NATIONAL ENERGY TECHNOLOGY LABORATORY

FY18 CROSSCUTTING (SENSORS AND CONTROLS) PEER REVIEW OVERVIEW REPORT

June 28, 2018

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

DISCLAIMER

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INTRODUCTION AND BACKGROUND

The National Energy Technology Laboratory's (NETL) Crosscutting Research Program is unique in its ability to foster applications of a given technology across several fossil energy programs and efficiently leverage resources to accomplish common goals. Often, processes and materials that advance one technology platform may well have application in another with little to no modification.

The Crosscutting Research Program leverages the latest technology trends in sensors and controls. These advanced capabilities accelerate progress toward addressing the challenges facing today's fossil power plants and realize the next generation of fossil energy technology platforms. The technologies developed by the Crosscutting Research Program improve power plant efficiency and reduce operating and maintenance costs, while maintaining reliable and resilient energy infrastructure.

The Crosscutting Research Program utilizes the advanced technological capabilities of NETL, including the open-source Multiphase Flow with Interphase eXchanges (MFiX) software suite for multiphase modeling, Extreme Environment Materials consortium to accelerate materials development, and NETL's Joule supercomputer for complex modeling and simulations.

The Crosscutting Research Program's Sensors and Controls research provides pivotal insights into optimizing plant performance and reliability while utilizing and furthering technological megatrends. The research is focused on developing cost-effective technologies capable of monitoring key parameters while operating in harsh environments, and aligning with self-organizing information networks for process control and decision making. The research portfolio is categorized into two key technology platforms: Advanced Sensors and Distributed Intelligent Controls.

The diverse sensors and control research portfolio uses manufacturing techniques that can embed sensors in a variety of plant components to monitor parameters like temperature, pressure, fluid composition, and the state of materials. Advanced sensors can operate in extreme environments, and condition-based monitoring algorithms provide improved maintenance of plant operations. Sensors and controls serve as an essential technology that enable systems operations under conditions where optimal performance is balanced with reliability.

Advanced Sensors

Researchers are devoted to creating novel sensor concepts that include optical, micro, and wireless sensors that can be embedded into several plant components using advanced manufacturing techniques. The increased ability to monitor plant components and transmit the data to a distributed network increases plant efficiency and reliability. Innovative approaches to sensing technologies and manufacturing and the utilization of sensor data have the potential to transform the energy landscape by optimizing plant performance and increasing the expected life cycle of materials.

Distributed Intelligent Controls

After sensors collect data from the power plants, the distributed controls network then processes the data to permit decision making. The controls research area develops systems with fast dynamics for non-steady-state and incorporates controls that are capable of handling systems that are inherently non-linear using real-time data. Using a dynamic process of highly integrated sensors allows for increased control of the power plant and is more robust than linear model predictive control algorithms. The program area also examines sensor placement to improve performance, management and cost of the entire control system, and to further optimize cognitive capabilities.

Office of Management and Budget Requirements

In compliance with requirements from the Office of Management and Budget, the U.S. Department of Energy (DOE) and NETL are fully committed to improving the quality of research projects in their programs. To aid this effort, DOE and NETL conducted a Fiscal Year 2018 (FY18) Crosscutting (Sensors and Controls) Peer Review Meeting with independent technical experts to assess the projects' technology readiness for work at the current Technology Readiness Level (TRL), the planned work to attain the next TRL, and offer recommendations. KeyLogic (NETL site-support contractor) convened a panel of four academic and industry experts* on May 21-22, 2018, to conduct a two-day peer review of four Crosscutting (Sensors and Controls) Program research projects.

TABLE 1. CROSSCUTTING (SENSORS AND CONTROLS) PEER REVIEW – PROJECTS REVIEWED

Project Number	Title	Lead Organization	Total Funding		Project Duration	
			DOE	Cost Share	From	To
FE0031548	High Temperature Electrochemical Sensors for In-Situ Corrosion Monitoring in Coal-Based Power Generation Boilers	West Virginia University	$1,334,953	$341,734	01/01/2018	12/31/2020
FWP-1022427 Tasks 21-24, 32-33	Advanced Sensors and Controls	NETL Research & Innovation Center (RIC)	$3,389,000	$80,000	01/01/2017	03/31/2021
FE0026219	Wireless 3D Nanorod Composite Arrays-Based High-Temperature Surface Acoustic Wave Sensors for Selective Gas Detection Through Machine Learning Algorithms	University of Connecticut	$400,000	$0	09/01/2015	08/31/2018
FE0031550	Technology Maturation of Wireless Harsh-Environment Sensors for Improved Condition-Based Monitoring of Coal-Fired Power Generation	University of Maine System	1,999,703	$504,722	01/11/2018	01/10/2021
			$7,123,656	$926,456		
			$8,050,112			

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

OVERVIEW OF THE PEER REVIEW PROCESS

DOE and NETL are fully committed to improving the quality and results of their research projects. Peer reviews are conducted to help ensure that the Office of Fossil Energy's (FE) research program, implemented by NETL, is compliant with the DOE Strategic Plan and DOE guidance. Peer reviews improve the overall quality of the technical aspects of research and development (R&D) activities, as well as overall project-related activities, such as utilization of resources, project and financial management, and commercialization.

