2021-2022

CRITICAL MINERALS SUSTAINABILITY PROGRAM

PROJECT PORTFOLIO

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

DISCLAIMER

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INTRODUCTION

PROGRAM OVERVIEW

Since 2014, the Department of Energy (DOE) through its Office of Fossil Energy and Carbon Management (FECM) and NETL have undertaken a research, development, and demonstration (RD&D) program that has focused on the extraction, separation, recovery, and purification of rare earth elements (REE) and critical minerals (CM) from coal-based resources which include run-of-mine coal, coal refuse (mineral matter that is removed from coal prior to shipment), clay/sandstone over/under-burden materials, ash (coal combustion residuals), aqueous effluents such as acid mine drainage (AMD), and associated solids and precipitates resulting from AMD treatment. Over the past seven years, DOE-NETL's program has conducted over 40 projects which have involved the mineral processing and process development expertise of our extramural stakeholders at universities and small businesses, as well as at the Los Alamos, Lawrence Livermore, Idaho, and Pacific Northwest national laboratories, and the intramural field work proposal (FWP) efforts at NETL's Research and Innovation Center (RIC). The projects have bracketed the full spectrum of technology readiness levels (TRLs) from the basic and applied sciences (TRL 1–3) through the design, construction and operation of bench/pilot-scale facilities (TRL 3–5/5–7), and most currently, conceptual design for operation of an engineering-scale prototype facility (TRL 7–8) that, when functional, will produce 1–3 metric tons mixed rare earth oxides (MREO) per day using coal-based resources and potentially alternative feedstock materials.

Since 2014, domestic coal-based resources that are REE-enriched have been identified and locations and quantities available for sustainable commercial use continue to be addressed with assistance from geospatial modeling. Development of advanced fiber optic probes and laser induced breakdown spectroscopy (LIBS) field sensors for in-situ field detection of REE at parts-per-billion (ppb) and parts-per-million (ppm) concentrations continues. Funding opportunities issued by NETL in 2016 directed extramural stakeholder efforts to produce at a minimum of 2 wt% (20,000 ppm) MREO preconcentrates. By 2018, small bench/pilot-scale facilities had been constructed, and currently the DOE-NETL program has demonstrated the technical feasibility of producing small quantities of high purity—approximately 98 wt% (980,000 ppm) and greater— MREO in three domestic first-of-a-kind small bench/pilot-scale facilities.

Research has also focused on optimization and efficiency improvement of conventional REE separation systems to achieve process economic viability as well as development of advanced, transformational REE and CM separation processes. Notably, all conventional and transformational REE and CM separation process designs have undergone rigorous techno-economic analysis (TEA) prior to bench/small-pilot-scale facility construction and operation.

In 2019, RD&D efforts at NETL were additionally directed to co-production of CM, as cobalt (Co), manganese (Mn), lithium (Li), and potentially aluminum (Al), zinc (Zn), germanium (Ge), and gallium (Ga) from domestic, coal-based, REE-containing feedstock materials. Currently, state-of-the-art conventional separation process concepts are being assessed for near-future production of 1–3 metric tons per day of high-purity MREO in engineering-scale prototype facilities.

In 2021, DOE-NETL's REE-CM program initiated basinal coalition efforts to address realization of the full economic potential value of U.S. natural resources for producing REE, CM, and high-value, nonfuel, carbon-based products, and to holistically assess not only upstream mining of resources and physical separation (e.g., beneficiation), but also midstream processing, separation, recovery, and purification of critical and high-value materials, and ultimately on-shore downstream manufacturing that incorporates these materials into commodity and/or national defense intermediate or end products.

BACKGROUND

Rare earth elements (Figure 1) are essential materials in a broad range of technologies significant to national security, energy, medical, and consumer products (Figure 2). REE occur throughout the earth's crust, commonly at low concentrations. They are not found in an isolated form readily available for extraction, but are distributed throughout a variety of minerals, and are also found in coal and coal by-products. REE-bearing mineral deposits are relatively rich in either light rare earth elements (LREE) or heavy rare earth elements (HREE), with LREE generally more abundant. The environmental footprint created by conventional REE processing techniques has long been a key consideration in determining where these elements are mined and subsequently produced.

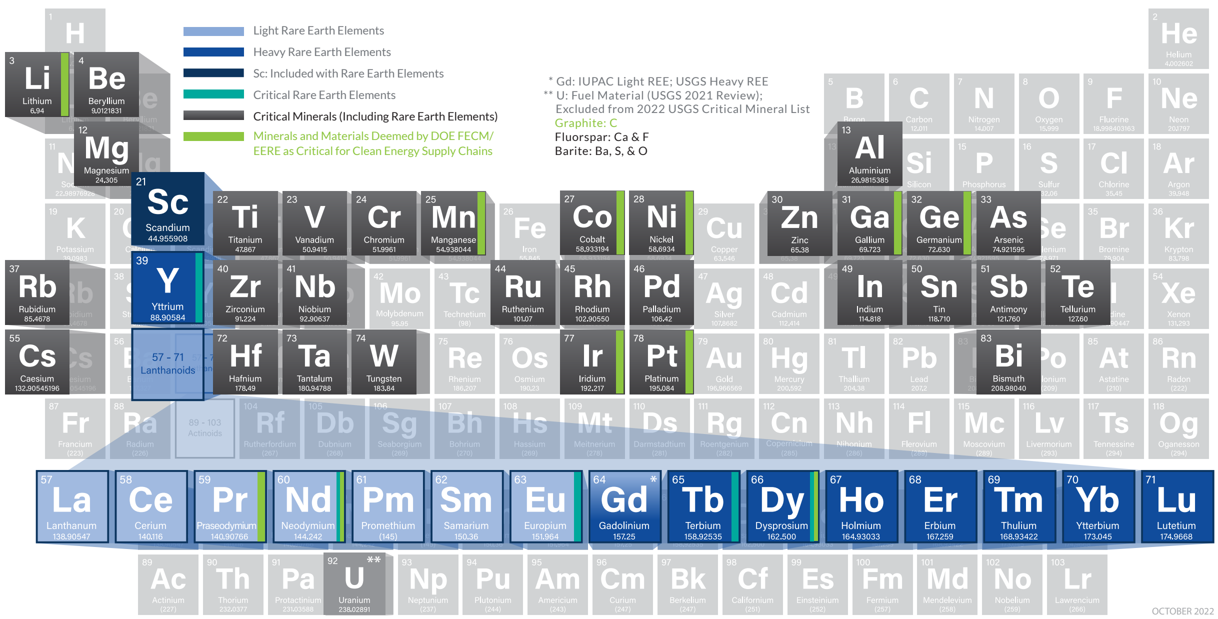


Figure 1. Rare earth elements (including scandium and yttrium) and additional critical minerals.

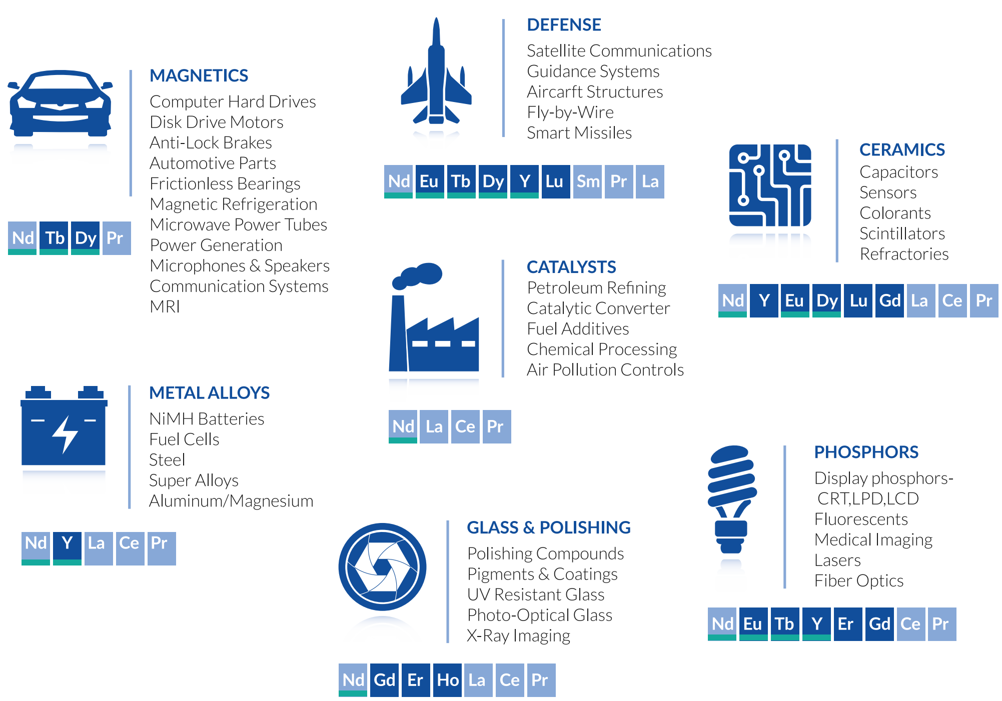


Figure 2. Rare earth element applications.

In contrast to the 1980s, when the United States produced more rare earth elements (REE)[1] than any other country in the world (Figure 3), the nation currently imports 80% of its REE directly from China, with portions of the remainder indirectly sourced from China through other countries. Similarly, the United States imports more than half of its annual consumption for thirty-one of the thirty-five critical minerals (CM)[2] and has no domestic production for fourteen CM and is therefore dependent on imports to supply demand for them [1].

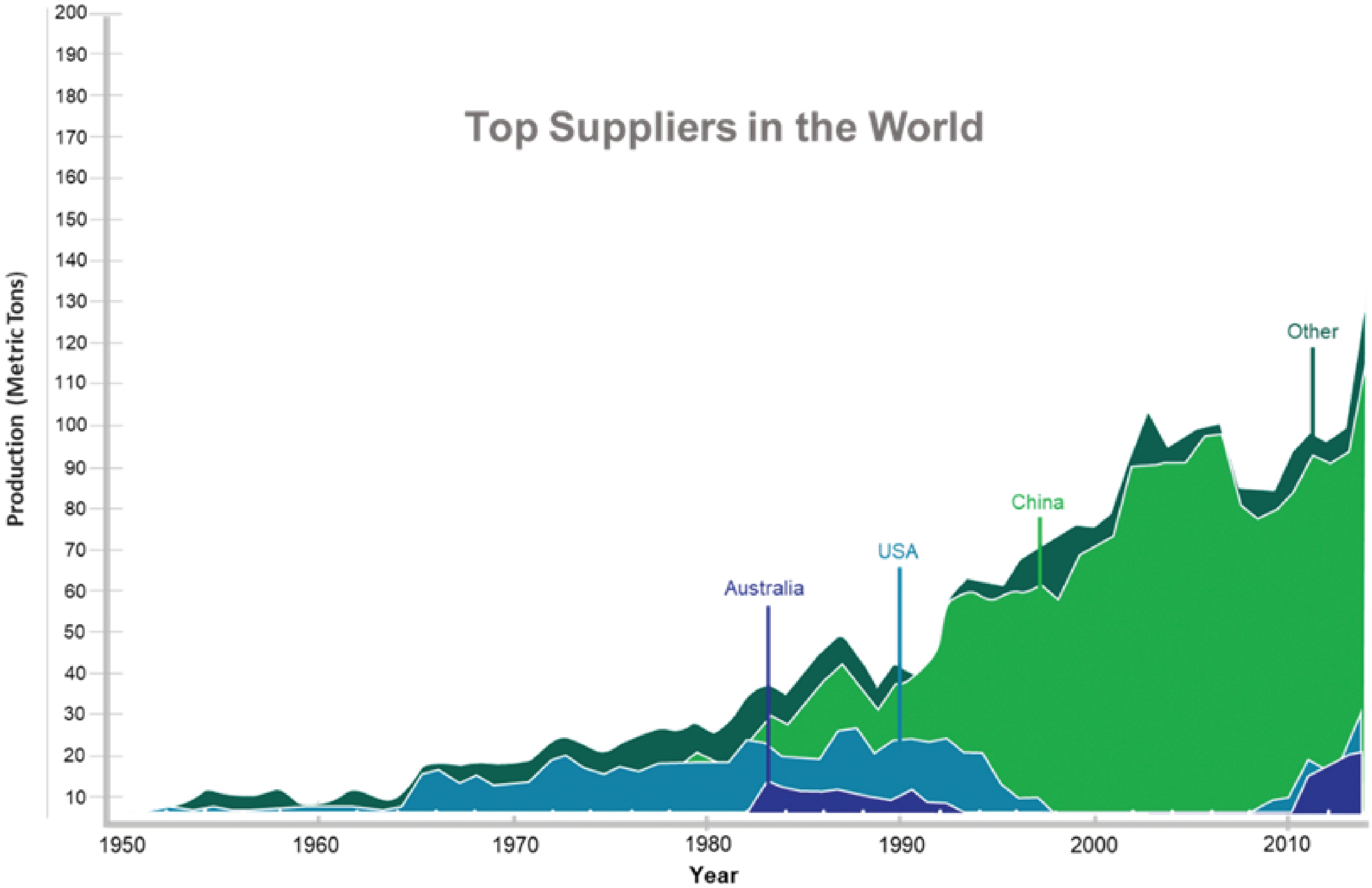


Figure 3. Major international rare earth suppliers.

[1]Rare Earth Elements: Lanthanum, cerium, praseodymium, neodymium, (promethium), samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium. Scandium and yttrium are often also included.

[2]Critical Minerals: Aluminum (bauxite), antimony, arsenic, barite, beryllium, bismuth, cesium, chromium, cobalt, fluorspar, gallium, germanium, graphite (natural), hafnium, indium, lithium, magnesium, manganese, nickel, niobium, platinum group metals, potash, the rare earth elements group, rhenium, rubidium, scandium, tantalum, tellurium, tin, titanium, tungsten, vanadium, yttrium, zinc, and zirconium. Critical minerals are nonfuel minerals or materials that are essential to our modern economy and national security and that have a supply chain vulnerable to disruption.

PROGRAM MISSION, OBJECTIVES AND GOALS

The mission of the DOE-NETL REE program between 2014 and 2020 was the development of an economically competitive and sustainable domestic supply of REE to assist in maintaining our nation's economic growth and national security. In 2020, the program's mission was expanded to include CM [2].

The objectives of the DOE-NETL 2014-2020 ***Feasibility of Recovering Rare Earth Elements*** program were to:

- Recover REE from coal and coal by-product streams, such as run-of-mine coal, coal refuse, clay/sandstone over/under-burden materials, power generation ash, and aqueous effluents as acid mine drainage (AMD).
- Advance existing and/or develop new second-generation or transformational extraction and separation technologies to improve process system economics and reduce the environmental impact of the coal-based REE value chain (Figure 4).

The goals of the program were to (1) validate the technical as well as economic feasibility of recovering REE from coal-based materials, and (2) accelerate the design, construction and near-term operation of a domestic engineering-scale prototype facility in an environmentally benign manner, producing 1–3 metric tons/day of mixed rare earth oxides or salts (MREO/MRES) from coal-based resources at purities of a minimum of 75 wt%.

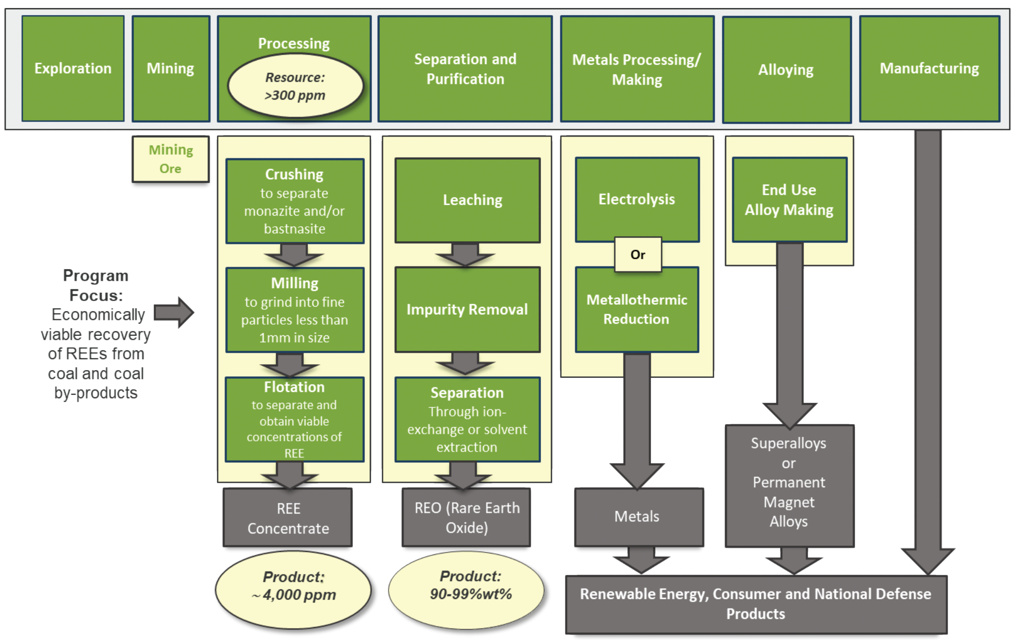


Figure 4. Rare earth value chain.

