NATIONAL ENERGY TECHNOLOGY LABORATORY

FY18 RARE EARTH ELEMENTS 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's (DOE) Office of Fossil Energy (FE) is charged with ensuring the availability of ultraclean (near-zero emissions), abundant, low-cost domestic energy from coal to fuel economic prosperity, strengthen energy independence, and enhance environmental quality. As a component of that effort, the National Energy Technology Laboratory (NETL) is engaged in research, development, and demonstration (RD&D) activities to create technology and technology-based policy options for public benefit. The Rare Earth Elements (REE) Program is focused on developing technologies for the recovery of REEs from Coal and Coal By-products.

In 2009, interest in strategic materials intensified, culminating in discussions regarding the Nation's ability to secure reliable supplies of rare earth metals (and other strategic materials). Strategic materials were identified as critical for growing the U.S. green energy and electronics industries, as well as for specialty military applications. DOE released the first Critical Materials Strategy in 2010 and NETL initiated a small investigative effort to explore the concept of extracting REEs from coal and coal by-products. Congress has since recognized the importance of this resource to U.S. economic security and appropriated funding in Fiscal Year 2014 (FY14) to identify the magnitude of the resource; develop capabilities to economically recover rare earth metals in an environmentally responsible manner; and provide an additional domestic, secure, and reliable resource for future advanced technology industries in United States.

NETL expanded its efforts in 2014 to assess the potential resource base for rare earth metals contained within underground coal resources and coal by-product waste streams from coal cleaning operations and power plants (post-combustion material). Initial research identified potential "hot spots" in select coal seams for REEs and confirmed that the quantity of these elements varied depending on geology, location, and other factors that were not yet fully understood. Efforts to explore the available technology for extracting these vital elements were undertaken, leading to the conclusion that additional research and technology development would be needed to convert this resource into a viable domestic commodity.

The REE Program consists of five core technology areas that are focused on development of REE separation and recovery technologies, addressing the current global REE separations market and process economics, and demonstrating the generation of environmentally benign REE separation processing capabilities.

- **Resource Sampling and Characterization** – While significant progress has been made in identifying field site locations and compositional assessment of potential coal and coal by-product REE-containing materials, continued effort is essential to identify the "best" source of materials to support future commercial REE production. Chemical and physical characterization efforts, addressing REE elemental concentrations and phase compositions in the coal and coal by-product resources, are essential in the development of viable REE separation processes.
- **Separation Technology Development** – NETL is developing REE separation and extraction capabilities from coal-based resources such as coal, coal refuse, clay/sandstone over/under-burden materials, aqueous effluents, and power generation ash. The REE Program is focused on developing economically feasible and environmentally benign technologies for separating REEs from resources starting with a minimum of 300 ppm total

REEs, and concentrating to a 2wt% mixed total REE oxide in the resulting processed material.

- **REE Sensor Development** – Development of portable sensors for field site identification of promising REE coal-based resources, as well as devices for determination of REE concentrations in process separation flow streams, is being considered. Tentatively, these technologies will be tested in the field, at bench-scale separation test facilities, and validated to commercial-ready status during use in pilot-scale demonstration projects.
- **Process & Systems Modeling** – Modeling efforts are being focused on development of multi-phase flow with interphase eXchanges (MFiX) computational fluid dynamics (CFD) software to simulate REE separation and optimization of the separation process. This effort is being conducted in close coordination with researchers who are developing and/or demonstrating viable 2nd Generation and/or advanced, new/novel REE separation concepts. The CFD models will be used as virtual test platforms to optimize process separation designs and ultimately package the modeling capability into a generalized toolset for public distribution as part of technology transfer.
- **Techno-Economic Analysis** – Techno-economic analyses are being conducted to evaluate the international REE market and to assess the economics of commercially producing REEs from currently considered 2nd Generation and Transformational separation processes. An REE market characterization will be performed and coal-based REE economic baseline/cost targets assessing potential benefits and job creation document will be undertaken.

