OVERVIEW REPORT

DOE/NETL Clean Coal Research Program
Turbines Program
FY2016 Peer Review Meeting

Pittsburgh, Pennsylvania
April 27-29, 2016

ASM INTERNATIONAL

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OVERVIEW REPORT
CLEAN COAL RESEARCH PROGRAM
TURBINES PROGRAM
FY2016 PEER REVIEW MEETING

Pittsburgh, Pennsylvania
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INTRODUCTION AND BACKGROUND

The U.S. Department of Energy (DOE) Office of Clean Coal and Carbon Management develops innovative, near-zero-emissions technologies that are integrated with carbon capture and storage (CCS) and improved fuel conversion efficiency through research and development (R&D) in the Advanced Energy Systems (AES) program. The R&D portfolio includes Advanced Combustion Systems, Gasification Systems, Coal and Coal-Biomass to Liquids, Advanced Turbines, and Solid Oxide Fuel Cells energy conversion systems. The AES program's key efforts are directed at improving fuel conversion efficiencies within the plant boundary by increasing plant availability, reducing water consumption, and achieving ultra-low emissions of traditional pollutants. Many of these technologies require new approaches to electricity generation, and simultaneously achieve higher efficiencies while capturing carbon dioxide (CO_2) as part of the conversion process. The research is targeted at improving overall system efficiency, reducing capital and operating costs, and enabling affordable carbon capture. The National Energy Technology Laboratory-managed (NETL) Turbines program is focused on developing turbomachinery and turbine-based cycles that will serve to improve the efficiency and reduce the cost of coal-fueled power plants with carbon capture.

The Turbines program is focused on developing turbomachinery that, when integrated with coal gasification and advanced combustion systems, will reduce the cost of generating electricity from coal power plants with carbon capture. Advances in turbine technology provide some of the most significant contributions to projected cost and efficiency improvements in both combustion and gasification applications. Furthermore, by increasing the conversion efficiency of fuel gas or boiler heat to electric power, advanced turbine technologies also reduce fuel requirements, the cost and size of equipment, and overall emissions.

The Turbines program is currently funding 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 build technology leadership for sustained jobs and enable clean energy to support the U.S. economy and global ecology: 1) Advanced Combustion Turbines, 2) Pressure Gain Combustion, and 3) Turbomachinery for Supercritical Carbon Dioxide (sCO_2) Power Cycles.

- **Advanced Combustion Turbines**—Advanced combustion turbines provide technology solutions for coal-based integrated gasification combined cycle (IGCC) systems. This technology pathway will complete work on the 2nd-Generation program goal to establish large-frame combustion turbines for IGCC that can operate on pure hydrogen with a turbine inlet temperature approaching 2,650°F. The program has demonstrated many of the subsystems needed to reach this goal, including full-scale, combustion-can operation on pure hydrogen at relevant temperatures and pressures.

- **Pressure Gain Combustion**—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 percent loss in pressure (pressure drop) is realized. 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.

- **Turbomachinery for sCO_2 Power Cycles**—Advanced turbine power cycles with sCO_2 as the working fluid is a transformational technology that will be the building block for future improvements in electric power generation. Supercritical CO_2 power cycles offer significant performance increases and up to 100 percent carbon capture. When combined with advanced heat exchangers, sCO_2 cycles make lower-cost carbon free coal combustion possible. And because of similarities in turbomachinery, advances in sCO_2 technology also benefit DOE applications outside of the Office of Fossil Energy (FE), including utility-scale solar and nuclear power production.

  The supercritical carbon dioxide power cycle operates in a manner similar to other turbine cycles, but it uses CO_2 as the working fluid in the turbomachinery. The cycle is operated above the critical point of CO_2 so that the fluid does not change phases (from liquid to gas), but rather undergoes drastic density changes over small ranges of temperature and pressure. This allows large amounts of energy to be extracted from equipment relatively small in size. Supercritical CO_2 turbines can have a gas path diameter as small as a few inches compared to several feet for utility-scale combustion turbines that operate on steam.

