FY19 TURBINES PEER REVIEW OVERVIEW REPORT

May 13, 2019

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

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INTRODUCTION AND BACKGROUND

The U.S. Department of Energy's (DOE) Advanced Turbines Program is conducted under the Clean Coal and Carbon Management Research Program (CCCMRP). Fossil fuels account for more than 80% of total U.S. primary energy use due to their abundance, high energy density, and the relatively low costs associated with production, safe transport, and use. However, the combustion of fossil fuels for electricity generation is the largest single source of carbon dioxide (CO_2) emissions in the nation, accounting for one-third of total U.S. CO_2 emissions. The control and mitigation of such greenhouse gases is a national focus. A primary goal of the President's Climate Action Plan is to "Cut Carbon Pollution in America."

Ensuring that the nation can continue to rely on clean, affordable energy from ample domestic fossil fuel resources is the principal mission of DOE's Office of Fossil Energy (FE) research programs. As a component of that effort, the CCCMRP—administered by FE and implemented by the National Energy Technology Laboratory (NETL)—is engaged in research, development, and demonstration (RD&D) activities with a goal to develop and deploy innovative energy technologies and inform data-driven policies that enhance U.S. economic growth, energy security, and environmental quality.

The Advanced Turbines Program is focused on the development of advanced turbine technologies that will accelerate turbine performance, efficiency, and cost-effectiveness beyond current state-of-the-art and provide tangible benefits to the public in the form of lower cost of electricity (COE), reduced emissions of criteria pollutants, and carbon capture options. The efficiency of combustion turbines has steadily increased as advanced technologies have provided manufacturers with the ability to produce highly advanced turbines that operate at very high temperatures. Further increases in efficiency are possible through the continued development of advanced components, combustion technologies, material systems, thermal management, and novel turbine-based cycles.

The Advanced Turbines Program supports three key technologies that will advance clean, low-cost, coal-based power production, while also taking advantage of all fossil fuel opportunities: (1) Advanced Combustion Turbines, (2) Pressure Gain Combustion (PGC), and (3) Turbomachinery for Supercritical Carbon Dioxide (sCO_2) Power Cycles.

Advanced Combustion Turbines

Advanced turbine research addresses component development for turbine systems fueled with coal-derived fuels (including hydrogen and syngas) and natural gas in combined-cycle applications with pre- or post-combustion carbon capture that can achieve greater than 65% combined-cycle efficiency (lower heating value [LHV], natural gas benchmark) and support load-following capabilities to meet the demand of a modern grid. To achieve this target, emphasis will be placed on advanced turbine concepts that are fueled with natural gas and coal-derived fuels, including hydrogen and syngas, and higher firing temperatures (3,100°F). Components from this program can be easily applied to existing and future gas turbine product lines for natural gas applications, which leverages existing equipment and products for component demonstration.

Component research and development (R&D) is being conducted that will allow higher turbine inlet temperatures; manage cooling requirements; minimize leakage; advance compressor and expander aerodynamics; advance the performance of high-temperature, load-following combustion systems with low emissions of criteria pollutants, including nitrogen oxides (NO_X); and lead to improved efficiency of the gas turbine machine in a combined-cycle application.

Pressure Gain Combustion

PGC has the potential to significantly improve combined-cycle performance when integrated with combustion gas turbines by realizing a pressure increase versus a pressure loss through the combustor of the turbine. Approximately half of the work produced by the turbine expander is used to drive the compressor and increase the pressure of the working fluid (air, in this case). This compressed air is conveyed to the turbine combustor where a nominal 5% loss in pressure (pressure drop) is realized. Concepts for PGC utilizes multiple physical phenomena—including resonant pulsed combustion, constant volume combustion, or detonation—to affect a rise in effective pressure across the combustor, while consuming the same amount of fuel as the constant pressure combustor.