The Nation's vast coal resources contain quantities of REEs that offer the potential to reduce our dependence on others for these critical materials and create new industries in regions where coal plays an important economic role. The development of an economically competitive supply of REEs will secure and maintain the Nation's economic growth and national security.

Office of Management and Budget Requirements

In compliance with requirements from the Office of Management and Budget, DOE and NETL are fully committed to improving the quality of research projects in their programs. To aid this effort, DOE and NETL conducted an FY18 REE Peer Review Meeting with independent technical experts to offer recommendations to strengthen projects (in this case, in-house tasks) during the period of performance. KeyLogic (NETL site-support contractor) convened a panel of five academic and industry experts[*] on March 20-21, 2018, to conduct a two-day peer review of seven REE Program research tasks performed by NETL's Research and Innovation Center (RIC).

TABLE 1. RARE EARTH ELEMENTS PEER REVIEW – TASKS REVIEWED

<table>
<tr><th>Task Number</th><th>Title</th><th>Lead Organization</th></tr>
<tr><td>Task 2</td><td>Rare Earth Element Characterization</td><td>NETL RIC</td></tr>
<tr><td>Task 3</td><td>Innovative Separations Technologies</td><td>NETL RIC</td></tr>
<tr><td>Task 4</td><td>Computational Fluid Dynamics Simulation and Modeling of REE Separations</td><td>NETL RIC</td></tr>
<tr><td>Task 5</td><td>Field Sampling</td><td>NETL RIC</td></tr>
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<tr><td>Task 8</td><td>Systems Engineering & Analysis</td><td>NETL RIC</td></tr>
<tr><td>Task 9</td><td>Assessment of Rare Earth Element Occurrences in Coal-Related Strata</td><td>NETL RIC</td></tr>
<tr><td colspan="3">The tasks were subject to recommendations-based evaluations. During recommendations-based evaluations, the independent panel provides recommendations to strengthen the performance of projects during the period of performance. Please see "Appendix A: Peer Review Evaluation Criteria Form" for more information.</td></tr>
</table>

[*] 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 FE's 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 March 20-21, 2018, KeyLogic convened a panel of five academic and industry experts to conduct a two-day peer review of seven research tasks supported by the NETL REE Program. Throughout the peer review meeting, these recognized technical experts offered recommendations to strengthen the tasks during the remaining period of performance. In consultation with NETL representatives, who chose the tasks 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 task team submitted a Project Technical Summary (PTS) and task presentation. The tasks' Technical Project Lead (TPL) provided the Field Work Proposal (FWP), the latest quarterly report, and 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 tasks.

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 task 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 task performer gave a presentation describing the task. 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 task's complexity, duration, and breadth of scope.

To facilitate a full and open discussion of task-related material between the task team and the panel, all sessions were limited to the panel, DOE/NETL personnel, and KeyLogic staff. The panel discussed each task to identify strengths, weaknesses, and recommendations in accordance with the Peer Review Evaluation Criteria. The panel offered a series of prioritized recommendations to strengthen the task during the remaining period of performance and assigned each task a score based on the NETL Peer Review Rating Definitions and Scoring Plan in the Peer Review Evaluation Criteria[†].

† 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 tasks evaluated at the FY18 REE Peer Review Meeting.

Overview of Task Evaluation Scores

The panel assigned a consensus score for each task, based on the following definitions. A rating of five or higher indicates that a specific task 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 various tasks subject to review, the panel assigned scores ranging from four to nine.

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

PROJECT SYNOPSES

For more information on the REE Program and project portfolio, please visit the NETL website: https://www.netl.doe.gov/research/coal/rare-earth-elements.

FWP-1022420

TASK 2: RARE EARTH ELEMENT CHARACTERIZATION

National Energy Technology Laboratory

Task Description: Rare earth element (REE) characterization will be undertaken using a suite of complimentary standard and advanced state-of-the-art characterization methods. These methods will use commercially available instrumentation and laboratory-developed technologies. The characterization methods will include traditional wet methods, as well as spectroscopic, microscopic, and thermogravimetric measurements. Methods for in situ characterization of field materials at site locations will also be developed. The purpose is to generate the most comprehensive information possible about the types and concentrations of REE in coal and coal by-product samples obtained for this project, their associations with mineral and other phases in the materials of interest, and their pertinent physical properties so as to facilitate design of separation schemes, and to understand the REE behavior when employing those separation methods.

