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Final Report
Strategic Center for Coal
Advanced Turbines
FY 2010 Peer Review Meeting

MEETING SUMMARY AND RECOMMENDATIONS REPORT

Morgantown, West Virginia
April 26 – 30, 2010

U.S. DEPARTMENT OF ENERGY
OFFICE OF FOSSIL ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY

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FINAL REPORT
STRATEGIC CENTER FOR COAL
ADVANCED TURBINES
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MEETING SUMMARY AND RECOMMENDATIONS REPORT

EXECUTIVE SUMMARY

The mission of the U.S. Department of Energy's (DOE) Office of Clean Coal (OCC) is to ensure the availability of ultra-clean, near-zero emission, abundant, and low-cost domestic energy from coal in order to fuel economic prosperity, strengthen energy security, and enhance environmental quality. The OCC is organized into nine technology programs. One of these programs, the OCC Advanced Turbines Program, is administered by the DOE Office of Fossil Energy's National Energy Technology Laboratory (NETL).

Advanced Turbines Program Targets:

Advanced turbines are being developed to operate on coal-derived fuels (syngas) and hydrogen. To achieve the APS goals, the Advanced Turbines Program has established the following targets:

By 2010, operating on syngas: increase combined-cycle (CC) power block efficiency by 2–3 percentage points over baseline; reduce NOx emissions to 2 ppm in the turbine exhaust at 15 percent oxygen when fueled with syngas; and reduce capital costs of CC power island by 20–30 percent when compared to today's turbines in existing integrated gasification combined-cycle (IGCC) plants.

By 2012, operating on hydrogen: maintain 2010 efficiency gains (2–3 percentage points for CC power block over baseline) when fueled with hydrogen; reduce NOx emissions to near-zero when fueled with hydrogen; maintain 2010 capital cost reductions (20–30 percent from baseline) when fueled with hydrogen; and reduce the cost impact of CO2 compression by reducing the auxiliary power requirement by 30–40 percent compared to current projections.

In compliance with requirements from the Office of Management and Budget (OMB), 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) 2010 Advanced Turbines 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., the American Society of Mechanical Engineers (ASME) convened a panel of eight leading academic and industry experts on April 26–30, 2010, to conduct a five-day Peer Review of selected Advanced Turbines Program research projects supported by NETL.

Overview of Office of Fossil Energy Advanced Turbines Program Research Funding

The total funding of the 15 projects reviewed, over the duration of the projects, is $204,326,418. Of this amount, $146,042,466 (71.5%) is funded by DOE, while the remaining $58,283,952 (28.5%) is funded by project partner cost sharing.

The 15 projects that were the subject of this Peer Review are summarized in Table ES-1 and in Section II of this report.

TABLE ES-1 ADVANCED TURBINES PROJECTS REVIEWED

Reference Number	Project No.	Title	Lead Organization	Principal Investigator	Total Funding[A] DOE	Total Funding[A] Cost Share	Project Duration[A] From	Project Duration[A] To
01	DE-FC26-05NT42644	Advanced Hydrogen Turbine Development Program	Siemens Energy, Inc.	Joseph Fadok	$66,730,745	$28,020,829	10/01/2005	03/31/2012
02	DE-FC26-05NT42643	Advanced IGCC/Hydrogen Gas Turbine Development	GE Energy	Reed Anderson	$60,360,352	$25,868,721	10/01/2005	09/30/2012
03	DE-FC26-08NT0005054	Combustion Dynamics in Multi-Nozzle Combustors Operating on High-Hydrogen Fuels	Pennsylvania State University—OSP	Domenic A. Santavicca	$400,000	$100,000	10/01/2008	09/30/2011
04	FWP-FEAA-070	Materials Issues in Coal-Derived Synthesis Gas/Hydrogen-Fired Turbines	Oak Ridge National Laboratory	Bruce Pint	$2,322,000	$0	10/01/2004	09/30/2010
05	DE-NT0006552	Degradation of Thermal Barrier Coatings From Deposits; and, Its Mitigation	Ohio State University Research Foundation	Nitin P. Padture	$432,000	$108,000	10/01/2008	09/30/2011
06	DE-NT0000752	An Experimental and Chemical Kinetics Study of the Combustion of Syngas and High-Hydrogen-Content Fuels	Pennsylvania State University—OSP	Robert J. Santoro	$719,999	$180,253	10/01/2009	09/30/2012
07	FY10.MSE.1610243.682; FY10.MSE.1610243.683	Performance of Materials for Oxy-Fuel Turbines	National Energy Technology Laboratory	Gordon Holcomb and Jeffrey Hawk	$599,163	$0	10/01/2008	09/30/2010
08	FWP-678403	Low-Swirl Injectors for Hydrogen Gas Turbines in FutureGen Power Plants	Lawrence Berkeley National Laboratory	Robert K. Cheng	$3,389,899	$0	07/01/2006	09/30/2010
09	FWP-AL05205018	Analysis of Gas Turbine Thermal Performance	Ames National Laboratory	Tom Shih	$695,000	$0	10/01/2004	09/30/2010
10	FY10.ESD.1610243.623	Aerothermal and Fundamental H_2 Studies and CO_2 Recycle Effects	National Energy Technology Laboratory	Doug Straub	$700,000	$0	10/01/2009	09/30/2010
11	DE-FC26-08NT0005055	Designing Turbine Endwalls for Deposition Resistance with 1400°C Combustor Exit Temperatures and Syngas Water Vapor Levels	Ohio State University—Department of Aerospace Engineering	Jeffrey P. Bons	$475,000	$180,270	9/30/2008	09/30/2011
12	DE-AC26-04NT41817	Carbon Capture Approaches for NGCC Systems	National Energy Technology Laboratory	Walter Shelton	$223,343	$0	11/01/2008	04/15/2010
13	DE-FC26-05NT42645	Coal-Based Oxyfuel System Evaluation and Combustor Development	Clean Energy Systems, Inc.	Roger E. Anderson	$4,707,837	$2,150,647	10/01/2005	09/30/2010
14	DE-NT0006833	Condition Based Monitoring of Turbine Combustion Components	Siemens Energy, Inc.	Getnet Kidane	$843,664	$814,365	10/01/2008	09/30/2011
15	DE-FC26-05NT42646	Zero Emissions Coal Syngas-Oxygen Turbo Machinery	Siemens Energy, Inc.	Dennis Horazak	$3,443,464	$860,867	09/30/2005	03/31/2010
				TOTALS	$146,042,466	$58,283,952		

Note: A: Funding amounts and project durations have been obtained from project summaries submitted by the principal investigator.

NETL ADVANCED TURBINES PROGRAM OVERVIEW

Future IGCC power plants utilizing pre-combustion CO_2 capture will produce a high-hydrogen-content fuel for the gas turbine. To advance the commercialization of advanced power plants based on IGCC technology, the Advanced Turbines Program is pursuing the development of advanced turbines fueled by syngas and high-hydrogen fuel. Limited short-term testing has indicated that high-hydrogen fuel can be fired in current-vintage (F-Class) turbines, but to achieve the program goals of increased efficiency, reduced emissions, and lower costs, advances in combustor technology, materials, and improved aerodynamics are required. Key research and development activity areas include the following:

> ***Combustor Design*** includes the design and development of the combustion portion of the turbine. This activity area leverages the current promising technologies to meet strategic system-level goals of an advanced syngas and high-hydrogen-fueled gas turbine. Efforts are focused on the measurement and assessment of the fundamental properties of hydrogen combustion and the use of these properties to design and develop low NO_x combustion systems. Inevitably, these systems will use nitrogen and possibly steam as diluents to control combustor temperatures and NO_x emissions. Several combustion technologies are under evaluation, including high- and low-swirl premixed, diffusion, hybrid forms of pre-mixed and diffusion, axial staging, and rich-lean catalytic combustors.
>
> ***Thermal Barrier Coatings*** involve assessing and developing thermal barrier coatings that can provide the performance and durability required for use in syngas and high-hydrogen-fueled advanced gas turbines. Efforts are focused on identifying candidate thermal barrier coating (TBC) architectures and material compositions with the proper thermal, mechanical, and chemical properties to reduce heat flux to combustor transition pieces, stationary nozzles, and rotating airfoils. Advanced TBC and bond coat architectures are being developed to improve durability and thermal performance in the harsh environment found in advanced gas turbines. To some extent, TBC bond coats and air foil base alloys are also being evaluated for improvement.
>
> ***Aero-Thermo-Mechanical Design*** involves the assessment of the unique aero-thermo-mechanical operational conditions associated with high-hydrogen turbines and investigates design improvements for addressing these unique design spaces. Efforts are focused on reducing cooling flow ratios, reducing sealing and leakage flow rates, reducing rotating blade count, and increasing expansion stage areas. These efforts will enable the operation of machines that have a higher power output and that better manage cooling air.

Overview of the Peer Review Process

NETL requested that ASME assemble an Advanced Turbines Peer Review Panel (hereinafter referred to as the Panel) of recognized technical experts to provide recommendations on how to improve the management, performance, and overall results of each individual research project. Each project team prepared a detailed project information form containing an overview of the project's purpose, objectives, and achievements, and a presentation to be given at the Peer Review Meeting. The Panel received the project information forms and presentations prior to the Peer Review Meeting.

At the meeting, each research team made an uninterrupted 45- to 120-minute PowerPoint presentation that was followed by a 30- to 50-minute question-and-answer (Q&A) session with the Panel. After the principal investigator and project team left the room, the Panel had a 30- to 40-minute discussion about the strengths, weaknesses, recommendations, and action items for each project. To facilitate a more open and free discourse of project-related material between the project team and the Panel, all sessions were limited to the Panel, ASME project team members, and DOE/NETL personnel.

After the group discussions, each Panel member individually evaluated the 15 projects, providing written comments based on a predetermined set of review criteria. For each of the nine review criteria, the individual reviewer was asked to score the project as one of the following:

Effective (5)

Moderately Effective (4)

Adequate (3)

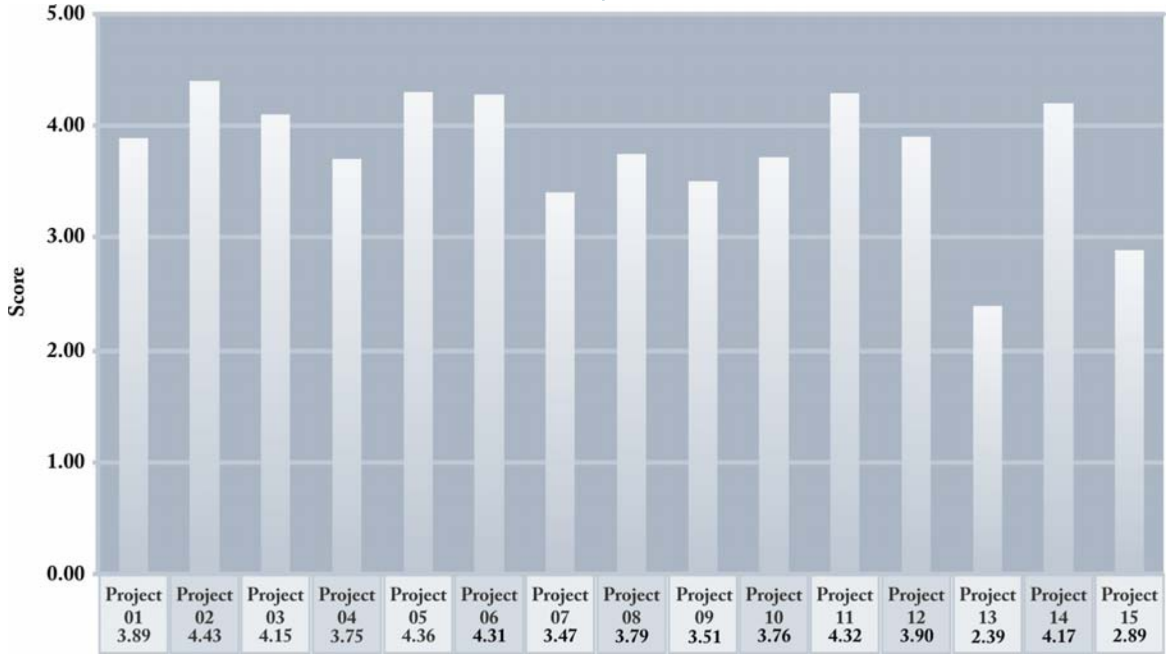
Ineffective (2)

Results Not Demonstrated (1)

The Panel occasionally had divergent views of a project. In the extreme case, this divergence is reflected in projects receiving ratings ranging from 1 to 4 or 2 to 5 in a particular criterion. This result should not be taken as an indication that the Panel was indecisive; rather, this reflects the varied backgrounds and differing perspectives of a diverse Panel. Such diversity is a strength allowing the Panel, as a whole, to review a wide range of projects on varied topics with a comparable overall level of expertise.

Figure ES-2 shows the overall average score, combining all nine review criteria, for the 15 projects.

FIGURE ES-2 AVERAGE SCORING, BY PROJECT



The "Project Average" in Table ES-3 shows the score for each criterion averaged across all 15 projects. The "Highest Project Rating" and "Lowest Project Rating" columns portray the highest and lowest scores, respectively, received by an individual project in a given criterion.

TABLE ES-3 AVERAGE SCORING, BY REVIEW CRITERION*

Criterion	Project Average	Highest Project Rating	Lowest Project Rating**
1. Scientific and Technical Merit	4.0	4.9	3.1/2.6
2. Existence of Clear, Measurable Milestones	3.8	4.5	3.1/2.6
3. Utilization of Government Resources	4.0	4.8	3.0/2.6
4. Technical Approach	3.9	4.9	3.3/2.4
5. Rate of Progress	3.8	4.6	3.4/2.8
6. Potential Technology Risks Considered	3.7	4.4	2.9/2.0
7. Performance and Economic Factors	3.7	4.6	2.4/2.3
8. Anticipated Benefits, if Successful	3.8	4.9	2.1/2.1
9. Technology Development Pathways	3.6	4.4	2.5/1.8

* The score for each project in a given criterion is by definition the average of *all reviewer* ratings for that criterion.

** To present a more accurate view of the lowest scores, two values have been given. The first value is the lowest score a criterion received in a project, excluding the lowest-rated project. The second value is the lowest score a criterion received in a project. This distinction is made because the lowest-rated project received significantly lower scores than the other projects reviewed.

For more on the overall evaluation process and the nine review criteria, see Section III.

Each project was categorized based on its stage of development, which ranged from fundamental research to proof-of-concept, as described in Table ES-4. This categorization enabled the Panel to appropriately score the Performance and Economic Factors and Technology Development Path criteria by providing context for the anticipated level of economic and developmental data for each project.

TABLE ES-4 DESCRIPTION OF DEVELOPMENT STAGES

Stage of Research	Description
Fundamental Research	The project explores and defines technical concepts or fundamental scientific knowledge. Projects are laboratory-scale and, traditionally but not exclusively, are the province of academia.
Applied Research	The project presents a laboratory- or bench-scale proof of the feasibility of potential applications of a fundamental scientific discovery.
Prototype Testing	The project develops and tests a prototype technology or process in the laboratory or field, maintaining predictive modeling or simulation of performance and evaluating scalability.
Proof-of-Concept	The project develops and tests a pilot-scale technology or process for field testing and validation at full scale, but is not indicative of a long-term commercial installation.
Major Demonstration *Not applicable in this peer review.*	The project develops a commercial-scale demonstration of energy and energy-related environmental technologies, generally with the intent of becoming the initial representation of a long-term commercial installation.

A summary of key project findings as they relate to individual projects can be found in Section IV of this report. Process considerations and recommendations for future project reviews are found in Section V.

For More Information

For more information concerning the contents of this report, contact the NETL Federal Project Manager and Peer Review Coordinator, José D. Figueroa, at (412) 386-4966 or Jose.Figueroa@netl.doe.gov.

I. INTRODUCTION

In fiscal year 2010, the American Society of Mechanical Engineers (ASME) was invited to provide an independent, unbiased, and timely peer review of selected projects within the U.S. Department of Energy (DOE) Office of Fossil Energy Advanced Turbines Program (administered by the Office of Fossil Energy's National Energy Technology Laboratory [NETL]). On April 26–30, 2010, ASME convened a panel of eight leading academic and industry experts to conduct a five-day peer review of selected Advanced Turbines research projects supported by NETL. This report contains a summary of the findings from that review.

Compliance with Office of Management and Budget Requirements

DOE, the Office of Fossil Energy, and NETL are fully committed to improving the quality and results of their projects. The peer review of selected projects within the Advanced Turbines Program was designed to comply with requirements from the Office of Management and Budget.

ASME Center for Research and Technology Development (CRTD)

All requests for peer reviews are organized under ASME's Center for Research and Technology Development (CRTD). CRTD's Director of Research, Dr. Michael Tinkleman, with advice from the chair of the ASME Board on Research and Technology Development, selects an executive committee of senior ASME members that is responsible for reviewing and approving all Panel members and ensuring that there are no conflicts of interest within the Panel or the review process. In consultation with NETL, ASME formulates the review meeting agenda, provides information advising the principal investigators (PIs) and their colleagues on how to prepare for the review, facilitates the review session, and prepares a summary of the results. A more extensive discussion of the ASME peer review methodology used for the Advanced Turbines Peer Review Meeting is provided in Appendix A. A copy of the meeting agenda is provided in Appendix B, and profiles of the Panel members are provided in Appendix C.

Overview of the Peer Review Process

ASME was selected as the independent organization to conduct a five-day peer review of 15 Advanced Turbines Program projects. ASME performed this project review work as a subcontractor to Leonardo Technologies, Inc., a NETL prime contractor. NETL selected the 15 projects, while ASME organized an independent review panel of eight leading academic and industry experts. Prior to the meeting, project PIs submitted an 11-page written summary (Project Information Form) of their project's purpose, objectives, and progress. The PI's also submitted their PowerPoint presentations to the Panel prior to the meeting. This project information is given to the Panel prior to the meeting, which allows the Panel to come to the meeting fully prepared with the necessary project background information.

At the meeting, each research team made a 45- to 120-minute oral presentation, followed by a 30- to 50-minute question-and-answer (Q&A) session with the Panel and a 30- to 40-minute Panel discussion of each project. The length of the presentation and Q&A session was primarily a function of the perceived time requirement for the PI to go through the presentation material, which depended on a number of factors, such as the project's complexity, duration, and breadth of scope. Based on lessons learned from prior peer reviews and the special circumstances associated with Advanced Turbines Program research, ASME decided that both the PI presentations and Q&A sessions with the Panel for the Advanced Turbines Peer Review were to be held as closed sessions, limited to the

Panel, ASME project team members, and DOE/NETL personnel. The closed sessions ensured open discussions between the PIs and the Panel. Panel members were also instructed to hold the presentations, PI project information forms, and the discussions that took place during both the Q&A session and panel discussions as confidential.

Each member of the Panel individually evaluated the project and provided written comments based on a predetermined set of review criteria. This publicly available document, prepared by ASME, provides a general overview of the Advanced Turbines Peer Review and the projects reviewed therein.

Peer Review Criteria and Peer Review Criteria Forms

ASME developed a set of agreed-upon review criteria to be applied to the projects reviewed at this meeting. ASME provided the Panel and PIs with these review criteria in advance of the Peer Review Meeting, and assessment sheets with the review criteria were pre-loaded (one for each project) onto laptop computers for each Panel member. During the meeting, the Panel members assessed the strengths and weaknesses of each project before providing both recommendations and action items. A more detailed explanation of this process and a sample Peer Review Criteria Form are provided in Appendix D.

The following sections of this report summarize findings from the Advanced Turbines Peer Review Meeting, organized as follows:

II. *Summary of Projects Reviewed in FY 2010 Advanced Turbines Peer Review*:

  A list of the 15 projects reviewed and the selection criteria

III. *An Overview of the Evaluation Scores in FY 2010*:

  Average scores and a summary of evaluations, including analysis and recommendations

IV. *Summary of Key Project Findings*:

  An overview of key findings from project evaluations

V. *Process Considerations for Future Peer Reviews*:

  Lessons learned in this review that may be applied to future reviews

II. SUMMARY OF PROJECTS REVIEWED IN FY 2010 ADVANCED TURBINES PEER REVIEW

NETL selected key projects within the Advanced Turbines Program, including projects being conducted at NETL, to be reviewed by the independent Peer Review Panel. The selected projects are listed below along with the name of the organization leading the research. A short summary of each of the above projects is presented in Appendix E.

PROJECTS REVIEWED

01: DE-FC26-05NT42644
Advanced Hydrogen Turbine Development Program—*Siemens Energy, Inc.*

02: DE-FC26-05NT42643
Advanced IGCC/Hydrogen Gas Turbine Development—*GE Energy*

03: DE-FC26-08NT0005054
Combustion Dynamics in Multi-Nozzle Combustors Operating on High-Hydrogen Fuels—*Pennsylvania State University—OSP*

04: FWP-FEAA-070
Materials Issues in Coal-Derived Synthesis Gas/Hydrogen-Fired Turbines—*Oak Ridge National Laboratory*

05: DE-NT0006552
Degradation of Thermal Barrier Coatings From Deposits; and, Its Mitigation—*Ohio State University Research Foundation*

06: DE-NT0000752
An Experimental and Chemical Kinetics Study of the Combustion of Syngas and High Hydrogen Content Fuels—*Pennsylvania State University—OSP*

07: FY10.MSE.1610243.682; FY10.MSE.1610243.683
Performance of Materials for Oxy-Fuel Turbines—*National Energy Technology Laboratory, Office of Research & Development*

08: FWP-678403
Low-Swirl Injectors for Hydrogen Gas Turbines in FutureGen Power Plants—*Lawrence Berkeley National Laboratory*

09: FWP-AL05205018
Analysis of Gas Turbine Thermal Performance—*Ames National Laboratory*

10: FY10.ESD.1610243.623
Aerothermal and Fundamental H_2 Studies and CO_2 Recycle Effects—*National Energy Technology Laboratory, Office of Research & Development*

11: DE-FC26-08NT0005055
Designing Turbine Endwalls for Deposition Resistance with 1400°C Combustor Exit Temperatures and Syngas Water Vapor Levels—*Ohio State University—Department of Aerospace Engineering*

12: DE-AC26-04NT41817
Carbon Capture Approaches for NGCC Systems—*National Energy Technology Laboratory, Office of Systems, Analysis, & Planning*

13: DE-FC26-05NT42645
Coal-Based Oxy-Fuel System Evaluation and Combustor Development—*Clean Energy Systems, Inc.*

14: DE-NT0006833
Condition Based Monitoring of Turbine Combustion Components—*Siemens Energy, Inc.*

15: DE-FC26-05NT42646
Zero Emissions Coal Syngas-Oxygen Turbo Machinery—*Siemens Energy, Inc.*

III. AN OVERVIEW OF THE EVALUATION SCORES FOR THE ADVANCED TURBINES PROGRAM

For each of the nine review criteria, individual reviewers were asked to score the project as one of the following:

Effective (5)

Moderately Effective (4)

Adequate (3)

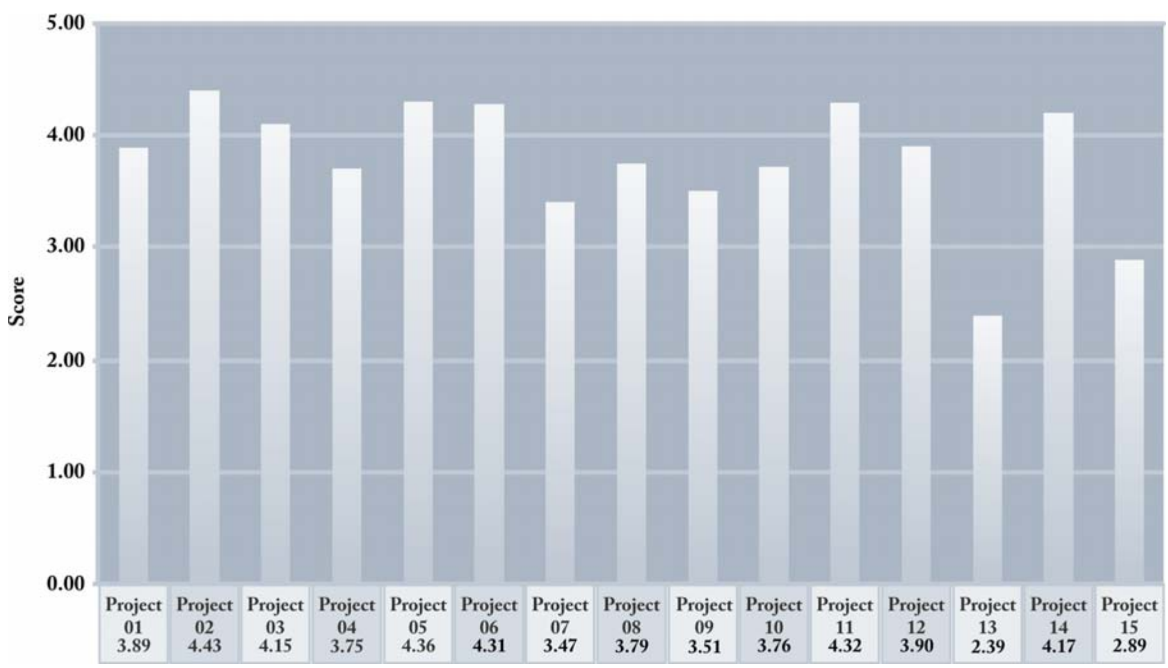
Ineffective (2)

Results Not Demonstrated (1)

The average scores for all the projects and across each rating criterion indicate that, overall, the Advanced Turbines Program is strong and has opportunities for improvement. The program consists primarily of well-managed and well-staffed projects aimed at developing innovative and marketable technologies that have considerable potential to provide valuable benefits to the turbine and gasification industries.

