Final Report
DOE/NETL Clean Coal Research Program
Advanced Energy Systems
FY 2012 Peer Review Meeting

Meeting Summary and Recommendations Report

Morgantown, West Virginia
April 23-27, 2012

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

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FINAL REPORT
CLEAN COAL RESEARCH PROGRAM
ADVANCED ENERGY SYSTEMS
FY2012 PEER REVIEW MEETING

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MEETING SUMMARY AND RECOMMENDATIONS REPORT

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DISCLAIMER

The work performed on this task/subtask was completed under Leonardo Technologies, Inc. (LTI), Prime Contract DE-FE-0004002 (Subtasks 300.02.02.000 & 300.02.09.000) for DOE/NETL.

MEETING SUMMARY AND RECOMMENDATIONS REPORT

EXECUTIVE SUMMARY

The mission of the DOE Clean Coal Research Program (CCRP), administered by the Office of Fossil Energy's National Energy Technology Laboratory (NETL), is to ensure the availability of ultraclean, near-zero emission, abundant, and low-cost domestic energy from coal in order to fuel economic prosperity, strengthen energy security, and enhance environmental quality.[1]

In fiscal year (FY) 2012, the CCRP has a structure that reflects the increased focus on carbon capture and storage (CCS) technologies. The structure aligns the existing work of the CCRP into two major program areas: CCS and Power Systems, and Carbon Capture, Utilization, and Storage Demonstrations. The CCS and Power Systems program area is composed of four research and development (R&D) sub-programs: Carbon Capture, Carbon Storage, Advanced Energy Systems, and Cross-Cutting Research.

The Advanced Energy Systems Program, the subject of this peer review report, focuses on improving the efficiency of coal-based power systems, enabling affordable carbon dioxide (CO_2) capture, increasing plant availability, and maintaining the highest environmental standards. The Program supports gasification-related R&D to convert coal into synthesis gas (syngas) that can in turn be converted into electricity, chemicals, hydrogen, and liquid fuels.

The Advanced Energy Systems Program consists of six elements:

1. Advanced Combustion Systems
2. Gasification Systems
3. Hydrogen Turbines
4. Hydrogen from Coal
5. Coal and Coal/Biomass to Liquids
6. Solid Oxide Fuel Cells

The FY2012 Advanced Energy Systems Peer Review includes projects that support the achievement of the Advanced Energy Systems Program's gasification and hydrogen turbines goals and objectives.

In compliance with requirements from the Office of Management and Budget, DOE and NETL are fully committed to improving the quality of research projects in their programs. To aid this effort, DOE and NETL conducted a FY2012 Advanced Energy Systems 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 23–27, 2012, to conduct a five-day Peer Review of selected Advanced Energy Systems research projects supported by NETL.

[1.] U.S. Department of Energy, Office of Fossil Energy, Office of Clean Coal, Office of Clean Coal Strategic Plan (Washington D.C.: U.S. Department of Energy, September 2006), http://fossil.energy.gov/programs/powersystems/publications/OCC_Strategic_Plan_external_Sept06.pdf.

Overview of Office of Fossil Energy Advanced Energy Systems Program Research Funding

The total funding of the 16 projects reviewed, over the duration of the projects, is $942,972,458. Of this amount, $714,055,561 (76%) is funded by DOE, while the remaining $228,916,897 (24%) is funded by project partner cost sharing. The 16 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 ENERGY SYSTEMS PROJECTS REVIEWED

***Projects 1-7: Turbine projects; Projects 8-15: Gasification Projects**

Reference Number	Project No.	Title	Lead Organization	Principal Investigator	Total Funding		Project Duration	
					DOE	Cost Share	From	To
1	FEAA070	Coating Issues in Coal-Derived Synthesis Gas/Hydrogen-Fired Turbines	Oak Ridge National Laboratory	Bruce Pint	$1,500,000	$0	01/01/2010	09/30/2012
2	ORD-2012.03.02 Task 5	Turbine Thermal Management - Secondary Flow Rotating Rig	National Energy Technology Laboratory – Regional University Alliance	Karen Thole & Michael Barringer	$2,148,952	$3,250,000	01/01/2011	09/30/2014
3	FE0004727	Mechanisms Underpinning Degradation of Protective Oxides and Thermal Barrier Coating Systems in HHC-Fueled Turbines	University of California, Irvine	Daniel Mumm	$500,000	$125,000	09/01/2010	08/31/2013
4	AL05205018	Analysis of Gas Turbine Thermal Performance	Ames National Laboratory	Tom Shih	$1,595,000	$0	10/01/2004	09/30/2012
5	FC26-05NT42645	Recovery Act: Oxy-Fuel Turbo Machinery Development for Energy Intensive Industrial Applications (Phase 2A)	Clean Energy Systems, Inc.	Rebecca Hollis	$34,707,837	$15,007,790	10/01/2005	09/30/2014
6	FC26-05NT42644	Recovery Act: Advanced Hydrogen Turbine Development	Siemens Energy Inc.	John Marra	$82,121,591	$53,091,433	10/01/2005	06/30/2015
7	FC26-05NT42643	Recovery Act: Advanced Hydrogen Turbine Development	GE Energy Inc.	Reed Anderson	$81,490,827	$52,819,059	10/01/2005	09/30/2014
8	DE-FE0007966	Advanced CO_2 Capture Technology for Low Rank Coal Integrated Gasification Combined Cycle (IGCC) Systems	TDA Research, Inc.	Gökhan Alptekin	$500,000	$125,000	10/01/2011	09/30/2012
9	FC26-05NT42469	Recovery Act: Scale-Up of Hydrogen Transport Membranes (HTM)	Eltron Research Inc.	Carl Evenson	$82,547,725	$5,115,175	10/01/2005	09/30/2015
10	FC26-98FT40343	Recovery Act: ITM Oxygen Technology for Integration in IGCC and Other Advanced Power Generation Systems	Air Products and Chemicals, Inc.	Douglas Bennett	$198,527,378	$92,696,155	09/01/1998	06/30/2014
11	DE-FE0007902	Scoping Studies to Evaluate the Benefits of an Advanced Dry Feed System on the Use of Low-Rank Coal in Integrated Gasification Combined Cycle (IGCC) Technologies	General Electric Company	Derek Aldred	$695,194	$173,798	10/01/2011	09/30/2012
12	DE-FE0007952	Mitigation of Syngas Cooler Plugging and Fouling	Reaction Engineering International	Michael Bockelie	$1,130,386	$310,864	10/01/2011	09/30/2014
13	FE0000489	Recovery Act: High Temperature Syngas Cleanup Technology Scale-Up and Demonstration Project	Research Triangle Institute	Raghubir Gupta	$171,792,957	$5,963,443	07/20/2009	09/30/2015
14	FE0005712	Model-Based Optimal Sensor Network Design for Condition Monitoring in an IGCC Plant	GE Global Research	Rajeeva Kumar	$956,714	$239,180	01/01/2010	12/31/2012

Reference Number	Project No.	Title	Lead Organization	Principal Investigator	Total Funding		Project Duration	
					DOE	Cost Share	From	To
15	ORD-2012.03.03 Task 4	Low Rank Coal Optimization	National Energy Technology Laboratory - Office of Research and Development	Chris Guenther	$6,291,000	$0	10/01/2011	09/30/2014
16	ORD.2012.04.02	Carbon Capture Simulation Initiative	National Energy Technology Laboratory - Office of Research and Development	David Miller	$47,550,000	$0	02/01/2011	01/31/2016
				TOTALS	$714,055,561	$228,916,897		

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

ADVANCED ENERGY SYSTEMS PROGRAM

The FY2012 Advanced Energy Systems Peer Review includes projects that support the achievement of the Advanced Energy Systems Program's gasification and hydrogen turbines goals and objectives. Research efforts for these projects are focused on the following goals.

Program Goals: Hydrogen Turbines

In 2012, demonstrate through full-scale component testing, hydrogen-fueled gas turbine technology with an increased efficiency of 2–3 percentage points and a 30% power increase above the hydrogen-fueled baseline machine. These advancements are associated with firing temperature increases culminating in full-scale combustion testing and advanced manufacturing trials for advanced hot gas component systems.

Key FY2012 milestones for hydrogen turbines include the following:

- Release turbulent flame speed correlation for hydrogen/syngas fuels.
- Complete full-can scale combustion testing with pre-production hardware at full load (i.e., 2012 hydrogen turbine) conditions.
- Complete manufacture of bi-cast vanes for engine test.
- Complete aero rig baseline testing.

Program Goals: Gasification Systems

In FY2012, the performance measures of gasification systems focus on supporting the development of advanced low-cost, low-carbon, and energy-efficient electrical generation technologies. The goal is to produce power with an integrated gasification combined cycle (IGCC) plant coupled with a CCS system, while targeting a minimal increase in the cost of electricity compared to the current baseline of conventional power generation plants.

Key FY2012 milestones for gasification systems include the following:

- Begin construction of the 30–100 tons per day (TPD) oxygen production test unit.
- Initiate testing of the 600 TPD high-pressure solid fuel pump.
- Complete the design of a test program for at least one warm gas technology's use of coal-derived syngas to remove trace contaminants at levels proposed under the Environmental Protection Agency's toxics rule limit for IGCC.
- Complete data generation and analysis to support a scoping study on novel technology designed to reduce the cost of low-rank coal gasification.

Overview of the Peer Review Process

NETL requested that ASME assemble an Advanced Energy Systems 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.

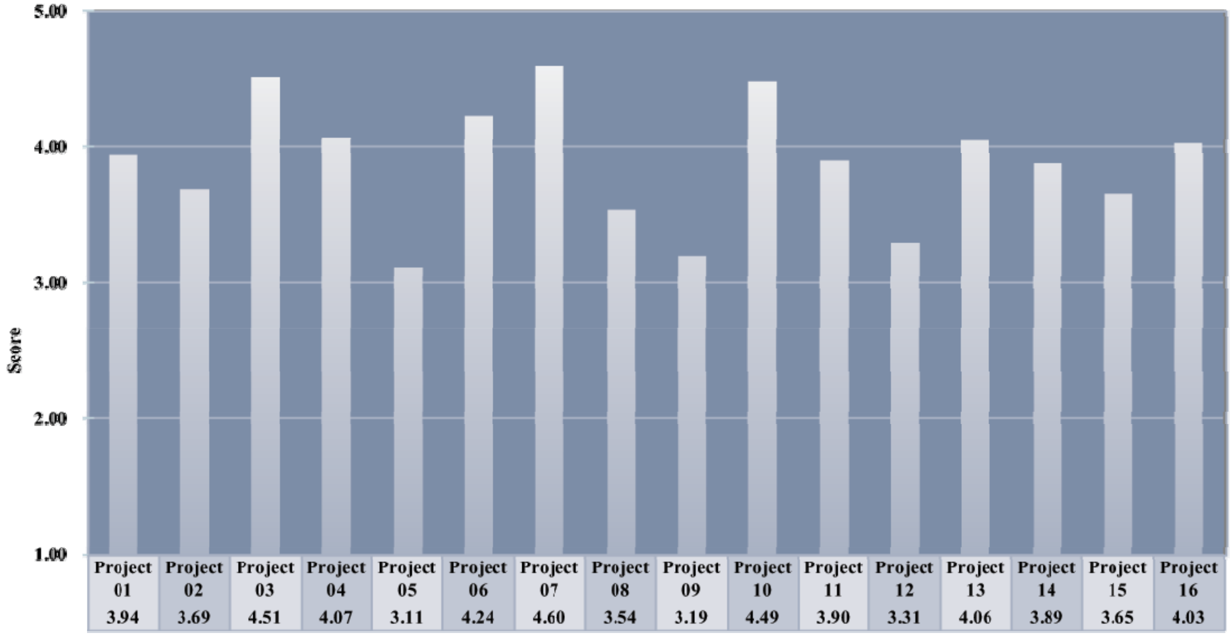
At the meeting, each research team made an uninterrupted 45- to 60-minute PowerPoint presentation that was followed by a 30- to 40-minute question-and-answer session with the Panel and a 50-minute Panel discussion and evaluation of each project. To facilitate a full and open discourse of project-related material between the project team and the Panel, all sessions were limited to the Panel, ASME project team members, and DOE/NETL personnel and contractor support staff.

After the group discussions, each panel member individually evaluated the 16 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)

Figure ES-2 shows the average project scores, combining the average of the nine review criteria for each of the 16 projects reviewed. As Figure ES-2 illustrates, it is relatively easy to look at the scores for an individual project and gain an impression of how well the project performed. While it is not the intent of this review to directly compare one project with another, an average score exceeding 3.0 generally indicates that a specific project was viewed favorably by the Panel. All sixteen projects reviewed from the Advanced Energy Systems Program exceeded this score.

FIGURE ES-2 AVERAGE SCORING, BY PROJECT



The “Project Average” in Table ES-3 shows the score for each criterion averaged across all 16 projects. This average intends to provide an accurate summary of the projects reviewed in the FY2012 Advanced Energy Systems Peer Review. The “Highest Project Rating” and “Lowest Project Rating” columns portray the highest and lowest scores received by an individual project in a given criterion.

Most criteria received average scores close to 4.0, with the highest-ranking review criterion, Scientific and Technical Merit, earning an average score across all projects of 4.2. Anticipated Benefits, If Successful earned a 4.1, and Utilization of Government Resources earned a 4.0. High scores in these three criteria indicate that overall the projects reviewed during the FY2012 Advanced Energy Systems Peer Review Meeting are innovative, scientifically sound, cost-effective projects aimed toward achieving both near- and long-term goals of the NETL Advanced Energy Systems Program.

The lowest-ranking review criterion was Performance and Economic Factors, indicating that several projects did not conduct sufficient cost and performance assessments to verify the potential of the technology to achieve the goals of the NETL Advanced Energy Systems Program. While Performance and Economic Factors had the lowest average across all projects, Potential Technology Risks Considered had the greatest range across projects, with project averages for that criterion ranging from 4.9 to 2.1. This large spread indicates that while some projects had robust risk assessments and mitigation plans, other projects reviewed did not sufficiently focus on this aspect of project management in the presentation and project summary information provided to the Panel.

TABLE ES-3 AVERAGE SCORING, BY REVIEW CRITERION

Criterion	Project Average	Highest Project Rating	Lowest Project Rating
1. Scientific and Technical Merit	4.2	5.0	2.9
2. Existence of Clear, Measurable Milestones	3.9	4.8	3.1
3. Utilization of Government Resources	4.0	4.9	2.9
4. Technical Approach	3.9	4.8	2.9
5. Rate of Progress	3.8	4.4	2.8
6. Potential Technology Risks Considered	3.7	4.9	2.1
7. Performance and Economic Factors	3.5	4.5	2.9
8. Anticipated Benefits, if Successful	4.1	5.0	3.0
9. Technology Development Pathways	3.9	4.8	3.1

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

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 Pathway 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.

MEETING SUMMARY AND RECOMMENDATIONS

I. INTRODUCTION

In fiscal year (FY) 2012, 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's Advanced Energy Systems Program (administered by the Office of Fossil Energy's National Energy Technology Laboratory [NETL]). On April 23–27, 2012, ASME convened a panel of eight leading academic and industry experts to conduct a five-day peer review of selected gasification and hydrogen turbine research projects supported by the NETL Advanced Energy Systems Program. 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 Energy Systems Program was designed to comply with requirements from the Office of Management and Budget.

ASME Center for Research and Technology Development

All requests for peer reviews are organized under ASME's Center for Research and Technology Development (CRTD). The CRTD 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 Energy Systems 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 16 Advanced Energy Systems Program projects. ASME performed this project review work as a subcontractor to prime NETL contractor Leonardo Technologies, Inc. NETL selected the 16 projects, while ASME organized an independent review panel of eight leading academic and industry experts. Prior to the meeting, project PIs submitted their PowerPoint presentations and a 12-page written summary (project information form) of their project's purpose, objectives, and progress. 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 60-minute oral presentation, followed by a 30- to 40-minute question-and-answer (Q&A) session with the Panel and a 50-minute Panel discussion and evaluation of each project. The length of the presentation and Q&A session was primarily a function of the perceived time required 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 Energy Systems Program research, both the PI presentations and Q&A sessions with the Panel for the Advanced Energy Systems Peer Review were held as closed sessions, limited to the Panel, ASME project team members, and DOE/NETL personnel and contractor support staff. The closed sessions ensured open discussions between the PIs and the Panel. Panel members were also instructed to hold the discussions that took place during the Q&A session as confidential.

Each member of the Panel individually evaluated every project and provided written comments based on a predetermined set of review criteria. This publically available document, prepared by ASME, provides a general overview of the Advanced Energy Systems 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 Energy Systems Peer Review Meeting, organized as follows:

II. *Summary of Projects Reviewed in FY 2012 Advanced Energy Systems Peer Review*: A list of the 16 projects reviewed and the selection criteria

III. *An Overview of the Evaluation Scores for the Advanced Energy Systems Program*: 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 FY2012 ADVANCED ENERGY SYSTEMS PEER REVIEW

NETL selected key projects within the gasification and hydrogen turbine technology areas of the Advanced Energy Systems 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: FEAA070
Coating Issues in Coal-Derived Synthesis Gas / Hydrogen-Fired Turbines
Oak Ridge National Laboratory

02: ORD-2012.03.02 TASK 5
Turbine Thermal Management - Secondary Flow Rotating Rig
National Energy Technology Laboratory

03: FE0004727
Mechanisms Underpinning Degradation of Protective Oxides and Thermal Barrier Coating Systems in HHC-Fueled Turbines
University of California, Irvine

04: AL05205018
Analysis of Gas Turbine Thermal Performance
Ames National Laboratory

05: FC26-05NT42645
Recovery Act: Oxy-Fuel Turbo Machinery Development for Energy Intensive Industrial Applications
Clean Energy Systems, Inc.

06: FC26-05NT42644
Recovery Act: Advanced Hydrogen Turbine Development
Siemens Energy, Inc.

07: FC26-05NT42643
Recovery Act: Advanced Hydrogen Turbine Development
GE Energy, Inc.

08: DE-FE0007966
Advanced CO_2 Capture Technology for Low Rank Coal Integrated Gasification Combined Cycle (IGCC) Systems
TDA Research, Inc.

09: FC26-05NT42469
Recovery Act: Scale-Up of Hydrogen Transport Membranes (HTM)
Eltron Research, Inc.

10: FC26-98FT40343
Recovery Act: ITM Oxygen Technology for Integration in IGCC and Other Advanced Power Generation Systems
Air Products and Chemicals, Inc.

11: DE-FE0007902
Scoping Studies to Evaluate the Benefits of an Advanced Dry Feed System on the Use of Low-Rank Coal in Integrated Gasification Combined Cycle (IGCC) Technologies
General Electric Company

12: DE-FE0007952
Mitigation of Syngas Cooler Plugging and Fouling
Reaction Engineering International

13: FE0000489
Recovery Act: High Temperature Syngas Cleanup Technology Scale-Up and Demonstration Project
Research Triangle Institute

14: FE0005712
Model-Based Optimal Sensor Network Design for Condition Monitoring in an IGCC Plant
GE Global Research

15: ORD-2012.03.03 TASK 4
Low Rank Coal Optimization
National Energy Technology Laboratory

16: ORD-2012.04.02
Carbon Capture Simulation Initiative
National Energy Technology Laboratory

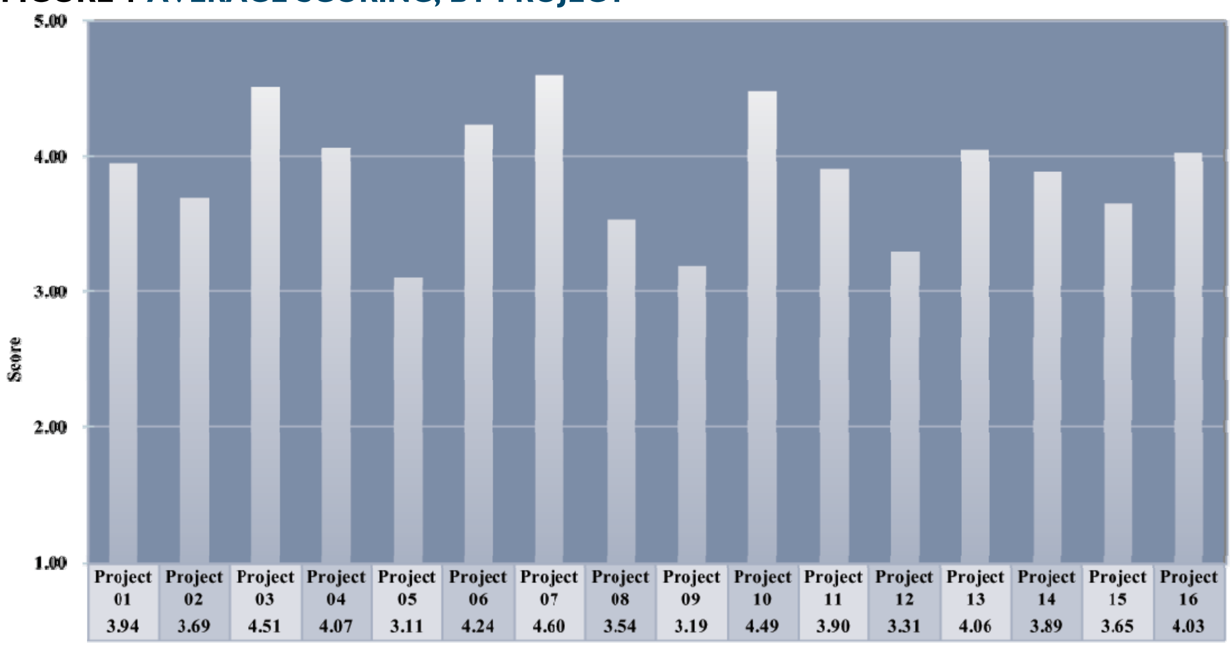
III. AN OVERVIEW OF THE EVALUATION SCORES FOR THE ADVANCED ENERGY SYSTEMS PROGRAM

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)

Figure 1 shows the average project scores, combining the average of the nine review criteria for each of the 16 projects reviewed. As Figure 1 illustrates, it is relatively easy to look at the scores for an individual project and gain an impression of how well the project performed. While it is not the intent of this review to directly compare one project with another, an average score exceeding 3.0 generally indicates that a specific project was viewed favorably by the Panel. All sixteen projects reviewed from the Advanced Energy Systems Program exceeded this score.

FIGURE 1 AVERAGE SCORING, BY PROJECT



The "Project Average" in Table 1 shows the score for each criterion averaged across all 16 projects. This average intends to provide an accurate summary of the projects reviewed in the FY2012 Advanced Energy Systems Peer Review. The "Highest Project Rating" and "Lowest Project Rating" columns portray the highest and lowest scores received by an individual project in a given criterion.

TABLE 1 AVERAGE SCORING, BY REVIEW CRITERION

Criterion	Project Average	Highest Project Rating	Lowest Project Rating
1. Scientific and Technical Merit	4.2	5.0	2.9
2. Existence of Clear, Measurable Milestones	3.9	4.8	3.1
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4. Technical Approach	3.9	4.8	2.9
5. Rate of Progress	3.8	4.4	2.8
6. Potential Technology Risks Considered	3.7	4.9	2.1
7. Performance and Economic Factors	3.5	4.5	2.9
8. Anticipated Benefits, if Successful	4.1	5.0	3.0
9. Technology Development Pathways	3.9	4.8	3.1

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

Most criteria received average scores close to 4.0, with the highest-ranking review criterion, Scientific and Technical Merit, earning an average score across all projects of 4.2. Anticipated Benefits, If Successful earned a 4.1, and Utilization of Government Resources earned a 4.0. High scores in these three criteria indicate that overall the projects reviewed during the FY2012 Advanced Energy Systems Peer Review Meeting are innovative, scientifically sound, cost-effective projects aimed toward achieving both near- and long-term goals of the NETL Advanced Energy Systems Program.

The lowest-ranking review criterion was Performance and Economic Factors, indicating that several projects did not conduct sufficient cost and performance assessments to verify the potential of the technology to achieve the goals of the NETL Advanced Energy Systems Program. While Performance and Economic Factors had the lowest average across all projects, Potential Technology Risks Considered had the greatest range across projects, with project averages for that criterion ranging from 4.9 to 2.1. This large spread indicates that while some projects had robust risk assessments and mitigation plans, other projects reviewed did not sufficiently focus on this aspect of project management in the presentation and project summary information provided to the Panel.

Three projects—project 05: FC26-05NT42645, Recovery Act: Oxy-Fuel Turbo Machinery Development for Energy Intensive Industrial Applications (Phase 2A); project 09: FC26-05NT42469, Recovery Act: Scale-Up of Hydrogen Transport Membranes (HTM); and project 12: DE-FE0007952, Mitigation of Syngas Cooler Plugging and Fouling—account for all of the "Lowest Project Ratings" in the nine criteria areas. Similarly, four projects—project 03: FE0004727, Mechanisms Underpinning Degradation of Protective Oxides and Thermal Barrier Coating Systems in HHC-Fueled Turbines; project 04: AL05205018, Analysis of Gas Turbine Thermal Performance; project 07: FC26-05NT42643, Recovery Act: Advanced Hydrogen

Turbine Development; and project 10: FC26-98FT40343, Recovery Act: ITM Oxygen Technology for Integration in IGCC and Other Advanced Power Generation Systems—account for all of the “Highest Project Ratings” in the nine criteria areas.

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 the overall key findings of the 16 projects evaluated at the FY2012 Advanced Energy Systems Peer Review.

General Project Strengths

The Panel was very impressed by the high-quality of most of the gasification and turbines projects they reviewed from DOE's Advanced Energy Systems Program. They indicated that the projects presented have ambitious goals and significant potential to advance gasification and turbine technology toward applications in coal-based power generation. The Panel found the projects to be essentially on track and to have a well-balanced portfolio of fundamental science, national laboratory research, and large-scale industry projects. The Panel was particularly impressed with the first-rate science being performed and the use of modeling to support experimentation in many of the projects, particularly the projects focused on increasing plant reliability, availability, and maintainability. Based on the progress made to date by the projects reviewed, the Panel was optimistic about the ultimate potential for gains in the improved cost of electricity for power plants with and without carbon capture.

Table 1 displays the average scores across all 16 projects for each of the nine individual criteria. All of the criteria received averages ranging from 3.5 to 4.2, and all projects received scores above "outstanding" (4.0) performance for three of the nine criteria. As depicted in Figure 1, seven of the 16 reviewed projects received average ratings of 4.0 or above, which is exemplary.

The three criteria in which all projects earned average scores of 4.0 or higher include Scientific and Technical Merit; Utilization of Government Resources; and Anticipated Benefits, if Successful. These high scores reflect the Panel's view that, overall, the projects were based on innovative, high-quality science and leveraged government resources well. If successful, these projects could contribute significantly to achieving both the near- and long-term goals of the NETL Advanced Energy Systems Program. In the remaining criteria, all projects received average ratings of 3.5 or above, signifying that the projects more than adequately considered project management, economics, risk factors, and technology development pathways.

The highest-rated project was project 07, "Recovery Act: Advanced Hydrogen Turbine Development," conducted by GE Energy. This project received an average rating across the nine criteria of 4.6 out of 5.0. Two other projects—project 03, "Mechanisms Underpinning Degradation of Protective Oxides and Thermal Barrier Coating Systems in HHC-Fueled Turbines" conducted by the University of California, Irvine and project 10, "Recovery Act: ITM Oxygen Technology for Integration in IGCC and Other Advanced Power Generation Systems" conducted by Air Products and Chemical, Inc—received average scores close to 4.5. In addition to these top three projects, four projects received ratings of "outstanding" or above (4.0 or greater). In general, high-scoring projects were characterized by knowledgeable principal investigators, innovative technical approaches, strong project management, an understanding of project risks, and thorough consideration of commercialization pathways.

General Project Weaknesses

Although the projects evaluated in the Advanced Energy Systems Program received above average ratings in all nine criteria, six areas fell short of an "outstanding" score: Existence of Clear, Measurable Milestones (3.9); Technical Approach (3.9); Rate of Progress (3.8); Potential Technology Risks Considered (3.7); Performance and Economic Factors (3.5); and Technology Development Pathways (3.9). The scores in these six areas indicate that the Panel found one or more projects to be behind schedule and that some project teams did not sufficiently identify and consider the economics, risks, or commercial viability of their technologies.

Several recurring themes arose during this Peer Review. The Panel considered it a weakness that some project teams lacked attention to the use of coal-derived fuels in downstream technologies under development, including separation systems, cleanup systems, and hydrogen turbines. Panel members pointed out that while several projects contained strong, fundamental work, the project teams did not clearly identify or articulate how their work would translate into real-world applications and environments. As a result, the project teams did not adequately demonstrate how their projects would be applicable to industry. In some cases, the Panel indicated that project teams lacked the necessary ties with original equipment manufacturers (OEMs) to ensure that their project was relevant to industry needs. It was also unclear to the Panel how widespread the impact some projects will be, due to issues involving access to or dissemination of information.

Another major theme identified by the Panel was the lack of economic analyses associated with technology scale-up. The Panel found that some project teams were paying insufficient attention to the competing technologies present in the target market, or to the performance and cost requirements their technology needs to meet in order to be competitive. Other recurring issues included insufficient testing periods, the listing of routine activities rather than milestones with performance-based targets, and the lack of comprehensive risk assessments and risk mitigation plans.

Issues for Future Consideration

While the majority of the recommendations provided by the Panel were technical in nature and specific to a particular project's technology or approach, several overarching themes did emerge. To improve the value of experimental results, the Panel suggested that several project teams should conduct testing under conditions that more closely represent real-world operation with coal-derived fuels. The Panel also encouraged the project teams to engage outside expertise to help ensure that the project testing represents current practice and offers value to industry. For example, it was suggested that at the very least, the project teams periodically review their results with OEMs to obtain industry guidance throughout the lifetime of the project. These recommendations would place the project teams and the Advanced Energy Systems Program as a whole in a better position to develop technologies that are suitable for real-world coal-based systems.

