Recovery of Rare Earth Elements and Critical Materials from Coal and Coal Byproducts

Report to Congress

May 2022

United States Department of Energy
Washington, DC 20585

Message from the Secretary

I am pleased to submit the enclosed report, *Recovery of Rare Earth Elements and Critical Materials from Coal and Coal Byproducts*. This report outlines achievements in realizing opportunities and resolving challenges for the separation, extraction, and recovery of Rare Earth Elements and other critical materials from coal and coal byproducts since 2017. It can be considered an update to a previous report to Congress produced in 2017. The report also provides information supporting the availability of critical materials (CM), including rare earth elements (REE), throughout the United States.

This report was prepared by the Department of Energy, Office of Fossil Energy and Carbon Management (FECM), and the National Energy Technology Laboratory (NETL) in conformance with the requirements in Section 7001 of the Energy Act of 2020, codified at 42 USC 13344.

The assessment and analysis effort were conducted in collaboration with industry, academia, and NETL's Research and Innovation Center. This report is being provided to the following: the Committee on Energy and Natural Resources of the Senate and the Committees on Science, Space, and Technology, and Energy and Commerce of the House of Representatives:

- **The Honorable Joseph Manchin**
  Chairman, Senate Committee on Energy and Natural Resources
- **The Honorable John Barrasso**
  Ranking Member, Senate Committee on Energy and Natural Resources
- **The Honorable Eddie Bernice Johnson**
  Chairwoman, House Committee on Science, Space, and Technology
- **The Honorable Frank Lucas**
  Ranking Member, House Committee on Science, Space, and Technology
- **The Honorable Frank Pallone, Jr.**
  Chairman, House Committee on Energy and Commerce
- **The Honorable Cathy McMorris Rodgers**
  Ranking Member, House Committee on Energy and Commerce

If you have any questions or need additional information, please contact Rebecca Ward, Deputy Assistant Secretary for Senate Affairs, or Ms. Elizabeth Noll, Deputy Assistant Secretary for House Affairs, Office of Congressional and Intergovernmental Affairs, at (202) 586-5450.

Sincerely,

Jennifer Granholm

Recovery of Rare Earth Elements and Critical Materials from Coal and Coal Byproducts

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I. EXECUTIVE SUMMARY

In accordance with the requirements in Section 7001 of the Energy Act of 2020, codified at 42 USC 13344, the Department of Energy (DOE), Office of Fossil Energy and Carbon Management (FECM), and the National Energy Technology Laboratory (NETL) have performed an assessment and analysis of the feasibility of economically recovering rare earth elements (REE) and other critical materials (CM) from coal and coal byproduct streams, such as low rank coals, coal refuse, coal ash, and acid mine drainage (AMD). Consistent with the requirements in Section 7001, this report presents the results of DOE/NETL's assessment and analysis to the Committees on Appropriations of the House of Representatives and the Senate.

In 2017, DOE published a similar report on this topic, "Report on Rare Earth Elements from Coal and Coal Byproducts." Rather than repeating details from that report, this report summarizes those findings and describes the findings and advances within DOE since that report was drafted. The two main findings from the 2017 report were that significant potential reserves of REE exist in coal and coal byproducts and that there were technical challenges associated with effectively extracting and separating mixed rare earth oxides (MREO) from such low-grade feedstocks, while minimizing environmental impact. Additionally, several knowledge gaps were identified.

Substantial progress has been made since the 2017 report was written. This progress can be summarized as follows:

1. Characterization of resources within unconventional and secondary sources have provided indications of a significant resource potential.

   Collection and analysis of over 4,000 new samples from coal, coal refuse, ash, and AMD in U.S. coal basins showed that REE concentrations in the sampled materials ranged from parts per billion (ppb) for raw AMD materials to thousands of ppm for unconventional and secondary coal-based resources. An analysis of resources supports that sufficient REE are present to extract quantities of ore sufficient to produce MREOs to operate multi-ton per day large-scale pilot facilities to assess commercial production.

2. Demonstrated the technical feasibility of producing high-purity critical minerals, including REE, from low grade source materials (~300ppm), such as coal and coal byproducts.

   DOE's First-of-a-Kind (FOAK) projects have demonstrated the technical feasibility of producing high purity REEs and other critical minerals from unconventional feedstocks (e.g., AMD, coal refuse, coal ash, and lignite coals). These projects exceeded the initial goals of 2wt percent purity REEs and by 2020 demonstrated purities from 67 percent (coal ash) to >98 percent purity (AMD and refuse) using multiple conventional processing approaches on these unconventional feedstocks.

These initial projects were foundational, providing confidence to move forward with system optimization and efficiency improvements (cost reduction) from four high volume source materials.

3. Environmentally sustainable pathways to commercial scale production of high purity critical minerals, including REE, from unconventional and secondary sources have been identified.

   DOE's domestic small-scale pilots are enabling the design of large-scale projects through process scale-up, optimization and efficiency improvements for REE and other CMs. Previous small scale FOAK projects that demonstrated feasibility to produce REE and other CMs from unconventional and secondary sources are the building blocks for future large-scale pilots, which will integrate conventional technologies with advanced separation technologies and novel techniques for high performance, economically recoverable, and environmentally sustainable production of REE and other CMs. These large-scale units could provide a share of U.S. demand within three to five years.

Significant progress has been made toward enabling commercial production of CMs in addition to the work establishing commercial production of REE from unconventional sources. Production of many CMs and REEs needed for the processing of battery materials, such as cobalt, lithium, and gallium, from coal-based sources appear promising. DOE's efforts in resource characterization and technology development are creating the conditions needed to enable large-scale pilot projects for producing hundreds of metric tons of mixed rare earth oxides/salts and other CMs for individual separation and reduction to metals to begin operations by 2025. Regional efforts have started that will build coalitions to evaluate the potential to establish full-scale projects and accelerate technology transfer.

This report details the achievements that DOE has made toward advancing the recovery of REE and CM from coal and coal byproducts summarized above. Key research and development needs required to enable the production of sustainable, domestic supply chains from such unconventional and secondary sources are also identified. Additionally, research activities which have been initiated to address these research needs, and technical challenges are described to show the breadth of planned activities within the FECM program and across the DOE.