Figure 1 shows the average project scores, averaging the scores of the nine review criteria for each of the 15 projects reviewed. The Panel viewed most projects favorably: six of the projects received an average project score at or above 4.0; seven of the projects were scored between 3.0 and 4.0 (with two of those projects nearly attaining scores of 4.0); two projects between 2.0 and 3.0 (with one of those projects nearly attaining a score of 3.0),and no project with an average score below 2.0. The project with the lowest average score earned a 2.4, while the project with the highest average score earned a 4.4. The average of the 15 project scores was 3.8. These results indicate that the Panel deemed the projects, on average, as more than adequate, based on the review criteria.

FIGURE 1 AVERAGE SCORING, BY PROJECT



General conclusions about the Advanced Turbines Program can also be drawn by looking at the average scores for each of the nine review criteria, which are shown in Table 1. All of the criteria received average scores of 3.6 or higher, reflecting that NETL and DOE are managing and funding projects that are developing innovative, economical, and scientifically rigorous technologies. The relatively low score for Technology Development Pathways reflects the Panel's perspective that several of the Advanced Turbines projects were not fully effective at identifying and developing pathways for successful technology applications and commercialization. The data also show that the Panel found that, on average, the Advanced Turbines Program is effectively developing projects of high scientific and technical merit, and effectively leveraging government resources.

TABLE 1 AVERAGE SCORING, BY REVIEW CRITERION*

Criterion	Project Average	Highest Project Rating	Lowest Project Rating**
1. Scientific and Technical Merit	4.0	4.9	3.1/2.6
2. Existence of Clear, Measurable Milestones	3.8	4.5	3.1/2.6
3. Utilization of Government Resources	4.0	4.8	3.0/2.6
4. Technical Approach	3.9	4.9	3.3/2.4
5. Rate of Progress	3.8	4.6	3.4/2.8
6. Potential Technology Risks Considered	3.7	4.4	2.9/2.0
7. Performance and Economic Factors	3.7	4.6	2.4/2.3
8. Anticipated Benefits, if Successful	3.8	4.9	2.1/2.1
9. Technology Development Pathways	3.6	4.4	2.5/1.8

* The score for each project in a given criterion is by definition the average of *all reviewer* ratings for that criterion.

** To present a more accurate view of the lowest scores, two values have been given. The first value is the lowest score a criterion received in a project, excluding the lowest-rated project. The second value is the lowest score a criterion received in a project. This distinction is made because the lowest-rated project received significantly lower scores than the other projects reviewed.

A copy of the Peer Review Criteria Form and a detailed explanation of the review process are provided in Appendix D.

IV. SUMMARY OF KEY FINDINGS

This section summarizes key findings from across the 15 projects evaluated at the Advanced Turbines Peer Review.

General Project Strengths

The Panel indicated that the majority of projects were sound, commending DOE for presenting a high-quality, diverse portfolio of projects with ambitious goals and significant potential to advance turbine technology. As reflected in Table I, the spread of average scores among the nine criteria was narrow, ranging from 3.6 to 4.0, and indicates that the Advanced Turbines Program was strong in all areas. The Program was rated particularly high in the Scientific and Technical Merit, Utilization of Government Resources, and Technical Approach criteria, reflecting the Panel's perception that, overall, the projects were based on sound science, used innovative technical approaches, and effectively leveraged available resources.

In general, the Panel was impressed by NETL's integration of lessons learned from past peer reviews, including increased emphasis on project technology barriers, commercial applications, and economics. The Panel found the majority of the project teams to be strong; these teams consisted of a wide range of expertise and industry partnerships and have access to impressive testing facilities that enabled innovative technical approaches and experimental designs to be developed. The Panel indicated that most projects are achieving promising results and producing valuable tools cost effectively.

The highest-rated project was Project 02, "Advanced IGCC/Hydrogen Gas Turbine Development," conducted by GE Energy, which received an average rating of 4.43 out of 5.0. Projects 05, "Degradation of Thermal Barrier Coatings From Deposits; and, Its Mitigation," conducted by Ohio State University Research Foundation; 06, "An Experimental and Chemical Kinetics Study of the Combustion of Syngas and High-Hydrogen-Content Fuels," conducted by Pennsylvania State University; and 11, "Designing Turbine Endwalls for Deposition Resistance with 1400°C Combustor Exit Temperatures and Syngas Water Vapor Levels", Ohio State University, also performed very strongly, receiving average scores of 4.36, 4.32, and 4.31, respectively. All four of these projects were lauded by the Panel for their innovative technologies and approaches, which can be attributed to strong project managers and teams with access to impressive testing facilities. These projects were also praised for effectively maintaining focus on technology development pathways that were aligned with industry needs and program goals.

General Project Weaknesses

As noted above, the projects evaluated in the Advanced Turbines Program did not significantly underperform across any particular criterion, which demonstrates efforts by NETL and DOE to address and bolster those aspects of their research programs that need strengthened. The lowest-scoring criterion, Technology Development Pathways, still earned an average score of 3.6—closer to a rating of 4.0 (Effective) than 3.0 (Adequate). However, as several projects performed very well under particular criteria, lower average scores indicate that particular projects underperformed. Specifically, the Panel found that several project teams did not identify and consider the commercial viability and risks of their technology in a meaningful way, failing to determine feasible development scenarios for the technology or conduct tests that represented real-world conditions.

The Panel recognized that several projects did not adequately consider end-use technology applications and pathways and/or were poorly aligned with the overarching objective of the NETL Advanced Turbines Program. The Panel surmised that this may be partly due to a lack of appropriate guidance and information from outside stakeholders (e.g., industry and original equipment manufacturers [OEMs]) in the research. The Panel specifically pointed out that some of the smaller projects seemed to collaborate with OEMs and maintain focus on the end results of the project better than some of the larger projects.

A number of projects also struggled in the areas of Performance and Economic Factors and Potential Technology Risks Considered. Such projects, even when there was access to adequate testing facilities, often did not have correct or sufficient information on real-world operating conditions. This information is essential to conduct the tests that are necessary to address all potential risks or prove the economic viability and competitiveness of the technology against those already commercially available. This was due to various factors such as innate difficulties in obtaining access to proprietary information and inadequate background research, in addition to a lack of appropriate guidance from industry. In isolated instances, the basic premise and objective of the project was questioned, with doubts as to whether the technology, given the current approach, was likely to successfully compete with other commercially available technologies.

The Panel indicated that the program had several areas of overlapping efforts among the projects. The Panel specified that several projects had done insufficient background research, unnecessarily duplicating previously completed efforts and experiments.

Lastly, the Panel found that some projects did not adequately make the distinction between goal statements and activity statements, noting that goals should have some relationship to cost performance goals in the NETL Program and not simply be lists of activities.

Issues for Future Consideration

While many of the recommendations provided by the Panel were technical in nature and specific to the particular project's technology or approach, several overarching themes emerged, addressing some of the general weaknesses discussed above.

The first relates to the operating conditions of the tests that project teams performed on the turbines, which were sometimes deemed unrealistic representations of commercial settings. The panel emphasized the importance of understanding and, to the extent possible, testing under real-world commercial conditions, including the full definition of the functions to be performed by the technology and under what set(s) of design basis conditions. Even some fundamental projects should develop or incorporate relatively well-defined functional specifications and design bases at the outset. Projects should then select the conditions under which the technology will be tested based on this information and practical limitations of experimental work. When possible, project teams should perform tests on real fuel compositions and under operating conditions reflective of the technologies in the Advanced Turbines Program (e.g., high-hydrogen-content fuels and syngas) by more actively eliciting information from industry (as well as through literature searches) and obtaining real fuel samples when possible. When it is not possible or practical to run tests under realistic conditions, the panel noted that project teams should demonstrate awareness of "real world" conditions, provide a sound rationale regarding why these conditions were not used, and identify what unknowns remain to be addressed at later stages of development.

Conducting project experiments under more realistic conditions, as described above, will enable projects to more accurately assess the economic performance of a project relative to other technologies, address technology risks, and identify and pursue the technology development pathways that have the strongest potential for success. In addition, information on realistic operating ranges and fuel compositions, as well as the underlying assumptions behind them, is particularly important for conducting sensitivity and uncertainty analyses, which were lacking in some projects. Determining the project results' sensitivity to variations in fuel composition, temperature, pressure, flow parameters, etc., as well as to assumptions regarding technology availability, is a critical component of evaluating project and technology risk.

The second area of concern relates to technology developmental pathways, specifically in terms of applications that are aligned with program goals. The Panel noted that several projects failed to consider the applicability of the project technology to high-hydrogen turbines, the key focus of the Advanced Turbines Program. While the Panel acknowledged that some of the more fundamental and applied research projects were appropriately conducting tests on simpler fuel compositions, they also indicated that the project teams should put greater emphasis on their plans for testing on high-hydrogen fuels and the specific benefits the technology would provide turbines running on these fuels.

Lastly, as noted above, the Panel recommends that projects clearly distinguish project activities from project goals. Project teams should describe project goals in terms of their relationship with, and contribution to, cost performance goals in NETL's Advanced Turbine Program.

V. PROCESS CONSIDERATIONS FOR FUTURE PEER REVIEWS

The Panel and DOE/NETL managers involved in the Advanced Turbines Program Peer Review offered positive feedback on the review process and constructive comments for improving future peer reviews. These comments were provided at the conclusion of the Peer Review Meeting. The following is a brief summary of ideas recommended for consideration when planning future peer review sessions.

General Process Comments

All involved agreed that the current peer review process requires little or no modification to remain effective. There was high praise both for the facilitation and organization of the meeting. The Panel members appreciated the time they were given prior to the Peer Review Meeting to read through the project information documents and noted this review period as an integral part of the process. They indicated that having more time to review the information would be even better. The efficiency of the SharePoint site from which the Panel members could download all of the project documents was also appreciated. The Panel suggested that, in addition to information on the projects, they be given background on the organizations and companies on the project team and a list of acronyms related to their project to provide additional useful context for their review. The Panel suggested that a fuller version of Adobe Acrobat be made available online so that they can enter notes and questions in the project information documents, particularly the presentations, to reference while writing their project comments.

The Panel found that nearly all projects were presented well, with the exception of one project, which was presented by a team that the Panel thought lacked the background to adequately answer their questions. The Panel found that the ground rules established for the reviews were for the most part effective in enabling candid Q&A sessions and that the presence of other project partners enhanced the ability of the project teams to respond to questions. The panel also noticed that it was helpful to have the project presenter(s) wait outside the meeting during the Panel's internal discussion in case it was necessary to call the team back into the meeting room to help clarify a point, which the Panel did a number of times throughout the review.

Meeting Agenda

The Panel indicated that overall the meeting agenda was well structured and provided adequate time for presentations, questioning, and subsequent Panel discussion without making the Panel feel rushed or overburdened. The Panel also made several observations and recommendations for future peer reviews regarding the ordering and scheduling of the projects.

Several Panel members noted that the order in which projects are presented impacted their ability to fairly and effectively evaluate them. The Panel recommended that projects that were related to each other be presented on the same day in order to provide the Panel with all the necessary information to evaluate them and maintain perspective.

The Panel also recommended that large, important projects be presented sometime after the first day of the peer review, since the Panel is still adjusting to the peer review process at the beginning of the week. The Panel noted that they would have been more effective in evaluating these higher priority projects if they were presented after the Panel had become fully absorbed in the peer review process. In addition, for the large projects, the Panel found it difficult to keep track of all the information presented over the two-hour period.

They suggested that an alternate schedule be considered for such projects with an additional Q&A session after the first half of the presentation.

Presentations

The Panel recognized that the project presentations and the review process were enhanced by the DOE presentation template and DOE's efforts to familiarize the principal investigators (PIs) with the presentation process. The Panel urged DOE to continue to emphasize the importance of the template in future reviews. They indicated that, overall, the template balanced providing structure and guidance for the presentations with allowing the PIs the freedom to emphasize the project aspects they considered particularly significant.

The Panel noticed, however, that some presentations could have benefited from additional guidance by providing the PI with key questions to address related to particular technology areas. Additional guidance could also be given to the project teams on the distinction between project activities and project goals, which should have some relationships to the cost-performance goals in the overall program.

Evaluation Process and Criteria

While the Panel noted that their introduction to the review process was quick and effective, there was some ambiguity on the context through which the Panel should evaluate certain criteria. In particular, at times, the Panel found it hard to separate the project from the program. Panel members often wanted to know more about the program and how the project fit into the larger program. On such occasions, the Panel elicited input from the NETL Program Manager during the discussion if clarification on a broader programmatic issue was necessary to evaluate a specific project. The Panel appreciated the program manager's availability to offer assistance in these cases because his input provided important context that sometimes altered the way the Panel viewed and rated a project.

Review Panel

The Panel noticed that the diverse areas of Panel members' expertise offered other members needed insight on various topics during discussion, providing more accurate and comprehensive ratings and comments. The Panel enjoyed the learning experience from working with their colleagues in the turbine field and thanked ASME and DOE for the opportunity to participate in this Peer Review.

APPENDICES

APPENDIX A: ASME PEER REVIEW METHODOLOGY

The American Society of Mechanical Engineers (ASME) has been involved in conducting research since 1909 when it started work on steam boiler safety valves. Since then, the Society has expanded its research activities to a broad range of topics of interest to mechanical engineers. ASME draws on the impressive breadth and depth of technical knowledge among its members and, when necessary, experts from other disciplines for participation in ASME-related research programs. In 1985, ASME created the Center for Research and Technology Development (CRTD) to coordinate ASME's research programs.

As a result of the technical expertise of ASME's membership and its long commitment to supporting research programs, the Society has often been asked to provide independent, unbiased, and timely reviews of technical research by other organizations, including the federal government. After several years of experience in this area, the Society developed a standardized approach to reviewing research projects. This section provides a brief overview of the review procedure established for the U.S. Department of Energy (DOE)/National Energy Technology Laboratory (NETL) FY 2010 Advanced Turbines Peer Review.

ASME Knowledge and Community Sector

One of the five sectors responsible for the activities of ASME's 127,000 members worldwide—the Knowledge and Community Sector—is charged with disseminating technical information, providing forums for discussions to advance the mechanical engineering profession, and managing the Society's research activities.

Board on Research and Technology Development

ASME members with suitable industrial, academic, or governmental experience in the assessment of priorities for research and development, as well as in the identification of new or unfulfilled needs, are invited to serve on the Board on Research and Technology Development (BRTD) and to function as liaisons between BRTD and the appropriate ASME sectors, boards, and divisions. The BRTD has organized more than a dozen research committees in specific technical areas.

Center for Research and Technology Development

CRTD has undertaken the mission to effectively plan and manage ASME's collaborative research activities to meet the needs of the mechanical engineering profession, as defined by the ASME members. The CRTD is governed by the BRTD, and day-to-day operations of the CRTD are handled by the director of research and his staff. The director of research serves as staff to the Peer Review Executive Committee, handles all logistical support for the Panel, provides facilitation of the actual review meeting, and prepares all summary documentation.

Advanced Turbines Peer Review Executive Committee

For each set of projects reviewed, the BRTD convenes a Peer Review Executive Committee to oversee the review process. The Executive Committee is responsible for guaranteeing that all ASME rules and procedures are followed, reviewing and approving the qualifications of those asked to sit on the Panel, ensuring that there are no conflicts of interest in the review process, and reviewing all documentation coming out of the project review. There must be at least three members of the Peer Review Executive Committee, all of whom must have experience relevant to the program being reviewed. Members of the FY 2010 Advanced Turbines Peer Review Executive Committee were as follows:

Richard T. Laudenat, Chair. Mr. Laudenat is the senior vice president of the ASME Knowledge and Communities Sector. He was previously a vice president of the ASME Energy Conversion Group and was a member of the ASME Energy Committee.

William Stenzel, Sargent & Lundy. Mr. Stenzel is a former chair of the ASME Power Division and past member of the ASME Energy Committee.

William Worek, University of Illinois. Dr. Worek is a past vice president of the ASME Energy Resources Group and former chair of the ASME Solar Energy Division. He currently serves on the ASME Mechanical Engineering Department Heads Committee.

Advanced Turbines Peer Review Panel

The Advanced Turbines Peer Review Executive Committee accepted résumés for proposed Advanced Turbines Peer Review Panel members from CRTD, from a call to ASME members with relevant experience in this area, and from the DOE/NETL program staff. From these sources, the ASME Peer Review Executive Committee selected an eight-member review panel and agreed that they had the experience necessary to review the broad range of projects under this program and did not without presenting any conflicts of interest. Panel members and qualifications are described in Appendix C.

Meeting Preparation and Logistics

Prior to the meeting, the project team for each project being reviewed was asked to submit an 11-page Project Information Form that detailed project goals, purpose, and accomplishments to date. A standard set of specifications for preparing this document was provided by CRTD. These Project Information Forms were collected and provided to the Panel prior to the meeting.

Also in advance of the review meeting, CRTD gave the project teams a standard presentation template and set of instructions for the oral presentations they were to prepare for the Panel. All presentations were created in PowerPoint; the Panel was also given hard-copy handouts of these slides.

The Project Information Forms and presentations for all projects were provided to the Panel well in advance of the meeting to help them to better prepare for their roles.

Project Presentations, Evaluations, and Discussion

At the Advanced Turbines Peer Review Meeting, presenters were held to a specific time limit (ranging from 45–120 minutes) to allow sufficient time for all presentations within the five-day meeting period. After each presentation, the project team participated in a 30–50 minute question-and-answer session with the Panel.

The Panel then spent 30–40 minutes evaluating the projects based on the presentation material. To start, each reviewer scored the project against a set of predetermined peer review criteria. The following nine criteria were used:

- Scientific and Technical Merit
- Existence of Clear, Measurable Milestones
- Utilization of Government Resources
- Technical Approach
- Rate of Progress
- Potential Technology Risks Considered
- Performance and Economic Factors
- Anticipated Benefits if Successful
- Technology Development Pathways

For each of these review criteria, individual Panel members scored each project as one of the following:

- Effective (5)
- Moderately Effective (4)
- Adequate (3)
- Ineffective (2)
- Results Not Demonstrated (1)

To facilitate the evaluation process, Leonardo Technologies, Inc. provided the Panel with laptop computers that were pre-loaded with Peer Review Criteria Forms for each project. The Panel then discussed the project for the purpose of defining project strengths, project weaknesses, recommendations, and a list of action items that the team must address to correct a project deficiency. After scoring the projects on these criteria and discussing the project, the Panel provided written comments about each project.

APPENDIX B: MEETING AGENDA

FY10 Advanced Turbines Peer Review

Waterfront Place Hotel, Morgantown, WV

April 26-30, 2010

U.S. Department of Energy - Office of Fossil Energy - National Energy Technology Laboratory

AGENDA

MONDAY, APRIL 26, 2010 - SALON D

7:00 - 7:30 a.m.	Registration - **FOYER D**
7:30 - 8:30 a.m.	Peer Review Panel Kick Off Meeting - Open to NETL and ASME staff only - Review of ASME Process - Michael Tinkleman/Ross Brindle, ASME - Role of Panel Chair - James Sorensen, ASME Peer Review Panel - Role of NETL - José Figueroa, NETL - Meeting logistics/completion of forms - Nicole Ryan/Justin Strock, TMS/NISC/IBM
8:30 - 9:15 a.m.	Overview - Open to NETL and ASME staff only - Advanced Turbines Technology Manager – Richard Dennis, National Energy Technology Laboratory (NETL)
9:15 - 9:30 a.m.	**BREAK - FOYER D**
9:30 - 11:30 a.m.	*01 - Project # NT42644* - Advanced Hydrogen Turbine Development Program – *Joseph Fadok*, **Siemens Energy, Inc.**
11:30 - 12:20 p.m.	Q&A
12:20 - 1:00 p.m.	Discussion, evaluation, and written comments
1:00 - 2:00 p.m.	**Lunch (on your own)**
2:00 - 4:00 p.m.	*02 - Project # NT42643* - Advanced IGCC/Hydrogen Gas Turbine Development – *Reed Anderson*, **GE Energy**
4:00 - 4:50 p.m.	Q&A
4:50 - 5:30 p.m.	Discussion, evaluation, and written comments

TUESDAY, APRIL 27, 2010 - SALON D

7:00 - 8:00 a.m.	Registration - **FOYER D**
8:00 - 8:45 a.m.	*03 - Project # NT05054* - Combustion Dynamics in Multi-Nozzle Combustors Operating on High-Hydrogen Fuels – *Domenic A. Santavicca*, **Pennsylvania State University – OSP**
8:45 - 9:15 a.m.	Q&A
9:15 - 9:55 a.m.	Discussion, evaluation, and written comments
9:55 - 10:10 a.m.	**BREAK - FOYER D**

FY10 Advanced Turbines Peer Review

Waterfront Place Hotel, Morgantown, WV

April 26-30, 2010

Tuesday, April 27, 2010 - Salon D

10:10 - 11:10 a.m.	*04 - Project # FWP-FEAA-070* - Materials Issues in Coal-Derived Synthesis Gas/Hydrogen-Fired Turbines – *Bruce Pint*, **Oak Ridge National Laboratory (ORNL)**
11:10 - 11:50 a.m.	Q&A
11:50 - 12:30 p.m.	Discussion, evaluation, and written comments
12:30 - 1:30 p.m.	**Lunch (on your own)**
1:30 - 2:15 p.m.	*05 - Project # NT06552* - Degradation of Thermal Barrier Coatings From Deposits; and, Its Mitigation – *Nitin P. Padture*, **Ohio State University Research Foundation**
2:15 - 2:45 p.m.	Q&A
2:45 - 3:25 p.m.	Discussion, evaluation, and written comments
3:25 - 3:40 p.m.	**BREAK - Foyer D**
3:40 - 4:25 p.m.	*06 - Project # NT00752* - An Experimental and Chemical Kinetics Study of the Combustion of Syngas and High Hydrogen Content Fuels – *Robert J. Santoro*, **Pennsylvania State University – OSP**
4:25 - 4:55 p.m.	Q&A
4:55 - 5:35 p.m.	Discussion, evaluation, and written comments

Wednesday, April 28, 2010 - Salon D

7:00 - 8:00 a.m.	Registration - **Foyer D**
8:00 - 9:00 a.m.	*07 - Project # FY10.MSE.1610243.682; FY10.MSE.1610243.683* - Performance of Materials for Oxy-Fuel Turbines – *Gordon Holcomb and Jeffrey Hawk*, **National Energy Technology Laboratory (NETL)**
9:00 - 9:40 a.m.	Q&A
9:40 - 10:20 a.m.	Discussion, evaluation, and written comments
10:20 - 10:35 a.m.	**BREAK - Foyer D**
10:35 - 11:35 a.m.	*08 - Project # FWP-678403* - Low-Swirl Injectors for Hydrogen Gas Turbines in FutureGen Power Plants – *Robert K. Cheng*, **Lawrence Berkeley National Laboratory (LBNL)**
11:35 - 12:15 p.m.	Q&A
12:15 - 12:55 p.m.	Discussion, evaluation, and written comments
12:55 - 1:55 p.m.	**Lunch (on your own)**
1:55 - 2:55 p.m.	*09 - Project # FWP-AL05205018* - Analysis of Gas Turbine Thermal Performance – *Tom Shih*, **Ames National Laboratory (AMES)**
2:55 - 3:35 p.m.	Q&A
3:35 - 4:15 p.m.	Discussion, evaluation, and written comments

FY10 Advanced Turbines Peer Review

Waterfront Place Hotel, Morgantown, WV

April 26-30, 2010

U.S. Department of Energy - Office of Fossil Energy - National Energy Technology Laboratory

Wednesday, April 28, 2010 - Salon D

4:15 - 4:30 p.m.	**BREAK - Foyer D**
4:30 - 5:30 p.m.	*10 - Project # FY10.ESD.1610243.623* - Aerothermal and Fundamental H_2 Studies and CO_2 Recycle Effects – *Peter Strakey and Douglas Straub*, **National Energy Technology Laboratory (NETL)**
5:30 - 6:10 p.m.	Q&A
6:10 - 6:50 p.m.	Discussion, evaluation, and written comments

Thursday, April 29, 2010 - Salon D

7:00 - 8:00 a.m.	Registration - **Foyer D**
8:00 - 8:45 a.m.	*11 - Project # NT05055* - Designing Turbine Endwalls for Deposition Resistance with 1400-C Combustor Exit Temperatures and Syngas Water Vapor Levels – *Jeffrey P. Bons*, **Ohio State University - Department of Aerospace Engineering**
8:45 - 9:15 a.m.	Q&A
9:15 - 9:55 a.m.	Discussion, evaluation, and written comments
9:55 - 10:10 a.m.	**BREAK - Foyer D**
10:10 - 11:10 a.m.	*12 - Project # NT41817* - Carbon Capture Approaches for NGCC Systems – *Walter Shelton*, **National Energy Technology Laboratory (NETL)**
11:10 - 11:50 a.m.	Q&A
11:50 - 12:30 p.m.	Discussion, evaluation, and written comments
12:30 - 1:30 p.m.	**Lunch (on your own)**
1:30 - 3:00 p.m.	*13 - Project # NT42645* - Coal-Based Oxy-Fuel System Evaluation and Combustor Development – *Ronald W. Bischoff*, **Clean Energy Systems, Inc.**
3:00 - 3:40 p.m.	Q&A
3:40 - 4:20 p.m.	Discussion, evaluation, and written comments
4:20 - 4:35 p.m.	**BREAK - Foyer D**
4:35 - 5:20 p.m.	*14 - Project # NT06833* - Condition Based Monitoring of Turbine Combustion Components – *Getnet Kidane*, **Siemens Energy, Inc.**
5:20 - 5:50 p.m.	Q&A
5:50 - 6:30 p.m.	Discussion, evaluation, and written comments

Friday, April 30, 2010 - Salon D

7:00 - 8:00 a.m.	Registration - **Foyer D**

FY10 Advanced Turbines Peer Review

Waterfront Place Hotel, Morgantown, WV

April 26-30, 2010

Friday, April 30, 2010 - Salon D

8:00 - 9:30 a.m.	*15 - Project # NT42646* - Zero Emissions Coal Syngas-Oxygen Turbo Machinery – *Dennis Horazak*, **Siemens Energy, Inc.**
9:30 - 10:10 a.m.	Q&A
10:10 - 10:50 a.m.	Discussion, evaluation, and written comments
10:50 - 11:05 a.m.	**BREAK** - **Foyer D**
11:05 - 1:05 p.m.	Overall meeting Wrap-up 10 minutes/Reviewers x 8

APPENDIX C: PEER REVIEW PANEL MEMBERS

After reviewing the scientific areas and issues addressed by the 15 projects to be reviewed, the Center for Research and Technology Development (CRTD) staff and the American Society of Mechanical Engineers (ASME) Peer Review Executive Committee, in cooperation with the NETL project manager, identified the following areas of expertise as the required skill sets of the FY 2010 Advanced Turbines Peer Review Panel:

- Hydrogen Turbines
- Conventional Turbine Design
- Coal Syngas and Higher Hydrocarbon Fuel
- Integrated Gasification Combined Cycle and Natural gas Combined Cycle Plants
- Low-Emission Power Generation Systems
- Design Enhancements to Increase Turbine Efficiency
- Capital Cost Analysis
- High-Temperature/High-Pressure Environments
- Novel Cooling Concepts for Turbines and Blades
- Materials and Thermal Barrier Coatings
- Sensors/Diagnostics/Controls
- Modeling and Simulations/Computational Fluid Dynamics
- Component Development and Testing
- Turbine/Compressor Aerodynamics
- Demonstration and Field Testing
- Injector/Combustion Design
- Design and Analysis Tool Development and Application
- Commercialization of Materials, Components, or Techniques
- Recycled Carbon Dioxide (CO_2) or CO_2/Steam as a Working Fluid

These required reviewer skill sets were then put into a matrix format and potential Panel members were evaluated on whether their expertise matched the required skill sets. This matrix also ensures that all the necessary skill sets are covered by the Panel. The Panel selection process also helps to ensure that the Panel represents the distinct perspectives of both academia and industry.