As part of their recommendations, the Panel also emphasized the importance of defining the economic and performance parameters necessary for successfully scaling up and commercializing the technologies. The Panel also noted the need for many project teams to restate milestones as measurable cost and performance targets.

V. PROCESS CONSIDERATIONS FOR FUTURE PEER REVIEWS

At the end of the Advanced Energy Systems Peer Review, the Panel and DOE/NETL managers involved offered positive feedback on the review process and constructive comments for improving future peer reviews. 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 is effective, especially the meeting organization and facilitation. Panel members found the openness of the NETL Technology Managers when asked for clarifying input on a broader programmatic issue to be beneficial to the overall review process, and felt that the Technology Managers showed an appropriate level of restraint in providing the information needed without biasing the outcome. However, the Panel requested that DOE/NETL make the interdependence of the projects clearer during the review process so that they can see how the projects interconnect to achieve overarching program goals.

The Panel noted that they were well informed about the meeting agenda and the length of the days, and that the SharePoint site enabled them to access the project information quickly and easily and prepare in advance for the peer review. Panel members also appreciated having fewer additional materials provided by the presenters because they found it easier to focus on the relevant information, but suggested that a list of references and links to additional research materials could be helpful. In addition, the Panel noted that the pre-meeting organization and practices continue to enable them to fit the integral step of project information review into their busy schedules prior to the Peer Review.

Meeting Agenda

While panel members found some presenters could have benefited from additional time, members agreed that the process ran smoothly and appreciated that the presentations remained on schedule for the most part. Overall, the Panel felt that the decision not to include two-hour presentations was appropriate. One Panel member suggested devoting more time to the question-and-answer sessions for larger projects while maintaining the one-hour time limit for presentations.

Presentations

The Panel noted that the two-minute introduction from the Technology Managers on the focus and scope of each project was beneficial, and it was recommended that this potentially be extended to five minutes to provide additional context. Overall, the Panel commented that DOE/NETL should encourage the principal investigators (PIs), particularly those of larger projects, to focus their presentations on more technical project details that are essential to the Panel's assessment and understanding of the project, such as the assumptions that were made and the progress that has been achieved. The Panel found it helpful that most of the project management items (e.g., budget/cost progress, Gantt charts, and earned value analysis) were moved to the end of the presentations for this review, as this information can be understood from the project information forms. The Panel also suggested that PIs be required to include a slide that details the project's contributions to the state of the art and DOE program goals.

The Panel questioned the value of slides on which the information was not legible or ones filled with detail that the presenters quickly clicked through without discussion. Panel members recommended that the guidelines for presenters be stricter in terms of the type of material they present, amount of information per slide, and the relevance of the information to the review process. The Panel agreed that DOE/NETL should identify standards for the slide presentations that address issues such as the font and font size, number of slides, and information to include.

Evaluation Process and Criteria

The Panel found the requirement to mention a corresponding action item or recommendation when mentioning a weakness to be helpful. One panel member suggested numbering the weaknesses and corresponding recommendations and action items in the reviewers' electronic comment forms in the future to clearly show this correlation. Panel members also felt that they would benefit from having an acronym list that they could reference to enhance their understanding of the project information forms and presentations.

Review Panel

The Panel acknowledged that the diverse areas of the panel members' expertise offered other members needed insight on various topics during discussion, which allowed all reviewers to provide more accurate and comprehensive ratings and comments. The Panel enjoyed the learning experience and camaraderie of collaborating with their colleagues in the advanced energy systems field and thanked ASME and DOE for the opportunity to participate in this Peer Review. The Panel also appreciated the professionalism of all parties involved with the Peer Review and valued their fellow reviewers' ability to cooperate and remain professional despite occasional differences of opinion.

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 DOE/ NETL fiscal year (FY) 2012 Advanced Energy Systems 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 (R&D), 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 plan and manage ASME's collaborative research activities effectively 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 Energy Systems 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 FY2012 Advanced Energy Systems Peer Review Executive Committee were as follows:

- **William Worek, Chair**. 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 and is a member of the ASME Board on Research and Technology Development.
- **Carl E. Atkinson, III, Voith Hydro Inc.** Mr. Atkinson is currently Vice Chair of the ASME Energy Committee and is past chair of the Power Division's Hydro-Power Technical Committee.
- **William Stenzel, Sargent & Lundy.** Mr. Stenzel is a former chair of the ASME Power Division and past member of the ASME Energy Committee. He currently serves as Vice Chair of the Power Division's Steam Generators Auxiliaries Technical Committee.

Advanced Energy Systems Peer Review Panel

The Advanced Energy Systems Peer Review Executive Committee accepted résumés for proposed Advanced Energy Systems 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 present 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 a 12-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 PowerPoint presentation template and set of instructions for the oral presentations they were to prepare for the Panel. The Panel was also given copies of these PowerPoint 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 Energy Systems Peer Review Meeting, presenters were held to a 45- to 60-minute time limit to allow sufficient time for all presentations within the five-day meeting period. After each presentation, the project team participated in a 30- to 40-minute question-and-answer session with the Panel.

The Panel then spent 50 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:

1. Scientific and Technical Merit
2. Existence of Clear, Measurable Milestones
3. Utilization of Government Resources
4. Technical Approach
5. Rate of Progress
6. Potential Technology Risks Considered
7. Performance and Economic Factors
8. Anticipated Benefits if Successful
9. Technology Development Pathways

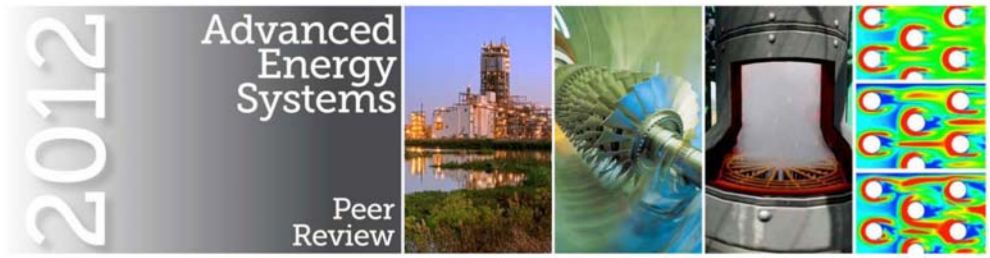
For each of these review criteria, individual panel members scored each project as one of the following:

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

To facilitate the evaluation process, Leonardo Technologies, Inc. (LTI) provided the Panel with laptop computers that were preloaded 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 action items that the team must address to correct a project deficiency. After discussing and scoring the projects on these criteria, each panel member provided written comments reiterating and expanding on the discussions about each project.

APPENDIX B: MEETING AGENDA

FY12 Advanced Energy Systems Peer Review



Waterfront Place Hotel
Morgantown, WV
April 23-27, 2012

AGENDA

Monday, April 23, 2012 – Salon E

7:00 – 8:00 a.m.	**Registration – Foyer E**
8:00 – 9:30 a.m.	**Peer Review Panel Kick Off Meeting** Open to National Energy Technology Laboratory (NETL) and American Society of Mechanical Engineers (ASME) staff only - Review of ASME Process – Michael Tinkleman, ASME - Role of Panel Chair – Ravi Prasad, ASME - Role of NETL – José Figueroa, National Energy Technology Laboratory (NETL) - Meeting logistics/completion of forms – Justin Strock/Nicole Ryan, LTI
9:30 – 10:30 a.m.	**Overview** Open to NETL and ASME staff only - Turbines Technology Manager – Richard Dennis, National Energy Technology Laboratory (NETL)
10:30 – 10:45 a.m.	**BREAK**
10:45 – 11:30 a.m.	***01 - Project # FEAA070*** – Coating Issues in Coal-Derived Synthesis Gas / Hydrogen-Fired Turbines – *Bruce Pint*, **Oak Ridge National Laboratory (ORNL)**
11:30 – 12:00 p.m.	Q&A
12:00 – 12:40 p.m.	Discussion
12:40 – 12:50 p.m.	Evaluation entry
12:50 – 1:50 p.m.	**Lunch (on your own)**
1:50 – 2:35 p.m.	***02 - Project # ORD-2012.03.02 Task 5*** – Turbine Thermal Management - Secondary Flow Rotating Rig – *Karen A. Thole and Michael Barringer*, **NETL Regional University Alliance**
2:35 – 3:05 p.m.	Q&A
3:05 – 3:45 p.m.	Discussion
3:45 – 3:55 p.m.	Evaluation entry

Monday, April 23, 2012 – Salon E

3:55 – 4:10 p.m.	**BREAK**
4:10 – 4:55 p.m.	***03 - Project # FE0004727*** – Mechanisms Underpinning Degradation of Protective Oxides and Thermal Barrier Coating Systems in HHC-Fueled Turbines – *Daniel R. Mumm*, **University of California, Irvine**
4:55 – 5:25 p.m.	Q&A
5:25 – 6:05 p.m.	Discussion
6:05 – 6:15 p.m.	Evaluation entry

Tuesday, April 24, 2012 – Salon E

7:00 – 8:00 a.m.	**Registration – Foyer E**
8:00 – 8:45 a.m.	***04 - Project # AL05205018*** – Analysis of Gas Turbine Thermal Performance – *Tom Shih*, **Ames National Laboratory**
8:45 – 9:15 a.m.	Q&A
9:15 – 9:55 a.m.	Discussion
9:55 – 10:05 a.m.	Evaluation entry
10:05 – 10:20 a.m.	**BREAK**
10:20 – 11:20 a.m.	***05 - Project # FC26-05NT42645*** – Recovery Act: Oxy-Fuel Turbo Machinery Development for Energy Intensive Industrial Applications – *Carlos Ortiz, Dan Davies, and Rebecca Hollis*, **Clean Energy Systems, Inc.**
11:20 – 11:50 a.m.	Q&A
11:50 – 12:30 p.m.	Discussion
12:30 – 12:40 p.m.	Evaluation entry
12:40 – 1:40 p.m.	**Lunch (on your own)**
1:40 – 2:40 p.m.	***06 - Project # FC26-05NT42644*** – Recovery Act: Advanced Hydrogen Turbine Development – *John Joseph Marra*, **Siemens Energy, Inc.**
2:40 – 3:10 p.m.	Q&A
3:10 – 3:50 p.m.	Discussion
3:50 – 4:00 p.m.	Evaluation entry
4:00 – 4:15 p.m.	**BREAK**
4:15 – 5:15 p.m.	***07 - Project # FC26-05NT42643*** – Recovery Act: Advanced Hydrogen Turbine Development – *Ashok Anand, Christine Zemsky, and Will York*, **GE Energy, Inc.**
5:15 – 5:45 p.m.	Q&A
5:45 – 6:25 p.m.	Discussion
6:25 – 6:35 p.m.	Evaluation entry

Wednesday, April 25, 2012 – Salon E

7:00 – 8:00 a.m.	**Registration – Foyer E**
8:00 – 9:00 a.m.	**Overview** Open to NETL and ASME staff only - Gasification Technology Manager – Jenny Tennant, National Energy Technology Laboratory (NETL)
9:00 – 9:15 a.m.	**BREAK**
9:15 – 10:00 a.m.	***08 - Project # FE0007966*** – Advanced CO_2 Capture Technology for Low Rank Coal Integrated Gasification Combined Cycle (IGCC) Systems – *Gökhan Alptekin*, **TDA Research, Inc.**
10:00 – 10:30 a.m.	Q&A
10:30 – 11:10 a.m.	Discussion
11:10 – 11:20 a.m.	Evaluation entry
11:20 – 12:20 p.m.	**Lunch (on your own)**
12:20 – 1:05 p.m.	***09 - Project # FC26-05NT42469*** – Recovery Act: Scale-Up of Hydrogen Transport Membranes (HTM) – *Carl Evenson*, **Eltron Research, Inc.**
1:05 – 1:45 p.m.	Q&A
1:45 – 2:25 p.m.	Discussion
2:25 – 2:35 p.m.	Evaluation entry
2:35 – 2:50 p.m.	**BREAK**
2:50 – 3:45 p.m.	***10 - Project # FC26-98FT40343*** – Recovery Act: ITM Oxygen Technology for Integration in IGCC and Other Advanced Power Generation Systems – *Lori L. Anderson and Phillip A. Armstrong*, **Air Products and Chemicals, Inc.**
3:45 – 4:25 p.m.	Q&A
4:25 – 5:05 p.m.	Discussion
5:05 – 5:15 p.m.	Evaluation entry

Thursday, April 26, 2012 – Salon E

7:00 – 8:00 a.m.	**Registration – Foyer E**
8:00 – 8:45 a.m.	***11 - Project # FE0007902*** – Scoping Studies to Evaluate the Benefits of an Advanced Dry Feed System on the Use of Low-Rank Coal in Integrated Gasification Combined Cycle (IGCC) Technologies – *Christine Zemsky, Jeff Rader and Tom Leininger*, **General Electric Company**
8:45 – 9:15 a.m.	Q&A
9:15 – 9:55 a.m.	Discussion
9:55 – 10:05 a.m.	Evaluation entry
10:05 – 10:20 a.m.	**BREAK**

Thursday, April 26, 2012 – Salon E

10:20 – 11:05 a.m.	***12 - Project # FE0007952*** – Mitigation of Syngas Cooler Plugging and Fouling – *Mike Bockelie*, **Reaction Engineering International**
11:05 – 11:35 a.m.	Q&A
11:35 – 12:15 p.m.	Discussion
12:15 – 12:25 p.m.	Evaluation entry
12:25 – 1:25 p.m.	**Lunch (on your own)**
1:25 – 2:20 p.m.	***13 - Project # FE0000489*** – Recovery Act: High Temperature Syngas Cleanup Technology Scale-Up and Demonstration Project – *Raghubir Gupta and Ben Gardner*, **Research Triangle Institute**
2:20 – 3:00 p.m.	Q&A
3:00 – 3:40 p.m.	Discussion
3:40 – 3:50 p.m.	Evaluation entry
3:50 – 4:05 p.m.	**BREAK**
4:05 – 4:50 p.m.	***14 - Project # FE0005712*** – Model-Based Optimal Sensor Network Design for Condition Monitoring in an IGCC Plant – *Rajeeva Kumar*, **GE Global Research**
4:50 – 5:20 p.m.	Q&A
5:20 – 6:00 p.m.	Discussion
6:00 – 6:10 p.m.	Evaluation entry

Friday, April 27, 2012 – Salon E

7:00 – 8:00 a.m.	**Registration – Foyer E**
8:00 – 8:45 a.m.	***15 - Project # ORD-2012.03.03 Task 4*** – Low Rank Coal Optimization – *Chris Guenther*, **National Energy Technology Laboratory (NETL)**
8:45 – 9:15 a.m.	Q&A
9:15 – 9:55 a.m.	Discussion
9:55 – 10:05 a.m.	Evaluation entry
10:05 – 10:20 a.m.	**BREAK**
10:20 – 10:50 a.m.	**Overview** Open to NETL and ASME staff only - Advanced Research Technology Manager – Robert Romanosky, National Energy Technology Laboratory (NETL)
10:50 – 11:35 a.m.	***16 - Project # ORD-2012.04.02*** – Carbon Capture Simulation Initiative – *David C. Miller*, **National Energy Technology Laboratory (NETL)**
11:35 – 12:05 p.m.	Q&A
12:05 – 12:45 p.m.	Discussion
12:45 – 12:55 p.m.	Evaluation entry
12:55 – 1:10 p.m.	**BREAK**
1:10 – 2:10 p.m.	**Meeting Wrap-up Session**

APPENDIX C: PEER REVIEW PANEL MEMBERS

After reviewing the scientific areas and issues addressed by the 16 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 identified the following areas of expertise as the required skill sets of the fiscal year (FY) 2012 Advanced Energy Systems Peer Review Panel:

- Membranes, catalysts, stability, sorbents
- Ceramic materials, ceramic powders
- Commercialization analysis
- High-temperature, high-pressure processes
- Pollutant identification, monitoring, and handling
- Module design, fabrication, and bench testing
- Computer simulation, modeling
- Cost and economic analysis
- Integrated gasification combined cycle (IGCC) design, operation, and controls
- Component testing
- Field testing, demonstrations, and training
- Gasifiers, novel designs, and absorption
- Syngas cleanup, multiple contaminants
- Syngas cooler fouling and plugging
- Hydrogen turbines
- Conventional turbine design
- IGCC and natural gas combined cycle plants
- Reduced or near-zero emissions
- Efficiency / high efficiency
- Capital cost analysis
- Novel turbine cooling
- Materials and thermal barrier coatings
- Sensors, diagnostics, and controls
- Modeling and simulations
- Component development and testing
- Turbine and compressor aerodynamics
- Demonstration and field testing
- Injector and combustor design
- Design and analysis tools

- Commercialization
- Carbon dioxide and carbon dioxide / steam use or recycling

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 skills. This matrix also ensures that all the necessary skill sets are covered by the Panel. The Panel selection process also helps to guarantee 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 eight individuals who had served on prior ASME Peer Review Panels were qualified to serve on the Advanced Energy Systems Peer Review Panel.

Appropriate résumés were then submitted to the ASME Advanced Energy Systems Peer Review Executive Committee for review. The following eight members were selected for the FY2012 Advanced Energy Systems Peer Review (* indicates a prior panel member):

- Klaus Brun, Ph.D., Southwest Research Institute*
- Arie Geertsema, Ph.D., GeertTech LLC*
- Daniel Kubek, Gas Processing Solutions, LLC*
- Ravi Prasad, Ph.D., Helios-NRG, LLC* – *Chair*
- James C. Sorensen, Sorensenergy, LLC*
- Douglas M. Todd, Process Power Plants, LLC*
- Ting Wang, Ph.D., University of New Orleans*
- Richard Wenglarz, Ph.D., Consultant*

Panel members reviewed 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.

FY2012 Advanced Energy Systems Peer Review Panel Members

Ravi Prasad, Ph.D., Panel Chair

Ravi Prasad of Helios-NRG, LLC and formerly a corporate fellow of Praxair Inc., has 60 U.S. patents and broad industrial experience in developing and commercializing new technologies, launching technology programs ($2–$50 million), supporting business development, building cross-functional teams, and setting up joint development alliances. He is a founding member of an alliance involving Praxair, British Petroleum, Amoco, Phillips Petroleum, Statoil, and Sasol to develop ceramic membrane syngas technology for gas-to-liquid processes.

Dr. Prasad also established and led programs for ceramic membrane oxygen technology; co-developed proposals to secure major DOE programs worth $35 million in syngas and $20 million in oxygen; identified novel, solid-state oxygen generation technology; and conceived and implemented a coherent corporate strategy in nanotechnology. He has championed many initiatives in India, including small on-site hydrogen plants, small gasifiers, and aerospace business opportunities; and developed implementation plans resulting in a new research and development center in Shanghai.

Dr. Prasad's technical areas of expertise include membranes and separations, hydrogen and helium, industrial gas production and application, ceramic membranes and solid oxide fuel cells, new technology development, technology roadmapping, intellectual property strategy development, technology due diligence, combustion, nanotechnology, gas-to-liquids, coal-to-liquids, and silane pyrolysis reactors.

Dr. Prasad is the director and a board member of the National Hydrogen Association, a member of the steering committee for Chemical Industry V2020, and has been a recipient for Chairman's & Corp Fellows awards for technology leadership. He has authored or co-authored 30 publications, is co-author of a book on membrane gas separation, and has presented at over 20 conferences and invited lectures.

Dr. Prasad has a B.S. in mechanical engineering from the Indian Institute of Technology in Kanpur, India, and an M.S. and Ph.D. in mechanical engineering and chemical engineering from the State University of New York, Buffalo, New York.

Klaus Brun, Ph.D.

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.

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, integrated gasification combined cycle plants, centrifugal compressors, steam turbines, and pumps.

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 is the inventor of the single wheel radial flow gas turbine and the semi-active plate valve*,* and is 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 International Gas Turbine Institute (IGTI) Oil & Gas Application Committee Best Paper awards in 1998, 2000, and 2005 for his work on gas turbine testing and degradation.

Dr. Brun is a member of ASME, the Gas Machinery Research Council, Sigma Xi (Research Society), and the American Petroleum Institute (API). He is the past chair of the ASME-IGTI Oil & 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 received 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.

Arie Geertsema, Ph.D.

Arie Geertsema has been president of the energy technology consulting company GeertTech LLC since 2009. Prior to starting GeertTech LLC, Dr. Geertsema was the senior vice president and later chief technology officer of Range Fuels Inc., a start-up company specializing in biomass to ethanol commercialization. While teaching fuel processing technology as an associate professor in chemical engineering at the University of Kentucky from 2002 to 2006, he served as the director of the University of Kentucky Center for Applied Energy Research where the main areas of activity were catalysis, carbon materials, and coal and environmental technologies. Dr. Geertsema also has more than 20 years of industry experience as a manager of gas processing at Australia's Commonwealth Scientific and Industrial Research Organisation from 1998 to 2000 and through his range of leadership positions at Sasol in South Africa from 1978 to 1998.

Dr. Geertsema's research interests include coal technology, gasification, gas processing and gas cleaning, Fischer-Tropsch, catalysis, petrochemical synthesis, separations technology, catalytic distillation, environmental research (e.g., air pollution, effluents, site remediation), biotechnology, fuel performance, process development, reactor design and development, piloting and commercialization of processes, and techno-economic and intellectual property evaluations.

Dr. Geertsema is a member of both the American Institute of Chemical Engineers and the American Chemical Society. In 1994, he received the Industrial Chemistry Silver Medal of the South African Chemical Institute for promoting industry-university collaboration. In 1993, he was awarded the Stokes Award of the 10th Annual International Pittsburgh Coal Conference for contributions to the commercialization of coal conversion technologies.

He received a B.Sc., M.Sc., and MBA from the University of Potchefstroom in South Africa. He holds a Dr.Ing (German Engineering Doctorate Degree) from the University of Karlsruhe, Germany.

Daniel Kubek

Daniel Kubek is a consultant specializing in synthesis gas and natural gas purification and separation. His clients include the Electric Power Research Institute – CoalFleet, for which he provides technical guidance on integrated processes for gasification projects; and the Gasification Technologies Council, for which he serves as an advisor on technical issues related to gasification, particularly in the areas of hydrogen sulfide removal and carbon capture.

Mr. Kubek was with Universal Oil Products LLC (UOP) for 18 years as senior technology manager. His industry career is based in the technical expertise areas of separations technology and engineering. His primary work was in solvent absorption, molecular sieve thermal-swing adsorption, membrane permeation, and pressure-swing adsorption technologies, as applied to natural gas and synthesis gas processing. He was the process manager responsible for all process design packages for multiple gasification projects and served as development manager for UOP's gas processing business. Before joining UOP LLC, he spent 17 years with Union Carbide.

In 2005, Mr. Kubek was awarded UOP's Don Carlson Award for Career Technical Innovation. From 1996 to 2006 he served as UOP's representative to the Gasification Technologies Council's Board of Directors. He is also a member of the American Institute of Chemical Engineers. He is the holder of eight patents and has co-authored 17 technical publications.

Mr. Kubek received a B.S. degree in chemical engineering from Rutgers University and earned an M.S. in chemical engineering from Purdue University.

James C. Sorensen

James Sorensen is a consultant with a primary focus on clean coal and supporting technologies, including integrated gasification combined cycle (IGCC), oxyfuel combustion, and coal-to-liquids. Prior to founding Sorensenergy, LLC, in 2004, 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 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 Research & Development, 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, research and development program management, technology consulting and training, proposal preparation and review, 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 has international experience with customers and partners in Algeria, Chile, China, Germany, Great Britain, Indonesia, Japan, The Netherlands, and elsewhere. He is also well published in the area of clean coal.

He received a B.S. in chemical engineering from the California Institute of Technology, a M.S. in chemical engineering from Washington State University, and a M.B.A. from the Harvard Business School.

Douglas M. Todd

Douglas 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 clean, economical electric power and other useful products from low-cost fuels. Mr. Todd's industry 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. Mr. Todd developed and introduced combined cycle and IGCC power plant technology on a worldwide basis.

Recent gas turbine technology development combined with technology partnerships has led to 20 successful IGCC projects, including co-production plants that account for 14 of these projects. Doug has led the IGCC Power Block technology into a variety of Process Power Plant applications for co-production of power and hydrogen, clean fuels, gas to liquids, and carbon dioxide reduction technologies. By applying integration techniques and unique modifications in the Power Block, various process technologies can be enhanced, improving economics and extending commercial applications for these processes.

Mr. Todd is a member of the American Institute of Chemical Engineers, the Gasification Technologies Council (GTC), and Energy Frontiers International. He received the first European Institution for Chemical Engineers Medal for Excellence in Gasification in 2002 and the GTC Lifetime Achievement Award in 2003. Mr. Todd has published numerous technical papers for various entities including ASME and the Electric Power Research Institute.

Mr. Todd received a B.S. degree in chemical engineering from Worcester Polytechnic Institute.

Ting Wang, Ph.D.

Ting 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 30 years. He is an experimentalist with significant computational fluid dynamics experience and has conducted both fundamental and applied research with funding from U.S. government agencies and industry. He was appointed by former Louisiana governor "Mike" Foster to serve as a member of the Comprehensive Energy Policy Advisory Commission.

Dr. Wang's research interests include gas turbine systems, transitional and turbulent boundary layers, fluid mechanics, heat transfer, curved flow, electronic equipment cooling, bi-diffusion natural convection, energy conservation, alternative fuels, and integrated gasification combined cycle power plants. He is currently conducting research in jet impingement cooling, separated-flow transition, combustor flow aerodynamics, heat transfer enhancement on micro-structured surfaces, biomass gasification combustion, and integrated gasification combined cycles.

Dr. Wang has published over 200 research papers and reports. He 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 and vice chair of the ASME International Gas Turbine Institute's (IGTI) Gas Turbine Heat Transfer Committee and a past Chair of the IGTI Coal, Biomass, and Alternative Fuels Committee.

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 is a consultant for advanced energy systems, particularly related to gas turbines. His energy system experience includes about 23 years at major energy companies and, most recently, 10 years at the South Carolina Institute for Energy Studies (SCIES) at Clemson University.

At SCIES, Dr. Wenglarz was Manager of Research for the University Turbine Research program organized as a consortium of government, industry, and about 110 member universities. Working with an industrial review board of up to 17 member companies (e.g., GE, ExxonMobil, BP, Siemens, etc.), he was responsible for establishing research objectives, evaluating and selecting university proposals to accomplish the objectives, and overseeing the university research projects awarded throughout the nation. He also oversaw workshops to disseminate the results of the university research to government, industry, and academia.

Prior to SCIES, Dr. Wenglarz held research and project management positions over about 16 years related to advanced turbine systems at Rolls Royce/Allison Gas Turbine Company. He managed a program that successfully demonstrated an Allison 501 gas turbine with first-stage ceramic vanes at an Exxon natural gas processing plant. He also conducted numerous plant economic analyses for the DOE/Allison Advanced Turbine System and the DOE/Allison Direct Coal Fired Turbine System Program. In addition, Dr. Wenglarz was responsible for developing and evaluating turbine flow path protection approaches from deposition, erosion, and corrosion for the Direct Coal Program. He also managed the Allison internal research and development program for coal fuels and the DOE/Allison Component Screening Program, both directed to developing a technology base for direct coal fueled turbines.

Dr. Wenglarz has over 80 publications and has delivered numerous invited presentations at the Von Karman Institute for Fluid Dynamics (Belgium), Yale University, UK Central Electricity Research Laboratories, Cambridge University, the Kentucky Energy Cabinet Laboratories, 8th Liege Conference on Materials for Advanced Power Engineering (Belgium), and the Sultzer Metco Gen 5 Ceramics Consortium. He also developed and presented a course segment on turbine corrosion and deposition at the DOE sponsored Short Course “Impact of Synfuels and Hydrogen Fuels Relevant to Gas Turbine Development”.

Dr. Wenglarz received B.S. and M.S. degrees from the University of Illinois, and a Ph.D. from Stanford University, all in engineering mechanics.

APPENDIX D: PEER REVIEW CRITERIA FORM

PEER REVIEW CRITERIA FORM

U. S. DEPARTMENT OF ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY
FY12 ADVANCED ENERGY SYSTEMS
PEER REVIEW

April 23 – 27, 2012

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) **Project Overview**; (2) **Technical Discussion**; and (3) **Technology Benefits**. 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 adjectival rating, descriptions of those ratings are provided below.

RATING 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 nine (9) criteria listed below. Definitions for these nine (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 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.

CRITERIA		RATINGS				
(Criteria Definitions, refer to Page 4)		(Rating 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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CRITERIA 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

Research, Development, and Demonstration (RD&D) 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

* Not relevant to this Peer Review.