FWP-1022420

TASK 3: INNOVATIVE SEPARATIONS TECHNOLOGIES

National Energy Technology Laboratory

Task Description: Rare earth element (REE) separation will develop and evaluate laboratory-scale physical, mechanical, and chemical separation techniques to extract/concentrate REE from coal and coal by-product streams. Information on the REE chemistry, mineralogy, associations, and concentrations derived from detailed characterization of these materials will be used to guide separation technique selection and development for promising materials. Off-the-shelf, as well as newly developed separation approaches, will be used as appropriate based on the by-product material's properties. Transformational laboratory-scale efforts will include novel chemical, electrical, thermal, and reactive grinding; photochemical, ultrasonic-assisted, microwave-aided, photophoretic, and/or plasma separations; and advanced sorbent development. Economics and environmental benefits, as well as safety and hazards of the separation techniques, will be evaluated. Results will be used in the development of an integrated process flow diagram and quantification of the potential for enhanced REE recovery will be established.

FWP-1022420

TASK 4: COMPUTATIONAL FLUID DYNAMICS SIMULATION AND MODELING OF REE SEPARATIONS

National Energy Technology Laboratory

Task Description: Models for rare earth element (REE) extraction by ion exchange (IX) reactions were previously developed from the literature and used to describe several extraction reactors using the National Energy Technology Laboratory (NETL) Research and Innovation Center's (RIC) computational fluid dynamics (CFD) software, multi-phase flow with interphase eXchanges (MFiX). The team will extend this capability to model the extraction of REE from coal by-products of interest to NETL. Past analytical studies at NETL have shown that different coal by-products have different concentrations and species of REE. For the REE-bearing material of interest to this project, it is expected that the rate of REE extraction and other kinetic information will be determined in the experimental part of this study. Analytical forms of these extraction rates will be implemented and verified in the CFD code in close collaboration with the experimental team. The REE extraction reactions will occur in an aqueous solution in reactors of different sizes designed to better understand the scale-up of this unit operation. Based on development of a fast and efficient computational method to track large amounts of particles, the team will be able to study different reactor sizes and flow rates (both liquid and solids) to optimize various extraction processes.

FWP-1022420

TASK 5: FIELD SAMPLING

National Energy Technology Laboratory

Task Description: This effort will help identify the most promising domestic coal and coal by-product materials that contain rare earths. The Field Site Materials Characterization and Inventory task includes travel to identified/permitted field sites, as well as Memorandum of Agreements (MOAs) with coal research organizations, to obtain samples for the National Energy Technology Laboratory (NETL) Research and Innovation Center's (RIC) material inventory housed in Pittsburgh, Pennsylvania. These characterization data will support continued development of the Rare Earth NETL Energy Data eXchange (EDX) database, which will be available for public use.

FWP-1022420

TASK 6: MINERALS PROCESSING FACILITY – NATIONAL ENERGY TECHNOLOGY LABORATORY

National Energy Technology Laboratory

Task Description: The Minerals Processing Facility will develop and evaluate laboratory-scale physical, mechanical, and chemical separation techniques to extract/concentrate minerals from coal and coal by-product streams. Information on feedstock chemistry, mineralogy, associations, and concentrations will be derived from detailed material characterization to guide separation technique selection and development for promising materials. Off-the-shelf, as well as newly developed separation approaches, will be used as appropriate. Economics and environmental benefits, as well as safety and hazards of the separation techniques, will be evaluated. Results will support the development of an integrated process flow diagram and quantification potential for enhanced mineral recovery. The laboratory will process bucket-sized quantities of coal by-products via intensive physical separations to enable the characterization of these materials, the testing of physical concentrating methods, and additional chemical and thermal processing of these fractions. The ability to process bucket-sized quantities of coal by-products, using small yet industrially relevant separation techniques in a batch mode, will allow the National Energy Technology Laboratory (NETL) Research and Innovation Center (RIC) to share research samples with many researchers working on characterization and separation.