Considering the areas of expertise listed above, the CRTD carefully reviewed the résumés of all those who had served on prior ASME Review Panels for DOE (acknowledging the benefit of their previous experience in this peer review process), a number of new submissions from DOE, and those resulting from a call to ASME members with relevant experience. It was determined that four individuals who had served on prior ASME Peer Review Panels were qualified to serve on the Advanced Turbines Peer Review Panel.

Appropriate résumés were then submitted to the Advanced Turbines Peer Review Executive Committee for review. The following eight members were selected for the FY 2010 Advanced Turbines Peer Review (* indicates a prior Panel member):

James Sorensen*, Sorensenergy, LLC—Panel Chair

Meherwan Boyce, The Boyce Consultancy Group, LLC

Klaus Brun, Southwest Research Institute

Paolo Chiesa, Politecnico di Milano

William H. Day*, Consultant

Douglas M. Todd*, Process Power Plants LLC,

Ting Wang*, University of New Orleans

Richard Wenglarz, Clemson University

Panel members reviewed pre-presentation materials prior to the meeting and spent five days at the meeting evaluating projects and providing comments. Panelists received an honorarium for their time as well as reimbursement of travel expenses. A brief summary of their qualifications follows.

FY 2010 Advanced Turbines Peer Review Panel Members

James C. Sorensen, Panel Chair

Mr. 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. Prior to founding Sorensenergy, LLC, he worked for Air Products & Chemicals, including positions 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. Mr. Sorensen was responsible for the sale of the ASU for the Tampa Electric Polk County IGCC facility, which included the first commercial application of the Air Products cycle for nitrogen integration of the ASU with the gas turbine. He was also involved with gas turbine integration associated with Air Products' ion transport membrane (ITM) Oxygen program. Prior responsibilities included project management of Air Products' baseload liquid natural gas projects, commercial management of synthetic natural gas production, and general management of the Membrane Systems department.

Mr. Sorensen's technical interests include IGCC, oxyfuel combustion, gas-to-liquids, and air separation and hydrogen/syngas technology. His programmatic interests include Electric Power Research Institute 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, technology and government sales and contracting, R&D program management, technology consulting and training, commercial contract development, and intellectual property.

Mr. Sorensen is the founding chairman of the Gasification Technologies Council, and is vice chairman of both the Council on Alternate Fuels and Energy Futures International. Mr. 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. He received a B.S. and an M.S. in chemical engineering from Caltech and Washington State University, respectively, and an M.B.A. from the Harvard Business School.

Meherwan Boyce, Ph.D.

Meherwan P. Boyce, Ph.D., P.E., C.Eng (UK), is the managing partner of The Boyce Consultancy Group, LLC. He is a fellow of ASME, the Institution of Mechanical Engineers, and the Institution of Diesel and Gas Turbine Engineers, and has 45 years of experience in the field of turbomachinery in both industry and academia. He has over 20 years of industrial experience as Chairman and CEO of Boyce Engineering International Inc., founder of Cogen Technologies Inc., and 5 years as a designer of compressors and turbines for various gas turbine manufacturers. Dr. Boyce's academic experience covers a 15-year period, which includes the position of professor of mechanical engineering at Texas A&M University and founder of the TurboMachinery Laboratories and the TurboMachinery Symposium, now in its thirtieth year. He is the author of several books, including the *Gas Turbine Engineering Handbook* (Elsevier) and *Cogeneration & Combined Cycle Power Plants* (ASME Press), and has contributed to several handbooks. Dr. Boyce is chair of the ASME PTC 55 Aircraft Gas Turbine Committee which writes the specifications for the testing of aircraft gas turbines. He is also a consultant to the aerospace, petrochemical, and utility industries on a global scale.

Dr. Boyce is past Chair of the Plant Engineering and Maintenance Division of ASME, Chair of the Electric Utilities Committee of ASME's International Gas Turbine Institute, and Chair of the ASME Conferences Committee. He was the pioneer of On-Line Condition Based Performance Monitoring and has developed models for various types of power plants and petrochemical complexes. His programs are being used around the world in power plants, offshore platforms, and petrochemical complexes. He is also a consultant for major airlines in the area of engine selection, noise, and emissions. In 2002, Dr. Boyce was chairman of two major conferences: the Advanced Gas Turbine and Condition Monitoring Conference sponsored by DOE and the Electric Power Research Institute, as well as the Gas Turbine Users Associations Conference.

Dr. Boyce received a B.S. in mechanical engineering from the South Dakota School of Mines and Technology in 1962, an M.S. in mechanical engineering from the State University of New York in 1964, and a Ph.D. in aerospace and mechanical engineering in 1969 from the University of Oklahoma.

Klaus Brun, Ph.D.

Dr. Klaus Brun currently manages the Rotating Machinery and the Flow Measurement groups at Southwest Research Institute. He has held positions in business development, project management, sales, marketing, and management, and has worked on a wide range of gas turbine project applications, including combined cycle power plants, pipeline compression stations, offshore compression, gas gathering, water-flood, enhanced oil recovery nitrogen injection, gas lift, liquid natural gas plants, gas re-injection, methanol production plants, gas storage, integrated gasification combined cycles (IGCC), steel mill off-gas power generation, and volatile organic compounds destruction.

Dr. Brun's doctoral thesis focused on internal flow measurements and computational fluid dynamics in mixed flow rotating machinery. In addition to his graduate work, he has been involved in research on automotive torque converters, rotating compressible flows (emphasis on jet/wake and secondary flows), bearing design (both fluid and magnetic), labyrinth seals, instrumentation and data acquisition, laser velocimetry, flow interferometry, complex geometry convection flows, advanced gas turbine cycles, and air emissions technology.

Dr. Brun's research interests are in the areas of turbomachinery aero-thermal fluid dynamics, process system analysis, energy management, advanced thermodynamic cycles, instrumentation and measurement, and combustion technology. He is widely experienced in performance prediction, off-design function, degradation, uncertainty diagnostics, and root cause failure analysis of gas turbines, combined cycle plants, IGCC centrifugal compressors, steam turbines, and pumps.

Dr. Brun is the inventor of the Single Wheel Radial Flow Gas Turbine*,* the Semi-Active Plate Valve*,* and co-inventor of the Planetary Gear Mounted Auxiliary Power Turbine. He has authored over 50 papers on turbomachinery and related topics, given numerous invited technical lectures and tutorials, and published a textbook on gas turbine theory. Dr. Brun won the ASME-IGTI Oil and Gas Application Committee Best Paper awards in 1998, 2000, and 2005 for his work on gas turbine testing and degradation. He is the Chair of the ASME-IGTI Oil and Gas Applications Committee, a member of the API 616 Task Force, a member of the Gas Turbine Users Symposium Advisory Committee, and a past member of the Electric Power and Coal-Gen Steering Committees.

Dr. Brun is a member of ASME, the Gas Machinery Research Council, Sigma Xi (Research Society), and the American Petroleum Institute. He has a B.S. in aerospace engineering from the University of Florida and an M.S. and Ph.D. in mechanical and aerospace engineering from the University of Virginia.

Paolo Chiesa, Ph.D.

Dr. Paolo Chiesa is the current director of the Technologies for Fossil Fuel Utilization and CO_2 Capture at the Laboratory for Energy and the Environment Piacenza (LEAP) of the Politecnico di Milano. He is an associate professor of energy and environmental systems at the Politecnico di Milano School of Industrial Engineering, where he has taught for eight years after spending three years as assistant professor of fluid mechanics. Dr. Chiesa was also a visiting researcher at the Princeton Environmental Institute, Princeton University in 2001.

Dr. Chiesa is the current Italian delegate in the Management Committee of the European Cooperation in Science and Technology. He is also the associated editor for the ASME Journal of Engineering for Gas Turbines and Power, and has reviewed technical papers for the *Energy—The International Journal*, *Chemical Engineering Communications*, the *International Journal of Hydrogen Energy*, the *International Journal of Greenhouse Gas Control*, *Advances in Environmental Research*, the *Journal of Solar Energy Engineering*, and *Applied Energy*.

Dr. Paolo's doctoral thesis focused on humid air gas turbine cycle fueled with natural gas or integrated with coal gasification processes. He obtained his Ph.D. in 1995 from the Politecnico di Milano. He was also awarded a 2-year post-doctoral fellowship by the Italian government for research on fossil-fuel-fired power plants with low CO_2 emissions. His thesis for a degree in mechanical engineering received in 1990 at the Politecnico di Milano focused on natural-gas-fired combined cycles for electric power generation.

William H. Day, Ph.D.

Dr. William H. Day is a consultant, whose recent work includes the South Carolina Institute for Energy Studies, as well as the Integrated Gasification Combined Cycle (IGCC) efforts for the U.S. Department of Energy. Prior to this, he spent 23 years at United Technologies (UTC) where he was a Pratt and Whitney (P&W) Fellow and manager of Advanced Industrial Programs. In 1985, Dr. Day transferred to UTC's Turbo Power & Marine Systems and became the director of Industrial Gas Turbine Programs. He recommended the development of a JT8D aeroderivative engine (which became the FT8), led the FT8 program planning effort, was the principal negotiator for UTC with the Chinese government and Chengdu engine company, and successfully negotiated a $150 million contract with the Chinese government for the FT8. He then became the director of Engineering and New Product Development, and led the development of the FT8 and the FT8-2, which incorporated a dry low NO_x combustor with dual fuel capability. Dr. Day also was the principal negotiator of the contract with Siemens to improve its V84 frame-type gas turbines with P&W technology and package and sell its current engines, led the joint program with Siemens, led the development of the packaging of the V84.2 and V64.3, and led the design and development of the turbomachinery flowpath and airfoils for the V84.3A. Additionally, he led the preliminary design and development planning of the FT4000 simple and intercooled cycles.

Before joining UTC, Dr. Day was Manager of Advanced Program Management and Product Planning for General Electric. In his 19 years at GE, Dr. Day's work included successfully proposing and then running the first Electric Power Research Institute and DOE industrial gas turbine development program; winning a four-way competition for a $32 million DOE High Temperature Turbine Technology Program and then managing the program; and managing development of IGCC systems.

In 1995, Dr. Day founded the Gas Turbine Association in Washington, DC that successfully lobbied Congress to retain the Advanced Turbine Systems Program and to establish the Next Generation Gas Turbine Program. Dr. Day has four patents and has published over 60 technical papers. He received a B.S. in mechanical engineering from Cornell University, and earned his M.S. and Ph.D. from the Polytechnic Institute of Brooklyn.

Douglas M. Todd
Mr. Todd is the owner and President of Process Power Plants LLC, a consulting company dedicated to integrating gas turbine combined cycles with gasification systems (IGCC) to provide extremely clean, economical electric power and other useful products from low-cost fuels. Mr. Todd's experience includes 35 years with General Electric (GE) in engineering, marketing, and product management positions, culminating with business management responsibility for GE's Process Power Plants Organization. He was responsible for developing and introducing combined cycle and IGCC power plant technology on a worldwide basis, including setting up an in-country Gas Turbine Manufacturing Agreement with China. Gas turbine technology development combined with technology partnerships led to worldwide acceptance of IGCC with 22 IGCC plants announced, totaling 6,000 MW. Mr. Todd was involved directly with 16 IGCC projects with eight different gasification technologies.

Mr. Todd received the first European Institution of Chemical Engineers Medal for Excellence in Gasification in 2002 and the Gasification Technologies Council Lifetime Achievement Award in 2003. He is a member of the American Institute of Chemical Engineers and has published numerous technical papers for various entities including ASME and the Electric Power Research Institute. Mr. Todd received a B.S. in chemical engineering from Worcester Polytechnic Institute.

Ting Wang, Ph.D.

Dr. Wang is the Jack and Reba Matthey Endowed Chair for Energy Research and the director of the Energy Conversion and Conservation Center at the University of New Orleans. Dr. Wang has been involved in energy conservation and power generation for the past 29 years. He is an experimentalist with significant computational fluid dynamics experience. In the area of power generation, his specialties lie in gas turbine power generation with applications in combined power generation, co-generation, integrated gasification combined cycles, mild gasification, distributed generation, and micro-turbine applications. He has conducted both fundamental and applied research with funding from U.S. government agencies and industry.

Dr. Wang has published over 200 research papers and reports. Dr. Wang is a Fellow of ASME and was the recipient of the ASME George Westinghouse Silver Medal for his contributions to the power industry. He is a member of the ASME Gas Turbine Heat Transfer Committee and the Chair of the Coal, Biomass, and Alternative Fuels Committee, both of which are committees of the ASME International Gas Turbine Institute. He was appointed by former Louisiana Governor Murphy J. (Mike) Foster, Jr., to serve as a member of the Comprehensive Energy Policy Advisory Commission. Dr. Wang received an M.S. from the State University of New York at Buffalo and a Ph.D. from the University of Minnesota.

Richard Wenglarz, Ph.D.

Richard Wenglarz received B.S. and M.S degrees from the University of Illinois, and a Ph.D. degree from Stanford University, all in engineering mechanics. He has held positions at the University of Newcastle Upon Tyne, Bellcomm, Bell Laboratories, Westinghouse R&D Center, Rolls Royce/Allison Division of General Motors, and the South Carolina Institute for Energy Studies (SCIES) at Clemson University.

His early experience involved dynamics and control for gyroscopic systems and manned space stations. Later experience concerned developing and applying analytical and experimental methods to evaluate deposition, erosion, and corrosion in advanced energy systems (e.g., gas turbines and fuel cells) operating with alternate fuels. Currently, Dr. Wenglarz is manager of research at SCIES for the DOE-sponsored University Turbine Systems Research program, which supports university gas turbine research nationwide.

Dr. Wenglarz has over 80 publications and presentations, including invited presentations at the Von Karman Institute for Fluid Dynamics, Yale University, UK Central Electricity Research Laboratories, Cambridge University, and the Kentucky Energy Cabinet Laboratories.

APPENDIX D: PEER REVIEW CRITERIA FORM

PEER REVIEW CRITERIA FORM

U. S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY
FY10 ADVANCED TURBINES PEER REVIEW

April 26 – 30, 2010

Project Title:	
Performer:	
Presenter:	
Name of Peer Reviewer:	
Date of Review:	

The following pages contain the criteria used to evaluate each project. The criteria have been grouped into three (3) major categories: (1) **Approach and Progress**; (2) **Project Merit**; and (3) **Deployment Considerations**. Additionally, each criterion is accompanied by multiple characteristics to further define the topic.

The Reviewer is expected to provide a **rating** and **substantive comments** which support that rating for each criterion. Please note that if a rating of ***"Results Not Demonstrated"*** is selected, **justifying comments must be included**. To assist with determining the criterion rating, adjectival descriptions of those ratings are provided below.

RATING CRITERIA DEFINITIONS	
Effective	**Effective** projects set ambitious goals, achieve results, are well-managed and enhance the likelihood of meeting program goals and objectives.
Moderately Effective	In general, a project rated **Moderately Effective** has set ambitious goals and is well-managed, and is achieving results. Better results could be realized by focusing on key technical issues, more efficient use of resources, and improvements in overall management.
Adequate	**Adequate** describes a project that needs to set more ambitious goals, achieve better results, improve accountability or strengthen its management practices.
Ineffective	**Ineffective** projects are unable to achieve results due to a lack of clarity regarding the project's purpose or goals, poor management, or some other significant weakness (e.g., technical problem).
Results Not Demonstrated	**Results Not Demonstrated** indicates that a project has not been able to develop acceptable performance goals or collect data to determine whether it is performing.

Page 1 of 5

PEER REVIEW RATING CRITERIA

Please evaluate the project against each of the 9 criterion listed below. Definitions for these 9 criteria are provided on page 4. For each criterion, select the appropriate rating by typing an "X" in the applicable cell. Definitions for the five ratings criteria are provided on page 1.

NOTE: If you rate any criterion as "Results Not Demonstrated," a justification for this rating is required. Please include your justification in the box at the end of this table.

CRITERION		RATING CRITERIA				
(Criterion Definitions, refer to Page 4)		(Rating Criteria Definitions, refer to Page 1)				
		Effective	Moderately Effective	Adequate	Ineffective	Results Not Demonstrated*
PROJECT OVERVIEW						
1	**Scientific and Technical Merit**					
2	**Existence of Clear, Measurable Milestones**					
3	**Utilization of Government Resources**					
TECHNICAL DISCUSSION						
4	**Technical Approach**					
5	**Rate of Progress**					
6	**Potential Technology Risks Considered**					
7	**Performance and Economic Factors**					
TECHNOLOGY BENEFITS						
8	**Anticipated Benefits, if Successful**					
9	**Technology Development Pathways**					
*Please explain why the project was rated "Results Not Demonstrated" for a particular criterion.						

Page 2 of 5

COMMENTS

Please provide your comments for each of the areas in the blocks below. Please substantiate your comments (i.e., facts on why you are making the statement). General statements without explanation (e.g., great project) are not sufficient. Please avoid any use of clichés, colloquialisms or slang.

Strengths:
Weaknesses:
Recommendations:
Action Items:
General Comments:

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CRITERION DEFINITIONS

PROJECT OVERVIEW

1: Scientific and Technical Merit
- The underlying project concept is scientifically sound.
- Substantial progress or even a breakthrough is possible.
- A high degree of innovation is evident.

2: Existence of Clear, Measurable Milestones
- At least two measureable milestones per budget period exist.
- Milestones are quantitative and clearly show progression towards project goals.
- Each milestone has a title, planned completion date and a description of the method/process/measure used to verify completion.

3: Utilization of Government Resources
- Research team is adequate to address project goal and objectives.
- Sound rationale presented for teaming or collaborative efforts.
- Equipment, materials, and facilities are adequate to meet goals.

TECHNICAL DISCUSSION

4: Technical Approach
- Technical approach is sound and supports stated project goal and objectives.
- A thorough understanding of potential technical challenges and technical barriers is evident.

5: Rate of Progress
- Progress to date against stated project goal, objectives, milestones, and schedule is reasonable.
- Continued progress against possible technical barriers is likely.
- There is a high likelihood project goal, objectives, and expected outcomes and benefits will be achieved.
- The budget is on track to achieve project goal and objectives.

6: Potential Technology Risks Considered
- Potential risks to the environment or public associated with widespread technology deployment have been considered.
- Project risks are identified and effective measures to address and mitigate these risks, including potential technical uncertainties and barriers, are presented.
- Scientific risks are within reasonable limits.

7: Performance and Economic Factors *
- Appropriate technology cost and performance assessments are conducted consistent with the level of technology development.
- Implementation cost estimates, if warranted, are sensible given uncertainties.
- There is a high likelihood of meeting ultimate DOE cost and performance goals.

TECHNOLOGY BENEFITS

8: Anticipated Benefits, if Successful
- There exist clear statements of potential benefits if research is successful.
- Technologies being developed can benefit other programs.
- Project will make a significant contribution towards meeting near- and long-term program cost and performance goals.

9: Technology Development Pathways *
- Researchers know and can describe a "real world" application and adequately discuss requirements (additional research, potential partners, and resources) for the next level of technology development.
- Market analyses, if appropriate, indicate the technology being developed is likely to be implemented if research is successful.
- Potential barriers to commercialization have been identified and addressed, if appropriate.

* Additional details to be considered for Criterion 7 (Performance and Economic Factors) and 9 (Technology Development Pathways) for specific Technology Development Stages are described on the next page.

Page 4 of 5

TECHNOLOGY DEVELOPMENT STAGES FOR ECONOMIC ANALYSIS & TECHNOLOGY DEVELOPMENT PATH

In past Peer Reviews, Peer Review Panelists have had difficulty scoring the "Economic Analysis" and "Technology Development Path" criterions, because the rating criteria were not specific to the stage of technology development. Research, Development, and Demonstration projects can be categorized based on the level of technology maturity. Listed below are five (5) technology development categories of RD&D projects managed by the National Energy Technology Laboratory. These technology maturation categories are often termed "stages," which provide a basis for establishing a rational and structured approach to decision-making and identifying performance criteria that must be met before proceeding to a subsequent stage of development.

Fundamental Research—Explores and defines technical concepts or fundamental scientific knowledge; laboratory-scale; traditionally but not exclusively the province of academia.

Applied Research—Laboratory- or bench-scale proof of the feasibility of multiple potential applications of a given fundamental scientific discovery.

Prototype Testing—Prototype technology development and testing, either in the laboratory or field; predictive modeling or simulation of performance; evaluation of scalability.

Proof-of-Concept—Pilot-scale development and testing of technology or process; field testing and validation of technology at full-scale, but in a manner that is not designed or intended to represent a long-term commercial installation.

Major Demonstration—Commercial-scale demonstration of energy and energy-related environmental technologies; generally a first-of-a-kind representation of a long-term commercial installation.

Table 1 describes economic analysis and technology development sub-criteria for each of the five technology development stages. These sub-criteria are examples of the types of information that is typically determined in technology research and development projects.

Please note that the Economic Analysis and Technology Development Path are examples of the types of information that should be provided for the projects being reviewed. Projects are not expected to address all sub-criteria for a given Technology Development Stage, but should address at least one of them.