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APPENDIX E: ADVANCED ENERGY SYSTEMS PROJECT SUMMARIES

Presentation ID Number	Project Number	Title
01	FEAA070	Coating Issues in Coal-Derived Synthesis Gas / Hydrogen-Fired Turbines
02	ORD-2012.03.02 Task 5	Turbine Thermal Management - Secondary Flow Rotating Rig
03	FE0004727	Mechanisms Underpinning Degradation of Protective Oxides and Thermal Barrier Coating Systems in HHC-Fueled Turbines
04	AL05205018	Analysis of Gas Turbine Thermal Performance
05	FC26-05NT42645	Recovery Act: Oxy-Fuel Turbo Machinery Development for Energy Intensive Industrial Applications (Phase 2)
06	FC26-05NT42644	Recovery Act: Advanced Hydrogen Turbine Development, Siemens Energy
07	FC26-05NT42643	Recovery Act: Advanced Hydrogen Turbine Development, GE Energy
08	DE-FE0007966	Advanced CO_2 Capture Technology for Low Rank Coal Integrated Gasification Combined Cycle (IGCC) Systems
09	FC26-05NT42469	Recovery Act: Scale-Up of Hydrogen Transport Membranes (HTM)
10	FC26-98FT40343	Recovery Act: ITM Oxygen Technology for Integration in IGCC and Other Advanced Power Generation Systems
11	DE-FE0007902	Scoping Studies to Evaluate the Benefits of an Advanced Dry Feed System on the Use of Low-Rank Coal in Integrated Gasification Combined Cycle (IGCC) Technologies
12	DE-FE0007952	Mitigation of Syngas Cooler Plugging and Fouling
13	FE0000489	Recovery Act: High Temperature Syngas Cleanup Technology Scale-Up and Demonstration Project
14	FE0005712	Model-Based Optimal Sensor Network Design for Condition Monitoring in an IGCC Plant
15	ORD-2012.03.03 Task 4	Low Rank Coal Optimization
16	ORD-2012.04.02	Carbon Capture Simulation Initiative

01: FEAA070

Project Number	Project Title			
FEAA070	Coating Issues in Coal-Derived Synthesis Gas/Hydrogen-Fired Turbines			
Contacts	**Name**	**Organization**	**Email**	
DOE/NETL Project Mgr.	Briggs White	NETL – Power Systems Division	Briggs.White@netl.doe.gov	
Principal Investigator	Bruce Pint	Oak Ridge National Laboratory	pintba@ornl.gov	
Partners	Prof. Ying Zhang, Tennessee Technological University			
Stage of Development				
__Fundamental R&D	X Applied R&D	__Prototype Testing	__Proof of Concept	__Demonstration

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, aero-engine technology (i.e., single-crystal [SX] superalloy blades, thermal barrier coatings, and sophisticated cooling techniques), they had to be rapidly scaled up and introduced into large gas turbines. Although the design fuel was natural gas, which is relatively clean, there were initial problems with reliability. These problems have been largely overcome following extended development work, and the high-efficiency gas turbine combined-cycle power-generation system is now considered to be a mature technology 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 the new challenge of accommodating the physical and chemical differences of these fuels while maintaining efficiency and reliability levels. These fuels also differ from natural gas in calorific value, flame speed, and impurity levels, for example, and will likely require changes in design and materials selection for some of the turbine components.

The high TET (typically exceeding 1,482°C or 2,700°F) 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. Therefore, the strongest alloys available (typically SX Nickel [Ni]-based superalloys) are used for the blades and vanes in the first stage, and possibly second stage, of the turbine, and operate at their temperature limits. These components also feature complex internal cooling passages, through which air from the turbine compressor is used to maintain the desired metal temperatures. Thermal barrier coatings (TBCs) are applied to the affected surfaces to minimize the amount of cooling air and maximize energy efficiency. Full functioning of the TBC is increasingly essential in order for the engine to meet performance targets, and unprecedented levels of materials reliability and performance consistency are required. Consequently, a major worldwide effort to understand the failure mechanisms of TBCs has been ongoing, with the goal of achieving the degree of predictability needed to allow the confident use of mechanism-based lifetime models, and with the hope of eventually being able to take full advantage of the temperature decrement provided by a TBC in engine design. In parallel with this effort, non-destructive evaluation (NDE) techniques are being devised to monitor the condition of the coating (preferably in-situ) to provide early indication of coating deterioration.

A TBC consists of a thin, metallic coating (or bond coating, ~50 µm thick), usually an aluminide (NiAl or [Ni,Pt]Al) formed by diffusion, or a MCrAlY-type overlay (metal-chromium-aluminum-yttrium, where M is typically Ni and Co [cobalt]) applied to the superalloy substrate; and a layer of ceramic, typically yttria-stabilized zirconia (YSZ) (125–500 micrometers [µm] thick, though there is strong interest in increased thermal resistivity, hence thicker ceramic layers) applied on top of the bond coating. The purpose of the bond coating is threefold: (i) to provide an anchoring surface for the ceramic layer; (ii) to protect against oxidation (since zirconia allows rapid transport of oxygen); and (iii) to offer some resistance to other forms of corrosion, including oxidation-sulfidation (from gaseous sulfur contaminants in the combustion products) and hot corrosion (from the presence of molten alkali sulfate deposits), 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, some TBC systems are insufficiently robust to provide predictable long-term performance in turbines fired by natural gas.

Turbine manufacturers have undertaken programs to address the changes needed to provide the capability of firing coal-derived gaseous fuels in their specific turbine designs and, understandably, many of the details of these efforts are considered to be proprietary. Reportedly, manufacturers “derate” or lower the TET when firing with coal-derived gaseous fuels by ~100°F. Depending on the source of the fuel and its impurity content, an earlier Oak Ridge National Laboratory (ORNL) project (2004–2007) identified the potential for deposition, erosion, or corrosion (D-E-C) on the hot gas path components. Coal ash contains a range of impurities capable of causing D-E-C, the severity of which depends on the type of gas cleaning used to process the syngas before it enters the turbine. In addition, there will be significantly higher levels of water vapor in the gas that enters the turbine after combustion of these fuels, from the cleanup scrubbers; the higher levels of hydrogen in the gas compared to natural gas; and, possibly, from steam dilution of the gas stream. Water vapor is well known to degrade oxidation resistance, including a decrease in spallation resistance of alumina scales formed on the metallic bond coating of a TBC. Also, the fuel gas may contain non-condensable species, such as sulfur-containing gases, so there may be potential for gas-phase sulfidation attack, depending on the partial pressure of sulfur in the gas that results from combustion. The overlying premise of this work is that the derating is likely a result of materials degradation at the highest turbine temperatures where TBCs are employed. Therefore, developing more robust TBCs capable of operating in the extreme environment of a turbine fired by coal-derived syngas or hydrogen is the current strategy to reduce the derating.

While it is uncertain how much sulfur and/or ash will enter the turbine, there will almost certainly be higher water vapor levels. Thus, the ORNL project has focused on understanding the role of water vapor; determining the effect of higher water vapor; and developing mitigation strategies for this environment. The primary focus of this project is on the metallic bond coatings and the “weak link”: the thermally grown oxide (predominantly alumina) layer that forms during service between the bond coating and ceramic top coating. In land-based gas turbines, bond coatings are predominantly overlay MCrAlY-type coatings (where M is Ni and/or Co) with alternatives being diffusion aluminide (including Platinum [Pt] modifications), Pt diffusion coatings (γ-γ' phase) and the new General Electric bond coating based on vapor-deposited NiAlCr+Zr (nickel-aluminum-chromium + zirconium). Numerous MCrAlY coating compositions are commercially available with performance highly dependent on the fabrication (spraying) method and parameters. Given ORNL’s extensive experience with the fabrication, performance, and characterization of diffusion coatings, initial experiments were performed on those coatings while partners were identified to assist in coating more relevant MCrAlY bond coatings.

Regarding the experience of the personnel, Pint (principal investigator) and Haynes (coating task leader) were participants in the 1994–2001 DOE Advanced Turbine Systems program, which involved providing technical oversight of materials and manufacturing projects, as well as performing research on key materials issues, including optimizing bond coatings to maximize the lifetime of the TBCs critical to the successful operation of these advanced turbines. Since that time, both have continued to work in TBC-related research and have an extensive and well-cited publication record. Unocic (characterization task leader) has been involved with the project since joining ORNL in 2009. This project taps the extensive capabilities of the research staff as well as the world-class ORNL research facilities in corrosion and characterization to tackle one of the most difficult materials problems.

MITIGATION STRATEGIES

While a major focus of the project has been investigating the role of water vapor, the project team is also investigating strategies to mitigate the detrimental role of water vapor. Two strategies have already been investigated—dopants (Y and La [lanthanum]) in the superalloy, and co-doping (Y and Hf [hafnium]) in the bond coating. Dopants in the superalloy appeared to have little effect on the 1,100°C YSZ lifetime. The bond coatings with Y and Hf consistently showed an increase in YSZ lifetime compared to a bond coating with the same nominal composition but only a Y addition. However, the co-doped coating showed the same (~30%) decrease in lifetime with the addition of water vapor as the MCrAlY coating. Therefore, the co-doped coating is not particularly resistant to the presence of water vapor. Currently, new bond coating compositions are being investigated using cast NiCrAl alloys.

ACCELERATED TESTING

Recent testing has focused on 1-hour (h) cycles at 1,100°C–1,150°C in order to fail the coatings in a reasonable amount of time. These conditions are not representative of a baseload, syngas-fired turbine in which bond coating temperatures will be much lower and cycle length (hot time between cooling) will be much longer; however, it is assumed that the failure mechanisms will be similar in all cases. Several experiments are being conducted to verify the performance closer to the expected conditions, especially the effect of water vapor on the coatings. The YSZ coating lifetime increased by 3x–8x by decreasing the cycle frequency from 1h to 100h, and the three specimens with MCrAlYHfSi (metal-chromium-aluminum-yttrium-hafnium-silicon) bond coatings are still running. Thus, the experiment time has increased significantly with 100h cycles. At a lower temperature (900°C), the reaction rate is much slower and longer times are needed to verify steady-state behavior. Long-term experiments are being conducted to measure the rate of Al interdiffusion and determine how the two bond coatings perform. It appears that the mass gain rate is higher with the MCrAlYHfSi bond coating.

EFFECT OF WATER VAPOR

The conclusion from the initial series of TBC experiments is that higher water vapor contents do not explain the need to derate syngas- and H_2-fired turbines. Results of EB-PVD (Electron Beam Physical Vapor Deposition, tested at 1,150°C) and APS YSZ (atmospheric plasma-sprayed yttria-stabilized zirconia, tested at 1,100°C) testing both show a general drop in YSZ lifetime between a dry environment and 10% water vapor (except for the γ+ γ' bond coating). However, no additional drop in lifetime was detected when the water vapor content was increased to 50% or 90%. While both of these results require further confirmation, the current results suggest that other factors besides water vapor need to be investigated to determine the cause of the derating.

EVOLUTION OF FY12 WORK PLAN

The task to evaluate the role of water vapor will be redirected after this year, based on the result that higher water vapor contents do not appear to be more detrimental to TBC performance.

However, the repeatable drop in TBC performance with the addition of water vapor suggests that all furnace cycling evaluations should be conducted in the presence of 10% water vapor. Two new sets of YSZ-coated specimens will be evaluated in FY2012. The group with diffusion bond coatings will be used to verify the previous results and more carefully study the differences between specimens exposed in dry and wet environments. A group with high velocity oxy-fuel (HVOF) bond coatings and APS YSZ also will repeat the prior results but focus on only one bond coating (MCrAlYHfSi) and include several different superalloys including higher Cr 1483 (provided by Siemens) and new lower Re (rhenium) superalloys CMSX7 and CMSX8 (modifications of CMSX4). One goal will be to produce a rougher HVOF bond coating, more similar to industry practice than the first batch of HVOF bond coatings. One group of coatings will be exposed in a carbon dioxide (CO_2)-water environment to determine the effect of CO_2.

The task to look at doped superalloys will also be phased out in order to focus on other mitigation strategies. The characterization task will continue to play an important role in this project. Given the formation of thin TGOs and the need to study the presence of alloy dopants, standard characterization techniques are not adequate to study the role of water vapor and dopants. Therefore, it is essential to create a task that uses more sophisticated characterization techniques and takes advantage of ORNL characterization facilities and personnel.

Relationship to Program

This project will support important advances within the turbines portfolio of the NETL Advanced Energy Systems program. A better understanding of the factors that cause the derating of syngas-fired turbines will enable better direction of the research for a solution.

In summary, the benefits of higher-performance coatings include the following:

- Elimination of the derating of syngas-fired turbines, resulting in higher efficiency, lower specific emissions, and smaller plant size
- Improvement in reliability of operation
- Reduction in unplanned stoppages for maintenance

Primary Project Goal

The primary goal of the project for the past two years was to use appropriate high-resolution characterization tools to develop a better mechanistic understanding of the role of higher water vapor content on the performance of TBCs in order to better direct the research to evaluate and develop mitigation strategies and/or new alloys and/or coatings better suited for the syngas-/hydrogen-fired gas turbine environment.

Objectives

The project has the following objectives:

1. Improve mechanistic understanding of the role of water vapor on TBC performance, including the effect of increasing the water vapor content above levels typically found in natural gas-fired turbines.
2. Use state-of-the-art characterization techniques such as analytical electron microscopy to understand the effect of water vapor on the microstructure and microchemistry of the TGO in TBCs.
3. Evaluate strategies to mitigate the detrimental role of water vapor, including (a) Y and La dopants in superalloys, (b) combined Y and Hf bond coatings in NiCoCrAl (nickel-

cobalt-chromium-aluminum)-type bond coatings, and (c) chemistry modifications of the bond coating to improve performance in the presence of water vapor.

4. Develop better laboratory methodologies for evaluating TBC performance (e.g., conduct furnace cycling evaluations in the presence of water vapor).

02: ORD-2012.03.02 Task 5

Project Number	Project Title			
ORD-2012.03.02 Task 5	Turbine Thermal Management—Secondary Flow Rotating Rig			
Contacts	**Name**	**Organization**	**Email**	
DOE/NETL Project Mgr.	Mary Anne Alvin	NETL – Regional University Alliance	Maryanne.alvin@netl.doe.gov	
Principal Investigator	Karen Thole Michael Barringer	Pennsylvania State University	kthole@psu.edu mbarringer@psu.edu	
Partners	Dr. Axel Glahn, Pratt & Whitney Dr. John Schmitz, Pratt & Whitney Dr. Atul Kohli, Pratt & Whitney			
Stage of Development				
__Fundamental R&D	X Applied R&D	__Prototype Testing	__Proof of Concept	__Demonstration

Technical Background

NETL is conducting research to advance the science and engineering knowledge base for technologies that will support the Hydrogen Turbine Technology Area. This advancement will be accomplished through component-scale testing and demonstration of technology advancements to meet the DOE advanced turbine development goals. These goals include a 3%–5% power island efficiency increase and a 30% power increase above hydrogen-fueled combined cycle base line machines. NETL's Field Work Proposal for Turbine Thermal Management research is being conducted by NETL's Office of Research and Development (ORD). The ORD research efforts are supported by the NETL-Regional University Alliance (NETL-RUA), URS Corporation (URS), and URS subcontractors. The NETL-RUA includes five research institutions: Carnegie Mellon University, University of Pittsburgh, Pennsylvania State University (Penn State), West Virginia University, and Virginia Polytechnic Institute and State University. This project is supported by NETL's Strategic Center for Coal.

The NETL-RUA Turbine Thermal Management project supports the Advanced Energy Systems Program's hydrogen turbine efforts through conduct of novel, fundamental, basic, and applied research in the areas of aerothermal heat transfer, coatings development, and secondary flow control. This research project utilizes the extensive expertise and facilities readily available at NETL and the participating universities. The research approach includes explorative studies based on scaled models and prototype coupon tests conducted under realistic high-temperature, pressurized, turbine operating conditions. In addition, knowledge gained from this project will further advance the aerothermal cooling and thermal barrier coating (TBC) technologies in the general turbine community. A three-year program has been structured to address the development and design of aerothermal and materials concepts in fiscal year (FY) 2012–FY2013, design and manufacturing of these advanced concepts in FY2013, and high-temperature, pressurized, prototype coupon testing of these concepts under conditions replicating modern gas turbine engines in FY2013–FY2014 and beyond.

The research results obtained through this project can directly benefit the U.S. power and utility turbine industry through better product development that specifically meets the Advanced Energy Systems Program's hydrogen turbine goals. Turbine technology benefited by this research will lead to products with higher efficiency and reduced emissions. Higher efficiency implies alleviating dependence on foreign oil and improving preservation of our natural domestic resources. Reduced emissions will not only yield better environmental conditions, but will also decrease costs for pollution control, including carbon capture and sequestration (CCS). Combined, these benefits will eventually lead to greater energy security and economy in the United States and globally.

The Turbine Thermal Management project consists of four research project areas that focus on a critical technology development in heat transfer, materials development, high-temperature testing, and secondary flow control. Collectively, these projects contribute to plant efficiency gain by permitting a higher turbine firing temperature as a result of realizing more effective cooling, developing and utilizing extreme temperature thermal barrier coating (TBC) protection systems, and reducing leakage flow. Task achievements will demonstrate reduced coolant usage, which in turn permits a greater working flow rate through the turbine section, resulting in elevated power delivery as well as life enhancement of the hot gas path components. This review is focused on the efforts of the Secondary Flow Rotating Rig project being conducted at Penn State.

PROJECT BACKGROUND

The hardware architecture within existing gas turbine engines, both aircraft and land-based power generation, is one in which significant secondary flow leakages and cooling requirements limit the firing temperatures and, ultimately, the fuel burn of the engine. Approximately 25% of the total air flow through a gas turbine engine bypasses the combustor and is used for cooling turbine airfoils, disks, internal rim cavities, and other turbine hardware. Of that 25% cooling flow, 5%–10% is associated with non-airfoil cooling. Industry analyses and predictions from proprietary performance codes show that eliminating 3.3% from the 25% total turbine cooling and leakage air (TCLA) to achieve 21.7% TCLA would reduce the fuel burn by 2.0%. This TCLA reduction is consistent with the elimination of unintended leakage paths, but requires understanding of the effects of the individual leak paths to ensure that design requirements for engine life and performance are not violated. Not only is fuel burn reduced, but the valuable, high-pressure, secondary flow can also be used to further cool components, thereby allowing higher firing temperatures that lead to higher efficiencies, with cooling being integral to maintain part life longevity.

The project is focused on the development of a new facility that would provide a radical change in the design philosophy of secondary air and cooling supply systems to reduce leakage flows by an order of magnitude, thereby creating what is essentially a zero-leakage secondary air system. Reducing these leakage flows would lead to overall improved usage of coolant flows. The research aims at developing and validating tools for the performance prediction of novel designs that would reduce the overall fuel burn in a land-based turbine. In state-of-the-art gas turbines, leakage flows are introduced into the hot gas path through interfaces defined by the stationary and rotating bounding hardware, as well as functional requirements such as supply pressures for the turbine cooling air. No attempt is made to design toward the most effective component/module interaction. A notional secondary flow system study has shown that reducing engine leakage rates could improve the following key technical areas:

1. Redistribution of purge flow supply and egress at High Pressure Turbine (HPT) rotor/stator interfaces (rim seals and cavities)
2. Redesign of rim seals to accommodate the desired purge flow redistribution that will involve transitioning to novel configurations
3. Balancing of turbine cooling air supply pressures with those in surrounding air system cavities
4. Optimization of High Pressure Compressor (HPC) rear hub purge flows for reduced windage losses

5. Reuse of cooling air as sealing air

While all of these items have to be pursued in order to meet the goal of substantial fuel burn reductions (higher efficiencies), the overall objective is to define a secondary air system configuration based on a fundamentally different design philosophy. The new facility will provide a means for studying these effects. Studies using the new facility will also include internal cooling of airfoils to encompass a full array of cooling design considerations.

Relationship to Program

This project will support important thermal management advances within the turbines portfolio of the NETL Advanced Energy Systems program. The Secondary Flow Rotating Rig project at Penn State has designed and will commission a new facility that would provide a radical change in the design philosophy of secondary air and cooling supply systems to reduce leakage flows by an order of magnitude, thereby creating what is essentially a zero-leakage secondary air system. Reducing these leakage flows would lead to overall improved usage of coolant flows. Industry analyses and predictions from proprietary performance codes show that by eliminating 3.3% from the 25% total turbine cooling and leakage air (TCLA) resulting in 21.7% TCLA, this would result in a reduction in the fuel burn by 2.0%. Such a facility and test rig for secondary air system research is currently unavailable in the United States, which represents a competitive disadvantage of the U.S. industry and research community when compared with the European Union.

The design operating envelope for the new facility at Penn State is well above the current capability of most continuous duration, rotating turbine rigs in the United States and Europe. This new facility will have the capability to test gas turbine internal air system leakage and cooling flows.

In summary, the benefits of this project include the following:

- Better products with higher efficiency and reduced emissions that will contribute to alleviating dependence on foreign oil and preserving domestic natural resources
- Better environmental conditions and decreased costs of pollution control, including CCS
- Greater energy security and economy in the United States and worldwide

Primary Project Goal

The primary goals of the *Secondary Flow Rotating Rig* project are to design, build, and operate a world-class, rotating turbine facility that will operate in a continuous steady-state manner at true physical engine scale. The new facility will allow experimental testing of new cooling improvement strategies for the turbine rotating blade platform. A 1.5 stage turbine test section will operate at near ~10,000 rotations per minute (rpm) and use a continuous air flow rate of up to 12.5 mass pounds per second (lbm/s) at a supply pressure near 60 pounds per square inch absolute (psia).

In this new facility, research is focused on addressing the fundamental flow effects of rotation on secondary air systems and aerothermal cooling in a gas turbine. The research aims to develop and validate tools for the performance prediction of novel designs that would reduce the overall fuel burn in a land-based turbine by as much as 2.0%. The development of the facility and test rig is being conducted in three phases, starting with building the infrastructure and designing the test rig in FY2011–FY2012; commissioning the test rig in FY2013; and acquiring and validating data for a baseline configuration in FY2014.

Objectives

The primary project objectives include the following tasks and milestones (*).

DOE-NETL TASK 5.1: Facility Development (FY2011–FY2013)

Task	Description	Details
5.1.	**Facility Development**	
5.1.1.	Facility Design	Building Layout, Infrastructure, Facility Flow Diagram
5.1.2.	Large Item Procurement	Compressor System, Cooling System, Dynamometer, Magnetic Bearings.
5.1.3.	Rig Design	Steel Ductwork, Plumbing, Instrumentation, Programmable Logic Control
5.1.4.	1 ½ Stage Turbine Test Section Design	Casings, Turbine, Shaft, Telemetry, Instrumentation, Magnetic Bearings
5.1.5.	Test Section Component Procurement	Machining, Inspection, Component Commissioning
5.1.6.	Building modifications/renovations	Mechanical, Electrical, Plumbing, Telecommunications, Fire
5.1.7.	Rig Construction	Ductwork Supports, Ductwork Installation, Piping, Assembly
5.1.8.	Bench Top Test Section Assembly	Trial Fits of Hardware and Instrumentation, Traverse Systems
5.1.9.	Control Room Infrastructure	Data Acquisition System, Magnetic Bearing Controls, Instrumentation
5.1.10.	Test Section Shakedown	Shakedown Magnetic Bearing System, Dynamometer, Torquemeter
5.1.11.	Rig Shakedown	PLC system, flow valves, cooling system, sealing

DOE-NETL TASK 5.2: Conduct Test Campaigns (FY2014–FY2017)

Task	Description	Details
5.2.	**Conduct Test Campaigns**	
5.2.1.	Test Campaign 1	1.5 Turbine Stage Baseline: Reduced Span Airfoil, No Cooling Flow
5.2.2.	Test Campaign 2	Rotor Disk Cooling and Egress Management (Version 1)
5.2.3.	Test Campaign 3	Rotor Disk Cooling and Egress Management (Version 2)
5.2.4.	Test Campaign 4	1.5 Stage Baseline: Full Span Airfoil, Internal Cooling Flow
5.2.5.	Test Campaign 5	1.5 Stage Rotating Cooled Blades (Version 1)
5.2.6.	Test Campaign 6	1.5 Stage Rotating Cooled Blades (Version 2)
5.2.7.	Test Campaign 7	1.5 Stage Combines Campaigns 2/5 and 3/6 for an Optimized System

03: FE0004727

Project Number	Project Title			
FE0004727	Mechanisms Underpinning Degradation of Protective Oxides and Thermal Barrier Coating Systems in HHC-Fueled Turbines			
Contacts	**Name**	**Organization**	**Email**	
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Principal Investigator	Daniel Mumm	University of California, Irvine	mumm@uci.edu	
Partners	None.			
Stage of Development				
X Fundamental R&D	__Applied R&D	__Prototype Testing	__Proof of Concept	__Demonstration

Technical Background

Thermal barrier coatings (TBCs) and components in the hot section of gas turbines experience in-service degradation due to the harsh environment of the hot-gas path. Relative to traditional use of natural gas in power generation turbines, materials degradation rates are accelerated by use of coal derived synthesis gas (syngas) and high hydrogen content (HHC) fuels. In this project the University of California, Irvine will provide an improved mechanistic understanding of the degradation of critical turbine system materials in HHC-fueled systems, and guide the development of more robust material sets for future hydrogen turbine systems. This project is managed by NETL under the University Turbine Systems Research (UTSR) program. NETL is researching advanced turbine technology with the goal of producing reliable, affordable, and environmentally friendly electric power in response to the nation's increasing energy challenges. NETL is leading the research, development, and demonstration of these hydrogen turbine technologies to achieve power production from HHC fuels derived from coal that is clean, efficient, and cost-effective; minimizes carbon dioxide (CO_2) emissions; and will help maintain the nation's leadership in the export of gas turbine equipment. This project was competitively selected under the UTSR program that permits academic research and student fellowships between participating universities and gas turbine manufacturers.

The overarching goal of this research program is to evaluate the potential impacts of coal-derived syngas and HHC fuels on the degradation of turbine hot-section components through attack of protective oxides and thermal barrier coatings. The primary focus of this research program is to explore mechanisms underpinning the observed degradation processes, and connections to the combustion environments and characteristic non-combustible constituents. Based on the mechanistic understanding of how these emerging fuel streams affect materials degradation, the ultimate goal of the program is to advance the Advanced Energy Systems Program's hydrogen turbine goals by developing materials design protocols leading to turbine hot-section components with improved resistance to service lifetime degradation under advanced fuels exposures.

This research program is focused on studying how differing combustion environments—relative to traditional natural gas fired systems—affect both the growth rate of thermally grown oxide (TGO) layers and the stability of these oxides and protective TBCs; and how low levels of fuel impurities and characteristic non-combustibles interact with surface oxides, for instance through the development of molten deposits that lead to behavior analogous to CMAS (calcium-magnesium-aluminosilicate) degradation in aero-turbine engines. The overall program comprises six inter-related themes, each comprising a research thrust over the program period, including: (i) evaluating the role of syngas and HHC combustion environments in modifying component surface temperatures, heat transfer to the TBC coatings, and thermal gradients within these coatings; (ii) understanding the instability of TBC coatings in the syngas and high-hydrogen environment with regards to decomposition, phase changes and sintering; (iii) characterizing ash deposition, molten phase development and infiltration, and associated corrosive/thermochemical attack mechanisms; (iv) developing a mechanics-based analysis of the driving forces for crack growth and delamination, based on molten phase infiltration, misfit upon cooling, and loss of compliance; (v) understanding changes in TGO growth mechanisms associated with these emerging combustion product streams; and (vi) identifying degradation resistant alternative materials (including new compositions or bi-layer concepts) for use in mitigating the observed degradation modes.

The project team is also assessing TGO development and TBC failure unique to HHC environmental exposures. High-resolution imaging and microanalysis is being used to explain the evolution of TGOs and surface deposits (molten phase formation, infiltration) unique to HHC fuel combustion, and explore thermochemical instabilities, thermomechanical drivers and thermal gradient effects, and stress evolution that may arise with enhanced sintering of the coatings in HHC environments. Test coupons with coatings fabricated by electron beam physical vapor deposition, exhibiting idealized microstructures, will be used to compliment (and compare with) studies of industry standard thermal spray coating systems. Representative syngas and HHC fuels with realistic levels of impurities and contaminants must be analyzed to explore differences in surface degradation and coating surface deposit formation, with experiments executed to study the melting and infiltration of simulated ash deposits. Reaction products and evolving phases associated with molten phase corrosion mechanisms will be identified, and the underlying thermodynamics, kinetics, and mechanics are being identified and quantified. New material systems (including bi-layer systems) for laboratory testing are being developed using advanced thermal spray techniques, and thermal gradient testing and combustion rig testing of material test coupons is being facilitated in this effort. Information on the resulting combustion environments needed to properly assess the impacts of the materials exposure conditions is being identified and used to guide the development of laboratory-scale simulations of material exposures.

Relationship to Program

This project will support important advances within the turbines portfolio of the NETL Advanced Energy Systems program. This UTSR project strives to show that gas turbines can operate on coal-based hydrogen fuels, increase combined cycle efficiency by 3%–5% points over the baseline, and reduce emissions. This project will support an increase in the life of turbine hot-section components, which will increase maintenance intervals and, ultimately, the life of the power system. As part of this effort, it is critical to assess whether these emerging turbine system operational scenarios significantly enhance the degradation of hot-section materials. This program provides an opportunity to quantitatively assess the potential impacts, understand them mechanistically, and guide mitigation based on mechanism-based materials design protocols.

Another benefit of this project is the attendant education of a future workforce trained in the advanced materials engineering concepts need to maintain U.S. leadership in gas turbine systems and advanced power generation technology.

Primary Project Goal

The primary goal of this project is to facilitate original equipment manufacturer (OEM) development of materials and coatings systems for turbine hot-section components that provide high reliability and stability in syngas and HHC fuel combustion environments. This effort is critical to enabling the development of more efficient and environmentally friendly hydrogen turbine technologies and achieving the overall hydrogen turbine goals of the Advanced Energy Systems Program. The project seeks to link and quantify the effects of the modified combustion environments, higher water vapor levels, higher sulfur concentrations, and exposure to flow stream impurities characteristic of syngas and HHC fuels, and identify any synergism among these factors influencing materials stability.

Objectives

The overarching goal of this research program is to evaluate the potential impacts of coal-derived syngas and HHC fuels on the degradation of turbine hot-section components through attack of protective oxides and coatings. The primary focus of the research effort is to develop an improved understanding of the mechanisms by which the HHC exposure environment affects oxide phase development and evolution during service; impacts the inherent stability and thermal conductivity of the hot-section thermal barrier coatings (TBCs); and results in unique surface deposits that can compromise coating integrity through molten phase infiltration and the associated thermochemical and thermomechanical processes. A broad goal of the overall project is to specify alternative or modified hot-section materials that offer optimized stability in syngas- and HHC-specific environments.

