NATIONAL ENERGY TECHNOLOGY LABORATORY

FY19 GASIFICATION PEER REVIEW OVERVIEW REPORT

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

DISCLAIMER

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INTRODUCTION AND BACKGROUND

The U.S. Department of Energy (DOE) Gasification Program is developing small-scale revolutionary modular designs for converting diverse types of coal into clean synthesis gas (syngas) to enable the low-cost production of electricity, high-value chemicals, hydrogen, transportation fuels, and other useful products to suit market needs. Advancements will help enable advanced power generation and other syngas-based technologies to be competitive in both domestic and international markets and to spur the use of abundant domestic coal resources, in turn contributing toward increased energy security and reviving depressed markets in traditional coal-producing regions of the United States.

The research and development (R&D) efforts of the Gasification Program apply to four key technology areas, which contribute towards increased efficiency and cost reductions of modular gasification/syngas-based systems. These four technology areas are (1) Air Separation, (2) Reactor Engineering Design, (3) Market-Optimized Design, and (4) Systems Integration.

- Air Separation focuses on the identification of new concepts and technologies for production of oxygen for use in gasification systems.
- The Reactor Engineering Design key technology area addresses the control of chemical reactions in increasingly modular and intrinsically efficient reactors, allowing for smaller reactors and streamlined processes, with a focus on conversion of coal into syngas.
- Market-Optimized Design concerns designs and strategies for modular gasification-based energy conversion plants, which can be flexibly right-sized, configured, and sited for local coal, waste coal and coal fines, and biomass blending for feedstock conversion to high-value marketable products.
- Systems Integration focuses on increasing the availability, reliability, efficiency, and flexibility of integrated gasification-based systems, which will result in improved overall performance and lowered costs.

In response to market needs for maximum flexibility at minimized costs, the program is centered on the idea of advanced modular gasification-based systems, with goals/objectives to advance the science, engineering, design, and technology for construction of advanced, modular coal conversion plants. The flexibility of modular configurations enables their deployment in a wide range of sites and applications that would not be practicable or cost-effective for a traditional, large-scale coal power plant.

It is expected that reaction intensification, innovative fabrication of reactor components, advanced materials and manufacturing methods, and increasingly sophisticated modeling and simulation will underpin the development of modular technology for using coal more efficiently to create more valuable end products from coal and other opportunity feedstocks.

Office of Management and Budget Requirements

In compliance with requirements from the Office of Management and Budget, DOE and the National Energy Technology Laboratory (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 2019 (FY19) Gasification Peer Review Meeting with independent technical experts to offer recommendations to strengthen projects during the period of performance and assess one project's technology readiness for work at the current Technology Readiness Level (TRL) and the planned work to attain the next TRL. KeyLogic (NETL site-support contractor) convened a panel of four academic and industry experts[*] on November 5-6, 2018, to conduct a peer review of six Gasification Program research projects.

TABLE 1. GASIFICATION PEER REVIEW – PROJECTS REVIEWED

Project Number	Title	Lead Organization	Total Funding		Project Duration	
			DOE	Cost Share	From	To
FE0031522	Advance Syngas Cleanup for Radically Engineered Modular Systems (REMS)*	Research Triangle Institute	$1,598,983	$399,745	12/1/2017	12/31/2019
FE0027995	Oxygen Binding Materials and Highly Efficient Modular System for Oxygen Production*	Research Triangle Institute	$1,999,526	$499,882	10/1/2016	6/30/2019
FE0031527	Pilot Testing of a Modular Oxygen Production System Using Oxygen Binding Adsorbents*	Research Triangle Institute	$3,000,000	$799,342	12/1/2017	11/30/2020
FE0028002	Low-Cost Oxygen (LCO) for Small-Scale Modular Gasification Systems*	Thermosolv LLC	$2,000,000	$500,000	10/1/2016	3/31/2019
FE0031528	Advanced Sorbents for Modular Oxygen Production for Radically Engineered Modular Systems (REMS) Gasifiers*	Thermosolv LLC	$1,571,031	$403,904	12/1/2017	11/30/2019
FE0012062	Dry Solids Pump Coal Feed Technology Program**	Gas Technology Institute	$5,428,067	$3,327,043	10/1/2013	9/30/2018
			$15,597,607	$5,929,916		
			$21,527,523			

* Recommendations-Based Evaluation: During recommendations-based evaluations, the independent panel provides recommendations to strengthen the performance of projects during the period of performance.