II. LEGISLATIVE LANGUAGE

REPORT.—Not later than 1 year after the date of enactment of this Act, the Secretary shall submit to the Committee on Energy and Natural Resources of the Senate and the Committees on Science, Space, and Technology, and Energy and Commerce of the House of Representatives a report evaluating the development of advanced separation technologies for the extraction and recovery of REE and other CM from coal and coal byproducts, including AMD from coal mines. Consolidated Appropriations Act, 2021, Div. Z, Title VII, Sec. 7001(b), Pub. L. No. 116-260 (Dec. 27, 2020).[1]

III. PRIOR FOUNDATION

Summary of FINDINGS from 2017 REPORT to CONGRESS

This section briefly summarizes the findings from the 2017 Report, "Report on Rare Earth Elements from Coal and Coal Byproducts", which was drafted in 2015 and includes suggested major R&D needs identified at the time. The first major finding from the 2017 Report was that there were indications of a large potential resource of REE in some U.S.-based coal measures—more than a magnitude higher than forecast global REE demand—but that the resource may vary significantly by location. The second major finding was that there are technical challenges associated with effectively extracting and separating high purity REEs from the low concentrations found in coal measures and other coal byproducts especially while minimizing the associated environmental impact. The economic feasibility of REE production from these sources was found to require improvements in both the understanding of REE occurrences in coal-bearing strata, as well as the technologies required to recover and refine these materials in marketable forms.

The following were identified as major knowledge gaps or technical needs related to the two primary findings described above:

1. REE distribution in U.S. coals and related minerals: Preliminary work established that there is variability in the REE contents associated with U.S. coal deposits, and that reasons for such variability are often unknown. Understanding this characteristic can lead to improved understanding of the mineral forms present, which in turn, can lead to separation technology improvements.

2. REE distributions within minerals associated with specific deposits: Preliminary work showed that REE can be expected to concentrate in specific portions of strata associated with a coal deposit and therefore in specific portions of the mined product (i.e., correlated with specific gravity).

[1] https://www.govinfo.gov/content/pkg/BILLS-116hr133enr/pdf/BILLS-116hr133enr.pdf. The section is codified at 42 U.S.C. § 13344.

3. Response of REE-bearing components associated with U.S. coals to industrial separation processes: For such low concentrations of REEs, knowledge of the responses of REE-bearing minerals to physical separation processes is essential for conceptual flowsheet designs, and therefore economic evaluations. This is also essential to inform the development of new separations technologies.

4. Effective design of systems specifically for REE recovery from deposits associated with U.S. coals: Economic analyses of systems for the recovery of REE-bearing concentrates from coal and coal byproducts will require flowsheet designs, from which material balance data, capital costs, and operating costs are extracted for use as inputs for financial modeling of conceptual operations. This activity must also be conducted such that the resulting waste is not objectionable from an environmental standpoint.

5. Economic feasibility assessments: As new results are generated from items 1-4 above, financial models of conceptual production operations will need to be further developed and refined, to enable the comparative assessment of new and existing extraction, processing, and refining technologies.

IV. Critical Minerals Program Portfolio

A. Organizational response and Work program

The work described in this document represents efforts managed and conducted by FECM/US Department of Energy and NETL, including NETL's Research and Innovation Center (RIC), throughout the period from 2014 until the present (2021). These activities consisted of programmatic solicitations, work at NETL-RIC, and other national laboratories under Field Work Proposals (FWP), and other specialized projects. The initial phases of work were focused on REE as may be found in coal and coal measures and included various coal waste streams, including post-combustion ashes, and solids and liquids associated with ACD.

Since the 2017 report, which catalogued activities through 2015, the scope of the research and development activities has been expanded. Several Executive Orders[2] broadened the scope to

[2] A series of Executive Orders have addressed deficiencies in the existing critical minerals supply chain. The content of these Executive Orders has contributed to the current shape and direction of the program. These are:

- Executive Order 14017—America's Supply Chains
- 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
- Executive Order 13868—Promoting Energy Infrastructure and Economic Growth
- Executive Order 13817—A Federal Strategy To Ensure Secure and Reliable Supplies of Critical Minerals

include all CM that are found on the United States Geological Survey (USGS) list.[3] These actions reflect a growing understanding of two concerns. First, domestic production of critical materials is an important element in building and maintaining a robust national supply chain that can support manufacture of component parts that include these minerals.[4] And second, recent reports evaluating international responses to concerns over the rate of climate change indicate that demand for these same CM will increase several fold.[5]

Figure 1 presents the flow of program activities from 2015 to 2021, which were focused on the characterization of unconventional resources containing REE, and the development of methods to extract REE from said resources via both conventional (funding opportunity announcements (FOA) 1202, 1627, and 2003) and novel methods (FOA 2404). The major activities and major accomplishments associated with these efforts are summarized in Section V, with resource characterization efforts detailed in Section V.A and the progression of the separation technology development levels from technology readiness levels (TRL) 2 through 5 detailed in Sections V.B and V.C. By 2018, recovery levels had significantly exceeded the original target levels for unconventional sources and attention moved to large-scale units—a major step toward commercialization (TRL 7-8). Additional work was started in fiscal year (FY) 20 that adds CMs as candidates for recovery as on-going field assessments suggest significant quantities of some CMs are found in the same source materials that have been evaluated for REEs.

[3] USGS prepares a list of critical minerals. An open file report on the process and which contains the current list is available at: https://pubs.usgs.gov/of/2021/1045/ofr20211045.pdf (accessed August 6, 2021).

[4] M. Summers, Understanding the Rare Earth Element Supply Chain: Identifying Domestic Gaps and Opportunities, See: PowerPoint Presentation (doe.gov).