The specific project objectives include the following:

- Evaluate the unique impacts of utilizing coal-derived syngas and HHC fuels on hot-section materials evolution and degradation, and develop a mechanistic analysis of the observed degradation processes as they correlate with fuel-dependent combustion environments.
- Procure baseline materials representative of commercially relevant overlay and bond coat materials, and assess oxide growth and phase development in simulated syngas/HHC combustion, with systematic variation of the byproduct stream composition and water vapor content.
- Explore the fundamental mechanisms by which water vapor and the unique balance of combustion byproduct gas constituents affect non-ideal oxide growth and TBC system lifetime, by utilizing novel specimen exposure protocols; carrying out selected experiments on a burner rig test system; and applying advanced microscopy and spectroscopic methods to quantitatively evaluate nanoscale materials evolution in relation to exposure environments.
- Develop materials design protocols that maximize the lifetime of protective oxides and TBCs in syngas and/or HHC combustion turbine exposures.
- Identify surface deposit chemistries, synthesize representative ‘ash’ constituents, characterize key thermal properties, and assess the underpinning mechanisms—characteristic of syngas/HHC fueled systems—by which these deposits enhance coating degradation rates.
- Identify optimized or alternative materials systems to mitigate deposit-induced failure processes characteristic of syngas and HHC fuel fired systems.
- Develop predictive models that guide the development of materials with improved hot-section durability and facilitate the development of hydrogen turbine systems.

These studies generally seek to address concerns that have arisen in regard to syngas- and HHC-based turbine studies, particularly the unexpected formation of non-ideal oxides that compromise coatings adhesion and durability. The project team has developed and applied novel techniques for exploring the mechanisms controlling the formation of interfacial oxides in relation to the combustion environment. In experiments that isolate the partial pressure of water vapor (pH_2O), hydrogen (pH_2) and carbon dioxide (pCO_2), etc. as variables, interfacial oxide formation has been systematically assessed and chemically characterized. Materials have been procured and studies initiated to study chemical and phase stability of TBCs in elevated temperature, high-water-vapor environments. Ash composition that may be representative of impurities in coal-derived syngas have been identified, synthesized, and carried forward into experimental procedures to characterize thermochemical stability. Advanced characterization techniques (Raman, in-situ X-ray diffraction, transmission electron microscopy studies) are being used to study coating phase decomposition and sintering degradation to assess impacts of HHC and syngas fuel combustion through side-by-side materials exposure studies. Bi-layer ceramic coatings incorporating perovskite outer layers and unique coating microstructures are being processed, and exposure testing is being initiated. An approach to infiltrate coating porosity with a material to inhibit glass phase wetting and infiltration is undergoing initial assessments, and a unique stress-measurement technique is being applied for in-situ monitoring of coating degradation during combustion environment exposure.

The project activities and goals are being guided by an existing mechanistic framework that describes various TBC failure mechanisms and utilizes comparative studies of materials exposed to simulated natural gas and syngas/HHC combustion environments to refine and validate predictive models, and to improve materials design protocols. An attendant objective of this project is to educate a future workforce trained in the advanced materials engineering concepts need to maintain U.S. leadership in gas turbine systems and advanced power generation technology.

04: AL05205018

Project Number	Project Title			
AL05205018	Analysis of Gas Turbine Thermal Performance			
Contacts	**Name**	**Organization**	**Email**	
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Partners	Iowa State University Purdue University University of Pittsburgh Siemens Mikro Systems Exa Corporation			
Stage of Development				
_X_ Fundamental R&D	__Applied R&D	__Prototype Testing	__Proof of Concept	__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 (e.g., integrated gasification combined cycle [IGCC]) that can enable the deployment of near-zero-emission power plants with carbon dioxide separation and capture. Whether the fuel burned is natural gas (the predominant fuel used in current electric power generation gas turbines); syngas, a high-hydrogen mixture; or an oxyfuel, the efficiency and service life of the gas turbine engine are strongly affected by the turbine component, the part of the system where 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 increase the temperature of the gas entering the turbine component, which can theoretically be as high as the adiabatic flame temperature from the combustion of the fuel and oxidizer. Although the temperatures sought today—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 the best superalloys and thermal-barrier coatings (TBC) can withstand while still maintaining structural integrity and reliable operation. Thus, to achieve a reasonable service life, cooling (e.g., internal, film, and impingement) is essential for all parts of the turbine with surfaces that come in contact with the hot gases.

Because cooling requires work input (i.e., the pressure of the cooling flow must be high enough to enter the turbine), effective cooling, which ensures that material temperatures never exceed the maximum allowable material temperature, must be accomplished efficiently. This issue deserves increasing attention for three major reasons. The first is that today's turbines are already designed to operate very close to the material's maximum allowable temperature based on existing design experience, which leaves little room for mistakes. The second is that industry's current goal is to reduce the cooling flow by 50% to further increase turbine efficiency, though it is already extremely difficult to cool effectively with the existing flow rates. This challenge indicates the need for new cooling strategies that can only come about with in-depth understanding of the effects of fluid mechanics on heat transfer and an understanding of how external heat transfer with and without film cooling on the hot-gas side is coupled to internal heat transfer on the cooling side through the superalloy and the TBC. The third is that when the fuel burned is syngas, a hydrogen fuel, or an oxyfuel, the heat transfer characteristics in the turbine on the hot-gas side can increase because of increases in water vapor content, increased erosion and deposition tendencies, and increases in the hot-gas mass flow rate, making cooling even more difficult. Thus, there is very little room for mistakes in the design of cooling strategies. For example, temperatures just 10 K–20 K above the maximum allowable temperature could lead to material degradation that terminates service life.

Current design and analysis tools used to explore, develop, and evaluate cooling strategies at the system 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 account 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 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 designs of cooling strategies that would allow for hot spots to form (i.e., local regions where the temperature could exceed the maximum allowable temperature).

As new designs with greatly reduced cooling flows are outside of current design experiences, it is important to develop and evaluate design tools, such as those based on computational fluid dynamics (CFD) approaches, with the potential to provide the appropriate level of understanding. Also, it is 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 guide the development of new cooling strategies.

Relationship to Program

This project will support important aerodynamics and heat transfer advances within the turbines portfolio of the NETL Advanced Energy Systems Program. Ames National Laboratory and Purdue University are designing cooling strategies to support the gas turbine industry's current goal to reduce cooling flows by 50% as a means to further increase turbine efficiency. This goal becomes increasingly challenging when considering low available cooling flow rates, gas turbine operation zones near the material's maximum allowable temperature, and the increasing heat transfer characteristics in high-hydrogen-fueled turbines with increased water vapor content and increased hot-gas mass flow rates.

Current design and analysis tools used to explore, develop, and evaluate cooling strategies 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 can be large enough to overheat materials. Currently, these unaccounted for variations are remedied by a factor of safety too generous in some places and not generous enough in other places. This project aims to develop and evaluate CFD-based design tools that can account for the large local variations in heat transfer and temperature distributions and can generate needed understanding of these variations, enabling turbine cooling designs that can handle turbine inlet temperatures of 1,755 K with significantly reduced cooling flow rates.

In summary, the benefits of this study include the following:

- Better design tools, better understanding of these tools, and new understanding of flow/heat transfer mechanisms that can lead to improved design concepts and enable more efficient (i.e., lower cooling flow rates and lower/higher pressure drops) and more effective (i.e., no hot spots) cooling strategies and designs, ultimately increasing fuel efficiency and lengthening service life.
- Biot number similarity will enable experiments that are less expensive.

- CFD studies on uncertainties in experimental methods will improve verification and validation and uncertainty quantification.

Primary Project Goal

The primary goal of this project is twofold. The first part of the goal is to develop, evaluate, and improve physics/mathematics-based analysis tools (e.g., Fluent and CFX) that can be used to examine and explore heat-transfer issues in the design of advanced cooling strategies for the turbine component. The second component of the goal is to use those analysis tools to provide fundamental understanding of the issues and support the development of effective and efficient cooling strategies. The analysis tools of interest are those that can properly account for the steady and unsteady three-dimensional heat transfer from the hot gas in the turbine blade passage through the turbine material—the TBC system and the superalloy—to the internal cooling passages as a function of the cooling strategy as well as the composition, mass flow rate, and temperature of the hot gas entering the turbine.

Objectives

The project's following four project objectives extend from 2004 to 2014:

1. Compile and capture the literature on the cooling of the turbine component that considers the systems perspective of the problem with 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 address verification, validation, and uncertainty quantification issues for CFD, experiments, and design of experiments.
3. Explore and examine heat-transfer issues that affect performance and service life of turbines 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.

05: FC26-05NT42645

Project Number	Project Title			
FC26-05NT42645	Recovery Act: Oxy-Fuel Turbo Machinery Development for Energy Intensive Industrial Applications (Phase 2A)			
Contacts	**Name**	**Organization**	**Email**	
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Partners	Siemens Energy, Inc., Oil and Gas Division Florida Turbine Technologies., Inc. Integrated Engineers and Contractors Corporation			
Stage of Development				
__Fundamental R&D	__Applied R&D	__Prototype Testing	X Proof of Concept	__Demonstration

Technical Background

NETL is researching next-generation turbine technology with the goal of producing reliable, affordable, diverse, and environmentally friendly electric power in response to the nation's increasing energy challenges. Future fossil fuel power-generation systems will require advanced emission control techniques such as carbon capture and sequestration (CCS) to comply with greenhouse gas regulations. Three prime candidate technologies permit carbon dioxide (CO_2) to be captured and safely stored: pre-combustion capture, post-combustion capture, and oxyfuel combustion technologies.

Clean Energy Systems, Inc. (CES) has been designing and demonstrating enabling technologies for oxyfuel power generation for more than a decade. Their secret is a high-pressure, oxyfuel combustion process based on proven rocket technology that uses photo-etched platelets to create precision metering channels for the atomization of reactants. This enables CES combustors to burn clean gaseous and/or liquid fuels with pure oxygen, rather than air, at near-stoichiometric conditions. Flame and hardware temperatures are controlled by the injection of demineralized water, creating a consistent, repeatable, robust ignition process. The result is a high-temperature, high-pressure gas—composed of primarily steam and CO_2—that can be used to drive steam turbines (conventional or advanced) or modified gas turbines.

In 2005, CES was awarded a cooperative agreement through NETL to study oxyfuel power systems as an economical means to produce power while capturing CO_2. This cooperative agreement began with engineering power cycle modeling and analysis to determine oxyfuel plant efficiencies and the cost of electricity produced when existing CO_2 capture technologies were added to the system. During this time, CES completed cycle studies and analyses of 45 oxy-synthesis gas combustor/turbine configurations and used the results to down-select one near-term and one long-term baseline power cycle.

CES cycle studies have shown that typical oxyfuel power cycles are capable of capturing greater than 99% of the produced CO_2 at competitive cycle efficiencies using diverse fuels. In these systems, a large oxyfuel combustor, or gas generator, powers a turbine train to generate electricity upstream of a CO_2 capture system. The gas generator combusts gaseous oxygen from an air separation unit with the selected fuel (e.g., natural gas, coal-derived synthesis gas [syngas], or biofuels) to produce a hot gas stream of steam and CO_2. Because air is eliminated from the combustion process, nitrogen oxide emissions are lower than current state-of-the-art control technology. Recycled water is used to cool the gas to the desired temperature of a high-pressure turbine (HPT) before it is reheated and further expanded through intermediate-pressure turbines (IPT) and low-pressure turbines. The pure CO_2 that is generated is readily separated from the residual steam, making it available for sequestration or commercial use. The process is also a net producer of high-quality water that can be used either onsite or offsite. Each component in the cycle, except for the main and oxyfuel reheat combustors, is already commercially proven and can be found in standard power generation applications.

Favorable results of the Phase 1 cycle studies led to the contract extension to Phase 2 in 2006 for oxyfuel combustor development and demonstration. During this phase, CES demonstrated oxy-syngas combustion with a proven 20 megawatt-thermal (MWt) oxyfuel combustor. This combustor had previously confirmed the oxyfuel proof-of-concept when it was coupled with an off-the-shelf steam turbine and accumulated over 1,300 hours of operation. Lessons learned from the demonstration led CES to complete the detailed design of a commercial-scale, 170 MWt oxyfuel combustor that was large enough to power industrial-sized oxyfuel facilities.

Thermodynamic analyses ascertain that cycle performance and cost of electricity are greatly enhanced when the inlet temperature of the IPT is increased to 1,400°F–2,280°F (760°C–1,250°C) or higher. Taking this into consideration, and the eventual cancellation of Phase 3 of the agreement, NETL authorized a restructuring of the Phase 2 work scope to incorporate the development of oxyfuel steam reheaters and high-temperature IPTs. Under this restructuring, CES developed and demonstrated an oxyfuel reheat combustor that could be directly coupled to a high-temperature IPT. A pilot-scale test article, based on a standard gas turbine combustion system, successfully reheated the steam/CO_2 drive gas from approximately 600°F to 1,400°F–1,700°F. CES also conducted pilot-scale testing utilizing a large 170 MWt oxyfuel combustor to power a gas turbine-derived hot gas expander capable of producing up to 30 megawatt-electric (MWe).

Though this work proved not only the core principles but also the hardware necessary for near-zero emission oxyfuel power systems, due to its scale, an additional revenue stream would be required to implement it (e.g., a government-enforced carbon tax or revenues gained from CO_2 byproduct used in enhanced oil recovery [EOR] or enhanced gas recovery). To make the power cycle more attractive, CES partnered with Florida Turbine Technologies, Inc. (FTT) in 2009 to complete the detailed engineering design of an advanced, industrial-scale oxyfuel IPT. With turbine inlet temperatures up to 2,000°F, this system aimed to further increase plant efficiencies and take advantage of economies of scale. However, due to funding constraints, only the design of this oxyfuel turbine (OFT) could be completed under Phase 2 of the cooperative agreement, leaving the advanced turbine technology unproven.

In September 2010, a modification to the cooperative agreement was issued that used $30 million in American Recovery and Reinvestment Act funds to develop and demonstrate a highly efficient intermediate-pressure OFT capable of supporting commercial-scale oxyfuel power generation with 99% CO_2 capture. The modification added Phase 2A to the statement of project objectives to design, manufacture, and test the aforementioned advanced OFT.

The incremental technology advances made under the CES-NETL cooperative agreement have facilitated early development and demonstration of enabling technologies for near-zero emission oxyfuel power generation using fossil fuels. With its hydrogen turbine portfolio, NETL is leading the research, development, and demonstration of next-generation turbine technologies to achieve power production from coal that is clean, efficient, and cost-effective; minimizes CO_2 emissions; and will help maintain the nation’s leadership in the export of gas turbine equipment.

Relationship to Program

This project will support important oxyfuel advances within the turbines portfolio of the NETL Advanced Energy Systems Program. The CES oxyfuel technology has the potential to offset a shortage of CO_2 available for CO_2 EOR. In a March 2010 white paper titled *U.S. Oil Production Potential From Accelerated Deployment of Carbon Capture and Storage*, which was, in part, based on the January 2009 DOE/NETL report *Storing CO_2 with Enhanced Oil Recovery*, Advanced Resources International identified prospective market conditions for CO_2 enhanced oil recovery (EOR) in the United States. They noted that about 395 billion barrels of U.S. original volumes of oil are amenable to CO_2 EOR, with over 72 billion barrels technically recoverable with current CO_2 EOR best practices. Advanced technology could increase the latter to over 106 billion barrels. The report estimates that under certain scenarios, the U.S. state and federal government will gain $30.70–$33.90 for each incremental barrel produced, while the private sector would gain $33.50–$38.10.

However, current CO_2 supplies are insufficient to meet these markets, as today's CO_2 flooding operations are limited by reliable supplies of affordable CO_2. The report later concludes that while the economic market potential for CO_2 in EOR for the continental United States is close to 10 billion tonnes, only about 3 billion tonnes of CO_2 will become available through 2030, assuming efficient distribution and full utilization of CO_2 for EOR. Based on the market scenario portrayed in this report and whether existing and future power generation facilities will need to fully capture and sequester their CO_2, CES will concentrate on contributing to closing the gap of the identified shortfall of 7 billion tonnes of CO_2 for CO_2 EOR over the next 20 years.

Primary Project Goal

The primary goal of Phase 2A is to design, manufacture, and test an industrial-scale intermediate-pressure OFT capable of full-load turbine inlet temperatures of approximately 2,000°F (1,093°C).

Objectives

The objectives of project Phases 1 and 2 have been completed, culminating in the final reports *Oxy-Syngas Cycle Analysis and Selection* and *Detailed Design of a Commercial Oxy-Syngas Combustor and Enclosure*. CES is now wholly focused on the Phase 2A project objective to design, develop, and test a commercial-scale OFT that can be deployed in second-generation commercial industrial oxyfuel power plants that capture and sequester more than 99% of the produced CO_2. This system aims to operate at a competitive cycle efficiency and cost of electricity using diverse fuels, including natural gas, coal-derived syngas, and gasified or liquid renewable fuels.

CES has partnered with FTT and Siemens Energy, Inc. to develop and demonstrate a reheat combustor-equipped IPT compatible with oxyfuel power systems. Although traditional steam turbines can accept the high-steam-content working fluid of the oxyfuel process, its elevated turbine inlet temperature is well above current hardware capacities. Gas turbine engines, however, routinely operate within the desired temperature range due to the use of sophisticated materials and cooling technology within the turbine. The development team has found that these engines can be adapted to fit the oxyfuel cycle with minimal changes.

For cost-reduction, schedule, and efficiency-of-effort reasons, the project team elected to purchase and modify a used gas turbine engine to accept the steam/CO_2 drive gas. The initial feasibility study selected the Siemens SGT-900 (formerly the Westinghouse W251 engine) as the preferred candidate for modification to an industrial-scale oxyfuel power-generation system. Factors in this decision included aerodynamic and thermodynamic performance, turbine size, firing temperature and pressure conditions, cooling system functionality, and the flexibility to incorporate necessary configuration changes to ensure mechanical integrity. Additional considerations included the availability of surplus equipment and access to technical data on the engine and auxiliary equipment.

The candidate turbine was purchased and shipped to a Siemens facility for disassembly, inspection, and repair, taking advantage of Siemens' gas turbine expertise. Reused components will be refurbished and reassembled with any required new or modified OFT components. Once complete, the new OFT, named the OFT-900, will be shipped to the selected test facility. To help minimize program cost and schedule, CES is modifying its existing test facility to support low-power demonstration of the OFT-900 with natural gas.

The team has established five critical milestones within the Phase 2A work scope that must be completed to ensure the project's success. These milestones include the completion of the turbine design, acquisition of critical hardware, pilot-scale reheat combustor demonstration, and the completion of OFT manufacture and testing. These milestones are described in further detail below.

1. **Release manufacturing drawings for modification of a Siemens SGT-900 to an industrial-scale OFT (Complete).** Prior to ordering any substantial hardware, a final design review was held to verify adequacy and completeness of the detailed engineering design completed by FTT to convert a Siemens SGT-900 B12 gas turbine engine to an IP OFT. No major deficiencies in the design were found by the CES-FTT-Siemens review team. Final manufacturing drawings were completed and released by FTT in April 2011, and in May CES issued a purchase order to Siemens for all new long-lead components required for engine conversion.

2. **Acquire a used SGT-900 or procure new parts required for a new oxy-turbine (Complete).** Because a conventional industrial gas turbine was selected for modification, it was paramount that a machine, or at least the required components, was purchased in a timely fashion. Soon after Phase 2A kicked off in October 2010, a Siemens team was charged with locating and pricing existing SGT-900 engines across the globe. In late November 2010, a suitable SGT-900 B12 Econopac was located at the Abitibi Bowater Plant in Fort Frances, Ontario, Canada. All engine records were provided by Siemens Hamilton, also based out of Ontario, who had conducted all the service on the machine. After thorough review, CES purchased the B12 Econopac, including necessary power plant equipment and spare parts, on January 6, 2011. The purchase occurred nine months ahead of schedule.

3. **Complete pilot-scale oxyfuel reheat combustor testing (Estimated Completion Date: June 2012).** To achieve desired turbine efficiencies, the turbine must be able to utilize drive gas at inlet temperatures of 2,000°F. Due to site and funding limitations, the OFT-900 engine demonstration will operate at partial load and reduced turbine inlet temperatures. However, CES will demonstrate near-full load operation of the oxyfuel reheat combustor technology via pilot-scale testing of a *single* oxyfuel reheat combustor (representing one of the eight circumferential combustors contained within the OFT engine annulus).

   As a risk mitigation strategy, the project team has designed and manufactured two different single-can oxyfuel reheat combustors that meet the fit-form-function requirements of the OFT-900's operating requirements. One design, led by FTT, uses a front-end mixer/swirler technique, similar to that of conventional gas turbine combustors. The other design, led by CES, makes use of patented platelet technology to intimately mix oxygen and natural gas in the presence of the steam/CO_2 working fluid. A dedicated test rig has been designed and built at CES' Kimberlina test facility, located in Bakersfield, California. Testing of both pilot-scale reheaters is scheduled for spring 2012.

Evaluation of the competing single-can reheat combustor designs will be based on the criteria established in the oxyfuel reheat combustor test plan. Design parameters such as exit temperatures, pressure losses, flow rates, emissions, combustion stability, and exhaust pattern factor will be recorded and compared. Upon test completion, the data gathered will be used to modify the reheat combustor design, if required, to ensure that an acceptable OFT inlet pattern factor is achieved.

4. **Manufacture and shipment the oxyfuel turbine to selected test facility (Estimated Completion Date: July 2012).** The purchased SGT-900 B12 unit was extracted from the Abitibi Bowater facility in Ontario, Canada and shipped to a TurboCare repair facility in Houston, Texas. Delivered in April 2011, TurboCare disassembled and inspected all components including the rotor, turbine diaphragms, seals, casing, hardware, gearbox, and bedplate arrangement. The condition of all reused items was documented and inspection reports were issued to CES. A majority of the engine components were found to be in satisfactory condition and could be re-used for the oxyfuel engine with minimal refurbishment. Only the combustion transition ducts required a greater level of repair (up to replacement) due to geometry impairments that had occurred during previous turbine operation.

   TurboCare is also leading the manufacturing effort of new components unique to the OFT. The six major components of the modification are a new inlet plenum, an inlet housing cover, a shaft cover, an outer flow guide, a thrust balance piston, and a piston seal set. For full-load operations, the OFT-900 will also require a set of exit guide vanes; however, these are not required at the partial loads at which the engine will be tested and have been left out of the manufacturing scope for the initial demonstration. New component manufacture began in mid-2011 when purchase orders for long-lead items were issued to multiple suppliers within the United States. The Siemens TurboCare team is working closely with FTT, the new component designer, to ensure that design intent is maintained during the manufacturing process. To date, TurboCare has received five of the six new major components. Once the sixth and final component is received, engine reassembly will commence.

   The fully assembled and packaged oxyfuel turbine will ship to CES' test site only after the engine has passed all required factory acceptance tests (e.g., clearances and rotor balance). The estimated turbine delivery to test site is mid-2012.

5. **Complete OFT testing (Estimated Completion Date: June 2013).** For funding and efficiency-of-effort reasons, the OFT will be demonstrated at partial power in a simple oxygen-natural gas power cycle. The test setup will utilize CES' existing 170 MWt oxyfuel combustor to power the new reheat combustor-equipped oxyfuel IPT. Produced power will be dissipated to onsite resistive load banks.

   Success will be measured by comparison to criteria established in the OFT test plan. This includes criteria for successful startup; operation without reheat combustors; operation with reheat combustors; and achievement of target mass flow rates, gas composition, pressures, temperatures, and power output. The primary test objective will be the production of power (>20 MW shaft) with minimal delays. Initial tests will focus on matching measured performance with predicted results, as this will directly determine the cost-competitiveness of the technology. Note that the limited operating hours will not allow duration testing of the materials selected for use in the turbine.

Successful demonstration of oxyfuel combustor/oxyfuel turbine operations is the ultimate objective of the program and will dictate the future direction of the technology. If successful, the hardware will be suitable for use in zero-emissions base-load power plants generating up to 200 MWe, for use as 150 MWe super clean peaking plants, or for other industrial uses. If unsuccessful, redesign may be required and will be followed by re-testing.

Accomplishment of the above goals will effectively shorten oxyfuel turbine development time from 10 years to 3 years, making the operation of all key components for a near zero-emission power plant possible by late 2015.

06: FC26-05NT42644

<table>
<tr><th>Project Number</th><th colspan="4">Project Title</th></tr>
<tr><td>FC26-05NT42644</td><td colspan="4">Recovery Act: Advanced Hydrogen Turbine Development</td></tr>
<tr><td>Contacts</td><td>Name</td><td>Organization</td><td colspan="2">Email</td></tr>
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BASF Catalysts LLC
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Florida Institute of Technology
Florida Turbine Technologies, Inc
Fopat Production, Inc.
Georgia Tech Research Corp.
Joliet Metallurgical Laboratories, Inc.
Makel Engineering, Inc.
Mikro Systems, Inc.
PCC Airfoils, LLC
Princeton University
Product Evaluation Systems
Purdue University
Siemens AG
Siemens Corporation
Siemens Industrial Turbomachinery, Ltd.
University of Florida
University of Texas at Austin
Virginia Tech</td></tr>
<tr><td colspan="5">Stage of Development</td></tr>
<tr><td>__Fundamental R&D</td><td>__Applied R&D</td><td>_X_Prototype Testing</td><td>__Proof of Concept</td><td>__Demonstration</td></tr>
</table>

Technical Background

To achieve higher turbine engine and plant efficiencies in line with DOE program goals, gas turbine engine operating conditions must be upgraded, and new enhanced technologies need to be developed and implemented. Studies conducted early in this project by Siemens Energy confirmed that the primary drivers of combined cycle efficiency are gas turbine firing temperature, pressure ratio, and turbine exit temperature. Therefore, the basis of project research is to develop technologies operating on synthesis gas (syngas) and hydrogen fuel that can increase these turbine operating conditions while maintaining low emissions. Siemens Energy's advanced technologies incorporate improved compressor aerodynamics, low nitrogen oxide (NO_x) syngas and hydrogen combustion systems, novel turbine cooling and aerodynamic improvements, novel manufacturing techniques, improved materials and coatings, and advanced sensors and diagnostics. These technologies are built based on Siemens Energy's extensive experience with high-temperature operation of G- and H-Class engines and their successful operating experience with syngas fuels in integrated gasification combined cycle (IGCC) applications. The targeted efficiency improvements and the significant increase in power island output will also lead to cost reduction on a $/kW basis.

To achieve higher engine and plant efficiencies, this project aims to upgrade operating conditions and develop new technologies through the following research and development efforts:

COMPRESSOR

Based on the selected engine design point, Siemens Energy conducted preliminary studies on an advanced compressor design to provide the required stage number and flow path geometry. Siemens Energy investigated a range of pressure ratios, assessed the implications of pressure on stage count, and conducted 2-D and 3-D analyses of the preferred concepts. Experimental rig validation of airfoil designs is now under way.

COMBUSTION SYSTEM

A key component in successfully developing a fuel-flexible hydrogen turbine is the combustion system. To achieve the challenging DOE program emission goal at the elevated firing temperature and pressure ratio, Siemens Energy investigated several competing combustion concepts, such as diffusion flame and premixed and catalytic combustion. Two technologies were down-selected from a total of four competing technologies at the end of Phase 1. Siemens Energy is developing candidate combustion systems specifically for syngas and hydrogen applications through component modeling studies, subscale test programs to evaluate critical combustion and operational issues, and validation testing. University partners have validated prediction methods for flame speed and ignition delay with hydrogen and syngas fuels. Full-scale combustion rig development testing of the selected configuration is continuing in line with the program development schedule.

TURBINE

Siemens Energy is evaluating aerodynamic and cooling concepts of advanced turbines to produce a turbine design with the lowest possible air cooling requirements, excellent mechanical integrity, and high efficiency. To achieve this, Siemens Energy is incorporating novel aerodynamic design concepts; highly effective cooling schemes; high-temperature, low-conductivity thermal barrier coating (TBC) systems; and advanced alloy castings into the turbine design. Universities are verifying models of selected cooling configurations through subscale testing. Advanced manufacturing demonstrations of the selected configurations are under way.

MATERIALS AND COATINGS

Advanced materials and coatings are critical to the successful advancement of engine components. Siemens Energy identified the materials property requirements for each hydrogen turbine component and potential materials technologies that could meet these requirements. Continuous efforts have been made to improve the oxidation resistance and mechanical properties of these components through the addition of alloying elements and oxide dispersion. Siemens Energy employed a design-of-experiment process to select optimum elements for bond coat enhancement and developed fabricated and modular airfoil concepts to optimize the use of next-generation alloys, including single crystal and/or currently unavailable yields, and provide a means for intra-component substrate material selection and coupling for optimized material properties.

SENSORS AND DIAGNOSTICS

Siemens Energy will implement advanced sensor and diagnostics technologies to support hydrogen turbine development. Incorporating these technologies will allow thermal, environmental, performance, and mechanical optimization of the advanced turbine operating on syngas and hydrogen fuels. The sensors and the associated diagnostic functions (e.g., fast-response fuel monitoring, fuel controlling turbine temperature monitoring, TBC monitoring, tip clearance control, and engine health monitoring) will mitigate the risks associated with the advanced components Siemens Energy is developing.

Relationship to Program

This project will support important hydrogen turbine advances within the turbines portfolio of the NETL Advanced Energy Systems Program. Improving combined cycle efficiency by 3–5 percentage points over the current state of the art contributes directly to the Advanced Energy Systems Program goals of improving IGCC plant efficiency to 45%–50% higher heating value.