FWP-1022420

TASK 8: SYSTEMS ENGINEERING & ANALYSIS – NATIONAL ENERGY TECHNOLOGY LABORATORY

National Energy Technology Laboratory

Task Description: An investigation of the production-limiting or economically prohibitive steps in the concentration and purification of rare earth elements (REEs) will be conducted. This effort will evaluate each step in the concentration and separation process that transforms a feedstock containing REE into a salable pure rare earth metal. The objective is to highlight bottlenecks within the process that could be improved with research, development, and deployment (RD&D). In addition, transformational processes developed by the National Energy Technology Laboratory (NETL) Research and Innovation Center (RIC) will be integrated into the existing models. Work will be initiated to develop a baseline metallurgical process flowsheet for the concentration and separation of REE from specific coal-based feedstocks. This work will begin identifying the specific processing steps that will need to be included in the concentration and separation of a specific coal-based feedstock. Once this flowsheet is developed, specific costs for each step in the process can then be identified. This will also identify all other saleable products that can be recovered from a specific feedstock. A preliminary high-level REE jobs analysis will be developed that will consist of an estimation of the economic impacts of constructing and operating an REE separations and processing facility (or facilities) in the United States. The primary objective of this effort will be to determine the relative impact an REE facility or industry could have on jobs. A second objective will be to quantify the economic importance of the rare earths to the U.S. economy, including the costs of a supply interruption.

FWP-1022420

TASK 9: ASSESSMENT OF RARE EARTH ELEMENT OCCURRENCES IN COAL-RELATED STRATA

National Energy Technology Laboratory

Task Description: To assess and predict occurrence of rare earth elements (REEs) requires development of an assessment method that leverages understanding of how REEs become concentrated in coal, under clays and other associated strata. In this task, the team seeks to develop an assessment approach to support prediction of REE occurrences in coal and associated strata that incorporates information and methods that account for the geologic history of the system and processes that result in their present-day occurrence. This approach will encompass information about depositional history, but also tectonic and diagenetic influences, and may leverage assessment strategies from petroleum and/or mineral resources (e.g., Rose et al., in review). This holistic approach should improve assessment and prediction of REE occurrences, addressing processes and mechanisms that could influence REE distributions post-deposition and facilitate prediction of areas of higher commercial prospectivity to guide field sampling, inform economic estimates of reserves, and guide other needs.

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.

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).

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

‡ 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.

strengths or weaknesses. Recommendations shall be ranked from most important to least, based on the major/minor strengths/weaknesses.

NETL REE 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* 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.
• Milestones and reports effectively enable progress to be tracked. • Reasonable progress has been made relative to the established project schedule and budget.
* 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.

NETL REE Peer Review Specific Evaluation Criteria
Supplemental to the Evaluation Criteria
Task 6: Minerals Processing Facility • How is the minerals processing lab different than other minerals processing (university or industrial) labs? • Can the minerals processing laboratory perform all the separations outlined in the performance goals, or are there gaps in equipment capability (i.e., chemical separations)? • Is the equipment within the minerals processing lab appropriate for processing multiple feedstock materials through to production of REEs with a minimum of 2 wt.% based on the NETL Research and Innovation Center's (RIC) process flow diagram?
Task 8: Systems Engineering & Analysis • Is the timeline for the NETL techno-economic analysis (TEA) model development, completion, and ready for use appropriate? • Are there gaps in the model that should be addressed? • Is the plan for the TEA model validation reasonable?