[5] IEA, The Role of Critical World Energy Outlook Special Report Minerals in Clean Energy Transitions, World Energy Outlook Special Report (May 2021) (https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions), and IEA, Energy Technology Perspectives 2010 – Scenarios & Strategies to 2050 (2010) (https://www.iea.org/reports/energy-technology-perspectives-2010)

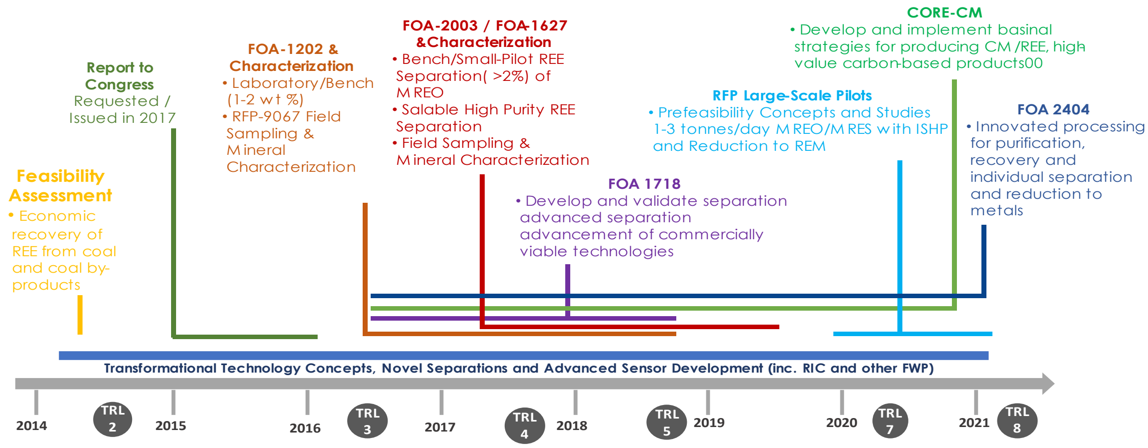


Figure 1. Programmatic activities conducted and underway from 2014 through 2021

(Note: Vertical line is release date and horizontal line represents TRLs covered)

The success of extraction and separations research efforts to date has resulted in plans to rapidly move forward with novel technologies developed through the program by initiating the design of large-scale pilots capable of separating and recovering significant quantities of MREOs at high purities. In parallel to that effort, plans are being made to test conventional and alternative separations technologies validated by the program at a scale which approach those of a commercial facility. Results of tests at both scales will enable a better understanding of the economic competitiveness of REEs produced from these unconventional sources, the costs to co-produce a slate of CMs, and will also inform life-cycle assessments to assess the environmental footprint for the technology pathways being developed.

The Carbon Ore, Rare Earth, and Critical Minerals (CORE-CM) initiative is designed to advance resource assessments of sources tied to past mining activities throughout the United States by verifying technically recoverable quantities of REEs and other CMs to provide domestically-sourced material, and to engage regional interests to bring unique supply chain issues and opportunities forward.

Throughout the activities detailed here, appropriated levels of funding were carefully managed to focus on the uncertainties highlighted in the 2017 Report. The funding was adequate to conduct focused studies to broaden the characterization activities and to develop small-scale experimental units for recovery and separation of mixed rare earths. This budget chart allowed FECM to gain a firm understanding of the landscape of technology needs for identifying potential critical mineral and carbon ore resources, extraction and concentration techniques, extractive metallurgy technology, and precursor manufacturing processes associated with coal, coal byproducts, and coal refuse.

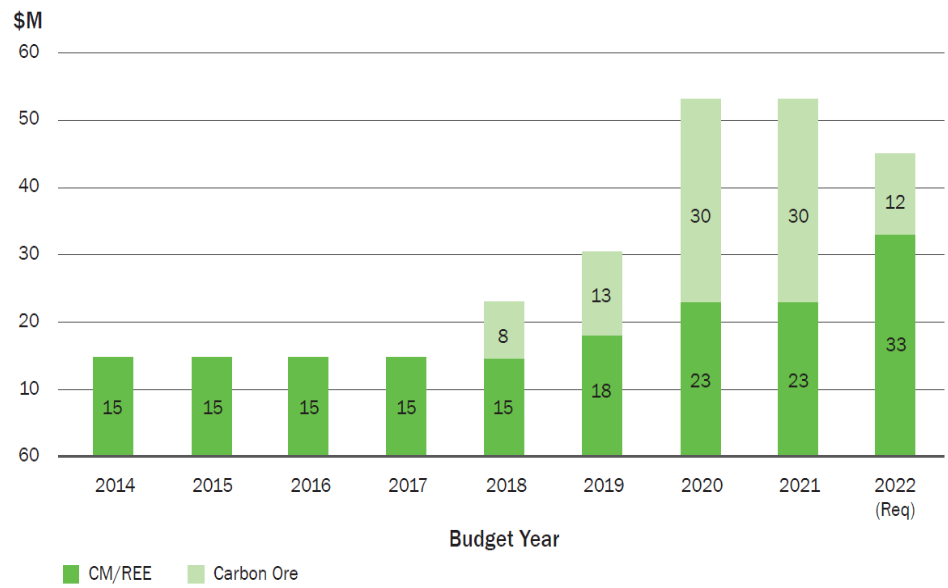


Figure 2. Historical FECM Budgets in Rare Earth Elements, Critical Minerals, and Carbon Ore R&D

This knowledge has enabled the generation of the research, development, demonstration, and deployment (RDD&D) requirements, goals, and milestones needed to accelerate the development of sustainable CM supply chains and advance production of high-value carbon products by 2030.

B. On-going activities – Cooperation within DOE and across other governmental organizations

The importance of CMs, including REEs, has been underscored by the actions of Congress and by several Executive Orders. These actions have engendered activity both across DOE and throughout the Federal Government. The activities described in this report cover only those performed by FECM, but these efforts are performed as part of a variety of Department-wide activities. Figure 3 briefly summarizes the types of activity underway within DOE Offices by topic and reflects coordination across the Department.