On May 21-22, 2018, KeyLogic convened a panel of four academic and industry experts to conduct a two-day peer review of four research projects supported by the NETL Crosscutting (Sensors and Controls) Program. Throughout the peer review meeting, these recognized technical experts offered recommendations and provided feedback on the projects' technology readiness for work at the current TRL and the planned work to attain the next TRL. In consultation with NETL representatives, who chose the projects for review, KeyLogic selected an independent Peer Review Panel, facilitated the peer review meeting, and prepared this report to summarize the results.

Pre-Meeting Preparation

Before the peer review, each project team submitted a Project Technical Summary (PTS), Technology Maturation Plan (TMP), and project presentation. The appropriate Federal Project Manager (FPM) or Technical Project Lead (TPL) provided the project management plan (PMP) or Field Work Proposal (FWP), the latest quarterly report, and up to three technical papers as additional resources for the panel. The panel received these materials prior to the peer review meeting, which enabled the panel members to fully prepare for the meeting with the necessary background information to thoroughly evaluate the projects.

To increase the efficiency of the peer review meeting, multiple pre-meeting orientation teleconference calls were held with NETL, the Review Panel, and KeyLogic staff to review the peer review process and procedures, evaluation criteria, and project documentation, as well as to allow for the Technology Manager to provide an overview of the program goals and objectives.

Peer Review Meeting Proceedings

At the meeting, each project performer gave a presentation describing the project. The presentation was followed by a question-and-answer session with the panel and a closed panel discussion and evaluation. The time allotted for the presentation, the question-and-answer session, and the closed panel discussion was dependent on the project's complexity, duration, and breadth of scope.

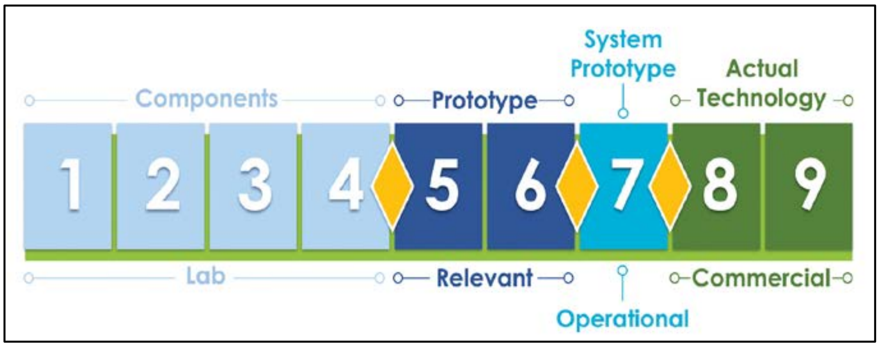
During the closed sessions of the peer review meeting, the panel discussed each project to identify strengths, weaknesses, and recommendations in accordance with the Peer Review Evaluation Criteria. The panel offered prioritized recommendations and an evaluation of TRL gate transition readiness for each project, based on the NETL Peer Review Rating Definitions and Scoring Plan in the Peer Review Evaluation Criteria (more information can be found in Appendix A: Peer Review Evaluation Criteria).

SUMMARY OF KEY FINDINGS

This section summarizes the overall key findings of the projects evaluated at the FY18 Crosscutting (Sensors and Controls) Peer Review Meeting.

Overview: Evaluation of TRL Gate Transition Readiness

NETL identifies key technology development gates as passing from (1) laboratory research to relevant environment research (TRL 4 to 5), (2) relevant environment research to operational system testing (TRL 6 to 7), and (3) operational system testing to successfully commissioned in an operating to commercial system (TRL 7 to 8).



Technology Readiness Levels and Decision Gates (in yellow)

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

- Project FE0031548 has attained a TRL 5. Upon completion of the project and addressing the review panel recommendations, the project will attain a TRL 6 and possibly a TRL 7.
- FWP-1022427 has attained a TRL 2 for three of the four sensors and a TRL 3 for the silica-based temperature sensor. The work appears to be well on schedule and the team has identified the future plans. Upon achievement of the review panel recommendations, FWP-1022427 will attain the planned end-of-project TRLs for each respective sensor technology.
- Project FE0026219 has attained a TRL 3. Upon achievement of the review panel recommendations and the project goals, Project FE0026219 will attain a TRL 4. The review panel indicated this would require NETL approval of a no-cost extension because of the material delay.
- Project FE0031550 has attained a TRL 5 for the temperature sensors. Upon achievement of the project goals and the review panel recommendations, they will attain the planned TRL of 7. Project FE0031550 has attained a TRL 3 for the strain sensors. Upon achievement of the project goals and the review panel recommendations, they will attain the planned TRL of 6-7.

PROJECT SYNOPSES

For more information on the Crosscutting Program and project portfolio (Sensors and Controls), please visit the NETL website: https://www.netl.doe.gov/research/coal/crosscutting/sensors-controls.