KEY TECHNOLOGY AREAS

From 2014-2020, the ***Feasibility of Recovering Rare Earth Elements*** program consisted of three key technology areas. These included (Figure 5):

- **Enabling Technologies:** Develop DOE-NETL's technology knowledge basis through resource identification, field sampling and characterization, techno-economic analysis development, and field and/or process sensor development.
- **Separations Technologies:** Address the viability of utilizing commercially available extraction and separation equipment and/or systems that have been developed for alternate technologies, and demonstrate their capability (i.e., technology transfer) for the extraction and separation of REE from coal-based materials. In parallel, develop new/novel embryonic/transformational REE extraction and separation concepts.
- **Process Systems:** Design/construct/operate bench-scale and/or pilot-scale systems to validate the capability of producing REE from coal-based resources.

PROGRAM DIRECTION

Transitioning the production of these dual-use materials and their associated supply chains back to the United States is a strategic priority, as evidenced by recent and proposed U.S. legislation, as well as by several recent executive orders [1,2]. Consequently, RD&D efforts to create new domestic sources of REE have been accelerated with the goal of making our domestic supply chains more resilient.

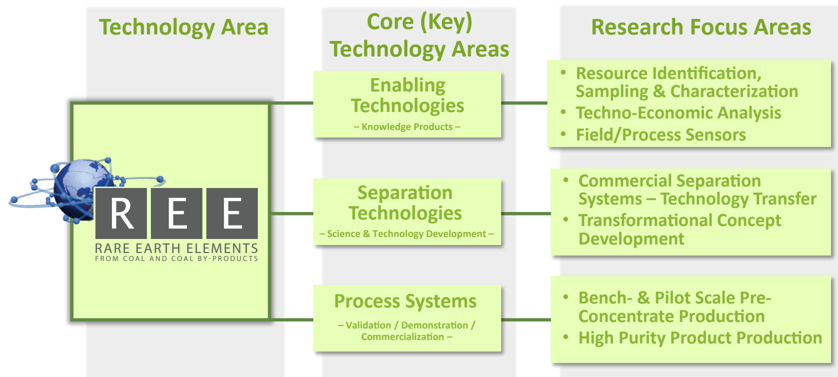


Figure 5. Program structure.

In order to comply with Executive Order 13817 [2], DOE's program expanded its technology development effort in 2019 to include the recovery of CM from coal-based resources. As a result, DOE's program in 2020 was renamed as the ***Critical Minerals Sustainability Program***, required existing domestic small pilot-scale facilities to co-produce CM in addition to producing REE.

Building on the accomplishments achieved between 2014 and 2020 in DOE-NETL's ***Feasibility of Recovering Rare Earth Elements*** program, and aligning the program to further support Executive Order 13817, the following five focus areas were identified for conduct in DOE-NETL's ***Critical Minerals Sustainability Program***:

- **Characterization Technology Development:** Technology development and validation for environmentally sustainable exploration and production of CM and REE from various sources. This includes the economic recovery of CM and REE through identification (including physical and chemical properties), mineral assays, prediction and assessment of resources and volumes of CM and REE from various feedstocks.
- **Sustainable Mining Technology Development:** Novel technology development and validation for sustainable conventional and unconventional mining to enable the recovery of CM and REE from sources that are not currently used for recovery, or that could be recoverable through the use of more sustainable practices.
- **Concentration and Processing Technology Development:** Advanced environmentally friendly and economically feasible technology development for beneficiation, concentration and processing of CM and REE. This includes development of models to be used as virtual test platforms to optimize process separation designs.
- **Individual Separation and Reduction to Metals Technology Development:** Environmentally friendly and economic technology development of individually separated high purity (ISHP) rare earth oxides/salts (REO/RES) and ultimately rare earth metals (REM) and CM. High purity elements will be critical for use in manufactured products.
- **Techno-Economic Analysis:** Evaluation of the international CM and REE markets and assessment of the economics of commercial production.

RD&D efforts will continue to enable the sustainable recovery of CM including REE throughout the supply chain. Understanding the basinal deposit relationships of these CM and REE from carbon ore,[3] other ores, mining by-products, abandoned mines and other valuable sources will enable projects to address resources holistically. Advanced technologies developed throughout the supply chain and co-production business models will continue to improve the economics of future projects. The program will strive to develop and test in engineering-scale prototype facilities the technologies that industry will need to establish a domestic supply chain to help fuel our nation's economic growth, transition to clean energy technologies, secure our energy independence by reducing our reliance on foreign sources, and increase our national security.

REFERENCES

1. Executive Order 13953, Addressing the Threat to the Domestic Supply Chain from Reliance on Critical Minerals from Foreign Adversaries and Supporting the Domestic Mining and Processing Industries, September 30, 2020.
2. Executive Order 13817, A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals, December 20, 2017. List of Critical Minerals posted in Federal Register/Vol. 83, No. 97/Friday, May 18, 2018/Notices.

[3]Carbon Ore: Coal, coal by-products, and coal waste streams such as acid mine drainage (AMD) and fly ash.

DESIGNS FOR PRODUCTION OF 1-3 METRIC TONNES PER DAY MIXED RARE EARTH OXIDES (>75 WT%)

Production of Mixed Rare Earth Oxides from Coal-Based Resources

Performer	**Various**
Award Number	Various
Project Duration	10/01/2020 – 03/07/2022
Total Project Value	~$1,950,000 (Phase I) and ~$19,000,000 total (Phase II)
Technology Area	Process Systems – Engineering-Scale Prototype Facility

Thirteen projects were selected for phase I, to receive an approximate total of $1.95 million in federal funding to develop conceptual designs using commercially viable technologies that will extract rare earth elements (REE) from U.S. coal and coal by-product sources. Each contract received up to $150,000 in DOE funding. The conceptual designs included system configurations, equipment features, performance characteristics, and associated costs for systems that produce at least 1–3 metric tons per day of mixed rare earth oxides (MREO) or mixed rare earth salts (MRES), and in some designs, other critical minerals (CM).

DOE's ***Critical Minerals Sustainability Program*** has demonstrated the technical feasibility of extracting these materials from coal-based resources. The program has moved from bench/pilot scale to engineering-scale prototype materials processing to address scale-up challenges for future opportunities.

In phase II, DOE exercised options to continue work on eight projects to complete feasibility studies of their concepts. The objective of the feasibility studies was to prove the technical and economic feasibility of the facility concept/configuration proposed to achieve the design criteria. The eight down-selected feasibility studies are as follows:

- Energy Fuels Holdings Corp. (Lakewood, CO)
- Materia USA, LLC (Inwood, NY)
- MP Mine Operations, LLC (Mountain Pass, CA)
- Tetra Tech, Inc. (Pittsburgh, PA)
- Texas Mineral Resources Corp. (Sierra Blanca, TX)
- University of North Dakota Energy and Environmental Research Center (Grand Forks, ND)
- West Virginia University Research Corporation (Morgantown, WV)
- Winner Water Services, Inc. (Sharon, PA)

These studies supported an Association for the Advancement of Cost Engineering (AACE) Class 4 cost estimate on conceptual facilities that can produce 1–3 metric tons per day of a minimum of 75 wt% MREO or MRES, and if feasible, additional CM. Additionally, some phase II awards elected to extend their proposed facilities further to refined metals, alloys, or other products. Cumulatively, nearly $19 million in federal funding was awarded for the eight phase II feasibility studies, which were managed by DOE's National Energy Technology Laboratory.

Rare earth elements: essential dual-use materials.

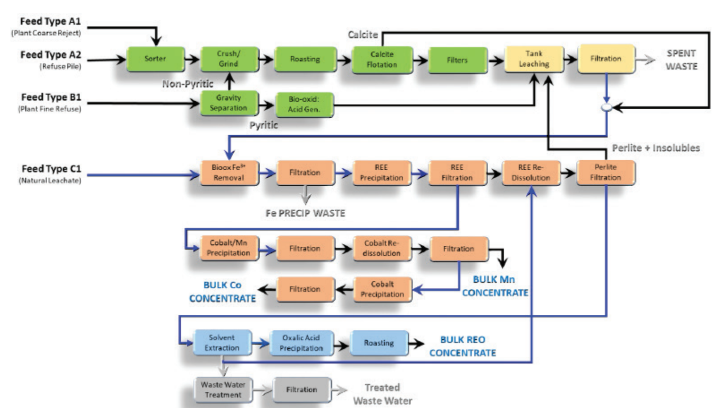
CONVENTIONAL RARE EARTH ELEMENT SEPARATION SYSTEMS

Demonstration of Scaled-Production of Rare Earth Oxides and Critical Materials from U.S. Coal-Based Sources

Performer	University of Kentucky
Award Number	FE0031827
Project Duration	10/01/2019 – 12/31/2022
Total Project Value	$ 6,250,000
Collaborators	Virginia Polytechnic Institute and State University; University of Utah; Mineral Separation Technologies, LLC; Alliance Resource Partners; Kentucky River Properties, LLC
Technology Area	Process Systems – Small Pilot-Scale Facility

University of Kentucky is extending the activities of the existing rare earth elements (REE) small pilot-scale plant to integrate and test new technologies and circuits to significantly reduce the cost of producing mixed rare earth oxides (MREO), cobalt, and manganese. Concentrate production will be increased from between 10 and 100 grams/day (current rate) to about 200 grams/day. To significantly reduce the primary cost of producing the concentrates, naturally occurring coal pyrite is being recovered and used in bioreactors to produce the acid needed for leaching. To assess the technical and economic potential of extracting REE from coal waste, a ¼-ton per hour modular small pilot plant was designed, constructed, and tested as part of an ongoing project funded by DOE. Although the small plant was successful in recovering REE and producing MREO having a purity level greater than 90 wt%, several economic barriers were encountered that required more detailed evaluations and modification of the process circuitry. A reduction in the chemical costs per kilogram of REO recovered is needed for the process to be economically viable for a typical coal source.

This project consists of a team of researchers from the University of Kentucky, University of Utah, and Virginia Tech. Alliance Coal is the host and provider of operational support for the pilot plant as well as the necessary quantity of qualified feedstock. Kentucky River Properties, LLC is collecting and transporting several tons of qualified feedstock to the pilot plant location. Mineral Separation Technologies provided a dual X-ray transmission sorter for separation of the feedstock into materials that contain potentially high concentrations of REE. The information garnered from simultaneous assessment of process cost will guide process development and circuit design to enhance performance success and the potential for commercialization. At the end of the project, a pathway will be established for the production of high-purity MREO (greater than 90 wt%) and other critical material concentrates (greater than 50 wt%) from bituminous coal resources in an environmentally friendly manner at a production rate of around 0.2 kg daily.



Integrated process flowsheet showing the addition of innovative technologies implemented to enhance the economic extraction of REE, Sc, Co and Mn from pre-combustion bituminous coal-based.

Rare Earth Element Extraction and Concentration at Pilot-Scale from North Dakota Coal-Related Feedstocks

Performer	**University of North Dakota Energy and Environmental Research Center (UNDEERC)**
Award Number	FE0031835
Project Duration	10/01/2019 – 06/30/2023
Total Project Value	$ 6,508,555
Collaborators	Barr Engineering; BNI Energy; Critical Materials Institute; Great River Energy; Microbeam Technologies; Minnkota Power; MLJ Consulting; North American Coal Corporation; North Dakota Geological Survey; North Dakota Industrial Commission; Rare Earth Salts
Technology Area	Process Systems – Small Pilot-Scale Facility

The University of North Dakota Energy and Environmental Research Center (UNDEERC) is demonstrating at small pilot scale a high-performance, economically viable and environmentally benign technology to recover rare earth elements (REE) from North Dakota (ND) lignite coal feedstocks. To achieve this goal, UNDEERC is:

- Designing and constructing a small pilot-scale system for continuous REE extraction from ND coal feedstocks capable of using a minimum 0.5 tons per hour feed rate of physically beneficiated lignite coal.
- Obtaining approximately 300 tons of ND lignite containing greater than 300 ppm REE to provide adequate material for shakedown and continuous testing in the small pilot-scale demonstration facility.
- Conducting initial parametric testing of a sample of the ND lignite at bench scale to cost-effectively identify optimal operating conditions and aid in the design of the small pilot-scale system.
- Commissioning the small pilot facility using selected high-REE-containing coals from various regions in ND.
- Conducting continuous small pilot-scale testing under optimal conditions for REE extraction and concentration using at least 100 tons of ND lignite that contains greater than 300 ppm REE.
- Confirming compatibility of REE concentrate generated during small pilot-scale testing with commercial-scale REE refining.
- Using results from the small pilot-scale testing to conduct a techno-economic analysis (TEA) and preliminary front end engineering design (pre-FEED) study on a potential commercial facility where an economic feasibility study and workforce assessment will be performed.
- Working with industry partners to develop a technology roadmap and commercial deployment plan.

UNDEERC's efforts will provide information on availability of the proposed feedstock; information on environmental impacts; process flow diagram(s); product yield and concentration; and estimated system costs.

Coarse (left) and fines (right) coal piles extracted from Freedom Mine.

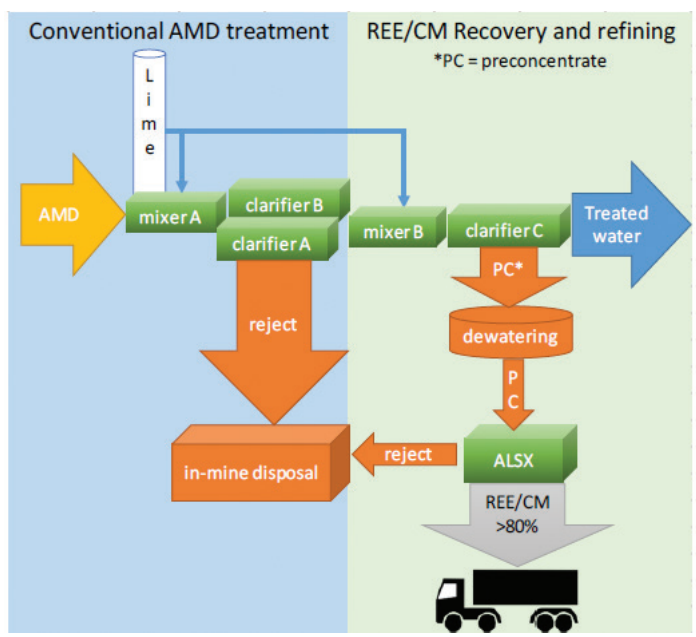
Development and Testing of an Integrated Acid Mine Drainage (AMD) Treatment and Rare Earth/Critical Mineral Plant

Performer	**West Virginia University Research Corporation (WVURC)**
Award Number	FE0031834
Project Duration	10/01/2019 – 12/31/2022
Total Project Value	$7,112,691
Collaborators	Rockwell Automation; Virginia Polytechnic Institute and State University
Technology Area	Process Systems – Small Pilot-Scale Facility

The primary objectives of this project are to design, construct, and test a small pilot-scale continuous integrated process for simultaneous and efficient treatment of up to 1,000 gallons per minute (gpm) of acid mine drainage (AMD) while producing an enriched REE/CM (rare earth elements/critical minerals) concentrate. WVURC, in conjunction with partners West Virginia Department of Environmental Protection and Rockwell Automation, Inc., will carry out the objectives in two developmental stages. The first stage will focus on the engineering design, construction, and assembly of a small pilot-scale process to be used in the project. To support these development efforts, WVURC will construct and test a small-scale, fully continuous test unit to emulate the performance of the upstream concentrator. This test unit will allow rapid optimization of various operational variables and limit the need for extensive testing at the larger-scale facility.

During the second stage of work, the integrated small pilot-scale plant will be operated on a continuous basis to validate process performance and refine process cost estimates. During both stages, additional efforts will focus on critical support tasks including technical and environmental systems analysis.

WVURC has identified that AMD produced from sulfur contained in coal and other ore bodies is an attractive source of REE/CM since it relies on natural processes to create a concentrate, easily extracted feedstock. WVURC has demonstrated that this process is environmentally beneficial since it would incentivize treatment of AMD. If successful, this plant will generate about 1,000 tons per year of REE/CM oxides with an estimated contained value of $237/kg.



Schematic flowsheet for AMD REE.
Conventional AMD treatment is shaded blue.

High Yield and Economical Production of Rare Earth Elements from Coal Ash

Performer	**Physical Sciences, Inc.**
Award Number	FE0027167
Project Duration	03/01/2016 – 03/31/2022
Total Project Value	$ 9,999,968
Collaborators	University of Kentucky Center for Applied Energy Research; Winner Water Services
Technology Area	Process Systems – Small Pilot-Scale Facility

In Phase 1, Physical Sciences, Inc. (PSI) and the University of Kentucky's Center for Applied Energy Research (UK CAER) undertook a comprehensive research effort to investigate the REE content including yttrium and scandium (REYSc) of coal-fired power plant ashes. PSI also conducted feasibility and techno-economic analysis (TEA) for recovery of REYSc from the coal ashes and developed the design of a small pilot-scale facility to economically produce salable REYSc-rich concentrates and commercially viable co-products from coal ash feedstock using environmentally safe and high-yield physical and chemical enrichment and recovery processes.