Rating Definitions and Scoring Plan

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

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

Rare Earth Elements Peer Review
March 20-21, 2018
NETL-Pittsburgh Building 922 Room 106A

Tuesday, March 20, 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, Logistics, and Task Overview
9:00 – 9:30 a.m.	Task 9: Assessment of Rare Earth Element Occurrences in Coal-Related Strata *Kelly Rose* – NETL; *Burt Thomas* – AECOM; and *Gabe Creason* – ORISE
9:30 – 10:00 a.m.	Question and Answer Session (Task 9)
10:00 – 10:15 a.m.	BREAK
10:15 – 10:45 a.m.	Task 5: Field Sampling *Evan Granite* – NETL; *Elliot Roth* – AECOM
10:45 – 11:15 a.m.	Question and Answer Session (Task 5)
11:15 – 11:45 a.m.	Task 2: Rare Earth Element Characterization *John Baltrus* – NETL
11:45 – 12:15 p.m.	Question and Answer Session (Task 2)
12:15 – 2:15 p.m.	Lunch/Closed Discussion (onsite cafeteria; cash only, orders will be placed in the morning) (Task-specific recommendations; Review Panel) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
2:15 – 2:30 p.m.	BREAK
2:30 – 3:15 p.m.	Task 3: Innovative Separations Technologies *Evan Granite and Bret Howard* – NETL; *Elliot Roth* – AECOM
3:15 – 3:45 p.m.	Question and Answer Session (Task 3)
3:45 – 4:05 p.m.	Task 6: Minerals Processing Facility – NETL *Tom Tarka, Evan Granite* – NETL; *Elliot Roth and Paul Zandhuis* – AECOM
4:05 – 4:30 p.m.	Question and Answer Session (Task 6)
4:30 – 4:35 p.m.	BREAK
4:35 – 5:30 p.m.	Closed Discussion (Task-specific recommendations; Review Panel) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
5:30 p.m.	Adjourn

Wednesday, March 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 – 9:15 a.m.	Task 8: Systems Engineering & Analysis – NETL *Morgan Summers and Tom Tarka* – NETL
9:15 – 9:30 a.m.	BREAK
9:30 – 10:15 a.m.	Question and Answer Session (Task 8)
10:15 – 10:30 a.m.	BREAK
10:30 – 11:30 a.m.	Closed Discussion (Task-specific comments; 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.	Task 4: Computational Fluid Dynamics Simulation and Modeling of REE Separations – NETL *Sofiane Benyahia* – NETL; *Liqiang Lu* – ORISE
12:45 – 1:00 p.m.	BREAK
1:00 – 2:00 p.m.	Question and Answer Session (Task 4)
2:00 – 2:15 p.m.	BREAK
2:15 – 3:30 p.m.	Closed Discussion (Task-specific recommendations; 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

Corby Anderson, Ph.D.

Corby Anderson is currently the Harrison Western Professor for the Kroll Institute for Extractive Metallurgy at the Colorado School of Mines. Dr. Anderson is an expert in the fields of extractive metallurgy, mineral processing, waste minimization, and recycling. Dr. Anderson is a registered engineer with more than 38 years of global experience in industry, management, engineering, design, economics, consulting, teaching, research, and professional service. He holds a BS from Montana State, an MS from Montana Tech, and a Ph.D. from the University of Idaho. Dr. Anderson is a Fellow of the Institution of Chemical Engineers and the Institute of Materials, Minerals, and Mining, as well as a Distinguished Member of the Society for Mining, Metallurgy, and Exploration (SME) and the University of Idaho Academy of Engineering. Dr. Anderson shares 11 patents, 5 new applications, and 2 new disclosures.

Kenneth N. Han, Ph.D.

Kenneth Han is Distinguished Professor Emeritus of Materials and Metallurgical Engineering at the South Dakota School of Mines and Technology (SDSM&T), as well as a National Academy of Engineering Member. Dr. Han received his BS and MS degrees from Seoul National University, an additional MS degree from the University of Illinois, and his Ph.D. from the University of California. Prior to joining SDSM&T in 1981, Dr. Han was a lecturer and senior lecturer in Chemical Engineering at Monash University in Melbourne, Australia, from 1971 to 1980. While at SDSM&T, he has served as the head of the Department of Metallurgical Engineering from 1987 to 1994, and as the dean of the College of Materials Science and Engineering from 1994 to 1999. Research topics he has worked on include hydrometallurgy, interfacial phenomena, metallurgical kinetics, solution chemistry, fine particle recovery, and electrometallurgy. Dr. Han has published more than 150 papers in international journals and presented more than 100 papers at international conferences. The author of 10 monographs, Dr. Han also holds 8 patents related to extractive metallurgy, and has won numerous awards from academic, technical, and professional societies.