FE0031548

HIGH TEMPERATURE ELECTROCHEMICAL SENSORS FOR IN-SITU CORROSION MONITORING IN COAL-BASED POWER GENERATION BOILERS

Xingbo Liu, West Virginia University

Project Description: West Virginia University Research Corporation will refine and validate the effectiveness of their previous electrochemical sensor for high temperature (HT) corrosion in coal-based power generation boilers; optimize the HT sensor; and develop a pathway toward commercialization. Sensors will be tested at two scales: (1) commercial-scale sensors will be optimized specifically for a net 700 MW Amec Foster Wheeler once-through, low-mass flux, vertical tube, Advanced Supercritical (A-USC) boiler and (2) bench-scale sensors will be tested under a range of operating conditions that would serve a variety of coal-fired combustion boilers. A software and a corrosion database will also be developed, enabling operators to interpret sensor data into actionable information.

Beginning TRL: 6

Current TRL: 6

Planned End-of-Project TRL: 7

DOE Funding: $1,334,953

Cost Share: $341,734

Duration: 01/01/2018 to 12/31/2020

FWP-1022427 TASKS 21-24, 32-33
ADVANCED SENSORS AND CONTROLS

Paul Ohodnicki, National Energy Technology Laboratory

Project Description: The Advanced Sensors and Controls Field Work Proposal (FWP) is primarily focused on the development of innovative sensors and controls relevant to improving the efficiency, availability, and environmental performance of fossil energy power generation systems, and carbon capture, utilization, and storage. It also supports the application of advanced diagnostics to challenging fossil energy research problems encountered in the development of transformational fossil energy technologies.

Beginning TRL: 2

Current TRL: 3

Planned End-of-Project TRL: 5

DOE Funding: $3,389,000

Non-DOE Share: $80,000

Duration: 01/01/2017 to 03/31/2021

FE0026219
WIRELESS 3D NANOROD COMPOSITE ARRAYS-BASED HIGH-TEMPERATURE SURFACE ACOUSTIC WAVE SENSORS FOR SELECTIVE GAS DETECTION THROUGH MACHINE LEARNING ALGORITHMS

Yu Lei, University of Connecticut

Project Description: This project aims at developing a wireless integrated gas/temperature microwave acoustic sensor capable of passive operation (no batteries) over the range 350 degrees Celsius to 1,000 degrees Celsius in harsh environments relevant to fossil energy technology, with specific applications to coal gasifiers, combustion turbines, solid oxide fuel cells, and advanced boiler systems. The proposed wireless sensor system is based on a surface-acoustic-wave sensor platform that is configured using a langasite piezoelectric crystal with Pt/Pd interdigital electrodes and yttria-stabilized zirconia films doped with Pd, Pt, or Au nano-catalysts to detect H_2, O_2, and NO_X gases and to also monitor the gas temperature in the harsh environment. Fully packaged prototype sensors will be designed, fabricated, and tested under gas flows of H_2 (<5 percent), O_2, and NO_X in laboratory furnaces, and the sensor response will be characterized for sensitivity, reproducibility, response time, and reversibility over a range of gas temperatures.

Beginning TRL: 1

Current TRL: 3

Planned End-of-Project TRL: 4

DOE Funding: $400,000

Cost Share: $0

Duration: 09/01/2015 to 08/31/2018

FE0031550

TECHNOLOGY MATURATION OF WIRELESS HARSH-ENVIRONMENT SENSORS FOR IMPROVED CONDITION-BASED MONITORING OF COAL-FIRED POWER GENERATION

Mauricio Pereira da Cunha, University of Maine System

Project Description: The University of Maine will develop, adapt, implement, test, and transition wireless harsh-environment surface acoustic wave (SAW) sensor technology in coal-fired power plants. The technology offers several potential advantages for inline monitoring of coal-based power generation systems including accurate, battery-free, maintenance-free wireless operation. The small footprint will potentially allow flexible sensor placement and embedding of multiple sensor arrays into a variety of components that can be sampled with a near-by interrogating antenna and radio frequency signal processing unit. The temperature and/or strain measurements acquired from wireless SAW sensors represent critical data for actively monitoring the health condition and detecting failures in boiler tubes, headers, and piping at several key locations in coal-based power generation facilities. Expected outcomes include a matured technology; advancements in the packaging of SAW sensors and antennas to allow long-term robust operation; refined wireless communications protocols and signal processing; improved thin films and sensor packaging; and prototype static and dynamic strain SAW sensors. The University of Maine will install and test their resulting prototype wireless sensor systems at a solid-waste-to-energy plant and a coal-fired power plant.