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

[*] 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 R&D activities, as well as overall project-related activities, such as utilization of resources, project and financial management, and commercialization.

On November 5-6, 2018, KeyLogic convened a panel of four academic and industry experts to conduct a peer review of six research projects supported by the NETL Gasification Program. Throughout the peer review meeting, these recognized technical experts offered recommendations to strengthen the projects during the remaining period of performance and assess one project's 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) and project presentation[†]. The appropriate Federal Project Manager (FPM) provided the Project Management Plan (PMP), the latest quarterly report, and up to three technical papers as additional resources for the panel (as applicable). The panel received these materials prior to the peer review meeting, which enabled the panel members to fully prepare for the meeting with the necessary background information to thoroughly evaluate the projects.

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

† Project FE0012062 (Dry Solids Pump Coal Feed Technology Program) also submitted a Technology Maturation Plan (TMP) to facilitate a TRL-based evaluation from the Peer Review Panel (reference Table 1).

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. For five of the projects (identified in Table 1), the panel offered a series of prioritized recommendations to strengthen the projects during the remaining period of performance and assigned each project a score based on the NETL Peer Review Rating Definitions and Scoring Plan in the Peer Review Evaluation Criteria[‡]. For the final project (Project FE0012062 "Dry Solids Pump Coal Feed Technology Program"), the panel offered prioritized recommendations and an evaluation of TRL gate transition readiness.

‡ Please see "Appendix A: Peer Review Evaluation Criteria Form" for more information.

