NATIONAL ENERGY TECHNOLOGY LABORATORY

FY19 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 developing 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 that address REE elemental concentrations and phase compositions in the coal and coal by-product resources are essential to 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 parts per

million (ppm) total REEs and concentrating to a 2 weight percent (wt%) mixed total REE oxide in the resulting processed material.

- **REE Sensor Development** – The 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 and Systems Modeling** – Modeling efforts are focused on the development of multiphase 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 assess the economics of commercially producing REEs from currently considered 2nd Generation and Transformational separation processes. An REE market characterization will be performed and a 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 the 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 and DOE Requirements

In compliance with requirements from the Office of Management and Budget and in accordance with the DOE Strategic Plan, DOE and NETL are fully committed to improving the quality of research projects in their programs by conducting rigorous peer reviews. This report presents an overview of the peer review process, provides a synopsis of the projects reviewed, offers a summary of key findings, and identifies the panel members that conducted the project evaluations.

DOE and NETL held an FY19 REE Peer Review Meeting with independent technical experts to assess the projects' technology readiness for work at the current Technology Readiness Level (TRL), evaluate the planned work to attain the next TRL, and offer recommendations. KeyLogic (NETL site-support contractor) convened a panel of five academic and industry experts[*] on March 18-19, 2019, to review four REE Program research projects.

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

TABLE 1. REE PEER REVIEW – PROJECTS REVIEWED

Project Number	Title	Lead Organization	Total Funding		Project Duration	
			DOE	Cost Share	From	To
FE0027006	Investigation of Rare Earth Element Extraction from North Dakota Coal-Related Feedstocks	University of North Dakota Institute for Energy Studies	$3,343,847	$965,500	3/1/2016	12/31/2019
FE0026927	Recovery of Rare Earth Elements from Coal Mine Drainage	West Virginia University Research Corporation	$3,411,874	$928,915	3/1/2016	6/30/2019
FE0027035	Pilot-Scale Testing of an Integrated Circuit for the Extraction of Rare Earth Minerals and Elements from Coal and Coal By-products Using Advanced Separation Technologies	University of Kentucky Research Foundation	$6,999,797	$1,820,212	3/1/2016	3/31/2020
FE0027167	High Yield and Economical Production of Rare Earth Elements from Coal Ash	Physical Sciences, Inc.	$6,999,165	$1,751,001	3/1/2016	3/31/2020
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.			$20,754,683	$5,465,628		
			$26,220,311			

OVERVIEW OF THE PEER REVIEW PROCESS

Peer reviews are conducted to help ensure that the FE's research program, implemented by NETL, is in compliance with requirements from the Office of Management and Budget and in accordance 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.

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

Pre-Meeting Preparation

Before the peer review, each project team submitted a Project Technical Summary (PTS), Technology Maturation Plan (TMP) and project presentation. The appropriate Federal Project Manager (FPM) 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 (TM) to provide an overview of the program goals and objectives.

Peer Review Meeting Proceedings

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

During the closed sessions of the peer review meeting, the panel discussed each project to identify strengths, weaknesses, and recommendations in accordance with the Peer Review Evaluation Criteria. The panel offered prioritized recommendations and an evaluation of TRL progression for each project, based on the NETL 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 projects evaluated at the FY19 REE 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 27 recommendations for NETL management to review and consider.

The panel offered several common strengths among the projects reviewed. The panel noted that the project teams exhibit a passion and commitment to their work, emphasize safety and training, and aim to address environmental issues. Some of the projects have implemented advanced programmable logic controller (PLC) systems into their processes, which minimizes risk during scaleup. The panel described most of the flowsheets presented by the teams as being technically sound. They also noted a focus on workforce development and the education of individuals on a much-needed skillset. The breadth and depth of the teams' acumen as mineral processors impressed the panel.

Conversely, the panel noted several areas for improvement among the projects reviewed, such as improving their understanding of the domestic REE supply chain and downstream markets and incorporating vendor relationships and customer perspectives early on in project development. The panel also pointed out that there appears to be a need for the project teams to improve their understanding of chemistry in relation to the characterization of source materials before carrying out their leaching investigations. Another common issue is that the REE source materials are low grade, and physical upgrading is highly limited. This could be addressed by focusing the project on fundamental studies to economically enrich the REE concentration from the leached products in the solution. The panel also noted that most of the project teams have spent a lot of time and effort in solvent extraction, which is unnecessary to some degree, because most of these studies have already been conducted by other researchers. In addition, some of the projects are experiencing issues with separating heavy-group REE (HREE) from light-group REE (LREE) in chemical precipitation and/or solvent extraction; these teams should have considered alternative solvents. Finally, the panel indicated that it would be beneficial if standard terminology was used by all the projects, which would enhance their interactions with industry.