In Phase 2, PSI, Winner Water Services (WWS) and UK CAER constructed both a micro-pilot facility located at PSI (Andover, Massachusetts), and a small pilot facility located at WWS (Sharon, Pennsylvania) for chemical processing. The small pilot plant was operated at the scale of approximately 0.4–1 tonne per day (tpd) ash throughput for physical processing and about 0.5 tpd for chemical processing. The plant produced at least 50 grams (g) of dry REYSc nitrates containing more than 10 wt% REYSc, and targeted 500 g of dry REYSc nitrate concentrate containing more than 20 wt% Sc. The ash material used in this effort was from the Dale power plant in Ford, Kentucky. The ash feedstock contained at least 300 parts per million (ppm) of REYSc content and had the potential to yield greater than 500 ppm of REYSc content.

The data obtained from the small pilot-scale plant operations will be used to enhance and validate the TEA analysis that was completed for both the physical and chemical processing plants at a scale of 600 tpd in Phase 1 and will be used to design a commercial scale plant (hundreds of tpd throughput) with a projected return on investment of less than seven years. Demonstration of PSI's technology to recover REYSc from coal ash will enable utilization of coal mining/coal combustion wastes in environmentally benign ways to produce REE of strategic importance for the United States while generating jobs and economic growth in economically depressed regions of this country.

PSI-WWS small pilot-scale facility.

Recovery of Rare Earth Elements from Coal Byproducts: Characterization and Laboratory-Scale Separation Tests

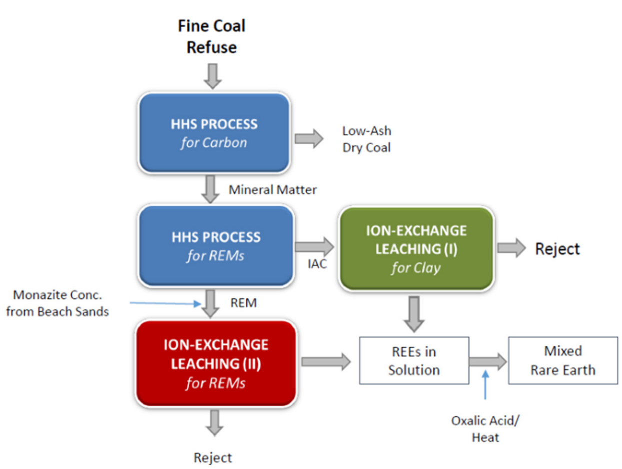
Performer	Virginia Polytechnic Institute and State University
Award Number	FE0029900
Project Duration	08/01/2017 – 03/31/2022
Total Project Value	$2,266,495
Technology Area	Reduction to Metals

Rare earth elements (REE) are critical for the development of renewable energy resources, national security, and advanced manufacturing. With the recent closure of the rare earth mine in California, the United States relies entirely on foreign imports mainly from China. According to a study commissioned by NETL, the U.S. coal and coal byproducts contain approximately 11 million metric tons of recoverable REE, which is comparable to the conventional rare earth reserves in the United States. One problem associated with the rare earth recovery is that the grain sizes of the rare earth minerals (REM) in coal matrix are small (<5 μm), which makes their economic recovery difficult using conventional minerals processing technologies. It is, therefore, necessary to study the fundamental mechanisms involved in the separation and extraction of REE from coal and coal byproducts.

The objective of this project was to collect fundamental information that can be used to develop disruptive physical and chemical separation technologies that are capable of extracting REE from coal-based feedstocks in a highly efficient, cost-effective, and environmentally benign manner. To meet the stated objective, a set of interrelated fundamental studies were conducted, subdivided into three broad groups of work that encompass:

1. Measurement of surface forces affecting the motions of ultrafine REE particles in confined fluids
2. Identification of mechanisms by which REE ions adsorb and desorb on clay minerals
3. Determination of the dissolution kinetics of REE in different leach solutions

The results obtained from these fundamental studies are expected to help accelerate the deployment of emerging separation technologies



REE recovery from fine coal refuse: new approach.

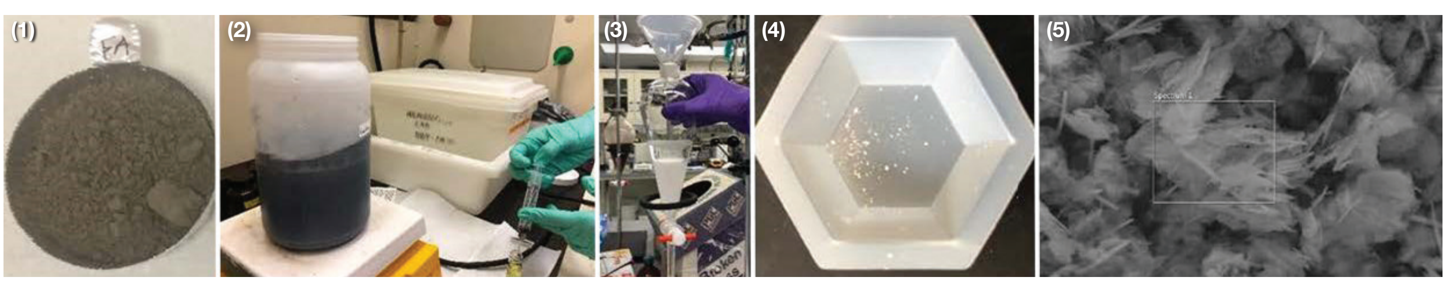
Rare Earth Element (REE) Extraction from Powder River Basin (PRB) Coal Byproducts

Performer	**National Energy Technology Laboratory**
Award Number	TCF-20-21358
Project Duration	12/02/2020–12/01/2023
Total Project Value	$1,620,000
Collaborators	University of Wyoming; Campbell County, WY; Gillette, WY; Energy Capital Economic Development
Technology Area	Enabling Technologies

The project will mature a promising process to produce rare earth elements (REE) from a coal-related feedstock—fly ash created from the combustion of Powder River Basin (PRB) coal—by partnering with leading academic and industrial entities in Wyoming. The project will culminate in the creation and start-up of a pilot-scale production facility to demonstrate the process performance and economics, reducing the risk to the construction of a full-scale facility.

The project objectives are to (1) identify the most promising feedstock(s) in the PRB for the extraction of REE and critical minerals (CM), (2) demonstrate the efficacy of extracting REE and CM in an economic manner, and (3) demonstrate the feasibility of up-scaling NETL extraction technologies to a pilot scale in the PRB. In order to meet these objectives, the team will leverage the regional geologic and industrial knowledge from the University of Wyoming consortium with the extraction chemistry capabilities and intellectual property from NETL to demonstrate the commercial viability of the REE extraction process. Moreover, patented NETL sorbent and membrane technologies will be leveraged for incorporation into downstream REE oxide production from each feedstock. The project will accelerate the use of PRB coal-related wastes as a critical mineral resource.

There is currently a gap in the production of domestic REE ore or concentrates, forcing REE refiners/concentrators to seek feedstocks from overseas. This technology will fill that gap by providing a REE concentrate from a domestic feedstock—coal refuse or coal fly ash—which is a byproduct of other industrial activities. The use of an industrial byproduct as a feedstock has the potential to make power generation from Wyoming coal more competitive and the presence of two revenue streams—electricity and REE concentrate—limits the impact of price shifts in either market. The focus on waste materials from PRB coal is notable because it represents 40% of U.S. coal production and ultimately could be used to meet a significant portion of U.S. demand for REE.



Rare earth elements and yttrium (REY) recovery processing chain of the tested PRB fly ash. Photos from left to right display: (1) PRB fly ash as received, (2) large laboratory scale step leaching process, (3) organic solvent extraction for REY purification; (4) final oxalate precipitant collected, (5) scanning electron microscope image of oxalate product containing 30 wt% REY.

NOVEL REE SEPARATION & ADVANCED SENSOR DEVELOPMENT

— FIELD WORK PROPOSAL (FWP) PROJECTS —

Minerals Sustainability (Resource Characterization)

Performer	**National Energy Technology Laboratory – Research and Innovation Center (NETL-RIC)**
Award Number	FWP-1022420
Project Duration	04/01/2018 – 03/31/2023
Total Project Value	$11,451,654
Technology Area	Enabling Technologies, Separation Technologies, and Process Systems

The work in this research focus area develops and validates a geo-data science-driven approach for systematically assessing unconventional REE/CM occurrences in sedimentary strata to identify targets of predicted higher prospectivity. This includes the development of predictive models and identification of key data and knowledge gaps that hinder resource predictions. This focus area also plugs these identified gaps in knowledge by targeted sample collection and characterization of geologic samples from archived or recently collected drill cores from domestic sedimentary strata. These efforts harmonize geological, geochemical, and geospatial datasets from DOE, USGS, state agencies, and other public sources to assess and validate if REE/CM occur in adequate concentrations and volumes to support commercial extraction in priority U.S. basins. A new task in this focus area will develop a national REE-CM (Rare Earth Element-Critical Minerals) database and virtual online dashboard for rapid and efficient assessment of REE-CM sedimentary resources. Finally, a second new task in this focus area will begin to collect, curate, and build a database of lithium brine chemistry and associated attribute (production volumes, etc.) data for major U.S. shale plays.

This effort will be beneficial, as CM occur in small quantities in coal and coal by-products (as compared to traditional ore bodies) and currently processes are being explored to economically recover CM/REE from coal and coal by-products. Furthermore, technologies that currently exist for the extraction of REE from other resources use large amounts of aggressive and toxic chemicals and are not suitable for deployment in the United States. Current methods for acid mine drainage (AMD) solids only extract REE as end-products, whereas Co, Ni, Zn, and Li are detected at very high concentrations and values in existing AMD solids.

This research is maximizing all REE and CM value from the AMD solids via cost-effective, characterization-informed, and environmentally friendly sequential leaching. An application of this approach would be the use of advanced characterization techniques on acid mine drainage solids to inform binding conditions of CM, including REE, Co, Ni, Zn, and Li, in these materials. The knowledge gained from characterization will be further developed into innovative and informed sequential extractions targeting the major REE and CM-hosting solid fractions for efficient and economical REE/CM recovery. This effort will make public basin and geographic trends in resource availability to help guide further research in the valorization of lithium resources in oil and gas wastewater.

Minerals Sustainability (Emerging Resources)

Performer	**National Energy Technology Laboratory – Research and Innovation Center (NETL-RIC)**
Award Number	FWP-1022420
Project Duration	04/01/2018 – 03/31/2023
Total Project Value	$11,451,654
Technology Area	Enabling Technologies, Separation Technologies, and Process Systems

Unconventional critical mineral resources are high-potential targets for industrial-scale resource recovery, but in many cases the modes of occurrence and method of enrichments are poorly understood. The research in this portfolio includes the core R&D related to understanding unconventional critical mineral resources, their potential recovery, and techniques that can help these unconventional resources emerge as viable industrial-scale sources of critical minerals. Advanced characterization methods are used to understand how these critical minerals are bound in these materials, such as coal ash and acid mine drainage solids, to give clues to the most environmentally benign methods of extraction and to help understand the opportunities for improvement of existing processes. This focus area is developing a biological process to facilitate release of critical materials (CM) from acid mine drainage (AMD) treatment solids. It is also maturing and optimizing a heap leach process for REE extraction from clays and legacy coal wastes. A new task this year is identifying technical barriers and developing in situ methods for REE and CM recovery from non-traditional subsurface resources including shales and coals.

AMD results from the interaction of groundwater with abandoned coal mines, producing waters that require treatment to minimize environmental impacts. This waste stream is a potentially valuable resource for REE and CM recovery. The Appalachian basin AMD alone could meet up to 30% of the U.S. annual REO demand in 2018. Even though AMD is a valuable domestic source of CM, it is currently being treated as a costly waste management problem, and the biotechnology has not yet been developed to economically extract CM from these resources.

Current treatment processes of AMD already concentrate CM into solid phases that could be released and recovered. AMD is treated by modifying pH and redox conditions to neutralize acidity and decrease the solubility of dissolved metals. The precipitation of these metals generates material often referred to as AMD treatment solids that must be managed at significant cost to treatment system operators. These AMD treatment solids are typically landfilled or pumped into abandoned mines for disposal. However, many of these solids are MnOX/FeOX/AlOX-laden materials that sequester CM to concentrations approaching those in ores. Microorganisms that naturally reside in the treatment solids may already have the capability to reduce the treatment's solids, and enrichment of these microorganisms would release trapped CM in a solution, called a pregnant leachate solution (PLS). This would create a value stream from these waste products that would improve the economics of AMD treatment while also addressing the need for a domestic source of CM.

Minerals Sustainability (Emerging Technologies)

Performer	**National Energy Technology Laboratory – Research and Innovation Center (NETL-RIC)**
Award Number	FWP-1022420
Project Duration	04/01/2018 – 03/31/2023
Total Project Value	$11,451,654
Technology Area	Enabling Technologies, Separation Technologies, and Process Systems

These technologies operate at various points in the CM supply chain and are considered important enabling technologies because they have the potential to dramatically improve the viability of existing processes or to make new markets for materials. One important effort at NETL is the development of high-volume materials technologies based on super-abundant mischmetal components, Ce and La.. NETL research focuses on development in two areas, High Strength Steels, and Environmental Barrier Coatings. Another technology seeks to develop improved sorbents for the extraction of CM from produced waters. A novel sorbent is also being developed using hollow fibers to improve high-volumetric rate applications. Two projects are also included in this focus area that are intended to take separate approaches to improving the real-time measurements of critical minerals in solutions. One focuses on fiber optic sensors and the other uses laser-induced breakdown spectroscopy (LIBS) designed for down-hole testing in geologic environments. Two projects seek to develop direct lithium extraction methods from produced waters. One is developing a low-cost Li sorbent synthesized from AMD treatment wastes to generate robust Li concentrate from different oil and gas produced waters and another uses a non-sorbent based direct lithium extraction process dependent on carbonation.

La and Ce are the most abundant REE in both conventional domestic sources (e.g., monazite and bastnasite minerals) and unconventional domestic sources (e.g., legacy coal mining and related waste streams). Despite a relatively high demand for these elements, they are currently considered low-value by-products of the extraction of more valuable REEs. This is due to the so-called REE balance problem, where significant extraction of co-occurring REEs, such as Nd, produces an oversupply of La and Ce and decreases their value. Meanwhile, current materials which rely on purified versions of expensive and scarce REE-oxides, such as $Yb2O_3$, as precursors, may exhibit similar or better performance using mixtures of REE-oxides that are readily produced from unconventional domestic sources.

Developing new materials which use domestically abundant REE at large rates will address the REE balance problem and increase the value of domestically abundant REE. Using mixed REE-oxide precursors derived from unconventional sources in place of purified REE-oxides without sacrificing material performance will save on costly purification steps. Both strategies will improve the economics of domestic REE production.

Minerals Sustainability (Systems Analyses)

Performer	**National Energy Technology Laboratory – Research and Innovation Center (NETL-RIC)**
Award Number	FWP-1022420
Project Duration	04/01/2018 – 03/31/2023
Total Project Value	$11,451,654
Technology Area	Enabling Technologies, Separation Technologies, and Process Systems

The focus of the task is to understand the cost, performance, and environmental footprint of CM concentration and separation from non-conventional feedstocks, identify cost and performance R&D needs in the extraction of CM from non-conventional feedstocks, understand the CM supply chain and current markets for existing products, and evaluate the economic benefits of in-house transformational processes within the CM supply chain. These efforts focus on LCA baseline studies for critical minerals and the development of an embedded demand database and the data and principles behind CM process flowsheet optimization calculations that facilitate cost and environmental performance optimization.

Several R&D challenges exist for the development of this independent baseline analysis. Currently there is no global industrial precedence for recovering CM from a non-traditional feedstock. This makes it challenging to collect cost, performance, and environmental data for complete CM processing systems but will still be possible since all the processes necessary to recover CM from these sources are commercially deployed in other industries. The cost and performance data will have to be collected for each individual process from a representative industry and adjusted to fit the proposed systems and scales. Environmental performance data is also limited for the extraction and processing of CM. Foundational environmental characterization modeling will be essential to ensuring environmentally responsible minerals production in the United States.

Knowledge and experience with TEA, baseline development, market analysis, and environmental assessments will be used to inform in-house research, and evaluate externally proposed projects at the request of the NETL CM Program and the Technology Development Center (TDC), while developing independent baseline analyses to recover CM from non-traditional feedstocks. These independent analyses will be paramount in identifying future R&D needs to advance the economic recovery of CM.