  Supercritical CO_2-based cycles take on two primary configurations relevant to the AES program: 1) an indirectly heated closed Brayton cycle for advanced combustion systems, and 2) a semi-closed directly heated oxy-fuel Brayton cycle for IGCC systems. In both cases, developmental challenges center on the effects of high-temperature operation (650°C – 760°C for indirect cycles and 1,300°C for direct cycles) on turbomachinery (expanders and compressors) and recuperators. Resolving these issues, and the additional challenges of oxy-fuel synthesis gas (syngas) combustion and turbine integration in the case of the IGCC direct-fired cycle, will realize the transformational benefits of sCO_2. The Advanced Turbines program is working in each area, managing the turbomachinery, oxy-syngas combustion, and related components.

Office of Management and Budget Requirements

In compliance with requirements from the Office of Management and Budget, DOE and NETL are fully committed to improving the quality of research projects in their programs. To aid this effort, DOE and NETL conducted a fiscal year (FY) 2016 Turbines Program Peer Review

Meeting with independent technical experts to assess ongoing research projects and, where applicable, to make recommendations for individual project improvement.

In cooperation with Leonardo Technologies, Inc. (LTI), ASM International convened a panel of leading academic and industry experts on April 27–29, 2016, to conduct a three-day peer review of selected Turbines program research projects supported by NETL.

Overview of Office of Fossil Energy Turbines Program Research Funding

The total funding of the six projects reviewed, over the duration of the projects, is $10,930,120. The funding and duration of the six projects that were the subject of this peer review are provided in Table 1.

TABLE 1. TURBINES PROGRAM PROJECTS REVIEWED

Reference Number	Project Number	Title	Lead Organization	Total Funding		Project Duration	
				DOE	Cost Share	From	To
01	FE0011762	Evaluation of Flow and Heat Transfer Inside Lean Pre-Mixed Combustor Systems Under Reacting Flow Conditions	Virginia Polytechnic Institute and State University	$499,948	$125,000	9/1/2013	8/31/2016
02	FE0025174	Investigation of Autoignition and Combustion Stability of High Pressure Supercritical Carbon Dioxide Oxycombustion	Georgia Tech Research Corporation	$799,754	$207,446	10/1/2015	9/30/2018
03	FWP-FEAA122	High Performance Thermal Barrier Coatings	Oak Ridge National Laboratory	$1,000,000	$0	10/1/2014	9/30/2016
04	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
05	FWP-2012.03.02	Turbine Thermal Management (Pressure Gain and Combustion)	NETL	$2,550,600	$0	10/1/2013	9/30/2016
06	FE0025495	Understanding Transient Combustion Phenomena in Low-NO_x Gas Turbines	Pennsylvania State University	$598,196	$149,549	10/1/2015	9/30/2018

OVERVIEW OF THE PEER REVIEW PROCESS

The U.S. Department of Energy (DOE) and the National Energy Technology Laboratory (NETL) are fully committed to improving the quality and results of their research projects. To support this goal, in fiscal year (FY) 2016, ASM International was invited to provide an independent, unbiased, and timely peer review of selected projects within the DOE/NETL Turbines program. The peer review of selected projects within the Turbines program was designed to comply with requirements from the Office of Management and Budget.

On April 27–29, 2016, ASM International convened a panel of four leading academic and industry experts to conduct a three-day peer review of six research projects supported by the NETL Turbines program. Throughout the peer review meeting, these recognized technical experts provided recommendations on how to improve the management, performance, and overall results of each research project.

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

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

Pre-Meeting Preparation

Several weeks before the peer review, each project team submitted a Project Technical Summary and the final PowerPoint slide deck they would present at the peer review meeting. Additionally, the appropriate Federal Project Manager (FPM) provided the project management plan and other relevant materials, including quarterly and annual reports (if applicable), and published journal articles (if applicable) that would help the peer review panel evaluate each project. The panel received all of these materials prior to the peer review meeting via a secure and confidential peer review SharePoint site, which enabled the panel members to fully prepare for the meeting with the necessary project background information to thoroughly evaluate the projects.

To increase the efficiency of the peer review meeting, a pre-meeting orientation teleconference/WebEx was held with the review panel and ASM International support staff prior to the meeting to review the peer review process and allow for the Portfolio Manager and Team Supervisor of the Turbines program to provide an overview of the program goals and objectives.

