemical Looping Combustion and Chemical Looping with Oxygen Uncoupling **	University of Utah	$1,333,803	$460,201	10/01/2016	12/31/2020
FE0027654	10 Megawatts Electric Coal Direct Chemical Looping Large Pilot Plant - Pre-Front End Engineering and Design Study **	Babcock & Wilcox	$3,289,925	$1,821,188	04/01/2017	03/31/2020
			$10,580,728	$2,281,389		
			$12,862,117			

* Recommendations-Based Evaluation: During recommendations-based evaluations, the independent panel provides recommendations to strengthen the performance of projects during the period of performance.

** TRL-Based Evaluation: During TRL-based evaluations, the independent panel offers recommendations and assesses the projects' technology readiness for work at the current TRL and the planned work to attain the next TRL.

^ For entire Field Work Proposal; costs do not include shared research costs in Execution Year 2019 (EY19), which are not tracked at the task level.

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 in compliance with requirements from the Office of Management and Budget and in accordance 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 three research projects supported by the Transformative Power Generation Program. Throughout the peer review meeting, these recognized technical experts offered recommendations for each project reviewed and provided feedback on two projects' technology readiness for work at the current TRL and the planned work to attain the next TRL. 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 projects subject to a TRL-based evaluation also shared a Technology Maturation Plan (TMP) to facilitate TRL evaluation from the Peer Review Panel (reference Table 1). The Federal Project Manager (FPM) provided the Project Management Plan (PMP) or Field Work Proposal (FWP), the latest quarterly report, and supplemental 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 Peer 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[†]. For one of the projects (identified in Table 1), the panel offered a series of prioritized recommendations by task to strengthen the project during the remaining period of performance. For the remaining two projects, the panel offered prioritized recommendations and an evaluation of TRL progression.

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

SUMMARY OF KEY FINDINGS

This section summarizes the overall key findings of the projects evaluated at the FY20 Transformative Power Generation 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 36 recommendations for NETL management to review and consider.

The panel offered several common themes among the projects reviewed. The projects were all technically sound and the teams showed a good understanding of general processes and how to execute tests at lab scale. The teams have qualified, experienced personnel to drive project development and established valuable interactions with other researchers (e.g., publishing peer-reviewed papers and attending conferences). The panel indicated there is a gap in the current TRL to commercialization (TRL 9) and that teams did not offer a clear, defined path toward commercialization or strategies to address the related challenges. While CLC is inherently a carbon capture technology and projects to be competitive with other capture technologies, the panel members indicated that it may be challenging to make this technology competitive under current market conditions (e.g., the technology's electricity generation prices per megawatt-hour were high compared to commercial electricity generation prices). In some cases, projects needed more connection between tasks and there was a need to share knowledge within the project to enhance outcomes. Finally, the panel offered that there should be more focus on bottlenecks for each chemical looping approach and that the projects should strategically investigate these issues to meet program goals.

Evaluation of Technology Readiness Level Progression

At the meeting, the Peer Review Panel assessed two projects' readiness to start work towards the next TRL based on a project's strengths, weaknesses, recommendations, issues, and concerns. For the various projects subject to review, the panel found that all were on track to attaining their respective planned end-of-project TRL based on achievement of the project goals as planned and addressing the Review Panel recommendations.

- Project FE0029160 has attained TRL 3. Project FE0029160 will attain TRL 4 upon demonstrating operation with copper oxide in the existing air reactor-fuel reactor loop, as well as a carrier regeneration capability, and providing supporting information to NETL that includes the results of the integrated experiments and estimates of how the experimental components and test results differ from the expected system performance goals.
- Project FE0027654 has attained TRL 5. Upon running the 250-kilowatt-thermal (kW_{th}) unit for a minimum of 500 hours on a variety of coal feeds and mitigation of the excessive nitrogen oxide (NO_X) formation, Project FE0027654 will attain TRL 6. Upon incorporating the knowledge gained from the 500-hour run and demonstration of autothermal operation on a 2.5-megawatt (MW) module, Project FE0027654 will attain TRL 7.