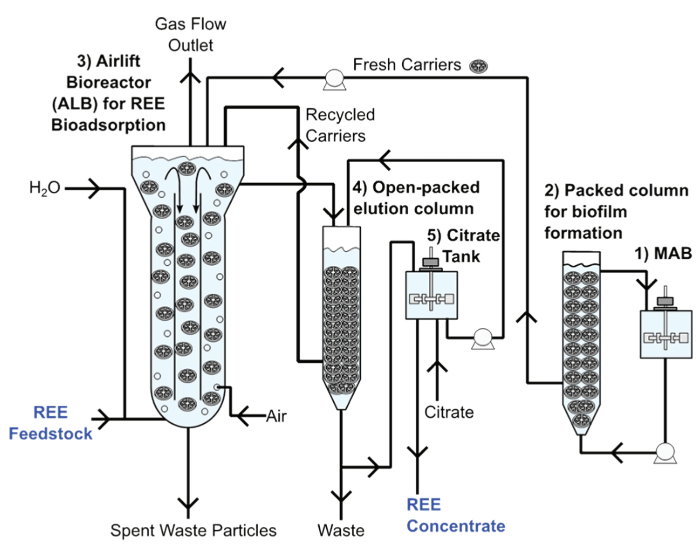
Application of Biosorption for REE Separation from Coal Byproducts

Performer	**Lawrence Livermore National Laboratory (LLNL)**
Award Number	FWP-LLNL-18-FEW0239
Project Duration	03/01/2018 – 09/30/2021
Total Project Value	$ 950,000
Collaborators	Duke University; University of Arizona
Technology Area	Separation Technologies

The objective of this research was to determine whether biosorption can be used as an inexpensive and cost-effective means for rare earth element (REE) recovery from leachates of pre-combustion and post-combustion coal by-products. focused on the development of a biofilm-based continuous flow-through system in an airlift bioreactor. This effort was also focused on improving the E. coli biofilm stability using a bioengineering approach to incorporate surface binding tags. These surface binding peptides are known to improve adhesion and increase biofilm stability under high shear force.

A Caulobacter biofilm formation activity had previously been completed. A single bacterial platform for application to the airlift bioreactor was be down-selected based on several evaluation criteria, including biofilm density (number of cells per unit area); biofilm forming efficiency (proportion of cells that attach to the surface in a cell population); biofilm stability; REE-binding ligand density (number of REE- binding ligands incorporated per cell); and REE adsorption capacity per unit area of the biofilm.

At the conclusion of LLNL's FWP with NETL, the project was expected to deliver a bench-scale demonstration of an airlift bioreactor for REE recovery and demonstrate its technical feasibility with preliminary economic viability analysis and a plan for commercialization.



Airlift bioreactor design and process schematic. The proposed system consists of a two-stage semicontinuous process including (1) a closed mechanically agitated bioreactor (MAB) used to grow the microbes, (2) an open cylindrical container as a packed column for biofilm formation on carrier disks, (3) an airlift bioreactor (ALB) for adsorption of REE onto biofilm carrier disks, and (4) an open-packed elution column (EC) with (5) circulating citrate from a citrate tank for REE desorption and recovery.

Evaluation of Laser-Based Analysis of Rare Earth Elements in Coal-Related Materials

Performer	**Los Alamos National Laboratory (LANL)**
Award Number	FWP-FE-781-16-FY17
Project Duration	10/25/2017 – 06/30/2022
Total Project Value	$ 1,000,000
Technology Area	Enabling Technologies

The primary objectives of this effort are to (1) develop and test analytical protocols for analyzing the concentration and mineralogy of rare earth elements (REE) in coal-related materials using laser-induced breakdown spectroscopy (LIBS) and Raman spectroscopy; (2) develop a field-portable system for LIBS and Raman analysis of REE in coal-related material; and (3) analyze the concentration and mineralogy of REE in a variety of coal-related materials principally from New Mexico coal deposits.

The project consists of two tasks. In the first, the team was to construct a field-portable prototype unit for LIBS/ Raman analysis of REE in coal-related materials; field test and demonstrate the unit at New Mexico field sites; and revise analytical protocols as applicable. Researchers will take advantage of LANL's extensive experience in developing LIBS for quantitative analysis of elements in various matrices and will use this expertise to develop protocols for analysis of REE in coal-related materials. LANL has made recent institutional investments (through laboratory directed research and development) to develop a combined LIBS plus Raman system that can determine both chemistry (LIBS) and physical form (Raman). Researchers will use this new system to explore simultaneous chemical and mineralogical analysis of REE in coal-related materials.

In the second task, the team will develop analytical methods specific to the quantification of REE in various coal-related materials, thereby developing a broader database on REE concentrations and physical forms in a variety of coal-related materials. This step is necessary in the development of protocols for quantitative analysis of REE using LIBS. Interpretation of the data requires determining calibration curves for REE in specific matrices because the efficiency of plasma generation (a first step in LIBS analysis) can be impacted both by physical form and overall chemistry.

The project successfully developed a method of using fluoroboric acid (HBF4) to digest coal, coal fly ash, and geological samples for REE analysis using inductively coupled plasma mass spectrometry (ICP-MS). HBF4 preparation and ICP-MS analysis were validated against reference materials and shown to be very accurate. Recently, the field-portable (backpack) prototype unit for LIBS and Raman analysis instrument has been fully assembled and the prototype is on track for demonstration in field tests in the summer and early fall of 2022.

Left: The field-portable LIBS and Raman (backpack) prototype unit undergoing field testing. Right: Close up of the field-portable unit

ENABLING TECHNOLOGIES

Development of Ligand-Associated Solid-Liquid Extraction Media System for Separation of High Purity Individual Rare Earth Elements from Coal-based Resources

Performer	**GlycoSurf, LLC**
Award Number	SC0021702
Project Duration	06/28/2021 – 06/27/2022
Total Project Value	$ 256,497
Collaborators	University of California - Los Angeles, Wayne State University
Technology Area	Enabling Technologies

Commercial sources of rare earth elements (REE) include bastnäsite ([La, Ce]FCO_3), monazite ([Ce, La, Th]PO_4), and xenotime (YPO_4). However, the processing of these materials to extract and recover the rare earth elements is challenging and very process intensive. There are numerous domestic sources of rare earth elements including waste materials such as coal fly ash from which REE could be extracted beneficially. Several physical and chemical methods are typically employed to separate the materials of interest from gangue material, which usually leads to the production of a mixed rare earth element concentrate. The mixed rare earth concentrate is then subjected to an entirely separate process to isolate the individual rare earth elements into high-purity materials for use in commercial applications.

This team will build on its past successes with ligand-associated separation media to develop a new class of sorption media, and a process to separate individual rare earth elements, resulting in individual high purity rare earth oxide (REO) powders. This new class of sorption media will combine two classes of ligands: (1) glycolipids and (2) DTPA analogs, synthesized in-house for fundamental proof-of-concept testing for the proposed novel process to concentrate REEs from coal leachates. The process will also allow for the separation of mixed light REE from the heavy REE, along with separation of these concentrates into individually separated REE materials. The team anticipates that Phase I will result in REO purity of >90% with less than ten processing steps, as opposed to hundreds to thousands of steps for current liquid-liquid separations.

Production of Critical Minerals from Coal-Based Resources

Performer	**RESPEC Company, LLC**
Award Number	SC0021742
Project Duration	06/28/2021 – 03/27/2022
Total Project Value	$249,929
Collaborator	West Virginia University
Technology Area	Enabling Technologies

Executive Order 13817 of 2017 listed 35 minerals deemed critical to the United States' national security and economy. Most of these minerals are not available to be mined from conventional sources in the United States; as a result, a mineral dependency vulnerability is created that can adversely impact our nation.

A comprehensive review of the potential to extract critical minerals from unconventional sources, such as coal-based resources, is an important step in improving the knowledge by advancing research efforts in this area. The nature of the unconventional deposits of critical minerals and extracting technologies that are limiting exploitation by our miners and producers, as described in Executive Order 13817, was not well understood.

In collaboration with West Virginia University (WVU), RESPEC's team was to develop a comprehensive study of the potential to extract critical minerals from coal-based resources. By combining industry and academia experience, the team would build concepts for quantifying and extracting critical minerals found in unconventional sources. The project team would also provide a detailed analysis of the potential applications of these minerals in developing advancing alloys or component production that are essential toward the economy or national security of the United States.

Understanding and quantifying our nation's available sources of critical and strategic minerals is a crucial component for ensuring a secure and reliable supply of these minerals. Extracting critical minerals from unconventional sources, such as coal-based resources, is an environmentally sound option that will promote reprocessing and recycling as well as using innovative techniques to recover these minerals in an economically feasible way.

The primary benefit of this research was to provide a comprehensive understanding of the potential of extracting critical and strategic minerals from coal-based resources. Identifying critical minerals in coal-based resources and evaluating the economic feasibility linked to extracting and processing those minerals are also important environmental benefits because of the potential to reprocess and recycle coal-waste facilities. Understanding and quantifying critical and strategic minerals resources available from unconventional sources will also provide the basis for determining our nation's available sources in the event of supply disruptions.

Development of Sorting Algorithm for Critical Mineral-rich Coal Resource Feedstocks for Use in Full-Stream Analyzers

Performer	**Microbeam Technologies, Inc.**
Award Number	SC0021837
Project Duration	06/28/2021 – 06/27/2022
Total Project Value	$249,886
Collaborator	Energy Technologies, Inc.
Technology Area	Enabling Technologies

This project addresses the issue of high variability of critical minerals (CM), including rare earth elements (REE), in coal feedstocks. The proposed project is aimed at developing a technology to sort coals based on REE-CM concentration. Sorting the high CM from low CM-containing feedstocks is essential to the economic viability of a commercial CM concentrate production facility. The inability to sort coal in real time is detrimental to REE-CM processing plants. This technology will assist these plants in reducing costs through efficient management of their incoming feedstocks materials.

The Phase I specific objectives include: (1) identify coal samples that represent high-rank and low-rank coals, (2) determine abundance and form of the REE-CM in selected coal samples, (3) analyze samples with the advanced sensors, and (4) develop algorithms for total REE, light REE, heavy REE, and individual REE and CM based on sensor responses.

The development of this technology is crucial to the success of REE-CM processing plants as it will allow these facilities to sort REE- and CM-rich materials in order to be as efficient as possible. The United States is highly dependent on importation of REE and CM, so domestic production will need to manage costs to be competitive with foreign producers. The growth of domestic REE and CM processing will create jobs and the ability to remain competitive will keep these facilities in business and further encourage additional growth.

Rare Earth Oxide (REO)-Based High-Voltage, High-Capacity LiNiPO4 as Cathode of High-Safety, High Energy-Density Solid-State Li-Ion Batteries (SSLiBs) for Electric Drive Vehicle Applications

Performer	**Bioenno Tech, LLC**
Award Number	SC0022475
Project Duration	02/14/2022 – 11/13/2022
Total Project Value	$200,000
Collaborator	Aegis Technology, Inc.
Technology Area	Enabling Technologies

This project will focus on (1) design, demonstration and cost-effective manufacturing of high-voltage cathode materials that are enhanced through rare-earth-oxide (REO)-based co-doping strategy; and (2) prototyping and demonstration of solid-state lithium-ion battery (SSLiB) pouch cells through our established processing procedure to evaluate cathode properties and provide reference for further optimization.

The successful development of the proposed SSLiBs for electric drive vehicles will significantly improve energy efficiency, reduce greenhouse gas (GHG) emissions, and improve the competitiveness of U.S. manufacturing in the global market. The successfully developed REO-based cathode will also facilitate the establishment of a cost-effective production and application of REO-based critical minerals (CM) in the U.S. manufacturing.

REDUCTION TO METALS

Hydrogen Plasma Reduction of REOs/Salt for REMs Production

Performer	Polykala Technologies, LLC
Award Number	SC0021544
Project Duration	02/22/2021 – 05/31/2022
Total Project Value	$200,000
Collaborator	Trimeric Corporation
Technology Area	Reduction to Metals

In this DOE SBIR Phase 1 project, Polykala Technologies, LLC (PT) will produce rare earth metals (REM) from rare earth oxides (REO) by recycling of rare earth materials from post-consumer products. Of the five critical rare earth elements (REE), (dysprosium [Dy], neodymium [Nd], terbium [Tb], europium [Eu], and yttrium [Y]), PT will target Nd, Y, and Dy, and also samarium (Sm) and cerium (Ce), two other critical materials. A novel very efficient and low-energy-consumption technology will be developed for production of five of the most valuable critical minerals (Nd, Y, Dy, Sm, Ce) from their corresponding oxides.

REE are crucial to the production of green energy motors in wind turbines, hybrid cars, electric vehicles, and electronic devices. REE are also used in defense systems, including precision-guided munitions, radar systems, avionics, night vision equipment, satellites, and guided missiles. China dominates REE production and exports and is continuing to reduce REE exports. The United States Department of Defense and Department of Energy are evaluating options to increase domestic production.

Ionic Liquid-based Electrowinning for Refining of Rare Earth Oxides/Salts

Performer	**TDA Research, Inc.**
Award Number	SC0021884
Project Duration	06/28/2021 – 03/27/2022
Total Project Value	$250,000
Technology Area	Reduction to Metals

Rare earth elements (REE) are used in a variety of energy and defense critical technologies, including permanent magnets and rechargeable batteries. A vast majority of extraction and processing to convert the rare earth oxides to metals is done overseas. Coal and coal-based resources represent a significant potential domestic source of REE. Current REE refinement technologies use high temperatures and highly reactive and toxic chemicals. The development of economical and environmentally benign new techniques and processes to refine rare earth oxides and salts would enable domestic production of REEs and provide a high-value product.

This project used computational techniques to design ionic liquids that can solvate individual rare earth cations from their oxide and salt forms. The solvated rare earth cations would be reduced to metals using an electrowinning process. In the Phase I effort the team applied their computation methods to a wide range of ionic liquids to identify those that have both a wide electrochemical stability window and which can be effectively synthesized in-house. They experimentally demonstrated the solvation and electrowinning processes at lab scale and explored basic process parameters such as temperature and time. An engineering analysis was performed to identify the scale-up and techno-economic challenges that we will need to be addressed in Phase II.

Rare earth elements are used in a variety of energy critical technologies, including permanent magnets and rechargeable batteries, but the USA lacks domestic production and refining capabilities. TDA Research is developing a low-temperature, lower cost refining process that can be used to convert rare earth salts/oxides to their constituent metals.

In 2018, the global REE market size was valued at USD $2.8 billion and was projected to grow at over 10% a year for the next five years. The development of a U.S.-based rare earth refining industry would greatly

Advanced Low-Energy Technique for Producing Rare Earth Metal using a Mixed Halide Molten Salt

Performer	**Phoenix Tailings, Inc.**
Award Number	SC0021920
Project Duration	06/28/2021 – 06/27/2022
Total Project Value	$250,000
Technology Area	Reduction to Metals

Phoenix Tailings, Inc. has invented a low-energy production process to reduce rare earth oxides (REO) to rare earth metals (REM) using a mixed halide molten salt. This process forms part of Phoenix's portfolio of reduction techniques that gives it the ability to produce several different metals from oxides in a significantly more energy-efficient manner.

Phase 1 represents the initial characterization of a mixed halide molten salt to determine the base parameters, including the optimal composition of the salt. Phoenix will then characterize a mixed oxy-halide molten salt to narrow down those parameters. It will then conclude with the production of a 100 g sample of dysprosium (Dy) metal from oxides in a lab environment. This will allow Phoenix to produce an initial techno-economic analysis of the production of REM.

Current DOE efforts have made significant progress in finding alternative sources of REE and have produced REO, the REM precursor. This proposal builds on that success by creating a low-energy process for turning REO into REM in a way that is economically resilient to China's market manipulation. This will complete the United States' domestic REE supply chain and guarantee its energy security.

This reduction in energy consumption and consequent reduction in operating costs increases the systems' economic margins. As such, it is more economically resilient to fluctuations in market prices caused by the Chinese government. China controls 90% of the world's production of rare earth elements (REE), which are crucial for wind energy production and electric vehicles. This will allow Phoenix to add to the current DOE progress in the recovery of REO from coal fly ash and complete the domestic supply chain by producing REM.

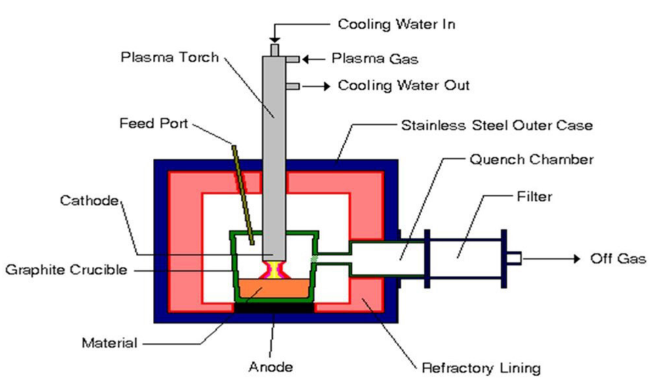
Multi-Sourced Collaboration for the Production and Refining of Rare Earth and Critical Metals

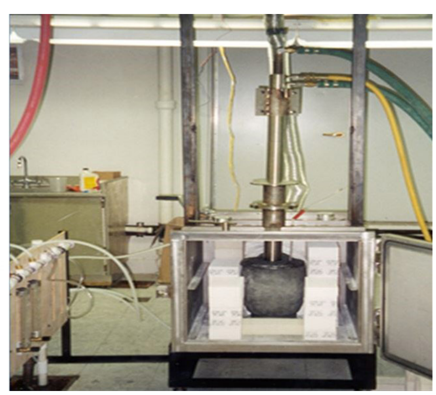
Performer	**University of Kentucky**
Award Number	FE0032119
Project Duration	12/01/2021 – 08/31/2022
Total Project Value	$211,409
Collaborators	Alliance Coal; Argonne National Laboratory; MP Materials Corp.; University of Alabama; Virginia Polytechnic Institute and State University
Technology Area	Rare Earth Recovery

The primary objective of this project is to identify and evaluate advanced refining and metal production technologies capable of extracting high-purity rare earth elements (REE) and critical minerals (CM) and metals from coal-based sources economically and in an environmentally friendly manner.