Peer Review Meeting Proceedings

At the meeting, each research team made an uninterrupted 30-minute PowerPoint presentation that was followed by a 45-minute question-and-answer session with the panel and a 75-minute panel discussion and evaluation of each project. The time allotted for the project presentation, the question-and-answer session, and the panel discussion was dependent on the individual project's complexity, duration, and breadth of scope. To facilitate a full and open discourse of project-related material between the project team and the panel, all sessions were limited to the panel, ASM International personnel, and DOE/NETL personnel and contractor support staff. The closed sessions ensured open discussions between the principal investigators and the panel.

Panel members were also instructed to hold the discussions that took place during the question-and-answer session as confidential.

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

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

Peer Review Evaluation Criteria

At the end of the group discussion for each project, the panel came to consensus on an overall project score. The panel’s consensus score for each project was based on the following definitions (the panel was welcome to assign any integer value ranging from 0 to 10):

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

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

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

SUMMARY OF KEY FINDINGS

This section summarizes the overall key findings of the six projects evaluated at the fiscal year (FY) 2016 Turbines Program Peer Review.

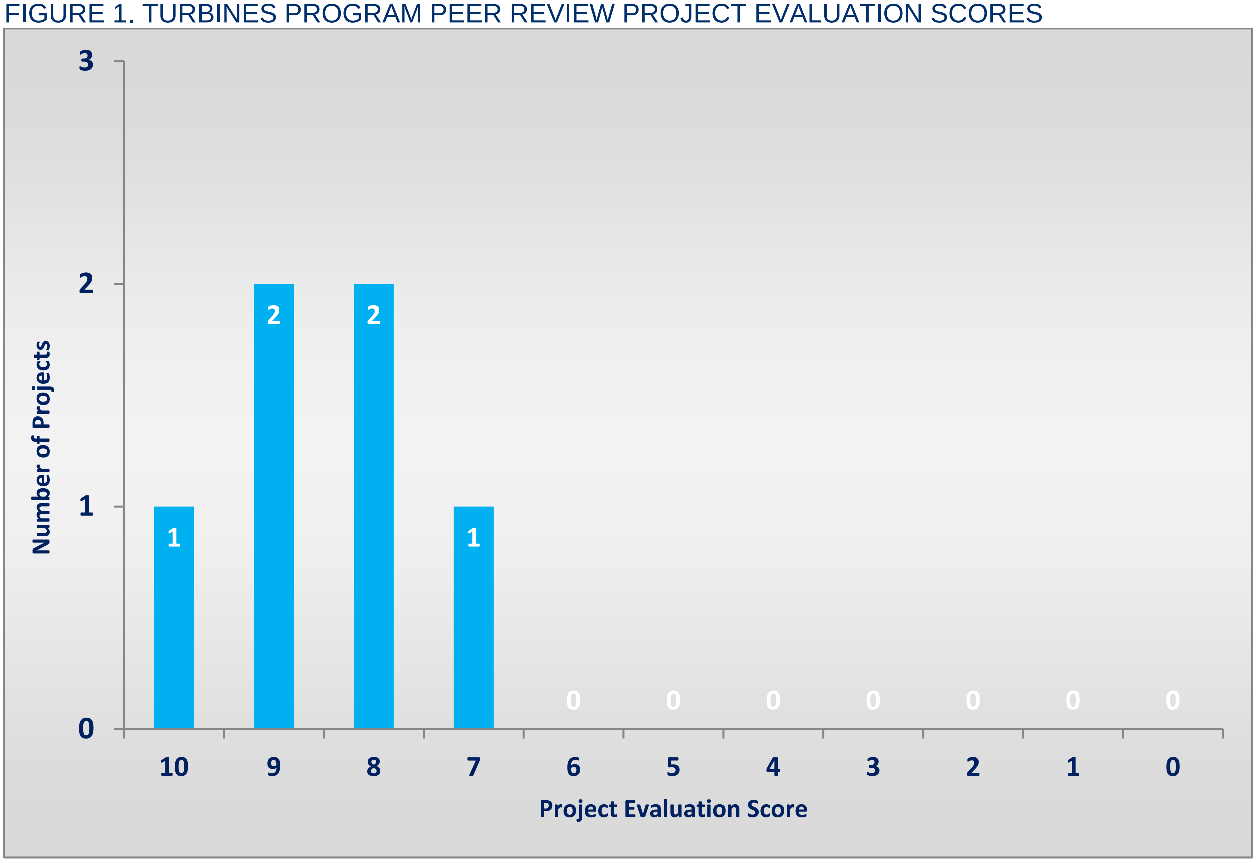
Overview of Project Evaluation Scores

The panel assigned a consensus score for each project based on the following definitions (the panel was welcome to assign any integer value ranging from 0 to 10):

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

While it is not the intent of this review to directly compare one project with another, a rating of 5 or higher indicates that a specific project was viewed as at least adequate by the panel. The number of projects given each project evaluation score is shown in Figure 1.

FIGURE 1. TURBINES PROGRAM PEER REVIEW PROJECT EVALUATION SCORES



PROJECT SYNOPSES

For more information on the Turbines program and project portfolio, please visit the NETL website: http://www.netl.doe.gov/research/coal/energy-systems/turbines.

01: FE0011762
EVALUATION OF FLOW AND HEAT TRANSFER INSIDE LEAN PRE-MIXED COMBUSTOR SYSTEMS UNDER REACTING FLOW CONDITIONS

Srinath Ekkad and David Gomez-Ramirez, Virginia Polytechnic Institute and State University

Technology Readiness Level: 2	***DOE Funding:*** $499,948
Duration: 9/1/2013 – 01/31/2018	***Cost Share:*** $125,000