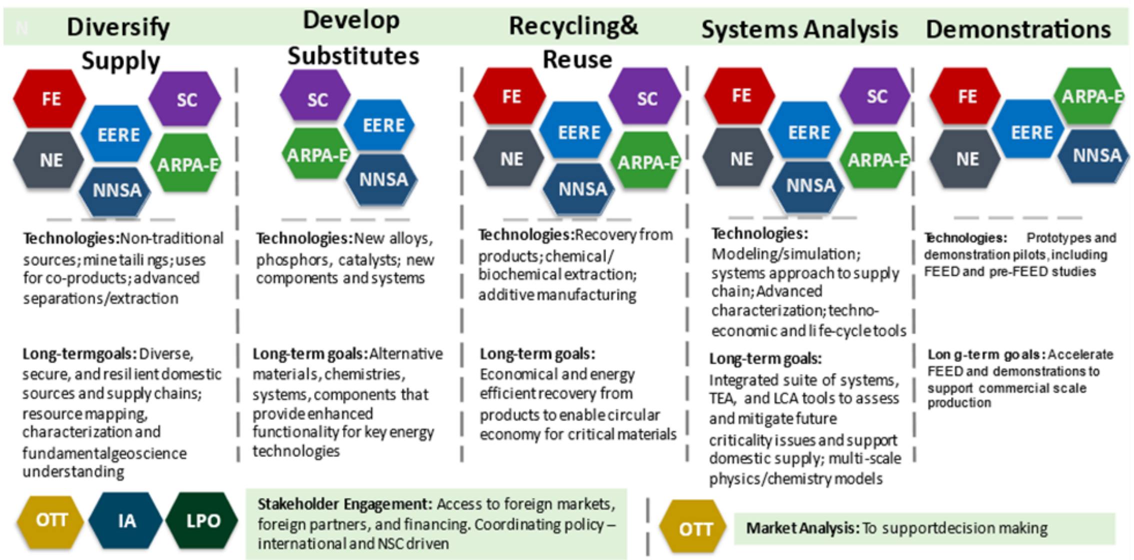


Figure 3: Mineral Sustainability program interactions within DOE by R&D topics

DOE addresses these challenges and opportunities through the Critical Minerals and Materials crosscut. DOE supports the recognition, coordination, and augmentation of existing activities, as well as the development of new activities, within the pillars that ground DOE's strategy for bolstering the critical materials supply chain: diversify supply in a safe, sustainable, and environmentally just way; develop substitutes; and improve reuse and recycling, conduct systems analysis, and demonstrations. Current DOE investments within the Advanced Research Program Agency-Energy, the Office of Science, the Office of Energy Efficiency and Renewable Energy, FECM, the Office of Nuclear Energy, and the Office of Technology Transitions support these pillars in a variety of areas, from extraction to processing and manufacturing to recycling and reuse.

In addition, under the aegis of the National Science and Technology Council (NSTC), there is on-going communication and discussion of plans, programmatic solicitations, and outcomes from on-going activities, such as the 100-day report for Executive Order (E.O.) 14017.

V. MAJOR OUTCOMES

The first three outcomes (Subsections V. A, B, and C) address the findings and gaps identified in the 2017 Report. Additional areas of investigations derived from Congressional Appropriations and E.O.s, for example inclusion of CMs, will be covered in Section V. D. Additional key insights derived from technical advances or interagency interactions are covered in Section V. E.

A. Characterization of resources within unconventional and secondary sources have provided indications of a significant resource potential.

An extensive campaign to collect and analyze samples collected from across the U.S. has added further confidence that unconventional sources can supply enough REE to meet domestic demand for decades. The sampling campaign, aided by an analysis of state, Federal, and other data sources, confirmed that sufficient materials are available to supply the DOE-funded 3 ton per day (3 tpd) prototype facilities for the lifetime of the projects and a broader deployment of larger, future facilities for decades. Efforts are underway to identify high priority resources for development and characterize the extent of the technically recoverable resource based on state-of-the-art recovery processes.

The 2017 report identified that sufficient resources existed to warrant further research, but that more extensive characterization efforts were required to determine the extent of the resource and to inform the development of extraction methods tailored to different unconventional resource types. Understanding how REEs occur in unconventional resources, identifying where promising resources are, and determining whether sufficient REEs exist within these materials are all critical to unlocking this potential resource. Further, development of technologies needs to address societal and environmental concerns and thereby enhance sustainable supply chains.

Notably, the data gathered for the 2017 report focused solely on REE rather than the broader slate of CM. The sampling campaign and associated analyses identified coal resources with an "…[estimated] minimum REE concentration of 500 parts per million (ppm) in coal mineral matter, 6 million MT of REEs could be recovered from within the boundaries of the known coal reserves in select western state coal basins in Montana, Wyoming, Colorado, Utah, New Mexico, and Arizona". Similar calculations show that 4.9 million MT are available from within the boundaries of the coal deposits found in Pennsylvania, West Virginia, Kentucky, and Virginia. These estimates are based on total recoverable coal resources."[6] These estimates indicate that significant tonnages of REE exist in the basins studied but were not intended to identify what level of those resources are technically recoverable resources.

[6] Report to Congress, 2017, available at: https://www.energy.gov/sites/prod/files/2018/01/f47/EXEC-2014-000442%20-%20for%20Conrad%20Regis%202.2.17.pdf

Since the 2017 report, improved knowledge of the occurrence and distributions of REEs associated with coal deposits has been acquired and continues to be refined through the sampling, characterization, and modeling activities in the CM program. These have been undertaken with the aim of better understanding the extent of the potential resource, standardizing and expanding characterization methods, and addressing gaps in sample data. These efforts have been foundational to developing models to identify promising unconventional REE deposits, and when coupled with laboratory separation studies, have supported development of processes to extract REEs from U.S. coals.

The sampling campaign and data from additional resource assessments performed using data from Federal, state, and other data sources confirm the general conclusion presented in 2017 and add further confidence to the conclusion that, with appropriate extraction processes, unconventional and secondary resources (UC) could meet domestic demand for decades. Work is now focusing on developing sound methods to predict and verify where the nation's best UC resources will be found.

Accomplishments

1. **Unconventional Sources Sufficient in Supply to Contribute to Domestic Supply**

Building on the 2017 report, an assessment to determine the potential of coal resources and related strata to meet domestic demand for REE was performed by DOE/NETL. The assessment focused on the resource potential from legacy mining and coal utilization materials as well as domestically produced coal.

Over 4,100 additional field samples have been analyzed and reported between 2014 and June 2020[7] under the Feasibility of Recovering Rare Earth Elements activity. The samples include various types of coal-related materials, including coal, coal refuse, ash, and AMD. The samples originated from various locations and coal basins, including Northern, Central, and Southern Appalachia; Gulf Lignite; Illinois; Powder River; Lignite/Williston; Rocky Mountain; Canyon City; Raton; Uinta-Piceance; and West/Northwest Basins. The REE concentrations in the sampled materials ranged from ppb for raw AMD materials to thousands of ppm for alternate coal-based resources.[8]

Based on the U.S. coal production data from the U.S. Energy Information Administration (EIA)[9], an average REE concentration of 66 ppm in coal; and assuming 100 percent of the REE in coal can be extracted, separated and recovered, it is estimated[10] that there would be sufficient

[7] See: https://edx.netl.doe.gov/ree/.
[8] E. Roth and M.A. Alvin, Locating and Extracting Rare Earth Elements from Domestic Coal-Based Resources, Advanced Materials and Processes, October 2020, pp. 24-27, https://static.asminternational.org/amp/202007/24/.
[9] U.S. Energy Information Administration, "Coal Data," 2020. [Online]. Available: https://www.eia.gov/coal/data.php.
[10] NETL Unpublished Report, M.A. Alvin and E. Roth, et al., 2020

bituminous, subbituminous, and lignite resources produced annually to support the production of 3 t/day MREO in engineering-scale prototype separations facility for 20 years, if 2018 production levels of bituminous, subbituminous, and lignite coals were maintained. There would similarly be sufficient individual production of coal fly ash, coal bottom ash, and potentially raw AMD to operate the 3 t/day MREO engineering-scale prototype facilities for 20 years, provided that the assumed REE concentration and yearly production levels of fly ash, bottom ash, and raw AMD were also maintained.