Previously, the Recipient successfully designed, constructed, and operated a pilot-scale rare earth processing facility that uses conventional approaches to extract and recover REE. Operational data from this facility has demonstrated the ability to successfully produce rare earth oxide (REO) concentrates at grades exceeding 90% and at production rates of 10 to 100 g/day. It is currently being expanded to 110 kg/year. However, this facility does not have the capability to produce individually separated high purity REE. Through this nine-month effort, the project team will deliver a pathway and research plan to apply advanced technologies for individually separated high purity rare earth and critical minerals production from coal-based sources and reduction to metal that will minimize environmental impact and reduce capital and operating expenses by more than 20% over conventional processes while delivering at a minimum the following rare earths and critical minerals: (REE) Y, Pr, Nd, Gd, Dy of greater than 99.5% purity, and (CM) Co, Mn, Ga, Sr, and Li of greater than 90% purity.

Research, development, and demonstration (RD&D) efforts to create new domestic sources of rare earth elements and other critical minerals have been accelerated with the goal of making our domestic supply chains more resilient. Technology development and optimization of process circuits from recovery of mixed rare earth oxides/mixed rare earth salts (MREO/MRES) and CM from diverse sources, through separation into individual CM or binary high-purity REO/RES, to conversion into rare earth metals (REM) is critical to establishing a resilient domestic supply chain that is not threatened by geopolitical competition.





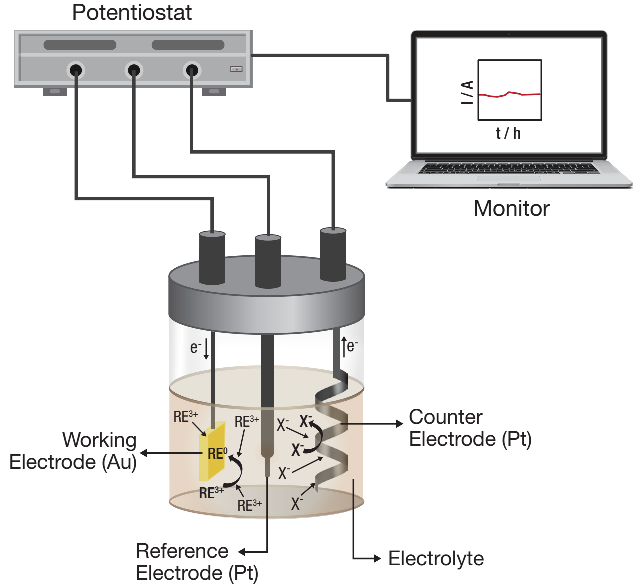
Advanced Thermal Plasma Reactor for REE and CM metal production.

Tunable Electrochemical Pathway for High-Purity Rare Earth Metals (REM) and Critical Minerals (CM)

Performer	**University of North Dakota Energy and Environmental Research Center (UNDEERC)**
Award Number	FE0032121
Project Duration	11/30/2021 – 08/30/2022
Total Project Value	$187,500
Collaborators	Trimeric Corporation; Current Lighting Solutions, LLC; Critical Materials Institute – Ames National Laboratory
Technology Area	Rare Earth Recovery

The objective of this project is to develop a technical research plan for defining and assessing the techno-economic viability of a tunable electrochemical pathway (TEP) for producing individually separated high-purity rare earth metals and critical minerals (CM) as industrially relevant CM compounds from lignite coals and combustion by-products originating from the Williston Basin. This project focuses on technology development that advances rare earth separation into ISHP materials and reduction to metals. Advanced ISHP and reduction to metals processes have the potential for reduced capital costs and operating expenses compared to conventional separation and metal reduction technologies such as solvent extraction and metallothermic reduction processes.

Research, development, and demonstration (RD&D) efforts to create new domestic sources of rare earth elements (REE) and other critical minerals (CM) have been accelerated with the goal of making our domestic supply chains more resilient. Technology development and optimization of process circuits from recovery of mixed rare earth oxides/mixed rare earth salts (MREO/MRES) and CM from diverse sources, through separation into individual CM or binary high-purity REO/RES, to conversion into rare earth metals (REM) is critical to establishing a resilient domestic supply chain that is not threatened by geopolitical competition. Distributed or modular processing facilities located in close proximity to multiple feedstocks that recover and concentrate MREO and CM, could (1) enable the development of a world-class American manufacturing base and workforce in coal and power plant communities, many of which are economically distressed (the economies of coal-producing regions will be revitalized by creating local jobs that recover and refine REE and CM from coal wastes for distributed manufacturing facilities); (2) advance environmental justice in low-income communities that have been disproportionately harmed by the adverse environmental impacts associated with coal mining through remediation of coal waste materials; and (3) insulate manufacturers from disruptions in supply by consolidating the extraction and production of individual critical materials by developing tightly integrated modular systems to ensure a supply consistent both in quality and price to meet their demands.



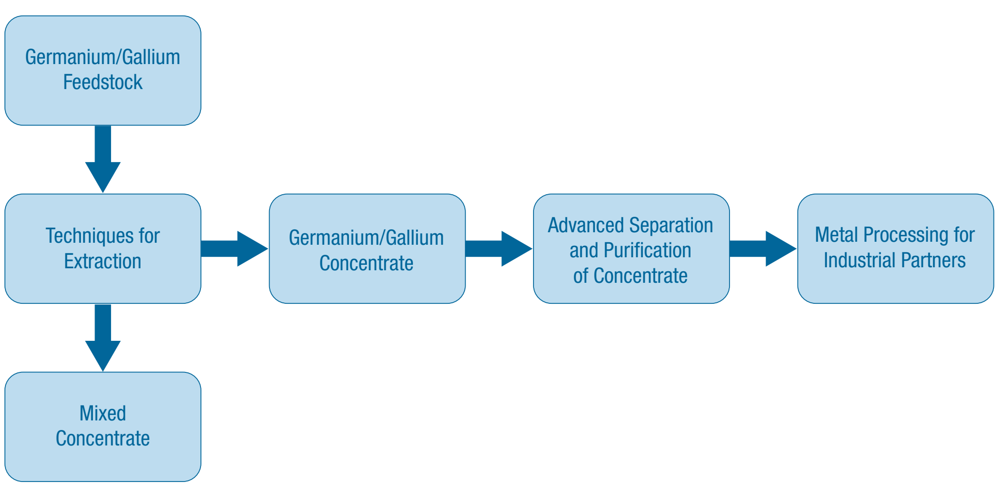
Schematic of the tunable electrochemical pathway proposed for this project.

Production of Germanium and Gallium Concentrates for Industrial Processes

Performer	**Microbeam Technologies, Inc.**
Award Number	FE0032124
Project Duration	01/1/2022 – 03/31/2023
Total Project Value	$251,471
Collaborators	University of North Dakota; Dennis James Consulting, LLC
Technology Area	Rare Earth Recovery

The objective of this project is to develop a conceptual design of a process to extract, separate, recover, and purify germanium (Ge) and gallium (Ga) from lignite coal-derived mixed rare earth element (MREE) concentrates. The process will be integrated into the University of North Dakota (UND) rare earth extraction process and will be designed to co-produce Ge and Ga concentrates. The potential multiphase effort involves an integrated development that spans the entire supply chain that includes feedstock sourcing, feedstock optimization, extraction, concentration, separation, refining, and product use in industrial applications. The scope of work for this project involves the development of an environmentally benign concept to produce Ge and Ga that is fully integrated with downstream applications and with the properties of the MREE species. The effort will involve the characterization of midstream feedstocks from UND's bench and pilot facilities; identification of optimal methods to recover and refine Ge and Ga for industrial applications; development of process flow diagrams of the Ge/Ga final production; and performance of a market analysis to determine the resource needed to produce quantities of refined product.

Research, development, and demonstration (RD&D) efforts to create new domestic sources of rare earth elements (REE) and other critical minerals (CM) have been accelerated with the goal of making domestic supply chains more resilient. Technology development and optimization of process circuits from recovery of mixed rare earth oxides/ mixed rare earth salts (MREO/MRES) and CM from diverse sources, through separation into individual CM or binary high-purity REO/RES, to conversion into rare earth metals (REM) is critical to establishing a resilient domestic supply chain that is not threatened by geopolitical competition.



Technology Development and Integration for Volume Production of High Purity Rare Earth Metals from Phosphate Processing

Performer	**Florida Polytechnic University**
Award Number	FE0032123
Project Duration	01/01/2022 – 09/30/2022
Total Project Value	$187,508
Collaborators	Pacific Northwest National Laboratory; Florida International University
Technology Area	Rare Earth Recovery

The proposed project will develop an integrated technical research plan based on advanced processes for recovery, separation, and purification of mixed rare earth oxides (MREO) to enable mass production of rare earth metals (REM) from phosphoric acid sludge feedstock.

Phosphoric acid sludge presents a highly beneficial resource as a feedstock material for economic recovery of REEs from phosphate processing for three primary reasons: (1) rich REE content at over 2000 ppm, greater than that of most other alternative REE resources; (2) highly abundant supply; and (3) processing of this stream does not interfere with the phosphate industry's primary line of business. The research strategy involves pre-treatment of the sludge to recover both the valuable liquid phosphate fraction and REE-containing solids, leaching of REE from the solids, a novel solvent extraction technology to separate REEs from the leaching solution, and precipitation and calcination to obtain high-purity MREO, followed by advanced separation to produce REM in either individual or group form.

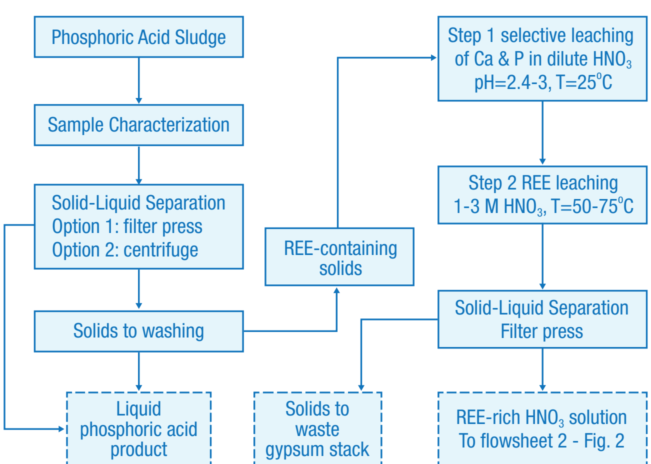


Figure 1. Conceptual Processing Flowsheet for Production of REM from Phosaphate Processing.

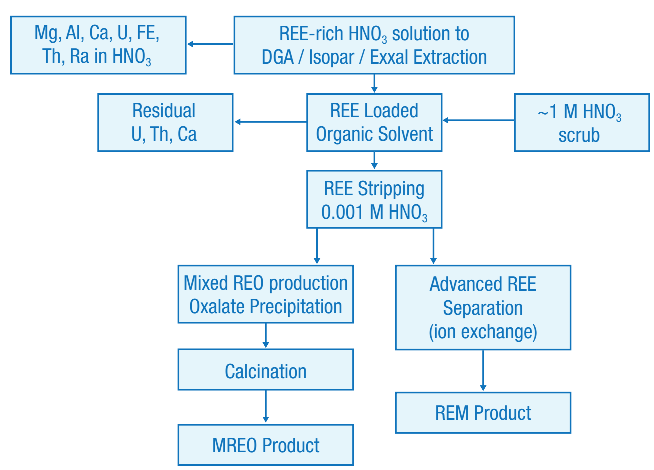


Figure 2. Flowsheet for Solvent Extraction and Advanced REE Separation.

Extraction, Separation, and Production of High Purity Rare Earth Elements and Critical Minerals from Coal-Based and Related Resources

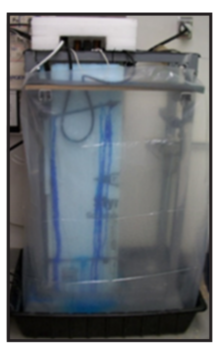
Performer	**University of Utah**
Award Number	FE0032122
Project Duration	01/16/2022 – 10/16/2022
Total Project Value	$187,500
Collaborator	Virginia Polytechnic Institute and State University
Technology Area	Rare Earth Recovery

The general objectives of this project are to develop concepts for rare earth metal (REM) and critical mineral (CM) production from coal and related resources and incorporate them into a technical research plan and an innovative process flow sheet that specifies new technology. The specific project objectives include (1) identification of targeted rare earth element (REE) and critical minerals (CM) market(s), annual production quantities, demand, and intermediate/end-use products, (2) identification of a targeted set of critical materials used in these markets/applications, and as the basis for development of proposed advanced purification, separation, and reduction to metals processes, (3) selection of feedstock and existing facilities for mixed rare earth oxides (MREO)/mixed rare earth salts (MRES) and CM production, (4) identification and preliminary assessment of a process for making independently separated high-purity (ISHP) rare earth oxides (REO)/rare earth salts (RES) and CM, (5) identification and preliminary assessment of an REM production process, (6) identification and preliminary assessment of a process for conversion of CM from pilot-scale facilities to industrial CM compounds, and (7) development of a conceptual process flow diagram illustrating circuit integration for REM/CM production from coal related resources.

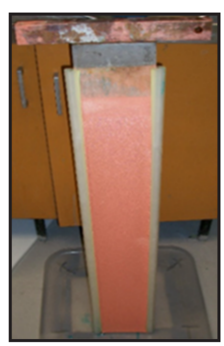
Success in this context will be defined by the potential viability of the flow diagram for the production of the desired purified REE/CM products as well as by the potential improvements in flow diagram over conventional technologies. The ultimate success will be defined in the long term by the implementation of new technologies that enable domestic production of needed high-purity REE/CM products from coal resources.

Hydrophobic-hydrophilic separation (HHS) process: Pilot scale facility

Multiple column leaching and pilot scale leaching facility (inset)



Pilot scale electrorefining facility



Electrorefined metal sheet

Pilot scale HAMR facility and high vacuum reduction setup (inset) for critical metals production

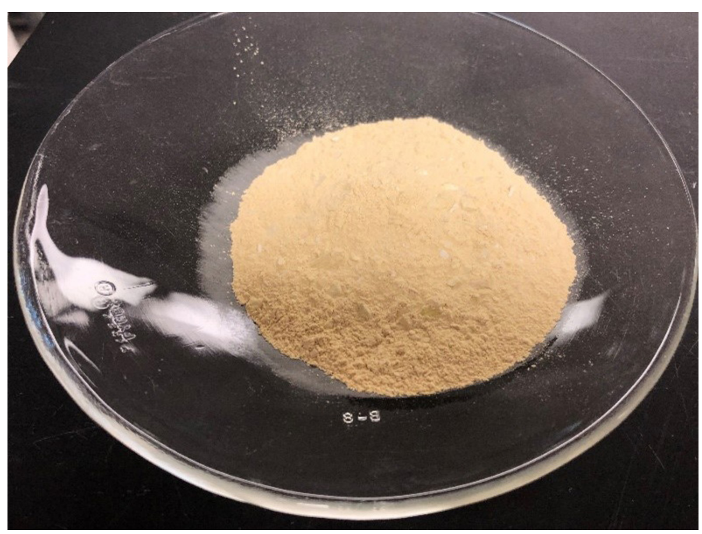
Advanced Processing of Rare Earth Elements and Critical Minerals from Acid Mine Drainage Feedstocks

Performer	**West Virginia University Research Corporation**
Award Number	FE0032120
Project Duration	01/14/2022 – 10/13/2022
Total Project Value	$187,497
Collaborators	Virginia Polytechnic Institute and State University; L3Eng
Technology Area	Rare Earth Recovery

The overall objective of this project is to design, develop, and deploy innovative process technologies to produce salable rare earth metals and critical minerals from acid mine drainage (AMD) feedstocks to reduce our nation's vulnerability to interruption by international competitors. In prior efforts, the project team has successfully developed and demonstrated technology to produce mixed rare earth oxides (REO) from raw AMD in an economically attractive and environmentally benign matter. The current effort seeks to extend the process technology development further downstream to include (1) the separation of at least five individual high-purity REO and (2) the production of at least five high-purity rare earth metals and alloys. In addition, the project will explore technology to synergistically produce at least five target critical minerals (CM) during the processing steps. The development activities of this project will focus on two novel technologies, namely task-specific ionic liquid separation for rare earth elements (REE) and CM separation and carboxylate reduction for the production of individually separated high-purity metals.

The team is constructing a full-scale integrated 500 gpm AMD treatment plant coupled with an REE/CM facility that will produce 21 tons REE/CM per year. This plant will provide feedstock for the team's proprietary downstream processes to meet the project goal: production of individually separated, high-purity REE/CM oxides and their further processing to elemental metals.