The goal of this Virginia Tech project is to provide a better understanding of the combustor swirling flow and its effect on liner surface heat transfer in order to improve prediction methods and design practices in combustor liner cooling for low-emissions combustors. Specifically, this project will focus on how the hot swirling gases interact with the liner wall of a gas turbine combustor to provide insight into the effect of swirl nozzle exit flows, the mixing characteristics of fuel/air, and resulting flow impingement on liner and dome regions. This effort will support the development of more effective cooling schemes to maintain and improve combustor durability.

02: FE0025174
INVESTIGATION OF AUTOIGNITION AND COMBUSTION STABILITY OF HIGH PRESSURE SUPERCRITICAL CARBON DIOXIDE OXYCOMBUSTION

Wenting Sun, Georgia Tech Research Corporation

Technology Readiness Level: 2	***DOE Funding:*** $799,754
Duration: 10/1/2015 – 9/30/2018	***Cost Share:*** $207,446

The Georgia Institute of Technology (Georgia Tech) project will focus on key knowledge gaps associated with supercritical carbon dioxide (sCO_2) oxy-combustion at high-pressure (up to 330 atm) conditions—namely, experimental studies of fundamental autoignition properties; development of an optimized chemical kinetic mechanism; and numerical and theoretical analyses of flow, mixing, and flame dynamics. The project has three basic objectives: 1) measurement of autoignition delays of CO_2 diluted oxygen/fuel mixtures (natural gas and synthesis gas [syngas]) in a high-pressure shock tube (the experimental conditions cover pressures from 150 to 330 atm and temperatures from 1,100 to 1,800 K); 2) development of an optimized compact chemical kinetic mechanism for sCO_2 oxy-combustion based on the data obtained; and 3) numerical and theoretical investigation of sCO_2 oxy-combustion at pressure using the kinetic mechanism developed.

03: FWP-FEAA122
HIGH PERFORMANCE THERMAL BARRIER COATINGS

Bruce Pint, Oak Ridge National Laboratory

Technology Readiness Level: 3	***DOE Funding:*** $1,000,000
Duration: 10/1/2014 – 9/30/2016	***Cost Share:*** $0

The Oak Ridge National Laboratory (ORNL), with support from Stony Brook University, will develop and evaluate approaches for improved alloys and coatings to provide the basis for more robust thermal barrier coating (TBC) materials systems needed for higher-efficiency land-based gas turbines, especially those fired with coal-derived synthesis gas (syngas) and hydrogen-enriched fuels. The project focuses on the high-temperature performance and advanced characterization of relevant metallic bond coatings and conventional and state-of-the-art multifunctional ceramic top coatings for TBC systems. This project benefited from work conducted under the prior DOE contract FWP-FEAA070.