The new technologies developed through this project have the potential to accelerate commercialization of advanced coal-based IGCC plants in the United States and around the world. Siemens Energy's advanced IGCC plant is projected to use 40% less water and 50% less solid waste than today's conventional pulverized coal plants. Compared to sub-critical pulverized coal plants, each year the hydrogen turbine IGCC plant is expected to reduce sulfur dioxide emissions by 2,080 metric tons, NO_x by 1,030 tons, carbon monoxide by 3,200 tons, and particulates by 400 tons. Siemens Energy will also incorporate carbon capture into the plant design to support national priorities for reducing the importation of fossil fuels from politically unstable sources. Cycle penalties associated with carbon capture and sequestration, while significant, can be partially recovered by incorporating the turbine technologies pursued in the NETL Advanced Energy Systems Program. Technologies developed through this program, including components that use new manufacturing techniques and have higher material limits, increased firing temperatures, increased gas turbine efficiency, and lower emissions, can be integrated into other current Siemens Energy gas turbine designs. Additional collateral benefits of the Siemens Energy's project include the creation of high-quality U.S. jobs, energy self-sufficiency through large coal deposits, increased exports, and hydrogen co-production for transportation or industrial uses.

Primary Project Goal

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

Objectives

This project has been implemented in two phases. Phase I, Conceptual Design and R&D Implementation Plan: Concept to Commercial Deployment, is complete. Phase II, Design and Validation Test Program, is about 60% complete, with the Base Program 75% complete and the American Recovery and Reinvestment Act Program 25% complete. The overall project objectives of these phases and the project goals for 2010, 2012, and 2015 are provided below.

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

The Phase I objectives include the following:

- Develop an R&D Implementation Plan that details 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 and simulations to show that these conceptual turbine designs will achieve DOE objectives when deployed in likely IGCC applications, 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 down-select the most promising concepts for further development in Phase II.

PHASE II–BASIC DESIGN AND VALIDATION TEST PROGRAM

The Phase II objectives include the following:

- Develop designs of components and systems required to meet the 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 DOE turbine performance goal.
- Integrate technologies and subsystems into commercial IGCC applications and natural gas-fired engines where applicable.

2010 PROJECT GOALS

At the end of fiscal year 2010, Siemens Energy used system studies and laboratory-scale testing to demonstrate the technology readiness of increasing overall IGCC efficiency by 2%–3% percentage points over the baseline, reducing the capital cost of combined cycle by 20%–30%, and reducing NO_x emissions to 2 ppm using syngas as a fuel.

To meet the goal of increasing combined cycle efficiency by 2%–3%, the efficiency of each subsystem must increase. An advanced combustion system is being developed that is capable of low NO_x emissions and can operate at a higher firing temperature. Rig tests have already shown a premix combustor capable of operating on 100% syngas at operating temperatures above those of G- and H-Class turbines. Materials development is pursuing coatings that will reduce thermal conductivity and allow higher operating temperatures than the baseline coating. Testing has already shown a 40% increase in spallation life over the baseline and an ability to raise the allowable operating temperature of the thermal barrier coating. These significant advances can be adapted to near-term applications and will commence engine testing in 2012.

The turbine section has been analyzed for operation at the intermediate temperature that is targeted to meet the 2010 efficiency goal. Plant performance system studies have been completed to establish the baseline, 2010 and 2015 syngas cases, and a high hydrogen case. The 2010 engine enhancements operating on syngas indicate a 3.5% increase in combined cycle efficiency over the baseline for the 2010 timeframe, which exceeds the 2%–3% program goal. To maximize overall plant performance and provide robustness to operational variations, a novel selective catalytic reducer is also being developed to meet the emissions goals. Accelerated tests of commercial-sized samples have been performed in relevant exhaust conditions and show excellent NO_x removal efficiency in oxygen- and water-rich conditions. Siemens Energy conducted a cost analysis which indicates that a significant increase in power is necessary to achieve the 20%–30% cost reduction goal. A reduction in overall power block cost is the target, combined with this increase in power.

2012 PROGRAM GOALS

The 2012 goal includes the verification of the advanced hydrogen turbine technologies with 90% carbon capture. Studies have shown that there is an 8%–10% impact on efficiency when pre-combustion carbon capture is added. Consequently, additional technological advancements to the gas turbine as defined in this program and plant optimizations on the overall system level are needed to recover and mitigate these losses.

2015 PROGRAM GOALS

By 2015, a 3%–5% increase in IGCC efficiency is targeted. This engine is expected to operate on high hydrogen fuel while achieving the goal of 2 ppm NO_x emissions from the stack. Plant performance system studies have shown that the advanced technologies being pursued under this project have the potential to meet or possibly exceed the project goals. Extensive laboratory data has been obtained through university research to enhance prediction tools and methods. These advanced predictive tools are being utilized to design an advanced premix combustion system that will operate on high hydrogen fuel. Full-scale testing in combustion rigs will continue the validation of these systems to achieve low NO_x emissions while operating at a high firing temperature. Material developments have progressed as planned with the plan to achieve intermediate goals for temperature limits and system life. Novel manufacturing techniques, improved bond coats, high-temperature low-conductivity thermal barrier coatings, and oxidation-resistant superalloys will be employed. University testing of advanced airfoils and new cooling designs are benefiting the turbine hot parts design development. Additionally, new sealing configurations are being developed to reduce the required cooling flow and thereby improve the overall gas turbine efficiency. A novel selective catalytic reducer will continue to be tested to verify long-term durability and high NO_x removal efficiency.

07: FC26-05NT42643

Project Number	Project Title			
FC26-05NT42643	Recovery Act: Advanced Hydrogen Turbine Development			
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Stage of Development				
__Fundamental R&D	__Applied R&D	X Prototype Testing	X Proof of Concept	__Demonstration

Technical Background

As demand for electricity continues to grow in the United States, there is a clear interest in reducing our dependency on foreign sources of energy. Coal is our most abundant domestic fossil energy resource. In an integrated gasification combined cycle (IGCC) plant, coal can be converted into synthesis gas (syngas). This process also lends itself well to carbon capture and storage whereby greenhouse gases such as carbon dioxide and carbon monoxide can be captured and stored rather than released into the environment. The resultant gas (either syngas or “carbon-free” syngas – i.e., high hydrogen fuel) can be burned in gas turbines for power production and industrial applications.

To burn both syngas and high hydrogen fuels more efficiently while reducing emissions, improvements in gas turbine technology are required. This advanced turbine project addresses key technology development needs required to achieve specific DOE performance goals for emissions, efficiency, and capital cost. The program 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 June 2014. Additional tasks were added to the project under the American Recovery and Reinvestment Act (ARRA) during budget period 3 to adapt and advance the technologies under development for industrial applications such as refineries and steel mills. This portion of the program will end in September 2014.

The program is composed 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 impact 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). Work in this area addresses the challenges of developing a combustion system that can burn both syngas and high hydrogen fuels to produce extremely low NO_x emissions while avoiding flameholding, flashback, and dynamics issues. The ARRA expansion of the combustion program will focus on increasing efficiencies in industrial gas turbines with carbon capture and sequestration (CCS) through higher firing temperatures and low NO_x emissions. The turbine/aero element of the program targets specific turbine technology improvements to address the efficiency targets that have been identified by DOE (3–5 percentage points improvement in combined cycle efficiency). The ARRA portion of the project specifically targets the stage 1 architecture as well as advanced sensor applications.

The materials portion of the program is focused on applying materials technology to enable the turbine to operate reliably at higher firing temperatures in the IGCC environment. The ARRA expansion on materials retains the same target attributes but focuses on hydrogen-fueled industrial applications with CCS.

In summary, this comprehensive program addresses the technology development needs for advanced gas turbines for IGCC use in power production and industrial applications by targeting the specific goals identified by the DOE for emissions, efficiency, and capital cost. The project builds on GE's existing gas turbine technology and product developments, and will develop, validate, and prototype test the turbine-related technologies and sub-systems needed to meet the DOE turbine portfolio goals.

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". Attaining this goal requires achieving low 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 GE Energy project team mapped the 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, with the project team evaluating over 30 different concepts. Near entitlement NO_x emissions were achieved, and two of the advanced concepts were selected for continued development in Phase II of the program.

In Phase II, focus shifted from single nozzles to a full-can size with multiple nozzles. The DOE 2010 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 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 100 hours of fired test time by the end of 2011, including several instances of full-load operation for more than 6 hours. Promising performance was retained on syngas and natural gas fuels.

The ARRA portion of this project takes the objectives from Phase II and applies them to industrial applications which typically require high levels of operational flexibility and availability. GE Energy has placed focus on increasing firing temperature (and efficiency) while continuing to deliver low NO_x emissions and high fuel flexibility (including hydrogen) and extending turndown—all while maintaining current inspection intervals and reliability levels. The ARRA project portion advances the concepts selected for Phase II to premixer designs that better manage the fuel and air available for combustion, improving operation flexibility while maintaining the low NO_x levels.

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. The ARRA project portion will continue by refining the down-selected combustion architecture design and readying it for a full-speed, full-load test.

TURBINE

Turbine development in this project focuses 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 (enabled through the materials program efforts discussed in the following section).

Chargeable flow reductions are being achieved through technologies that enable reduced part cooling and reduced wheelspace flow. During Phase II, the GE Energy project team achieved reductions in cooling flow requirements through advances in film cooling design on hot gas path components. Additional cooling technology advancements will be pursued during the remainder of Phase II. During Phase II, the project team is developing technologies to reduce flows in the wheelspace cavities 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. Recently, a rotating test vehicle has been and continues to be used to perform evaluation and optimization of the design advances. Funded under the ARRA portion of the project, new stage 1 architecture is being developed to further reduce cooling flow beyond the capability of the base program. Concepts are being evaluated for both the stage 1 nozzle and bucket. Once evaluated, the task will focus on a path that will yield the highest reduction in cooling flow. Casting trials of the preferred architecture will be performed and iterations between GE and the casting supplier will be conducted to further improve and refine the technology.

The GE Energy project team is achieving non-chargeable flow reductions by focusing on 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. Technology advancements 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. Under the ARRA portion of the project, flow reductions, and hence efficiency improvements, are being explored through enhanced integration of the combustion and turbine systems. Concepts that improve this integration are being evaluated in a cold-flow test rig to determine their effectiveness in comparison to a baseline configuration.

Mass flow through the turbine is constrained by the last-stage annulus area. Increased bucket height, and resulting annulus area, allows 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 have 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 where 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.

In the ARRA portion of the project, advanced sensors are also being leveraged to improve performance, emissions, and operability. The focus is on utilizing and integrating a variety of advanced sensor technologies into gas turbine operation and control. Recent developments in high-temperature sensors and electronics will be leveraged to develop in-situ data to enable more precise measurement and control. This technology has the potential to provide important real-time data in traditionally immeasurable locations of the turbine. The application of turbine emission species, fuel property sensors, and exhaust gas composition sensors are being assessed to measure the performance of the combustor in real time. In cooler sections of the turbine, wireless-transmission-enabled sensors are being explored to improve the ability to access data from sensors. The technologies selected will be developed to the point of field test readiness with defined control schemes to improve gas turbine performance. The use of these technologies will enable direct sensing at the location of interest, rather than model-based estimation of those parameters using sensors remote to the location of interest, thereby improving the accuracy of the estimate, which in turn will enable more advanced controls that will improve performance of gas turbines.

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 GE Energy project team characterized the IGCC environment 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 ceramic matrix composites (CMCs). Project development of TBCs has focused on improving the phase stability and property changes under elevated temperature exposure and on increasing thermal resistance. Evaluations have also considered dimensional stability, erosion, impact, and spall resistance. The project team has conducted two iterations of TBC development and down-selected to the final TBC composition candidates.

Metallic coatings are tailored to serve as a bond coat under a TBC or as a stand-alone environmental coating. The GE Energy project team's development of an improved metallic coating bond coat has focused on TBC adhesion and their development of an improved metallic environmental coating has focused on resistance to environmental attack (high-temperature corrosion). The project team has conducted two iterations of metallic coating improvements and a down-selected to the finalists. Final evaluations and characterization of the best coating will be completed during the remainder of Phase II.

Materials focus in the ARRA portion of the program is on the improvement of corrosion-resistant alloys that are especially critical for industrial applications where contaminants can be introduced through the air. They are being targeted to withstand high temperatures in the high moisture and potentially corrosive environments of hydrogen-fueled industrial applications. The goal is to allow the current inspection intervals to remain the same for an advanced turbine. Analytical methods, such as modeling for microstructure and property prediction, were used to create the first round of alloy chemistries. Environmental and corrosion testing that replicates expected conditions is being used to determine the best candidates for turbine conditions. Design curves that account for corrosion are being generated for use on future designs. Compatible coatings for the alloys in development are also being developed.

Ceramic matrix composite components material systems can operate at much higher temperatures than traditional metal systems and require little or no cooling flow. The project team has performed fundamental CMC material property tests and has conducted prototype manufacturing trials. In an IGCC environment, CMC components will require a protective environmental barrier coating. Evaluation of different EBC coatings was performed and a coating selection made.

The ARRA portion of the program is focused on CMC component design and fabrication activities that are necessary to prepare for validation testing in an engine environment. The targeted application is uncooled gas turbine components that operate in the hot gas path environment with higher efficiencies than existing gas turbines. Initial components have been designed, manufactured, and are now undergoing initial testing, design iterations, and improvements that will continue through the end of the program.

SYSTEMS

The GE Energy project team has developed cycle models to determine the performance and output characteristics resulting from the technology advancements being made on the program. The models now include all new/unique systems that will be required for carbon capture and sequestration. Altogether there are six different configurations that have been replicated: a baseline plant for both syngas and hydrogen fuels, as well as 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, the project team will use systems analysis to validate the achievement of project goals.

In the ARRA portion of the project, the systems efforts have evaluated the impact that the technologies developed in this program will have on industrial applications with and without carbon capture and sequestration. Due to the large variation in requirements for industrial gas turbine, the project team considered two main applications: a steel mill scenario and a refinery scenario. The project team compared new technologies with a baseline gas turbine configuration and evaluated the impact on efficiency, carbon dioxide (CO_2) release, and emissions. The findings were generalized to the broader industry, resulting in an overall estimate of industry-wide reduction of CO_2 output, fuel consumption, and other emissions as a consequence of successfully deploying the technologies developed under this project. The systems approach is continuously being refined and updated based on the technology advances throughout the project and is guiding component design and development as more information is obtained.

Relationship to Program

This project will support important hydrogen turbine advances within the turbines portfolio of the NETL Advanced Energy Systems Program. As outlined, the project provides the technology to offset much of the performance and cost penalty associated with implementing carbon capture, utilization, and sequestration 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 envisioned to be retrofitable to the existing fleet of gas turbines in service (including natural gas-fired plants), the improvement opportunity extends 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 the current and future energy challenges facing the United States. In 2011 it is estimated that about 92 U.S. domestic full-time equivalent personnel from GE and its direct contractors were employed by the program. Additionally over $5 million of supplier contracts were placed throughout the country, with over 70 suppliers receiving orders in excess of $10,000.

Primary Project Goal

The primary goal of this project is to develop the technologies required for a fuel-flexible (e.g., coal-derived hydrogen or syngas) gas turbine for IGCC use in power production and industrial applications that meets DOE turbine performance goals for efficiency, emissions, and cost.

Objectives

The objectives of this project are to develop the technology for a fuel-flexible gas turbine—able to use both coal-derived hydrogen and syngas—that achieves the following DOE turbine performance goals:

- 2–3 percentage points improvement in combined cycle efficiency by 2010 and 3–5 percentage points improvement in combined cycle efficiency by 2015 above the baseline state-of-the-art combined cycle turbines in IGCC power production applications.
- Less than 2 ppm NO_x in an atmosphere containing 15% oxygen.
- Significant IGCC plant capital cost reduction.

For the ARRA program, the main project goals include identifying and developing a set of gas turbine technology advancements that will improve the efficiency, emissions, and cost performance of gas turbines for industrial applications (e.g., cement plants, chemical plants, refineries, steel and aluminum plants, and manufacturing facilities) with carbon capture and sequestration. The same 2 ppm target is used for NO_x, with a 3 to 5 percentage point improvement in combined heat and power efficiency.

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

In each major area of the project, the project team used the above process to establish goals and created a detailed Technology Validation Roadmap that depicted the technical milestones that would be achieved over the duration of the program to meet the goals, along with associated funding requirements. By establishing a milestone frequency of approximately one per quarter, each for the Phase II and the ARRA portions of the project, the roadmap provides the project with frequent opportunities to assess interim progress toward the ultimate program goals. In addition to the roadmap, the project team uses an Earned Value Management System to simultaneously assess scope, cost, and schedule on a quarterly basis. Finally, the plant level model is also used to assess interim progress by folding in actual improvements relative to the targets as results are obtained.

08: DE-FE0007966

Project Number	Project Title			
DE-FE0007966	Advanced CO_2 Capture Technology for Low Rank Coal Integrated Gasification Combined Cycle (IGCC) Systems			
Contacts	**Name**	**Organization**	**Email**	
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Stage of Development				
__Fundamental R&D	__Applied R&D	X Prototype Testing	__Proof of Concept	__Demonstration

Technical Background

Coal accounts for 56% of U.S. power generation and its contribution is expected to increase since the United States has 25% of the world's coal reserves. Coal-fueled integrated gasification combined cycles (IGCCs) are environmentally superior to pulverized coal (PC)-fired boilers not only because they are more efficient at producing electricity, but also because they can be equipped with more cost-effective carbon capture and pollution control technologies. Since half of the coal in the United States is low rank (e.g., high in alkali and moisture), it is expected that most of the new IGCC installations will use these feedstocks. Unfortunately, the system analysis carried out by DOE (DOE/NETL-2007/1281) suggests that conventional low-temperature technologies used to capture carbon dioxide (CO_2) from an IGCC (such as Selexol) will increase the cost of electricity (COE) to prohibitive levels. New technologies are needed to meet DOE's goal of capturing 90% of carbon emissions with a less than 10% increase in the COE.

There are also technological challenges facing the effective utilization of low-rank coals in IGCC plants, caused by the presence of high concentrations of alkali compounds, ash, and moisture. The contaminants generated during gasification can cause excessive fouling and corrosion of the equipment, and inhibit or poison the catalyst or sorbents used in the process. For example, pre-combustion CO_2 capture systems commonly use two or three stages of water-gas shift (WGS) to convert the synthesis gas into a CO_2/hydrogen (H_2) mixture. Depending on the desulfurization process, $CoMoS_2$ (cobalt molybdenum disulfide)-based "sour shift" catalyst or FeCr (ferrochrome) and Cu/Zn/Al_2O_3 (copper/zinc/aluminum oxide)-based "sweet" catalysts are included in various system designs. A prior study carried out by TDA Research, Inc. (TDA), the Research Triangle Institute, and the University of Kentucky (Contract No. DE-FC26-08NT0006289) showed that these catalysts are vulnerable to attack by the alkali compounds. Thermodynamic analysis shows that the potassium (K) and sodium (Na) readily react with the Mo (even if it is in a sulfided state) to form highly stable molybdate phases, such as sodium molybdates (Na_2MoO_4, Na_2MoO_7) and potassium molybdate (K_2MoO_4), even in the presence of only small amounts of these compounds. In fact, only 10 parts per billion by volume (ppbv) and 25 ppbv of Na and K salts at 60 bar will drive the formation of the unreactive molybdate phases. The Cu/ZnO/Al_2O_3 (copper-zinc oxide-aluminum oxide) catalyst is also subject to chemical attack primarily due to K-Al and Na-Al interactions, which lead to the formation of aluminates that are inactive for water dissociation. Hence, if an IGCC plant is to run on low-rank coal, there is a need to reduce the concentration of alkali compounds in the gas and also to use catalysts and sorbents that can tolerate these species.

TDA proposes to demonstrate the technical and economic viability of a new IGCC power plant designed to efficiently process low-rank coals. The plant uses an integrated CO_2 scrubber/ WGS catalyst to capture over 90% capture of the CO_2 emissions, while increasing the cost of electricity COE by less than 10% compared to a plant with no carbon capture.

TDA's system uses a high-temperature physical adsorbent capable of removing CO_2 above the dew point of the synthesis gas (syngas) and a contaminant-tolerant WGS catalyst that can effectively convert carbon monoxide (CO) into H_2 and CO_2 in the presence of a wide range of contaminants, particularly the alkali, sulfur, and phosphorous compounds introduced into the gas during the gasification of low-rank coals. The integrated operation of the WGS catalyst and CO_2 removal processes in a single step drives the equilibrium-limited WGS reaction toward H_2 without the need to add large amounts of water (H_2O) to the syngas, greatly reducing the cost of carbon capture. The preliminary system analysis suggests that maintaining the H_2O:carbon (C) ratio close to that required by the reaction stoichiometry rather than using an excess of close to 2.0 (which was the basis for a recent DOE analysis) will improve process efficiency by more than 2%. The process intensification provided by carrying out two unit operations (WGS and CO_2 removal) in the same reactor will reduce the capital cost and improve the process economics.

In an ongoing DOE/NETL project, TDA has already developed the sorbent for pre-combustion CO_2 capture (Contract No. DE-FE0000469). The project team successfully scaled up the production of the new sorbent and demonstrated stable CO_2 capacity for over 11,000 cycles at the bench-scale. A process analysis carried out by University of California, Irvine (UCI) showed that the efficiency of the plant is 2%–3% higher than an IGCC plant equipped with Selexol. Two field demonstrations are scheduled in Summer of 2011 at the Wabash River IGCC plant and the National Carbon Capture Center (NCCC), in collaboration with ConocoPhillips and Southern Company. TDA also developed a contaminant-tolerant WGS catalyst in another DOE project (DE-SC0004379). In bench-scale tests, the project team has demonstrated that their catalysts outperform commercial shift and sour shift catalysts (Shiftmax 120 and Sour Shift D-1026 both provided by Süd-Chemie) while maintaining stable performance in the presence of contaminants originating from coal-biomass co-gasification, including Na, K, phosphorus (P), chlorine (Cl), and sulfur (S), all of which will also be present in the syngas generated by the gasification of low-rank coals.

In this project, TDA will work with UCI, Southern Company, and ConocoPhillips to demonstrate the viability of the new technology. The project team will optimize the sorbent/catalyst and process design and assess the efficacy of the integrated WGS/CO_2 capture system, first in bench-scale experiments and then in a slipstream field demonstration using actual coal-derived syngas. The results will feed into a techno economic analysis using Aspen Plus™ software to estimate the impact of the contaminant-tolerant WGS catalyst/CO_2 capture system on the thermal efficiency of the plant and COE. All analyses will be consistent with DOE/NETL Cost Estimation Guidelines.

TDA will partner with Southern Company to carry out a three-week field test, using 100 standard cubic feet per hour (SCFH) syngas slipstream generated in Southern Company's air-blown pilot-scale gasifier in Wilsonville, AL. Southern Company has long had an interest in using low-rank, high-sodium lignites as the feedstock for their advanced plant designs. Hence, the project team will use North Dakota Beulah-Zap lignite in the demonstration work. The project team will also work with UCI on the process design and optimization. The project team will calculate mass and energy balances for a commercial scale IGCC plant integrated with our

WGS catalyst/CO_2 sorbent technology using Aspen Plus™. UCI will benchmark the performance of the new system against a plant that uses a Selexol-based gas cleanup and carbon capture technology. The analysis will be extended to include Montana Rosebud sub-bituminous coal as well as North Dakota lignite. TDA will also work closely with ConocoPhillips (a leading developer of gasification systems), who will help the team assess the commercial viability of the new technology, and with MeadWestvaco and Süd-Chemie to address any scale-up and mass manufacturing issues related to the production of the WGS catalyst/CO_2 sorbent combination. All analyses will be consistent with DOE/NETL's Cost Estimation Guidelines.

Relationship to Program

This project will support important carbon capture advances within the gasification portfolio of the NETL Advanced Energy Systems Program.

In summary, the benefits of the project include the following:

- TDA's technology improves the IGCC process efficiency needed for economically viable production of power from low-rank coals.
- The new process can increase the thermal efficiency of IGCC operating on low-rank coals by 2%–4% while ensuring that the increase in COE will be less than 10%.
- This technology could also be applied to IGCC power plants operating on other types of coal, providing similar benefits

Primary Project Goal

TDA Research, Inc. proposes to demonstrate the technical and economic viability of a new IGCC power plant designed to efficiently process low-rank coals. The plant uses an integrated CO_2 scrubber/WGS catalyst to capture over 90% of the CO_2 emissions while increasing the cost of electricity by less than 10% compared to a plant with no carbon capture.

Objectives

The project objective is to demonstrate that TDA's integrated WGS catalyst/CO_2 removal process is a practical and cost-effective method for pre-combustion CO_2 capture in IGCC power plants operating on low-rank coals. The work plan is divided into the following seven tasks with specific goals and milestones:

- Task 1: Conduct project management and planning.
- Task 2: Optimize the catalyst/sorbent to provide high CO2 capacity and WGS conversion.
- Task 3: Evaluate the impact of syngas contaminants on the sorbent/catalyst through multiple cycle tests and address system economics early in the project.
- Tasks 4 and 5: Complete the process model and system design and estimate the overall thermal efficiency of TDA's process integrated with an IGCC. Show that the new process is at least 2% more efficient than the Selexol-based carbon capture and sequestration (CCS) system and that the increase in COE is less than 10% compared to IGCC without CCS.
- Task 6: Modify the existing prototype system for combined WGS and CO2 removal; complete over 1,000 cycles with the bench-scale system; and carry out system and process economic analysis to show the overall thermal efficiency, levelized COE, and cost of CO2 capture ($/ton) for TDA's process.

- Task 7: Carry out a 3-week field demonstration of the combined WGS/CO2 removal prototype unit integrated with a gasifier operating on low-rank U.S. coal at the NCCC.

09: FC26-05NT42469

Project Number	Project Title			
FC26-05NT42469	Recovery Act: Scale-Up of Hydrogen Transport Membrane (HTM)			
Contacts	**Name**	**Organization**	**Email**	
DOE/NETL Project Mgr.	Arun Bose	NETL – Gasification Division	arun.bose@netl.doe.gov	
Principal Investigator	Carl Evenson	Eltron Research Inc.	cevenson@eltronresearch.com	
Partners	URS Corporation CVR Partners LP			
Stage of Development				
_Fundamental R&D	__Applied R&D	__Prototype Testing	X Proof of Concept	__Demonstration

Technical Background

This technology is based on use of a dense metallic composite membrane system for the separation of hydrogen (H_2) and carbon dioxide (CO_2) from a coal-based synthesis gas (syngas) stream, although it does have wider applicability to other H_2-containing streams. These membranes have been shown to meet or exceed the DOE 2010 targets for flux, selectivity, and cost in bench-scale tests. The membrane has been operated up to 1,000 pounds per square inch gauge (psig) and differential pressures over 500 psig on simulated syngas compositions. Membrane life has been shown for about 8,000 hours. Some early work on impurity testing has shown tolerance to sulfur up to 20 parts per million (ppm). The membrane has also been integrated into a water-gas shift (WGS) reactor, facilitating high conversion of carbon monoxide (CO). Process design and economic studies have shown cost and thermal efficiency benefits. Membranes have been tested with all syngas components including CO, CO_2, hydrogen sulfide (H_2S), water (H_2O), and H_2.

A scaled-up version of the membrane has been tested on "live" coal-based syngas at both Eastman's Kingsport Tennessee facility and at the University of North Dakota Energy and Environmental Research Center. These membranes were manufactured as tubes five feet in length. The longest tubes that can be tested in the laboratory at Eltron Research, Inc. (Eltron) are two feet, although Eltron more typically uses six-inch tubes. The tests on live syngas were very instructive and provided extremely useful information for the path-forward development program.

The data from these tests, coupled with computational fluid dynamics and solid design expertise from project partner URS Corporation, have allowed Eltron to design the next scale-up step—the Process Development Unit (PDU)—which will be designed in a shell and tube configuration with commercial-length tubes (10 feet in length). This will be the first application of a tube bundle in the process; all previous work has been done with a single tube-in-tube configuration or at smaller scales in a planar configuration.

Relationship to Program

This project will support important advances in hydrogen transport membranes within the gasification portfolio of the NETL Advanced Energy Systems Program.

Benefits of the project include the following:

- High-purity hydrogen (>99.999%) can be delivered from coal-based syngas at lower cost than conventional technology.

- Retention of CO_2 at high pressure will lower the capture cost and improve the higher heating value efficiency of a plant capturing CO_2 for sequestration, primarily through significantly reduced compression requirements.
- Technology may enable process simplification and intensification when incorporated into membrane reactors (concept demonstrated under separate SBIR contract).
- Technology can be applied for recovery of H_2 from other systems such as natural gas partial oxidation, diesel or naphtha reforming, refinery streams, chemical processes, and fuel processing for fuel cells.

Primary Project Goal

The primary goal of this project is to scale up hydrogen transport membrane technology systems for cost-effective, energy-efficient H_2 production and carbon capture from industrial sources, and enable early technology commercialization by reducing time, technology risk, and cost.

Objectives

Program objectives are grouped into the following five major areas:

- **Materials Development:** Develop and test membrane alloy systems that give the best flux without risk of membrane embrittlement; develop catalyst compositions that do not limit flux and provide the requisite tolerance to impurities; and understand the importance of the interface between the membrane and catalyst.
- **Performance Screening:** Establish the range of operating conditions for the system giving the best performance using WGS composition syngas; evaluate the effect of impurities on performance; and perform membrane life testing for longer than 600 hours.
- **Process Design:** Integrate the system into integrated gasification combined cycle (IGCC) flow sheets, testing different configurations with and without co-production of power and H_2; evaluate the impact of different impurity management techniques; and compare economics, including capital expenses and operating expenses, to alternative technologies.
- **Mechanical Design:** Address manufacturing issues for scaling up the system, taking into account maintenance costs, initial capital costs, and system robustness; address issues such as welding, sealing, catalyst deposition techniques, and alloy manufacture for tubular system.
- **System Scale-up:** Design, build, and operate a ~12 lb/day system on coal-based syngas slipstream, developing operating procedures and gathering initial engineering data for further scale-up; design, build, and operate a PDU at ~250 lb/day. Design, build, and operate a 4–10 tons/day Pre-Commercial Module.