PGC projects focus on assessing the potential benefit of PGC system technology for combined-cycle gas turbines. Researchers are focused on combustion control strategies and fundamental understanding of pressure wave-flame interaction that will lead to lab-scale testing and component prototyping for turbine integration with PGC. Project participants are developing systems models for combined-cycle turbine systems to define the path to configurations that exceed 65% combined-cycle efficiency. These models will be validated against experimental data. In addition, these projects will document the technical gaps for PGC development and turbine integration to focus continued R&D.

Turbomachinery for Supercritical Carbon Dioxide Power Cycles

Projects for this key technology are focused on developing technology for sCO_2-based power cycles that are applicable to fossil fuel applications. This includes developing high-pressure and high-temperature oxygen and fuel (oxy-fuel) combustion systems with CO_2 as the diluent that can be incorporated into turbines designed for directly heated sCO_2-based power cycles. This area also includes advancing the technical capabilities and understanding of sCO_2 gas turbine-turbomachinery interactions, influences of high fluid densities on turbomachinery design, and/or commissioning components within the high operating pressures and temperatures anticipated for sCO_2 service.

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

DOE and NETL held a Fiscal Year 2019 (FY19) Turbines Peer Review Meeting with independent technical experts to assess the projects' technology readiness for work at the current Technology Readiness Level (TRL), evaluate the planned work to attain the next TRL, and offer recommendations. KeyLogic (NETL site-support contractor) convened a panel of four academic and industry experts[*] on April 16-18, 2019, to conduct a peer review of five Turbines Program research projects.

TABLE 1. TURBINES PEER REVIEW – PROJECTS REVIEWED

Project Number	Title	Lead Organization	Total Funding		Project Duration	
			DOE	Cost Share	From	To
FE0023965	Advanced Multi-Tube Mixer Combustion for 65% Efficiency	General Electric Company	$6,608,516	$2,832,221	1/1/2015	12/31/2020
FWP-1022408	Turbine Thermal Management: Task 2.0 Pressure Gain Combustion	NETL-RIC	$1,600,000^	$0	10/1/2017	12/31/2021
FE0024007	Development of Low-Leakage Seals for Utility-Scale Supercritical Carbon Dioxide (sCO_2) Turbo Expanders	General Electric Company	$6,824,098	$1,793,304	10/1/2014	8/31/2019
FE0024006	High Temperature Ceramic Matrix Composite (CMC) Nozzles for 65% Efficiency	General Electric Company	$6,564,478	$3,097,624	10/1/2014	3/31/2021
FE0025011	Improving Turbine Efficiencies Through Heat Transfer and Aerodynamic Research in the Steady Thermal Aero Research Turbine (START)	Pennsylvania State University	$3,600,000	$1,399,627	10/1/2015	9/30/2021
			$25,197,092	$9,122,776		
			$34,319,868			

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

^ Total funding from 10/01/2016 to 12/31/2018.

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

OVERVIEW OF THE PEER REVIEW PROCESS

Peer reviews are conducted to help ensure that the FE's 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 research and development (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 five research projects supported by the NETL Turbines Program. Throughout the peer review meeting, these recognized technical experts offered recommendations and provided feedback on the 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), Technology Maturation Plan (TMP), 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 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 (TM) 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 prioritized recommendations and an evaluation of TRL progression for each project, based on the NETL 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 Turbines 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 29 recommendations for NETL management to review and consider.

The panel offered several common strengths among the projects reviewed. The panel noted that all the projects teams were qualified, experienced, and multidisciplinary, which imparted confidence in the likelihood of project success. The project teams also consulted or partnered with outside experts (e.g., industry, academia, government), allowing for a more comprehensive approach to the engineering development process. Many of the technologies reviewed were novel concepts, which impressed the panel. Overall, the panel expressed that the projects were well-selected, progressing toward commercialization, and could have a substantial impact on the gas turbine industry. The panel stated that the projects reviewed are excellent examples of the types of projects that DOE should be funding.