Table 1 summarizes the contributions that might be produced from the various unconventional and secondary sources, with a focus placed on either wastes from coal resources already produced or as new material from on-going production of coal, be it for value added products from carbon (e.g., carbon fiber, graphite, etc.) or other end uses. The values reported are based on publicly available data of legacy mining materials estimated to be in place, annual production rates of waste materials (e.g., acid mine drainage, coal refuse, ash, etc.) and domestic coal production rates. Averaged concentration data for each source type was leveraged, which in some cases is expected to present a lower bound, or more conservative estimate of the resource. These estimates are based on the best available data from 2016, and insufficient information is available to provide a full technically recoverable resource assessment.

Based on the estimated at-resource-recovery levels of 100 percent and 50 percent shown in Table 1, there are sufficient amounts of each feedstock type to supply numerous 3 tpd prototype facilities for the lifetime of the projects and larger facilities could also be constructed in areas of more concentrated resources.[11] Notably, sufficient bituminous, subbituminous, and lignite resources are produced annually to support multiple 3 t/day MREO facilities for each coal type based on current production rates. Existing legacy ash and refuse materials could also support more than one prototype facility for the life of the project based on the reference REE concentrations. Raw AMD from coal mining in Appalachia can also potentially support a 3 tpd prototype facility depending on the accuracy of current annual AMD flows in the region, but the technologies developed for coal AMD also show promise for CM/REE recovery from AMD from hardrock mining in the Western United States. All in all, with more than 250 billion tons of coal reserves (2020) in the United States, 11-17 million tons of REE are estimated to exist within the remaining coal, enough to supply the nation for decades to come.[12]

[11] Recovery levels greater than 80% and approaching 100% have been demonstrated at the pilot-scale, but actual recovery levels will be dependent on market conditions, project economics, and other considerations.

[12] U.S. Energy Information Administration, https://www.eia.gov/coal/reserves/

Table 1: Estimates of REEs in coal and coal byproducts

	Coal[1]	Coal Combustion Ash[2]			Coal Refuse[3]		Acid Mine Drainage from Appalachian Basin[4]	
	Domestic Production in 2016 (tons)	Actively Produced (2016)		Landfilled (Since 1991)	Actively Produced (Appalachia)	Landfilled	Sludge	Raw AMD
		Fly ash (tons)	Bottom Ash (tons)	Coal Combustion Products				
Resource Estimate	728,000,000	37,800,000	10,100,000	~1.5 billion tons	~360 million	Estimate: 2 billion tons in PA alone	Unknown	1.5 to 6.6 million gpm
Assumed REE Concentration	at 62 ppm, low side[5]	80 - ~ 1200 ppm (~400 ppm average)[6]			62 - ~700 ppm (low estimate is 62 ppm)		~660 to 750 ppm (708 ppm average)	<0.5 ppm
Potential REE Produced (tons/year)								
100% Recovery	49,800	16,670	4,450	661,000	24,600	136,700	------	807 - 3560
50% Recovery	24,900	8,330	2,230	331,000	12,300	68,300	------	404 - 1780
20% Recovery	10,000	3,330	891	132,000	4,920	27,300	------	161-711
	Most of the Coal is combusted	REE concentrations vary greatly depending upon the coal that is combusted within the power plant. The combustion process increases the REE concentration in the post combustion ash but also makes it more difficult to extract.			REE concentrations vary greatly between layers within a coal seam. This variation can translate to variations within the coal.		Acid mine reclamation sites are distributed throughout a region.	Very low concentrations of REE

1. EIA 2016 Coal Report, https:/www.eia.gov/coal/annual/pdf/acr.pdf
2.The American Coal Ash Association, https:/www.acaa.org/Portals/9Files/PDFs/ACCA-Brochure-Web.pdf
3.Estimated 2/1 ratio of rock and refuse to coal production in Appalachia combined with data from EIA Coal Report
4. Draft report: :Rare earth elements in Appalachian Basin mine drainage", Paul Ziemkiewicz, WVU
5. Finkelman, R. B., 1993, Trace and minor elements in Coal, Org. Geochem. 593-607 (Springer), https:/link.springer.com/chapter/10.1007%2F978-1-4615-2890-6_28
6. Estimations of Clarkes for Carbonaceous biolithes: World averages for trace element contents of black shales and coals. M.P. Ketris, Ya.E. Yudovich

[Note: The 124,000 value appears to have been calculated for PA only.]

Continuing activities will improve on the high-level resource assessment by both gathering and analyzing additional samples from on-going development of extraction and beneficiation processes and from the CORE-CM activities that are building regional capabilities to analyze and report concentration data that shows where higher concentrations of REE and other CM exist within unconventional sources. Cutting-edge methods are being deployed leveraging artificial intelligence/machine learning (AI/ML) to accelerate discovery through the integration and processing of new data. These efforts are being conducted in coordination with the USGS and will lay the groundwork for the rapid creation of a large domestic supply of REEs and CMs.

2. Characterizing Resources from Unconventional Sources

Research has shown that REE concentrations and compositions vary significantly within sedimentary source material, with enriched zones, or "hot spots".[13] The ability to characterize and predict these hot spots (which show significantly higher levels of REEs than the average for all coal) could decrease the uncertainty in estimating the REEs within a deposit and inform the application of extraction technologies. The Unconventional Rare Earth Elements and Critical Minerals (URC) Assessment Method under development is a first-of-its-kind, big-data, machine learning-enabled approach that uses geoscience (i.e., geologic history of volcano eruptions, water flows, etc.) to improve prediction and identification of domestic resource deposit locations.[14] Version 1 of the method is currently being validated for the Powder River Basin (PRB) using core samples procured from the region. Field studies and core characterization efforts led by NETL, and University of Wyoming researchers has led to the identification of REE enrichments in PRB coals across multiple scales. Two distinct types of REE relative enrichments that have been previously described by the research team (Bagdonas et al., 2019) are apparently occurring throughout the PRB, across a wide regional extent. REE concentrations indicate geochemical sorting, so they may be highly variable with depth of the coal seam, yet appear to be predictable in terms of occurrence, as well as relative abundance.