Evaluation of TRL Progression

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

- Project FE0027006 has attained TRL 3. Upon achievement of water balance and waste management, research of selectivity options, and system simulation, Project FE0027006 will attain TRL 4. Upon achieving a demonstration of a semi-continuous process with cost estimation, water balancing, and selectivity, Project FE0027006 will attain TRL 5.
- Project FE0026927 has attained TRL 4. Following the identification and implementation of process improvements (e.g., acid choice, reduction of reagent consumption, better solvent extractants) that support economic viability through completion of a techno-economic analysis (TEA), Project FE0026927 will attain TRL 5.
- Project FE0027035 has attained TRL 5. Upon achievement of the following, Project FE0027035 will attain TRL 6:
    - Improving the understanding of roasting chemistry and reporting the results to DOE/NETL.
    - Studying different solvent efficacy on costs/yields.
    - Proving economic viability by completing a detailed, third-party-led cost estimation.
    - Defining the next steps in project scoping (i.e., develop the strategy moving forward).
- Project FE0027167 has attained TRL 2. Upon testing and validation of laboratory performance requirements, establishing core technology, updating performance attributes, and establishing initial performance requirements, Project FE0027167 will attain TRL 3.

PROJECT SYNOPSES

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

FE0027006

INVESTIGATION OF RARE EARTH ELEMENT EXTRACTION FROM NORTH DAKOTA COAL-RELATED FEEDSTOCKS

MICHAEL MANN, NOLAN THEAKER, STEVE BENSON, AND DAN LAUDAL – UNIVERSITY OF NORTH DAKOTA INSTITUTE FOR ENERGY STUDIES

Project Description: In Phase I of this project, the University of North Dakota (UND) project team identified locations in North Dakota with coal-related feedstocks having exceptionally high rare earth elements (REE) content and developed a simple, highly effective, and low-cost method to concentrate the REEs in the lignite feedstocks using a novel technology that takes advantage of the unique properties of lignite. In laboratory experiments, UND achieved greater than 2% concentration of rare earths in the mixed rare earth concentrate while recovering up to 35% of the rare earths from the incoming feedstock. In Phase II, UND is partnering with Microbeam Technologies, Barr Engineering, Pacific Northwest National Laboratory (PNNL), and MLJ Consulting to investigate the feasibility of recovering REEs from North Dakota lignite and lignite-related feedstocks. The team will scaleup the technology and demonstrate it at a scale of 10 to 20 kilograms per hour feedstock throughput and evaluate the economics for a commercial-scale, rare-earths-concentrating facility in North Dakota. The project also includes development of a commercialization plan and market assessment. The Lignite Research Program of the North Dakota Industrial Commission, North American Coal Corporation, Great River Energy, Minnkota Power Cooperative, Great Northern Properties, UND, and the North Dakota University System are cost-sharing this project.

FE0026927

RECOVERY OF RARE EARTH ELEMENTS FROM COAL MINE DRAINAGE

PAUL ZIEMKIEWICZ – WEST VIRGINIA UNIVERSITY RESEARCH CORPORATION

Project Description: In Phase II of the project, West Virginia University (WVU) and its partners will develop a cost-effective and environmentally benign process to recover rare earth elements (REEs) from solid residues (sludge) generated during treatment of acid mine drainage (AMD). This project will take advantage of autogenous processes that occur in coal mines and associated tailings that liberate, then concentrate, REEs. Phase I findings showed elevated concentrations of REEs, particularly in low-pH AMD, and nearly all precipitating with more plentiful transition metals in the AMD sludge. REE extraction using hydrometallurgical methods produced a concentrate with 4.6% total REE content. A techno-economic analysis (TEA) also found that REE extraction from AMD sludge is economically attractive, with a refining facility projected to generate positive cash flow within five years. During Phase II, a continuously operating bench-scale unit will be constructed and operated, yielding 3 grams/hour of REE concentrate.

FE0027035

PILOT-SCALE TESTING OF AN INTEGRATED CIRCUIT FOR THE EXTRACTION OF RARE EARTH MINERALS AND ELEMENTS FROM COAL AND COAL BY-PRODUCTS USING ADVANCED SEPARATION TECHNOLOGIES

RICK HONAKER – UNIVERSITY OF KENTUCKY RESEARCH FOUNDATION

Project Description: In Phase I of this project, the University of Kentucky (UK) identified two bituminous coal-related feedstocks qualified as having ample supply with high rare earth element (REE) content (above 300 parts per million [ppm]) and developed a preliminary design for a mobile pilot plant to recover REEs from those feedstocks. In laboratory experiments, UK achieved greater than 80% concentration of rare earths in the mixed rare earth concentrate while recovering greater than 75% of the rare earths from the incoming feedstock. In Phase II, UK will develop and test a one-fourth ton/hour pilot-scale plant for the extraction of REEs from Central Appalachian and Illinois Basin bituminous coal preparation plant refuse materials. The system integrates both physical and chemical (ion exchange and solvent extraction) separation processes that are commercially available and environmentally acceptable. The innovative enabling technology utilized in the proposed system includes an advanced froth flotation process and a novel hydrophobic-hydrophilic separation process.