Conversely, the panel noted several areas for improvement among the projects reviewed, such as enhancing risk assessments and mitigation strategies. Most projects were considered high risk and the teams did not present a convincing contingency plan in the event of a major component failure. During the presentations at the peer review, some project teams did not offer sufficient evidence that a failure modes and effects analysis (FMEA) had been performed. The lack of detail and documentation about FMEA concerned the panel, because this analysis is considered key to a successful development plan. The panel also pointed out that the project schedules could be enhanced and did not encompass development through commercialization. To remedy these concerns, the panel believes that the project teams should perform feasibility assessment studies that include downstream system integration and industrial implications for commercialization. Each project team should also complete a detailed FMEA and present it to DOE.

Evaluation of TRL Progression

At the meeting, the Peer Review Panel assessed each project's 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 FE0023965 has attained TRL 4. Upon successful completion of Task 2.7 (Multi-Can, Full-Scale Fired Test), Project FE0023965 will attain TRL 6.
- Project FWP-1022408 Task 2.0 has attained TRL 3. Upon successful commissioning and testing of the cooled rig, successful continuous operation on natural gas, understanding the

true operating boundaries of the technology, and validating the computational fluid dynamics (CFD) models, Project FWP-1022408 Task 2.0 will attain TRL 4.

- With regard to the face-seal, Project FE0024007 has attained TRL 4. Upon completion of the 24-inch test program, Project FE0024007 will attain TRL 6. With regard to the radial seal, Project FE0024007 has attained TRL 2. Upon finalizing the seal design and rotating testing, Project FE0024007 will attain TRL 4.
- Project FE0024006 has attained TRL 4. Upon completion of the design and testing in a relevant environment, Project FE0024006 will attain TRL 5. Once the project team has completed the rainbow testing outside of the project scope, the project will attain TRL 7.
- Project FE0025011 has attained TRL 3. Upon achievement of industry-acceptable heat transfer test data from the rotating rig, Project FE0025011 will attain TRL 5.

PROJECT SYNOPSES

For more information on the Turbines Program and project portfolio, please visit the NETL website: https://netl.doe.gov/coal/turbines.

FE0023965

ADVANCED MULTI-TUBE MIXER COMBUSTION FOR 65% EFFICIENCY

JOE WEBER AND MICHAEL HUGHES – GENERAL ELECTRIC COMPANY

Project Description: General Electric (GE) Power & Water will lead the technical tasks for this project and GE-Global Research (as a sub-awardee) will provide consulting services for materials and cooling assessments. GE will develop their multi-tube mixer combustion technology as an innovative turbomachinery component that contributes towards the U.S. Department of Energy (DOE) goal for advanced gas turbine efficiencies that are greater than 65% in combined-cycle applications. This project will develop and synthesize GE combustion system with goals of achieving low nitrogen oxide (NO_X) emissions up to turbine inlet temperatures of 3,100°F while also supporting the load-following needs of a modern grid. Phase I is structured to first push the temperature entitlement by creating an ultra-compact design that minimizes both NO_X formation and the surface area that needs to be cooled, followed by a second push that gives the architecture the adjustability it needs to meet the engine load-following requirements. This initial phase will be focused on in-depth engineering analysis and design with a minimal amount of laboratory testing to enable a down-select of the top three combustion architectures.

FWP-1022408

TURBINE THERMAL MANAGEMENT: TASK 2.0 PRESSURE GAIN COMBUSTION

DONALD FERGUSON – NATIONAL ENERGY TECHNOLOGY LABORATORY

Project Description: The objective of this work is to accelerate the deployment of rotating detonation combustors (RDCs) for gas turbine applications and to explore additional power cycles that may benefit from pressure gain attained through combustion. This will be accomplished through a combination of experimental testing of several RDC test rigs, as well as the development of computational tools for predicting performance in close conjunction with research partners in the National Aeronautics and Space Administration (NASA) and the U.S. Department of Defense (DOD). This effort will conduct research that will demonstrate: (1) a viable strategy for the development of a low-loss inlet capable of achieving a pressure gain when utilized in an RDC by 2019, (2) pressure gain in a National Energy Technology Laboratory (NETL) research combustor (up to 1 megawatt and 20 atm) by 2021, and (3) pressure gain in an RDC coupled with a turbine (at the Air Force Research Laboratory) by 2022.