Beginning TRL: 5[a] and 3[b]

Current TRL: 5[a] and 3[b]

Planned End-of-Project TRL: 7[a] and 6-7[b]

DOE Funding: $1,999,703

Cost Share: $504,722

Duration: 01/11/2018 to 01/10/2021

[a] Temperature Sensor [b] Strain Sensor

APPENDIX A: PEER REVIEW EVALUATION CRITERIA

PEER REVIEW EVALUATION CRITERIA AND GUIDELINES

Peer reviews are conducted to ensure that the Office of Fossil Energy's (FE) research program, implemented by the National Energy Technology Laboratory (NETL), is compliant with the U.S. Department of Energy (DOE) Strategic Plan and DOE guidance. Peer reviews improve the overall quality of the technical aspects of research and development (R&D) activities, as well as overall project-related activities, such as utilization of resources, project and financial management, and commercialization.

In the upcoming NETL peer review, a significant amount of information about the projects within its portfolio will be covered in a short period. For that reason, NETL has established a set of rules for governing the meeting so that everyone has an equal chance to accurately present their project accomplishments, issues, recent progress, and expected results for the remainder of the performance period (if applicable).

The following pages contain the criteria used to evaluate each project. Each criterion is accompanied by multiple characteristics to further define the topic. Each reviewer is expected to independently assess all the provided material for each project prior to the meeting and engage in discussion to generate feedback for each project during the meeting.

Technology Readiness Level (TRL)-Based Evaluation

At the meeting, the Facilitator and/or Panel Chairperson will lead the Peer Review Panel in assessing a project's readiness to start work towards the next TRL based on a project's strengths[†], weaknesses[‡], recommendations, issues, and concerns. NETL identifies key technology development gates as passing from (1) laboratory research to relevant environment research (Technology Readiness Level [TRL] 4 to 5), (2) relevant environment research to operational system testing (TRL 6 to 7), and (3) operational system testing to successfully commissioned in an operating to commercial system (TRL 7 to 8). NETL TRL definitions are included below.

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

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

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

NETL Peer Review Evaluation Criteria
1. Degree to which the project, if successful, supports the DOE Program's near- and/or long-term goals.
• Program goals are clearly and accurately stated. • Performance requirements[1] support the program goals. • The intended commercial application is clearly defined. • The technology is ultimately technically and economically viable for the intended commercial application.
2. Degree to which there are sufficient resources to successfully complete the project.
• There is adequate funding, facilities, and equipment. • Project team includes personnel with the needed technical and project management expertise. • The project team is engaged in effective teaming and collaborative efforts, as appropriate.
3. Degree of project plan technical feasibility.
• Technical gaps, barriers, and risks to achieving the performance requirements are clearly identified. • Scientific/engineering approaches have been designed to overcome the identified technical gaps, barriers, and risks to achieve the performance requirements. • Remaining technical work planned is appropriate considering progress to date and remaining schedule and budget. • Appropriate risk mitigation plans exist, including Decision Points when applicable.
4. Degree to which progress has been made towards achieving the stated performance requirements.
• The project has tested (or is testing) those attributes appropriate for the next TRL. The level of technology integration and nature of the test environment are consistent with the aforementioned TRL definition. • Project progress, with emphasis on experimental results, shows that the technology has, or is likely to, achieve the stated performance requirements for the next TRL (including those pertaining to capital cost, if applicable). • Milestones and reports effectively enable progress to be tracked. • Reasonable progress has been made relative to the established project schedule and budget.
5. Degree to which an appropriate basis exists for the technology's performance attributes and requirements.
• The Technology Readiness Level (TRL) to be achieved by the end of the project is clearly stated[2]. • Performance attributes for the technology are defined[2]. • Performance requirements for each performance attribute are, to the maximum extent practical, quantitative, clearly defined, and appropriate for and consistent with the DOE goals as well as technical and economic viability in the intended commercial application.
6. The project Technology Maturation Plan (TMP) represents a viable path for technology development beyond the end of the current project, with respect to scope, timeline, and cost.
[1] If it is appropriate for a project to not have cost/economic-related performance requirements, then the project will be evaluated on technical performance requirements only. [2] Supported by systems analyses appropriate to the targeted TRL. See Systems Analysis Best Practices.

APPENDIX B: NETL TECHNOLOGY READINESS LEVELS

NETL Technology Readiness Levels

The National Energy Technology Laboratory (NETL) supports a wide range of research, development, and demonstration (RD&D) projects, from small, short-duration materials development and property characterization projects up to large-scale power plant demonstrations. The nature and complexity of the technology under development will have implications for the application of the Technology Readiness concept, particularly with respect to supporting systems analysis requirements.

Accompanying the Technology Readiness Level (TRL) definitions and descriptions provided in the table below are Systems Analysis Best Practices. These Best Practices serve as a critical resource to guide the identification of performance attributes and to establish corresponding performance requirements for a given technology which are, in turn, tied to the intended commercial application and higher-level goals (e.g., program goals). A systems analysis is carried out to estimate the performance and cost of the technology based on the information (e.g., experimental data) that is expected to be available at a particular TRL. The results, when compared with conventional technology, are used to inform the next stage of development and provide specific experimental and analysis success criteria (the performance requirements). The performance requirements that may be appropriately tested at a particular TRL must be substantially met, thereby supporting the feasibility of commercial success/goal achievement, prior to proceeding to the subsequent TRL. Note that, as with the TRL descriptions, these Systems Analysis Best Practices are "gate-in"; that is, prerequisites to achieving the associated TRL.