04: FE0025011
IMPROVING TURBINE EFFICIENCIES THROUGH HEAT TRANSFER AND AERODYNAMIC RESEARCH IN THE STEADY THERMAL AERO RESEARCH TURBINE (START)

Karen Thole, Pennsylvania State University

Technology Readiness Level: 3	***DOE Funding:*** $3,600,000
Duration: 10/1/2015 – 9/30/2021	***Cost Share:*** $1,399,627

The 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 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 for 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 inform the gas turbine industry in introducing these new cooling technologies into operating gas turbines. This work builds on the previous NETL-Regional University Alliance (RUA) Contract FWP-2012.03.02.

05: FWP-2012.03.02
TURBINE THERMAL MANAGEMENT (PRESSURE GAIN AND COMBUSTION)

Donald Ferguson and Peter Strakey, National Energy Technology Laboratory

Technology Readiness Level: 2	***DOE Funding:*** $2,550,600
Duration: 10/1/2013 – 9/30/2016	***Cost Share:*** $0

The National Energy Technology Laboratory turbine research effort supports the Turbines program by conducting novel, fundamental, basic, and applied research in the areas of aerothermal heat transfer, pressure gain combustion (PGC), and supercritical carbon dioxide (sCO_2) power cycles. This research is expected to render measurable outcomes that will meet the U.S. Department of Energy's advanced turbine development goals of a 3 to 5 percentage point increase in power island efficiency and a 30 percent power increase above the hydrogen-fired combined cycle baseline. PGC, specifically rotating detonation combustion (RDC), has been identified as a possible means to contribute a 4 to 6 percent gain in overall system efficiency with potential for reductions in nitrogen oxide (NO_X) emissions. The goal of NETL's applied research effort is to provide theoretical, computational, and experimental analysis to better understand RDC and begin to optimize various aspects of the technology to realize its potential for improved thermal efficiency.

06: FE0025495
UNDERSTANDING TRANSIENT COMBUSTION PHENOMENA IN LOW-NO_X GAS TURBINES

Jacqueline O'Connor, Pennsylvania State University

Technology Readiness Level: 2	***DOE Funding:*** $598,196
Duration: 10/1/2015 – 9/30/2018	***Cost Share:*** $149,549

The Pennsylvania State University (Penn State) will conduct the project with support from industrial partner GE Global Research (GE). A three-step approach to understand, and eventually predict, unstable combustion resulting from transient operation will be used. Transients in equivalence ratio, fuel composition, and fuel splitting will be studied. Three transient characteristics will be considered when designing each transient test: timescale, amplitude, and direction. The first step toward quantifying the impact of transients on combustion stability will be to map relevant timescales in the combustion system at steady-state operation under a variety of target conditions, which will be selected with input from GE to best represent operating conditions of interest for industrial gas turbine engines. The second step will be to collect data during transient events, where the transient events are designed to mirror key timescales and operating conditions that were measured in the first portion of the study. The final step will be to analyze the data in order to both understand fundamental combustion behaviors in response to transients and identify precursor signals during the transient before unstable combustion arises. Analysis of these high-fidelity data will enable descriptions of the nonlinear behaviors that occur during transients, as well as important characteristics about the beginning and end states of each transient.