Table 1. Economic Analysis and Technology Development Sub-Criteria

Technology Development Stage	Economics Analysis Sub-Criteria	Technology Development Path Sub-Criteria
Fundamental Research	• Material costs available • Potential cost benefits over conventional systems identified	• Scientific feasibility proven • Application(s) considered • Potential technology developers identified
Applied Research	• Component or sub-system costs estimated • First-order cost-benefit analysis available • Material and energy balances calculated	• Conceptual process proposed • Potential applications well defined • Process feasibility established
Prototype Testing	• Conceptual process costs developed • Market analysis completed • Risk assessment completed	• Process test data available • Engineering scale-up data developed • Optimum operating conditions identified
Proof-of-Concept	• Process contingency costs identified • Full-scale process costs, including O&M calculated • Full-scale installation costs developed	• Major technology components thoroughly tested and evaluated • Technology demonstration plans firmly established • Major component optimization studies performed
Major Demonstration	• Installation costs determined	• Business and commercialization plans developed

APPENDIX E: ADVANCED TURBINES PROJECT SUMMARIES

Presentation ID Number	Project Number	Title
01	DE-FC26-05NT42644	Advanced Hydrogen Turbine Development Program
02	DE-FC26-05NT42643	Advanced IGCC/Hydrogen Gas Turbine Development
03	DE-FC26-08NT0005054	Combustion Dynamics in Multi-Nozzle Combustors Operating on High-Hydrogen Fuels
04	FWP-FEAA-070	Materials Issues in Coal-Derived Synthesis Gas/Hydrogen-Fired Turbines
05	DE-NT0006552	Degradation of Thermal Barrier Coatings From Deposits; and, Its Mitigation
06	DE-NT0000752	An Experimental and Chemical Kinetics Study of the Combustion of Syngas and High-Hydrogen-Content Fuels
07	FY10.MSE.1610243.682; FY10.MSE.1610243.683	Performance of Materials for Oxyfuel Turbines
08	FWP-678403	Low-Swirl Injectors for Hydrogen Gas Turbines in FutureGen Power Plants
09	FWP-AL05205018	Analysis of Gas Turbine Thermal Performance
10	FY10.ESD.1610243.623	Aerothermal and Fundamental H_2 Studies and CO_2 Recycle Effects
11	DE-FC26-08NT0005055	Designing Turbine Endwalls for Deposition Resistance with 1400°C Combustor Exit Temperatures and Syngas Water Vapor Levels
12	DE-AC26-04NT141817	Carbon Capture Approaches for NGCC Systems
13	DE-FC26-05NT42645	Coal-Based Oxyfuel System Evaluation and Combustor Development
14	DE-NT0006833	Condition Based Monitoring of Turbine Combustion Components
15	DE-FC26-05NT42646	Zero Emissions Coal Syngas-Oxygen Turbo Machinery

01: DE-FC26-05NT42644

Project Number FC26-05NT42644	Project Title Advanced Hydrogen Turbine Development Program			
Contacts DOE/NETL Project Mgr.	**Name** Robin Ames	**Organization** NETL – Power Systems Division	**Email** Robin.Ames@netl.doe.gov	
Principal Investigator	Joseph Fadok	Siemens Energy Inc.	joseph.fadok@siemens.com	
Partners	Agilis Engineering Contractors; ASE Quest; BASF Catalysts LLC; Causey Machining; CDI Engineering Consultants; COIC; Cranfield University; Creative Power Solutions (CPS); CTL (Cincinnati Testing Laboratories, Inc.); DLR; Enel ; Engineous Software; EERC; Florida Institute of Technology; Florida Turbine Technologies; Georgia Tech; Guild Associates; ILT; Integrated Energy Technologies; Joliet Metallurgical Lab; Mastersons Machining Corp; MECO; Metcut Research Inc; Mikro Systems; NASA; Optical Support Inc.; Parker Hannifin Corporation; PCC Airfoils Inc; Praxair Inc.; Princeton University; Purdue University; Sulzer Innotec; Sulzer Metco; TAFA Inc. & Praxair Surface Tech. Inc.; Texas A&M University; Thors Lab; TRANS-TECH INC; University of Central Florida; University of Cincinnati; University of Florida; UT-Battelle LLC; Virginia Tech			
Stage of Development				
__ Fundamental	__ Applied R&D	__ Proof of Concept	X Prototype Testing	__ Demonstration

Technical Background:

This project seeks to improve combined cycle efficiency by 3–5 percentage points over the current state of the art, and contributes directly to the NETL Advanced Turbines Program goals of improving integrated gasification combined cycle (IGCC) plants to 45%–50% Higher Heating Value (HHV) efficiency. To achieve higher engine and plant efficiencies and move toward meeting DOE program goals, gas turbine engine operating conditions must be upgraded and new, enhanced technologies must be developed and implemented. Studies conducted early in the project confirmed the primary drivers of combined cycle efficiency to be gas turbine firing temperature, pressure ratio, and turbine exit temperature; therefore, the basis of this research is the development of technologies that are necessary to improve these turbine operating conditions using synthesis gas (syngas) and hydrogen fuel, while maintaining low gas turbine emissions. The advanced technologies being developed are comprehensive, including improved compressor aerodynamics; low-(nitrous oxide) NO_x syngas- and hydrogen-capable combustion system, novel turbine-cooling and aerodynamic improvements; novel manufacturing techniques; improved materials and coatings; and advanced sensors/diagnostics. These technologies are built upon Siemens extensive experience in high-temperature, G-Class engines and successful operating experience with syngas fuels in IGCC applications. The targeted efficiency improvements and significant increase in power island output will also lead to cost reduction on a dollars/kilowatt (KW) basis.

COMPRESSOR

Based on the selected engine design point, preliminary studies were carried out on an advanced compressor design to provide the required stage number and flow-path geometry. A range of pressure ratios was also investigated and the implication on stage count was assessed. Both 2D and 3D analyses of the preferred concepts are being completed.

COMBUSTION SYSTEM

A key component in developing a successful, fuel-flexible hydrogen turbine is the combustion system. Several competing combustion concepts, such as diffusion, premixed, and catalytic flames, were investigated in order to achieve the very challenging program emission goal at the elevated firing temperature and pressure ratio. Of four competing technologies, two were downselected at the end of Phase 1. The candidate combustion systems are being developed through component modeling studies specifically for syngas and hydrogen application; subscale test programs to evaluate critical combustion and operational issues; and validation testing. University partners are validating prediction methods for flame speed and ignition delay with hydrogen and syngas fuels.

TURBINE

Advanced turbine aerodynamic and cooling concepts are being evaluated and developed to produce a turbine design with the lowest possible cooling requirements, excellent mechanical integrity, and high efficiency. To achieve these goals the following elements are being incorporated into the turbine design: novel aerodynamic design concepts; highly effective cooling schemes; high-temperature, low-conductivity, thermal barrier coating (TBC) systems; and advanced alloy castings. Models of selected cooling configurations are being verified through subscale testing at universities.

MATERIALS AND COATINGS

Advanced or novel materials and coatings are critical to successful systems development and the development of advanced engine components. The project identifies material property requirements for each hydrogen-turbine component as well as potential materials technologies that could meet these requirements. Continuous efforts have been made to improve materials' oxidation resistance and mechanical properties by alloying elements' addition and oxide dispersion. A design of experiment process was employed to select optimum elements for bond coat enhancement. Fabricated and modular airfoil concepts are being developed to optimize the utilization of next-generation alloys and/or currently unavailable yields, and to provide a means for selecting and coupling intra-component substrate materials in order to achieve optimized material properties.

SENSORS AND DIAGNOSTICS

Advanced sensors and diagnostics technologies will be implemented to support hydrogen turbine development. Incorporating these technologies will allow thermal, environmental, performance, and mechanical optimization of advanced turbines operating on syngas and hydrogen fuels. The sensors and the associated diagnostic functions will mitigate risks associated with the advanced components being developed, including fast-response fuel monitoring, fuel-controlling turbine-temperature monitoring, TBC monitoring, tip clearance control, engine health monitoring, and others.

Relationship to Program:

This project will support important advances in numerous areas associated with the hydrogen turbine focus of the NETL Advanced Turbines Program. The new technologies developed in this program have the potential to accelerate commercialization of advanced coal based IGCC plants in the United States and around the world, as the advanced IGCC plant is projected to use 40% less water and 50% less solid waste than today's conventional pulverized coal (PC) plants. Compared to sub-critical PC plants, the hydrogen turbine IGCC plant is expected to reduce sulfur dioxide (SO_2) emissions by 2,080 metric tons per year, NO_x emissions by 1,030 tons per year, carbon monoxide (CO) by 3,200 tons per year, and particulates by 400 tons per year.

Carbon capture and sequestration (CCS) will also be incorporated into the plant design. Recently proposed legislation requires carbon emissions regulation; therefore, incorporating CCS into this design directly supports national priorities.

Technologies developed within this program can be integrated into other current Siemens Energy gas turbine designs. This includes new manufacturing techniques, higher material limits, increased firing temperatures, increased gas turbine efficiency, and lower emissions.

Additional collateral benefits include the creation of high-quality jobs in the United States, energy self-sufficiency through large coal deposits, increased exports, and hydrogen (H_2) co-production for transportation.

Primary Project Goal:

The primary goals of this project are to develop and validate gas turbine technologies to improve combined cycle (CC) plant efficiency by 3–5 percentage points above current state-of-the-art systems operating in IGCC type plants; to reduce CC plant cost by 20%–30% when compared to the baseline; and to reduce NO_x emissions to meet the 2 parts per million (ppm) program target.

Objectives:

This project has been implemented in two phases: Phase I–Conceptual Design and R&D Implementation Plan: Concept to Commercial Deployment; and Phase II–Basic Design and Validation Test Program. Phase 1 is complete and Phase 2 is approximately 50% complete. Listed below is a statement of the overall project objectives for Phases 1 and 2.

PHASE I–CONCEPTUAL DESIGN AND R&D IMPLEMENTATION PLAN: CONCEPT TO COMMERCIAL DEPLOYMENT

- Develop an R&D Implementation Plan that defines, in detail, the approach, options, cost, risk, schedule, and deliverables associated with the R&D required to meet DOE goals and objectives.
- Develop a conceptual design of the turbine that meets program goals.
- Produce power-system-level performance models/simulations to show that these conceptual turbine designs deployed in likely IGCC applications will achieve DOE objectives, and conduct the necessary R&D needed to focus or direct Phase II work.
- Conduct necessary materials, combustion, and turbine-cooling feature tests to establish the feasibility of identified concepts and downselect the most promising concepts for further development in Phase II.

PHASE II–BASIC DESIGN AND VALIDATION TEST PROGRAM

- Develop component and systems designs needed to meet project objectives.
- Develop validation test plans for technologies, systems, and components.
- Perform validation testing of systems and components to demonstrate the ability to attain the Advanced Turbines Program performance goal.
- Integrate technologies and subsystems with commercial IGCC applications and natural-gas-fired engines, where applicable.

Several universities and small businesses are supporting development testing, validation, and modeling in key areas such as combustion kinetics, turbine-cooling technology development, aerodynamics, and advanced alloy materials development.

SPECIFIC PROGRAM GOALS FOR 2010, 2012, AND 2015

2010 — By the end of fiscal year (FY) 2010, Siemens Energy, Inc. will demonstrate the following through system studies and laboratory scale testing: the technology readiness to increase overall IGCC efficiency by 2–3 percentage points over the baseline; a 20%–30% reduction in combined cycle capital cost; and 2 ppm NO_x emissions using syngas as a fuel.

In order to meet the 2%–3% combined cycle efficiency increase, each subsystem has been tasked with increasing performance. An advanced combustion system is being developed that is capable of low NO_x emissions and a higher firing temperature, where rig tests have already shown a premix combustor capable of operating on 100% syngas at above G- and H-Class turbine temperatures. Materials development is pursuing coatings that will increase temperature capability and reduce thermal conductivity when compared to the baseline coating. Testing has already shown a 40% increase in spallation life over the baseline as well as an ability to raise the allowable operating temperature for the thermal barrier coating. These significant advances can be adapted to near-term applications.

The turbine section has been analyzed for operation at the intermediate temperature that is targeted to meet the 2010 efficiency goal, while plant system-performance studies have been completed to establish baseline, 2010, and 2015 syngas and high hydrogen cases. The 2010 engine enhancements exceed the program goal, indicating a 3.5% increase in combined cycle efficiency over the baseline for syngas fuel in the 2010 timeframe. To maximize overall plant performance and provide robustness to operational variations, a novel selective catalytic reduction (SCR) system is also being developed to meet the emissions goals. Accelerated tests of commercial-sized samples have been performed in relevant exhaust conditions, showing excellent NO_x-removal efficiency in oxygen and water-rich conditions. Cost analysis has indicated that a significant increase in power is necessary to achieve a 20%–30% cost reduction. This power increase, in addition to a reduction in overall power block cost, is the target.

2012 — The 2012 goal will include verification of the advanced hydrogen turbine technologies with carbon capture incorporated. The target operation will be at 90% carbon capture, which studies have shown to cause an 8%–10% reduction in efficiency when pre-combustion carbon capture is added. Consequently, additional technological advancements to the gas turbine are needed in order to recover a large portion of these losses.

2015 — By 2015, a 3%–5% increase in IGCC efficiency is targeted. This engine is expected to operate on high-hydrogen fuel, achieving 2 ppm NO_x emissions from the stack. Plant system-performance studies have shown that the performance potential of the technologies being pursued can meet the project goals.

Extensive laboratory data has been obtained through university research to enhance prediction tools and methods, which will be used to design advanced premix combustion systems that will operate on high-hydrogen fuel. Full-scale testing in combustion rigs will continue toward validating the low NO_x emissions and high firing temperature; material developments have progressed as planned, meeting intermediate goals in temperature limits and lifetime. Novel manufacturing techniques; improved bond coats; high-temperature, low-conductivity thermal barrier coatings; and oxidation-resistant superalloys will be employed. Development of the turbine design is being informed by university testing of advanced airfoils and cooling designs, and new sealing configurations are being developed to reduce the required cooling flow, and improve the turbine's overall efficiency. In order to verify long-term durability and high NO_x removal efficiency, hydrogen-based SCR testing will continue.

02: DE-FC26-05NT42643

Project Number FC26-05NT42643	**Project Title** Advanced IGCC/Hydrogen Gas Turbine Development			
Contacts DOE/NETL Project Mgr.	**Name** Robin Ames	**Organization** NETL – Power Systems Division	**Email** Robin.Ames@netl.doe.gov	
Principal Investigator	Reed Anderson	GE Energy	reed.anderson@ge.com	
Partners	GE Aviation GE Global Research			
Stage of Development				
__Fundamental R&D	__ Applied R&D	X Prototype Testing	__Proof of Concept	__Demonstration

Technical Background:

Improvements in gas turbine technology are required to burn both synthesis gas (syngas) and high-hydrogen fuels cleaner and more efficiently. This project within the Advanced Turbines Program addresses key technology development needs that are required to achieve specific DOE performance goals relative to emissions, efficiency, and capital cost. The project consists of two phases. Phase I, which began in October 2005 and concluded in September 2007, was focused on conceptual design and preliminary technology development. The output of Phase I was a down-selection of the key technologies that are being further developed and validated at the component level in Phase II. The Phase II effort is anticipated to end in September 2012.

The project consists of three main technical focus areas (combustion, turbine/aero, and materials) and a systems-level activity. The systems-level approach translates the integration of technology improvements into plant performance, and investigates the various system trade-offs and their impacts on overall plant performance. The combustion element of the program is focused on improving combustion technology to achieve the DOE nitrogen oxide (NO_x) emissions target of 2 parts per million (ppm). This work addresses the challenges of developing a combustion system that is able to burn both syngas and high-hydrogen fuels to produce extremely low NO_x emissions, while also avoiding flameholding, flashback, and dynamics issues. The turbine/aero element of the program addresses specific turbine technology improvements to address the efficiency targets that have been identified by DOE (3%–5% improvement in combined cycle efficiency). The materials portion of the program focuses on applying materials technology that enables the turbine to operate reliably at higher firing temperatures in the integrated gasification combined cycle (IGCC) environment.

The following is a brief discussion of development activities in each of the program's technical focus areas; combustion, turbine, materials, and systems.

COMBUSTION

The combustion goal for the program is "reliable, ultra-low NO_x combustion of high-hydrogen fuels for advanced gas turbine cycles." Achieving this goal requires NO_x levels at the targeted high operating temperatures while also avoiding flashback, achieving a relatively low pressure drop, managing dynamics, and expanding fuel flexibility.

In Phase I, the project team mapped NO_x entitlement characteristics for the fuels of interest over the targeted temperature range and quantified the effects of the major NO_x drivers. Using a single-nozzle test rig and supporting analysis, testing and iterative improvements were performed on multiple concepts. Over 30 different concepts were also evaluated. Near NO_x entitlement emissions were achieved, and two of the advanced concepts were selected for continued development in Phase II of the program.

In Phase II, project focus shifted from single nozzles to a full can size with multiple nozzles. The 2010 DOE targets were achieved with low, single-digit NO_x emissions for operation on 100% premixed syngas at F-Class conditions. Later in Phase II, the DOE 2012 targets were achieved with single-digit NO_x emissions for operation on high-hydrogen fuel (60%–100% hydrogen [H_2] by volume) in excess of F-Class conditions. System pressure drop and dynamic responses were also favorable. A level of reliability and durability on H_2 fuel was also demonstrated, with over 50 hours of fired test time in 2009, including several instances of full-load operation for more than six hours. Promising performance was retained on syngas and natural gas fuels.

During the rest of Phase II, the main focus will be on expanding demonstrated performance at the full can level to the 2015 conditions; addressing requirements such as reliability, manufacturability, and durability; and further increasing the size of the demonstration tests.

TURBINES

Turbine development is focused on achieving increased efficiency and output through reduced chargeable and non-chargeable cooling flows, improved turbine mass flow, improved aerodynamic efficiency, and higher firing temperature.

Chargeable flow reductions are being achieved through technologies that enable reduced part cooling and reduced wheelspace flow. During Phase II, reductions in cooling flow requirements were achieved through advances in film cooling design on hot-gas path components. Additional cooling technology advancements will be pursued during the remainder of Phase II. Technologies to reduce flows in the wheelspace cavities are being developed through a combination of test rigs and analysis. Test results from a stationary cascade rig, with and without rotational effects, were used to calibrate computational models and identify improvements. A number of design advances were selected for further evaluation. Later in Phase II, a rotating test vehicle will be used to perform final evaluation and optimization of the design advances.

Non-chargeable flow reductions are being achieved by focusing on technology advancements for the interface between the combustor transition pieces and the first-stage turbine nozzles. A test rig was designed, fabricated, and utilized to evaluate sealing concepts. Design improvements were tested and refined, enabling the targeted flow reduction to be achieved. Several additional improvement areas will be evaluated and optimized during the remainder of Phase II.

Mass flow through the turbine is constrained by the last-stage annulus area. Increased bucket height and the resulting annulus area allow for increased mass flow, improved aerodynamics, and increased gas turbine output. The technology advancement of increased bucket height is being pursued by a combination of improved analytical methods and validation testing. A series of wheelbox tests has been performed to test last-stage buckets with simulated operational vibratory stimulus. Results have enabled improvements in the predictive capability of the analytical tools. Later in Phase II, the improved analytical tools will be used to design an optimized bucket concept that will be validated through wheelbox testing.

Turbine aerodynamic efficiencies have been tested in a specially designed, multi-stage, aerodynamic validation test rig. Detailed performance characterizations were conducted over a wide range of flow rates. Derivatives on tip clearance and purge flows were also obtained. Preliminary analysis of the test data supports the initially projected improvement potential. Subsequent testing will evaluate and validate advancements.

MATERIALS

The objective of the materials development portion of the program is to increase the temperature capability of the hot-gas path components while addressing some of the unique characteristics of an IGCC environment.

In Phase I, the IGCC environment was characterized through a combination of IGCC field hardware evaluation and actual syngas fuel sampling at a commercial IGCC plant. As a result, laboratory test conditions were created for use in Phase II that replicated actual operation in an IGCC environment.

Materials focus in Phase II is on thermal barrier coatings (TBCs), metallic coatings, and CMCs (ceramic matrix composites).

TBC development has focused on increased thermal resistance and on improvements in phase stability and property changes under elevated temperature exposure. Evaluations have also considered dimensional stability, erosion, impact, and spall resistance. Two iterations of TBC development have been conducted, and a down selection to the final TBC composition candidates has been made.

Metallic coatings are tailored to serve as a bond coat under a TBC or as a stand-alone environmental coating. Development of an improved metallic bond coat has focused on TBC adhesion, while development of an improved metallic environmental coating has focused on resistance to environmental attack (high temperature corrosion). Two iterations of metallic coating improvements have been conducted, and a down selection to finalists has been made. Final evaluations and characterization of the best coating will be completed during the remainder of Phase II.

Ceramic matrix composite (CMC) material systems can operate at much higher temperatures than traditional metal systems, and require little or no cooling flow. Fundamental CMC material property tests have been performed and prototype-manufacturing trials are complete. In an IGCC environment, CMC components will require a protective environmental barrier coating (EBC). Evaluation of different EBC coatings was performed and a coating was selected.

SYSTEMS

Cycle models have been developed to determine the performance and output characteristics resulting from the technology advancements being made in the program. The models now include all new or unique systems that will be required for carbon capture and sequestration (CCS). Altogether, six different configurations have been replicated—a baseline plant for both syngas and hydrogen fuels, including 2010 (syngas), 2012 (hydrogen), and 2015 (syngas and hydrogen) technology configurations. The models have been, and will continue to be, used to perform sensitivity studies on new and/or optimal integration schemes between the different systems and subsystems of the IGCC plant. At the end of the project, systems analysis will be used to validate that project goals have been achieved.

Relationship to Program:

This project will support important advances in the hydrogen turbine pathway of the NETL Advanced Turbines Program. As outlined, the program provides the technology to offset much of the performance and cost penalties associated with implementing CCS in an IGCC plant, thereby supporting the use of U.S. domestic coal reserves for lower-cost power generation with ultra-low emissions (from both a NO_x and CO_2 perspective). Because portions of the technology are likely applicable to the existing fleet of gas turbines in service (including natural gas-fired plants), opportunities for improvement extend well beyond new plant installations. Finally, investment in these technologies is strengthening and expanding the workforce of skilled engineers, scientists, and manufacturers that are available to address current and future energy challenges facing the United States. In 2008–2009, it is estimated that about 35 U.S. domestic, full-time equivalent personnel from GE and its direct contractors were employed by the program, with approximately 30 people spending greater than 25% of their time on this project specifically. Additionally, roughly $2 million per year in supplier contracts was placed throughout the country, with more than 20 suppliers receiving orders in excess of $10,000.

Primary Project Goal:

The objective of this program is to develop the technologies required for a fuel-flexible (coal-derived hydrogen or syngas) gas turbine for IGCC and FutureGen-type applications that meets DOE turbine performance goals related to efficiency, emissions, and cost.

Objectives:

The primary objective is to develop the technology for a fuel-flexible gas turbine that is able to use both coal-derived hydrogen and syngas and that achieves key DOE Fossil Energy Turbine Program performance goals, including:

- Efficiency: Compared to baseline state-of-the-art CC turbines in IGCC applications, a 2–3 percentage points improvement in combined cycle (CC) efficiency by 2010, and a 3–5 percentage points improvement in CC efficiency by 2015
- Emissions: Less than 2 ppm NO_x in an atmosphere containing 15% oxygen
- Cost: Significant reduction in IGCC plant capital costs

Based on these top-level program goals, more detailed requirements were determined for each technology area based on in depth performance analysis with IGCC models/simulations. The analysis was an iterative process that assessed the sensitivity of efficiency, emissions, and cost metrics to changes in each technology area, and included specific technologies that could be deployed over the duration of the project. The intersection of these two pieces of information formed the basis for the turbine targets. For example, a lower target for leakage flow was established based on the sensitivity of efficiency, emissions, and cost to leakage flow, in addition to knowledge of specific potential sealing technology advancements. Individual contributions from each area are tied together via the plant-level simulation in order to validate that top-level program objectives can be achieved.

In each major area of the program (~15 total), the above process was used to establish goals. A detailed Technology Validation Roadmap was created to depict the technical milestones that need to be achieved over the duration of the program in order to meet project goals, along with their associated funding requirements. By establishing a milestone frequency of approximately one per quarter, the roadmap provides the project team frequent opportunities to assess interim progress toward the ultimate program goals. Beyond the roadmap, an Earned Value Management System is utilized to assess scope, cost, and schedule simultaneously and on a quarterly basis. Finally, the plant-level model is used to assess interim progress by folding in actual (rather than target) improvements as results are obtained.

03: DE-FC26-08NT0005054

Project Number FC26-08NT0005054	**Project Title** Combustion Dynamics in Multi-Nozzle Combustors Operating on High-Hydrogen Fuels			
Contacts DOE/NETL Project Mgr.	**Name** Mark C. Freeman	**Organization** NETL – Power Systems Division	**Email** Mark.Freeman@netl.doe.gov	
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Partners	Dr. Tim Lieuwen, Georgia Institute of Technology			
Stage of Development				
X_Fundamental R&D	__Applied R&D	__Prototype Testing	__Proof of Concept	__Demonstration

Technical Background:

Combustion dynamics refers to a resonant coupling between combustion chamber acoustics and unsteady heat release, resulting in pressure fluctuations that can compromise the physical integrity of the combustion system. This phenomenon is especially common in the lean, premixed-gas turbine combustors that are required to meet nitrogen oxide (NO_x) emissions regulations. Therefore, the successful development of low-emissions gas-turbine power-generation systems that can operate on coal-derived, high-hydrogen content fuels is critically dependent on the ability to design lean, premixed combustors that are capable of stable operation throughout their intended operating range.

Current understanding of combustion dynamics in lean, premixed-gas turbine combustion systems is primarily limited to longitudinal-mode instabilities in single-nozzle combustors operating on natural gas. Low-emissions gas-turbine combustion systems, however, employ multi-nozzle configurations, exhibit both longitudinal and transverse instabilities, and will be expected to operate on high-hydrogen content fuels. Therefore, the industry's current understanding of combustion dynamics is insufficient for predicting the stability characteristics of current and future multi-nozzle gas-turbine combustion systems. This fact may be the largest risk to deploying new fuel-flexible, low-emissions technology.

This project is a direct extension of previous research conducted by the principal investigators on the forced-flame response of single-nozzle combustors under the sponsorship of the DOE, the National Science Foundation, and a number of the gas-turbine manufacturers. The fundamental understanding and insights, the innovative diagnostics, and the flame response modeling approaches that were developed in the previous single-nozzle studies will be employed in the study of multi-nozzle instabilities. In addition, the project team will study new phenomenology associated with the multi-nozzle configuration, as well as new diagnostics, data analysis, and flame response modeling that will be required to characterize and describe this behavior. This research represents the first attempt to investigate fundamental instability mechanisms in a multi-nozzle research combustor.

Relationship to Program:

This project will support important advances within the combustion area of the NETL Advanced Turbines Program. Current understanding of combustion dynamics in lean, premixed gas-turbine systems is primary limited to longitudinal-mode instabilities in single-nozzle combustors operating on natural gas. The industry's current lack of capabilities to translate single-nozzle test results to results in the field may be the largest risk in deploying new fuel-flexible, low-emissions technology. This project, which represents the first fundamental study of the instability mechanisms in multi-nozzle lean, premixed gas-turbine combustors, will provide insights and new understanding that will substantially mitigate this risk.

Primary Project Goal:

The primary goal of this project is to develop accurate and robust flame response models that can be incorporated into design tools for predicting longitudinal and transverse instabilities in lean, premixed multi-nozzle combustors operating on high-hydrogen fuels.

Objectives:

The project objectives include the following:
Obtain fundamental understanding of the response of lean, premixed-gas multi-nozzle combustors operating on high-hydrogen, coal-derived fuels to both transverse and longitudinal fluctuations of the air flow rate.
Use this understanding to formulate and validate longitudinal and transverse flame response models that can be used to predict instability amplitudes in multi-nozzle annular and can combustors. Such models are an essential tool for preventing or minimizing the incidence of detrimental combustion instabilities in future gas turbines.