PROJECT SYNOPSES

For more information on the Transformative Power Generation Program and project portfolio, please visit the NETL website: https://netl.doe.gov/coal/tpg.

FWP-1022461 TRANSFORMATIONAL TECHNOLOGIES FOR NEW AND EXISTING PLANTS

TASK 12.1: OXYGEN CARRIER DEVELOPMENT

TASK 13.2: BENCH-SCALE REACTOR TESTING

NATIONAL ENERGY TECHNOLOGY LABORATORY

Task Descriptions: The goal of Task 12.1 is to develop oxygen carriers with high fuel conversion and high-attrition resistance for the National Energy Technology Laboratory (NETL) 50-kilowatt-thermal (kW_{th}) tests. This subtask is assessing the performance and durability of new and existing oxygen carrier materials for chemical looping combustion (CLC) systems. The goals for this sub-subtask center on developing a fundamental understanding of how an oxygen carrier functions and using this knowledge to improve the service life and performance of CLC oxygen carrier materials. The bench-scale testing (Task 13.2) provides a realistic environment to advance the Technology Readiness Level (TRL) for oxygen carrier materials and the NETL Chemical Looping Reactor test facility is one of the only units to demonstrate self-sustaining CLC reactions while simultaneously evaluating the relative oxygen carrier makeup costs.

FWP-1022461 TRANSFORMATIONAL TECHNOLOGIES FOR NEW AND EXISTING PLANTS

TASK 12.2.1: FUNDAMENTAL PARTICLE DEGRADATION

NATIONAL ENERGY TECHNOLOGY LABORATORY

Task Description: This subtask is assessing the performance and durability of new and existing oxygen carrier materials for chemical looping combustion (CLC) systems. The goals for this sub-subtask center on developing a fundamental understanding of how an oxygen carrier functions and using this knowledge to improve the service life and performance of CLC oxygen carrier materials. The National Energy Technology Laboratory (NETL) has unique diagnostic equipment – the high-temperature environmental confocal scanning laser microscope systems (CSLMs) – capable of operating in controlled oxidizing and reducing conditions using air (containing $^{16}O_2$) and an $^{18}O_2$ isotope and other gases, along with conventional analytical and microstructural techniques that include thermogravimetry analysis (TGA) and scanning electron microscopy (SEM).

FWP-1022461 TRANSFORMATIONAL TECHNOLOGIES FOR NEW AND EXISTING PLANTS

TASK 12.2.3: HIGH FIDELITY ATTRITION MODELS

NATIONAL ENERGY TECHNOLOGY LABORATORY

Task Description: The overall goals for high-fidelity (computational fluid dynamics [CFD]) modeling activity within the scope of chemical looping is the development, testing, and application of predictive simulation tools to address technical challenges to the development of chemical looping technology. The current focus is on using these tools to address the challenge of attrition. The objective is to use CFD simulations to predict the multiphase hydrodynamics of chemical looping systems, including the forces and mechanical stresses (attrition precursors) experienced by particles. The subsequent analysis of these simulations will be used to (1) analyze assumptions about flow fields in reactor-scale, low-fidelity attrition models and correlations; (2) coordinate with experiments to differentiate material properties (material function) versus reactor dynamics (machine function); (3) design chemical looping components with reduced mechanical stress and forces; and (4) examine material attrition coefficients calibrated with experiments to predict the attrition in other systems of interest.

FWP-1022461 TRANSFORMATIONAL TECHNOLOGIES FOR NEW AND EXISTING PLANTS

TASK 13.1: LAB-SCALE TESTING

NATIONAL ENERGY TECHNOLOGY LABORATORY

Task Description: The purpose of Task 13.1 is to develop and utilize a controlled testing environment to support the National Energy Technology Laboratory's (NETL) efforts in developing chemical looping combustion (CLC) oxygen carriers, reactors, and components. The goal is to develop and support an "intermediate" testing environment that can evaluate oxygen carriers under realistic yet controlled conditions. One focus area is the study of attrition mechanisms and the second is solid fuel chemistry with an oxygen carrier.