The URC model is being improved based on the initial validation experiments and work to apply it to the Appalachian Basin is underway. On-going tests are being applied to confirm the presence of both significant quantities of REEs in several sources and the presence of some critical minerals[15] closely associated with the same deposits. For example, CMs that have been

[13] See: Bagdonas, D.; Nye, C.; Thomas, R.; Rose, K. Rare Earth Element Occurrence and Distribution in Powder River Basin Coal Core, Wyoming, 2019 Thirty Sixth Proceedings of the International Pittsburgh Coal Conference, Sept 3–6, 2019; pp 13; and Bagdonas, D.; Phillips, E; Montross, S.; Thomas, R.; Rose, K.; Quillian, S. Refining the Characterization of Western Coal Stocks: Occurrence and distribution of rare earth elements in the Powder, River Basin, Wyoming. The 45th International Technical Conference on Clean Energy, July 27, 2021, Clearwater Florida.

[14] Creason, C. G.; Montross, S. N.; Justman, D.; Mark-Moser, M.; Thomas, R.; Bean, A.; Rose, K. Toward A Geo-Data Science Method for Assessing Rare Earth Elements and Critical Mineral Occurrences in Coal and Other Sedimentary Systems; DOE/NETL-2021/2653; NETL Technical Report Series; U.S. Department of Energy, National Energy Technology Laboratory: Albany, OR, 2021; p 32. DOI: 10.2172/1809028.

[15] PSU preliminary cobalt report, UND assessments of lignite, and list of CMs found as a candidate for extraction during laboratory and bench-scale testing.

found in feedstocks used in extraction and separation projects described below include gallium, germanium, aluminum, cobalt, nickel, manganese, lithium, and vanadium. Ongoing projects conducted under FOA 2003 (Process Scale-Up and Optimization/Efficiency Improvements for Rare Earth Elements (REE) and Critical Materials (CM) Recovery from Coal-Based Resources)[16] have identified the extractability of certain CMs (i.e., cobalt, nickel, manganese, germanium, gallium, etc.) from coal refuse, AMD, and lignite feedstock materials.

In addition, further modeling and field studies (to add to the original sample analyses discussed earlier) are underway coordinated with USGS, the University of Wyoming, the West Virginia Geologic and Economic Survey, Ramaco Carbon and North American Coal, to increase geospatial data and to inform exploration and strategic development of CM/REE resources. This work makes use of the USGS CoalQual database,[17a,b] which was vital to the 2017 report, while addressing key gaps in that and other coal databases. These efforts further refine estimates and identify REEs and other CMs in unconventional and secondary sources in basins across the United States. In addition, NETL has analyzed 45 underclay samples collected from rock cores drilled through coal producing formations in West Virginia (Central Appalachian Basin) and found REE concentrations ranging from 203 to 615 ppm.

3. Developing the Analytical Methods to Enable Innovation in Extraction and Deployment

Over the last 6years, the program has developed novel analytical methods to address the challenges associated with recovering REEs and CMs from unconventional sources. These include methods that can determine how (what oxidation state) and where (what part of the host material) the REEs occur, rapid detection of REE concentration (in seconds rather than hours), and the screening of a diverse range of candidate sources. These methods are critical for unconventional resources, which vary substantially both from conventional ores and from one another in how REEs occur in the material. These efforts have already been successful in identifying certain unconventional sources that are promising for development and in reducing the amount of time it takes to commercialize cost-competitive methods to produce REE from these materials.

Since 2015, NETL RIC has conducted extensive characterization efforts to identify potential feedstocks from REE-containing coal-based materials (e.g., underclay, coarse coal refuse, coal fines, and bottom and fly ash). Multimodal characterization coupled with advanced 2D/3D image processing has led to an in-depth understanding of the occurrence and distribution of

[16] More information about FOA 2003 can be found at: Program Portfolio – NETL Critical Minerals Sustainability Program (doe.gov)

[17a] Lin, R.H., Soong, Y., Granite, E.J. "Evaluation of trace elements in U.S. coals using the USGS COALQUAL database version 3.0. Part I: Rare earth elements and yttrium (REY)", International Journal of Coal Geology, 192, 1-13, May 2018.

[17b] Lin, R.H., Soong, Y., Granite, E.J. "Evaluation of trace elements in U.S. coals using the USGS COALQUAL database version 3.0. Part II: Non-REY critical elements", International Journal of Coal Geology, 192, 39-50, May 2018.

REE phases and associated minerals. This fundamental knowledge will facilitate the development of novel extraction techniques versus conventional mining methods. In addition, FECM's research continues to systematically address technology areas that promote innovation and accelerate the creation of a domestic REE and CM industry. This includes the development of analytical devices that can measure the concentration of REEs in seconds or minutes compared to current laboratory analysis methods, which can take hours to days to complete. The ability to take "real time" measurements of CM/REE concentrations allows process control in extraction and enrichment systems that typically operate at steady state. This ultimately enables process optimization and accelerates process intensification (reducing costs) of CM/REE processes, as well as assists in de-risking deployment of potential CM/REE facilities. These systems can also be used for rapid source material characterization, reducing the cost and time of screening source materials sampled around the nation. This detailed knowledge is also serving as the basis for development of instrumentation that can quickly identify individual REEs in liquids and solids; these types of devices could be employed in process control during extraction and separation of individual REEs.

Future Research Needs

1. Regional Resource Assessments of Critical Minerals in Unconventional and Secondary Sources

Improved knowledge of the occurrence and distributions of CM/REE associated with unconventional and secondary sources has been acquired at select sites through Critical Minerals Program activities, including some tied to the laboratory separations projects as discussed in subsequent Subsections. However, to create a verifiable national assessment, it would need to be based on basin-by-basin information that can leverage regional knowledge. A comprehensive basinal inventory of critical mineral resources from unconventional and secondary sources will provide industry with a clear understanding of the potential within these basins. DOE is working with Department of the Interior (DOI) to understand the characteristics needed for standard methodologies, and the calculation of uncertainty. To accelerate these assessments from UC resources nation-wide, DOE has initiated CORE-CM Initiative that will empower coalitions of industry, academia, research institutions, local, state, Federal and Tribal nations, to assess the resource potential within their regions for potential future CM projects. The CORE-CM projects will reinvigorate manufacturing activities in each region. Industry investment cannot be made without a basic understanding of the opportunity with respect to the primary and co-products of various sources, the resource types, mass/volume estimates (with a high degree of certainty), and available existing infrastructure. Furthermore, projects outside of CORE-CM will continue to conduct analysis on feedstocks and resulting products as has been traditionally done.