04: FWP-FEAA-070

<table>
<tr><td colspan="1">Project Number
FWP-FEAA-070</td><td colspan="4">Project Title
Materials Issues in Coal-Derived Synthesis Gas/Hydrogen-Fired Turbines</td></tr>
<tr><td>Contacts
DOE/NETL Project Mgr.</td><td>Name
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<tr><td>Partners</td><td colspan="4">Prof. Ying Zhang, Tennessee Technological University</td></tr>
<tr><td colspan="5">Stage of Development</td></tr>
<tr><td>__Fundamental R&D</td><td>X Applied R&D</td><td>__Prototype Testing</td><td>__Proof of Concept</td><td>__Demonstration</td></tr>
</table>

Technical Background:

State-of-the-art gas turbines currently available for use in land-based power generation systems are the result of extensive development work carried out in the 1990s. A critical factor in their development was that, in order to operate at the high turbine entry temperature (TET) required for high efficiency, aeroengine technology (i.e., single-crystal [SX] superalloy blades, thermal barrier coatings, and sophisticated cooling techniques) had to be rapidly scaled up and introduced into these large gas turbines. Even though the design fuel was relatively clean natural gas, there were initial problems with reliability. These problems have been largely overcome following extended development work so that the high-efficiency gas turbine combined-cycle (GTCC) power generation system is now considered a mature technology that is capable of achieving high levels of availability. The transition to coal-derived synthesis gas (syngas) or hydrogen as the primary fuel for these machines introduces new challenges in order to accommodate the physical and chemical differences of these fuels while maintaining efficiency and reliability levels. Differences from natural gas in properties such as calorific value, flame speed, and impurity levels will very likely require changes in design and materials selection for some of the turbine components.

The high TET required in state-of-the-art natural gas-fired turbines necessitates reliable cooling of some components, since the temperature of the combustion gas is higher than the melting temperature of the available hot-gas path alloys. The result is that the strongest alloys available (typically SX nickel [Ni]-based superalloys) are used for the blades and vanes in the first—and possibly second—stage of the turbine, and essentially operate at their temperature limits. These components are also provided with complex internal cooling passages through which air from the turbine compressor is used to maintain the desired metal temperatures. The amount of cooling air must be minimized in order to maximize engine efficiency, and this is attempted through the application of thermal barrier coatings (TBCs) to the affected surfaces. It is increasingly essential that the TBC is fully functional in order for the engine to meet performance targets, requiring an unprecedented level of materials reliability and performance consistency. Consequently, there has been an ongoing, worldwide effort to understand the failure mechanisms of TBCs. The aim is to achieve the degree of predictability needed to allow the confident use of mechanism-based lifetime models, and there is hope of being able to take full advantage (in engine design) of the temperature decrement provided by a TBC. In parallel with this development, non-destructive evaluation (NDE) techniques are being devised to enable monitoring of the condition of the coating (preferably in-situ) in order to provide early indication of coating deterioration.

A TBC typically consists of a thin, metallic or bond coating and a layer of ceramic. The coating is usually a nickel aluminide (NiAl) or a platinum-modified nickel aluminide [(Ni,Pt)Al] that is formed by diffusion, or an MCrAlY-type overlay (where M can be Ni, cobalt [Co] or NiCo), and is typically about 50 micrometers [µm] thick. The coating is applied to the superalloy substrate, and a layer of ceramic, (typically yttria-stabilized zirconia [YSZ]), is applied on top. This second layer is usually 125–500 µm thick, although there is a strong interest in increased thermal resistivity and, therefore, thicker ceramic layers.

The purpose of the bond coating is threefold; it provides an anchoring surface for the ceramic layer; oxidation protection (since zirconia allows rapid transport of oxygen); and some resistance to other forms of corrosion, which could include oxidation-sulfidation (from gaseous sulfur [S] contaminants in the combustion products) and hot corrosion (from the presence of deposits of molten alkali sulfates), should the requisite corrodents gain access to the metallic surface. The composition of the ceramic layer is optimized for good structural stability and toughness as well as reduced thermal conductivity. While the reliability of TBC systems has increased significantly, their long-term performance in natural gas-fired turbines is still unpredictable.

Relationship to Program:

This project will support advances within the materials area of the NETL Advanced Turbines Program through the development of higher performance coatings. Such coatings can enable the following:

- Improved reliability of operation
- Reduction in unplanned stoppages for maintenance
- Reduction of coating-superalloy interdiffusion
- Increased airfoil lifetime due to increased number of possible refurbishment cycles

Primary Project Goal:

The original goals of the project were to define the overall needs for improved or new materials for the reliable operation of gas turbines fired with coal syngas and/or H_2-enriched fuel gases, and to explore routes for fulfilling the identified needs through computational and experimental methods. The focus for the past three years has been to maximize the service lifetime of metallic coatings that can be used as bond coatings in TBCs, by applying a mechanistic understanding of the factors that contribute to alloy and coating degradation in the extreme environments anticipated in syngas/hydrogen-fired gas turbines.

Objectives:

The objectives of this project are:

- Define the gaseous environment expected to be encountered by the hot-gas path components, leading to development of guidelines for improved syngas impurity specifications to better define syngas cleanup system requirements.
- Estimate the temperatures of components of interest, as well as the gas temperatures and pressures along the hot gas path, in order to provide realistic materials performance targets
- Evaluate approaches for improved coatings to provide the basis for more robust hot-gas path components.

05: DE-NT0006552

Project Number	Project Title			
DE-NT0006552	Degradation of Thermal Barrier Coatings From Deposits; and, Its Mitigation			
Contacts	**Name**	**Organization**	**Email**	
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Principal Investigator	Nitin Padture	Ohio State University	Padture.1@osu.edu	
Partners	Prof. Sanjay Sampath, University of Stony Brook, NY			
Stage of Development				
_X_ Fundamental R&D	___Applied R&D	__Proof of Concept	__Prototype Testing	__Demonstration

Technical Background:

Integrated gasification combined cycle (IGCC) turbine engines rely on fuel flexibility, utilizing synthesis gas (syngas) in place of natural gas. However, syngas can potentially contain particulate impurities. If turbine engines ingest these impurities, it can lead to particulate deposition on and significant damage to ceramic thermal barrier coatings (TBCs) that protect and insulate metallic components. This damage can have catastrophic consequences, leading to a loss of strain tolerance or spallation of the TBCs. In aero engines, the ingestion of airborne sand (calcium-magnesium-aluminosilicate [CMAS]) is of great concern. In recent years, the development of TBCs made of alternate ceramics, including our own research in this area, has effectively mitigated these consequences. Some of these ideas are used in this project to design TBCs that can mitigate the risk of fly ash attacks, a possible particulate impurity in syngas.

This project studies the interaction of fly ash deposits with conventional yttria-stabilized zirconia (YSZ) TBCs. The results of this analysis have led to the selection of alternate TBC ceramics to mitigate the detrimental effects of fly ash on the TBCs. In this study, gadolinium zirconate (GZO), which has been previously studied as a TBC, is found to mitigate representative fly ash attacks in isothermal testing at operating temperatures. Testing of these prototype TBCs under thermal gradient is underway. The detailed mechanisms of this mitigation effect are being investigated, which will result in the creation of guidelines for TBC materials selection and the development of a family of TBCs that is resistant to high-temperature attack by fly ash deposits.

Relationship to Program:

This project supports important advances in ceramic TBCs in the materials focus area of the NETL Advanced Turbines Program. Upon successful project completion, an alternative or set of alternative ceramics for TBCs will be indentified and understood. With this understanding and the selection of appropriate ceramics, the effects of syngas impurities will be mitigated, potentially allowing for less downtime or less clean fuel consumption while eliminating the detrimental effects on thermally protected components.

Primary Project Goal:

The primary project goal is to understand the degradation mechanisms of TBCs by common impurities, such as fly ash, in syngas-fired turbine engines and to develop a material or a set of materials to mitigate this degradation for IGCC turbine engine TBCs.

Objectives:

The primary objectives of this project include the following:

1. Identify the phases and compositions of fly ash and deposits on conventional TBCs, and study the nature of chemical attacks (infiltration, chemical reaction products) and mechanical damage (strain-tolerance loss, cracking, delamination) on TBCs.
2. Analyze within frameworks of chemical-interaction principles and mechanics models, and understand the critical issues pertaining to the damage mechanisms.
3. Identify alternate ceramics for TBCs based on the understanding of these critical issues.
4. Utilize the air plasma spray (APS) method to fabricate TBCs with new compositions and microstructures, and study interactions between these new TBCs and fly ash at high temperatures in isothermal and thermal gradient situations, with and without the presence of water vapor.
5. Develop an understanding of the mechanisms that mitigate deposit-induced degradation in the new TBCs.
6. Analyze these results within the framework of models that encompass chemical attacks and mechanics. Provide guidelines for the design of TBCs that are resistant to degradation by fly ash deposits.
7. Transfer the technology pertaining to successful TBCs with optimized compositions and microstructures to original equipment manufacturers (OEMs) for further development and possible utilization in IGCC engines.

06: DE-NT0000752

Project Number	**Project Title**			
DE-NT0000752	An Experimental and Chemical Kinetics Study of the Combustion of Syngas and High-Hydrogen-Content Fuels			
Contacts DOE/NETL Project Mgr.	**Name** Mark C. Freeman	**Organization** NETL– Power Systems Division	**Email** Mark.Freeman@netl.doe.gov	
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Partners	Professor Frederick Dryer, Princeton University, 609 258-5206 Professor Yiguang Ju, Princeton University, 609-258-5644			
Stage of Development				
_X_ Fundamental R&D	__Applied R&D	__Proof of Concept	__Prototype Testing	__Demonstration

Technical Background:

Integrated gasification combined cycle (IGGC) systems, when combined with effective methods for sequestering carbon dioxide (CO_2), offer a clean approach for accessing known large coal resources in the United States for power generation. Understanding the most effective way to combust high hydrogen content (HHC) fuels that result from the gasification process is critical to the implementation of IGCC. HHC fuels are composed mostly of hydrogen (H_2) and carbon monoxide (CO). However, HHC fuels can also contain diluents such as water (H_2O) and CO_2. For example, oxygen-blown gasification yields ~25% H_2, 40% CO, 20% H_2O, and 15% CO_2, although product streams of interest may vary considerably from these values. A further complication when using HHC fuels is that their composition is also affected by the gasification technology employed, the specific coal that is utilized, and whether biomass or other feedstocks are co-gasified with coal.

Despite the compositional diversity of HHC fuel, IGCC systems will be required to operate under the same stringent pollution standards as gas turbines burning natural gas, particularly with respect to nitrogen oxides (NO_x). Current technology has had great success in reducing NO_x emissions through the implementation of lean, premixed strategies for natural gas-fired gas turbines. A similar strategy can potentially work for HHC fuels. However, problems with ignition, blowout, flashback, and combustion instability have been observed in lean, premixed gas turbine systems operated on natural gas. It is unknown how HHC fuels will behave when operated under lean, premixed conditions.

Accurate experimental guidance and detailed, kinetic mechanism-based computational modeling are important in designing fuel-flexible combustion systems that can achieve very low NO_x emissions while operating at optimum efficiency. With natural gas, lean, premixed combustion has emerged as a very successful route to operating gas turbine combustion systems at very low NO_x emission levels. Recent modeling work that assesses humid-air-cycling operations with methane (CH_4) shows that operating limits are affected by H_2O as a dilution species. Moreover, the relative importance of Zeldovich NO_x, N_2O-NO_x, and Fenimore-NO_x (if trace hydrocarbons are present) formations is affected by combustion temperature and kinetically coupled redistributions amongst hydroxide (OH), oxygen (O), hydroperoxyl (HO_2) and hydrogen (H) radicals due to the presence of water. Diluent CO_2 generates similar coupling effects, as demonstrated by recent laminar flame computations. Contaminants frequently remain in HHC fuels after processing. Small amounts of hydrocarbons such as CH_4, ethane (C_2H_6) and ethylene (C_2H_4) and other contaminants such as small amounts of SO_x (~100 parts per million [ppm]) and NO_x can be present in HHC fuels.

At present, even fundamental kinetic models for H/CO mixtures are not developed sufficiently to reproduce experimental measurements. The effects of small amounts of small hydrocarbons, sulfur (S), NO_x, and carbonyls on this base model cannot be quantitatively pursued until the base model is further refined. Adding these kinetic influences and refining the base model will require added experimental observations to enhance the validation database and improve fundamental kinetic reaction sets and parameters. This project will conduct fundamental and applied experiments and will conduct fundamental and applied experiments and develop and validate a kinetic model over a wide set of experimental configurations, compositional initial conditions, and initial temperature and pressure conditions.

With this challenge in mind, a coherent research program has been designed and assembled that incorporates the research expertise necessary to address both the experimental and kinetic modeling advances required.

The experimental data will be established using a High Pressure Laminar Flame Reactor (HPFLR) that will allow investigation of the fundamental reaction rates needed to model HHC fuels. The HPLFR will operate a pressures as high as 30 atmospheres and can be used to study important homogenous and heterogeneous wall reactions over a temperature range of 600–1,100 Kelvin (K). This device will also be able to provide sufficient, accurate data corresponding to pressures and temperatures relevant to gas turbine operating conditions. Additional studies will be conducted in a turbulent flow reactor capable of operation at 30 atm and temperatures as high as 800K, which simulate fluid flow conditions as well as appropriate pressure and temperature conditions that allow comparison with actual gas turbine systems. To address the problem of flame speed and burning rate, a high-pressure, pressure-release combustion chamber will be used to make highly accurate measurements of flame speed and determine the mass burning rate.

All of these experimental studies will contribute to developing the HHC chemical kinetic model, a key achievement of the proposed work.

Relationship to Program:

This project will support important research advances in chemical kinetics and numerical design capabilities within the combustion focus area of the NETL Advanced Turbines Program. The proposed studies will develop a new, validated, HHC kinetic mechanism tailored specifically to HHC fuels and the success of the proposed research will advance numerical design capabilities for gas turbines operating on HHC fuels. The project will address wider temperature and pressure ranges than those addressed in presently available studies, and kinetic models will be extended to include the effects of small hydrocarbon species and NO_x on ignition and combustion behavior—an area of special interest for HHC fuels. The integration of the detailed kinetic model with a multi-time scale method will enhance the computation efficiency by one order of magnitude.

Primary Project Goal:

The primary goal of this project is to resolve the recently noted difficulties for existing elementary kinetic models that predict experimental ignition delay, burning rate, and kinetic characteristics of homogenous chemical oxidation of H and H/CO fuels with air (including pure air and with air diluted with N and/or CO_2) at the contemplated range of pressures and dilutions for gas turbine applications with low NOx emissions.

Objectives:

The major objective of this project is to assess and develop a validated, HHC fuel-kinetic mechanism by including new experimental data and unaccounted reaction pathways for the low flame temperatures and high pressures of gas turbine applications. To carry out these objectives, new experimental data will be obtained on ignition delay time, burning rate, and speciation for the oxidation kinetics of HHC fuel compositions in the presence of nitrogen (N), water vapor, and CO_2 diluents and a limited number of contaminant species (NO_x, CH_4, C_2H_6, and C_2H_4) at pressures (1–30 atmosphere [atm]) over varying concentrations. Special attention is given to understanding important elementary reactions that influence burning rate pressure dependence and ignition delay at high pressure and low flame temperature. A final key objective is to develop a detailed, HHC fuel kinetic-mechanism-based, multi-time-scale algorithm to increase the computation efficiency of gas turbine-combustion numerical modeling by one order of magnitude.

Specific project tasks include the following:

VI.C.1 Complete project management and planning.

VI.C.2 Conduct studies of high-pressure HHC fuel kinetics using HPLFR.

VI.C.2.1 Verify HPLFR system operation.

VI.C.2.2 Generate of kinetic databases for HHC fuel combustion with contaminant/additive effects.

Subtask 1—Study surface effects on kinetics; compare with silica reactor walls, metal wall material.

Subtask 2—Generate database on the effects of contaminants: NOx, CH_4, C_2H_6, and C_2H_4.

VI.C.3 Measure burning rates and intermediate species of high-pressure HHC fuel combustion by using a nearly constant-pressure bomb with two-photon absorption laser-induced fluorescence (TALIF) and laser-induced fluorescence (LIF).

VI.C.3.1 Measure HHC fuel-burning rates at high pressures and low flame temperature.

VI.C.3.2 Measure the effects of additives on burning rates and flame speeds at high pressures.

VI.C.3.3 Measure O and OH concentrations at high pressures.

VI.C.4 Perform a kinetic assessment of, validate, and develop a comprehensive C1 mechanism.

VI.C.4.1 Assess and develop a comprehensive HHC fuel-combustion mechanism.

VI.C.4.2 Develop a multi-time-scale model to enhance computation efficiency using the detailed mechanisms.

VI.C.5 Conduct HHC fuel-ignition delay studies in a high-pressure, high-temperature flow reactor.

VI.C5.1 Study ignition delay times of HHC fuels with added minor hydrocarbon species.

VI.C5.2 Study ignition delay times of HHC fuels at pressure/temperatures near the third explosion limit.

07: FY10.MSE.1610243.682; FY10.MSE.1610243.683

Project Number	**Project Title**			
FY10.MSE.1610243.682; FY10.MSE.1610243.683	Performance of Materials for Oxyfuel Turbines (Materials Performance in Oxyfuel Turbine Environments; Materials Performance in High CO_2 + Steam Environments; Stress-Environment Synergies in Advanced Combustion Systems: II Advanced Turbines)			
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Principal Investigator	Gordon Holcomb Jeff Hawk	NETL – ORD	Gordon.Holcomb@netl.doe.gov; Jeffrey.Hawk@netl.doe.gov	
Partners	Siemens Power Generation			
Stage of Development				
__ Fundamental R&D	_X_ Applied R&D	__ Proof of Concept	__ Prototype Testing	__ Demonstration

Technical Background:

The goal of the overall turbine research at NETL is to develop oxyfuel turbine and combustor technologies for highly efficient (50%–60%), near-zero emissions, coal-based power systems by 2012. Oxyfuel combustion, which burns fuel in oxygen rather than in air, generates combustion gas with a much higher percentage of carbon dioxide (CO_2) than conventional systems, allowing for easier and more efficient carbon capture. The project team has proposed using conventional steam turbines for the high-pressure turbine and low-pressure turbine.

Materials issues related to high-temperature operation of higher efficiency power plants, including hydrogen- and oxyfuel-fired gas turbines, require materials with higher temperature capability than the current generation of turbines. Research to extend the usable critical temperature of nickel superalloys has focused on maintaining the strength and integrity of grain boundaries, as well as the interface between the grain boundary phases (carbide and/or TCP) and the matrix. This research has also aimed to improve the long-term stability of fine, strengthening precipitates at the operating temperature. Along with achieving these goals, it is essential to understand how temperature, stress, and environment affect grain boundary, matrix, and surface/coating interface stability as a consequence of exposure to the gas turbine environment.

A promising technology that generates electricity from turbines powered by oxygen-fired natural gas or synthesis gas (syngas) will allow more economical CO_2 capture than generation that uses air-fired fuels. The intermediate pressure turbine (IPT), which operates at the highest temperatures in the proposed system, will utilize existing gas turbine technology at this stage of development. However, the oxyfuel turbine steam-CO_2-oxygen environment is different from gas turbine environments. The project team is evaluating the materials performance of nickel- and cobalt-based alloys and alloy/coating systems in the oxyfuel turbine environment to qualify them for use. The team evaluated the effect of this environment on oxidation of the alloys as well as the low-cycle fatigue behavior of the exposed alloy. These projects provide technical assistance to Siemens Power Generation in support of the Zero Emissions Coal Syngas Oxygen Turbo Machinery NT42646 project, while also seeks fundamental information on the roles of the various species in oxidation, the effects on microstructural features from exposure to these species, and the effects of microstructure changes from low-cycle fatigue life on mechanical performance.

The first year of the project focused on the environments, alloys, and coating systems expected in the SGT-900 gas turbine, especially in the IPT where the inlet temperature can reach 1,180°C. The NETL team exposed oxidation coupons and low-cycle fatigue (LCF) specimens for a range of temperatures (as identified by Siemens Power Generation) that represent the blades and vanes in three distinct stages of the SGT-900. The environment (also identified by Siemens Power Generation) was steam with 10% CO_2 and 0.2% oxygen (O_2). The oxidation coupons were then examined by NETL to determine oxidation kinetics and any changes within the microstructure due to exposure to this environment. The LCF specimens were subsequently returned to Siemens Power Generation for testing at air temperature. At this point, the LCF specimens will be examined in the scanning electron microscope (SEM), looking particularly for changes in the failure mode that are indicated by details on the fracture surface following exposure to CO_2 and O_2 in the gas stream. In addition, thin sections that are representative of the deformed and nondeformed regions will be examined in the transmission electron microscope (TEM) to evaluate the extent of microstructural changes within the bulk that might affect deformation and cause subsequent failure. This information will be evaluated with respect to LCF data.

One outcome from fiscal year (FY) 2009 was the observation that oxidation in the three mixed oxidants (water [H_2O], CO_2, and O_2) can lead to higher oxidation rates than combinations of only two of them. Other researchers have observed that varying the oxygen activity in steam can greatly influence the oxidation behavior. A similar effect may occur in the presence of CO_2 and may help explain the increased oxidation in the three mixed oxidants.

In Quadakkers' steam results, differences in oxygen and water activities changed the oxidation behavior of 9Cr ferritic steels from protective (with iron-chromium [FeCr] oxide scales) to unprotective (with fast-growing Fe-oxide scales). The minimum level of Cr required for FeCr oxides in ferritic steels lies at approximately 9–12Cr, and small changes in the environment can tip the behavior toward rapid oxidation. In a similar fashion, the minimum level of Cr that is required for protective Cr_2O_3 (Chromium [III] oxide) scales to form in nickel-chromium (NiCr) and cobalt-chromium (CoCr) alloys (instead of a less protective NiCr or CoCr oxide) usually lies in the 19–22Cr range, and is also a function of silicon, titanium, and aluminum. The amount of Cr in Ni and Cr alloys tends to be lowered for strength considerations, so in many cases the Cr content is close to this tipping point.

In steam, the change in oxidation behavior is associated with the effect of releasing hydrogen (arriving at the metal-scale interface via hydroxide [OH^-] diffusion) and enhancing the internal oxidation of Cr. A similar mechanism, or perhaps an enhancement of the same mechanism, could be present with CO_2 in addition to H_2O and O_2.

The second (current) year of the project proposed to accomplish the following tasks:

1. Understand the oxidation mechanisms in the oxyfuel turbine environment better, by varying the oxygen activity in the mixed-oxidant environments.
2. Examine, on a microscopic scale, the mixed-oxidant environment's effects on the mechanical properties of the alloys of interest, both in terms of the mode of fracture as well as the changes in deformation within the grain and along the grain boundary regions.
3. Assist Siemens Power Generation further by exposing additional LCF specimens to fill in the gaps in low-cycle fatigue data needed for more accurate design life assessment.

It is important to note the similarities between the environments examined in these projects for oxyfuel turbines and the ones involved in flue gas recycle paths proposed for use in coal-fired boiler retrofits for oxyfuel combustion (i.e., wet CO_2 with excess oxygen). Knowledge gained in this project may have direct applications in other high-temperature CO_2-rich environments.

LABORATORY EXPOSURES BASICS

Oxidation coupons (e.g., bare metal, metal with a bond coat, and metal with a bond coat and thermal barrier coating) and LCF specimens are exposed under isothermal conditions for 1,000 hours at operation temperature.

In FY 2009, the oxidation coupons and LCF specimens were exposed to test temperatures of 630°C, 693°C, 748°C, and 821°C, which correspond to blade and vane temperatures in the STG-900. The testing environment was steam with 10% CO_2 and 0.2% O_2. The main alloys and bond coat compositions are shown in Table 1. The 9Cr ferritic alloys T91 and T92 were added for the test at 630°C.

TABLE 1. NOMINAL ALLOY AND BOND COAT COMPOSITIONS

Alloy	Ni	Co	Cr	Al	Ti	Mn	Ta+Nb	W	Fe	Mo	C	Re	Y
X-45	10.1	Bal	24.8			0.6		7.8	1.0		0.25		
ECY-768	9.7	Bal	23.8	0.1	0.2		3.5	7.0	0.2		0.59		
Inconel 738	Bal	8.5	15.8	3.5	3.3		1.7	2.5		1.7	0.12		
Inconel 939	Bal	18.9	22.5	1.9	3.8		2.4	2.0			0.14		
Udimet 520	Bal	12.5	19.0	2.0	3.0			1.2		6.3	0.06		
Bond Coat	Bal		17.0	10.0								1.5	0.3

The same alloys were selected in FY 2010, including the boiler tube alloys T91 and T92. Two additional environments were chosen to widen the oxygen activities: steam with 10% CO_2 and 2% O_2; and steam with 10% CO_2 and 2% N_2-H_2 mixture with 4% H_2. The exposure temperatures are 630°C and 748°C. The activity of O_2 in the environment with 2% (N_2 with 4% H_2) is 1.7×10^{-17} at 630°C and 3.7×10^{-14} at 748°C.

The project team has examined ECY-768, Udimet 520, and Inconel (IN)738 LCF specimens in the SEM and identified failure modes. Siemens Power Generation has provided additional material, not exposed to the mixed-oxidant environments, to better evaluate the changes in microstructure as a consequence of mixed oxidant exposure. This allows selected specimens to be examined in the TEM, evaluating the effect on deformation of exposure in the mixed-oxidant environment relative to unexposed alloy. Siemens Power Generation also provided low-cycle fatigue data so that any anomalous fatigue data can be investigated to see if it is related to exposure to this environment.