FE0029160

DEVELOPMENT OF ENABLING TECHNOLOGIES FOR CHEMICAL LOOPING COMBUSTION AND CHEMICAL LOOPING WITH OXYGEN UNCOUPLING

UNIVERSITY OF UTAH

Project Description: Chemical looping with oxygen uncoupling (CLOU) is a variant of chemical looping combustion (CLC) in which the oxidized oxygen carrier spontaneously releases gaseous oxygen (O_2) in the fuel reactor, allowing efficient combustion of solid fuels, such as coal, that are challenging to convert in conventional CLC systems. Under this project, the University of Utah, in partnership with Reaction Engineering International and CPFD Software, will develop technologies to improve system performance and reduce costs of CLC and CLOU. The project focuses on oxygen carrier management and reactor design and operation. Project objectives include: (1) developing "zero-loss" technology to recover and regenerate oxygen carrier materials that exit the system due to attrition; (2) achieving more controllable management of solids in loop seals and gas-solid separators; (3) better incorporating chemical reactions into computational simulations; (4) improving heat recovery and management; and (5) investigating a novel dual oxygen carrier reactor design.

FE0027654

10 MEGAWATTS ELECTRIC COAL DIRECT CHEMICAL LOOPING LARGE PILOT PLANT - PRE-FRONT END ENGINEERING AND DESIGN STUDY

BABCOCK & WILCOX COMPANY

Project Description: Babcock & Wilcox (B&W) is collaborating with Ohio State University (OSU) to develop an iron-based coal-direct chemical looping (CDCL) technology, including testing of a 25-kilowatt-thermal (kW_{th}) small-pilot unit. This project will expand this program by completing a front-end engineering design (FEED) study of a 10-megawatt-electric (MWe) CDCL large pilot plant. The design will integrate with the existing steam cycle and balance-of-plant equipment at a selected host site, either the Dover Light & Power plant in Dover, Ohio, or First Energy's W. H. Sammis Power Plant in Stratton, Ohio. The applicants will prepare a budget and schedule for constructing and operating the 10-MWe pilot and conduct an updated technoeconomic analysis (TEA) at the 550-MWe commercial scale to evaluate the ultimate cost and performance relative to the U.S. Department of Energy (DOE) goals.

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-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 Technology Readiness Level (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 (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). 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 strengths, weaknesses, overall score, and prioritized recommendations for each project. The 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, strengths and weaknesses shall be characterized as either "major" or "minor" during the Review Panel's 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 correct or mitigate the impact of weaknesses, expand upon a project's strengths, or progress along the technology maturation path (TRL-based evaluation). 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 U.S. Department of Energy (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 Technology Readiness Level (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 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. *(This criterion is not applicable to a recommendations-based evaluation)*
[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.

<u>Rating Definitions and Scoring Plan</u> (not applicable to TRL-based evaluation)

The Review Panel will be required to assign a 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: DOE TECHNOLOGY READINESS LEVELS

The following is a description of U.S. Department of Energy (DOE) Technology Readiness Levels (TRLs).

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
System Operations	**TRL 9**	Actual system operated over the full range of expected mission conditions	The technology is in its final form and operated under the full range of operating mission conditions. Examples include using the actual system with the full range of wastes in hot operations.
System Commissioning	**TRL 8**	Actual system completed and qualified through test and demonstration	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this Technology Readiness Level (TRL) represents the end of true system development. Examples include developmental testing and evaluation of the system with actual waste in hot commissioning. Supporting information includes operational procedures that are virtually complete. An Operational Readiness Review (ORR) has been successfully completed prior to the start of hot testing.
	TRL 7	Full-scale, similar (prototypical) system demonstrated in relevant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Examples include testing full-scale prototype in the field with a range of simulants in cold commissioning (1). Supporting information includes results from the full-scale testing and analysis of the differences between the test environment, and analysis of what the experimental results mean for the eventual operating system/environment. Final design is virtually complete.
Technology Demonstration	**TRL 6**	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. Examples include testing an engineering-scale prototypical system with a range of simulants (1). Supporting information includes results from the engineering-scale testing and analysis of the differences between the engineering-scale, prototypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and 6 is the step-up from laboratory scale to engineering scale and the determination of scaling factors that will enable design of the operating system. The prototype should be capable of performing all the functions that will be required of the operational system. The operating environment for the testing should closely represent the actual operating environment.