FE0024007

DEVELOPMENT OF LOW-LEAKAGE SHAFT END SEALS FOR UTILITY-SCALE SUPERCRITICAL CARBON DIOXIDE (sCO_2) TURBO EXPANDERS

RAHUL BIDKAR – GENERAL ELECTRIC COMPANY

Project Description: General Electric Company (GE), in partnership with Southwest Research Institute (SwRI), will develop expander shaft end seals for utility-scale supercritical carbon dioxide (sCO_2) power cycles. Phase I includes a conceptual design of a utility-scale end seal capable of meeting the component-level and system-level objectives. GE and SwRI will perform thermodynamic optimization and turbomachinery preliminary design to arrive at a conceptual layout for a utility-scale sCO_2 power plant. GE will then develop face seals as a solution to the end shaft sealing needed for sCO_2 turbo expanders. Finally, a conceptual design of a dedicated sCO_2 facility at SwRI will be developed with sufficient fidelity to enable generation of a detailed Phase II cost and schedule proposal.

FE0024006

HIGH TEMPERATURE CERAMIC MATRIX COMPOSITE (CMC) NOZZLES FOR 65% EFFICIENCY

JOE WEBER AND JOHN DELVAUX – GENERAL ELECTRIC COMPANY

Project Description: General Electric (GE) Power & Water will develop cooled high-temperature ceramic matrix composite (CMC) nozzles (non-rotating airfoil hardware) as an innovative turbomachinery component contributing towards the U.S. Department of Energy's (DOE) goal for advanced gas turbine efficiencies that are greater than 65% in combined-cycle applications, including coal-based integrated gasification combined-cycle (IGCC). This project, by leveraging existing design and analysis knowledge and techniques for CMC materials, will utilize extensive analytical evaluations to develop and refine designs for a CMC nozzle in an industrial gas turbine hot gas path. The Phase I project scope of work will consist of three elements: (1) design and analyze attachment configurations: a bayonet style and a more traditional airfoil with two end-walls; (2) investigate impingement and film cooling; and (3) define sealing approaches, design key sealing features, and analyze sealing effectiveness for the best designs. Limited bench flow testing will be performed to support these efforts. The design, or designs, will be the basis for development and testing in a potential future Phase II.

FE0025011

IMPROVING TURBINE EFFICIENCIES THROUGH HEAT TRANSFER AND AERODYNAMIC RESEARCH IN THE STEADY THERMAL AERO RESEARCH TURBINE (START)

KAREN THOLE – PENNSYLVANIA STATE UNIVERSITY

Project Description: Pennsylvania State University (Penn State), in conjunction with its industry partner, Pratt & Whitney (P&W), will test new cooling improvements for the turbine rotating blade platform in order to increase machine efficiency and reduce costs. The scope of the project includes: (1) the planning and execution of the Steady Thermal Aero Research Turbine (START) facility and instrumentation upgrades to include a heated main gas path with full-span airfoils, long-wave infrared thermography, and unsteady pressures; (2) the design and manufacturing of a rainbow set of blades with baseline and advanced cooling configurations; (3) measurements of aerodynamics and heat transfer for baseline and advanced configurations over a range of cooling flows, Reynolds numbers, rotational Reynolds numbers, and flow angles; and (4) continual assessment of additive manufactured components to reduce costs and advance cooling designs. The project will focus on performing the first open-literature, consecutive comparisons of baseline and advanced cooling configurations in a test turbine with realistic engine hardware and flow conditions. The project will also allow direct comparisons of airfoil heat transfer measurements to be made in three relevant testing environments: low speed and temperature, high-pressure temperature static conditions, and high-velocity rotational conditions. This back-to-back comparison will provide data to guide the gas turbine industry in introducing these new cooling technologies into operating gas turbines.