The scope of the project must be taken into account when applying the Systems Analysis Best Practices – they may not be strictly applicable as written to each project. For example, it is an unreasonable expectation for a project developing a sensor, or fuel cell cathode, or thermal boundary coating for a turbine airfoil to perform a full-scale power plant simulation to determine the performance requirements of the specific technology in the course of pursuing TRL 4. However, the project must explicitly tie the quantitative goals/objectives for the technology to referenced system studies as well as relevant industry and/or market requirements in such a manner that their pedigree is readily traceable. Science and Technology (S&T)/Technology Development and Integration Center (TDIC) management must ensure that this occurs through language in the Funding Opportunity Announcement (FOA) topic (and in the subsequent project Statement of Project Objectives [SOPO]/Project Management Plan [PMP]/Technology Maturation Plan [TMP]).

TRL	Definition	Description	Systems Analysis Best Practices
1	**Basic principles observed and reported**	Core Technology Identified. Scientific research and/or principles exist and have been assessed. Translation into a new idea, concept, and/or application has begun.	Assessment: Perform an assessment of the core technology resulting in (qualitative) projected benefits of the technology, a summary of necessary R&D needed to develop it into the actual technology, and principles that support of the viability of the technology to achieve the projected benefits.
2	**Technology concept and/or application formulated**	Invention Initiated. Analysis has been conducted on the core technology for practical use. Detailed analysis to support the assumptions has been initiated. Initial performance attributes have been established.	White Paper: A white paper describing the intended commercial application, the anticipated environment the actual technology will operate in, and the results from the initiation of a detailed analysis (that will at least qualitatively justify expenditure of resources versus the expected benefits and identify initial performance attributes).
3	**Analytical and experimental critical function and/or characteristic proof-of-concept validated**	Proof-of-Concept Validated. Performance requirements that can be tested in the laboratory environment have been analytically and physically validated. The core technology should not fundamentally change beyond this point. Performance attributes have been updated and initial performance requirements have been established.	Performance Model and Initial Cost Assessment: This performance model is a basic model of the technology concept, incorporating relevant process boundary conditions, that provides insight into critical performance attributes and serves to establish initial performance requirements. These may be empirically- or theoretically-based models represented in Excel or other suitable platforms. In addition, an initial assessment and determination of performance requirements related to cost is completed.
4	**Basic technology components integrated and validated in a laboratory environment**	Technology Validated in a Laboratory Environment. The basic technology components have been integrated to the extent practical (a relatively low-fidelity integration) to establish that key pieces will work together, and validated in a laboratory environment. Performance attributes and requirements have been updated.	System Simulation and Economic Analysis: These models incorporate a performance model of the technology (may be a simple model as developed for TRL 3, or something more detailed – either should be validated against empirical data gathered in the laboratory) into a model of the intended commercial system (e.g., power plant). In addition, an economic analysis (e.g., cost-of-electricity) of the technology is performed, assessing the impact of capital costs, operating and maintenance costs, and life on the impact of the technology and its contributions to the viability of the overall system in a commercial environment. These analyses serve to assess the relative impact of known performance attributes (through sensitivity analyses) and refine performance requirements in the context of established higher-level technical and economic goals (e.g., programmatic or DOE R&D goals). These models are typically created in process simulation software (e.g., ASPEN Plus) or other suitable platforms. DOE maintains guidance on the execution of techno-economic analyses [1].

TRL	Definition	Description	Systems Analysis Best Practices
5	**Basic technology components integrated and validated in a relevant environment**	Technology Validated in a Relevant Environment. Basic technology component configurations have been validated in a relevant environment. Component integration is similar to the final application in many respects. Data sufficient to support planning and design of the next TRL test phase have been obtained. Performance attributes and requirements have been updated.	System Simulation and Economic Analysis Refinement: A more detailed process model for the technology, validated against empirical data gathered in the laboratory, will be developed and incorporated into system simulations. This provides greater fidelity in the performance and cost estimation for the technology, facilitating updates to performance attributes and requirements (including updates to the economic analysis). This also allows greater evaluation of other process synergy claims (e.g., state-of-the-art technology is improved by the use of the new technology). Cost estimation should be either vendor-based or bottom-up costing approaches for novel equipment.
6	**Prototype validated in a relevant environment**	Prototype Validated in Relevant Environment. A prototype has been validated in a relevant environment. Component integration is similar to the final application in most respects and input and output parameters resemble the target commercial application to the extent practical. Data sufficient to support planning and design of the next TRL test phase have been obtained. Performance attributes and requirements have been updated.	System Simulation and Economic Analysis Refinement: Performance and cost models are refined based upon relevant environment laboratory results, leading to updated performance attributes and requirements. Preliminary steady-state and dynamic (if appropriate for the technology) modeling of all critical process parameters (i.e., upper and lower operating limits) of the system prototype is completed. Cost estimation should be either vendor-based or bottom-up costing approaches for novel equipment. Key process equipment should be specified to the extent that allows for bottom-up estimating to support a feasibility study of the integrated system.
7	**System prototype validated in an operational system**	System Prototype Validated in Operational Environment. A high-fidelity prototype, which addresses all scaling issues practical at pre-demonstration scale, has been built and tested in an operational environment. All necessary development work has been completed to support Actual Technology testing. Performance attributes and requirements have been updated.	System Simulation and Economic Analysis Refinement: Performance and cost models are refined based upon relevant environment and system prototype R&D results. The refined process, system and cost models are used to project updated system performance and cost to determine if the technology has the potential to meet the project goals. Performance attributes and requirements are updated as necessary. Steady-state and dynamic modeling all critical process parameters of the system prototype covering the anticipated full operation envelope (i.e., upper and lower operating limits) is completed. Cost models should be based on vendor quotes and traditional equipment estimates should be minimal.