10: FC26-98FT40343

Project Number	Project Title			
FC26-98FT40343	Recovery Act: ITM Oxygen Technology for Integration in IGCC and Other Advanced Power Generation Systems			
Contacts	**Name**	**Organization**	**Email**	
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Principal Investigator	Douglas Bennett	Air Products and Chemicals, Inc.	bennetdl@apci.com	
Partners	Ceramatec, Inc. The Pennsylvania State University Concepts NREC Williams International, LLC			
Stage of Development				
__Fundamental R&D	__Applied R&D	__Prototype Testing	X Proof of Concept	__Demonstration

Technical Background

Modern cryogenic distillation for oxygen production is a mature technology. Indeed, air separation plants are now some of the most efficient distillation-based separations known. However, because the overall thermodynamic efficiency of modern cryogenic air separation units approaches theoretical limits, few significant breakthroughs are expected that would lead to a step-change reduction in the cost of producing oxygen. Two alternative technologies, adsorption and polymeric membrane separations, are limited in practice: the efficiency limitations inherent in the former restricts its application to relatively small plants (<150 tons per day [TPD] oxygen production), while the latter does not provide the separation factor and flux required for economical, large-scale oxygen production.

Recognizing the potential for membrane technology to impact oxygen cost, Air Products and Chemicals, Inc. (APCI) has identified a class of ceramic materials with high flux and selectivity characteristics that can form the basis for cost-efficient membranes. These ion transport membrane (ITM) materials separate oxygen from air at a high temperature in an electrochemically driven process. The oxygen in air is ionized on the surface of the ceramic and diffuses through the membrane as oxygen ions, forming oxygen molecules on the other side. Impurities such as nitrogen are rejected by the membrane. Because these materials conduct electrons as well as ions, no external source of electrical power is required. The resulting air separation system produces not only pure oxygen, but also a hot, pressurized, oxygen-depleted stream from which significant amounts of energy can be extracted. Significant reductions in capital and operating costs of oxygen production are predicted. This potential for efficiently co-producing oxygen and power at reduced cost addresses the goals of the DOE Advanced Energy Systems Program.

ITM membranes are fabricated from non-porous, multicomponent, metallic oxides that operate at high temperatures and have exceptionally high oxygen flux and selectivity. The materials were chosen from the class of oxide ceramics known as perovskites, which lose oxygen from their crystal structure with increasing temperature, forming vacancies in the oxygen sub-lattice. Oxygen ions can be transported through such materials by “hopping” from vacancy site to vacancy site. As oxygen ions pass through the material, electrons flow in the opposite direct to maintain charge neutrality. Because the ceramic is an oxide, only oxygen ions can occupy the vacancy sites—all other species, such as nitrogen or argon or other constituents of air, are thermodynamically excluded. Thus, ITM oxygen mixed conductors can separate oxygen from oxygen-containing gases with essentially complete selectivity, and without an external electrical circuit. A simple oxygen anion gradient is all that is required to drive oxygen flow across the membrane material. This gradient can be set up by creating a partial pressure difference in oxygen on opposite sides of a membrane.

A conceptualization of the ITM oxygen membrane is illustrated in Figure 1. Air is compressed and heated and passed over one side of the membrane, while the other side is kept at relatively low pressure. Oxygen from the air is ionized on the surface of the membrane, and the resulting oxygen anions pass through the membrane to the low-pressure side. Oxygen anions react to form oxygen molecules on the low-pressure side of the membrane, liberating electrons that then pass back through the material toward the high-pressure side. Because no other constituents pass through the membrane, the relatively low-pressure oxygen produced this way is of very high purity.

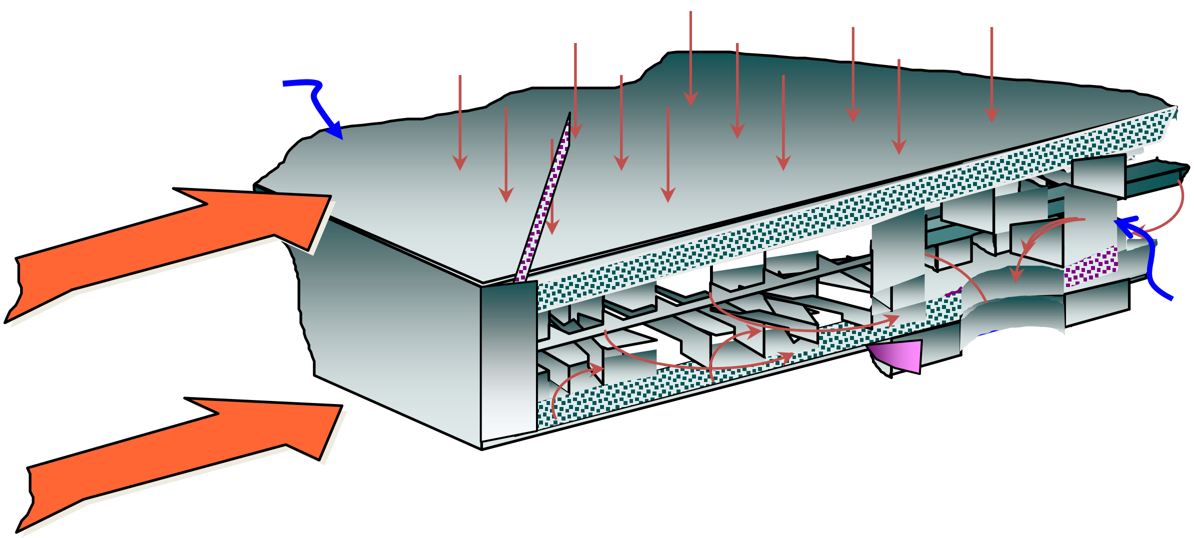

Figure 1: ITM Air Separation using Planar Wafer Concept

In concert with DOE, APCI pursued the ion transport concept, resulting in a multiphase project that was initiated in 1998 to perform fundamental materials development and advancement of process concepts for this novel approach. Progression of this work resulted in five project phases: Phases I and II are complete; Phase III, the subject of this review, is active through September 2013; Phase IV activities were under a congressionally directed effort and were recently completed; and the Phase V effort, which is supported by American Recovery and Reinvestment Act (ARRA), is running concurrently with Phase III. Phase V is also included this review. Because the overall shared project goal for Phase III and Phase V, the objectives of each phase serve to differentiate the work. Phase III is focused on scale-up of the ITM separation process with the primary objective of building and operating a 30–100 TPD Intermediate-Scale Test Unit (ISTU), and on the maturation of the module fabrication processes that would theoretically supply an ITM process with membrane modules. The Phase V objective is to develop and scale up a manufacturing process and capability to fabricate ceramic components and membrane modules. This effort was supported with ARRA funding as an opportunity to accelerate novel yet viable technology and to grow domestic manufacturing capability.

Phase I of the program, which focused on the technical feasibility of the approach, was completed in 2001. Phase I was focused on materials and the development and testing of a ceramic membrane wafer architecture. A perovskite material was chosen as the basis for further scale-up. The material has a combination of properties sufficient to meet commercial requirements for performance and operating life, including high oxygen flux, good material strength at high temperature, and resistance to system contaminants, such as sulfur. In addition, the material is amenable to standard ceramic processing techniques that facilitate the design and manufacture of multilayer, planar wafer structures. A planar architecture was chosen to help maximize the surface area in a separation device.

Phase I efforts also included process research and development (R&D) and the design, construction, and operation of an approximately 0.1 TPD Technology Development Unit (TDU). The TDU test data enabled the establishment of cost and performance targets for stand-alone, tonnage-quantity, commercial ITM Oxygen plants and integration schemes of ITM oxygen with IGCC and other advanced power-generation systems.

Phase II activities, also complete, were focused on testing the performance of full-size ITM oxygen modules in a 5 TPD sub-scale engineering prototype (SEP) facility specially designed for this purpose. During Phase II, the team fabricated thin, cost-optimized multilayer ITM devices that achieved oxygen production rates exceeding commercial performance targets at anticipated commercial operating conditions with significant engineering lifetime. ITM oxygen modules were scaled up to commercial size, built, and tested during Phase II. Tests in the SEP facility generated process information for the current Phase III activity.

Phase II efforts also refined the design of planar membrane wafers. The high-pressure air on both sides of each wafer creates compressive stresses within the ceramic that stabilize the wafer. The planar design makes for a very compact separation device, while facilitating good gas-phase mass transfer. All of the layers are made of the same ceramic material, and therefore expand and contract together during temperature changes.

The planar wafers were scaled to their full commercial dimensions and produced in volume on a pilot production line using standard ceramic tape-casting technology. The production activities established the feasibility of achieving the low-cost production required to meet overall economic targets.

In Phase II, commercial-scale modules, capable of producing up to 0.5 TPD of oxygen were built by co-joining multiple wafers to form a unified ceramic device. The modules were also fitted with a terminating end cap and ceramic pipe. The entire device, including all joints, is composed of the same ceramic, thus minimizing the potential for differential stresses caused by non-uniform expansion across the body of the device.

Phase II tasks culminated in the design, construction, and commissioning of a 5 TPD SEP facility and produced tonnage-quantity oxygen exceeding 99% purity. The SEP was designed to provide design data from testing the performance of individual commercial-scale modules in a small array.

The SEP was designed, constructed and commissioned in Sparrows Point, Maryland, during the final portion of Phase II. This unit features a prototype ITM pressure vessel which holds six commercial scale modules in a 2x3 array. Each module has a dedicated permeate train with vacuum pump and controller, flow and purity measurement. The SEP is located adjacent to a commercial cryogenic gas air separation unit (ASU), and is deployed in a recycle loop configuration, taking make-up gases from the commercial plant and recycling and recompressing its own offgas as the balance of the feed. The feed stream to the membranes is first heated by recuperative heat exchange with the non-permeate stream, then brought to final temperature by an induction heater. Nominal membrane operating conditions for the unit are 800°C–900°C, 200 pounds per square inch gauge (psig) feed pressure, and <1 atmosphere (atm) permeate pressure. The SEP is equipped with sufficient flow capability to simulate feed gas velocities anticipated in commercial service.

Air Products carried out the first experiment in the SEP in January 2006. Operation continued into Phase III. As of December 2011, the SEP has operated for a total on-stream time of more than 950 days. Expected values of purity and flux have been measured during multiple runs, including oxygen purities reaching 99.9%.

Initial runs have been done using modules capable of producing half-a-ton per day of oxygen. The duct was later modified to accept 1-TPD modules. Modules equipped with ceramic-metal seals are loaded into the pressure vessel and connected to the oxygen permeate piping. A flow duct is placed around the modules to give a flow path with minimal excess space between duct walls and modules to minimize bypass of feed air. The cold wall vessel lid is bolted in place to finish preparation for the run.

Operation of the process involves a series of pressure, flow and temperature ramps to bring the system to operating conditions while managing the mechanical stresses in the ceramic modules. The membrane material has a relatively large coefficient of thermal expansion along with a chemical expansion as oxygen vacancies are created in the lattice structure at elevated temperature. Changes in oxygen partial pressure, as well as temperature, can create stresses in ceramic parts, which must be managed in order to maximize ceramic reliability.

Oxygen flow rate and purity from individual modules are monitored continuously once steady state is achieved. Multiple runs have been performed at the SEP since 2006 in order to investigate a number of operating parameters. Fully assembled 1-TPD modules were tested in the SEP and oxygen product rate was measured at up to the expected 1 TPD. Insulation type and configuration have been optimized for the flow duct. Various types of ceramic-to-metal seals have been tested, as have a range of start-up and shutdown schedules designed to maximize ceramic reliability while reducing start-up and shutdown times. Multiple banks of modules were tested, and their ability to withstand rapid transients in process conditions was studied. Full-scale 1-TPD modules were also tested, as were various mechanical components designed for use in the 30–100-TPD ISTU.

Based on the knowledge gained through experimental and process design efforts, ITM technology has been successfully scaled up from 0.1 TPD to 5 TPD and APCI is currently constructing a 30–100-TPD unit that will be operational in 2013. In concert with the experimental and demonstration efforts, APCI is actively evaluating process economics and viable designs for large-scale and commercial scale ITM systems.

Development of the ITM oxygen technology during Phase III will culminate in testing in the 30–100-TPD ISTU, to be located in Convent, Louisiana. The ISTU will have the capability to test large arrays of ITM oxygen modules while operating in a power coproduction mode. Tests will be focused on measuring module array performance and on the efficacy of the process control system, which allows power and oxygen coproduction. The objective of the ISTU testing is to provide additional scale-up data to enable designs for larger ITM oxygen systems to be tested and operated in the future.

The basic ISTU process configuration comprises two separate subsystems: one making power, and the other making oxygen. The power production process can be operated somewhat independently of the ITM process, thus isolating each system from the other, especially during startup and other transients, and increasing the overall reliability of the process.

Air Products broke ground at the Convent, Louisiana, site in September 2011 and is currently constructing the ISTU there. All major equipment has been delivered or is in the late stages of fabrication, with commissioning scheduled for mid-2012.

The commercial concept of an ITM oxygen separation vessel contains an array of multi-wafer modules in a common flow duct and connected through a series of manifolds to an oxygen header below. Each commercial-scale module produces about 1 TPD of oxygen. Many modules are arrayed in parallel and series to meet the production requirements of a large tonnage oxygen plant.

In 2010, as part of ARRA, APCI received funding through DOE for Phase V. Work includes further advancing ITM oxygen technology by designing, constructing, and commissioning a ceramic membrane manufacturing facility (CerFab) suitable to supply a 2,000-TPD test unit, and also performing supporting development work for the manufacturing facility, the 2,000-TPD test unit design, and low-carbon emission applications of ITM technology. Air Products entered into Phase 5 of the program under the ARRA terms and with the ARRA funding.

During Phase V, APCI is working with Ceramatec and Penn State University to carry out advanced materials development, conceptual and detailed engineering development, and process development for the CerFab .The project team is also testing work to support the materials development and a limited operating campaign at the CerFab. The work began in April 2011 and is scheduled to conclude in December 2013.

As of December 2011, the project team has secured the location of Tooele, Utah for the CerFab facility and has specified the process for making membrane modules. The team has also obtained equipment quotes and has scoped the CerFab project thoroughly with an associated schedule and budget. Ceramatec has developed the unique processes required to produce membranes on a large scale, and APCI has developed advanced process schemes in which the membrane modules may be implemented in future applications.

Relationship to Program

This project will support important advances in ITM technology within the gasification portfolio of the NETL Advanced Energy Systems program.

The ITM oxygen project takes a radically different approach to producing low-cost, high-quality tonnage oxygen, which will enhance the performance of integrated gasification combined cycle (IGCC) plants that produce coal-derived syngas that can be burned in a combustion turbine or used to produce clean transportation fuels and hydrogen fuel. System studies confirm the ITM benefits on IGCC, including a 9% reduction in IGCC plant-specific costs ($/kW), a net power megawatt-electric (MWe) increase of 15%, and a plant efficiency increase of 1.2%. Studies have indicated that there is potential for the use of ITM oxygen in other applications, such as oxygen-enriched combustion of coal and full oxy-combustion. Other oxygen-intensive industries such as iron and steel, glass, non-ferrous metallurgy, chemicals, petro-chemicals, refineries, gas conversion (e.g., gas to liquids), and pulp and paper would also realize cost, environmental, and productivity benefits as a result of success of the ITM oxygen project. As an example, DOE recently presented the benefits of applying ITM oxygen to an oxycombustion application. ITM oxygen is also expected to have good benefits as a standalone oxygen generator in conjunction with a natural gas combined-cycle (NGCC) unit for the coproduction of power.

Primary Project Goal

The goal of the ITM oxygen project is to develop and scale up a novel air separation technology for integration with IGCC and other advanced power generation technologies.

Objectives

The objective of Phase III is to increase the scale of the engineering test facility from 5 TPD to approximately 100 TPD of oxygen in an Intermediate-Scale Test Unit (ISTU). The ISTU features oxygen production from an ITM coupled with turbomachinery for power coproduction, and will provide data for further scale-up and development. To support a larger test facility, the project team is expanding efforts in the areas of materials development, engineering development, ceramic processing development, and component testing.

The objective of Phase V is to accelerate the adoption of ITM oxygen technology by developing and constructing systems and infrastructure that will enable the manufacturing of ITM membrane modules and deployment of ITM technology at industrial-energy plant scales. This objective includes the optimization of the materials processing technology and refinement of the module fabrication techniques to supply a conceptual 2,000-TPD ITM oxygen facility (the ITM Oxygen Development Facility). The objective further includes a short operating campaign that demonstrates the capability of the fabrication facility to produce components and devices for separating oxygen from air- and oxygen-containing streams.

11: DE-FE0007902

Project Number	Project Title			
DE-FE0007902	Scoping Studies to Evaluate the Benefits of an Advanced Dry Feed System on the Use of Low-Rank Coal in Integrated Gasification Combined Cycle (IGCC) Technologies			
Contacts	**Name**	**Organization**	**Email**	
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Partners	Eastman Chemical Company			
Stage of Development				
__Fundamental R&D	_X_Applied R&D	__Prototype Testing	__Proof of Concept	__Demonstration

Technical Background

DOE solicited proposals for projects that would significantly reduce the cost of generating electricity and achieve 90% carbon capture in integrated gasification combined cycle (IGCC) power plants using low rank coals. GE's gasification process is unable to cost-effectively convert many low rank coals into electricity using its current commercial slurry feed system technology, which involves wet grinding the coal and feeding it to the gasifier in the form of a concentrated aqueous slurry. This system is very effective and reliable for lower moisture content feeds, such as eastern U.S. bituminous coals. However, because of the high inherent moisture in many western U.S. low rank coals, too much water ends up being fed to the gasifier when these coals are fed as a slurry. This moisture increases the oxygen demand of the gasifier, because much larger quantities of water than desired need to be vaporized and heated up to the reaction temperature. The additional energy required to achieve this task is never fully recovered downstream of the gasifier. Some competitive gasification technologies solve the problem of feeding low rank coal by employing a dry feed system that first dries and grinds the coal, then uses a series of valves and lock hoppers to pressurize the coal, and finally meters and conveys the coal into the gasifier via pneumatic transport. The lock hopper systems needed for this process are expensive, have high operating and maintenance costs, and can suffer from reliability and flow control issues.

For the past several years, GE has been developing a novel dry feed system for low rank coal based on the Posimetric (trademark of General Electric Company and/or its affiliates) Feeder technology acquired from Stamet Inc. In this new dry feed system, referred to as the Posimetric Feed System, low rank coal is dried and ground at atmospheric pressure, simultaneously pressurized and metered using the Posimetric Feeder, and pneumatically transported into the gasifier using sour carbon dioxide (CO_2) recycled from the gasification plant. Unlike lock hopper-based feed systems which pressurize the coal in batches, the Posimetric Feed System is a continuous feed system that simultaneously pressurizes and meters the coal in one device. GE expects the Posimetric Feed System to be simpler, more reliable, and more cost effective than lock hopper-based systems, enabling GE to use this new feed system as a way to begin competing in the low rank coal gasification market. As a global leader in gasification and IGCC systems, GE's entry into this market should help not only to further the use of western U.S. low rank coals, but also to advance the deployment of U.S.-based IGCC technology that runs on low rank coal and is configured for carbon capture, utilization, and sequestration.

Relationship to Program

This project will support important gasifier optimization advances within the gasification portfolio of the NETL Advanced Energy Systems Program. The project team aims to demonstrate the advantage, in terms of the significantly reduced cost of electricity, of GE's new Posimetric Feeder-based dry feed system for generating electrical power from low rank coal in an IGCC plant configured for 90% carbon capture. Successful demonstration of this advantage is intended to provide the impetus for further demonstration work at the commercial scale with an industrial partner such as Eastman Chemical. Once demonstrated commercially, this new dry feed system will effectively double the coal feed envelope of GE's gasification process, allowing the use of western U.S. low rank coals in addition to eastern bituminous coals. By increasing the number of possible projects that could be developed, the larger feed envelope should contribute significantly to the advancement of IGCC in the United States.

Primary Project Goal

The primary goal of this project is to demonstrate the advantage, in terms of the significantly reduced cost of electricity, of GE's new Posimetric Feeder-based dry feed system for generating electrical power from low rank coal in an IGCC plant configured for 90% carbon capture. Successful demonstration of this advantage is intended to provide the impetus for further demonstration work at the commercial scale with an industrial partner such as Eastman Chemical.

Objectives

This project consists of the following three broad objectives:

- Complete a pair of techno-economic case studies to demonstrate reductions in the cost of electricity of GE's new dry feed system, compared with GE's current, commercially available slurry feed system, for generating electrical power from low rank coal in an IGCC plant configured for 90% carbon capture.
- Generate an up-to-date commercial design for the new dry feed system for use in the second of the two techno-economic case studies.
- Complete an assessment of the development and commercialization status of GE's Posimetric Feeder, the key component of the new dry feed system, which combines both coal pressurization and coal metering in a single device.

Both techno-economic case studies—the Base Case (Task 3), which uses GE's current, commercially available slurry feed system, and the Advanced Technology Case (Task 5), which uses GE's new dry feed system based on the Posimetric Feeder—will use the assumptions and methods employed in the DOE study, *Cost and Performance Baseline for Fossil Energy Plants – Vol. 3a: Low Rank Coal to Electricity: IGCC Cases*, to the extent possible, to allow DOE to relate the results of this project to previously funded techno-economic analyses. In addition, the project team will use relevant plant operating and equipment reliability data from Eastman Chemical's Kingsport, TN coal gasification facility, as appropriate, to ensure that the case studies reflect commercial realities as closely as possible. To ensure a meaningful comparison of the slurry and dry feed systems, the common assumptions and methods used will be clearly documented (Task 2). Once both case studies have been completed, the results for the two cases will be compared, showing the technical and economic advantages of the new dry feed system over the current slurry feed system (Task 6) for low rank coal and 90% carbon capture.

Although GE has previously completed both pilot unit and commercial designs for the Posimetric Feed System, an updated design suitable for use in a commercial-scale IGCC plant with 90% carbon capture will be generated for this project. In addition to the design, the GE project team will document the various components that were considered, the integration issues that were addressed, and the decision process that was followed (Task 4).

The following paragraphs provide additional detail about the work that will be completed in each of the seven project tasks:

- **Task 1: Project planning and management**
  This task involves the establishment of a project management plan and the ongoing monitoring and management of the project with respect to that plan. It also includes the writing of the quarterly, topical, and final reports.
- **Task 2: Establish key assumptions and methods**
  The key technical assumptions and system performance requirements will be documented to ensure that a common basis is used to design and analyze both the Base and Advanced Technology Cases. The key cost assumptions and calculation methods will also be documented to provide the context for understanding the results that will be reported. As much as possible, the technical and cost assumptions and the calculation methods that were used to complete the DOE study *Cost and Performance Baseline for Fossil Energy Plants – Vol. 3a: Low Rank Coal to Electricity: IGCC Cases* will be duplicated. This will make it easier for DOE to relate the results of this study to work that was previously done. The most significant deviations from the assumptions used in the above DOE report include the following: The captured CO_2 is compressed and pipelined for use in an EOR field rather than disposed of in a saline aquifer; the plant consists of a single train (i.e., single gasifier, single GE 7F gas turbine, and single steam turbine) rather than a dual train; and the site was moved from Montana to the Texas Gulf Coast near fields that are viable candidates for enhanced oil recovery (EOR). These changes were made because GE believes that, given the current economic and regulatory climate, selling stand-alone, dual-train IGCC plants with CO_2 capture for underground disposal is not a viable business model. However, smaller plants that sell CO_2 for EOR applications may be a viable product.
- **Task 3: Design and analyze Base Case (Slurry Feed System)**
  The Base Case consists of an IGCC plant configured for 90% carbon capture. Low rank coal (Montana Rosebud Powder River Basin coal) is fed to the gasifier in the form of an aqueous slurry using GE's commercially available Slurry Feed System. During this task, the GE project team will generate process flow diagrams, calculate heat and material balances for the entire plant, simulate the performance of the power block, and calculate the plant efficiency and output. They will also estimate the reliability, availability, and maintainability of the plant. Key pieces of equipment in the gasification and power block portions of the plant will be designed and costed using GE's in-house methods and database. The cost of the rest of the equipment in the plant will be calculated using appropriate factors from previous studies, both GE in-house studies as well as previously published DOE work. The plant performance and cost estimates will then be used to calculate the cost of electricity for the Base Case.
- **Task 4: Design Posimetric Feed System**
  GE's design for a commercial Posimetric Feed System will be updated and configured so that it is suitable for integration with the IGCC plant in the advanced technology case. The various equipment and configuration choices that GE considered during the design work will be discussed, along with the decision-making process that was followed in arriving at the final design.

- **Task 5: Design and analyze Advanced Technology Case (Posimetric Feed System)**
  The configuration of the Advanced Technology Case is the same as the Base Case, with the exception that the Slurry Feed system is replaced with GE's new Posimetric Feed System. Also, because some CO_2 from the carbon capture section of the plant is required as carrier gas for the Posimetric Feed System, the syngas processing configuration is slightly different between both cases. The project team will complete process simulation; plant performance; reliability, availability, and maintainability analysis; equipment costing; and cost of electricity calculations similar to those done for the Base Case for the Advanced Technology Case.
- **Task 6: Compare the base and advanced technology cases**
  During this task, the project team will compare and discuss the results of both cases, including the auxiliary loads; power output; efficiency; capital cost; operating cost; reliability, availability, and maintainability analysis; and cost of electricity. The effects of replacing the Slurry Feed System with the Posimetric Feed System will be highlighted.
- **Task 7: Summarize data to support potential value of advanced technology**
  One of the constraints imposed on both the Base Case and the Advanced Technology Case is that only commercially available technology may be used. However, the heart of the Advanced Technology Case—the Posimetric Feed System— is not yet commercially available. The purpose of this task, therefore, is to provide credible support for the assumptions and claims made for the Posimetric Feed System. Thus, this task will summarize the laboratory and pilot unit work that GE has completed for the Posimetric Feeder and other components of the Posimetric Feed System. Data supporting the design decisions made for Task 4 and the performance calculations completed for Task 5 will be highlighted. Then, the current status of and prospects for the Posimetric Feed System technology will be assessed in light of the experimental work. Finally, the future development path to commercialization will be discussed.

12: DE-FE0007952

Project Number	**Project Title**			
DE-FE0007952	Mitigation of Syngas Cooler Plugging and Fouling			
Contacts	**Name**	**Organization**	**Email**	
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Partners	University of Utah Gasification Industry OEM			
Stage of Development				
__Fundamental R&D	__Applied R&D	X Prototype Testing	__Proof of Concept	__Demonstration

Technical Background

To become cost competitive with conventional power plants, gasification plants need to improve plant economics and efficiency and increase plant availability. The current synthesis gas (syngas) coolers—fire-tube heat exchangers located after the coal gasifier and before the syngas combustion turbine—used in integrated gasification combined cycle (IGCC) plants offer high efficiency, but their reliability is generally lower than other process equipment used in the gasification island. The principle downtime events associated with syngas coolers result from syngas cooler plugging and fouling. Ash deposits develop on surfaces upstream of the syngas cooler, break loose, and then lodge in the syngas cooler tube inlet, causing plugging and increased erosion in the tube. During fouling, ash deposits that consist of micron-sized particulates with a tendency to bond together form on the fireside surface of the syngas cooler tube, leading to reduced heat extraction from the hot syngas and lowering the thermal efficiency of the syngas cooler. Both ash deposit mechanisms result in reduced equipment life and increased plant shutdowns and maintenance costs, which contributes to the current inability for IGCC to be competitive with conventional power plants.

The success of the project will result in technology that can improve the reliability, availability, and maintainability of the syngas cooler, as well as the overall gasification plant, with minimal impact on syngas cooler capital and operating costs. Hence, the results from this project will support the DOE goals of lower-cost IGCC plants with carbon capture, while maintaining the highest environmental standards.

Relationship to Program

This project will support important gasifier optimization advances within the gasification portfolio of the NETL Advanced Energy Systems Program. The project results support the goals of the NETL Advanced Energy Systems Program gasification portfolio to use gasification to provide power from coal with 90% carbon capture and minimal increases in the cost of electricity (COE). Coal gasification has the potential to significantly reduce U.S. dependence on foreign energy sources and dramatically reduce the environmental impact of using coal for power generation. However, before IGCC plants can achieve widespread deployment, this technology must be able to compete economically with conventional technology. This project will help reduce operating costs by increasing the availability of the unit operation syngas cooler. Improving the performance of the syngas cooler through the mitigation of plugging and fouling occurrences in the plant will have a positive impact on the reliability, availability, and maintainability of IGCC plants.

Primary Project Goal

The primary goal of this project is to develop technologies that reduce the COE, while maintaining or improving plant efficiency through the mitigation of the plugging and fouling of the syngas cooler used in IGCC plants. Furthermore, a successful project will demonstrate through a detailed techno-economic analysis that DOE COE objectives can be met with the development of an effective syngas cooler improvement technology that mitigates syngas cooler plugging and fouling and accommodates expected future process improvements to IGCC technology. The successful achievement of this goal will result in improved availability and reliability of the syngas cooler, significantly contributing to DOE's IGCC availability and cost reduction goals. Successful demonstration of DOE performance and cost objectives will validate the feasibility of subsequent scale-up prototype testing of the plugging and fouling mitigation technology.

Objectives

This project will address DOE targets for gasification plant availability and cost through the following project objectives:

- Develop a better understanding of ash deposition onto refractory and metal surfaces associated with syngas coolers used in IGCC plants with two-stage gasifiers.
- Evaluate plugging and fouling of syngas cooler designs.
- Develop methods to mitigate syngas cooler plugging and fouling.
- Define and begin to validate specific means to implement mitigation methods.