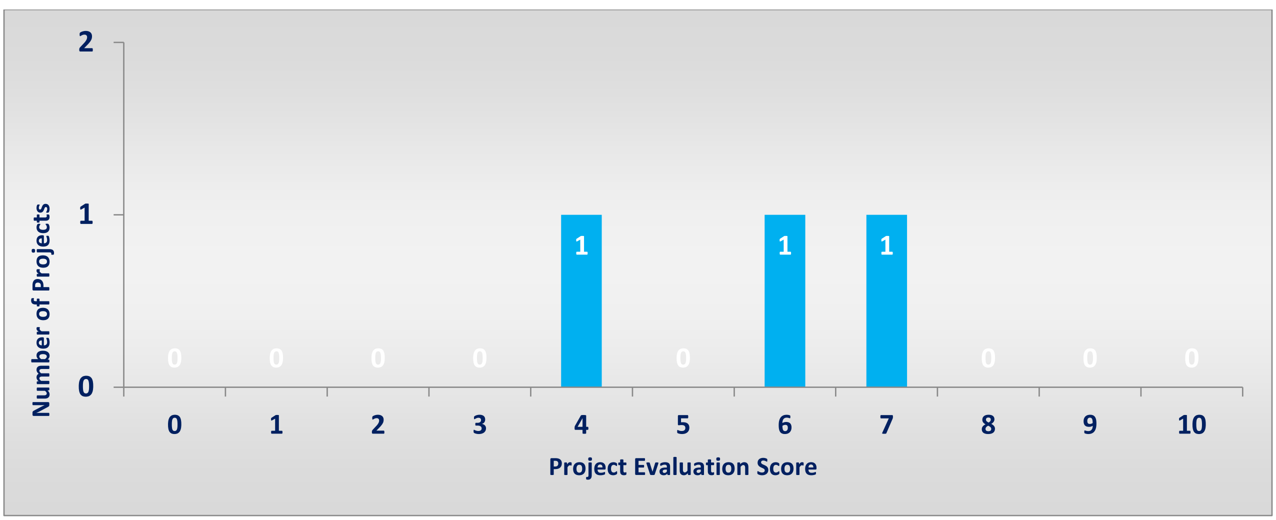
SUMMARY OF KEY FINDINGS

This section summarizes the overall key findings of the projects evaluated at the FY19 Gasification Peer Review Meeting. The panel concluded that the peer review provided an excellent opportunity to comment on the relative strengths and weaknesses of each project. The presentations and question and answer sessions provided additional clarity to complement the pre-meeting documentation. The peer review also provided an insight into the range of technology development and the relative progress that has been made by the project teams. The technical discussion enabled the panel to contribute to each project's development by identifying core issues and by making constructive recommendations to improve project outcomes. The panel generated 17 recommendations for NETL management to review and consider for incorporation into a project's Statement of Project Objectives or Statement of Work as a peer review milestone.

Overview of Project Evaluation Scores (Recommendations-Based Evaluations)

The panel assigned a score for each project subject to a recommendations-based evaluation (reference Table 1), based on the following definitions. A rating of five or higher indicates that a specific project was viewed as at least adequate by the panel. The panel was permitted to assign any integer value ranging from 0 to 10. For the three projects subject a recommendations-based evaluation, the panel assigned scores ranging from four to seven.

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



FY19 Gasification Peer Review Project Evaluation Scores

General Project Strengths (Recommendations-Based Evaluations)

The panel was impressed by the quality of the Gasification Program projects they reviewed. They indicated that the projects represent significant potential for the development of gasification technologies that can be scaled down to modularization to support program goals using the Radically Engineered Modular Systems (REMS) concept. The panel was optimistic about the potential for these projects to further progress toward achieving DOE's challenging goals and continuing along the pathway to commercial application. The following are noteworthy project strengths from the panel members that relate to one or more projects:

- Taking the necessary steps to validate the potential application of the technology for REMS, such as thermogravimetric analysis (TGA), kinetics, and hot and cold flow testing.
- Establishing a project goal to meet or exceed the NETL requirements for competing with a large cryogenic air separation plant.
- Developing new and promising cobalt-based sorbents for a wide range of adsorption processes, including pressure swing adsorption (PSA), temperature swing adsorption (TSA), and pressure-temperature swing adsorption (PTSA).
- Successfully developing the composition and physical form for a cobalt-free sorbent that operates at a reasonable temperature and meets the project's sorbent criterion of 0.5 percent by weight oxygen (O_2).

General Project Weaknesses (Recommendations-Based Evaluations)

Observations that panel members noted as project weaknesses included the following:

- There is no defined cost savings for REMS scale (1 to 5 MWe) relative to the current state-of-the-art technology.
- There is no complete design basis and functional specification that supports the techno-economic analysis (TEA), including: flows, conditions, and compositions (including trace constituents; e.g., arsenic [As], mercury [Hg], selenium [Se], hydrogen cyanide [HCN]) in and out; design or expected availability; operation and maintenance costs; and complete operating envelope (i.e., steady/non-steady state).
- The absence of an accelerated sorbent life testing protocol makes the TEA cost performance predictions uncertain.
- There is an inadequate scale-up protocol from 0.011 to 0.022 tons O_2/day to the modular scale of 10 to 50 tons O_2/day.