TRL	Definition	Description	Systems Analysis Best Practices
8	**Actual technology successfully commissioned in an operational system**	Actual Technology Commissioned. The actual technology has been successfully commissioned for its target commercial application, at full commercial scale. In almost all cases, this TRL represents the end of true system development.	System Simulation and Economic Analysis Validation: The technology/system process models are validated by operational data from the demonstration. Economic models are updated accordingly.
9	**Actual technology operated over the full range of expected operational conditions**	Commercially Operated. The actual technology has been successfully operated long-term and has been demonstrated in an operational system, including (as applicable) shutdowns, startups, system upsets, weather ranges, and turndown conditions. Technology risk has been reduced so that it is similar to the risk of a commercial technology if used in another identical plant.	Commercial Use: Models are used for commercial scaling parameters.

[1] *Performing a Techno-Economic Analysis for Power Generation Plants, DOE/NETL-2015/1726, July 2015.*

Glossary of Terms

Actual Technology: The final product of technology development that is of sufficient size, performance, and reliability—ready for use at the target commercial application. The technology is at Technology Readiness Levels (TRLs) 8–9.

Basic Technological Components Integrated: A test apparatus that ranges from (1) the largest, most integrated and/or most realistic technology model that can reasonably be tested in a laboratory environment, to (2) the lowest-cost technology model that can be used to obtain useful data in a relevant environment.

Commissioning/Commission: The actual system has become operational at target commercial conditions and is ready for commercial operations.

Concept and/or Application: The initial idea for a new technology or a new application for an existing technology. The technology is at TRLs 1–3.

Core Technology: The idea, new concept, and/or new application that started the research and development (R&D) effort. Examples include: (1) a new membrane material, sorbent, or solvent; (2) new software code; (3) a new turbine component; (4) the use of a commercial sensor technology in more durable housing; or (5) the use of a commercial enhanced oil recovery technology to store CO_2. Typically, this is a project's intellectual property.

Economic Analysis: The process of estimating and assigning costs to equipment, subsystems, and systems, corresponding to models of and specifications for the commercial embodiment of the technology. Such analyses include the estimation of capital costs, as well as operating and maintenance costs. Component service life and corresponding replacement costs are often a crucial aspect of these analyses. *See Performing a Techno-Economic Analysis for Power Generation Plants, DOE/NETL-2015/1726, July 2015,* for further guidance.

Fidelity: The extent to which a technology and its operating environment/conditions resemble that of the target commercial application.

Integrated: The functional state of a system resulting from the process of bringing together one or more technologies or subsystems and ensuring that each function together as a system.

Laboratory Environment: An environment isolated from the commercial environment in which lower-cost testing is performed to obtain high-quality, fundamental data at earlier TRLs. For software development, this is a small-scale, simplified domain for a software mockup.

Operational System: The environment in which the technology will be tested as part of the target commercial application.

Performance Attributes: All aspects of the technology (e.g., flux, selectivity, life, durability, cost, etc.) that must be tested or otherwise evaluated to ensure that the technology will function in the target commercial application, including all needed support systems. Systems analysis may assist in the identification of relevant performance attributes. It is likely that the performance attributes list will increase as the technology matures. Performance attributes must be updated as new information is received and formally reviewed at each TRL transition.

Performance Requirements: Criteria that must be met for each performance attribute before the actual system can be used at its target commercial application. These will be determined, typically via systems analysis, in consideration of program goals, requirements for market competitiveness for the target commercial application, etc. Performance requirements may change over time, and it is unlikely that all of them will be known at a low TRL.

Program: The funding program. The program goals will be used to judge project value and, in concert with systems analysis, will support acceptable performance requirements for the project. The funding program will also determine whether the system will be tested under one or several sets of target commercial applications.

Project: The funding mechanism for technology development, which often spans only part of the technology development arc. Some projects may contain aspects that lack dependence; these may have different TRL scores, but this must be fully justified.

Proof-of-Concept: Reasonable conclusions drawn through the use of low-fidelity experimentation and analysis to validate that the new idea, and resulting new component and/or application, has the potential to lead to the creation of an actual system.