FE0027167

HIGH YIELD AND ECONOMICAL PRODUCTION OF RARE EARTH ELEMENTS FROM COAL ASH

PRAKASH JOSHI – PHYSICAL SCIENCES, INC.

Project Description: In this Phase II project, the team of Physical Sciences Inc. (PSI), the University of Kentucky Center for Applied Energy Research (CAER), and Winner Water Services will develop and demonstrate a pilot-scale plant to economically produce salable rare earth element- (REE) rich concentrates, including yttrium and scandium (REYSc), and commercially viable co-products from coal ash feedstock using environmentally safe and high-yield physical and chemical enrichment/recovery processes. The pilot plant will operate at the scale of approximately 0.4 to 1 ton per day (tpd) ash throughput for physical processing and about 0.5 tpd for chemical processing, producing at least 50 grams of dry REYSc nitrates concentrate containing more than 10% by weight of REYSc and targeting 500 grams of dry REYSc nitrates concentrate containing more than 20% REYSc by weight. The ash feedstock will come from the Dale power plant in Ford, Kentucky, with at least 300 parts per million (ppm) of REYSc content, though more than 500 ppm is anticipated. The data obtained from the pilot plant operations will be used to enhance and validate the techno-economic analysis (TEA) that was completed for both the physical and chemical processing plants at a scale of 600 tpd in Phase I and use it to design a commercial-scale plant (hundreds of tpd throughput) with return on investment in less than seven years.

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-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 Technology Readiness Level (TRL) based on a project's strengths[‡], weaknesses[§], recommendations, issues, and concerns. 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 strengths, weaknesses, overall score, and prioritized recommendations for each project. The 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.

Under a recommendation-based evaluation, strengths and weaknesses shall be characterized as either "major" or "minor" during the Review Panel's 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)

‡ 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.

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 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 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.

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

Rare Earth Elements Peer Review
March 18-19, 2019
NETL-Pittsburgh Building 922 Room 106A

Monday, March 18, 2019

8:00 a.m. (no earlier)	*Panel Members Arrive at NETL-Pittsburgh for Security Check*
8:15 – 8:30 a.m.	*Morning Presenters Arrive, Visitors escorted 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 FE0027006 – Investigation of Rare Earth Element Extraction from North Dakota Coal-Related Feedstocks *Michael Mann, Nolan Theaker, Steve Benson, and Dan Laudal* – University of North Dakota Institute for Energy Studies
9:45 – 10:30 a.m.	Question and Answer Session
10:30 –10:45 a.m.	BREAK
10:45 – 12:15 p.m.	Closed Discussion (Peer Review Panel Evaluation) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
12:15 – 1:15 p.m.	Lunch
1:00 p.m. (no later)	*Afternoon Presenters Arrive at NETL-Pittsburgh for Security Check*
1:15 – 2:00 p.m.	Project FE0026927 – Recovery of Rare Earth Elements from Coal Mine Drainage *Paul Ziemkiewicz* – West Virginia University Research Corporation
2:00 – 2:45 p.m.	Question and Answer Session
2:45 – 3:00 p.m.	BREAK
3:00 – 4:30 p.m.	Closed Discussion (Peer Review Panel Evaluation) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
4:30 p.m.	Adjourn

Tuesday, March 19, 2019

8:00 a.m. (no earlier)	*Panel Members and Morning Presenters Arrive at NETL-Pittsburgh for Security Check*
8:15 – 8:30 a.m.	*Escort Panel Members and Morning Presenters to NETL-Pittsburgh Building 922 Room 106A*
8:30 – 9:15 a.m.	Project FE0027035 – Pilot-Scale Testing of an Integrated Circuit for the Extraction of Rare Earth Minerals and Elements from Coal and Coal By-products Using Advanced Separation Technologies *Rick Honaker* – University of Kentucky Research Foundation
9:15 – 10:00 a.m.	Question and Answer Session
10:00 – 10:15 a.m.	BREAK
10:15 – 11:45 a.m.	Closed Discussion (Peer Review Panel Evaluation) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
11:45 – 12:45 p.m.	Review Panel Working Lunch
12:30 p.m. (no later)	*Afternoon Presenters Arrive at NETL-Pittsburgh for Security Check*
12:45 – 1:30 p.m.	Project FE0027167 – High Yield and Economical Production of Rare Earth Elements from Coal Ash *Prakash Joshi* – Physical Sciences, Inc.
1:30 – 2:15 p.m.	Question and Answer Session
2:15 – 2:30 p.m.	BREAK
2:30 – 4:00 p.m.	Closed Discussion (Peer Review Panel Evaluation) *DOE HQ/NETL and KeyLogic peer review support staff attend as observers.*
4:00 – 4:30 p.m.	Peer Review Panel Wrap-Up Session
4:30 p.m.	Adjourn