General Project Observations and Recommendations (Recommendations-Based Evaluations)

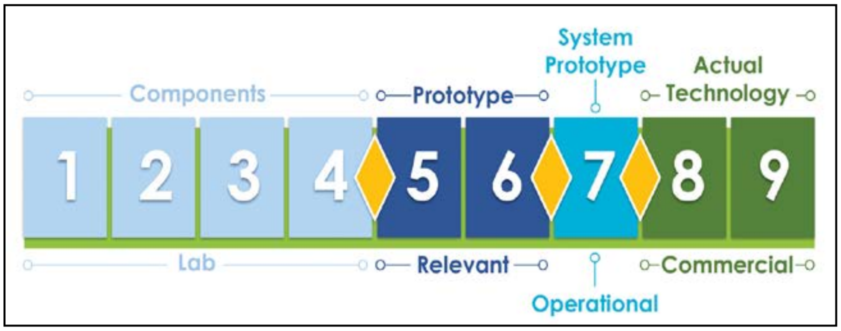
The panel members offered recommendations that were technical in nature and specific to each particular project's technology or approach. The panel's recommendations addressed the weaknesses and offered suggestions to further improve upon project accomplishments. Panel recommendations included:

- Determine the cost/performance for a modularized package that would support 1- to 5-MW power production.
- Complete a design basis and functional specification that supports the TEA, including: flows, conditions, and compositions (including traces; e.g., As, Hg, Se, HCN) in and out; design or expected availability; operation and maintenance costs; and complete operating envelope (i.e., steady/non-steady state).

- Create an accelerated sorbent life testing protocol.
- Develop a protocol for a scale-up from 0.011 to 0.022 tons O_2/day to modularized 10 to 50 tons O_2/day.

Evaluation of TRL Gate Transition Readiness (TRL-Based Evaluation)

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)

The panel assessed one project's readiness to start work towards the next TRL based on the project's strengths, weaknesses, recommendations, issues, and concerns (reference Table 1). For the project subject to a TRL-based evaluation, the panel stated that the technology has attained TRL 5. The technology will attain TRL 6 after validating the Side Exit Upward Discharge (SEUD) at full scale for a variety of feedstocks, feed rates, and operating pressures for a reasonable time. Following the achievement of the panel's four recommendations and completing an extended time test for a minimum of 50 hours; providing resources to complete any additional extended time testing as may be required for customer acceptance; credibly modeling the full-scale commercial system, subject to acceptance by a customer; and determining the ability to integrate with a selection of gasifiers, the technology will attain TRL 7.

PROJECT SYNOPSES

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

FE0031522

ADVANCE SYNGAS CLEANUP FOR RADICALLY ENGINEERED MODULAR SYSTEMS (REMS)

ATISH KATARIA – RESEARCH TRIANGLE INSTITUTE

Project Description: This project aims to address key knowledge gaps (focused on low-sulfur coals, but ultimately applicable to all coals) to develop modular designs for the cleanup of warm synthesis gas (syngas). These sorbent-based designs would enable 1- to 5-megawatt (MW) Radically Engineered Modular Systems (REMS)-based plants to be cost competitive with large, state-of-the-art commercial plants that use abundant domestic coal reserves. With the project's successful completion, these small-scale modular desulfurization processes may have inherent cost benefits, reduce emissions, and improve thermal efficiencies.

FE0027995

OXYGEN BINDING MATERIALS AND HIGHLY EFFICIENT MODULAR SYSTEM FOR OXYGEN PRODUCTION

SHAOJUN JAMES ZHOU – RESEARCH TRIANGLE INSTITUTE

Project Description: Research Triangle Institute (RTI) and partner Air Liquide will develop innovative materials that reversibly bind oxygen (O_2) to enable efficient, high-capacity separation of O_2 and nitrogen (N_2). The project will leverage Air Liquide's commercial process expertise in O_2 production, specifically by defining initial performance targets of O_2 separation materials. These innovative materials, in turn, enable the development of separation media in the form of adsorbents or membranes that can be used in a modular O_2 separation process. The materials development work involves synthesis and screening of suitable O_2 carriers that can reversibly bind with O_2 in solid form, be stable under process conditions, and have high O_2 capacities. The technology development and material optimization work involves optimizing material properties for O_2 separation and producing solid adsorbents/membranes for the O_2 production process. The goal is to achieve a bed-factor of less than 600 pounds-sorbent/tons per day (tpd) O_2 for solid adsorbents, an O_2/N_2 separation factor greater than 20 for membranes, and O_2 purity greater than 95 percent at a cost that is projected to be lower than current stand-alone air separation systems. A preliminary design and cost estimate for a 5-tpd modular air separation unit will be developed, and a techno-economic analysis (TEA) will be conducted for modular systems that produce 5 to 50 tpd O_2.