Prototype: A test apparatus necessary to thoroughly test the technology, integrated and realistic as much as practical, in the applicable TRL test environment.

Relevant Environment: More realistic than a laboratory environment, but less costly to create and maintain than an operational environment. This is a relatively flexible term that must be consistently defined by each program (e.g., in software development, this would be "beta testing").

Systems Analysis: The analytic process used to evaluate the behavior and performance of processes, equipment, subsystems, and systems. Such analyses serve to characterize the relationships between independent (e.g., design parameters and configurations, material properties, etc.) and dependent variables (e.g., thermodynamic state points, output, etc.) through the creation of models representative of the envisioned process, equipment, subsystem, or system. These analyses are used to determine the variables important to desired function in the target commercial application (i.e., performance attributes) and the associated targets that must be achieved through R&D and testing to realize program and/or commercial goals (i.e., performance requirements). Models and simulations may use a variety of tools, such as Excel, Aspen Plus, Aspen Plus Dynamics, etc., depending upon the scope of the development effort and the stage of development. *See Performing a Techno-Economic Analysis for Power Generation Plants, DOE/NETL-2015/1726, July 2015,* for further guidance.

Systems Analysis Best Practices: These best practices serve as a guide for the level of systems and economic analysis rigor and level of effort appropriate for each TRL. The scope of the project (the subject and nature of the technology under development) must be considered when applying these best practices. For example, the analytical effort associated with the development of a thermal barrier coating is quite different than that appropriate to the development of a post-combustion CO_2 capture system.

Target Commercial Application: This refers to one specific use for the actual system, at full commercial scale, which supports the goals of the funding program. A project may include more than one set of target commercial applications. Examples are:

1. Technologies that reduce the cost of gasification may be useful for both liquid fuels and power production.
2. Technologies that may be useful to monitor CO_2 storage in more than one type of storage site.

Technology: The idea, new concept, and/or new application that started the R&D effort plus other R&D work that must be done for the project's core technology to translate into an actual system.

Technology Aspects: Different R&D efforts, both within and external to any given project. Examples include material development, process development, process simulation, contaminant removal/control, and thermal management.

Validated: The proving of all known performance requirements that can reasonably be tested using the test apparatus of the applicable TRL.

APPENDIX C: MEETING AGENDA

Crosscutting (Sensors and Controls) Peer Review
May 21-22, 2018
NETL-Pittsburgh Building 922 Room 106A

Monday, May 21, 2018

8:00 a.m.	Arrive at the NETL-Pittsburgh Entrance Gate for Security Check
8:15 – 8:30 a.m.	Escort Visitors to NETL-Pittsburgh Building 922 Room 106A
8:30 – 9:00 a.m.	Peer Review Panel Kickoff Session - Welcome, Introductions, Peer Review Process, and Meeting Logistics
9:00 – 9:45 a.m.	Project FE0031548 – High Temperature Electrochemical Sensors for In-Situ Corrosion Monitoring in Coal-Based Power Generation Boilers *Xingbo Liu* – West Virginia University
9:45 – 10:30 a.m.	Question and Answer Session
10:30 – 10:45 a.m.	BREAK
10:45 – 12:00 p.m.	Closed Discussion (TRL-Based Evaluation; Review Panel) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
12:00 – 1:00 p.m.	Lunch (onsite cafeteria; cash only, orders will be placed in the morning)
1:00 – 1:45 p.m.	Project FWP-1022427 Tasks 21-24, 32, 33 – Advanced Sensors and Controls *Paul Ohodnicki* – NETL
1:45 – 2:30 p.m.	Question and Answer Session
2:30 – 2:45 p.m.	BREAK
2:45 – 4:00 p.m.	Closed Discussion (TRL-Based Evaluation; Review Panel) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
4:00 p.m.	Adjourn

Tuesday, May 22, 2018

8:00 a.m.	Arrive at the NETL-Pittsburgh Entrance Gate for Security Check
8:15 – 8:30 a.m.	Escort Visitors to NETL-Pittsburgh Building 922 Room 106A
8:30 – 9:15 a.m.	Project FE0026219 – Wireless 3D Nanorod Composite Arrays-Based High-Temperature Surface Acoustic Wave Sensors for Selective Gas Detection Through Machine Learning Algorithms – University of Connecticut *Yu Lei* – University of Connecticut
9:15 – 10:00 a.m.	Question and Answer Session
10:00 – 10:15 a.m.	BREAK
10:15 – 11:30 a.m.	Closed Discussion (TRL-Based Evaluation; Review Panel) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
11:30 – 12:00 p.m.	Lunch (onsite cafeteria; cash only, orders will be placed in the morning)
12:00 – 12:45 p.m.	Project FE0031550 – Technology Maturation of Wireless Harsh-Environment Sensors for Improved Condition-Based Monitoring of Coal-Fired Power Generation *Mauricio Pereira da Cunha* – University of Maine System
12:45 – 1:30 p.m.	Question and Answer Session
1:30 – 1:45 p.m.	BREAK
1:45 – 3:00 p.m.	Closed Discussion (TRL-Based Evaluation; Review Panel) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
3:00 – 3:30 p.m.	Peer Review Panel Wrap-Up Session
3:30 p.m.	Adjourn