Technology Development	**TRL 5**	Laboratory-scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity, laboratory scale system in a simulated environment with a range of simulants (1) and actual waste (2). Supporting information includes results from the laboratory scale testing, analysis of the differences between the laboratory and eventual operating system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. The major difference between TRL 4 and 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical.
Technology Development	**TRL 4**	Component and/or system validation in laboratory environment	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants and small-scale tests on actual waste (2). Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL 4–6 represent the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function.

Research to Prove Feasibility	**TRL 3**	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development (R&D) is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative tested with simulants (1). Supporting information includes results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. At TRL 3 the work has moved beyond the paper phase to experimental work that verifies that the concept works as expected on simulants. Components of the technology are validated, but there is no attempt to integrate the components into a complete system. Modeling and simulation may be used to complement physical experiments.
	TRL 2	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies. Supporting information includes publications or other references that outline the application being considered and that provide analysis to support the concept. The step up from TRL 1 to TRL 2 moves the ideas from pure to applied research. Most of the work is analytical or paper studies with the emphasis on understanding the science better. Experimental work is designed to corroborate the basic scientific observations made during TRL 1 work.
Basic Technology Research	**TRL 1**	Basic principles observed and reported	This is the lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples might include paper studies of a technology's basic properties or experimental work that consists mainly of observations of the physical world. Supporting Information includes published research or other references that identify the principles that underlie the technology.

[1] Simulants should match relevant chemical and physical properties.

[2] Testing with as wide a range of actual waste as practicable and consistent with waste availability, safety, ALARA, cost and project risk is highly desirable.

Source: U.S. Department of Energy, "Technology Readiness Assessment Guide." Office of Management. 2011.

APPENDIX C: MEETING AGENDA

Transformative Power Generation Peer Review
October 22-24, 2019
NETL-Pittsburgh Building 922 Room 106A

Tuesday, October 22, 2019

8:00 a.m. (no earlier)	*Panel Members Arrive at NETL-Pittsburgh for Security Check*
8:30 a.m. (no earlier)	*Morning Presenters Arrive, Visitors Escorted to NETL-Pittsburgh Building 922 Room 106A*
8:30 – 9:00 a.m.	Peer Review Panel Kickoff Session *DOE HQ/NETL, KeyLogic Peer Review Support Staff, and Panel Members Attend* - Facilitator Opening, Review Panel Introductions, Technology Manager Welcome, Peer Review Process and Meeting Logistics
9:00 – 9:15 a.m.	FWP-1022461 Transformational Technologies for New and Existing Plants *Doug Straub* – NETL-RIC
9:15 – 10:05 a.m.	NETL/RIC FWP-1022461 Task 12.1: Oxygen Carrier Development and Task 13.2: Bench-Scale Reactor Testing *Task 12.1 Lead: Ranjani Siriwardane and Task 13.2 Lead: Doug Straub* – NETL-RIC
10:05 – 10:50 a.m.	Question-and-Answer Session
10:50 – 11:05 a.m.	BREAK
11:05 – 12:35 p.m.	Closed Discussion (Recommendations-Based Evaluation; Review Panel) *DOE HQ/NETL and KeyLogic Peer Review Support Staff Attend as Observers*
12:35 – 1:35 p.m.	Lunch
1:15 p.m. (no earlier)	*Afternoon Presenters Arrive at NETL-Pittsburgh for Security Check*
1:35 – 2:05 p.m.	NETL/RIC FWP-1022461 Task 12.2.1: Fundamental Particle Degradation *Task 12.2.1 Lead: James Bennett* – NETL-RIC
2:05 – 2:35 p.m.	Question-and-Answer Session
2:35 – 2:50 p.m.	BREAK
2:50 – 4:05 p.m.	Closed Discussion (Recommendations-Based Evaluation; Review Panel) *DOE HQ/NETL and KeyLogic Peer Review Support Staff Attend as Observers*
4:05 p.m.	Adjourn