The project work effort consists of the following major areas: laboratory-scale experiments, modeling work, analysis of syngas cooler fouling deposits, an economic evaluation, and, if approved, field testing for validation of the selected technology developed under this project to mitigate syngas cooler plugging and fouling. The following sections provide more information on each of the work efforts.

LABORATORY-SCALE EXPERIMENTS

The laboratory-scale testing will be conducted by the University of Utah. This work will evaluate the adhesion strength of ash deposits to the surface in tests using coal-derived syngas over a range of temperatures (700°C–1,050°C), surface materials (metal, refractory), and fuels. Some of the ash deposits evaluated under this project will be generated using a 1 ton/day high-pressure, pilot-scale gasifier at the University of Utah. Fouling deposits provided by an original equipment manufacturer (OEM) will also be used for experimentation in a Laminar Entrained Flow Reactor (LEFR). LEFR deposition and in-situ and ex-situ cleaning testing will incorporate impinging jet blowing nitrogen to dislodge the ash deposits and thereby determine the adhesion strength.

The pilot-scale entrained flow gasifier will be used to generate ash material under conditions that are more representative of what occurs in a commercial-scale gasifier. Using project funding, the gasifier is being modified to allow operation that is more similar to that of a two-stage gasifier.

In the smaller scale LEFR testing, fuel is fed to the top of the reactor at a low rate. As the fuel passes through the reactor, it will undergo heat-up, pyrolysis, and gasification. At the reactor exit, the ash material will be captured in a candle filter. After sufficient ash buildup, a nitrogen jet is activated and the nitrogen flow rate required to remove the deposit is recorded. The adhesion strength of the deposit to the plate is proportional to the velocity of the impinging jet. This procedure was used in a previous DOE-funded project and proved to be a reliable, repeatable, and cost-effective method to evaluate many samples.

For selected tests and ex-situ cleaning experiments, prior to performing the impinging jet tests, the ash deposit and the plate on which it resides will be placed in a muffle furnace and heat treated in a non-oxidizing environment to determine if heat soaking the deposit increases the adhesion bond strength of the ash deposit to the plate. The bond strength test will be performed external from the Laminar Entrained Flow Reactor in a purpose-built, standalone test rig that uses an impinging nitrogen jet.

MODELING

Reaction Engineering International (REI) will perform process and engineering model calculations (e.g., single particle gasification, furnace/gasifier process models, thermodynamic equilibrium, and solid-state diffusion calculations) as needed to assist with test design and data interpretation. The work effort will make extensive use of computational fluid dynamics (CFD) modeling using REI's in-house, proprietary, comprehensive CFD modeling tool. A project collaborator from the gasification industry will provide heat/mass balance and process condition information for use as CFD model inputs.

REI will perform CFD modeling for industrially relevant syngas cooler designs to investigate the conditions that cause plugging and fouling in the syngas cooler and evaluate methods to mitigate these issues. The project team will model alternative process conditions, syngas cooler geometry changes (e.g., using larger diameter tubes and varying syngas cooler orientation), and equipment changes (e.g., filters, traps, baffles, flow area expansions) upstream of the syngas cooler that could reduce fouling and plugging. Additional detail on CFD modeling of plugging and fouling is provided below:

Plugging

REI's CFD models contain sub-models that are designed to capture the in-flight aerodynamic effects of arbitrarily shaped particles. Particle trajectories for non-spherical particles are calculated with an empirically based drag coefficient modification. Particles are characterized by a shape factor and by the ratio of the surface area of a sphere with the same volume as the particle to the actual particle surface area; the shape factor is then used in computations of the particle drag. REI uses this model routinely for evaluating industrial systems, such as boiler systems.

In this project, REI will perform CFD modeling for the syngas cooler and upstream region to better understand plugging of the syngas cooler tubes. Parametric sensitivity cases will be performed for a range of assumptions on syngas flow conditions (e.g., flow rate, temperature, particle starting location, and particle shape) to provide information on how syngas cooler plugging could change with different conditions. If possible, information about deposit shapes will be extracted from the syngas cooler deposits to be provided to the project.

Fouling

The gas and wall temperatures in the syngas cooler region are much lower than standard ash sticking temperatures, implying that particles should not stick to surfaces they contact. The project team's hypothesis for deposit growth is as follows:

1. For an initially clean wall, thermophoresis effects and turbulent eddies push the fine particulate in the syngas (sub-micron and micron-sized particulate) toward the cool surfaces of the heat exchanger. If the particles are above the Tamman temperature—defined as one-half the sticking temperature on an absolute basis—then the particles will

stick to the surface. Fine particles sinter together through inter-diffusion, and large particles that impact the cold wall will bounce and not stick to the wall.

2. As the deposition layer builds, metal sulfides, including iron sulfide (FeS), nickel sulfide (NiS), and other compounds, provide the adhesion mechanism to capture and bond larger particles onto the growing deposit layer.
3. The strength of the fouling deposit can increase over time if exposed to elevated temperatures (e.g., 650°C) due to solid-state diffusion of the fine particles contained in the deposit matrix.

Traditional approaches to predict fouling involve the use of empirical indices and ASTM ash fusion temperatures. With the advance of sophisticated analytical tools, such as scanning electron microscopy (SEM), computer-controlled SEM, and chemical fractionation that can more fully characterize the inorganic matter in coal, improved methods have been developed that utilize a more accurate description of the coal and thus allow more accurate models to be developed. REI has invested significant effort to gain a basic understanding of the physical properties involved in the process in order to develop basic, generic models for predicting fouling that can be used to solve real-world problems.

REI's proprietary Fouling and Deposit Growth Model is a mechanistic model that includes the impacts of (1) ash properties (e.g., individual particle composition, particle size, temperature, density, viscosity, and surface tension), (2) included/excluded minerals (e.g., pyrite), (3) local conditions (e.g., gas composition, temperature, and heat flux to surfaces), and (4) properties of deposits (e.g., composition, temperature, density, viscosity, surface tension , and the strength of sintered material). The model provides predictions for the properties of particles exiting the furnace in-flight, deposition rate (growth rate) and properties of the sintered deposits on walls, and the impacts of fouling on gas phase properties, including overall heat transfer.

A Mineral Matter Transformation Model is contained in the Fouling and Deposit Growth model and is key to providing useful predictions. The Mineral Matter Transformation Model accounts for vaporization of the minerals in the ash of the fuel during devolatilization. The vapors nucleate to form metal sulfide submicron aerosol (e.g., FeS and NiS). The Mineral Matter Transformation model provides the predicted state of the aerosols and micron-sized particulates (i.e., composition, size) prior to deposition. These models have been used in several commercial and DOE-funded projects to investigate the impacts of fuel switching and changing firing conditions.

SYNGAS COOLER DEPOSIT ANALYSIS

Fouling deposits from the syngas cooler at an IGCC plant will be obtained and analyzed at a commercial laboratory that specializes in deposit analysis from solid fuel-fired systems. The deposits will be analyzed using SEM to determine deposit morphology and using energy-dispersive X-ray spectroscopy (EDS) methods to determine chemical structure. The fuel fired at the plant during the time period of deposit formation will be obtained and analyzed. The fuel will be sent to a commercial laboratory for analysis, including ultimate/proximate analysis, bulk ash composition, and ash fusion temperature. A gasification industry OEM that develops and provides technical support to an IGCC plant will provide the deposit samples and fuel samples. The commercial laboratories performing the tests will provide raw data and analysis. REI will be responsible for reviewing and interpreting the data from the laboratory analyses to determine how this information impacts project understanding and hypotheses of deposit formation mechanisms.

ECONOMIC EVALUATION AND IMPACT ON COST OF ELECTRICITY OF SYNGAS COOLER IMPROVEMENTS

The project collaborator from the gasification industry has agreed to use their in-house models to estimate the impacts of the identified cooler improvements on syngas cooler costs and COE.

IDENTIFY MITIGATION TECHNOLOGY TO VALIDATE

Approximately three months prior to the end of Budget Period 2, REI will review the results from the laboratory experiments, modeling, and economic investigations performed in the project. The project team will then select a mitigation concept/technology to field test in a syngas cooler at an IGCC plant during Budget Period 3. REI will solicit input for the technology selection from all project participants and stakeholders, project collaborators from the gasification industry, and DOE. The decision on the selection of the technology for further development and validation testing will be based on consensus (using the data collected and analyzed in Budget Period 1 and Budget Period 2) of which technology will be most economical and effective at reducing the plugging and fouling of the syngas cooler. Based on preliminary discussions with the project team's collaborator from the gasification industry, it will be important that the selected technology not create operational problems for the syngas cooler or other processes at the plant. In this regard, the perceived risk by the plant personnel for performing a field test and the amount of technical support to be provided by the plant will be one of the criteria for selecting a technology. Justification for the identified technology—and reason(s) that other technologies were not recommended—will be documented.

TECHNICAL DECISION POINT

The last part of the project planned is to conduct a field test at a commercial IGCC plant to test the applicability of the chosen technology. The field test would be performed in Budget Period 3; however, at present, funding for Budget Period 3 is not authorized. Prior to starting work on the Budget Period 3 field test, REI will obtain DOE review and concurrence.

REI will produce a position paper with the continuation application to provide the Federal Program Manager with text, graphics, figures, and an explanation that defines the function and assumptions of relevant calculations (e.g., data analysis, modeling work, and calculation results) that were involved in the selection of the technology for field testing in Budget Period 3. Also to be included is a revised Statement of Project Objectives that includes a detailed scope of work further developed and broken down into tasks and subtasks. An environmental questionnaire, revised budget pages with increased detail at the subcontractor and budget category level, and an updated project management plan will also be submitted as supplemental documentation to the continuation application.

VALIDATE SELECTED MITIGATION TECHNOLOGY

In Budget Period 3 (if funded), REI will work with the project collaborator from the gasification industry to identify a plant to perform the field test. Design review would be performed by the project collaborator from the gasification industry. If feasible, preliminary tests would be performed using the University of Utah 1 ton/day pressurized pilot-scale gasifier. If approved by the OEM, REI and the project collaborator from the gasification industry would provide technical support for the field test, and REI would evaluate the field test results.

If a field test at a commercial IGCC plant cannot be arranged, an alternative path forward would be to develop a mechanical design of the syngas cooler that incorporates the best-performing technology.

13: FE0000489

Project Number	**Project Title**			
FE0000489	Recovery Act: High Temperature Syngas Cleanup Technology Scale-Up and Demonstration Project			
Contacts	**Name**	**Organization**	**Email**	
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Partners	Tampa Electric Company Shaw Engineering AMEC CH2M Hill BASF Corp. Süd-Chemie Eastman Chemical			
Stage of Development				
__Fundamental R&D	__Applied R&D	__Prototype Testing	X Proof of Concept	__Demonstration

Technical Background

Gasification of coal or other carbonaceous feedstocks has gained significant interest in recent years as a means to produce synthesis gas (syngas) for power generation or to produce fuels and chemicals for other applications. However, to fully exploit the potential of gasification for coal and other feedstocks, such as petroleum coke (petcoke), the process requires high thermal and chemical efficiencies at competitive costs. Because gasification of coal and petcoke generates a syngas with a significant amount of contaminants, including sulfur compounds (e.g., hydrogen sulfide [H_2S] and carbonyl sulfide [COS]); hydrogen chloride (HCl); ammonia (NH_3); and heavy metals such as mercury (Hg), arsenic (As), and selenium (Se), efficient syngas cleaning technologies are a key enabling technology for further deployment of gasification into the power and chemical sector. Even conventional technologies for removing contaminants, such as the Selexol or the Rectisol processes, are struggling with new syngas cleaning specifications and requirements. Optimizing thermal efficiency to maximize cost competitiveness is challenging for these conventional technologies because they require substantial cooling of the syngas. In addition, conventional technologies must add equipment to help meet new cleanup specifications for syngas that require more control of the trace contaminants, resulting in increased process costs. With the added emphasis on the removal of carbon dioxide (CO_2) and pollutants from coal-based systems, the objective of maximizing thermal and chemical efficiencies at competitive costs has become even more important.

For the last 20 years, Research Technology Institute (RTI), with DOE/NETL support, has been developing technologies for efficient and cost-effective removal of various contaminants from syngas at elevated temperatures (greater than 400°F). These technologies—which can remove reduced sulfur species (e.g., H_2S and COS), heavy metals (e.g., Hg, As, and Se), HCl, NH_3, hydrogen cyanide (HCN), and CO_2 at these temperatures—form the foundation of RTI's warm syngas cleanup platform. The modular nature of these technologies provides flexibility to tailor the syngas cleanup process to produce syngas that is suitable for either power or chemical production applications using the most cost-competitive syngas cleanup process.

One of the key highlights of RTI's research and development (R&D) program for the syngas cleanup technologies was a field test completed with real coal-derived syngas at Eastman Chemical Company's Coal-to-Chemicals facility in Kingsport, TN. RTI's desulfurization technology has been successfully demonstrated at a 0.3 megawatt-electric (MWe) pilot plant using coal-derived syngas. With over 3,000 hours of operation, sulfur removal efficiencies of greater than 99.9% have been achieved. Furthermore, parametric testing during this pilot plant test has demonstrated the robustness of the process over a wide range of operating conditions and with integrated operation of RTI's direct sulfur recovery process (DSRP), which converts the sulfur dioxide from sorbent regeneration into an elemental sulfur byproduct. Additional slipstream testing of other contaminant cleaning technologies at Eastman also demonstrated removal of Hg, As, NH_3, and HCN at elevated syngas temperatures.

The second highlight of this R&D program was an independent study by Nexant that concluded that the use of RTI's warm gas cleanup process in an integrated gasification combined cycle (IGCC) process scheme can achieve an overall thermal efficiency gain of 3.6% higher heating value (HHV) at reduced capital cost in comparison to a Selexol-based cleanup process. This thermal efficiency gain represents about a 10% increase in the net power output of an IGCC plant. In addition to the thermal efficiency gain, the warm syngas cleanup technology also reduced the capital cost of an IGCC plant by more than 5%, reducing capital requirements per kW of power generation capacity by about 14%. Therefore, the warm syngas cleanup technology has key advantages that are important to enabling IGCC and facilitating market penetration. A pathways study conducted by DOE/NETL in November 2010 concluded that RTI's warm gas cleanup process coupled with warm gas carbon capture improved overall efficiency by 3.7% (HHV) and reduced capital cost on a $/kW basis by 15%, confirming the Nexant results.

RTI's R&D project for the warm syngas cleanup technologies was included in the 2007 Advanced Power Systems Peer Review Meeting. Overall, the review was very positive about the strengths and accomplishments of the R&D program. However, the review did recognize that all the technologies in RTI's warm syngas cleanup technology portfolio were not at the same stage of development. The final hurdle for the high-temperature desulfurization process (HTDP) commercial deployment was a large-scale demonstration. By contrast, some of the other technologies, primarily the regenerable high-temperature CO_2 sorbents and the trace contaminant removal process (TCRP), were still being tested at the laboratory scale.

In July 2009, RTI and DOE signed a cooperative agreement to design, build, and test the more advanced technologies of RTI's warm syngas cleanup technologies at pre-commercial scale, which was one of the recommendations of the 2007 Advanced Power Systems Peer Review. The pre-commercial-scale system is expected to process the equivalent of 50 MWe, or about 1.5 million standard cubic feet per hour (scfh) (dry basis) of syngas, and will be operated at Tampa Electric Company's 250 MWe IGCC plant at Polk Power.

The size of this slipstream was carefully selected to mitigate the subsequent risk associated with a full commercial unit. Anticipated scale-up factors for subsequent commercial units are less than 10 for IGCC applications and potentially as low as one for chemical applications. These levels of risk are not expected to cause any significant issues for securing financing for the first few commercial systems based on successful operation of this pre-commercial-scale system.

The design process for this pre-commercial-scale system began with a competitive selection process to choose the engineering firm. Shaw Group was selected from seven engineering firms: Jacobs, KBR, SNC Lavalin, Foster Wheeler, Bechtel, Pegasus TSI, and Shaw Group. A pre-feed package was completed for the warm syngas cleanup technologies to optimize incorporation of the knowledge and expertise acquired during laboratory- and pilot-scale testing into the engineering design. The pre-feed package was completed in October 2010.

In September 2010, DOE added carbon capture and sequestration to the project scope. This additional scope provided the opportunity to demonstrate CO_2 capture and sequestration into a saline aquifer at the IGCC plant site and demonstrate cost-effective capture of sulfur and CO_2 in IGCC plants through the integration of the HTDP desulfurization technology and an advanced activated methyl diethanolamine (MDEA) process. The integration of the sulfur-selective HTDP technology with the non-selective CO_2 activated MDEA process minimizes the net overall cost of separating sulfur and CO_2 as byproduct streams. Another promising feature of this integration is the ability to achieve syngas specifications that permit the use of the clean syngas for chemical applications at costs substantially lower than the cost of Rectisol, the standard coal-derived syngas cleaning choice for chemical applications.

The system has been designed with the following test units to demonstrate RTI's warm syngas cleaning technologies at commercial operating conditions:

- High Temperature Desulfurization Process (HTDP) – This unit will process syngas flow equivalent to about 50 MWe (about 1.5 million scfh of syngas on dry basis) and produce a desulfurized syngas with a total sulfur (H_2S and COS) concentration of less than 10 parts per million by volume (ppmv).
- Water Gas Shift Reactors – This unit will utilize a sweet shift process to convert sufficient carbon monoxide to CO_2, enabling 90% capture of the CO_2 in the syngas slipstream. The sweet shift reactor will use a conventional shift catalyst, but the process will be optimized to minimize steam consumption (i.e., reduce parasitic power losses) and to maximize carbon capture potential.
- Activated MDEA Process – This unit employs an advanced activated amine system from BASF Corporation for nonselective separation of the CO_2 and H_2S present in the syngas stream. This advanced activated amine system has enhanced capabilities for CO_2 capture but has previously been excluded from use in coal-based applications because of its sensitivity to sulfur exposure in coal-derived syngas. Because of the selective upstream sulfur removal by the HTDP unit, the CO_2 capture target of 90% (based on total carbon in the syngas) can be achieved by this amine process without the detrimental effects of higher sulfur exposure. Because the amine process does provide some additional non-selective sulfur removal at low levels, the integration of these two processes is expected to reduce overall sulfur in the treated syngas to very low (less than 100 parts per billion [ppb]) concentrations. These integrated processes are also expected to achieve such a significant overall sulfur reduction at costs substantially below that of conventional Selexol and Rectisol processes, thus expanding the application of RTI's warm gas cleanup technology beyond power generation to applications such as chemicals, fertilizers, fuels, and hydrogen.
- CO_2 Compression and Drying – This unit will compress and dry the CO_2 product from the activated MDEA process, enabling its sequestration in a deep saline aquifer available on Tampa Electric Company's plant site.
- Trace Contaminant Removal Process (TCRP) – Because of Tampa Electric Company's primary utilization of petcoke in their feedstock and the subsequent reduction in coal-based contaminants in their syngas, the TCRP unit will be tested on-stream at Eastman Chemical Company's coal gasification facility in Kingsport, TN, rather than at Tampa Electric Company. This approach will enable more rapid development and scale-up of the TCRP technologies by testing and optimizing multiple contaminant removal configurations on actual coal-derived syngas starting as early as

2012 and operating in parallel to the engineering, procurement, construction, and operation of the pre-commercial demonstration plant at Tampa Electric Company.

To effectively integrate these new elements into the pre-commercial plant design, RTI worked diligently with Süd-Chemie on water gas shift reactors, BASF Corporation on the activated MDEA process, and Shaw on the integration of all of these systems with Tampa Electric Company's existing IGCC plant.

In parallel with these engineering design issues, RTI, Tampa Electric Company, and Shaw have worked on completing the necessary federal, state, and local permits required for this pre-commercial-scale system. This effort has also included required permitting for the CO_2 well. All required permits have been submitted, and all but the well permit have now been approved. Well permit approval is expected by the end of May 2012.

Relationship to Program

This project will support important gas cleaning advances within the gasification portfolio of the NETL Advanced Energy Systems Program. The original results from the techno-economic studies by Nexant and DOE have demonstrated that the commercial deployment of the warm syngas cleanup technologies could result in both significant thermal efficiency improvements and capital cost improvements for IGCC. The work completed to date on this project is confirming many of the cost estimates made about equipment, materials, and installation cost factors used in these estimates. New techno-economic studies are demonstrating that these cost, performance, and thermal efficiency advantages are also applicable for applications that require CO_2 capture and sequestration and for chemical, fertilizer, fuel, and hydrogen production applications.

The next big challenge for RTI's warm syngas cleanup platform is that the scale-up factor from previous pilot testing to a full commercial unit would be about 2,000 for a 600 MWe IGCC plant and more than 100 for most chemical applications. With this significant scale-up factor from pilot plant data from the field testing at Eastman (0.3 MWe), the risk is far too large to attract funding for commercial deployment. A key benefit for this project is to mitigate the scale-up risk for subsequent commercial deployment to an acceptable level through a 50 MWe demonstration.

In addition to reducing the scale-up risk, the current demonstration project will also provide the opportunity to develop commercially meaningful information about reliability, availability, and maintenance; demonstrate start-up and shut-down procedures for a commercial system; and accumulate operating experience under realistic industrial conditions.

The scope of the project has also resulted in several additional benefits, including the following:

- Demonstration of CO_2 sequestration in a saline aquifer from a commercially operating IGCC and a chance to investigate the fate of CO_2 in this aquifer.
- Demonstration of the cost-competitiveness of the integration of the sulfur-selective HTDP process and non-selective CO_2 activated MDEA process for producing suitable sulfur and CO_2 byproduct streams for diverse commercial applications.
- The potential for the integration of HTDP and activated MDEA to achieve syngas specifications suitable for chemical production applications at a substantial reduction from the typical cost of a Rectisol or Selexol system.

Primary Project Goal

The primary goal of this project is to utilize a pre-commercial-scale demonstration plant to mitigate the technical risks associated with scale-up of warm syngas cleaning and CO_2 capture and sequestration technologies, enabling subsequent commercial deployment.

Objectives

The original objectives of this project included the following:

- Mitigate technical design risks for a commercial plant with adequate design data obtained from the pre-commercial plant operation.
- Demonstrate continuous operation of the HTDP system, processing a syngas flowrate of 1.5 million scfh and producing a desulfurized syngas with a total sulfur concentration (H_2S and COS) of less than 10 ppmv.
- Complete 5,000 to 8,000 hours of operation.
- Capture up to 300,000 tons of CO_2.
- Establish reliability, availability, and maintenance targets for a full-scale commercial system.
- Establish operating experience to enable startup/shutdown, system turndown, and operator training for a commercial system.
- Scale up and evaluate performance of the direct sulfur recovery process integrated with HTDP.
- Scale up and evaluate performance of the TCRP unit (including but not limited to mercury, arsenic, and selenium) with a syngas slipstream.

Because of budget limitations and a lack of interest in DSRP testing by the host site, RTI recommends that the DSRP testing be removed from the project scope. As mentioned above, the TCRP testing will be performed at Eastman Chemical Company's coal gasification facility.

14: FE0005712

Project Number	**Project Title**			
FE0005712	Model-Based Optimal Sensor Network Design for Condition Monitoring in an IGCC Plant			
Contacts	**Name**	**Organization**	**Email**	
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Partners	GE Global Research			
Stage of Development				
__Fundamental R&D	_X_ Applied R&D	__Prototype Testing	__Proof of Concept	__Demonstration

Technical Background

Integrated gasification combined cycle (IGCC) technology that is currently being commercialized by GE holds promise to generate clean and efficient power from coal. A key challenge in accelerating its commercialization is to increase IGCC plant reliability and availability. The critical components affecting IGCC plant availability are gasifiers and radiant syngas coolers (RSC) in the core gasification section, which operate at very high temperature and pressure in a corrosive environment. Currently, in the absence of online monitoring, the plant is operated conservatively and is shut down periodically for manual inspection and maintenance of the gasifier refractory lining, which adversely impacts plant availability and efficiency. Similarly, the heat transfer performance in the RSC degrades over time due to fouling buildup from ash and slag, which also affects the plant efficiency. This project aims to develop a systematic sensor network design methodology for online condition monitoring of these critical components using model-based optimal sensor placement. Furthermore, online condition monitoring will also enable increased plant efficiency and flexibility when coupled with advanced control strategies such as model-predictive control.

Relationship to Program

This project will support important gasifier optimization advances within the gasification portfolio of the NETL Advanced Energy Systems Program. Online condition monitoring is critical to enhancing power generation plant reliability and availability. In the absence of any direct measurements due to the extremely harsh operational environment, the plant is currently shut down frequently for planned or unplanned inspection and maintenance of gasifier refractory lining. The project's model-based solution for obtaining optimal sensor placement will address a critical need by providing reliable and accurate online condition monitoring of the gasifier refractory degradation and RSC fouling.

The main benefits of this project include the following:

- Capability for real-time online monitoring of gasifier refractory degradation and RSC fouling. It is a key enabler for avoiding unnecessary or unplanned plant shutdowns that are expensive and adversely impact plant availability and operation costs.
- Improved online monitoring of critical system components, including gasifier and RSC health, integrated with advanced control will allow a less conservative and more flexible operation, pushing closer to the system operational boundaries depending on the degradation level, and thus improving overall plant power generation efficiency.

- A general modular tool, which can be applied to other process units for optimal sensor placement for online performance and condition monitoring, will be delivered to DOE for public benefit.

Primary Project Goal

The goal of this project is to develop a sensor network design based on models of an IGCC plant that support the development of an online condition monitoring system. In particular, this project aims to accomplish the following:

- Develop a sensor network design with the optimal combination and placement of sensors to enable online monitoring of refractory condition and RSC fouling.
- Demonstrate the effectiveness of the designed sensor network solution in identifying the RSC fouling profile and gasifier refractory wear at random locations with pre-specified accuracy through extensive benchtop simulation.
- Develop a sensor network design methodology that will be general enough to apply to condition monitoring of other critical components in coal-fired power plants.

Objectives

The objectives of this project include the following:

- Focus on condition monitoring through optimal placement of sensors in and around the gasification section.
- Enhance available models for the gasification section and RSC to be consistent with the condition monitoring requirements. More specifically, extend the gasifier model to include a transient 3-D thermal model of the refractory lining to relate the effects of hot surface wear on potential temperature sensors placed in the refractory lining. Similarly, extend the RSC model to include a 1-D fouling variation along the length of the RSC and its effects on potential sensors like heat flux, temperatures, and strain used for online monitoring.
- Identify requirements for sensor network for condition monitoring.
- Develop a set of computational tools to systematically address the problem of optimal sensor placement through a combination of model-based estimation and non-linear optimization in the presence of a) modeling and sensor errors and b) anticipated loss of sensors due to harsh environment. The solution to optimal sensor placement (OSP) problems requires solving with either mixed integer (MIP) or integer programming (IP) problems. As part of this objective, the project team will identify and develop various efficient algorithms for solving MIP/IP problems within OSP framework for various degree of model complexity, and develop the computational tools in a modular fashion so that they can be adapted easily for application to condition monitoring of other critical components in coal-fired power plants.
- Demonstrate the performance of the developed solution through extensive computer simulations. Use test cases for various refractory degradation conditions and RSC fouling variations to evaluate and demonstrate the model-based OSP algorithm for monitoring the condition of the gasifier refractory and fouling of the RSC online within pre-specified accuracy.

15: ORD-2012.03.03 Task 4

Project Number	Project Title			
ORD-2012.03.03 Task 4	Low Rank Coal Optimization			
Contacts	**Name**	**Organization**	**Email**	
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Partners	Southern Company KBR URS West Virginia University Penn State University Particulate Solid Research Tech IV Imaging Alpemi Virginia Tech			
Stage of Development				
__Fundamental R&D	_X_ Applied R&D	__Prototype Testing	__Proof of Concept	__Demonstration

Technical Background

New gasifiers coming online in the 21st century will require greater fuel flexibility, reliability, availability, and maintainability (RAM) as well as higher throughput and conversion. In addition, new gasifiers will need to integrate with gas cleanup and carbon management equipment. These critical technological issues must be addressed in the development and deployment of new gasifiers in order to minimize risk and encourage investment. At NETL, physics-based computational models are used in collaboration with industrial stakeholders to evaluate and optimize gasifier operation, research new designs, and provide performance data for commercial scale-up. Generating this type of information is both fast and inexpensive compared to the traditional approach of building and testing at multiple scales prior to commercialization. These models provide insight into the commercial performance of new designs, and have the potential to accelerate technologies from bench to commercial scale by allowing researchers to skip some intermediate steps (scales). Without these computational models, obtaining commercial-scale information would require either extrapolating lessons learned and performance data from smaller units—which could be 10, 50, or more times smaller than the planned commercial-scale units—or using empirical correlations, which are difficult to integrate information into a comprehensive model, especially when the effects of temperature and chemical reactions are present. Because the underlying physics is often the same, even in diverse technologies, these models enable researchers to learn from competing technologies. At NETL, scientists have developed in-house multiphase computational fluid dynamic (CFD) model MFIX (Multiphase Flow with Interphase eXchanges) as well as the Carbonaceous Chemistry for Computational Modeling (C3M), which allows all the major reaction-rate mechanisms inherent in the gasification process to be coupled to the hydrodynamic predictions, from both MFIX and other leading commercial multiphase solvers. The MFIX and C3M models are recognized as leading research tools in the area of reacting gas-solids flows and have both won Federal Laboratory Awards for technology transfer; MFIX has also been recognized for its excellence with an R&D 100 Award.