APPENDIX D: PEER REVIEW PANEL MEMBERS

Rare Earth Elements Peer Review
March 18-19, 2019
NETL-Pittsburgh Building 922 Room 106A

Corby Anderson

Corby Anderson joined the Department of Metallurgical and Materials Engineering at the Colorado School of Mines as the Harrison Western Professor of Metallurgical and Materials Engineering. Dr. Anderson teaches and conducts research as a member of the Kroll Institute for Extractive Metallurgy. He is an expert in the fields of extractive metallurgy, mineral processing, waste minimization, and recycling. Dr. Anderson has an extensive background in industrially oriented research and was responsible for the development and success of the Center for Advanced Mineral and Metallurgical Processing at Montana Tech.

Dr. Anderson is a registered engineer with more than 39 years of global experience in industry, management, engineering, design, economics, consulting, teaching, research, and professional service. 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. He holds a B.S. from Montana State, an M.S. from Montana Tech, and a Ph.D. from the University of Idaho.

Chris Haase

Chris Haase serves as Director of the Critical Materials Institute after working at GE Ventures, where he was Senior Director, leading new business creation and investment activities in the areas of oil and gas, power, and renewables. With background in defense and natural resources, Dr. Haase has served as an early-stage technology manager and investor in four corporate venture capital organizations: Shell Technology Ventures Fund 1, BTG Ventures, Shell GameChanger, and GE Ventures. In upstream energy, Dr. Haase served as the head business advisor to the Chief Technology Officer of Royal Dutch/Shell, managing alignment of research and development (R&D) funding with the company's long-term corporate strategy and value chains, while also launching Shell's latest venture fund, Shell Ventures. Additionally, Dr. Haase was Shell's manager for external research in Houston, Texas, where he helped Shell close many innovative partnership agreements with major universities and small enterprises in North America. With a background in oil and gas exploration and joint venture management, Dr. Haase has worked on several oil and gas development projects, joint ventures, and high-value divestments involving assets in the Gulf of Mexico, South Atlantic, North Sea, Middle East, and Australia.

A former U.S. Department of Defense (DOD) Fellow and adjunct professor at the U.S. Naval Academy, Dr. Haase held R&D positions with the Naval Ocean Systems Center (now the Space and Naval Warfare Systems Command [SPAWAR]) and DOD, and also served as a longtime volunteer commercialization advisor for the U.S. Missile Defense Agency and the Texas Emerging Technology Fund. An inventor with several patents, Dr. Haase received his Ph.D. and M.S. degrees in mathematics from the University of Chicago, his MBA from Erasmus University in Rotterdam, and his B.S. degree (Summa Cum Laude) from Ohio State University.

Kenneth N. Han

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. 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.

His research topics 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, he also holds 8 patents related to extractive metallurgy, and won numerous awards from academic, technical, and professional societies. Dr. Han received his B.S. and M.S. degrees from Seoul National University, an additional M.S. degree from the University of Illinois, and his Ph.D. from the University of California.

Marc LeVier

Marc LeVier is the President of K. Marc LeVier & Associates, Inc., which provides insights on metallurgical processes and analytical laboratory data to investors and mining and engineering companies to minimize risk, maximize profitability, and improve operating efficiency. Mr. LeVier has more than 45 years of experience in mineral process engineering, project management, and operations, covering iron ore, base metals, precious metals, uranium, coal, rare earths, and industrial minerals. He has previously been employed as the President, CEO, and Director at Great Western Minerals Group Ltd; President, CEO, and Director at Texas Rare Earth Resources; and Senior Director of Metallurgical R&D at Newmont Mining Corporation.

He has received numerous awards and honors (e.g., American Institute of Mining, Metallurgical, and Petroleum Engineers [AIME] James Douglas Gold Medal Recipient; SME Distinguished Member; SME Ivan B. Rahn Education Award; SME Presidential Citation; Arthur C. Daman Lifetime Achievement Award; and 2017 St. Barbara Day Award Recipient) and authored publications like the Journal of Hydrometallurgy and International Journal of Mineral Processing. Mr. LeVier is a member of SME, the Mining and Metallurgical Society of America (MMSA), and the Canadian Institute of Mining and Metallurgy (CIM). He received his B.S. and M.S. degrees in Metallurgical Engineering from Michigan Technological University and an Honorary Doctor of Science from Montana Tech of the University of Montana.

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.