Wednesday, October 23, 2019

8:00 a.m. (no earlier)	*Panel Members, Morning Presenters Arrive at NETL-Pittsburgh for Security Check*
8:30 – 9:00 a.m.	NETL/RIC FWP-1022461 Task 12.2.3: High Fidelity Attrition Models *Task 12.2.3 Lead: Dave Huckaby* – NETL-RIC
9:00 – 9:30 a.m.	Question-and-Answer Session
9:30 – 10:15 a.m.	Closed Discussion (Recommendations-Based Evaluation; Review Panel) *DOE HQ/NETL and KeyLogic Peer Review Support Staff Attend as Observers*
10:15 – 10:30 a.m.	BREAK
10:30 – 11:00 a.m.	NETL/RIC FWP-1022461 Task 13.1: Lab-Scale Testing *Task 13.1 Lead: Sam Bayham* – NETL-RIC
11:00 – 11:30 a.m.	Question-and-Answer Session
11:30 – 12:15 p.m.	Closed Discussion (Recommendations-Based Evaluation; Review Panel) *DOE HQ/NETL and KeyLogic Peer Review Support Staff Attend as Observers*
12:15 – 1:15 p.m.	Review Panel Working Lunch
12:45 p.m. (no earlier)	*Afternoon Presenters Arrive at NETL-Pittsburgh for Security Check*
1:15 – 2:00 p.m.	Project FE0029160 – Development of Enabling Technologies for Chemical Looping Combustion and Chemical Looping with Oxygen Uncoupling *Kevin Whitty* – University of Utah
2:00 – 2:45 p.m.	Question-and-Answer Session
2:45 – 3:00 p.m.	BREAK
3:00 – 4:15 p.m.	Closed Discussion (TRL-Based Evaluation; Review Panel) *DOE HQ/NETL and KeyLogic Peer Review Support Staff Attend as Observers*
4:15 p.m.	Adjourn

Thursday, October 24, 2019

8:00 a.m. (no earlier)	*Panel Members, Morning Presenters Arrive at NETL-Pittsburgh for Security Check*
8:30 – 9:15 a.m.	Project FE0027654 – 10 Megawatts Electric Coal Direct Chemical Looping Large Pilot Plant - Pre-Front End Engineering and Design Study *Luis Velazquez-Vargas* – Babcock & Wilcox
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 (TRL-Based Evaluation; Review Panel) *DOE HQ/NETL and KeyLogic Peer Review Support Staff Attend as Observers*
11:30 – 12:00 p.m.	Peer Review Panel Wrap-Up Session *DOE HQ/NETL, KeyLogic Peer Review Support Staff, and Panel Members Attend*
12:00 p.m.	Adjourn

APPENDIX D: PEER REVIEW PANEL MEMBERS

Transformative Power Generation Peer Review
October 22-24, 2019
NETL-Pittsburgh Building 922 Room 106A

Indrajit (Indra) Bhattacharya, Ph.D.

Dr. Indrajit Bhattacharya is the Senior Research and Development (R&D) Professional for Electricity, Energy, and Policy at Tri-State Generation and Transmission Association, Inc. He has more than 10 years of experience in the utility industry as an expert in corporate R&D on advanced power generation technologies. His experience with carbon capture technologies for coal- and gas-fired power plants, power plant operation, power markets, low-carbon economy, national electrification initiatives, resource planning, shale gas production, enhanced oil recovery, and oil and gas exploration is extensive. Dr. Bhattacharya works on engaging and building relationships with external stakeholders and has an extensive network of industry contacts in the power generation sector. He also performs as a consultant for Colorado's R&D portfolio focused on power generation and technology commercialization opportunities.

Santosh Gangwal, Ph.D.

Dr. Santosh Gangwal has more than 42 years of experience in coal/biomass gasification/pyrolysis, syngas conditioning/conversion, fuel desulfurization, combined-cycle power systems, fuel cells, carbon capture, solar energy storage, and techno-economic evaluation. He is a recognized expert in gas-solid reactions, catalyst/sorbent preparation, and production scale-up, and has managed complex, multimillion dollar, multiple team member research programs totaling more than $60 million from the U.S. Department of Energy, U.S. Department of Defense, U.S. Environmental Protection Agency, and private industry. He has published 14 patents and more than 225 peer reviewed publications and conference proceedings.