Research, development, and demonstration efforts to create new domestic sources of REE and other CM have been accelerated with the goal of making domestic supply chains more resilient. Technology development and optimization of process circuits from recovery of mixed rare earth oxides/mixed rare earth salts and CM from diverse sources, through separation into individual CM or binary high-purity REO/RES, to conversion into rare earth metals (REM) is critical to establishing a resilient domestic supply chain that is not threatened by geopolitical competition.



High-grade rare earth concentrate produced by the WVU research team.

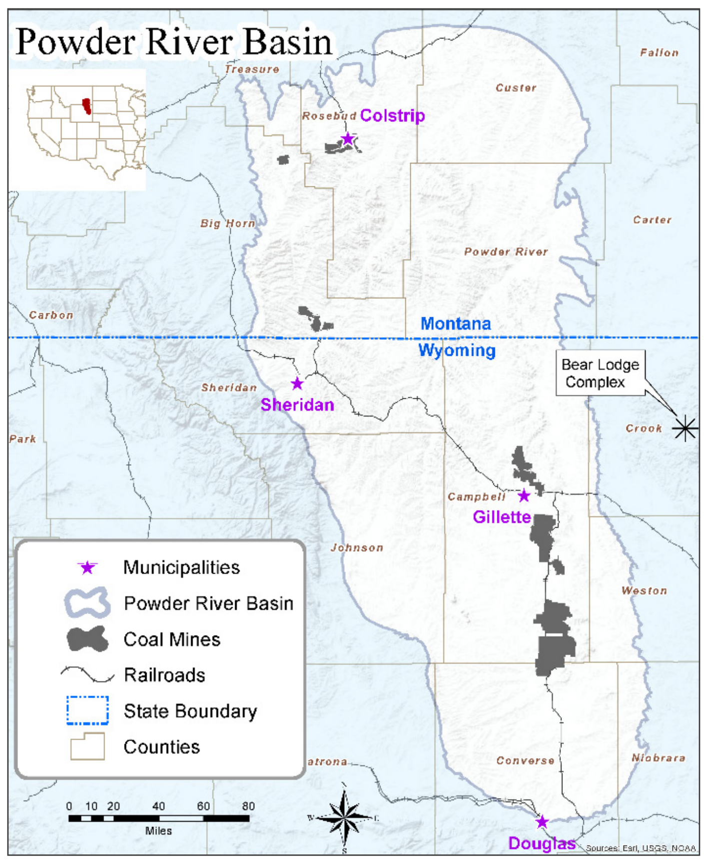
CARBON ORE, RARE EARTH, AND CRITICAL MINERALS (CORE-CM) INITIATIVE

Powder River Basin Core-Cm: Advancing Strategies for Carbon Ore, Rare Earth Element and Critical Mineral Resource Development in the Nation's Largest Coal Producing Basin

Performer	**University of Wyoming**
Award Number	FE0032048
Project Duration	09/01/2021 – 08/31/2023
Total Project Value	$1,980,720
Collaborators	Montana Bureau of Mines and Geology - Montana Technological University; Campbell County, WY; Energy Capital Economic Development; Los Alamos National Laboratory; Battelle; BSI Energy Ventures; Gillette College
Technology Area	Rare Earth Recovery

The objectives of this University of Wyoming effort are to provide an economic benefit to the Powder River Basin (PRB) of Wyoming and Montana by stimulating new resource development around the nation's largest coal mines; establish strategic plans to maximize the development potential of carbon ore, rare earth element, and critical mineral (CORE-CM) resources while leveraging the highly trained workforce, existing coal technologies, energy infrastructure, and wide public acceptance of energy technology in the basin; offer a low-cost pathway to the national security benefits associated with domestic CORE-CM industries; and bring together a committed network of stakeholders from all parts of the CORE-CM value chain. The team will complete initial assessments, gap analyses, and strategic plans for resource evaluation, including an initial geologic model of CORE-CM resources; CORE-CM potential of regional waste streams; infrastructure, industry, and business; technology development and field testing; technology innovation centers; and stakeholder outreach and education, including workforce development programs and forums to facilitate technology transfer.

This project will benefit those who live and work in the PRB, including residents in need of retraining and those just entering the workforce. Furthermore, the project aims to develop a sustainable domestic industry around the existing carbon ore infrastructure in the PRB that could advance CORE-CM resource development and promote commercialization of value-added products.



Map of the Powder River Basin of Wyoming and Montana.

Bringing Alaska's Core-CM Potential into Perspective

Performer	**University of Alaska - Fairbanks**
Award Number	FE0032050
Project Duration	09/01/2021 – 08/31/2023
Total Project Value	$1,908,642
Collaborators	University of Alaska - Anchorage; Alaska Division of Geophysical and Geological Surveys; JWP Consulting, LLC; ESP Research, Inc.; Technology Holdings, LLC; Ahtna, Inc.
Technology Area	Rare Earth Recovery

CORE-CM projects develop and implement strategies that enable each specific U.S. basin to realize its full economic potential for producing rare earth elements (REE), critical minerals (CM), and high-value, nonfuel, carbon-based products from basin-contained resources.

The primary objective of this project is to reduce our nation's reliance on imported REE and CM by establishing Alaska's resources as competitive sources of supply. The University of Alaska has documented encouraging REE-CM concentrations in preliminary studies of coal at two sites, but otherwise Alaska has not seen a systematic analysis of its resource potential. This project will systematically perform a set of broad basinal assessments of Alaska's carbon ores, rare earth elements, and critical minerals (CORE-CM) found in several of Alaska's basins. Included in the analysis will be two obvious basins: (1) that hosting Alaska's only operating coal mine, and (2) the basin hosting North America's largest large-flake graphite deposit.

The team will also investigate opportunities to create high-value, non-fuel products from carbon ores in basins associated with REE-CM resources to increase their economic potential. Alaska contains many and varied CORE-CM basins, each with its own set of challenges. Eighty percent of Alaska is without roads, and an even greater area does not have access to the only power grid in the state, which primarily connects Fairbanks to Anchorage. The team must consider factors in addition to mineral content within a basin and will devise a priority matrix for ranking CORE-CM basins. Final rankings will consider the quality of the CORE-CM content, access to infrastructure or ability to build it, readiness of technology to exploit the resource in that location, environmental factors, and market potential. Final rankings will consider the quality of the CORE-CM content, access to infrastructure or ability to build it, readiness of technology to exploit the resource in that location, environmental factors, and market potential.

This project will significantly contribute to our understanding of the nation's domestic CORE-CM resources by examining for the first-time potential sources in Alaska. The team will begin a process for assessing and characterizing this unknown potential with active cultivation of a full range of stakeholders. NETL is investing in establishment of a field laboratory in one of the most environmentally protected areas of the United States.

Red rock reveals a variety of minerals present in the mountains near Mt. Foraker in Denali National Park and Preserve.

Core-CM in the Greater Green River and Wind River Basins: Transforming and Advancing a National Coal Asset

Performer	University of Wyoming
Award Number	FE0032047
Project Duration	09/01/2021 – 08/31/2023
Total Project Value	$1,959,654
Collaborators	Colorado Geological Survey; Coalgeo, LLC; Los Alamos National Laboratory; Wyoming Energy Authority; Colorado Northwestern Community College; Western Wyoming Community College; BSI Energy Ventures
Technology Area	Rare Earth Recovery

This project will develop strategic and novel development plans for the abundant carbon ore (CORE), rare earth elements (REE), and critical minerals (CM) feedstocks located in the Greater Green River Basin (GGRB) and Wind River Basin (WRB), including waste streams from coal, coal byproducts, trona, helium, uranium, phosphate, and oil and gas industries. The project team will complete initial assessments, gap analyses, and strategic planning under several categories including (1) assessment of feedstocks, (2) waste stream reuse assessments, (3) infrastructure, industry, and businesses, (4) technology pairing and development, (5) technology innovation center planning, and (6) stakeholder outreach and education, including workforce development programs and forums to facilitate technology transfer.

The overall objective of this effort will be to develop and catalyze regional economic growth, job creation, and technology innovation in the GGRB-WRB of Wyoming and Colorado by increasing the supply of carbon ore, rare earth elements, and critical minerals (CORE-CM) to manufacturers of non-fuel carbon-based products and products reliant upon CM. The project will comprise a coalition team to describe the relationships, technology, infrastructure, and scientific understanding of these resources needed to achieve this objective.

The project could result in a viable pathway for a regional development opportunity, utilizing the abundant CORE-CM feedstocks located in the GGRB-WRB. Additionally, this project will provide CORE-CM education opportunities and information to the public.

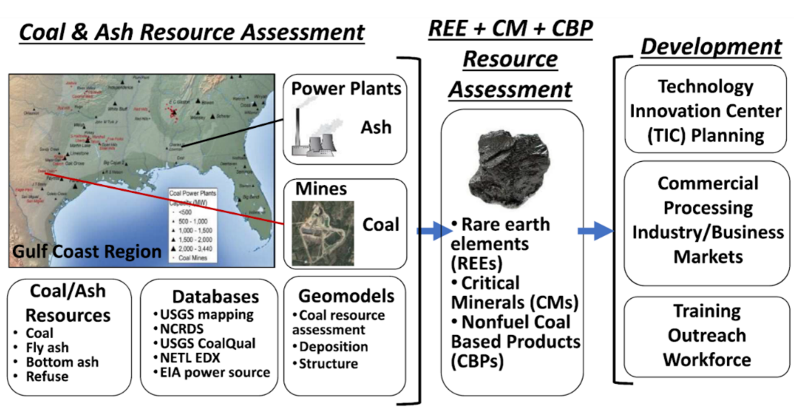
A coal sample pulled from a location within the Greater Green River and Wind River Basins of WY & CO. This sample exhibits the uniqueness of coal-based materials for CORE-CM purposes. It has high-rank coal for utility in carbon ore products as well as clay materials hosting various rare earth elements and critical minerals.

Assessment of Rare Earth Elements and Critical Minerals in Coal and Coal Ash in the U.S. Gulf Coast

Performer	University of Texas at Austin
Award Number	FE0032053
Project Duration	09/15/2021 – 09/14/2023
Total Project Value	$1,879,190
Collaborators	Geological Survey of Alabama; United States Geological Survey (USGS); University of Kentucky; University of North Dakota Institute of Energy Studies; University of Wyoming
Technology Area	Rare Earth Recovery

The objectives of the study are to quantify rare earth elements (REE) and critical minerals (CM) resources in feedstocks within the U.S. Gulf Coast Basin including coal from mines, coal ash from power plants, and refuse. REE and CM will also be quantified in water co-produced with oil in reservoirs adjacent to coal resources. Additional objectives include linking these mineral resources to manufacturing of high-value products, including nonfuel carbon-based products (CBPs), planning the development of a Technology Innovation Center, and stakeholder outreach and education to achieve the overall goal of enhancing economic growth and job creation to support economic development in the Gulf Coast. The methods involve development of coal and ash resource assessments by leveraging previous coal assessments and using power plant ash data. The geological assessment involves mapping the resources and considering depositional environments and structural data, resulting in a detailed geomodel of the Gulf Coast coals.

Analysis of REE and CM in ~200 samples of coal and ash are designed to substantially expand the existing database and deepen our understanding of the potential for these resources. The Gulf Coast Basin has many surface lignite mines that have been highly under-sampled for REE and CM; however, potential REE and CM resources may be as high as shown in studies of North Dakota lignite. In addition, much of the coal combusted in power plants in the Gulf Coast over the past decade is sourced from the Powder River Basin in Wyoming, which has been shown to be promising in terms of REE and CM recovery. The intensive industrialization in the Gulf Coast region represents a large market for REE and CM products. The comprehensive assessment of REE and CM is designed to evaluate the volumes of these feedstocks and link upstream and midstream supply chains with downstream processing and manufacturing to enhance U.S. national and economic security.

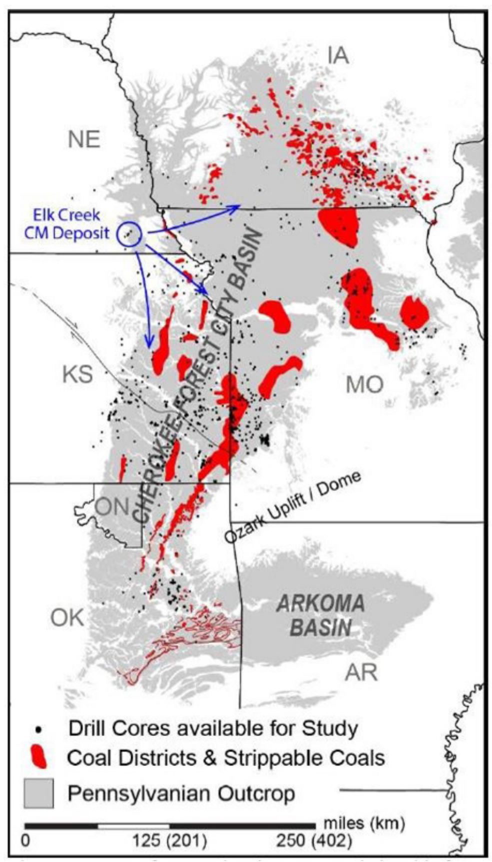


Critical Minerals in Coaly Strata of the Cherokee-Forest City Basin

Performer	**University of Kansas Center for Research**
Award Number	FE0032056
Project Duration	09/15/2021 – 09/14/2023
Total Project Value	$1,981,250
Collaborators	Iowa Geological Survey; Kansas Geological Survey; Missouri Geological Survey; Nebraska Geological Survey; Oklahoma Geological Survey; Osage Nation
Technology Area	Rare Earth Recovery

The overall objective is to integrate new and legacy critical mineral (CM) geochemical data with new basin-wide stratigraphic correlations of coal resources and genetically related strata within the greater Cherokee-Forest City Basin (CFCB) which encompasses parts of Kansas, Iowa, Missouri, Nebraska, Oklahoma, and Osage Nation. Analyses will include new and/or existing drill cores located throughout the basin and assays from coal mine waste sites in historic mine districts to assess the rare earth elements (REE) and critical mineral potential within the region. The Recipient will also test a novel downhole elemental analysis tool at a number of new and/or existing well localities that are proximal and reliably correlated to drill cores.

This study will encompass: (1) a basinal assessment of carbon ore, rare earth, and critical mineral (CORE-CM) resources, including aggregation of historical data, new depositional and structural modeling, and CORE-CM resource assessment; (2) development of a basinal strategy for reuse of waste streams and assist in the development of necessary infrastructure needed to mine and process both natural and waste REE/critical mineral materials; (3) development of a technology assessment and field-testing plan to identify technology gaps associated with the mining process and ways in which the mining technique may be improved; (4) planning for a technology innovation center that fosters public-private partnerships (providing a nucleus of expertise and facilities) that are focused on rapid commercialization of CORE-CM resources within the basin and identification of emerging technologies that can incorporate coal and coal by-products as a feedstock; and (5) development of a stakeholder outreach and education plan that will include educational forums, workshops, digital media, and publications.



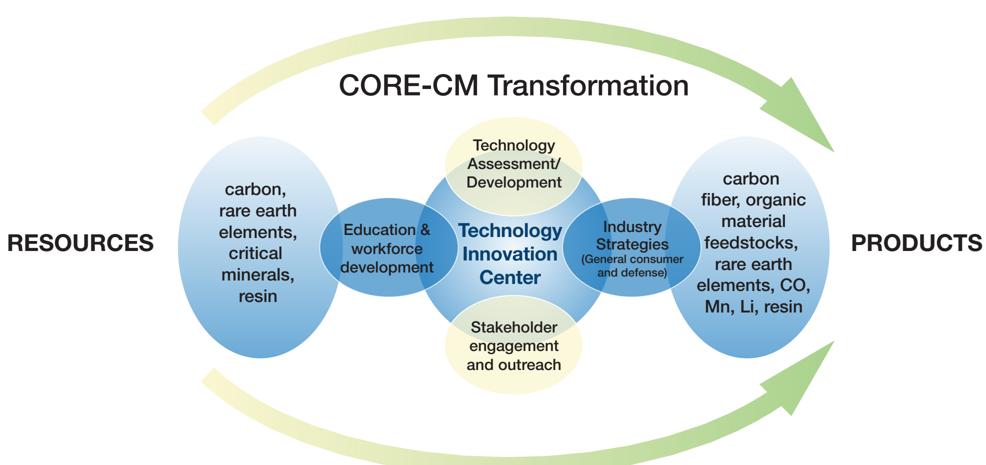
Map of Pennsylvanian outcrop belt with former coal mine districts and near-surface strippable coals.