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. DOE 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.

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)

‡ 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.

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 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 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 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 hottesting.
	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.

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
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

Turbines Peer Review
April 16-18, 2019
NETL-Pittsburgh Building 922 Room 106A

Tuesday, April 16, 2019

8:00 a.m. (no earlier)	*Panel Members Arrive at NETL-Pittsburgh for Security Check*
8:30 a.m.	*Morning Presenters Arrive, Escort Visitors 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 Presentation
9:00 – 10:00 a.m.	Project FE0023965 – Advanced Multi-Tube Mixer Combustion for 65% Efficiency *Joe Weber and Michael Hughes* – General Electric (GE) Company
10:00 – 10:45 a.m.	Question and Answer Session
10:45 – 11:00 a.m.	BREAK
11:00 – 12:15 p.m.	Closed Discussion (Peer Review Panel Evaluation) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
12:15 – 1:15 p.m.	Lunch
1:00 p.m. (no later)	*Afternoon Presenters Arrive at NETL-Pittsburgh for Security Check*
1:15 – 2:15 p.m.	Project FWP-1022408 – Turbine Thermal Management: Task 2.0 Pressure Gain Combustion *Donald Ferguson, Peter Strakey, Clint Bedick, and Todd Sidwell* – NETL-RIC
2:15 – 3:00 p.m.	Question and Answer Session
3:00 – 3:15 p.m.	BREAK
3:15 – 4:30 p.m.	Closed Discussion (Peer Review Panel Evaluation) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
4:30 p.m.	Adjourn

Wednesday, April 17, 2019

8:30 a.m. (no earlier)	*Panel Members and Morning Presenters Arrive at NETL-Pittsburgh for Security Check*
8:45 – 9:00 a.m.	*Escort Panel Members and Morning Presenters to NETL-Pittsburgh Building 922 Room 106A*
9:00 – 10:00 a.m.	Project FE0024007 – Development of Low-Leakage Shaft End Seals for Utility-Scale Supercritical Carbon Dioxide (SCO_2) Turbo Expanders *Rahul Bidkar* – General Electric (GE) Company
10:00 – 10:45 a.m.	Question and Answer Session
10:45 – 11:00 a.m.	BREAK
11:00 – 12:15 p.m.	Closed Discussion (Peer Review Panel Evaluation) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
12:15 – 1:15 p.m.	Review Panel Working Lunch
1:00 p.m. (no later)	*Afternoon Presenters Arrive at NETL-Pittsburgh for Security Check*
1:15 – 2:15 p.m.	Project FE0024006 – High Temperature Ceramic Matrix Composite (CMC) Nozzles for 65% Efficiency *Joe Weber and John Delvaux* – General Electric (GE) Company
2:15 – 3:00 p.m.	Question and Answer Session
3:00 – 3:15 p.m.	BREAK
3:15 – 4:30 p.m.	Closed Discussion (Peer Review Panel Evaluation) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
4:30 p.m.	Adjourn

Thursday, April 18, 2019

8:00 a.m. (no earlier)	*Panel Members and Morning Presenters Arrive at NETL-Pittsburgh for Security Check*
8:15 – 8:30 a.m.	*Escort Panel Members and Morning Presenters to NETL-Pittsburgh Building 922 Room 106A*
8:30 – 9:30 a.m.	Project FE0025011 – Improving Turbine Efficiencies Through Heat Transfer and Aerodynamic Research in the Steady Thermal Aero Research Turbine (START) *Karen Thole* – Pennsylvania State University
9:30 – 10:15 a.m.	Question and Answer Session
10:15 – 10:30 a.m.	BREAK
10:30 – 11:45 a.m.	Closed Discussion (Peer Review Panel Evaluation) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
11:45 – 12:15 p.m.	Peer Review Panel Wrap-Up Session *DOE HQ/NETL, KeyLogic peer review support staff, and Panel Members attend.*
12:15 p.m.	Adjourn

APPENDIX D: PEER REVIEW PANEL MEMBERS

Turbines Peer Review
April 16-18, 2019
NETL-Pittsburgh Building 922 Room 106A

Klaus Brun, Ph.D.