APPENDIX D: PEER REVIEW PANEL MEMBERS

Crosscutting (Sensors and Controls) Peer Review
May 21-22, 2018
NETL-Pittsburgh Building 922 Room 106A

Ronald Griebenow

Ronald Griebenow is an Executive Consultant for Woyshner Services Company, Inc. He has more than 30 years of experience in power plant reliability, performance improvement, and operations training for the electric power industry. Mr. Griebenow spent more than nine years as a Director with GP Strategies Corporation, primarily in a business development role helping to define and implement equipment condition and plant performance monitoring and diagnostic projects. He was also one of the instructors for GP's Performance Knowledge Series training courses and managed several large performance improvement projects. Mr. Griebenow joined GP Strategies through the acquisition of Performance Consulting Services (PCS), where he was the President and a co-founder. PCS specialized in engineering support, training, and software products directed toward increasing plant performance and availability, optimizing manpower usage, and reducing overall operating costs.

In addition to his responsibilities for corporate management and business development for PCS, Mr. Griebenow spent eight years on contract to the Electric Power Research Institute (EPRI) as the Director of EPRI's Fossil Plant Simulator and Training Center. His responsibilities included development and management of the Center, management of EPRI fossil plant simulator and training projects, and technology transfer to EPRI member utilities. Mr. Griebenow received a B.S. in Mechanical Engineering from the University of Idaho. He is a member of the American Society of Mechanical Engineers (ASME), a member of ASME's Committee for Certification of Operators of High Capacity Fossil Fuel Fired Plants and the Performance Test Codes (PTC) 100 Standards Committee, and a registered Professional Engineer in the state of South Carolina.

Aaron Hussey

Aaron Hussey is an experienced professional with a project engineering, project management, and continual improvement background in many industries, including manufacturing, fossil power, and nuclear power. He is the Founder & Principal of Integral Analytics, which combines analytic techniques with machinery knowledge inside of existing industrial equipment and business processes with a current focus on power generation assets. He also served as the Director of the International Society of Automation (ISA) – Power Industry Division (POWID). He is currently serving as the Fleet M&D Track Chair and Marketing Coordinator for ISA POWID 2018. Previously, he has served as the Vice President of Technical Services at Expert Microsystems, as a Senior Project Manager at Electric Power Research Institute (EPRI), and as a Production Engineer at TURBOCAM International. He received his B.S. in Mechanical Engineering from the University of North Carolina.

Xinsheng Lou, Ph.D.

Dr. Xinsheng Lou is currently a Technology and R&D Group Manager at GE Power, working on steam power. Previously, he has worked as a Technology Manager and Technical Expert for ALSTOM Power Plant Laboratories, where he led R&D projects on fossil power system modeling, diagnostics, controls, and optimization.

Dr. Lou majored in Thermal Energy and Power Engineering, receiving a B.S. from the Power Engineering Department at Southeast University (Nanjing, China) in 1990, and an M.S. and a Ph.D. from the Stake Key Laboratory on Coal Combustion (SKLCC) and Huazhong University of Science and Technology (Wuhan, China) in 1993 and 1996, respectively. From August 1996 to August 1997, he conducted research on gas turbine diagnostics in the Energy Conversion Lab at Nanyang Technological University (Singapore). He also holds a Ph.D. in Systems and Controls Engineering under Electrical Engineering and Computer Science (EECS), which was awarded by Case Western Reserve University (Cleveland, Ohio, USA) in 2000.

Dr. Lou has published more than 30 papers and issued many research reports and patents/patent disclosures. He is a Senior Member of the Institute for Electrical and Electronics Engineers (IEEE), affiliated with the Societies of Energy and Power, Control Systems, Computational Intelligence, and Engineering Management. He is also a Director of the International Society of Automation (ISA) – Power Industry Division (POWID), and served as session developer and chaired multiple sessions for ISA POWID 2009. He serves as an industrial advisor for multiple universities in the United States.

Michael von Spakovsky, Ph.D.

Dr. Michael von Spakovsky has more than 30 years of teaching and research experience in academia and more than 17 years of industry experience in mechanical engineering, power utility systems, aerospace engineering, and software engineering. He received his B.S. in Aerospace Engineering in 1974 from Auburn University and his M.S. and Ph.D. in Mechanical Engineering in 1980 and 1986, respectively, from the Georgia Institute of Technology. While at Auburn, Dr. von Spakovsky worked for three and a half years at the National Aeronautics and Space Administration (NASA) in Huntsville, Alabama, and from 1974 to 1984 and from 1987 to 1989, worked in the power utility industry, first as an engineer and then as a consultant. From 1989 to 1996, Dr. von Spakovsky worked as both an educator and researcher at the Swiss Federal Institute of Technology in Lausanne, Switzerland, where he led a research team in the modeling and systems integration of complex energy systems and taught classes in the thermodynamics of indirect and direct energy conversion systems (including fuel cells).

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