To improve data sets sufficiently to calculate technically recoverable resources for the basins currently represented in the separation projects, additional RDD&D is needed to determine:

- What verifiable, potentially recoverable resources exist in unconventional and secondary sources from these basins?
- How do we quantify results and communicate that to industry to enhance understanding of the resource potential?

2. Database Integration, Toolsets, Modeling and Instrumentation

Based on the samples collected for the prior report[18] and additional samples gathered during the intervening years, data support the existence of substantial REE resources existing at concentrations that appear to be technically recoverable in quantities sufficient to supply a robust recovery activity. This assumes costs to recover them are in line with market prices. However, an amount adequate to support the energy transition envisioned by many, while creating a sustainable domestic supply chain (See IEA, 2021), represent a substantial increase in demand over current global markets. More refined estimates are expected as part of the on-going work and would be better able to project totals that are technically recoverable from the major coal basins in the United States. In addition, the methodologies and tools developed for coal basins/fields may be leveraged to support development of other databases (not tied to sedimentary basins) that can be used for other unconventional and secondary sources. These will be made available for use throughout DOE and to other Federal Agencies. Similarly, improved understanding of occurrences within deposits (including underclays) supported by field-deployable, accurate, and rapid characterization instrumentation can improve both resource assessments and optimize recoveries. These capabilities offer the potential to reduce costs (and the time required) for exploration and for processing.

To develop a national estimate of the CM/REE that may be technically recoverable, and to develop effective field measurement techniques and real-time process instrumentation, additional RDD&D is needed to determine:

- Which basins contain coal with enriched levels of REEs and CMs; and which unconventional and secondary deposits contain technically recoverable resources based on emerging technologies developed and tested in the Critical Minerals Program?
- How can the improved characterization methods be effectively transferred to industry?
- How do we integrate advanced measurement capabilities into on-going field efforts and organizations developing process control for early-entry plants to optimize technology roll-out?

[18] 2017 Report to Congress, loc. cit.

B. Demonstrated the technical feasibility to produce high-purity CM, including REE, from low grade source materials, such as coal and coal byproducts.

> *DOE's FOAK projects and complementary research activities have demonstrated the technical feasibility of producing high purity rare earth elements and other critical minerals from unconventional feedstocks (e.g., AMD, coal refuse, coal ash and lignite coals). These projects exceeded the initial goals of 2wt% purity REEs and by 2020 demonstrated purities ranging from 95 percent (coal ash) to greater than 98 percent purity (AMD and refuse). These projects were foundational, providing confidence to move forward with further process development and optimization to improve the efficiency and reduce production costs.*

Unconventional and secondary sources of CMs pose unique challenges for cost-effective and environmentally benign processing compared to conventional CM ores. These include a significantly lower concentration than conventional ores and a wide range of contaminants, which can be detrimental to extraction and enrichment. For example, the unconventional sources evaluated here have REE concentrations ranging from the parts per billion (0.0000001 percent) to the hundreds of parts per million (e.g., 300 ppm, or 0.03 percent) compared to 0.5 percent to 40 percent for conventional ores. These challenges made it unclear if recovery would be technically feasible, as the matter had never before been validated.

To address this challenge, two separate research efforts were established: (1) laboratory- and bench-scale projects were initiated that explored whether conventional separations techniques could be applied to extract REE from unconventional and secondary sources and (2) investigations into novel processes for REE recovery were explored.

The results demonstrated that production of REEs and other CMs is possible from coal and coal byproducts, thus demonstrating the feasibility for innovative processes to recover REEs from diverse coal and coal byproducts (AMD, coal refuse, coal ash, and lignite). After validation, a number of the projects proceeded to bench- and pilot-scales for further maturation. The research projects included research performed at NETL's RIC and those funded through partnerships with universities, research institutions, and industry.

Having been validated for this set of unconventional sources, these technologies and techniques might justify assessment for application to recover CMs from other low-grade source material such as byproducts from hardrock mining.

ACCOMPLISHMENTS

1. Produced high concentration REEs from a variety of unconventional sources at high recovery rates, suggesting commercial-scale recovery could be feasible.

The DOE/NETL demonstrated that high purity MREO could be produced from unconventional and secondary sources, validating their feasibility as a new potential domestic source of CMs. High recovery levels were demonstrated at scales ranging from laboratory- to pilot-scale, with a number of pathways explored to accommodate unique characteristics of individual feedstocks. For example, in the lignite coals, the REEs are organically bound, and these organic associations permit simple dilute acid leaching directly from the lignite. The technology is simpler than most REE mineral processing methods, potentially offering significant cost savings with respect to hardrock sources. Different processing schemes were likewise developed to apply conventional technologies to the characteristics of each particular feedstocks to reduce that cost and environmental footprint of extraction.

Table 2 summarizes the four small-scale bench and pilot projects designed to validate that a high grade of MREO could be produced from these unconventional sources using conventional ore processing techniques. These projects were focused on achieving a given purity, validating that REEs from unconventional sources could be upgraded to the level of purities normally associated with conventional ores rather than on achieving large quantities of materials. In each case, the projects were able to exceed the initial DOE requirement of 2wt percent purity within six months—well ahead of schedule—and then proceeded to reach very high purities as high as 99wt percent over a three-year period.