At Elliott Group, Dr. Klaus Brun leads a team of more than 50 professionals that focus on developing and improving products and technology for the oil and gas, process-chemical, and petrochemical industries. Previously, he worked at Southwest Research Institute, Solar Turbines, General Electric (GE), and Alstom in various positions from engineering to leadership management.

Dr. Brun's background is in machinery technology/applications for the oil and gas and electric power industries. Having worked on hundreds of compression and generation plant projects, he is widely recognized as a technical expert on compressor stations, power plants, gas turbines, combined cycles, centrifugal compressors, reciprocating compressors, and power cycles.

Dr. Brun holds 9 patents (with 3 more pending), has authored more than 350 technical papers, and has co-authored 3 textbooks on gas turbines and compressors. He is an American Society of Mechanical Engineers (ASME) Fellow and has won several awards, including an R&D 100 Award in 2007 for his Semi-Active Valve invention, the ASME Industrial Gas Turbine Award in 2016, and 11 individual ASME Oil & Gas Committee Best Paper awards. He has served as the chair of the ASME-International Gas Turbine Institute (IGTI) Board of Directors, Chairman of the ASME Oil & Gas Applications Committee, and editor of the Global Gas Turbine News. He is currently the chair of the sCO_2 Power Cycles Symposium, the ASME Oil & Gas Applications Committee, and the Thermo-Mechanical Energy Storage Workshop, as well as a member of the American Petroleum Institute (API) 616 and ASME Performance Test Code (PTC)-10 Task Forces, the Asia Turbomachinery Symposium, and the Fan Conference Advisory Committee. Dr. Brun is the Executive Correspondent and a regular columnist of Turbomachinery International Magazine and Gas Compression Magazine, and an Associate Editor of the ASME Journal of Gas Turbines for Power and the Elsevier Solar Power Journal. Dr. Brun received his M.Sc. and Ph.D. in Mechanical Engineering from the University of Virginia.

Jerzy Sawicki, Ph.D., P.E.

Dr. Jerzy T. Sawicki, P.E., was appointed Vice President for Research at Cleveland State University (CSU) in May 2013, where he previously served as Associate Vice President for Research from 2010 to 2012 and interim Vice President for Research from June 2012 to May 2013.

Dr. Sawicki joined CSU as an assistant professor in 1993. He is the Donald E. Bently and Agnes Muszynska Endowed Chair, a professor of mechanical engineering, and the Director of the Center for Rotating Machinery Dynamics and Control. His research interests are in structural dynamics, automatic control, rotor dynamics, magnetic bearings, mechatronics, and structural health monitoring. He has published more than 200 peer-reviewed journal papers/conference articles and 1 research monograph; co-edited 3 books; and advised numerous graduate students, post-docs, and research scientists. Dr. Sawicki serves as an Editor-in-Chief for the ASME Journal of Engineering for Gas Turbines and Power. He has served as a program committee member, organizer of special sessions, and an invited or keynote speaker for numerous international conferences. From 2014 to

2017, Dr. Sawicki was a member of the Executive Committee of the Council on Research (CoR) of the Association of Public and Land-Grant Universities (APLU).