APPENDIX A: ACRONYMS AND ABBREVIATIONS

Acronym or Abbreviation	Definition
AES	Advanced Energy Systems (NETL program)
AESD	ASME Advanced Energy Systems Division
ASME	American Society of Mechanical Engineers
ASU	air separation unit
atm	atmospheres
CCC	Copyright Clearance Center
CCS	carbon capture and storage
CO_2	carbon dioxide
COE	cost of electricity
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
FE	Office of Fossil Energy
FY	fiscal year
GE	General Electric
GTL	gas-to-liquids
IGCC	integrated gasification combined cycle
IPO	independent professional organization
ITM	ion-transport membrane
LNG	liquefied natural gas
LTI	Leonardo Technologies, Inc.
MIT	Massachusetts Institute of Technology
MW	megawatt
NASA	National Aeronautics and Space Administration
NETL	National Energy Technology Laboratory
NO_X	nitrogen oxide
NPS	Naval Postgraduate School
ORNL	Oak Ridge National Laboratory
P&W	Pratt & Whitney
Penn State	Pennsylvania State University
PGC	pressure gain combustion
R&D	research and development
RD&D	research, development, and demonstration
RDC	rotating detonation combustion
RUA	Regional University Alliance (NETL initiative)
scfm	standard cubic feet per minute
sCO_2	supercritical carbon dioxide

Acronym or Abbreviation	Definition
SNG	synthetic natural gas
START	Steady Thermal Aero Research Turbine facility
syngas	synthesis gas
TBC	thermal barrier coating
TRL	technology readiness level

APPENDIX B: PEER REVIEW EVALUATION CRITERIA FORM

PEER REVIEW EVALUATION CRITERIA AND GUIDELINES

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

Peer Review Title:	
Dates:	
Project Title:	
Performer:	
Name of Peer Reviewer:	

The following pages contain the criteria used to evaluate each project. Each criterion is accompanied by multiple characteristics to further define the topic. Each Reviewer is expected to independently assess the provided material for each project, considering the Evaluation Criteria on the following page. Prior to the meeting, the Reviewers will independently create a list of strengths and weaknesses for each project based on the materials provided. To assist Reviewers in capturing their thoughts both before and during the meeting, an optional form is attached at the end of this document.

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

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

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

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

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

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

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

RATINGS DEFINITIONS AND SCORING PLAN

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

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

APPENDIX C: TECHNOLOGY READINESS LEVEL DESCRIPTIONS

Research, Development, and Demonstration (RD&D) projects can be categorized based on the level of technology maturity. Listed below are nine (9) TRLs of RD&D projects managed by the National Energy Technology Laboratory (NETL). These TRLs provide a basis for establishing a rational and structured approach to decision-making and identifying performance criteria that must be met before proceeding to the next level.

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

APPENDIX D: MEETING AGENDA

Wednesday, April 27, 2016 – Ellwood Room (Turbines Program)

8:00 – 9:00 a.m.	**Registration – 2nd Floor Foyer**
9:00 – 9:30 a.m.	**Peer Review Panel Kickoff Session – Turbines** Open to National Energy Technology Laboratory (NETL) and ASM International staff only - ASM International Welcome - Role of Panel Chair - Technology Manager / Division Director, Systems Engineering & Analysis (SEA) Team and Panel Question and Answer - Peer Review Process and Meeting Logistics
9:30 – 10:00 a.m.	**07 – Project # FE0011762** – Evaluation of Flow and Heat Transfer Inside Lean Pre-Mixed Combustor Systems Under Reacting Flow Conditions *Srinath Ekkad and David Gomez-Ramirez* – **Virginia Polytechnic Institute and State University**
10:00 – 10:45 a.m.	Q&A
10:45 – 12:00 p.m.	Discussion
12:00 – 1:00 p.m.	**Lunch (on your own)**
1:00 – 1:30 p.m.	**08 – Project # FE0025174** – Investigation of Autoignition and Combustion Stability of High Pressure Supercritical Carbon Dioxide Oxycombustion *Wenting Sun* – **Georgia Tech Research Corporation**
1:30 – 2:15 p.m.	Q&A
2:15 – 3:30 p.m.	Discussion

Thursday, April 28, 2016 – Ellwood Room (Turbines Program)