FE0031527

PILOT TESTING OF A MODULAR OXYGEN PRODUCTION SYSTEM USING OXYGEN BINDING ADSORBENTS

SHAOJUN JAMES ZHOU – RESEARCH TRIANGLE INSTITUTE

Project Description: RTI will design, fabricate, and test a 10 to 20 kilogram (kg)/day modular O_2 production system. The effort will include optimization and scale-up of the O_2-binding adsorbent; process studies to form the adsorbent material into structured beds for rapid pressure swing adsorption (PSA) cycles with low pressure drop, fast mass transfer, and low attrition; cycle development studies to optimize the PSA process; and development of simulation tools for rapid cycle modeling and numerical evaluation/optimization. In addition, the unit will undergo parametric and long-term testing for at least 1,000 hours. Producing O_2 using the proposed binding materials should cost (depending on the O_2 capacity) 30 to 40 percent less than cryogenic distillation. The technology could reduce the cost of air separation and, therefore, the cost of products from all O_2-intensive industries.

FE0028002

LOW-COST OXYGEN (LCO) FOR SMALL-SCALE MODULAR GASIFICATION SYSTEMS

VIJAY SETHI – THERMOSOLV LLC

Project Description: Thermosolv LLC will work with commercialization partner, LP Amina, Inc., and the Western Research Institute (WRI) to develop and scale-up a high-temperature, sorbent-based vacuum pressure swing adsorption oxygen production technology to a continuous oxygen production process for small-scale distributed applications. The goal is to develop an advanced oxygen production technology based on improved perovskite ceramic sorbents that will result in significantly lower oxygen cost compared to commercial state-of-the-art technologies. The sorbent-based oxygen production process utilizes oxygen-storage properties of perovskites to (1) adsorb oxygen from air in a solid sorbent and (2) release the adsorbed oxygen into a vacuum or a sweep gas such as carbon dioxide (CO_2) and/or steam for gasification systems or recycled flue gas for oxy-combustion systems. Based on bench-scale testing in WRI's existing test facilities, a 1-ton per day (tpd) facility will be designed, assembled, debugged, and tested to develop credible process economics for small-scale modular power plants in the less than 5-megawatt (MW) size range. LP Amina will develop a simulation model for reactor design and cycle optimization and work closely with Thermosolv to design the 1-tpd oxygen plant. Process controls will be developed by WRI. Procurement, fabrication, plant assembly, shakedown, and operations will be the responsibility of Thermosolv.

FE0031528

ADVANCED SORBENTS FOR MODULAR OXYGEN PRODUCTION FOR RADICALLY ENGINEERED MODULAR SYSTEMS (REMS) GASIFIERS

VIJAY SETHI – THERMOSOLV LLC

Project Description: The purpose of this project is to develop advanced oxygen sorbents that fully utilize the high-oxygen storage capacity of perovskites (calcium titanium oxide minerals) and scale up their manufacture to 80 to 250 kilograms (kg) per batch. The targeted sorbents will be utilized in a modular oxygen production plant able to support the oxidant feed of an oxygen-blown Radically Engineered Modular Systems (REMS) gasifier scaled to a range of 1 to 5 MW. The project team will develop composite pellets consisting of an inert core coated with the functional material by exploring various commercially available pelletized supports—including alumina, silica, and iron carbide—and various techniques to coat them with a thin layer of the functional material. Developing composite sorbent pellets to efficiently and fully utilize the high adsorption capacity of perovskites could be an advancement in modular air separation technology.