Relationship to Program:

This project is directed toward providing important advances within the materials pathway of the NETL Advanced Turbines Program. Project research aids materials development by identifying factors that affect material mechanical properties for gas turbine airfoils and vanes in mixed-oxidant environments, leading to optimization strategies that improve performance relative to these environments, and subsequently aiding the selection of alloys for use in carbon capture technologies (primarily oxyfuel turbines, but also oxyfuel retrofits of coal boilers). Proper alloy development, optimization, and materials selection enables the lowering of gas turbine capital costs by not specifying materials that are more expensive than absolutely necessary. In addition, it may be possible to lower operating costs by using materials that can withstand the environment without increasing the number of unscheduled shutdowns from materials degradation. Better understanding of the oxidation and mechanical properties in these environments may also allow the alloy to reach higher temperatures in the gas turbine, yielding even greater efficiency gains with concomitant operating cost reductions.

Project success would benefit efforts to use the STG-900 gas turbine as IPT in a proposed oxyfuel system, and provide gained oxidation and mechanical property knowledge in oxyfuel combustion environments. Other benefits include the following:

- Enables Siemens Power Generation to validate STG-900 alloys and alloy-coating systems for use in the proposed oxyfuel system.
- Increases understanding of mixed-oxidant corrosion, potentially leading to improved alloy selection (or alloy development) for oxyfuel combustion environments—environments that include other applications in addition to the use of STG-900.
- Examines oxygen activity which, beyond aiding the understanding of mixed-oxidant corrosion, can also relate back to excess oxygen (or deficient oxygen) choices made in combustion engineering design.
- Correlates the effects of mixed-oxidant environment on LCF behavior, leading to greater understanding of the role of temperature and environment on changes within the matrix and along grain boundaries that can influence deformation mechanisms and, ultimately, fracture mode.
- Develops a screening methodology to enable the quick evaluation of the effects that mixed-oxidant environments have on static crack growth in high-temperature superalloys. While not dynamic in nature, understanding the role of environment and temperature on crack propagation will provide important information on potential alloys for oxyfuel and hydrogen turbines.
- Gains insight on the effects that mixed-oxidant environments have on nickel- and cobalt-based superalloy performance through surface oxidation and penetration of oxygen along the grain boundaries. Assesses the potential for alloying to change the microchemistry of the grain boundaries in order to make them more resistant to the mixed-oxidant environment.

Primary Project Goal:

The primary goal of this project is to assess the materials behavior of superalloys for oxyfuel turbine applications.

Objectives:

Several objectives need to be accomplished to achieve the goal of assessing the materials behavior of superalloys for oxyfuel turbine applications. For each objective, individual measurable milestones (or tasks) are shown that meet the objective and thus address the goal. A milestone will be listed with its primary objective, even if it supports more than one objective.

Objective A—Examine and understand the behavior of alloys used in the SGT-900 in oxyfuel environments to assist Siemens Power Generation with qualifying the use of the SGT-900 as the intermediate pressure turbine in the proposed oxyfuel system.

1. *Test Specimens and Agreement, FY 2009*
   Obtain coated and uncoated LCF test specimens and oxidation coupons from Siemens Power Generation, and reach agreement with Siemens Power Generation on the specific exposure test details for including environment, sample arrangement, and temperatures.
2. *Thermodynamics, FY 2009*
   Complete thermodynamic analyses of environment-alloy interactions. The task also examines the potential for significant chromia evaporation to occur.
3. *Complete Exposure Tests and Deliver Specimens, FY 2009*
   Complete the 1,000-hour sample exposure tests in steam with 10% CO_2 and 0.2% O_2, and deliver the environment-exposed LCF test specimens to Siemens Power Generation for low-cycle fatigue testing.
4. *Analysis of Oxidation Coupon Exposure Tests, FY 2009*
   Complete analysis of oxidation coupon specimens. Specific analyses include light microscopy and scanning electron microscopy (including elemental mapping of selected samples) of as-oxidized and cross-sectioned surfaces, identifying the extent of surface and internal oxidation.

Objective B—Broaden the understanding of environment-material interactions occurring in oxyfuel turbine environments by examining the role of oxygen in the multiple-oxidant environment.

5. *Test Specimen and Environment Selection, FY 2010*
   Select and obtain additional LCF test specimens and oxidation coupons, and identify exposure test conditions. Obtain material from selected LCF-tested specimens to evaluate the extent of oxidation along grain boundaries that might cause a change in failure mode.
6. *Complete Tests and Deliver Specimens, FY 2010*
   Compete new 1,000-hour exposure tests on oxidation coupons and LCF specimens in steam with 10% CO_2 and three oxygen activities, and deliver all of the LCF test specimens to Siemens Power Generation.

Objective C—Broaden the understanding of environment-material interactions occurring in oxyfuel turbine environments by examining the microstructural changes and mechanical behavior in the multiple-oxidant environment.

7. *Analysis of Exposure Tests and Fractured LCF Specimens, FY 2010*
   Complete analysis of oxidation specimens from FY 2009 and 2010, and analyze fracture characteristics of the LCF specimens returned from Siemens Power Generation, noting any changes in failure deformation mode.
8. *Develop Static-Crack-Growth Test Methodology and Design Environmental Chamber, FY 2010*
   Prepare a screening tool for future mechanical property evaluations of alloys that may be used in mixed-oxidant environments, utilizing static crack growth testing to assess possible change in failure mode along grain boundaries or internal oxidation within the grains that might lead to lower-than-expected life.
9. *Mechanical Behavior With Respect to Alloy Chemistry/Microstructure, FY 2010*
   Assess the effect of mixed-oxidant environments on current-generation gas turbine alloy microstructures (SEM of fracture mode and TEM of internal changes,

primarily along grain boundaries, including changes in microchemistry in the region adjacent to the grain boundary plane). Evaluate causes for mechanical behavior change and determine corrective strategy, either optimizing the current generation alloys for use in this environment or suggesting alternative materials that better resist mixed-oxidant environmental attack.

08: FWP-678403

<table>
<tr><td>Project Number
FWP-678403</td><td colspan="4">Project Title
Low-Swirl Injectors for Hydrogen Gas Turbines in FutureGen Power Plants</td></tr>
<tr><td>Contacts
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<tr><td>Partners</td><td colspan="4">LBNL Computational Research Division
National Energy Technology Laboratory
Siemens Energy Inc.
University of California, Irvine
University of Iowa
United Technologies Research Center/ Pratt & Whitney Power Systems</td></tr>
<tr><td colspan="5">Stage of Development</td></tr>
<tr><td>__ Fundamental</td><td>_X_ Applied R&D</td><td>__ Proof of Concept</td><td>__ Prototype Testing</td><td>__ Demonstration</td></tr>
</table>

Technical Background:

The FutureGen near-zero emissions, integrated gasification combined cycle (IGCC) coal power plant would produce gaseous high-hydrogen-content fuel (HHF) from coal and separates the HHF from a concentrated carbon dioxide (CO_2) stream for capture and subsequent sequestration. A key component of the IGCC plant is a cost-competitive, fuel-flexible combustion turbine that operates on HHF with high efficiency and ultra-low emissions of nitrogen oxides (NO_x). The mission of the NETL Advanced Turbines Program is to develop gas turbines that meet the emissions, efficiency, and cost targets required to achieve no more than a 10% increase in the cost of electricity from mature IGCC plants with CO_2 capture and sequestration.

Combustion is a critical component of and challenge to the development of a hydrogen turbine that operates on HHF as the primary energy source and is capable of meeting NO_x emissions limits of 2 parts per million (ppm), corrected to 15% O_2 (at 15% O_2), while maintaining the same reliability as existing commercial machines. To reduce NO_x emissions from combustion, the standard approach is to burn at low flame temperatures. However, due to the risk of encountering premature flame blow-off and flame instabilities in many gas turbine combustors when burning at low flame temperatures, flue gas treatment by selective catalytic reductions (SCR) may be required to achieve the aggressive < 2 ppm NO_x goal. The SCR approach sacrifices efficiency and impacts the cost of electricity (via capital cost, efficiency, maintenance, and capacity output).

This project supports the mission of the Advanced Turbines Program through the development of a simple, ultra-low-emission, fuel-flexible combustion technology known as the Low-Swirl Injector (LSI) for the HHF gas turbines. Laboratory experiments have verified the potential of the LSI concept to meet the < 2 ppm NO_x emission target without requiring SCR. The current goal is to develop LSI conceptual prototypes that capture these benefits for the HHF gas turbines that burn a variety of fuels during the different phases of the operating cycle. As an integral part of the project team's effort, basic studies on premixed, turbulent synthesis gas (syngas) and HHF flames are also pursued; the results are published in the open literature to share with the other projects in the Advanced Turbines Program.

The LSI is based on a patented flame-stabilization principle conceived at Lawrence Berkeley National Laboratory (LBNL) in 1991. It operates in the lean, premixed turbulent-combustion mode, which is the foundation of the dry-low-NO_x (DLN) methods employed in almost all advanced low-emissions gas turbines. The LSI technology exploits the dynamic self-propelling nature of premixed turbulent flames. It enables them to burn freely in a divergent flow that is formed only when the swirl intensities are deliberately set below the critical vortex breakdown threshold. This approach is fundamentally different than the high-swirl concepts utilized in all current DLN gas turbine combustors (e.g., General Electric, Siemens, Pratt, Alstom, and Solar) where toroidal vortices with strong recirculation and intense shear turbulence are generated to hold and continuously ignite the turbulent premixed flames. Compared to its high-swirl counterparts, the LSI's unique flowfield produces a stable flame that blows off at a lower lean limit and also emits less NO_x.

Originally intended as a laboratory burner for basic research on flame/turbulence interaction processes, the operating principle of the LSI has since been investigated extensively by laser diagnostic methods. The development of the LSI for commercial applications began in 1994. Since then, prototypes have been developed and tested for industrial process heaters, water heaters, and boilers. Maxon Corp. of Muncie, Indiana, licensed the technology and is marketing two lines of LSI industrial burners with thermal outputs of 90 kW to 28 MW. LBNL's gas turbines development commenced in 1999 in collaboration with Solar Turbines of San Diego. The LSI developed for Solar's Taurus 70 (7 MW) gas turbine is a drop-in replacement for the company's $SoLoNO_x$ injector. This LSI is made from a production $SoLoNO_x$ swirler by changing its operation mode from high swirl to low swirl. Rig tests of individual LSI showed that a switch from high-swirl to low-swirl operation reduced NO_x by 60%, with the lowest level at < 2 parts per million (ppm) NO_x at 15% oxygen (O_2). When fitted with a full set of 12 LSIs, a Taurus 70 operated with natural gas achieved < 5 ppm NO_x. Other LSI natural gas developments include an 80 kW Elliott microturbine for a combined-heat-and-power system being demonstrated in Northern California and a LSI pilot for an F-frame combustor that has been developed and rig-tested in collaboration with Siemens Energy Incorporated.

SCIENTIFIC UNDERPINNING

The key component of the LSI is a patented swirler that supplies the fuel/air reactants through two flow passages: an outer swirl annular section with guide vanes to impart swirl and a center channel to allow a portion of the reactants to bypass the swirl vanes. The non-swirling center bypass is a critical requirement. It inhibits recirculation and promotes the formation of a divergent flow downstream of the nozzle exit. The LSI flame self-propels in the divergent flow and is detached from the nozzle. A "floating flame" is the distinct feature of the LSI. From laboratory studies, scaling rules for guiding engineering designs have been developed. The rules are expressed in terms of the swirl number, *S*, which controls the divergence rate of the LSI flowfield.

Eq. 1: $$S = \frac{2}{3} * \tan\alpha \frac{1-R^3}{1-R^2+\left[m^2\left(\frac{1}{R^2}-1\right)^2\right]R^2}$$

In Eq. 1, α is the swirl blade angle, and $m = m_c/m_s$ is the ratio of the flows through the bypass, m_c, and the swirl annulus, m_s. $R = R_c/R_b$ is the ratio of the radii of the center bypass tube, R_c, and the LSI nozzle, R_B. In Eq. 1, α and R are fixed by the swirler geometry and m provides the only means to tune the LSI to the desired swirl number range of $0.4 < S < 0.55$. For a single-stage burner (i.e., one stream of fuel/air mixture supplying the two flows passage), this can be accomplished by covering the center bypass with a perforated plate with a blockage ratio that creates the appropriate pressure drop to achieve the proper flow splits, m. For natural gas, the guidelines are $0.4 < S < 0.55$, $0.5 < R < 0.8$, $37° < \alpha < 45°$ with the swirler recessed at $2R_B$ to $3R_b$ from the nozzle exit. These guidelines have been applied to industrial burners of 5 cm < R_b < 56 cm, as well as LSI gas turbines of 5 cm < R_b < 10 cm. For operational flexibility, S can also be varied by staging the LSI with independent supplies and controls for m_c and m_s and their fuel-to-air ratios.

To expand the scientific foundation needed for this project, the project team developed an analytical model to show how the LSI flame responds to load change and variations in fuel composition. The model describes the coupling between the divergent flow produced by the LSI nozzle and the turbulent flame speed, S_T, against which the flame propels. Particle image velocimetry measurements have shown that the nearfield of the divergent flow is self-similar. Two parameters are invoked to characterize self-similarity: the virtual origin of the divergent flow, x_0, and the non-dimensional axial aerodynamic stretch rate, a_x. The turbulent flame characteristics are expressed in terms of the turbulent flame speed, S_T, and the position of the flame, x_f. Analysis of S_T for natural gas, hydrocarbon, and hydrogen flames shows that they increase linearly with turbulent fluctuation, u'. The model is an equation (Eq. 2) for the velocity at x_f, showing how the coupling between the flowfield self-similarity feature and linear turbulent flame speed correlations allows the LSI flame to remain stationary through a wide range of velocities and fuel-air equivalence ratios, Φ.

Eq. 2: $$1 - \frac{dU}{dx}\frac{(x_f - x_0)}{U_0} = \frac{S_T}{U_0} = \frac{S_L}{U_0} + \frac{Ku'}{U_0}$$

The two terms on the far right-hand side simply state that S_T increases linearly with u' at a slope of K above the baseline value of the laminar flame speed, S_L. This slope is an empirical value from measurements. The first term of the right-hand side tends to a small value at typical gas turbine bulk flow velocity U_0 of > 30 m/s because the laminar flame speeds of lean hydrocarbon and hydrogen fuels are on the order of 0.2 to 1 m/s. The second term on the right-hand side is the turbulent intensity, u'/U_0. This term is constant in accordance with the behavior of near-isotropic turbulence produced by the perforated plate at the center core of the LSI. On the left-hand side, self-similarity means that the normalized axial aerodynamic divergence rate, $a_x = dU/dx/U$, is constant in the second term. The consequence is the flame position, $x_f - x_0$, reaching an asymptotic value at large U_0. Therefore, when S_L is held constant for a given fuel at a given fuel-air ratio, the flame does not change its position with load when $U_0 >> SL$. The asymptotic behavior has been confirmed by visual observations in industrial burners and in gas turbines.

Recent laboratory studies show that the turbulent flame speed correlation constant, K, for hydrogen (H_2) flames is 50% higher than that of the hydrocarbon flames. For an LSI with fixed S, the model predicts that the positions of the H_2 flames are closer to the nozzle exit than the natural gas flames. The prediction of an upstream shift in the flame position has been validated by experiments at atmospheric and simulated gas turbine conditions conducted respectively at LBNL and in the SimVal Facility at the National Energy Technology Laboratory in Morgantown, West Virginia. The NETL experiments also show that the LSI can meet the emissions target of < 2 ppm nitric oxide (NO) (at $15O_2$) at firing temperature of 2650°F with pure H_2, and can demonstrate its capability to accept different fuels without requiring moving parts in the swirler or fuel/air staging for the two passages. However, due to the high diffusivity and reactivity of H_2 compared to the hydrocarbons, the characteristics of the H_2 flames are found to be very sensitive to the turbulent shear stresses produced by the LSI and within the combustor. Therefore, the components of the LSI combustor, such as the swirl blade, the fuel injectors, the nozzle exit, and the combustor entry, all need to have aerodynamically smooth profiles to lower the shear stresses and to prevent premature HHF flame flashback and unwanted flame attachment.

Because the LSI is a novel concept, basic research remains an essential part of the project team's work. To support the development of high-fidelity computational fluid dynamics (CFD) tools for engineering design, the team collaborates with engineers at gas turbine manufacturers, as well as researchers at academic and research institutions. The team's experimental data has been used to validate the computations performed at Solar Turbines, Siemens, United Technology Research Center, and Stanford University. To gain better insight into LSI's combustion instability characteristics, the preliminary studies are conducted in collaboration with Siemens and the University of Iowa. The team also formed a partnership with LBNL's Computational Research Division to develop a new modeling approach for H_2 flames to improve the fidelity of CFD. DOE Office of Science supports the LBNL computation researchers who are the world's leaders in direct numerical simulations of turbulent flames in a physically meaningful domain. They focus their basic research on Fossil Energy's interest (i.e., H_2 combustion) to demonstrate the direct benefit of using supercomputers to solve real-world problems. Due to its origin as a research burner, the knowledge gained from the LSI numerical studies and the results of the analysis is fundamental and also benefits other projects in the Advanced Turbines Program.

UNIQUENESS OF THE PROJECT

The LSI is a new combustion method that shows good promise to meet the performance, cost, and emissions goals of the Advanced Turbines Program. The technology evolved from fundamental studies, and the knowledge and experience gained from previous basic studies and developments for heating and power systems, contribute to the scientific foundation for this project. In tandem with the applied research, basic studies targeting the specific needs for hardware development are also conducted. The progress thus far has shown the value of leveraging the expertise from gas turbine manufacturers, national laboratories, and universities to pursue synergistic applied and basic studies. The project team will continue using this approach for the prototype-testing phase of this project, which aims to address issues relevant to the nozzle configuration, fuel injection scheme, mixing, safety, and operation of the LSI in a utility-size gas turbine.

Relationship to Program:

This project will support important advances within the combustion focus of the NETL Advanced Turbines Program. If successful, this project will produce a simple, cost-effective, fuel-flexible combustion system for gas turbines in IGCC power plants that will operate with ultra-low emissions at different phases of the operation cycle. If the aggressive NO_x goal can be accomplished without needing to invoke nitrogen dilution in the combustion process or selective catalytic reduction for flue gas cleanup, there will be a significant increase in IGCC system efficiency and reductions in the cost and the complexity of the plant system and operation. Knowledge gained from this project is directly applicable to adapting the LSI technology to gas turbines of all sizes, including those operating on alternate fuels derived from renewable and bio-sources. The pressure drop, ΔP, across the LSI is lower than the conventional high-swirl design due to the opening of the center channel. The lower ΔP can also be exploited in combination with advancements in other gas turbine components to increase gas turbine efficiency. Fundamental knowledge of turbulent H_2 and HHF flames gained from this project contributes to the scientific foundation needed for the development of fuel-flexible gas turbines and other combustion systems.

Primary Project Goal:

The primary goal of this research is to develop a robust, ultra-low-emission, low-swirl combustor for the gas turbines in near-zero-emissions coal power plants that burn HHF derived from coal gasification as a base-load fuel.

Objectives:

The project has the following main objectives:

1. Scale and verify LSI operation with natural gas for utility-size gas turbines.
2. Optimize LSI swirler and nozzle for operation with H_2.
3. Develop and test a conceptual LSI prototype capable of three-fuel (natural gas, syngas, HHF) operation.
4. Improve the understanding of turbulent H_2 flames and LSI flame acoustics.

Objective 1 has been reached; current activities are focused on Objectives 2–4.

MILESTONES ACCOMPLISHED:

1. Scaled LSI to utility-size gas turbines for natural gas operation (second quarter fiscal year [FY] 2007)
2. Demonstrated the feasibility of LSI firing with H_2 at gas turbine conditions (third quarter FY 2007)
3. Demonstrated firing LSI with syngas at gas turbine conditions (third quarter FY 2007)
4. Rig-tested LSI at the power output of utility-size gas turbines (second quarter FY2008)
5. Optimized LSI swirler for firing with H_2 (second quarter FY 2008)
6. Characterized the differences in the structures of lean, premixed, turbulent H_2 and methane flame and the implication on models (first quarter FY 2009)
7. Established the criteria to evaluate computational methods for LSI flames (second quarter FY 2009)
8. Finalized the design of the LSI pilot for F-Class gas turbines (second quarter FY 2009)
9. First report on the oscillation characteristics of low-swirl burner (LSB) flames (third quarter FY 2009)
10. Preliminary conclusion on the origin of the NO_x “floor” of lean H_2 flames (third quarter FY 2009)

FUTURE OBJECTIVES:

Three-Fuel LSI Development Objectives

1. Contract a gas turbine manufacturer for a feasibility study of three-fuel operation (first quarter FY 2010)
2. Conceptual layout of an LSI/combustor assembly for three-fuel gas turbines (fourth quarter FY 2010)
3. First rig test of subscale three-fuel LSI/combustor assembly (fourth quarter FY 2011)
4. Revise design of three-fuel LSI/combustor assembly (first quarter FY12)
5. Design full-scale, three-fuel LSI prototype (second quarter FY 2012)
6. Operability test of full-scale, three-fuel LSI/combustor (second quarter FY 2013)
7. In-engine test of LSI/combustor; identify and monitor potential impact on relevant turbine performance parameters (first quarter FY 2014)
8. Demonstrate LSI three-fuel turbines on a host site selected by the original equipment manufacturer (fourth quarter FY2014)

Utility-Scale Natural Gas LSI Objectives:

1. Engine-ready LSI pilot for natural gas operation (third quarter FY 2010)
2. Rig test of LSI pilot with alternate fuels (second quarter FY 2011)

Component and Subcomponent Development Objectives:

1. Verify performance of H_2 LSI with modified nozzle (third quarter FY 2010)
2. Conceptual fuel injection scheme for multi-fuel operable LSI (fourth quarter FY 2010).
3. Engineering guidelines for H_2 LSI (first quarter FY 2011)

Core Technology Support Research Objectives:

1. Measure turbulent flame speeds at gas turbine conditions (second quarter FY 2010)
2. Report on the acoustic signatures of LSI flames and the impact on H_2 operation (fourth quarter FY 2010)

09: FWP-AL05205018

Project Number FWP-AL05205018	**Project Title** Analysis of Gas Turbine Thermal Performance			
Contacts DOE/NETL Project Mgr.	**Name** Robin Ames	**Organization** NETL – Power Systems Division	**Email** Robin.Ames@netl.doe.gov	
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Partners	Iowa State University University of Pittsburgh			
Stage of Development				
__Fundamental R&D	X Applied R&D	__ Proof of Concept	__Prototype Testing	__ Demonstration

Technical Background:

Developing turbine technologies that operate on coal-derived synthesis gas (syngas), hydrogen fuels, and oxyfuels is critical to the development of advanced power-generation technologies such as integrated gasification combined cycle and to the deployment of near-zero-emission power plants that can lead to the capture and separation of carbon dioxide (CO_2). The efficiency and service life of the gas turbine engine are strongly affected by the turbine component, regardless of whether the fuel burned is natural gas (the predominant fuel used in current electric power generation gas turbines), syngas, a hydrogen mixture, or an oxyfuel. The thermal energy contained in the high-pressure and high-temperature gas is converted into mechanical energy to drive the compressor and the electric generator. The most effective way to increase the efficiency of the turbine component is to raise the temperature of the gas entering the turbine component. This temperature can be as high as the adiabatic flame temperature from the combustion of fuel and oxidizer. Although the temperatures sought today of up to 1,755 kelvin (K) are still considerably lower than the adiabatic flame temperature (indicating that there is still room to increase efficiency by increasing inlet temperature), 1,755 K already far exceeds the maximum temperature that the best super alloys and thermal barrier coatings (TBC) can withstand while still maintaining structural integrity and reliable operation (i.e., 1,320–1,475 K for super alloys without TBC and 1,475–1,625 K with TBC). Thus, cooling (e.g., internal, film, and impingement) is essential to achieve a reasonable service life for all parts of the turbine surfaces that come in contact with the hot gases.

Since cooling requires work input (e.g., raising the pressure of cooling flow high enough to enter and cool the turbine), effective cooling (i.e., ensuring material temperatures never exceed the maximum allowable material temperature) must be accomplished efficiently. This issue deserves increasing attention for three major reasons:

1. Today’s turbines are already designed to operate very close to the maximum allowable temperature of materials currently used in turbine design, limiting the margin of error during the cooling process.
2. The industry’s current goal is to reduce cooling flow by 50% to further increase operational efficiency; however, it is already extremely difficult to cool effectively with the existing flow rates. New cooling strategies can be developed only with in-depth understanding of the effects of fluid mechanics on heat transfer, as well as how the super alloy and the TBC couple external heat transfer on the hot-gas side (both with and without film cooling) with the internal heat transfer on the cooling side.
3. When syngas, hydrogen fuels, or oxyfuels are burned, the heat transfer characteristics in the turbine on the hot-gas side can increase because of increased water vapor content,

increased erosion and deposition tendencies, and increased hot-gas mass flow rate, which could make cooling even more difficult. Therefore, the margin of error allowed in the design of cooling strategies is small. For example, a temperature of 10–20 K beyond the maximum allowable temperature of the material will lead to material degradation, subsequently reducing turbine service life.

Current design and analysis tools used to explore, develop, and evaluate cooling strategies at the systems level do not account for the effects induced by individual heat-transfer enhancement elements in internal cooling passages (e.g., ribs and pin fins) or for each hole for film cooling. Typically, a bank of ribs or pin fins is represented by a single effective heat-transfer coefficient, which smears out local variations induced by each rib and each pin fin. If the variations in the heat-transfer coefficient induced by each rib or pin fin could produce temperature variations that are sufficiently large, then not accounting for them could lead to cooling strategies designs that would allow for hot spots to form (i.e., local regions where the temperature could exceed the maximum allowable material temperature). Thus, it is important to develop and evaluate design tools, such as those based on computational fluid dynamics (CFD), that can provide the needed understanding. It is also important to use CFD design and analysis tools to understand the effects of design and operating parameters on the flow and heat-transfer processes that could be used to guide the development of new cooling strategies.