Transforming Uinta Basin Earth Materials for Advanced Products (Tube-Map)

Performer	University of Utah
Award Number	FE0032046
Project Duration	09/15/2021 – 08/14/2023
Total Project Value	$2,022,143
Collaborators	Colorado School of Mines; JWP Consulting, LLC; Los Alamos National Laboratory; Utah Advanced Materials and Manufacturing Initiative; Utah Geological Survey; Utah State University Eastern; Wolverine Fuels, LLC
Technology Area	Rare Earth Recovery

CORE-CM projects will develop and implement strategies that enable each specific U.S. basin to realize its full economic potential for producing REE, CM and high-value, nonfuel, carbon-based products from basin-contained resources. CORE-CM projects will focus on the following six objectives: (1) basinal assessment of CORE-CM resources, (2) basinal strategies for reuse of waste streams, (3) basinal strategies for infrastructure, industries, and businesses, (4) technology assessment, development, and field testing, (5) technology innovation centers, and (6) stakeholder outreach and education. The objectives of this project are to quantify, assess, and plan to enable the transformation of Uinta Basin earth resources such as coal, oil shale, resin, rare earth elements, and critical materials into high-value metal, mineral, and carbon-based products that can be used in advanced products such as carbon fiber composites in aircraft and high-powered magnets and batteries in electric vehicles. The transformation begins with understanding the geology, which enables discovery of value-added resources, followed by innovative mining to optimize resource recovery, metallurgical processing to separate minerals and purify metals, chemical engineering to enable production of value-added carbon-based products, training and education to prepare the workforce, stakeholder engagement and outreach to facilitate sustainable development, and industry support to drive implementation and manufacturing.

This vision includes large-scale extraction of multiple resources that can, through integrated and innovative processing, be used to produce multiple value-added products and create new industries as well as a more diversified Uinta Basin economy.



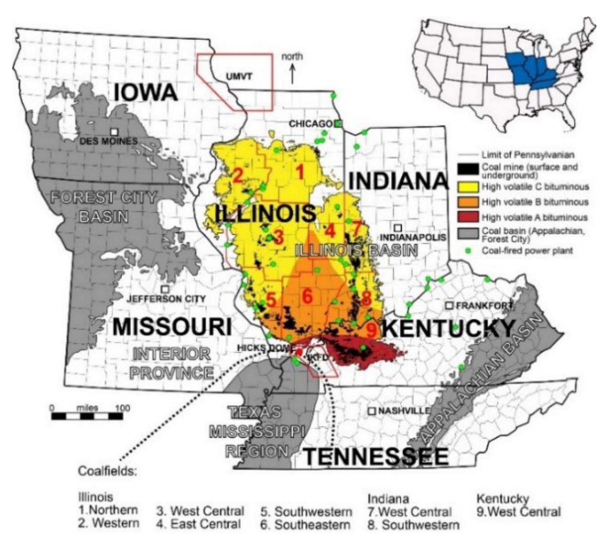
Illinois Basin Carbon Ore, Rare Earth, and Critical Minerals Initiative

Performer	**University of Illinois Urbana-Champaign – Illinois State Geological Survey**
Award Number	FE0032049
Project Duration	09/21/2021 – 09/20/2023
Total Project Value	$1,876,384
Collaborators	Southern Illinois University; University of Kentucky; Indiana Geological and Water Survey; Iowa Geological Survey; Tennessee Geological Survey; Kentucky Geological Survey; Carpenter Global, SynTerra Corp.; Oak Ridge National Laboratory
Technology Area	Rare Earth Recovery

Carbon ore, rare earths, and critical minerals (CORE-CM) projects focus on six objectives: (1) basinal assessment of CORE-CM resources, (2) basinal strategies for reuse of waste streams, (3) basinal strategies for infrastructure, industries, and businesses, (4) technology assessment, development, and field testing, (5) technology innovation centers, and (6) stakeholder outreach and education. This Illinois Basin (IB) CORE-CM project will evaluate the domestic occurrence of strategic elements in coal, coal-based resources, and waste streams from coal use in the region of the IB. The Illinois State Geological Survey-led project will conduct a basin-wide assessment of CORE-CM in coal, coal-based, and waste stream resources that will include CORE-CM availability and abundances. Additionally, the project will assess the mining practices, separation technologies, and local infrastructure necessary to produce and provide CORE-CM resources for U.S. industry and stimulate regional economic growth.

The project team performing this work includes state geological surveys, regional universities, national laboratories, and industries active in the region of Illinois, Indiana, Iowa, Kentucky, and Tennessee. The Illinois Basin assessment will catalog and model existing geochemical and geological data to identify areas of CORE-CM resources in the area having potential economic viability. Regional infrastructure, industries, and businesses, either existing or required to integrate and utilize CORE-CM resources in the IB, will be evaluated. A strategic stakeholder and outreach program will be designed to engage relevant industries and commercial interests. Technologies most relevant to the Illinois Basin distribution and occurrence of CORE-CM in relation to mining techniques, the processing and separation of CORE-CM, and the incorporation of CORE-CM into products will be identified, characterized, and described.

A technology innovation center will be developed to address IB CORE-CM-specific analytical challenges, extraction requirements, resource assessments, and product creation and will serve as a focus for outreach, industry participation, and the pursuit of commercial opportunities. CORE-CM projects will develop and implement strategies that enable each specific U.S. basin to realize its full economic potential for producing rare earth elements, critical minerals and high-value, nonfuel, carbon-based products from basin-contained resources.



Simplified map of the Illinois Basin showing nine distinct coal-producing areas. UMVT = Upper Mississippi Valley type; IKFD = Illinois-Kentucky Fluorspar District.

Consortium to Assess Northern Appalachia Resource Yield (CANARY) of CORE-CM for Advanced Materials

Performer	Pennsylvania State University
Award Number	FE0032052
Project Duration	10/01/2021 – 09/30/2023
Total Project Value	$1,584,543
Collaborators	Colorado School of Mines; Tetra Tech, Inc.; University of Kentucky Research Foundation; Virginia Polytechnic Institute and State University
Technology Area	Rare Earth Recovery

The Consortium to Assess Northern Appalachia Resource Yield (CANARY) of CORE-CM for Advanced Materials comprises university, private industry, and state, local, and federal government personnel to evaluate the carbon ore, rare earth element, and critical mineral (CORE-CM) production potential of the Northern Appalachian (NA) basin covering, Maryland, Ohio, Pennsylvania, and West Virginia. CORE-CM projects will develop and implement strategies that enable each specific U.S. basin to realize its full economic potential for producing REE, CM and high-value, nonfuel, carbon-based products from basin-contained resources. CORE-CM projects will focus on the following six objectives: (1) basinal assessment of CORE-CM resources, (2) basinal strategies for reuse of waste streams, (3) basinal strategies for infrastructure, industries, and businesses, (4) technology assessment, development, and field testing, (5) technology innovation centers, and (6) stakeholder outreach and education.

The proposed project will build on prior work by and current expertise of Penn State and other leading research universities and industrial partners, including some who currently own, develop, and operate carbon ore and critical mineral plants in the United States. CANARY will also collaborate with U.S. and state geological surveys and will review the USGS National Geochemical Database, ongoing efforts of the Earth Mapping Resources Initiative, historic mining and processing sites, and data currently held by the project team members.

To identify information gaps, the consortium will use GIS and machine learning applications to map the resource, infrastructure, and market data in consultation with NETL Research and Innovation Center geospatial modeling activities. Research needs and technology gaps will be assessed, and resources targeted for sampling and characterization. This effort will provide a complete Northern Appalachian CORE-CM value chain basinal assessment to enable quick development of commercial projects.

CANARY will catalyze regional growth and job creation related to CORE-CM as we envision the capability of domestic production of these critical components needed for future development of an advanced, technology-driven society.

Williston Basin CORE-CM Initiative

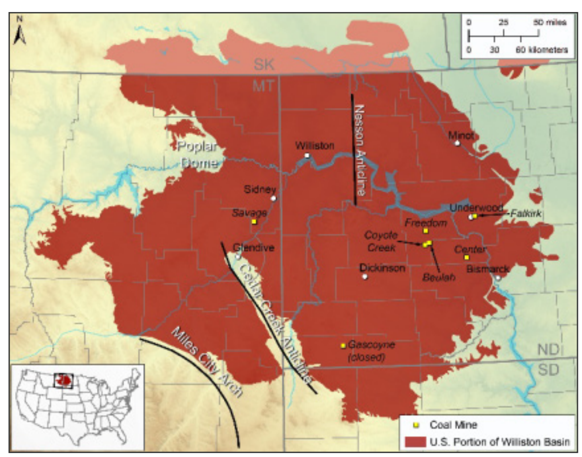
Performer	**University of North Dakota Energy & Environmental Research Center (UNDEERC)**
Award Number	FE0032060
Project Duration	10/01/2021 – 05/31/2023
Total Project Value	$2,517,750
Collaborators	Ames National Laboratory, Montana Tech of the University of Montana, North Dakota State University, Pacific Northwest National Laboratory
Technology Area	Rare Earth Recovery

CORE-CM projects will focus on the following six objectives: (1) basinal assessment of CORE-CM resources, (2) basinal strategies for reuse of waste streams, (3) basinal strategies for infrastructure, industries, and businesses, (4) technology assessment, development, and field testing, (5) technology innovation centers, and (6) stakeholder outreach and education.

The University of North Dakota Energy & Environmental Research Center will form and lead a coalition team of nearly 30 partners encompassing all value chain segments, focused on expanding the use of coal and coal-based resources to produce rare-earth elements (REE), critical minerals (CM), and nonfuel carbon-based products in the Williston Basin. This basin, centered in western North Dakota with portions reaching into South Dakota, Montana, and Canada, contains over 800 years of lignite coal at existing rates of use. The primary development of Williston Basin lignite coal has been in North Dakota, providing coal resources to a series of power facilities totaling greater than 4000 MW of generation capacity. The project work constitutes Phase 1 of a long-term program with objectives to identify the existing knowledge base and gaps and to develop a series of assessments/plans. Research will be conducted to identify and compile the existing, extensive Williston Basin knowledge base related to REE, CM, and nonfuel carbon-based products.

Specific efforts will focus on assessment of coal characteristics, identification of waste streams available, development of regional business planning opportunities, assessment of existing technologies, development of plans to create technology innovation centers, and stakeholder outreach. This assessment may result in databases, models, and a series of assessments/plans that are intended to guide the next phase of activities, with the overall goal of expanding and transforming the use of coal and coal-based resources within the Williston Basin.

Successful development of this opportunity could help to catalyze regional economic growth and job creation.



Map of the Williston Basin.

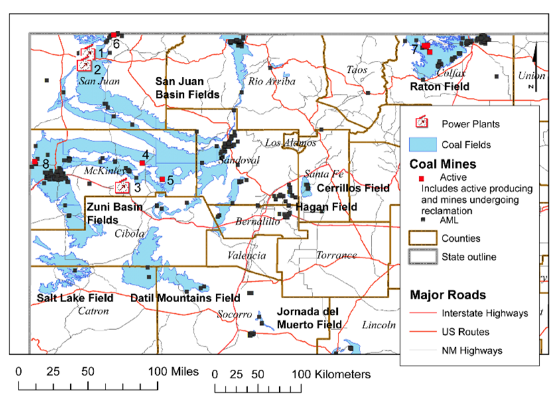
Carbon Ore, Rare Earth, and Critical Minerals (CORE-CM) Assessment of San Juan River-Raton Coal Basin, New Mexico

Performer	New Mexico Institute of Mining and Technology
Award Number	FE0032051
Project Duration	10/01/2021 – 09/20/2023
Total Project Value	$1,945,930
Collaborators	Sandia National Laboratories; Los Alamos National Laboratory; San Juan College; SonoAsh, LLC
Technology Area	Rare Earth Recovery

The specific objective of this project is to determine the REE and CM resource potential in coal and related stratigraphic units in the San Juan and Raton Basins, New Mexico. The project will (1) identify and quantify the distribution of REE and CM in coal beds and related stratigraphic units in the San Juan and Raton basins, (2) identify and characterize the sources of REE and CM, and (3) evaluate the basinal industry infrastructure and determine the economic viability of industrial upgrading. New Mexico Tech will (1) conduct a basinal assessment for CM and REE potential, using state-of-the-art technologies to estimate basin-wide CM and REE resources in coal and related stratigraphic units; (2) identify, sample, and characterize coal waste stream products; (3) conduct bench tests to develop a basinal reuse of waste strategy; (4) illustrate the current status of the feedstock supply of REE and CM to understand the basinal REE industry's capital expenditures and obstacles to expanding REE-related business development; (5) develop a life-cycle analysis to establish pathways, process engineering, and design requirements to upgrade REE processing industry, (6) evaluate technology gaps, (7) establish a Center of Excellence (COE) and training center for coal ash beneficiation at San Juan County; and (8) create REE research-based activities that can be shared during the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) summer geology teacher workshop and assemble REE research-related articles for a REE-centered issue of Lite Geology.

This project will delineate favorable geologic terranes and priority areas containing potential REE and CM deposits for the DOE mandate, which is also a priority of the NMBGMR and State of New Mexico. This project also is important to the State of New Mexico because REE and CM resources must be identified before land use decisions are made by government officials.

Future mining of REE and CM will directly benefit the economy of NM. Furthermore, it is crucial to re-establish a domestic source of REE and CM in the United States to help secure the nation's clean energy future, reducing the vulnerability to material shortages related to national defense, and to maintain our global technical and economic competitiveness. Another aspect of this project is the training of the future workforce because students at New Mexico Tech and San Juan College will be hired to work on this project. Sampling locations will include active and inactive mines, and post-combustion coal ash landfills.



1 San Juan-Public Service Co. of NM plant and San Juan underground mine (Westmoreland)
2 Four Corners-Arizona Public Service Co. plant and Navajo mine (Bisti Fuels Co., LLC)
3 Escalante-TriState plant
4 El Segundo mine (Lee Ranch Coal)
5 Lee Ranch mine (Lee Ranch Coal)
6 La Plata (reclamation)
7 York Canyon and Ancho mines (reclamation)
8 McKinley mine (reclamation)

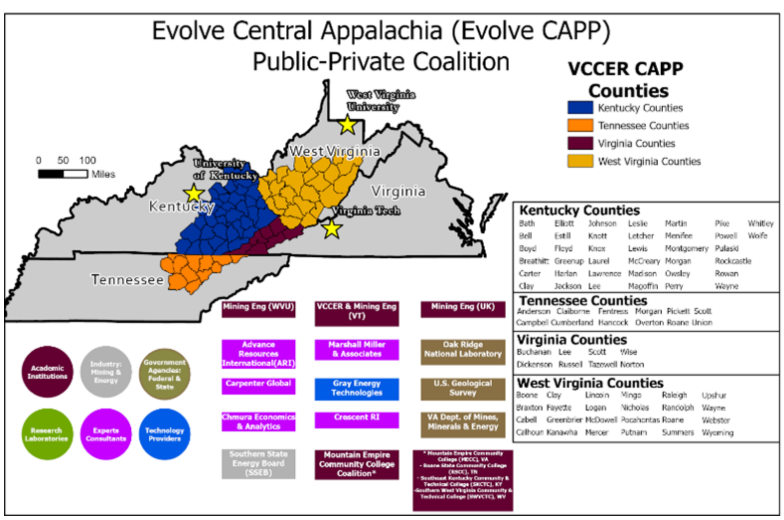
Location of coal fields, active and inactive mines, and coal burning power plants in the project area.

Evolve Central Appalachia (Evolve CAPP)

Performer	**Virginia Polytechnic Institute and State University**
Award Number	FE0032055
Project Duration	10/01/2021 – 09/30/2023
Total Project Value	$2,111,491
Collaborators	West Virginia University; University of Kentucky; Marshall Miller and Associates; Advanced Resources International; Virginia Department of Energy; Mountain Empire Community College; Crescent RI; Carpenter Global; Gray Energy Technologies; Chmura Economics and Analytics; Southern States Energy Board; United States Geological Survey; Oak Ridge National Laboratory
Technology Area	Rare Earth Recovery

Project-specific objectives are to determine the quantity and distribution of CORE-CM resources in the region, formulate strategies to utilize coal waste streams to produce useful fuels and materials, formulate strategies to encourage business development, guide research and development of new technologies, formulate plans to establish technology innovation centers, and formulate and implement stakeholder outreach and education initiatives. In addition, the research team will evaluate regional infrastructure and identify industries and businesses that may benefit from current and future CORE-CM production and utilization. Strategies will be presented to spur economic growth, close supply chain gaps, promote investment in the region, and address workforce education and training opportunities.

The team will collaborate with business and industrial partners to accelerate commercial deployment of promising technologies than can recover and utilize CORE-CM resources in an environmentally and socially responsible manner. National interest and U.S. independence in critical raw materials and national security will be addressed in the overall technology assessment process. This project could help to reduce U.S. dependence on foreign sources of REE and CM by utilizing the region's vast natural resources and skilled people to extract additional CORE-CM resources from coal and associated byproducts to develop additional revenue streams through the manufacture of intermediate and end-use carbon-based products.