At NETL, the performance estimates obtained from a computer model are being evaluated to provide the user with a clear understanding of the range and likelihood of behaviors resulting from a given variability in the operating parameters or design alternatives. Such variation in performance may result from uncertainties in the input parameters. Therefore, to give quantitative error-bars on the simulation data to help designers, decisionmakers, and operators, it is critical to develop a practical framework to quantify the various types of uncertainties and assess the impact of their propagation in the computer models of the physical system. There is a growing recognition of the fact that CFD model validation cannot be complete without explicit accounting of various uncertainties. Uncertainty quantification tool kits such as PSUADE (Problem Solving environment for Uncertainty Analysis and Design Exploration) from Lawrence Livermore National Laboratory or DAKOTA (Design Analysis Kit for Optimization and Terascale Applications) from Sandia National Laboratory can be coupled with NETL's in-house suite of high-fidelity multiphase software—such as C3M, MFIX-DEM (discrete element method), MFIX Continuum, Hybrid MFIX, and MFIX-PIC—and lower-fidelity multiphase reduced order models (ROMs) to achieve, for the first time, a framework to conduct uncertainty quantification. Under this task, the project team will focus on developing a hierarchy of TRIG co-feed models with uncertainty to demonstrate the utility.

In parallel to the efforts to develop and improve reacting multiphase CFD models, NETL is continually developing further functionality within C3M. The development of C3M has centered around two central goals: (1) provide users a platform to perform virtual kinetic experiments to evaluate and explore the effect of operating conditions (e.g., heating rate, temperature, pressure) and the impact of different fuels on conversion rates and yields inside a typical gasification process; and (2) provide multiphase CFD users with a source of kinetic information at their fingertips to evaluate and select appropriate kinetic (rates and yields) and quickly incorporate them into the multiphase CFD model of choice. The C3M software platform interfaces with leading kinetic packages (Niksa Energy Associate's PC Coal Lab®, University of Utah's CPD [chemical percolation devolatilization] model, Advanced Fuel Research's FG-DVC [Functional-Group, Depolymerization, Vaporization, Crosslinking] model, and NETL's in-house data) and state-of-the-art multiphase CFD models (NETL's MFIX, ANSYS FLUENT, and CPFD BARRACUDA), giving the user—with appropriate licensing—access to one of the largest sources of carbonaceous chemistry in the world and a fast, affordable means to incorporate gasifier chemistry into a multiphase CFD model.

Relationship to Program

This project will support important advances in low-rank coal optimization within the gasification portfolio of the NETL Advanced Energy Systems program.

Benefits of the project include the following:

- The C3M software platform interfaces with leading kinetic packages and state-of-the-art multiphase CFD models and, with appropriate licensing, gives the user access to one of the largest sources of carbonaceous chemistry in the world, as well as a fast, affordable means to incorporate gasifier chemistry into a multiphase CFD model.
- The framework to conduct uncertainty quantification for both hydrodynamic and kinetic quantities for reacting multiphase flow models
- Co-pyrolysis and co-gasification NETL kinetic data for multiphase CFD modeling
- A hierarchy of co-feed TRIG models that can be used by industrial stakeholders (Southern Co. and KBR) for development, optimization, and commercialization plans

- Torrefaction data for analysis of energy content, composition, kinetics, grindability, and lock-bridge and TRIG performance

Primary Project Goal

The primary goal of this project is to enable low-rank coal and mixed-feed gasification performance prediction and improvements by developing a hierarchy of models with uncertainty quantification coupled with NETL's in-house kinetic database, Carbonaceous Chemistry of Computational Modeling (C3M).

Objectives

The Low Rank Coal Optimization project is based on three areas of concentration: TRIG Model Development; Fuel Pretreatment; and Fundamental Gasification Code Development. These three areas work in parallel to develop appropriate kinetics and computational models for co-feed TRIG applications and optimization.

TRIG MODEL DEVELOPMENT

The gasification team goal is to use an integrated approach to combine theory, computational modeling, experimentation, and industrial input to develop physics-based methods, models, and tools to support the development and deployment of advanced gasification-based devices and systems. The activities in this task directly support these goals by developing and applying computational and modeling tools to simulate complex flows in applications such as transport or entrained-flow gasifiers. The primary objective of this work is to develop a hierarchy of models for numerical simulations of TRIG co-feed conditions that span fast-running ROMs to high-fidelity, multiphase CFD models. A hierarchy of CFD models will be developed or improved from the current state-of-the-art, offering trade-offs between physical details and computational cost, with uncertainty quantification associated with each model of choice. These tools will be made available to aid in the design and optimization of operating conditions and in the establishment of performance trends in the gasifiers. Results of this work will be shared with industry (Southern Company and KBR) to aid in their understanding of the TRIG reactor under co-feed conditions and the potential for commercialization.

Objectives for each phase of the work are given below:

Year 1 Objectives

- Combine ongoing Eulerian-Lagrangian (E-L) efforts by incorporating parallelization, heat transfer and reactive chemistry models, MPPIC (multi-phase particle-in-cell), and MPPIC-cutcell techniques into the MFIX CVS (concurrent versioning system) main branch. The consolidated version of the code will be made public to the MFIX community along with supporting documentation/user manual. The new features of the code will be validated against data obtained from the rectangular bed (two-dimensional [2-D] bed) available in the cold-flow circulating fluidized bed (CFB) facility at NETL. The current state-of-the-art capabilities of MFIX will be tested by developing a co-fed (low-rank and biomass) E-E (Eulerian-Eulerian) model for a TRIG gasifier.
- Conduct experiments at smaller scale and pose the data as mini-blind challenges to the modeling community in order to enable greater participation and provide a better opportunity for modelers to refine and improve their models to demonstrate the accuracy and foster greater acceptance of these codes. These small-scale cold models include the rectangular BFB and a 12-cm diameter CFB.

- Provide data from the large-scale CFB riser for models validation in support of the development of advanced gasification system such as the TRIG system for low-rank coals.
- Identify and document primary sources of uncertainties in input parameters for gasifier simulations. Develop a practical software framework for non-intrusive uncertainty propagation through MFIX with the aid of an uncertainty quantification toolbox and perform code verification for three-dimensional (3-D), unsteady multiphase flow.
- Conduct a literature survey of different cohesive models and their implementation and verification in the MFIX CFD code. This includes both 2-D and 3-D simulations of small-scale fluidized bed systems and comparison with available data from the literature.
- Update proper orthogonal decomposition (POD) Multiphase ROM to allow for transport of multiple species and thermal energy. Generalize POD Multiphase ROM methodology to broad set of multiphase flow applications and submit manuscript for publication on existing POD Multiphase ROM methodology.
- Develop cohesive submodel into the MFIX continuum model.

Year 2 Objectives

- Continue development of the coarser MPPIC-EL and hybrid-ELE hydrodynamic models, and the incorporation of heat transfer and reactive chemistry effects. Advanced parallelization strategies will be implemented to further reduce the simulation turnaround time. Experimental data from the 2-D bubbling fluidized bed as well as simulation data from the more accurate DEM-EL model will be used for verification, validation, and improvement of sub models in MPPIC-EL and hybrid-ELE models. A realistic simulation representative of complex gasifier geometry will be conducted with the latest available models.
- Continue the experiment in the rectangular unit to explore the influence of physical properties of bed materials on gas-solid fluidization, for use in CFD model validation. Examine the mechanisms of solids elutriation (solids ejection to the freeboard caused by a bubble break at the bed surface) in the 10 cm bubbling fluidized bed (BFB) rig. Advanced instruments such as PIV (particle image velocimetry), ECVT (electrical capacitance volume tomography), and LDV (laser Doppler velocimetry) will be used to investigate this phenomenon. Data generated from these measurements will be used to validate CFD models. Moreover, the influence of the central gas/solid jet on solid dispersion will be investigated. The data will be used not only for model validation but can also help better the design of the advanced TRIG system.
- Conduct 2-D and 3-D simulations of low-velocity bubbling fluidized bed systems using a realistic particle size distribution of particles. Cohesive forces affecting the formation and stability of small agglomerates will be quantified and compared with other competitive forces (hydrodynamic and collision). The simulation predictions will be compared with experimental observations obtained at these low hydrodynamic velocities.
- Evaluate various uncertainty quantification analysis methods for the non-reacting and reacting multiphase flow problems of interest.
- Develop chemical reaction methodology for inclusion into POD Multiphase ROM and apply the POD Multiphase ROM to a test case gasifier.

Year 3 Objectives

- The MPPIC and hybrid models will be validated at laboratory scale by comparing the experimental data from NETL's 12-inch CFB riser. This system will be co-fed to emulate the feedstock of a TRIG gasifier. The validated model will be used to simulate a co-fed TRIG gasifier-like system with detailed chemistry and realistic geometry.
- Explore the gas behavior in gas-solid fluidization in the rectangular BFB cold model rig using very fine powder as seed particles. Gas flow in and out of the bubbles as well as in the emulsion phase will be measured by the PIV and LDV. Data generated from these experiments will be posed as challenges to model validation. Investigation into the elutriation, segregation, and attrition of solids will continue, as will investigation into the effect of central gas/solid jet on solids dispersion to the 30-cm diameter cold flow circulating fluidized bed (CFCFB) riser, using the ECVT.
- Develop an integrated software framework for MFIX with the capability to perform robust design optimization under uncertainty for gasifiers.
- Conduct 2-D and 3-D simulations of high-velocity entrained flow risers using a realistic particle size distribution and comparison with experimental observations. The stability of the formed agglomerates will be assessed and compared with those obtained at low-speed fluidization.
- Improve POD Multiphase ROM performance so that it can be directly linked to the control of gasifiers or during a gasifier simulation.

FUEL PRETREATMENT AND FEEDING

The objective of this sub-task is to support the development of coal/biomass feeds and co-feed feeder technology for TRIG systems that improve efficiency and reduce development and operating costs. The result will be the ability to design and optimize dry feed systems to operate at high pressures with lower cost, higher efficiency and greater RAM, which reduces the parasitic energy losses for carbon capture, improves reliability and up time, and reduces the cost of development and operation.

Year 1 Objectives

- Bring the torrefaction rig through shakedown and begin collecting data and generating samples.
- Install the high-energy ball mill in B13 and begin validating the hybrid work index developed with West Virginia University.
- Fabricate a custom mid-pressure triaxial tester to extend confining pressure range to the lower end of lock-bridge feeder stresses.
- Install a linear variable differential transformer (LVDT) on the high-pressure triaxial tester.

Year 2 Objectives

- Complete the engineering for the support systems needed for the custom mid-pressure triaxial tester.
- Install and test the mid-pressure triaxial tester.
- Demonstrate a calibrated, successful simulation of a triaxial test in MFIX-DEM and publish results.
- Complete work on hybrid work index and publish results.

Year 3 Objectives

- Integrate the frictional flow submodel developed in MFIX-DEM into the main code as an option.
- Simulate a lock-bridge type feeder with MFIX-DEM main code.

FUNDAMENTAL GASIFICATION CODE DEVELOPMENT

The objective of the proposed work is to continue to develop the methodology and associated software needed to implement kinetic models for coal devolatilization, tar gas-phase chemistry, soot formation, and biomass chemistry generated from PC Coal Lab, CPD, and other commercial software packages into the module for C3M that is coupled to the MFIX model. Extension of the graphical user interface (GUI) to accommodate other multi-phase codes (Fluent, Barracuda, etc.) will also be implemented. In addition, the proposed work will investigate the kinetics and mechanisms of pyrolysis and gasification for mixed and low-rank feedstocks. The results of these investigations will be used to improve the utility and accuracy of existing NETL computational models (C3M) in predicting the effects of mixed and low-rank feedstock used in advanced gasifiers. The effects of feedstock processing conditions on reaction kinetics will also be explored, with the secondary goal of demonstrating improved control of gasification reactions via feedstock processing refinements.

Year 1 Objectives

- Implement the heterogeneous char-based gasification kinetics available in PC Coal Lab, and devise an experimental methodology to quantify the mechanism of soot formation at high temperatures.
- Build up and modify reactor systems for a tar cracking and soot formation kinetic study.
- Obtain co-gasification kinetic data using various gasifying agents at multiple pressures.

Year 2 Objectives

- Quantify the soot formation mechanism from the experimental program devised in Year 1; update the GUI with soot formation kinetics; and commence CFD simulations of small-scale experimental gasification rigs and the National Carbon Capture Center TRIG gasifier in order to verify/compare the various gasification kinetic models.
- Generate and obtain tar cracking and soot formation rate data.
- Study the effect of feedstock processing and pretreatment (ash washing, torrefaction, particle size, etc.) on co-gasification kinetics.

Year 3 Objectives

- Finish the formulation of soot formation kinetics and implementing these in the C3M GUI and complete the CFD-based comparison of small-scale and large-scale gasifiers using all of the kinetic models developed in Years 1 and 2.
- Investigate control of gasification kinetics with the influence of catalysis, particle size, operating conditions, and feedstocks (multiple and mixed).

16: ORD- 2012.04.02

Project Number	Project Title			
ORD- 2012.04.02	Carbon Capture Simulation Initiative			
Contacts	**Name**	**Organization**	**Email**	
DOE/NETL Project Mgr.	David Miller	NETL – Office of Research and Development	David.Miller@netl.doe.gov	
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Partners	Lawrence Berkeley National Laboratory Lawrence Livermore National Laboratory Los Alamos National Laboratory Pacific Northwest National Laboratory Carnegie Mellon University West Virginia University Princeton University Boston University University of Utah			
Stage of Development				
__Fundamental R&D	_X_ Applied R&D	__Prototype Testing	__Proof of Concept	__Demonstration

Technical Background

There is an urgent need to accelerate the development of carbon capture and sequestration (CCS) technologies and meet the DOE goal of beginning widespread deployment of CCS in 8–10 years. Currently, the fastest way to deploy carbon capture technology is to scale up existing technologies, such as amine scrubbing, to the capacity required for use in a power plant, and to deploy the technology to the hundreds of existing power plants. However, estimates show that this could increase the cost of electricity (COE) by as much as 80% in new pulverized coal (PC) power plants while reducing the power plant's net efficiency by about 30%. The time required for moving a new concept from the research laboratory to industrial deployment is another major issue; prior experience shows that this process takes anywhere from 20 to 30 years.

Meeting DOE's aggressive goal to begin deployment of carbon capture technology within 8–10 years will require the development of new approaches that take concepts from the laboratory to the power plant more quickly and at a lower cost. DOE is developing advanced carbon capture technology through its CCS research, development, and deployment (RD&D) program, and supporting a number of laboratory- and pilot-scale projects on second-generation carbon capture technologies; six demonstration-scale projects under the Clean Coal Power Initiative (CCPI); the demonstration-scale FutureGen 2.0 project; and three projects for capturing and storing carbon dioxide (CO_2) from industrial sources.

The complementary approach taken by the Carbon Capture Simulation Initiative (CCSI), which is based on advanced modeling and simulation, has the potential to dramatically reduce this development time. The 20–30 years of development time required for commercial deployment is mainly a result of the testing required at progressively larger scales, from laboratory-, to pilot-, to demonstration-scale, ensuring that the risk in each step is as small as possible. Four to six such tests at different scales could be required before commercial deployment. CCSI will develop science-based models that can be used in conjunction with pilot-scale data to allow larger steps to be taken earlier and with greater confidence, thereby reducing the time and expense required to achieve commercial deployment of carbon capture technology.

Recent experience in other industries, such as the aerospace and automotive industries, has demonstrated that simulations can be used to accelerate technology development. The challenge addressed by CCSI is to use the recent advances in simulation technology and to develop a science-based capability to assess and mitigate the risk of scaling up carbon capture technologies. There is precedent for using computational science techniques in energy technology development to reduce development cost and time. CCSI will enable decisionmakers, who must make large capital investments, to be informed by science-based models with quantified uncertainty and estimated technical risk. This will enable smarter demonstrations and could ultimately accelerate demonstrations by several years.

At the outset of the effort, it is particularly important to develop capabilities that can address the largest potential sources of CO_2. For this reason, the initial CCSI effort will focus on methods applicable to PC power plants, which generate nearly half the electricity in the United States and emit about one-third of all CO_2 from U.S. sources. Existing PC power plants will generate 95 percent of the coal-based CO_2 emissions projected to be released from 2010 through 2030. A recent analysis suggests that roughly 325 coal-fired generating units–accounting for roughly two-thirds (200 gigawatts [GW]) of current U.S. coal-based generating capacity–are suitable for carbon capture.

Given the importance of PC power plants, a consideration of options for initial industrial challenge problems concluded that the CCSI development effort should focus on a small number of judiciously chosen Industrial Challenge Problems (ICP). Solid-sorbent-based post-combustion capture technology was chosen as the first ICP for CCSI because, while DOE/NETL is sponsoring a number of sorbent development efforts, significant work remains to define and optimize the reactors and processes needed for successful sorbent capture systems. Sorbents offer an advantage because they can reduce the regeneration energy associated with CO_2 capture and reduce parasitic load. Most of the work on sorbents has been restricted to developing the sorbent itself, with only very recent studies considering the design of the reactor system and integration with the power plant. Thus, solid-sorbent systems are at the start of the traditional process development cycle. An ICP focused on solid sorbents will accelerate the analysis of options for this emerging technology. The target is to use the CCSI toolset to help identify promising solid-sorbent processes and accelerate the scale-up from 25 megawatt-electric (MWe) to commercial demonstration scales.

While detailed component simulations for solid sorbents will be much different than those used in liquid solvents, the computational interfaces developed for either technology will share many common features (e.g., ability to handle multiphase devices). In the initial phase of development, many aspects of the CCSI toolset will lack details of a specific coal plant configuration (e.g., the boiler combustion process, feedwater heaters, and condenser details) and, thus, will be treated as part of a more general process flowsheet.

The following list of activities represents the approach that CCSI will employ to develop the toolset:

1. Assemble best tools, data, and multidisciplinary, highly collaborative teams.
2. Identify and fill gaps in simulation capabilities, including model validation and quantification of uncertainty.
3. Integrate software tools to produce complete and consistent simulations, which allow seamless migration among multiphysics models at different scales.

4. Work closely with technology developers for scale-up, troubleshooting, and commercialization, as well as accelerated adoption of tools and approaches.
5. Maintain a knowledge base of CCSI data, "best practices," and customized tools.

As shown below, CCSI is organized into eight elements that fall under two focus areas. The first focus area, Physicochemical Models and Data, addresses the steps necessary to model and simulate the various technologies and processes needed to bring a new CCS technology into production. The second focus area, Analysis and Software, involves developing the software infrastructure to integrate the various components and implement the tools that are needed to make quantifiable decisions regarding the viability of new CCS technologies. A separate Industry Advisory Board ensures the strength of the industry partnerships.

Table 1: CCSI Elements by Focus Area

Physicochemical Models and Data	**Analysis and Software**
1. Basic Data and Models	5. Integration Framework
2. Particle and Device Scale Models	6. Uncertainty Quantification
3. Process Synthesis and Design	7. Risk Analysis and Decisionmaking
4. Plant Operations and Control	8. Software Development Support
Industry Collaboration Industry Advisory Board	

Relationship to Program

This project will support important advances in carbon capture simulation within the Computation Energy Science focus area of the NETL Advanced Energy Systems Program.

Over five years, CCSI will develop an integrated, validated suite of models, tools, and methodologies for accelerating the development and deployment of carbon capture technology. The steps taken by CCSI to reach that target include the following: Develop a framework for integrating particle (droplet) and device-scale models with process synthesis and design and process control; Develop specific physical models for the ICP; Validate the models and quantify uncertainties; Use the modeling results during the scale-up of carbon capture processes to assess and mitigate technical and financial risks, improve designs, and shorten the design cycle; and support decisionmaking to move to larger scales more quickly and with better designs, considerably reducing the cost and time required for the commercialization of carbon capture technology.

Primary Project Goal

The primary project goal is to provide technology developers and plant operators with a validated suite of models and simulation tools that enable the rapid development and deployment of new carbon capture technologies. The CCSI toolset will provide tools and methodologies that accurately predict the performance of equipment and processes; reduce the uncertainty associated with system integration and scale-up; and accelerate the commercial development of integrated carbon capture technologies. The CCSI toolset will include validated models of carbon capture equipment and processes as well as new design and analysis tools and methodologies. Industries utilizing the CCSI toolset will be able to reduce the time and expense of new technology development—from discovery, to demonstration, to widespread deployment—by a minimum of five years. The total cost savings that could be realized by using the CCSI toolset to scale up and widely deploy just one carbon capture technology is estimated to be approximately $500 million (net present value basis).

Objectives

CCSI will develop and deploy state-of-the-art computational modeling and simulation tools to accelerate the commercialization of carbon capture technologies from discovery to development, demonstration, and ultimately the widespread deployment to hundreds of power plants. By developing the CCSI toolset, a comprehensive, integrated suite of validated science-based computational models, this initiative will provide simulation tools that will increase confidence in designs, thereby reducing the risk associated with incorporating multiple innovative technologies into new carbon capture solutions. The scientific underpinnings encoded into the suite of models will also ensure that learning will be maximized for successive technology generations.

The CCSI toolset will accelerate the development and deployment cycle for bringing new CCS technologies to market in several important ways:

- Promising concepts will be more quickly identified through rapid computational screening of devices and processes.
- The time to design and troubleshoot new devices and processes will be reduced through science-based optimal designs.
- The technical risk in taking technology from laboratory scale to commercial scale will be more accurately quantified.
- The deployment costs will be stabilized more quickly by replacing some of the physical operational tests with virtual power plant simulations.

The success of CCSI will be measured by the development and delivery of the following components of the CCSI toolset:

- Validated sorbent submodels for candidate sorbents that can be used within both high-fidelity simulations and process simulations
  - A simple kinetic model for amine-based solid sorbents which accurately captures the competing uptake/release of CO_2 and water
  - A high-fidelity multiscale kinetic/diffusion model for amine-based solid sorbents that also accounts for the microstructure of the sorbent particle
  - Reduced order model (ROM) implementation of the high-fidelity, multiscale sorbent model for computationally efficient incorporation into high-fidelity equipment models and process models

- Validated, high-fidelity models of solid sorbent carbon capture equipment at various scales, including 1 MW-pilot scale, intermediate scales, and full scale
  - High-fidelity, full-scale model of solid sorbent adsorber and regenerator
  - High-fidelity, 1 MWe-scale model of solid sorbent adsorber and regenerator
  - High-fidelity, intermediate-scale (~25 MWe) model of solid sorbent adsorber and regenerator
  - High-fidelity, intermediate-scale (~100 MWe) model of solid sorbent adsorber and regenerator

- Models, computational tools, user interfaces, and accompanying methodology for optimal process synthesis and process design
  - One-dimensional process models of solid sorbent adsorbers and regenerators
  - Superstructure-based optimization framework to determine optimal process configurations
  - Heterogeneous simulation-based process optimization framework

- Uncertainty Quantification Framework to assess the effect of uncertainty in underlying parameters and models on the predicted performance of equipment and processes in a carbon capture system
- Risk Analysis and Decisionmaking Framework, which incorporates multiple risk contributors including technology readiness, uncertainty in models and simulations, economic uncertainty, and technical scale-up risk
- Reduced order model development tools to automatically develop ROMs from high-fidelity models in a form suitable for incorporation into larger-scale models and simulations

APPENDIX F: LIST OF ACRONYMS AND ABBREVIATIONS

Acronym or Abbreviation	Definition
°C	degrees Celsius
°F	degrees Fahrenheit
Al	aluminum
Al_2O_3	aluminum oxide
APCI	Air Products and Chemicals, Inc.
API	American Petroleum Institute
APS YSZ	atmospheric plasma-sprayed yttria-stabilized zirconia
ARRA	American Recovery and Reinvestment Act
As	arsenic
ASME	American Society of Mechanical Engineers
ASU	air separation unit
atm	atmosphere
BFB	bubbling fluidized bed
BRTD	ASME Board on Research and Technology Development
C3M	Carbonaceous Chemistry for Computational Modeling
CCC	Copyright Clearance Center
CCPI	Clean Coal Power Initiative
CCRP	Clean Coal Research Program
CCS	carbon capture and sequestration
CCSI	Carbon Capture Simulation Initiative
CerFab	ceramic membrane manufacturing facility
CES	Clean Energy Systems, Inc.
CFB	circulating fluidized bed
CFCFB	cold-flow circulating fluidized bed
CFD	computational fluid dynamics
CH_4	methane
cm	centimeter
CMC	ceramic matrix composite
Co	cobalt
CO	carbon monoxide
CO_2	carbon dioxide
COE	cost of electricity
$CoMoS_2$	cobalt molybdenum disulfide
COS	carbonyl sulfide
CPD	Chemical Percolation Devolatilization
Cr	chromium
CRTD	ASME Center for Research and Technology Development
$Cu/Zn/Al_2O_3$	copper/zinc/aluminum oxide
DAKOTA	Design Analysis Kit for Optimization and Terascale Applications
D-E-C	deposition, erosion, corrosion

Acronym or Abbreviation	Definition
DOE	U.S. Department of Energy
DSRP	direct sulfur recovery process
EB-PVD	Electron Beam Physical Vapor Deposition
ECVT	electrical capacitance volume tomography
EDS	energy-dispersive X-ray spectroscopy
E-E	Eulerian-Eulerian
E-L	Eulerian-Lagrangian
Eltron	Eltron Research, Inc.
EOR	enhanced oil recovery
Fe	iron
FeCr	ferrochrome
FeS	iron sulfide
FG-DVC	Functional-Group, Depolymerization, Vaporization, Crosslinking
FTT	Florida Turbine Technologies. Inc.
FY	fiscal year
GTC	Gasification Technologies Council
GUI	graphical user interface
GW	gigawatt
H_2	hydrogen
H_2O	water
H_2S	hydrogen sulfide
HCl	hydrogen chloride
HCN	hydrogen cyanide
Hf	hafnium
Hg	mercury
HHC	high hydrogen content
HHV	higher heating value
HPC	high pressure compressor
HPT	high pressure turbine
HTDP	high-temperature desulfurization process
HTM	hydrogen transport membrane
HVOF	high-velocity oxyfuel
ICP	Industrial Challenge Problems
IGCC	integrated gasification combined cycle
IGTI	International Gas Turbine Institute
IP	integer programming
IPT	intermediate-pressure turbine
ISTU	intermediate-scale test unit
ITM	ion transport membranes
K	potassium
K	Kelvin
K_2MoO_4	potassium molybdate

Acronym or Abbreviation	Definition
kW	kilowatt
La	lanthanum
lb	pound
LDV	laser Doppler velocimetry
LEFR	Laminar Entrained Flow Reactor
lpm/s	mass pounds per second
LTI	Leonardo Technologies, Inc.
MCrAlY	metal-chromium-aluminum-yttrium
MCrAlYHfSi	metal-chromium-aluminum-yttrium-hafnium-silicon
MDEA	methyl diethanolamine
MFIX	Multiphase Flow with Interphase eXchanges
MFIX-CVS	Multiphase Flow with Interphase eXchanges—Concurrent Versioning System
MFIX-DEM	Multiphase Flow with Interphase eXchanges—Discrete Element Method
MIP	mixed integer programming
MPC	multi-physics code
MPPIC	multi-phase particle-in-cell
MW	megawatt
MWe	megawatt-electric
MWt	megawatt-thermal
N_2	nitrogen
Na_2MoO_4	sodium molybdate
Na_2MoO_7	sodium molybdate
NDE	non-destructive evaluation
NETL	National Energy Technology Laboratory
NETL-RUA	National Energy Technology Laboratory Regional University Alliance
NGCC	natural gas combined-cycle
NH_3	ammonia
Ni	nickel
NiAlCr+Zr	nickel-aluminum-chromium + zirconium
NiCoCrAl	nickel-cobalt-chromium-aluminum
NiCrAl	nickel-chromium-aluminum
NiS	nickel sulfide
NO_x	nitrogen oxide
O_2	oxygen
OCC	Office of Clean Coal
OEM	original equipment manufacturer
OFT	oxyfuel turbine
OMB	Office of Management and Budget
ORD	Office of Research and Development
ORNL	Oak Ridge National Laboratory
OSP	optimal sensor placement

Acronym or Abbreviation	Definition
p	partial pressure
PC	pulverized coal
pCO_2	partial pressure of carbon dioxide
PCM	proof-of-concept module
PDU	process development unit
Penn State	Pennsylvania State University
pH_2	partial pressure of hydrogen
pH_2O	partial pressure of water vapor
PI	principal investigator
PIV	particle image velocimetry
pO_2	partial pressure of oxygen
POD	proper orthogonal decomposition
ppb	parts per billion
ppm	parts per million
ppmv	parts per million by volume
PSA	pressure swing adsorption
psia	pounds per square inch absolute
psig	pounds per square inch gauge
PSUADE	Problem Solving environment for Uncertainty Analysis and Design Exploration
Pt	platinum
R&D	research and development
RAM	reliability, availability, and maintainability
RD&D	research, development, and demonstration
Re	rhenium
REI	Reaction Engineering International
ROM	reduced order model
RSC	radiant syngas coolers
RTI	Research Technology Institute
S	sulfur
scfh	standard cubic feet per hour
Se	selenium
SEM	scanning electron microscopy
SEP	sub-scale engineering prototype
SOFC	solid oxide fuel cell
SOFC/GT/ST	solid oxide fuel cell / gas turbine / steam turbine
SX	single-crystal
syngas	synthesis gas
TBC	thermal barrier coating
TCLA	total turbine cooling and leakage air
TCRP	trace contaminant removal process
TDA	TDA Research, Inc.
TDU	Technology Development Unit

Acronym or Abbreviation	Definition
TEM	transmission electron microscope/microscopy
TET	turbine entry temperature
TGO	thermally grown oxide
TPD	tons per day
TRIG	Transport Reactor Integrated Gasification
URS	URS Corporation
UTSR	University Turbine Systems Research
UOP	Universal Oil Products LLC
WGS	water-gas shift
XRD	x-ray diffraction
Y	yttrium
YSZ	yttrria-stabilized zirconia
Zn	zinc
Zr	zirconium