Relationship to Program:

This project will support important advances within the heat transfer and aerodynamics focus of the NETL Advanced Turbines Program. It also supports DOE's goal of developing future high-performance, high-efficiency, and near zero-emission power plants. The key aspect of the project is to develop and evaluate physics/math-based analysis tools that can be used to examine heat-transfer issues in turbine components and to apply those analysis tools to support the development of advanced turbines for near-zero-emission, coal-based power systems. This project will provide insights on flow and heat-transfer mechanisms to guide design; explore, develop, and evaluate innovative concepts for cooling; and provide data needed by zero/first-order methods for design and analysis of complete turbine systems.

Current cooling design and analysis tools at the systems level do not account for the large local variations in heat transfer and temperature distributions that can occur in turbine cooling, variations that are large enough to overheat materials. Currently, these unaccounted variations are remedied by inconsistent safety measures that cause over-cooling in some turbine locations and insufficient cooling in others. This work develops and evaluates CFD-based design tools that account for the large local variations in heat transfer and temperature distributions, and generates understanding of these variations, enabling turbine cooling design that can handle turbine inlet temperatures of 1,755 K with half of the cooling flow rate.

Primary Project Goal:

This project has two main goals. The first goal is to develop, evaluate, and improve physics/math-based analysis tools such as Fluent and/or CFX that can be used to examine and explore heat-transfer issues in the design of cooling strategies for the turbine component. The second goal is to apply those analysis tools to support the development of effective and efficient cooling strategies by providing fundamental understanding of the issues. The project team is interested in tools that can properly account for the steady and unsteady three-dimensional heat transfer of hot gas from inside the turbine blade passage, through the turbine material (the TBC system and the superalloy), and into the internal cooling passages in order to develop a cooling strategy that considers the composition, mass flow rate, and temperature of the hot gas entering the turbine.

Objectives:

The following four project objectives extend from 2004 to 2014:

1. Compile the literature on turbine component cooling that considers the systems perspective of the problem, including exterior aerodynamics in the blade passages, flow in the internal cooling passages, the superalloy and the thermal barrier coating that are used to make the turbine, the seals and gaps, and tip leakage flows.
2. Develop methods to assess errors in CFD solutions.
3. Explore and examine heat-transfer issues that affect turbine performance and service life that are of interest to electric power generation and gas turbines fueled by natural gas, syngas, hydrogen fuels, and oxyfuels.
4. Explore and develop the understanding needed to construct innovative cooling strategies.

10: FY10.ESD.1610243.623

Project Number FY10.ESD.1610243.623	**Project Title** Aerothermal and Fundamental H_2 Studies and CO_2 Recycle Effects			
Contacts DOE/NETL Project Mgr.	**Name** Kent Casleton	**Organization** NETL – ORD	**Email** Kent.Casleton@netl.doe.gov	
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Partners	West Virginia University; University of Pittsburgh			
Stage of Development				
_X_ Fundamental	_ Applied	__Proof of Concept	__Prototype Testing	_ Demonstration

Technical Background:

Advanced power systems will continue to require improved environmental performance and efficiency. Future research and development will focus on these improvements and on meeting demands for cost-effective energy.
The NETL Advanced Turbines Program has a goal to achieve nitrogen oxides (NO_x) emissions levels of less than 2 parts per million by volume (ppmv) at target turbine inlet temperatures that are higher than temperatures for the current fleet of engines. The NO_x emissions goal is three to five times lower than the current state-of-the-art gas turbine combustors. The highly variable fuel compositions of high-hydrogen-content fuels should have a significant impact on the development and operation of future gas turbine combustors. Some concerns that are likely to be important to the use of fuels with high-hydrogen content in gas turbines include flashback, combustion dynamics, flame blowoff, NO_x formation, and heat transfer.

The goal of higher turbine efficiencies will require the turbine inlet temperatures of future turbine systems to increase substantially above current levels. Cooling air will also need to be controlled to avoid an increase in NO_x emissions. The focus of the Aerothermal Research activity is to collect aerothermal heat-transfer data at elevated pressures and temperatures, simulating gas turbine operating conditions. These validation datasets will be available to improve aerothermal cooling effectiveness, reduce NO_x emissions, and increase turbine efficiencies.

The Department of Energy is supporting the development of gas turbines for integrated gasification combined cycle (IGCC) applications. These turbines would use either coal synthesis gas (syngas) or other high-hydrogen-content fuels. However, flame flashback and combustion instabilities can result, causing potential damage to hardware, when syngas or high-hydrogen-content fuels are used in existing lean, premixed gas turbines. To meet these challenges and meet DOE's aggressive NO_x goals, NETL is investigating a novel concept that involves highly strained, dilute, hydrogen-diffusion flames. Nitrogen, an available byproduct from oxygen-blown IGCC power plants, is used to dilute the hydrogen fuel. The diluted fuel, combined with very high-injection velocities and small fuel injectors, significantly reduces NO_x. This work seeks to determine the NO_x emission capabilities for this concept at temperatures and pressures applicable to gas turbine systems.

Carbon capture and removal is an important component of DOE's portfolio for the next generation of power systems. IGCC and high-hydrogen-content fuel turbines are key elements in the overall program. Currently, the majority of gas turbines are fueled by natural gas. Exhaust-gas recirculation (EGR) could potentially offer an option for improving the efficiency of post-combustion carbon dioxide (CO_2) removal in natural gas-fired engines. In this concept, a portion of the engine exhaust gas is utilized for EGR. This process increases the CO_2 levels in the plant exhaust gas while decreasing the volume of combustion products for post-combustion processing. When combined, these factors could reduce the cost of CO_2 removal significantly. The purpose of this project is to evaluate the effects of CO_2 recycle levels on combustion characteristics such as flame anchoring, swirl and mixing, combustion dynamics, and emissions.

AEROTHERMAL HEAT-TRANSFER STUDIES

Achieving DOE's efficiency goals for land-based gas turbines will require engine-firing temperatures to be increased above the current state of the art. This increase in operating temperature will put significant demands on materials and cooling methodologies. This project seeks to collect aerothermal heat-transfer data at elevated pressures and at simulated gas turbine conditions. These validation datasets will be useful for improving aerothermal cooling effectiveness, reducing NO_x emissions, and increasing turbine efficiencies. Data will be collected on a baseline fuel and a fuel that is representative of the hydrogen turbine environment.

This project leverages the aerothermal heat-transfer expertise at the University of Pittsburgh with NETL's extensive background in and experimental facilities for high-pressure combustion in gas turbine systems. The main objective of this project is to explore systematically the issues of aerothermal cooling that are pertinent to high-hydrogen and oxyfuel turbine systems. The project team will investigate different cooling strategies, including backside impingement and film cooling for bare coupons and coupons with thermal barrier coatings.

The primary focus of activities to date has included the following:

- Completing all safety-related requirements associated with installing a new optically accessible pressure vessel component into the existing combustion test rig
- Completing the shakedown of the aerothermal rig and associated test modules
- Developing and implementing techniques to measure the hot-side surface temperature of the test coupon
- Working with an external partner (Apogee Scientific) to implement a multispectral optical-imaging approach to determine test-coupon surface-temperature distributions. The initial application would be for the measurement of temperatures on the coupon back-side surface
- Initiating Phase 1 testing— flat coupons with back-side impingement cooling

Modifications and shakedown testing have been completed. Based on these preliminary tests, the following items have been highlighted:

- The new safety instrumented system performed well.
- The approach for optically measuring the hot-side surface temperature was successfully demonstrated.
- The target gas temperatures (greater than 1,200°C) and surface temperatures (800°C–1,000°C) are easily achieved.

Preliminary testing also identified the following areas for improvement:

- The smooth wall liner was removed from the system. As a result, the schedule has suffered. The modified system has not yet been tested.
- There were some issues with rust particles in the air lines. These particulates deposited on the back side of the test coupon and caused some issues with the

optical viewports. A portion of the air piping has been replaced and filters have been installed.

HYDROGEN DILUTE DIFFUSION COMBUSTION STUDIES

Existing lean, premixed gas turbines operating on natural gas are susceptible to a number of problems, including flame flashback and combustion instabilities, when they are operated using fuels that contain large amounts of hydrogen. Combustion strategies for syngas and hydrogen that utilize diffusion flames, in which the fuel and air are not premixed prior to combustion, are much less prone to combustion instabilities. The challenge is to design a diffusion combustor that operates at high turbine-inlet temperatures but still meets DOE's aggressive NO_x goals.

NETL's approach to this challenge involves highly strained, dilute-hydrogen diffusion flames. Nitrogen, an available byproduct in an oxygen-blown IGCC power plant, is used to dilute the hydrogen fuel. This reduces peak flame temperature, increases mixing to reduce flame size, and improves static flame stability. The diluted fuel injector uses very high injection velocities and small fuel injectors to reduce NO_x production significantly. This project combines small-scale laboratory experiments; larger scale, high-pressure experiments; and computational modeling to explore the use of flame strain for reducing NO_x emissions, characterizing NO_x formation in highly strained, dilute diffusion hydrogen flames, and determining if this approach is viable for a hydrogen combustor.

Recent project accomplishments include the following:

- Investigated geometry and scalability issues involved in the design of a multi-point, array-style injector for achieving DOE's NO_x emissions goals. The flame-holding stability of a three-lobed injector design was evaluated and appears to be superior to an annular air injector and a star-shaped injector design, while also providing comparable NO_x emissions and lower pressure drop.
- Performed computational fluid dynamics (CFD) simulations to model the flame. These were validated against experimental results and then used to refine scaling laws for NO_x emissions and to identify improved injector designs for better performance.
- Completed a detailed mechanical design of an array-style injector for high-pressure testing in NETL's SimVal test facility at representative gas turbine conditions.
- Determined the effects of combustion product recirculation, array spacing, and adiabatic combustion environment on NO_x emissions and flame-holding stability for a dump-plane-style injector.

CO_2 RECYCLE EFFECTS (CO_2 RECYCLE FOR IMPROVED CARBON CAPTURE)

Exhaust gas recirculation (EGR) is being considered as a possible option in advanced gas turbine systems as a way to concentrate CO_2 in the exhaust. This process would improve the efficiency of CO_2 post-combustion removal processes and reduce the volume of flue gas that would need to be processed. This could ultimately lead to a significant decrease in the cost of carbon removal. However, these changes to the overall combustion environment could affect the combustion process and potentially affect the combustion stability and emissions. The goal of this research is to examine the impact of EGR on combustion phenomena such as combustion dynamics.

Testing is performed in a fully premixed, atmospheric-pressure, laboratory-scale burner. Fuels to be studied include various blends of hydrogen (H_2) and methane (CH_4) diluted with nitrogen (N_2) and CO_2 to simulate EGR. Acoustic pressure and velocity as well as global and spatially resolved heat release measurements are made to evaluate the impact of fuel composition and dilution on various physical mechanisms that drive the combustion instabilities. The effect of EGR on flame temperature and emissions with respect to safe operating limits (relative combustion dynamics) will also be considered in order to assess the potential for efficiency or environmental impact improvements.

Complementary simulation studies are performed using chemical reactor network (CRN) modeling and CFD simulation using commercial CFD software. CFD simulations are used to determine detailed flow and temperature fields. While CRNs can be computationally much less expensive, once they are validated they can be used to explore details of the chemistry.

Relationship to Program:

This project will support important advances within the heat transfer and aerodynamics pathway of the NETL Advanced Turbines Program. If the aerothermal project is successful, it will improve confidence and acceptance of advanced cooling concepts, which will result in subsequent improvements in overall cycle efficiency for high-hydrogen-content fuel or oxyfuel turbine systems. If the project successfully achieves acceptable NO_x emissions levels through strained high-hydrogen diffusion flames that are diluted with nitrogen, the project will result in a gas-turbine combustor concept that shows acceptable NO_x performance and will achieve other associated benefits, including reduced susceptibility to combustion instability issues and flashback. If the CO_2 recycle project is successful, it will identify the impact of CO_2 exhaust-gas recycle on combustor operability, including emissions reduction and control of thermoacoustic instabilities, potentially leading to a viable approach to reduce the cost of carbon capture from turbine exhaust.

Primary Project Goal:

The primary goal of this project is to provide advanced research and development of highly efficient turbine combustors with near-zero emissions for coal-derived fuels, such as syngas or hydrogen, and for fuels that are more conventional.

Objectives:

Some of the pertinent project objectives for this fiscal year are as follows:

1. Aerothermal—Establish baseline heat-transfer data for back-side impingement cooling and film cooling for flat coupons as a function of pressure, flow, and temperature.
2. H_2 Dilute Diffusion combustion—Complete the design and fabrication of an array-style low-NO_x injector and test the injector at gas turbine conditions to determine the baseline NO_x emissions.
3. CO_2 recycle studies—Evaluate the impact of CO_2 recycle on combustion dynamics in the laboratory-scale combustor in both high- and low-swirl stabilization configurations. Measure the emissions of the laboratory-scale combustor, evaluating the effects of CO_2 recycle. Evaluate the ability of computational modeling to predict emissions for CO_2 recycle.

11: DE-FC26-08NT0005055

Project Number FC26-08NT0005055	**Project Title** Designing Turbine Endwalls for Deposition Resistance with 1400°C Combustor Exit Temperatures and Syngas Water Vapor Levels			
Contacts DOE/NETL Project Mgr.	**Name** Mark C. Freeman	**Organization** NETL – Power Systems Division	**Email** Mark.Freeman@netl.doe.gov	
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Partners	Ohio State University Brigham Young University			
Stage of Development				
X__Fundamental R&D	__Applied R&D	__Proof of Concept	__Prototype Testing	__Demonstration

Technical Background:

Due to significant advances in materials and cooling technologies over the last few decades, turbine inlet temperatures for large power-generation gas turbines have been steadily increasing. At the same time, political and economic pressures are pushing utilities to consider fuel flexibility by using synthesis fuels (synfuels) that have higher concentrations of trace elements and ash compared to "clean-burning" natural gas. Current plans to transition from current synthesis gas (syngas) to high-hydrogen fuels produced from coal syngas and oxyfuels will only exacerbate these challenges with high water vapor levels. The combination of increased engine operating temperatures and synfuel integration warrants a reevaluation of current hot-gas path design to consider the potential impact of deposition.

In the first-stage high-pressure turbine vane (nozzle), the majority of material system failures occur at the junction of the vane and the passage endwall. Secondary flows in this region create unique challenges for thermal management and efficient cooling design. Recent initiatives of passage endwall contouring and vane leading edge modifications have been developed for use with natural gas-fired turbines, and thus their compatibility with ash-bearing and/or high steam-content synfuels at elevated operating temperatures has yet to be assessed. Clearly, there is a critical need to explore innovative endwall designs that could both increase turbine durability and mitigate the adverse effects of deposition in the endwall.

Relationship to Program:

This project will support important advances in the heat transfer and aerodynamics pathway of the NETL Advanced Turbines Program. This project will explore modifications to turbine endwall geometries that will both increase their aerodynamic performance and reduce the potential for degradation caused by deposition. Through this project's efforts, DOE and the U.S. gas turbine industry will gain valuable insights into factors that affect the safe, efficient operation of modern industrial turbines with alternative fuels and will gain access to new, innovative endwall designs that are tailored for this more adverse operating environment. In addition, a critical, new deposition modeling capability will be validated and exercised using state-of-the-art engine hardware.

Primary Project Goal:

The primary goal of this multi-year research effort is to explore the possibility of modifying turbine endwall geometries to both increase their aerodynamic performance and reduce the potential for degradation caused by deposition. The effort includes both experimental and computational components. The experimental work is divided between two reacting flow turbine test facilities: one at Brigham Young University (BYU) and the other at Ohio State University (OSU). The facility at BYU will be used for high-temperature (up to 1,400°C) deposition experiments with film cooling capability. This facility will also be adapted to allow elevated diluent (water vapor) concentrations. The OSU facility provides the capability to test actual turbine vane flowpaths at operating temperatures with film cooling. Experimental data from both facilities will provide critical validation for computational models of deposition being developed under this same research effort.

Objectives:

Project objectives through December 2009 included the following:

- Select computational framework for deposition modeling initiative.
- Develop and validate particle deposition model.
- Modify BYU's turbine accelerated-deposition facility (TADF) to accommodate 1,400°C gas temperatures.
- Complete OSU's turbine reacting flow rig (TuRFR) assembly and check out.
- Conduct hot cascade tests with deposition in OSU's TuRFR facility.

Future project objectives include the following:

- Perform endwall optimization using computational fluid dynamics.
- Test modified endwall with and without film cooling in TuRFR to determine deposition resistance.
- Conduct deposition testing in BYU TADF at 1,400°C.
- Conduct deposition testing in BYU TADF with augmented water vapor levels.

12: DE-AC26-04NT41817

Project Number DE-AC26-04NT41817	**Project Title** Carbon Capture Approaches for NGCC Systems			
Contacts DOE/NETL Project Mgr.	**Name** Walter Shelton	**Organization** NETL - Systems Division	**Email** Walter.Shelton@netl.doe.gov	
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Partners	(none)			
Stage of Development				
__Fundamental R&D	X Applied R&D	__ Proof of Concept	__ Prototype Testing	__ Demonstration

Technical Background:

A series of system studies that include performance estimates and economic assessments were formulated for natural gas combined cycles (NGCC) with carbon capture and sequestration (CCS). Cases 1 through 5 cover a range of different approaches for carbon capture based on post-combustion, pre-combustion, or oxycombustion. None of these systems are currently deployed; they vary from systems that can be considered commercially available to systems that are conceptual and require considerable development.

TABLE 1. OVERVIEW OF THE CASE MATRIX FOR THIS STUDY.

Case	Description	Steam Cycle	Combustion Turbine	Steam Generation	Oxidant	Nitrogen oxides (NO_x) Control	Carbon dioxide (CO_2) Separation	CO_2 Capture
Ref non-capture	No capture	2,400 pounds per square inch gauge (psig)/1,050°F/1,050°F	Advanced F Class	Heat-recovery steam generator	Air	Low-NO_x burner and selective catalytic reduction	N/A	90%
Ref capture	Post-combustion capture	2,400 psig/1,050°F /1,050°F	Advanced F Class	Heat-recovery steam generator	Air	Low-NO_x burner and selective catalytic reduction	Mono-ethanolamine	90%
1	Post-combustion with flue gas recycle	2,400 psig/1,050°F /1,050°F	Advanced F Class	Heat-recovery steam generator	Air	Selective catalytic reduction	Mono-ethanolamine	90%
2	Pre-combustion auto thermal reforming	2,400 psig/1,050°F /1,050°F	Advanced F Class	Heat-recovery steam generator	Air	Selective catalytic reduction	Methyl-diethanolamine	90%
3	Pre-combustion, high-pressure partial oxidation	2,400 psig/1,050°F /1,050°F	Advanced F Class	Heat-recovery steam generator	Air	Selective catalytic reduction	Methyl-diethanolamine	90%
4	Oxycombustion with carbon dioxide recycle	2,400 psig/1,200°F /1,200°F	High-pressure ratio CT	Heat-recovery steam generator	Oxygen	N/A	Oxyfuel	>99%
5	Oxycombustion with water/steam recycle	CES design	CES design	N/A	Oxygen	N/A	Oxyfuel	>99%

The reference NGCC cases are consistent with Cases 13 and 14 in the NETL "Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity," Revision 2 (anticipated publication April 2010). This reference NGCC with CCS case utilizes an amine absorber for post-combustion CO_2 separation.

To improve upon the reference case post-combustion capture process, Case 1 considers exhaust-gas recirculation. In this approach, a portion of the flue gas stream (here, 35% and 50%) is recirculated to the gas turbine compressor; the remainder of the flue gas stream enters the amine carbon-capture system. This approach demonstrates several improvements over a case without recirculation. Namely, it increases the CO_2 concentration and decreases the oxygen (O_2) concentration of the stream entering the amine system. This improves capture performance by requiring less auxiliary power, and lowers the steam requirements, resulting in higher net efficiency.

The project team has considered two cases that use pre-combustion capture. In Case 2, auto thermal reforming (ATR) is used to convert natural gas into a syngas composed primarily of hydrogen, carbon monoxide, and nitrogen. After the ATR section, water-gas shift and acid-gas removal are used to provide a hydrogen-rich fuel. In Case 3, the process is similar, but the ATR is replaced by a partial-oxidation reactor. Both cases require the inclusion of a gas turbine that operates on a hydrogen-rich fuel. Currently, NETL is sponsoring the development of this type of gas turbine for integrated gasification combined cycle applications with General Electric and Siemens. The technology would then be applicable to these NGCC cases and provide additional candidate processes for next-generation gas turbines.

The project team has considered two cases that use oxycombustion capture. In Case 4, the streams entering the combustor consist of oxygen, natural gas, and CO_2. The oxygen is supplied by a high-purity (98.5% O_2) air-separation unit, and the CO_2 is supplied by recirculating a large percentage (~90%) of the flue gas after cooling to remove water. The remaining flue gas is then compressed to a pressure of 2,215 pounds per square inch absolute (psia). This compression process removes any remaining water. In Case 5, a variation of a process developed by Clean Energy Systems (CES, which received NETL funding for development) was modeled. This process includes a high-pressure gas generator that uses natural gas, oxygen, and the injection of water and steam. The process considered differs from CES because it includes steam injection in this section. The produced gas stream enters a high-pressure expander, and the exhaust enters a second combustion section supplied with additional natural gas and oxygen. This combustor exhaust then enters a series of expanders to generate additional power. The expansion ends at a low pressure of ~ 2 psia. Subsequent cooling and compression removes water, and the final CO_2 stream is ready for sequestration at 2,215 psia. The recovery of water produced by fuel combustion is another feature under assessment for the oxycombustion cases, particularly whether the production of water during this process results in net water production.

Relationship to Program:

This project will support important advances within the systems studies focus of the NETL Advanced Turbines Program. The study benefits include the following:

- The information will be valuable when comparing different ways of meeting future energy demands in a carbon-constrained environment.
- NETL has a suite of models and cost estimates available that are based on different approaches for carbon capture in NGCC power plants. These models can serve as a

basis for developing new studies that will enable quick comparisons with similar proposed future processes as technologies evolve and are further developed.

- The cases considered serve as a means for identifying areas requiring additional research and development, while indicating what can be expected to be currently available.
- This study expands DOE/NETL modeling capabilities by considering both currently available processes (post-combustion) and exploring new developing options (pre-combustion and oxycombustion).

Primary Project Goal:

The objective of the study is to estimate the performance and cost of NGCC power plants with CCS. Most of the technology configurations examined here have been proposed and examined in previous studies by several different research groups and companies. The goal of this project was to generate and examine the cases using a consistent set of both process and economic assumptions in a single comprehensive study.

Objectives:

The project objectives include the following:

1. Utilize ASPEN PLUS simulations to complete performance estimates for multiple configurations of NGCC with CCS, including post combustion, pre combustion and oxycombustion processes.
2. Use consistent economic assumptions to complete capital cost estimates and levelized cost of electricity (LCOE) estimates for each NGCC with CCS.
3. Document the results of the analysis in a report that details the avoided cost of CO_2 capture and compares the different carbon capture approaches that were explored.

13: DE-FC26-05NT42645

Project Number DE-FC26-05NT42645	**Project Title** Coal-Based Oxyfuel Systems Evaluation and Combustor Development			
Contacts DOE/NETL Project Mgr.	**Name** Robin Ames	**Organization** NETL – Power Systems Division	**Email** Robin.Ames@netl.doe.gov	
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Partners	Siemens Energy Florida Turbine Technologies, Inc.			
Stage of Development				
_Fundamental	__ Applied R&D	_Proof of Concept	X Prototype Testing	__ Demonstration

Technical Background:

Clean Energy Systems, Inc. (CES) has developed a high-pressure, oxyfuel combustion technology based upon proven rocket technology. Precision gas-stream metering and atomization enables its combustors to burn clean gaseous and/or liquid fuel with gaseous oxygen (O_2) at near-stoichiometric conditions, utilizing injections of demineralized water for temperature control. The CES design uses photo-etched platelet technology to create precision metering channels within its injectors that are robust, consistent, and repeatable. Because air is eliminated from the combustion process, nitrogen oxide (NOx) emissions are lower than current state-of-the-art control technology. The resultant drive gas (combustion products) is mainly a mixture of steam and carbon dioxide (CO_2) at a high temperature and pressure.

The drive gas is used to power steam turbines (conventional or advanced) or modified aero-derivative gas turbines. The process is a net producer of high-quality water and this excess can either be used on site or used to supplement cooling tower make-up water. A nearly pure CO_2 stream is readily separated from the residual steam in a geothermal-type condenser and is available for sequestration or commercial use. Each component in the CES cycle, except for the main and reheat (RH) oxyfuel combustors, is already commercially proven and can be found in standard power-generation applications.

With continual unrest in energy-producing areas of the world, increasing energy prices, and greater awareness of the problems associated with global warming, there is a clear need to develop energy systems that are more efficient, make use of a wide variety of fuel sources, lower plant emissions, and serve the needs of base load, distributed power, or peaking power systems. The CES combustion technology addresses each of these dimensions.

Relationship to Program:

This project will support important advances in zero-emissions fossil-fuel power generation within the oxygen turbines focus of the NETL Advanced Turbines Program. Each component in the CES cycle, except for the main and RH oxyfuel combustors, is commercially proven and can be found in standard power-generation applications.

The CES cycle has the following advantages:

- Compatible with multiple opportunity fuels
- Supports zero-atmospheric-emission power plants with full CO_2 recovery (> 99%)
- Supplies cost-effective CO_2 for EOR, EGR, and ECBM recovery
- Can produce power and H_2 for the hydrogen economy
- Improves plant efficiencies as advanced turbines become available
- Provides peak electricity-generating service at low cost, with ultra-low emissions
- Provides thermal energy for the desalination of water while also producing electricity and CO_2 for EOR
- Captures waste heat to improve LNG process efficiencies and economics while decreasing on-site emissions
- Retrofits existing must-run facilities with ultra low-emission power generation as a means to supplement and maintain existing critical power generation infrastructure.
- Fulfills reliability-must-run requirements by peaking power plant technology

With continual unrest in energy-producing areas of the world, increasing energy prices, and greater awareness of the problems associated with global warming, there is a clear need to develop energy systems that are more efficient, make use of a wide variety of fuel sources, lower plant emissions, and serve the needs of base load, distributed power, or peaking power systems. CES combustion technology addresses each of these issues.