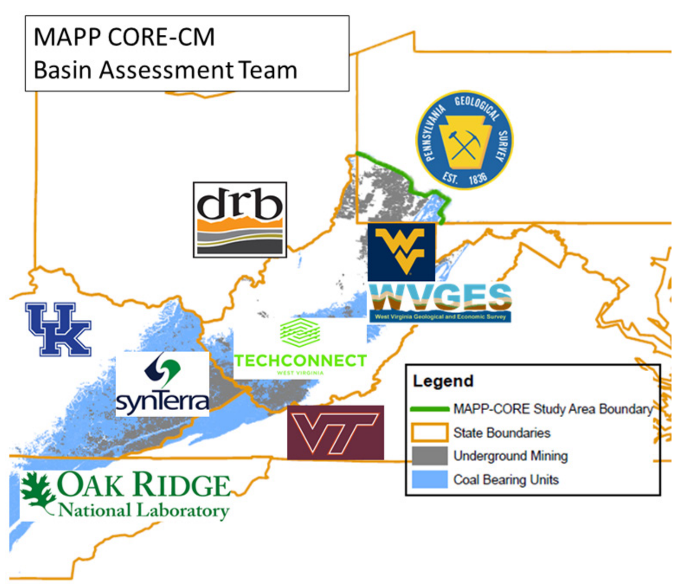
Mid-Appalachian Carbon Ore, Rare Earth and Critical Minerals Initiative

Performer	**West Virginia University Research Corporation**
Award Number	FE0032054
Project Duration	10/01/2021 – 09/30/2023
Total Project Value	$2,202,128
Collaborators	University of Kentucky; Virginia Polytechnic Institute and State University; West Virginia Geological Survey, Kentucky Geological Survey, Pennsylvania Geological Survey, Synterra Corporation, Oak Ridge National Laboratory, DRB Geological Consulting; TechConnect WV
Technology Area	Rare Earth Recovery

CORE-CM projects will develop and implement strategies that enable each specific U.S. basin to realize its full economic potential for producing rare earth elements (REE), critical minerals (CM), and high-value, nonfuel, carbon-based products from basin-contained resources. CORE-CM projects will focus on six objectives: (1) basinal assessment of CORE-CM resources, (2) basinal strategies for reuse of waste streams, (3) basinal strategies for infrastructure, industries, and businesses, (4) technology assessment, development, and field testing, (5) technology innovation centers, and (6) stakeholder outreach and education.

The overall objective of the West Virginia University Research Corporation (WVURC) in this project will be to focus on the expansion and transformation of the use of coal and coal-based resources—including waste streams—to produce products of high value to the 21st century energy and manufacturing ecosystem. The project will accomplish these goals via a basin assessment of Central Appalachian resources, including waste streams, that could be reused as feedstocks and raw materials in processes that produce carbon ore, rare earth and critical minerals (CORE-CM) products. The team will prepare R&D plans to fill information gaps in the assessments of CORE-CM resources and regional waste streams. A technology and economic gap assessment to address barriers and spur growth for the basin's CORE-CM resources will be developed, including preparing initial research plans to fill those gaps. In addition, the team will prepare plans for stakeholder outreach and education needed to support these activities. This effort will culminate with the preparation of initial plans for a technology innovation center that will be developed and operated by a basin-specific public-private partnership, leveraging facilities and resources of the MAPP-CORE team.

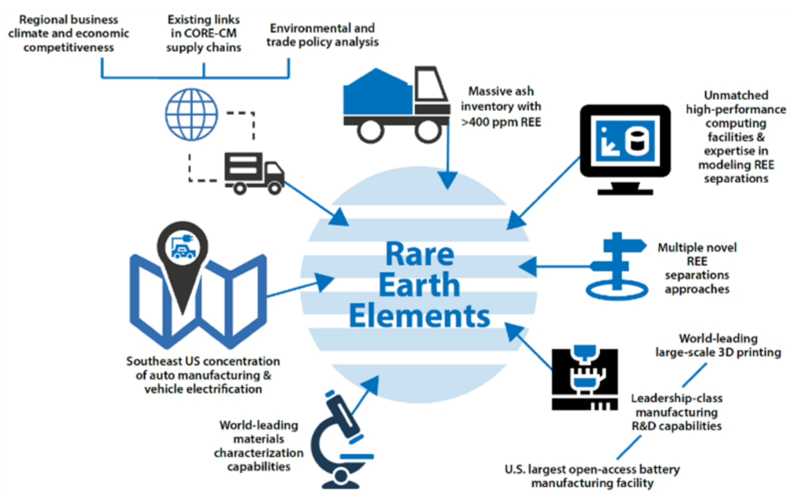
This project will perform the initial strategy development and economic and technical gap assessment for the mid-Appalachian region, defined as the states of Kentucky, Tennessee, Virginia, and West Virginia. The project team also includes resource assessments for southwestern Pennsylvania, recognizing the geologic and geographic connections between these regions



Manufacturing Valuable Coal-Derived Products in Southern Appalachia

Performer	**Collaborative Composite Solutions Corporation**
Award Number	FE0032045
Project Duration	09/15/2021 – 09/14/2023
Total Project Value	$1,982,746
Collaborators	Geological Survey of Alabama; Southern Company Services, Inc.; University of Alabama; University of Alabama at Birmingham; University of Tennessee
Technology Area	Rare Earth Recovery

The Institute for Advanced Composites Manufacturing Innovation, or IACMI - The Composites Institute, is a national Manufacturing USA Institute managed by Collaborative Composite Solutions Corporation (CCS). CCS will develop strategies for manufacturing valuable, non-fuel products from coal in Southern Appalachia. The project focuses on using coal resources from the southern Appalachian Basin situated in east Tennessee, northwest Georgia, and northern Alabama. Key participants include University of Tennessee, Southern Company, state geological surveys of Alabama and Tennessee, Oak Ridge National Laboratory, University of Alabama, University of Alabama at Birmingham, Roane State Community College, and several other stakeholders that are informally supporting the project. The project will assess the southern Appalachian Basin's coal resources and identify strategies for developing technologies to cost-effectively produce valuable non-fuel products from those resources. The program objective is to transform distressed coal communities into thriving manufacturing communities with high-wage jobs producing coal-based products. Initial product priorities include rare earth elements extracted from coal ash, as well as carbon fibers and graphite made from coal. Potential product applications include (i) automobiles, capitalizing on the region's vibrant automotive manufacturing industry and the emergence of electric vehicles manufacturing; and (ii) resilient infrastructure that can withstand natural events such as hurricanes, tornadoes, and floods that frequently occur in the southeastern United States. A critical project element is economics and policy analysis on the interrelationships and risks or resource availability, market demand, supply chains, infrastructure, workforce, tax and regulatory policy, technology, and national security.



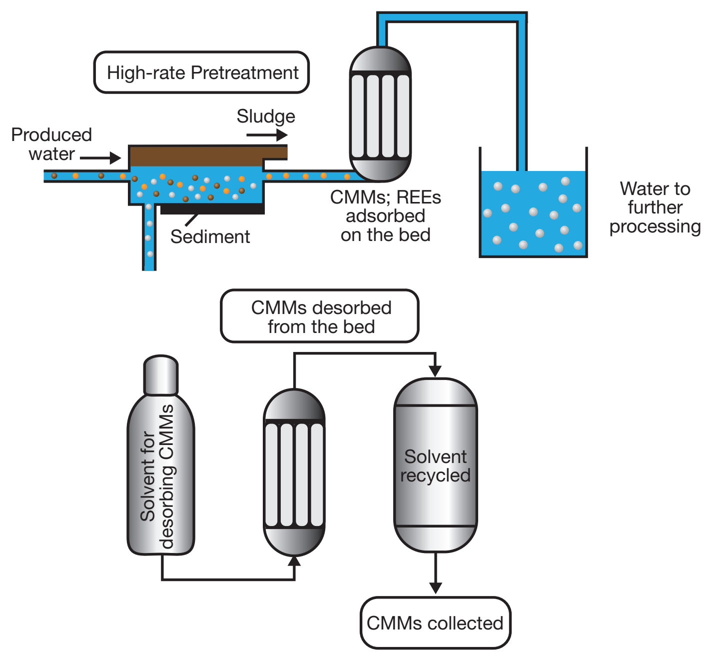
CRITICAL MINERALS FROM PRODUCED WATERS

Low-Cost Environment-Friendly Critical Materials Recovery from Produced Water

Performer	Altex Technologies Corporation
Award Number	SC0022939
Project Duration	06/27/2022 – 03/26/2023
Total Project Value	$199,994
Collaborator	Pennsylvania State University
Technology Area	Rare Earth Recovery

The objective of this project is to develop low-cost, low energy consumption, and environment-friendly technologies to recover critical minerals and materials (CMM), including rare earth elements (REE), from oil-field produced water. Currently, the United States is heavily dependent on foreign markets for REE and CMM, and thus domestic sources are desired to secure supply chains. Additionally, current disposal methods of produced water are plagued by high energy consumption and expenses, and present seismic, climate, health, and toxicology concerns. Accordingly, this effort aims to address these challenges by reducing the costs of REE recovery and produced water treatment.

In this project, a novel sorption technology which leverages a metal organic framework will be used to recover critical materials from produced water. Material synthesis and characterization, demonstration of the sorption technology, development of a full-scale design, techno-economic assessment (TEA), and life cycle analysis (LCA) of the full-scale process will be performed. Currently available sorbent materials will be improved and optimized to increase the percentage of REE recovered and address selective recovery of a wider range of materials. Analysis, lab-scale fabrication, and testing will be used to achieve this goal. Lab-scale test data will be used to optimize the process design and demonstrate the technical and economic feasibility of the innovation. It is anticipated that commercialization of the proposed technology could significantly lower the cost of REE and reduce dependency on volatile external markets.



Extraction of Value-added Minerals from Produced Water Through Novel Multistage Nanofiltration

Performer	**Greenpath Systems, LLC.**
Award Number	SC0022863
Project Duration	06/27/2022 – 06/26/2023
Total Project Value	$199,948
Collaborators	University of Oklahoma; A&A Tank Truck Co.
Technology Area	Rare Earth Recovery

Recent growth in oil and gas production through fracking has increased the amount of generated wastewater, known as produced water, that requires treatment in order to meet environmental regulations. Wastewater treatment processes may employ several types of membranes, including microfiltration (MF), ultrafiltration (UF), and nanofiltration (NF). The main difference in these processes is the solute size that can be separated from the wastewater stream. For example, while typical UF membranes have pore sizes of 10–100 nm and are used to remove proteins, organic acids, oil emulsions, microbes, and viruses from wastewater, NF membranes with 1–5 nm pore sizes can separate monovalent and multivalent ions based on the charge and size. Typical produced waters contain magnesium (Mg) and bromine (Br) on the order 1000 ppm, and lithium (Li), boron (B), barium (Ba), and iodine (I) on the order of 50 ppm. Therefore, produced water presents an opportunity as an unconventional resource, which may support the expanded requirement for Li necessary for technologies such as Li-ion batteries and may also support increased domestic supply of Mg. In this project, a multistage NF process leveraging NF membranes with different pore sizes will be employed to separate Li and Mg salts from one another, as well as other species present in produced water.

Critical Minerals and Materials Recovery from Oil and Gas Produced Water

Performer	**Materials Modification Inc.**
Award Number	SC0022866
Project Duration	06/27/2022 – 03/26/2023
Total Project Value	$200,000
Collaborator	University of Wyoming
Technology Area	Rare Earth Recovery

Critical minerals and materials (CMM) are essential for clean energy technologies, and the demand for CMM is expected to significantly increase in the near term, owing to increased deployment of solar, wind, and battery storage technologies. More specifically, lithium (Li) is a critical mineral that finds application in a host of technologies, including Li-ion batteries, thermonuclear fusion reactors, CO_2 adsorbents, and medical products. One strategy for increasing domestic production of CMM is recovery from unconventional sources, such as produced water from the oil and gas industries. In the case of Li, technologies such as adsorbents, membrane-based processes, solvent extraction, and electrolysis-based systems allow for recovery from oil and gas produced waters. Water produced as by-product of industrial oil and gas activities typically contains various inorganic and organic contaminants, including salts, oil, and grease, for example. However, on average, about 95 mg/L of Li is present. In this project, Li will be selectively recovered from produced water using a liquid-liquid solvent extraction process, employing selectively functionalized ionic liquids as solvents. The extraction behavior will be analyzed as a function of various parameters, including produced water dilution, acidity, temperature, ionic liquid type, and addition of cosolvents. The extraction efficiencies obtained in these studies will be benchmarked against a traditional solvent used in metal ion extraction. In addition, the efficiency of Li extraction using the ionic liquid and the recyclability of the ionic liquid itself will also be studied. The overall goal of this effort is to transition produced water from a liability into an asset by extracting valuable CMM, such as Li, using a solvent extraction process. In doing so, it will be demonstrated that this unconventional resource could serve as a viable and sustainable domestic source of CMM.

ABBREVIATIONS

AACE .... Association for the Advancement of Cost Engineering

Al .... aluminum

ALB .... air lift bioreactor

AlO_x .... aluminium oxide

AMD .... acid mine drainage

B .... boron

Ba .... barium

Br .... bromine

CANARY .... Consortium to Assess Northern Applachia Resource Yield

CAPP .... Central Appalachia

CBP .... carbon-based products

CCS .... Composite Solutions Corporation

Ce .... cerium

[Ce, La, Th]PO_4 .... monazite

CFCB .... Cherokee-Forest City Basin

CM .... critical mineral(s)

CMM .... critical minerals and materials

Co .... cobalt

COE .... Center of Excellence

CORE .... carbon ore

CORE-CM .... carbon ore, rare earth element, and critical mineral

DOE .... Department of Energy

DTPA .... FPM to supply definition

Dy .... dysprosium

EC .... elution column

Eu .... europium

FECM...Office of Fossil Energy and Carbon Management

FEED .... front end engineering design

FeO_x .... iron oxide

FWP .... Field Work Proposal

FY .... fiscal year

g .... gram

Ga .... gallium

Gd .... gadolinium

Ge .... germanium

GIS .... geographic information system

GGRB .... Greater Green River Basin

GHG .... green house gas

gpm .... gallon per minute

HAMR .... high vacuum reduction

HBF_4 .... fluoroboric acid

HHS .... hydrophobic-hydrophilic separation

HREE .... heavy rare earth element(s)

I .... iodine

IACMI .... Institute for Advanced Composites Manufacturing Innovation

IB .... Illinois Basin

ICP-MS .... inductively coupled mass spectroscopy

IKFD .... Illinois-Kentucky Fluorspar district

ISHP .... individually separated high purity

kg .... kilogram

La .... lanthanum

[La, Ce]FCO_3 .... bastnäsite

LANL .... Los Alamos National Laboratory

LCA .... life cycle analysis

Li .... lithium

LIBS .... laser induced breakdown spectroscopy

$LiNiPO_4$ .... lithium, nickel, potassium, oxygen (orthorhombic compound)

LLC .... limited liability company

LLNL .... Lawrence Livermore National Laboratory

LREE .... light rare earth element(s)

MAB .... mechanically agitated bioreactor

MAPP .... Mid-Appalachian

MF .... microfiltration

mg .... milligram
Mg .... magnesium
mg/L .... milligram per liter
Mn .... manganese
MnO_x .... manganese oxide
MREE .... mixed rare earth element(s)
MREO .... mixed rare earth oxide(s)
MRES .... mixed rare earth salt(s)
MW .... megawatt
NA .... Northern Appalachian
Nd .... neodymium
ND .... North Dakota
NETL .... National Energy Technology Laboratory
NF .... nanofiltration
Ni .... nickel
nm .... nanometer
NM .... New Mexico
NMBGMR .... New Mexico Bureau of Geology and Mineral Resources
pH .... acidity/basicity measure
PLS .... pregnant leachate solution
ppb .... parts per billion
ppm .... parts per million
Pr .... praseodymium
PRB .... Powder River Basin
PSI .... Physical Sciences, Inc.
PT .... Polykala Technologies
R&D .... research and development
RD&D .... research, development, and demonstration
REE .... rare earth element(s)
REM .... rare earth metal(s)
REO .... rare earth oxide(s)
RES .... rare earth salt(s), Rare Earth Salts (company)
REY .... rare earths and yttrium
REYSc .... rare earths, yttrium, and scandium
RIC .... Research and Innovation Center
SBIR .... small business innovative research
Sc .... scandium
Sm .... samarium
Sr .... strontium
SSLiB .... solid state Li-ion battery
Tb .... terbium
TCF .... Technology Commercialization Fund
TDC .... Technology Development Center
TEA .... techno-economic analysis
TEP .... tunable electrochemical pathway
Th .... thorium
tpd .... tonne(s) per day
TRL .... technology readiness level
UF .... ultrafiltration
UK .... University of Kentucky
UK CAER ... University of Kentucky Center for Applied Energy
µm .... micrometer
UMVT .... Upper Mississippi Valley type
UND .... University of North Dakota
UNDEERC .... University of North Dakota Energy and Environment Research
U.S. .... United States
USA .... United States of America
USD .... United States Dollar
USGS .... United States Geological Survey
VCCERR .... Virginia Center for Coal and Energy Research
WRB .... Wind River Basin
wt% .... percentage by weight
WVU .... West Virginia University
WVURC .... West Virginia University Research Corporation
WWS .... Winner Water Services
Y .... yttrium
Yb_2O_3 .... ytterbium oxide
YPO_4 .... xenotime (yttrium orthophosphate)
Zn .... zinc

NOTES

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https://edx.netl.doe.gov/ree/

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