FE0012062

DRY SOLIDS PUMP COAL FEED TECHNOLOGY PROGRAM

TIMOTHY SAUNDERS – GAS TECHNOLOGY INSTITUTE

Project Description: The objective of this project is to develop fuel feed technology for high-pressure gasifiers that will result in lower-cost coal gasification plant construction and/or operation for power production with carbon capture. The project will conduct dry solids pump (DSP) feed system test operations at 400 tons per day (tpd) (up to 600 tpd), collect and analyze the resultant data, and develop and update the models needed to prepare a conceptual design of a 1,000-tpd DSP operation. This project will provide researchers with the test data, analytical models, and operational experience needed to design a 1,000-tpd, high-pressure DSP system.

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.

Recommendations-Based Evaluation

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

[§] 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.

Under a recommendation-based evaluation, consensus strengths and weaknesses shall be characterized as either "major" or "minor" during the Review Panel's consensus discussion at the meeting. For example, a weakness that presents a significant threat to the likelihood of achieving the project's stated technical goal(s) and supporting objectives should be considered "major," whereas relatively less significant opportunities for improvement are considered "minor."

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

NETL Peer Review Evaluation Criteria
1. Degree to which the project, if successful, supports the DOE Program's near- and/or long-term goals.
• Program goals are clearly and accurately stated. • Performance requirements[1] support the program goals. • The intended commercial application is clearly defined. • The technology is ultimately technically and economically viable for the intended commercial application.
2. Degree to which there are sufficient resources to successfully complete the project.
• There is adequate funding, facilities, and equipment. • Project team includes personnel with the needed technical and project management expertise. • The project team is engaged in effective teaming and collaborative efforts, as appropriate.
3. Degree of project plan technical feasibility.
• Technical gaps, barriers, and risks to achieving the performance requirements are clearly identified. • Scientific/engineering approaches have been designed to overcome the identified technical gaps, barriers, and risks to achieve the performance requirements. • Remaining technical work planned is appropriate considering progress to date and remaining schedule and budget. • Appropriate risk mitigation plans exist, including Decision Points when applicable.
4. Degree to which progress has been made towards achieving the stated performance requirements.
• The project has tested (or is testing) those attributes appropriate for the next TRL. The level of technology integration and nature of the test environment are consistent with the aforementioned TRL definition. • Project progress, with emphasis on experimental results, shows that the technology has, or is likely to, achieve the stated performance requirements for the next TRL (including those pertaining to capital cost, if applicable). • Milestones and reports effectively enable progress to be tracked. • Reasonable progress has been made relative to the established project schedule and budget.
5. Degree to which an appropriate basis exists for the technology's performance attributes and requirements.
• The 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.

Rating Definitions and Scoring Plan (not applicable to TRL-based evaluation)

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

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

APPENDIX B: NETL TECHNOLOGY READINESS LEVELS

NETL Technology Readiness Levels

NETL supports a wide range of R&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 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.

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.
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 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 research and development (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

Gasification Peer Review
November 5-6, 2018
NETL-Pittsburgh Building 922 Room 106A

Monday, November 5, 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 - Facilitator Opening, Review Panel Introductions, Technology Manager Welcome, Peer Review Process and Meeting Logistics Presentation
9:00 – 9:45 a.m.	Project FE0031522 – Advance Syngas Cleanup for Radically Engineered Modular Systems (REMS) *Atish Kataria* – Research Triangle Institute
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 (Recommendation-Based Evaluation; Review Panel) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
12:00 – 1:00 p.m.	Lunch
1:00 – 1:45 p.m.	Project FE0027995 – Oxygen Binding Materials and Highly Efficient Modular System for Oxygen Production, Project FE0031527 – Pilot Testing of a Modular Oxygen Production System Using Oxygen Binding Adsorbents *Shaojun James Zhou* – Research Triangle Institute
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 (Recommendation-Based Evaluation; Review Panel) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
4:00 p.m.	Adjourn