Dr. Sawicki holds a Ph.D. in mechanical engineering from Case Western Reserve University; an M.S. in mechanical engineering from Gdańsk University of Technology, Poland; and an M.S. in applied mathematics from the University of Gdańsk, Poland. He is an ASME Fellow and a U.S. representative to the International Organization for Standardization (ISO)/Technical Committee (TC) 108/Subcommittee (SC) 2/Working Group (WG) 7 international committee. In addition, Dr. Sawicki is a recipient of several best paper awards, the University Distinguished Faculty Award for Research, and a Siemens-Westinghouse Distinguished Speaker. Dr. Sawicki received the Ohio Outstanding Engineering Educator Award from the Ohio Society of Professional Engineers and is a registered professional engineer, licensed in Ohio.

Norman Z. Shilling, D.Sc., P.E.

Prior to entering private consulting practice, Dr. Norman Shilling, P.E., was the Senior Product Manager for GE Energy's gasification product line, responsible for developing policy and regulatory strategies and providing advocacy in Washington and international forums on solutions for greenhouse gases.

Frequently called upon to share his expertise in gasification, carbon capture, and storage in relation to policy and regulation, Dr. Shilling has given conference and seminar speeches at many U.S. and global industry conferences. In addition, he provided testimony to many regulatory and legislative bodies and is a member of several key coal forums and workgroups.

Dr. Shilling's experience in environmental and utility power generation includes serving as Product Line Leader for gas turbines, focusing on applications involving unconventional fuels, integrated gasification combined cycle (IGCC), and the integration of power production with chemical refinery plants and steel mills. Dr. Shilling has been a key leader in many GE strategic technology planning initiatives. He previously served as Program Manager for low-emissions locomotive diesel development and as Environmental Systems Engineering Manager at GE's Research Center, collaborating with many GE businesses on pollution prevention and energy efficiency initiatives. Dr. Shilling was also an Advanced Engineering Manager at GE's Environmental Systems, where he was responsible for the development of advanced scrubbers and particulate controls for utility power plants. Prior to the start of his GE career, Dr. Shilling worked in nuclear steam generator development and advanced automotive power plant development.

Dr. Shilling holds an M.S. degree from the Massachusetts Institute of Technology and B.Sc. and D.Sc. degrees from the New Jersey Institute of Technology. He has taught in the graduate engineering school at Penn State University and is a licensed professional engineer.

Robert Steele, Ph.D.

Dr. Robert Steele is the Program Manager of the Combined-Cycle Turbomachinery Program (P79) at the Electric Power Research Institute (EPRI) in Charlotte, North Carolina. He directs all aspects regarding industrial gas turbine research and development, including hot section/combustor life cycle; compressor/turbine rotor life extension and durability; and combustor monitoring, tuning, and turndown. His gas turbine expertise is in combustion-driven pressure dynamics, combustor rig testing and instrumentation, and ultralow nitrogen oxide (NO_X) designs.

Prior to joining P79, Dr. Steele was a Senior Project Manager in the EPRI Advanced Generation group, with a specific focus on coal applications and large project demonstrations. He has focused on IGCC gas turbine syngas applications; new oxygen separation technologies, including the Air Products' Ion Transport Membrane; and advanced laser techniques for measuring gasifier flame temperatures. He has particular expertise in carbon dioxide (CO_2) handling, with emphasis on advanced compression, power plant integration, thermos-physical properties of CO_2 mixtures, and pipeline transportation.

Dr. Steele has 25 years' worth of experience in gas turbine combustion research, development, and testing, as well as in the electric power generation industry, including carbon capture, compression, and storage. Prior to joining EPRI, Dr. Steele was a Vice President and Combustion Team Leader at Ramgen Power Systems in Bellevue, Washington. He was directly involved in the development of lean premixed trapped vortex combustion designs for gas turbines and supersonic compressor designs for industrial gas compression applications, with a specific focus on CO_2. In addition, he also worked at Solar Turbines in San Diego, California, as the Mars SoLoNOx™ Engine Combustion Team Leader.

Dr. Steele holds a B.S. degree in Mechanical Engineering from the University of Calgary, and both an M.S. degree in Aeronautics and Astronautics and a Ph.D. in Mechanical Engineering from the University of Washington.