Alex King, Ph.D.

Alex King has been the Director of the Critical Materials Institute (CMI) at the U.S. Department of Energy's (DOE) Ames Laboratory since 2013, where he oversees innovation in the processing and recycling of rare-earth minerals, the development of substitute materials for these elements, and economic analysis of their global supply.

Dr. King received his BS in Physical Metallurgy from the University of Sheffield, England, and his Ph.D. in Metallurgy and the Science of Materials from the University of Oxford, England. Before joining the faculty at the State University of New York at Stony Brook, where he also served as the Vice Provost for Graduate Studies (Dean of the Graduate School), Dr. King was a postdoc at Oxford and the Massachusetts Institute of Technology (MIT). He was appointed as Professor and Head of the School of Materials Engineering at Purdue in 1999, and Director of DOE's Ames Laboratory in January 2008. In June 2013, Dr. King stepped down as the Ames Laboratory director to devote his time to the directorship of CMI. He has served as the President of the Materials Research Society, Chair of the Gordon Conference on Physical Metallurgy, and Chair of the Universities' Materials Council.

Jack Lifton

Jack Lifton is a Founding Principal of Technology Metals Research, LLC, and a Senior Fellow of the Institute for the Analysis of Global Security. Mr. Lifton is also a consultant, author, and lecturer on the market fundamentals of the technology metals, a term he coined to describe those strategic rare metals whose electronic properties make our technological society possible. These include the rare earths, lithium, and most of the rare metals. Educated as a physical chemist specializing in high-temperature metallurgy, Mr. Lifton was a researcher, then both a marketing and manufacturing executive, before becoming a metal trader specializing in the field of technology metals and rare metals.

After 50 years of industry involvement, Mr. Lifton currently advises both original equipment manufacturer (OEM) high-tech industry and the global institutional-investment community on the natural resource issues that impact either a proposed business model or a high-volume manufacturing plan for the mass market. His work today is principally as a due-diligence consultant for institutional investors, looking into opportunities where the availability of rare metals and technology metals are a factor in determining the probability of commercial success of a metals-related venture.

Courtney Young, Ph.D.

Courtney Young is Department Head and Prater Distinguished Professor of Metallurgical & Materials Engineering at Montana Tech of the University of Montana. Dr. Young is a graduate of three premiere mineral/coal processing and extractive metallurgy institutions, having obtained his BS in Mineral Processing Engineering from Montana Tech (then known as Montana College of Mineral Science and Technology) in 1984, his MS in Mining and Minerals Engineering from Virginia Polytechnic Institute and State University (Virginia Tech) in 1987, and his Ph.D. in Metallurgical Engineering from the University of Utah College of Mines and Earth Sciences in 1995.

Dr. Young has expertise in surface chemistry, electrochemistry, and spectroscopy. His specialties in mineral processing/extractive metallurgical engineering include mineral characterization, flotation, physical separations, leaching, cyanide, uranium, gold processing, adsorption, and applications thereof to recycling and wastewater remediation.

While a faculty member at Montana Tech, Dr. Young has worked with numerous companies and the Center for Advanced Mineral & Metallurgical Processing (CAMP) at Montana Tech. The subject matter included furthering the understanding of flotation technology, selecting and testing ore process options, flowsheet design for mineral processing of rare earth elements, and researching and developing solutions to environmental problems. Dr. Young has applied for a patent on his research for developing a novel carbon adsorption process for the extraction of gold from thiosulfate solutions. The non-cyanide technology has the potential to make thiosulfate leaching cost-effective and therefore competitive to cyanide leaching.