Tuesday, November 6, 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 FE0028002 – Low-Cost Oxygen (LCO) for Small-Scale Modular Gasification Systems, Project FE0031528 – Advanced Sorbents for Modular Oxygen Production for Radically Engineered Modular Systems (REMS) Gasifiers *Vijay Sethi* – Thermosolv LLC
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 (Recommendation-Based Evaluation; Review Panel) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
11:30 – 12:30 p.m.	Lunch
12:30 – 1:15 p.m.	Project FE0012062 – Dry Solids Pump Coal Feed Technology Program *Timothy Saunders* – Gas Technology Institute
1:15 – 2:00 p.m.	Question and Answer Session
2:00 – 2:15 p.m.	BREAK
2:15 – 3:30 p.m.	Closed Discussion (TRL-Based Evaluation; Review Panel) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
3:30 – 4:00 p.m.	Peer Review Panel Wrap-Up Session
4:00 p.m.	Adjourn

APPENDIX D: PEER REVIEW PANEL MEMBERS

Gasification Peer Review
November 5-6, 2018
NETL-Pittsburgh Building 922 Room 106A

Francis Lau

Mr. Francis Lau is the Senior Vice President and Chief Technology Officer of Synthesis Energy Systems (SES). He joined SES in September 2008 and is currently responsible for technology commercialization and continued development. Mr. Lau was also Executive Director of Gasification and the Gas Processing Center at the Gas Technology Institute (GTI), where he led research and development (R&D), demonstration, and deployment programs aimed at the clean, efficient conversion of coal, biomass, and other feedstocks to synthetic natural gas (SNG), electricity, hydrogen, and clean liquid fuels. He was involved in the development of several gasification and related technologies.

Mr. Lau has published numerous papers on energy topics and holds several patents on energy conversion systems. He won the 2003 Pitt Award for his contributions to coal conversion R&D. He has a B.S. in chemical engineering from the University of Wisconsin and an M.S. in chemical engineering from Northwestern University.

Norman Z. Shilling

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

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

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

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

James Sorensen

Mr. James Sorensen is a consultant with a primary focus on clean coal and supporting technologies, including IGCC, oxyfuel combustion, and coal-to-liquids. He is the former Chief Operating Officer and now a Senior Advisor of GTLpetrol. Prior to founding Sorensenergy, LLC, he worked for Air Products and Chemicals as Director of New Markets with responsibility for Syngas Conversion Technology Development and Government Systems, and as 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 liquefied natural gas projects, commercial management of SNG production, and general management of the Membrane Systems department.

Mr. Sorensen's technical interests include IGCC, oxyfuel combustion, gas-to-liquids (GTLs), and air separation and hydrogen/syngas technology. His areas of expertise include project conception and development, consortium development and management, technology and government sales and contracting, R&D program management, technology consulting and training, commercial contract development, and intellectual property. Mr. Sorensen is the founding Chairman of the Gasification Technologies Council and is Vice Chairman of both the Council on Alternate Fuels and Energy Futures International. He holds eight U.S. patents, one of which involves ASU/gas turbine integration for IGCC. He is also well published in the area of clean coal.

Mr. Sorensen received his B.S. and M.S. degrees in chemical engineering from the California Institute of Technology and Washington State University, respectively, and an MBA from the Harvard Business School.

Douglas Todd

Mr. 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 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.

Mr. Todd led the IGCC power block technology into a variety of process power plant applications for co-production of power and hydrogen, clean fuels, GTLs, and carbon dioxide (CO_2)-reduction technologies. By applying integration techniques and unique modifications in the power block, various process technologies have been enhanced, improving economics and extending commercial applications for these processes. Recent gas turbine technology development combined with technology partnerships have led to 20 successful IGCC projects, including co-production plants that account for 14 of these projects. Mr. Todd has led the IGCC power block technology into a variety of process power plant applications for co-production of power and hydrogen, clean fuels, GTLs, and CO_2-reduction technologies.

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 the American Society of Mechanical Engineers and EPRI. Mr. Todd received a B.S. degree in chemical engineering from Worcester Polytechnic Institute.