Dr. Gangwal provides technical expertise and assistance in the development of novel energy-related chemical processes as the Vice President of SKG Process Development, Inc. He is presently engaged in projects related to clean fuel production from syngas, hydrogen production, carbon dioxide (CO_2) capture, catalyst design and manufacture, and contaminant removal from fuels. He recently retired from Southern Research Institute, where he was a Director of Business Development in the Energy and Environment Division for more than eight years. Prior to Southern Research, he was the Senior Program Director and Senior Research Chemical Engineer at Research Technical Institute (RTI), where he was employed for more than 22 years. While there, he procured and successfully managed projects totaling more than $30 million. He was responsible for developing and managing projects in cleanup and conversion of biomass- and coal-derived syngas to fuels and alcohols and also spearheaded the development of an internationally recognized syngas desulfurization program at RTI that grew into the Center for Energy Technology. Dr. Gangwal has a Ph.D. and an M.S. in chemical engineering from the University of Waterloo, as well as a B.S. in chemical engineering from the Indian Institute of Technology.

James Sorensen

Mr. James Sorensen is a consultant with a primary focus on clean coal and supporting technologies, including integrated gasification combined cycle (IGCC), oxyfuel combustion, and coal-to-liquids. He is the former Chief Operating Officer and now a Senior Advisor of GTLpetrol. Prior to founding Sorensenergy, LLC, he worked for Air Products and Chemicals as Director of New Markets with responsibility for Syngas Conversion Technology Development and Government Systems, and as Director of Gasification and Energy Conversion. In the latter position, he had commercial responsibility for numerous studies involving air separation unit (ASU)/gas turbine integration for IGCC. Mr. Sorensen was responsible for the sale of the ASU for the Tampa Electric Polk County IGCC facility, which included the first commercial application of the Air Products cycle for nitrogen integration of the ASU with the gas turbine. He was also involved with gas turbine integration associated with Air Products' ion transport membrane oxygen program. Prior responsibilities included project management of Air Products' baseload liquefied natural gas projects, commercial management of synthetic natural gas production, and general management of the Membrane Systems department.

Mr. Sorensen's technical interests include IGCC, oxyfuel combustion, gas-to-liquids (GTLs), and air separation and hydrogen/syngas technology. His areas of expertise include project conception and development, consortium development and management, technology and government sales and contracting, R&D program management, technology consulting and training, commercial contract development, and intellectual property. Mr. Sorensen is the founding Chairman of the Gasification Technologies Council and is Vice Chairman of both the Council on Alternate Fuels and Energy Futures International. He holds eight U.S. patents, one of which involves ASU/gas turbine integration for IGCC. He is also well published in the area of clean coal.

Mr. Sorensen received his B.S. and M.S. degrees in chemical engineering from the California Institute of Technology and Washington State University, respectively, and an MBA from the Harvard Business School.

Götz Veser, Ph.D.

Dr. Götz Veser is the Nickolas A. DeCecco Professor of Chemical Engineering in the Swanson School of Engineering and associate director of the Center for Energy at the University of Pittsburgh. He obtained a diploma in chemical engineering at the University of Karlsruhe (now Karlsruhe Institute of Technology), and a Ph.D. in physical chemistry at the Fritz Haber Institute, Berlin – both in Germany. Following a Feodor-Lynen Postdoctoral Fellowship at the University of Minnesota, he held positions at the University of Stuttgart and at the Max-Planck-Institute for Coal Research (Mülheim an der Ruhr), before returning to the United States to join the University of Pittsburgh in 2002.

Dr. Veser's research interests span catalytic reaction engineering, functional nanomaterials, and process intensification, with applications in energy, carbon capture, and fuels processing technology. He serves on the editorial board of multiple journals in the area of reaction engineering, as "Science Ambassador" for the National Academy of Sciences and the National Academy of Engineering, and on the board of the North American Catalysis Society.