7:00 – 8:00 a.m.	**Registration – 2nd Floor Foyer**
8:00 – 8:30 a.m.	**09 – Project # FWP-FEAA122 –** High-Performance Thermal Barrier Coatings *Bruce Pint* – **Oak Ridge National Laboratory (ORNL)**
8:30 – 9:15 a.m.	Q&A
9:15 – 10:30 a.m.	Discussion
10:30 – 10:45 a.m.	**BREAK**
10:45 – 11:15 a.m.	**10 – Project # FE0025011** – Improving Turbine Efficiencies Through Heat Transfer and Aerodynamic Research in the Steady Thermal Aero Research Turbine (START) *Karen Thole* – **Pennsylvania State University**
11:15 – 12:00 p.m.	Q&A
12:00 – 1:15 p.m.	Discussion
1:15 – 2:15 p.m.	**Lunch (on your own)**
2:15 – 2:45 p.m.	**11 – Project # FWP-2012.03.02 –** Turbine Thermal Management (Pressure Gain and Combustion) *Donald Ferguson and Peter Strakey* – **National Energy Technology Laboratory (NETL-ORD)**
2:45 – 3:30 p.m.	Q&A
3:30 – 4:45 p.m.	Discussion

Friday, April 29, 2016 – Ellwood Room (Turbines Program)

7:00 – 8:00 a.m.	**Registration – 2nd Floor Foyer**
8:00 – 8:30 a.m.	**12 – Project # FE0025495** – Understanding Transient Combustion Phenomena in Low-NOx Gas Turbines *Jacqueline O'Connor* – **Pennsylvania State University**
8:30 – 9:15 a.m.	Q&A
9:15 – 10:30 a.m.	Discussion
10:30 – 10:45 a.m.	**BREAK**
10:45 – 11:45 a.m.	**Turbines Program Peer Review Wrap-Up Session**

APPENDIX E: PEER REVIEW PANEL MEMBERS

Michael von Spakovsky, Ph.D. – Panel Chair

Dr. von Spakovsky has over 29 years of teaching and research experience in academia and over 17 years of industry experience in mechanical engineering, power utility systems, aerospace engineering, and software engineering. He received his B.S. in Aerospace Engineering in 1974 from Auburn University and his M.S. and Ph.D. in Mechanical Engineering in 1980 and 1986, respectively, from the Georgia Institute of Technology. While at Auburn he worked for three and a half years at the National Aeronautics and Space Administration (NASA) in Huntsville, Alabama and from 1974 to 1984 and from 1987 to 1989 worked in the power utility industry first as an engineer and then as a consultant. From 1989 to 1996, Dr. von Spakovsky worked as both an educator and researcher at the Swiss Federal Institute of Technology in Lausanne, Switzerland where he led a research team in the modeling and systems integration of complex energy systems and taught classes in the thermodynamics of indirect and direct energy conversion systems (including fuel cells).

In January of 1997, Dr. von Spakovsky joined the Mechanical Engineering faculty at Virginia Tech as Professor and Director of the Energy Management Institute (now the Center for Energy Systems Research). He teaches undergraduate and graduate level courses in thermodynamics and intrinsic quantum thermodynamics, kinetic theory and the Boltzmann equation, fuel cell systems, and energy system design. His research interests include computational methods for modeling and optimizing complex energy systems; methodological approaches (with and without sustainability and uncertainty considerations) for the integrated synthesis, design, operation, and control of such systems (e.g., stationary power systems; grid/microgrid/producer/storage and district heating/cooling networks; high performance aircraft systems); theoretical and applied thermodynamics with a focus on intrinsic quantum thermodynamics applied to nanoscale and microscale reactive and non-reactive systems; and fuel cell applications for both transportation and centralized, distributed, and portable power generation and cogeneration. He has published widely in scholarly journals and conference proceedings (over 220 publications) and has given talks, keynote lectures, seminars, and short courses (e.g., on fuel cells and intrinsic quantum thermodynamics) worldwide. Included among his various professional activities and awards is *Senior member of the American Institute of Aeronautics and Astronautics (AIAA)*; *Fellow of the American Society for Mechanical Engineers (ASME)*; the *2014 ASME James Harry Potter Gold Medal*; the *2012 ASME Edward F. Obert Award*; the *2005*, *2008*, and *2012 ASME Advanced Energy Systems Division (AESD) Best Paper Awards*; the *ASME AESD Lifetime Achievement Award*; former Chair of the *Executive Committee* for the ASME AESD; elected member of Sigma Xi and Tau Beta Pi; Associate Editor of the *ASME Journal of Electrochemical Energy Conversion and Storage;* and former Editor-in-Chief (11-year tenure) and now Honorary Editor of the *International Journal of Thermodynamics*.