Primary Project Goal:

Develop a detailed design of a pre-commercial oxyfuel combustor, taking into consideration the state of the art in the turbine industry with regard to size and operating states.

Objectives:

PHASE I

a. Model oxy-syngas combustion rankine cycle for best efficiency

Completed: September 2006

- CES used Aspen Plus to model the elements of an oxy-syngas power plant to identify oxyfuel cycle(s) with the highest efficiency. This included: (1) modeling all major plant systems and support equipment (2) screening approximately 45 oxy-syngas combustor/turbine configurations for the most promising concepts; (3) evaluating air separation unit (ASU) technologies; (4) modeling coal gasification and syngas cleanup technologies; (5) modeling heat-recovery steam generators; (6) modeling plant cooling and reheat systems; and (7) modeling CO_2 capture and conditioning systems. CES also evaluated existing turbines for a best fit with DOE objectives (syngas operation, high cycle efficiency, zero atmospheric emissions, and turbine availability by 2015) and modeled efficiency against capital costs of integrating subsystems into plant-wide systems.
- Following Aspen Plus screenings, the 45 oxy-syngas cycle configurations were reduced to the two most promising cycles, each with variations in system configuration, power output, fuel, and subsystem alternatives. CES selected an indirect oxy-syngas cycle as the near-term [2010] best case, and conducted further analyses. Using commercially available technology, this cycle employed a pressurized heat recovery steam generator to extract heat from the steam/CO_2 drive gas in order to produce pure steam for current steam turbines. For the long-term model [2015], a direct cycle was selected which incorporated four sequential technology improvements which CES and Siemens believed to be the most likely technologies to reach fruition. These improvements are as follows: (1) improved

oxy-combustor and high-pressure turbines; (2) a 10% reduction in intermediate pressure turbine (IPT) cooling and coolant leakage flows; (3) ASU efficiency improvements; and (4) advanced CO_2 compressors.

- CES and Siemens summarized these results in a white paper that reflects the product of modeling zero-emissions oxyfuel combustion power plants in both near-term (2010) and long-term (2015) cases. Results indicate that a 30% increase (higher heating value) in coal-to-grid efficiency is possible for the near-term cycle. For 2015 and beyond, given step-wise incorporation of technology breakthroughs, it should be possible to reach an efficiency of approximately 39%. The white paper also listed areas of long-term development (beyond 2015) capable of improving plant efficiency toward the DOE goal of 50 percent. Collectively, these improvements could boost long-term cycle efficiency by 4 percentage points, to approximately 43%.

b. Combustor preliminary design concept:

- CES assessed the utility of using its existing 20-megawatt-thermal (MWth) oxyfuel combustor at Kimberlina Power Plant (KPP) in Bakersfield, CA for syngas performance testing, and concluded that there were no safety or operational issues to preclude such testing. *Completed: January 2006*
- To conduct syngas testing, a mixing station was designed and fabricated at KPP to replicate various desired syngas compositions. In parallel, the plant facility and its oxycombustor were modified to accept syngas fuel (fuel and O_2 circuits were reversed to accommodate the mass flow differences in the lower heating value fuel). Tube trailers of constituent gases were acquired on a fast-track basis, and both NG and syngas injector configurations were tested with syngas and H_2-depleted syngas. The combustor was fired for up to 2.5 hours at power levels between 2.3 and 4.6 MWth, with flow, pressure, temperature, and emission data collected. *Completed: September 2006*
- Analysis of the syngas test data led CES to conclude that its existing main-injector design handled syngas extremely well. CES proposed the development of a 50 MWth syngas combustor (later 100 MWth) based upon existing 20 MWth and planned 170 MWth NG-fired combustors. The syngas combustor would incorporate modifications to the main oxyfuel-water injector to accommodate the lower heating value of syngas and H_2-depleted syngas. The concept would utilize a main injector to mix and react O_2 and syngas fuel, diluent (demineralized water) injectors to lower the drive gas temperature to available turbine inlet technology, and a control system to operate the combustor. This concept was approved and used as a basis for the detailed design of a pre-commercial, 100 MWth combustor during Phase II. Design of the main syngas injector followed lessons learned from prior NG combustor designs and specific syngas testing during Phase I. Design of remaining combustor components—specifically the combustion chamber, diluent water injectors, igniter, fuel, and O_2 manifolding— would closely follow the design of CES' 170 MWth commercial NG combustor. *Completed: September 2006*

c. Prepare research and development (R&D) implementation plan (R&DIP):
Submitted: March 2006

- An R&DIP was developed which included definitions of technical issues and approaches, subtask interdependencies, risk/benefit assessments, decision points, deliverables, and schedules for each subtask in this three-phase program. *Submitted to DOE 30 March 2006.*

PHASE II

a. Detailed design of a pre-commercial-scale combustor

- Detailed design work on a pre-commercial-scale oxy-syngas combustor began October 2, 2006. Design progress was leveraged by lessons learned from parallel CES development projects in NG-fired oxyfuel combustors. Common features among these projects included combustor barrel size (12-inch internal diameter [ID]), oxyfuel process (oxyfuel combustors with demineralized water injection), valve and instrumentation layout, compact skid design, and control system design. Although the heat rate of equivalent NG-fired combustors is much higher than that for lower caloric-value, coal-derived syngas (170 MWth for NG versus 100 MWth for syngas), process mechanics proved to be very similar. CES also utilized combustion-design information gained from previous DOE/NETL and Lawrence Livermore National Laboratory (LLNL) cycle studies and extensive field operating experience with a 4-inch NG combustor at KPP.
- The oxyfuel combustor drawing set was organized via a drawing tree that listed all the drawings needed for the manufacturing and assembly of the combustor's main injector, combustion chamber, cool-down chambers, and diluent injectors. To meet this need, 36-drawing sets of detailed engineering drawings were created. As an example of leveraging NG design efforts and lessons learned in KPP combustor operations, the syngas main-injector design incorporates a more corrosion-resistant material in the outer platelet layer for improved durability. *Completed September 2009*
- A piping and instrumentation diagram (P&ID) was the first element created for the combustor skid assembly (enclosure). The P&ID incorporated all piping, valves, and instrumentation required for the enclosure, including piping sizes, valve types and design, valve failure modes, and wiring layout. Detailed piping drawings and a complete listing of valve specifications (control, remote shutoff, check, throttling, and manual shutoff/isolation valves), piping and tubing specs, and instrumentation specs (compact/conditioning orifices and mass flow meters, differential and gauge pressure transmitters, resistance temperature detectors thermocouples and transmitters) were subsequently accomplished for all commodity and support systems. The enclosure will be approximately 11 feet wide, 11 feet high, and 30 feet in length. *Completed September 2009*
- The control system approach for the oxyfuel combustor utilizes smart valves and reporting protocols (Foundation Fieldbus and Hiway Addressable Remote Transducer) where feasible to take advantage of their internal diagnostics capabilities and reduced wiring requirements. Hard-wired controls were avoided except where valve response time was critical. In the case of the latter, direct-wired 4-20 milliamp (mA) signals were used. Control system logic is documented via SAMA (Scientific Apparatus Makers Association) symbols and diagramming conventions. These functional control diagrams are commonly used in the power industry to represent control logic that includes continuous, binary logic, and sequential functions. SAMA diagrams represent the language of choice throughout the power industry for instrumentation and control systems. *Completed April 2008*

b. Prepare validation test plan (see CES-Siemens white paper, July 29, 2008)

- The original purpose of the validation test plan was to define the test program for the oxy-syngas combustor, which would be fabricated and tested during Phase III. When fabrication of the combustor became unlikely due to the loss of federal funding, CES and Siemens proposed an alternative pathway to advancing the DOE goal of early deployment of advanced turbines. Their July 2008 white paper proposed accelerating the development of an oxyfuel IPT by adapting a gas turbine with a performance envelope that is compatible with the oxyfuel CES cycle. This would permit the design, fabrication, and testing of such an advanced turbine—the

OFT-900—by 2012. With this in mind, CES proposes to refocus the validation test plan from supporting a (cancelled) stand-alone, oxy-syngas test of the CES oxyfuel combustor to a coupled test of both the CES oxyfuel combustor and the advanced Siemens Energy OFT-900 turbine. The test plan will define the tests that would be performed, test parameters, test goals, data acquisition and methods, data analyses, schedules, and fuels. As CES has already demonstrated its 20 MWth oxyfuel combustor's compatibility with and suitable performance on simulated syngas, CES proposes to utilize NG in lieu of syngas to speed testing. Use of NG permits earlier testing and lower costs, as it eliminates the lead time and the cost to install gasification equipment. Subsequent testing with coal-derived syngas and high-H_2 and/or H_2-depleted fuels could follow when funding is available. Test plan completion is expected in September 2010.

c. Design and test syngas reheat combustor

- CES contracted with Florida Turbine Technologies (FTT) to design and fabricate a prototype reheat (RH) combustor, in order to test the efficacy of reheating the drive gas that exits a high-pressure turbine, prior to its delivery to an IPT, as a means of improving plant efficiency. Prior to beginning the design, FTT evaluated the feasibility of modifying an existing turbine combustor can to serve as an oxyfuel RH combustor. Using a CES-furnished J79 combustor can, FTT cold-flowed it in an instrumented facility to definitize the combustor's flow characteristics. An expert in turbine design and operations, FTT utilized proprietary in-house codes for gas turbine combustors to analyze the J79 can's flow test results; this analysis showed that the can had potential as an interim RH combustor. Under CES direction, FTT designed, modified, and instrumented two J79 combustors as oxyfuel RH combustors. FTT also designed instrumentation and test fixtures needed to hot-fire the modified combustors and evaluate their performance. *Completed November 2008*
- To test the prototype reheater, CES built a test fixture for the combustors and modified KPP subsystems to accommodate reheater testing. The latter involved the following: (1) designing and fabricating steam-, O_2-, and fuel (NG)-delivery systems; (2) adding exhaust and attemperation systems; (3) designing and installing an RH combustor control system; and (4) integrating the RH control system with the plant's existing oxyfuel combustor (steam source for the RH combustor). *Completed August 2009*
- Testing the new J79 RH Combustors began with cold-flow tests (steam and O_2, no ignition) to document their flow characteristics (*Completed September 2009*). This was followed by a period of hot-fire testing, which was periodically interrupted by conflicts with other planned test schedules. Initial hot-fire testing ended January 2010 and data analysis is in progress. Based on those results, additional testing may be recommended on reconfigured RH designs.

d. Detailed engineering redesign of an SGT-900 to an oxyfuel IPT (OFT-900)

- This task was added in July 2009 to accelerate the availability of the first advanced oxyfuel IPT by 5–10 years. It consists of the detailed engineering redesign of an existing aero-derivative gas turbine to serve as a high-temperature IPT suitable for use in the oxyfuel CES cycle. The Siemens SGT-900 was selected due to its combination of technical performance (inlet temperature and power output) and reasonable acquisition/modification costs. CES selected FTT as the lead engineering firm due to their extensive experience in turbine modeling and modifications and their close working relationship with the owner of the SGT-900 design, Siemens Energy. The scope of work covers the following:
    - (1) Turbine systems design and component integration;
    - (2) Rotor system design;
    - (3) Casing design and modification;

(4) Oxyfuel RH system;
(5) Turbine airfoil life assessment; and
(6) Turbine-exhaust-frame design modifications.

In the oxyfuel CES cycle, the axial flow compressor is eliminated and the existing combustion system is replaced by oxyfuel RH combustors delivering 80% steam and 20% CO_2. This task is scheduled for completion in September 2010.

14: DE-NT0006833

<table>
<tr><td colspan="1">Project Number
DE-NT0006833</td><td colspan="4">Project Title
Condition Based Monitoring of Turbine Combustion Components</td></tr>
<tr><td>Contacts
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Yanko Sheiretov, JENTEK Sensors, Inc.</td></tr>
<tr><td colspan="5">Stage of Development</td></tr>
<tr><td>__ Fundamental R&D</td><td>__ Applied R&D</td><td>__Proof of Concept</td><td>X Prototype Testing</td><td>__Demonstration</td></tr>
</table>

Technical Background:

This project is directed to develop wear and crack sensors for real-time condition monitoring of critical combustion parts to improve the reliability and availability of combustion turbines. The sensor system will directly monitor the prime failure modes of combustion parts, as well as wear and crack propagation, rather than monitoring indirect parameters that indicate these failure modes (e.g., temperature and strain). To accomplish these objectives, Siemens Energy, Inc. teamed with two innovative small companies (K Sciences GP, LLC and JENTEK Sensors, Inc.) that developed promising sensor concepts for monitoring hot component wear and cracking.

The program consists of six major tasks:

- Task 1 specifies the development needs of the monitoring system.
- Task 2 develops the wear sensor.
- Task 3 develops the crack sensor.
- Task 4 develops the models that assess part life.
- Task 5 develops the online parts condition monitoring system.
- Task 6 demonstrates the system in a gas turbine engine.

FIBER OPTIC WEAR SENSOR DEVELOPMENT

The wear sensor is based on fiber-optic technology specifically designed to monitor wear progression as the sensor tip erodes together with the wearing part. It is based on the optical light transmission principle governed by the Beer-Lambert Law, which states that there is a logarithmic dependence between the transmission or transmissivity of light intensity (I) through a substance and the product of the absorption coefficient (α) and the distance (L) the light travels through the material. The functional relationship of the parameters is expressed as follows:

$$I_1 = I_0 e^{-\alpha L}$$

The high-temperature wear sensor uses dual fiber-optic sensing elements with different attenuation coefficients. The sensing fibers detect optical emission from the hot–combustion-environment wearing surface in order to monitor wear progression as the sensing element erodes together with the wearing part. The sensor can operate by extracting light from the thermal radiation of the wear surface or from an external light introduced from a co-located fiber. The selection of the input light source depends on the temperature condition of the wearing part. At low temperatures, an external light source is used.

MAGNETIC SENSOR DEVELOPMENT

The multifunction magnetic sensor is an eddy-current sensor based on JENTEK's meandering winding magnetometer (MWM) array technology, which monitors crack and surface temperature by monitoring changes in the electrical and magnetic characteristics of the material. The MWM-array technology has specially-arranged conducting windings that consist of a drive winding to create a magnetic field and multiple sensing elements. To monitor cracks and temperature, a time-varying magnetic field is created by applying a current at a prescribed frequency to the drive winding. The resulting material-dependent response is processed using a multivariate inverse method and pre-computed sensor response database to allow the conductivity to be measured independently over a wide, dynamic range of nonlinear sensor responses. The change in conductivity can be related to temperature or crack initiation. When a crack, corrosion, or any material damage alters the flow of the eddy currents, the inductive sensing coils sense an absolute magnetic field that is altered locally by the presence of the crack or other damage. The measured quantities are absolute; they are compensated for lift-off (proximity) variations.

JENTEK developed and demonstrated low-temperature versions of this technology that they will adapt for high-temperature application under this program.

Relationship to Program:

This project, part of the Advanced Research Program, will support important wear and crack sensor advances to enable improvements in power plant availability, reliability, and maintainability. The high-temperature wear and magnetic sensors allow optimization of engine maintenance intervals based on real-time condition assessment of critical combustion parts, improving power plant availability, reliability, and maintainability. Direct monitoring of the prime failure modes of combustion parts, as well as wear and crack propagation, contrasts with the monitoring of indirect parameters that cause these failure modes. Direct monitoring provides accurate assessment of parts' condition and the remaining design life of parts while the engine is running.

There are additional benefits to developing each sensor technology: wear and crack sensing at high temperatures can be applied to many energy applications.

Primary Project Goal:

The goal of this project is to develop wear and crack monitoring technologies to enable real-time condition monitoring and assessment of critical hot-section combustion parts. This monitoring and assessment will allow optimization of maintenance intervals and improve power plant availability, reliability, and maintainability. The system will directly monitor the prime failure modes of combustion parts, as well as wear and crack propagation.

Objectives:

The project has the following objectives:

- Develop and demonstrate a high-temperature multifunction magnetic sensor to monitor cracking and temperature in hot-section combustion components.
- Develop and demonstrate a high-temperature wear sensor to monitor wear in hot-section combustion components.

15: DE-FC26-05NT42646

Project Number FC26-05NT42646	**Project Title** Zero Emissions Coal Syngas-Oxygen Turbo Machinery			
Contacts DOE/NETL Project Mgr.	**Name** Robin Ames	**Organization** NETL – Power Systems Division	**Email** Robin.Ames@netl.doe.gov	
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Stage of Development				
__ Fundamental R&D	_X_ Applied R&D	__ Proof of Concept	__ Prototype Testing	__Demonstration

Technical Background:

The NETL Advanced Turbines Program is driven by the potential for highly efficient, utility-scale, coal-based power generation without nitrous oxide (NO_x) emissions and with almost 100% carbon dioxide (CO_2) capture. Oxyfuel combustion provides a conceptually simple way to remove CO_2 from a fossil-fueled power plant. In these systems, hydrocarbon fuel is burned with nearly pure oxygen and evaporating feedwater to produce a working fluid comprising mostly steam and CO_2. The working fluid produces power in advanced expansion turbines, after which its water component is condensed, leaving the CO_2 to be compressed and stored or utilized. The use of oxygen instead of air removes nitrogen from the combustion process, virtually eliminating NO_x emissions.

Power generation using oxyfuel combustion has been demonstrated on a small scale by Clean Energy Systems, Inc. (CES) of Rancho Cordova, California. Making these oxyfuel cycles competitively efficient requires advanced, steam-like turbines operating at gas-turbine temperatures, which have not yet been developed. This project attempts to develop such a high-efficiency, advanced turbine that utilizes oxyfuel.

Work during the first two years of the contract focused on cycle optimization, conceptual turbomachinery design, risk analyses, estimated economics, and market demand. Those efforts were concluded in 2007 and reviewed at the 2007 peer review. Funding limitations after 2007 slowed the pace of the project and prompted the project team to shift its focus from developing a new technology to adapting an existing gas turbine, the SGT-900, into an oxyfuel expander, the OFT-900. (See Siemens and CES white paper, 2008, for more details.)

During this time, the University of California at Irvine completed an independent simulation of oxyfuel plant performance using an OFT-900. Critical design considerations for the OFT-900 include the life of the components in its hot gas path, which led to the materials evaluation work. A critical design consideration of the OFT-900 (expander portion of the SGT-900) pertains to the life of the components in the hot gas path of an oxy-fuel power plant. The SGT-900 is designed for, and used commercially with, the products of natural gas combustion in air. Using a turbine where the gas is a mixture of steam and CO_2 is a significant departure from the normal operating environment of gas turbine materials. The materials used in the oxyfuel OFT-900 must be able to meet the demands of a new drive-gas environment and resist the oxidation and corrosive effects of the concentrated steam/CO_2 working fluid.

In order to assess the behavior of the alloy systems in an oxyfuel environment, oxidation and mechanical testing were performed and oxidation and corrosion studies were performed in steam/CO_2 and natural gas environments at Cranfield University in the United Kingdom. The gas composition selected for oxidation testing was 90% steam and 10% CO_2 by volume, simulating the approximate drive-gas composition at the inlet of the OFT-900. To obtain accelerated oxidation results, test temperatures were hotter than expected operating temperatures

The results indicate that, for all alloys tested, oxidation is more aggressive in a steam/CO_2 environment than in a typical gas turbine environment. Samples exposed to the steam/CO_2 environment showed increased bond-coat beta depletion (measure of oxidation). One reason for this bond coat depletion is the higher water vapor content of the drive gas, which interfered with the formation of protective oxide scales and instead formed less-protective transient oxides.

Beyond this past year's work to assess the effects of the oxyfuel environment on oxidation and mechanical properties of the blade and vane systems, the Siemens-FTT-CES team has planned materials tests that will provide design life information for blade, vane, and rotor materials in the oxyfuel OFT-900. Hold-time LCF tests will be performed to determine the fatigue-creep interaction of specimens exposed to the oxyfuel environment, and no-hold-time tests will be performed to determine the fatigue properties of the exposed specimens. Lastly, fracture mechanics properties, such as fracture toughness and fatigue crack growth, will be tested on the rotor steel in the steam/CO_2 environment to determine the effect, if any, of the environment on these properties.

Relationship to Program:

This project supports important advances in coal syngas turbomachinery within the oxyfuel turbines focus area of the NETL Advanced Turbines Program. New, advanced turbines for oxyfuel combustion will eliminate NO_x emissions, since the oxidizer is pure oxygen instead of air, and validate materials that are acceptable for use in oxyfuel environments.

Successful project completion will help NETL meet its overarching objectives of achieving greater than 99.5% CO_2 capture at coal power plants and enabling the continued use of coal, the least expensive and most abundant domestic fuel, in a carbon constrained economy. This technology will apply to oxyfuel turbines using natural gas (same drive gas) for near-term applications such as peaking power generation with enhanced oil recovery (EOR). Process improvements in steam cooling and other design technologies, such as rim-cavity sealing, will also benefit gas turbine products.

Primary Project Goal:

Develop high-efficiency, advanced turbine technology that utilizes oxyfuel-based working fluid and ensure that it is ready for commercialization around 2015.

Objectives:

Project partner CES was granted a complementary award (Program DE-FC26-05NT42645) to develop an oxyfuel combustor to supply the working fluid for Siemens turbines. CES is also responsible for modeling the plant cycle and optimizing the fluid conditions to maximize the efficiency under baseline, near-term, and far-term scenarios of hardware development.

The objectives for the Siemens turbine-development program are as follows:

1. Work with CES to define the baseline, near-term, and far-term temperature and pressure conditions necessary to maximize the cycle efficiencies for turbines in each time frame, and use this feedback for cycle selection.
2. Develop conceptual turbine designs that are suitable for the three cycles (baseline, near-term, and far-term) up to a point where risk analysis can be performed; use this information to solidify a future approach to detailed design that will minimize the technical risks.
3. Prepare a realistic assessment of available materials and processes, and develop a plan to bridge the gap between available materials and those needed to manufacture the turbines as designed.
4. Perform cost estimates and feasibility studies to be used in economic analysis and risk analysis.

APPENDIX F: LIST OF ACRONYMS AND ABBREVIATIONS

Acronym/ Abbreviation	Definition
AGR	acid-gas removal
Al	aluminum
ASME	American Society of Mechanical Engineers
ASU	air separation unit
ATR	auto thermal reforming
BRTD	Board on Research and Technology Development
BYU	Brigham Young University
C	carbon
CCC	Copyright Clearance Center
CCS	carbon capture and storage
CES	Clean Energy Systems, Inc.
CFD	computational fluid dynamics
Ch	chromium
CH_4	methane
C_2H_6	ethane
C_2H_4	ethylene
CC	combined cycle
Co	cobalt
CO	carbon monoxide
CO_2	carbon dioxide
CPR	Creative Power Solutions
Cr_2O_3	chromium [III] oxide
CMAS	calcium-magnesium-aluminosilicate
CMC	ceramic matrix composite
CRTD	Center for Research and Technology Development
CTL	Cincinnati Testing Laboratories, Inc.
DLN	dry-low-NO_x
DLR	German Aerospace Center
DOE	U.S. Department of Energy
EBC	environmental barrier coating
ECBM	enhanced coal-bed methane
EERC	Energy and Environment Research Center
EGR	exhaust-gas recirculation
EGR	enhanced gas recovery
EOR	enhanced oil recovery
Fe	iron
FY	fiscal year
GTCC	gas turbine combined cycle
H_2	hydrogen
H_2O	water
HHC	high hydrogen content

Acronym/ Abbreviation	Definition
HHF	high-hydrogen-content fuel
ID	internal diameter
IGCC	integrated gasification combined cycle
IPT	intermediate pressure turbine
K	degrees Kelvin
KPP	Kimberlina Power Plant
LBNL	Lawrence Berkeley National Laboratory
LCF	low-cycle fatigue
LCOE	levelized cost of electricity
LSI	Low-Swirl Injector
LTI	Leonardo Technologies, Inc.
MDEA	methyldiethanolamine
MEA	monoethanolamine
Mn	manganese
Mo	molybdenum
MWM	meandering winding magnetometer
MWth	megawatt-thermal
Nb	niobium
NDE	non-destructive evaluation
NETL	National Energy Technology Laboratory
NG	natural gas
NGCC	natural gas combined cycle
Ni	nickel
NiCr	nickel-chromium
NO_x	nitrogen oxides (e.g., NO, NO_2)
NSF	National Science Foundation
OCC	Office of Clean Coal
OEM	original equipment manufacturers
O-F	oxy-fuel
OH^-	hydroxide
OMB	Office of Management and Budget
OSU	Ohio State University
P&ID	piping and instrumentation diagram
POX	partial oxidation
ppm	parts per million
ppmv	parts per million by volume
psia	pounds per square inch absolute
psig	pounds per square inch gauge
Re	rhenium
RH	reheat
S	sulfur
SAMA	Scientific Apparatus Makers Association
SCR	selective catalytic reductions

Acronym/ Abbreviation	**Definition**
SEM	scanning electron microscope
SO_x	sulfur oxide compounds (e.g., SO, SO_2)
SX	single-crystal
synfuel	synthesis fuel
syngas	synthesis gas
Ta	tantalum
TADF	turbine accelerated-deposition facility
TBC	thermal barrier coatings
TET	turbine entry temperature
Ti	titanium
TuRFR	turbine reacting flow rig
W	tungsten
WGS	water-gas shift
Y	yttrium
YSZ	yttria-stabilized zirconia