Knox T. Millsaps, Jr., Ph.D.

Knox T. Millsaps, Jr., is the chair of the Department of Mechanical and Aerospace Engineering at the Naval Postgraduate School (NPS) in Monterey, California, and the director of the NPS Marine Propulsion Laboratory, where he conducts research in the area of power and propulsion. Other positions he has held at NPS include associate chairman of the Department of Mechanical and Aerospace Engineering, associate provost of academic affairs, and associate provost of institutional development.

Dr. Millsaps' teaching interests span power and propulsion, fluid mechanics, thermodynamics, energy conversion, and heat transfer. His research interests include turbomachinery, power and propulsion, rotordynamics, fluid structure interactions, condition-based maintenance of rotating and reciprocating machinery, advanced energy systems, and alternate and synthetic fuels.

Prior to working at NPS, Dr. Millsaps worked for Pratt & Whitney, focusing on unsteady, three-dimensional flow. He served two years as congressional staff in the office of Representative John M. Spratt, Chairman, House Budget Committee and Senior Member, House Armed Services Committee. He also served as a Brookings Legislative Fellow for Representative Spratt, working on procurement and research and development issues, missile defense, DOE weapons laboratories (National Nuclear Security Administration and stockpile stewardship), strategic forces, space assets, electronic warfare, and procurement reform.

Dr. Millsaps is past chair of the board of directors of the American Society of Mechanical Engineers (ASME) International Gas Turbine Institute, editor-in-chief of *Global Gas Turbine News*, a member of ASME and the American Institute of Aeronautics and Astronautics, and associate editor for ASME's *Journal of Gas Turbines and Power*. Additionally, he served as a member of the ASME Board on Government Affairs and the ASME Energy Committee. In 2005, Dr. Millsaps received an award for Best Paper from the International Gas Turbine Institute, Marine Committee.

Millsaps holds a B.S. in engineering science and physics from the University of Florida, a M.S. in AeroAstro from the Massachusetts Institute of Technology (MIT), and a Ph.D. in AeroAstro and finance from MIT, Sloan and Harvard Business School.

Norman Z. Shilling, D. Sc., PE

Prior to entering into private consulting practice, Dr. Norman Z. Shilling was a Senior Product Manager for General Electric (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 gas. Frequently called upon to share his expertise in gasification, carbon capture, and sequestration as related to policy and regulation, Dr. Shilling has spoken at many U.S. and global industry conferences, provided testimony to many regulatory and legislative bodies, and participated in 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. He also 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. Before that, he was an Advanced Engineering Manager for GE environmental systems, responsible for the development of scrubbers and particulate controls for utility power plants.

Before his successes with GE, where he was a key leader in many strategic technology-planning initiatives, Dr. Shilling contributed in various ways to the development of nuclear steam generators and advanced automotive power plants.

Shilling holds a M.S. in heat transfer and fluid mechanics from the Massachusetts Institute of Technology and a B.S. and D.SC. in mechanical engineering 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.

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, Sorensen worked for Air Products and Chemicals as director of new markets with responsibility for Syngas Conversion Technology Development and Government Systems and 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. Sorensen's achievements include the first commercial integration of a gas turbine with an ASU and an integration involving ion-transport membrane (ITM) oxygen technology. Prior roles with Air Products include managing baseload liquefied natural gas (LNG) projects, synthetic natural gas (SNG) production, and the Membrane Systems department.

Sorensen's technical interests include IGCC, oxyfuel combustion, gas-to-liquids (GTL), and air separation and hydrogen/syngas technology. His programmatic interests include Electric Power Research Institute (EPRI) CoalFleet, Fossil Energy R&D, DOE's Clean Coal Power Initiative, DOE's FutureGen program, and commercial projects. His areas of expertise include project conception and development, consortium development and management, government sales and contracting, R&D program management, technology consulting and training, commercial contract development, and intellectual property. He is the founding chairman of the Gasification Technologies Council and is vice chairman of both the Council on Alternate Fuels and Energy Futures International. Sorensen 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.