Table 2. Summary of FOA 1202 Project Achievements in MREO Production from 2018 - 2021

Facility	**Quantity MREO Produced Annually**				**Comments**
	2018 FOA 1202	**2019 FOA 1202**	**2020 FOA 1202**	**2021 FOA 1202**	
University of Kentucky	0.6 kg @ 80 percent purity -Pilot-	1.5 kg @ >90 percent purity -Pilot-	0.5 kg @ ~98 percent purity -Pilot-	N/A	1
West Virginia University	44 g @ 95-99 percent purity FOA 1202 & FOA 1718 -Bench-		N/A	N/A	2
Physical Sciences, Inc.	0.01 kg MRES @ ≤10 percent purity -Pilot- (0.004 kg MREO equivalent)	0.149 kg MRES @ ≤14 percent purity -Pilot- (0.057 kg MREO equivalent)	1.06 kg MRES @ ≤67 percent purity -Pilot- (0.41 kg MREO equivalent)	1.76 kg of MRES @ ≤91 percent purity -Pilot- (0.67 kg MREO equivalent)	3

University of North Dakota	5-10 g @ 5-15 percent purity -Bench-	500 g @ 30-85 percent purity -Bench- 4000 g @ 4-9 percent purity -Bench-	N/A	N/A	4

Comments:
1. University of Kentucky: Current plans under FOA 2003 are to perform approximately 20 one-day tests during calendar year 2021. Feedstock is bituminous coal. These tests have been experimentally designed to assess parametric effects and process circuitry. The test cycle involves considerable preparation before each test, in processing samples collected during the test, analyzing samples, and final data reduction. Facility MREO Production Design Criteria: under FOA 1202: 0.08kg/da (19kg/yr).
2. West Virginia University: Under FOA 1202 and FOA 1718, WVU didn't have a production target, only a grade criteria. WVU's strategy for FOA 1202 was to evaluate the feasibility of extraction from AMD sludge (Appalachian coals) while achieving a 2 percent grade (concentration). WVU achieved 95 percent. Under FOA 1718, the University demonstrated that making a pre-concentrate directly from AMD resulted in much better economics and a higher grade MREO product (99 percent). Since January 2020, under FOA 2003, WVU's objectives were to develop and demonstrate a process for making pre-concentrate on a large scale. The work contracted under FOA 2003 (DE-FE0031834) is to build a pilot plant. This is currently underway. The plan assumes that the plant will be constructed and undergo shake-down during 2021, allowing time for a limited production run. In 2022, another six months of operation are planned under the existing contract. Facility MREO Design Criteria: Produce product at a 1tpy rate with an MREO grade >90 percent.
3. Physical Sciences, Inc: The original feedstock was a bituminous coal fly ash with an REE concentration of ~500 ppm. This process produces mixed REE salts in the form of nitrates. MREO content was estimated based on the ratio of molecular weights of MREs and MREO. The product grade progressed from~10 percent to 90 percent during the development as follows: 2018: 10 percent; 2019: 14 percent; 2020: 67 percent; and 2021: >90 percent (projected value).
4. UND project feedstock is ND lignite.

The projects listed in Table 2 above involved the combination of several standard and novel technologies that were deployed, evaluated, and modified for extraction from a variety of unconventional and secondary sources. The primary technologies deployed have been applied to separations of concentrated ore bodies (e.g., conventional REE ores) but never before with unconventional and secondary low-grade sources. The use of conventional technologies as a backbone for these studies creates confidence that robust technology combinations can be developed fairly quickly—some conventional and some advanced—and all of which follow sound environmental and socially-responsible practices. This phase of the work was intended to advance concepts from laboratory-scale and bench-scale work (TRL3 and TRL5) to the small-scale pilots described here:

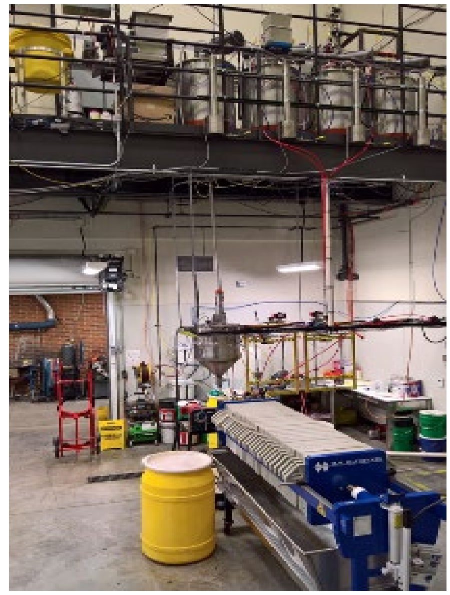
- The University of Kentucky developed a system that integrates both physical and chemical separation process (acid leaching) and that are commercially available and environmentally acceptable.

University of Kentucky small pilot-scale test facility

- West Virginia University and its partners developed a cost-effective and environmentally benign process to recover REEs from solid residues (sludge) generated during treatment of AMD as well as raw AMD fluids. This project took advantage of naturally-occurring processes that occur in coal mines and associated tailings that liberate, then concentrate, REEs. Findings showed elevated concentrations of REEs, particularly in low-pH AMD, and nearly all precipitating with more plentiful transition metals in the AMD sludge.

West Virginia University bench-scale facility

- The University of North Dakota simplified an acid leaching REE extraction process to a single step for economic benefit. The "by-product" of upgraded lignite can be used for carbon ore products, such as activated carbon, production of humic acid and upgraded fuel. The hydrometallurgical processes remove impurities using commercially available equipment and requires no novel chemicals. This process is low-cost and environmentally benign, using ambient temperature and moderate pH for mineral processing.



University of North Dakota bench-scale facility

- Physical Sciences, Inc. (PSI) researchers have demonstrated potential to produce economically salable REYSc-rich concentrates and commercially viable co-products from coal ash. The environmentally safe and high-yield physical and chemical enrichment and recovery processes were developed and are being utilized at the current small pilot-scale facility run by PSI's partner, Winner Water Services, Inc.

Physical Sciences, Inc. (PSI) small pilot-scale facility

Researchers within NETL's RIC engaged an effort to develop novel REE extraction and recovery methods tailored to unconventional sources in an effort parallel to the laboratory-, bench-, and pilot-scale projects described above. These efforts were focused on minimizing the chemical usage and process conditions associated with REE extraction, to both reduce the cost and environmental impacts associated with extraction.[19]

Three promising approaches were selected for maturation from the laboratory- (TRL 2-3) to bench-scale (TRL 3-4) and subsequently achieved success in producing >95 percent purity (>950,000 ppm) MREO from a variety of sources, including waste products, such as coal ash, acid mine drainage, and other materials resulting from legacy mining operations. These approaches, described in Table 3 and in the bullets below, have moved on to field tests or pilot-scale (TRL 5-6) for validation at larger scales.

Table 3. Summary of NETL-RIC Advanced Extraction Project Milestones from 2018 - 2021

Project Name	Feedstocks Addressed	Purity Produced	Recovery Level	Status	Project Partners
BIAS Solid Sorbents Approach: Leverage ligand-metal chelation chemistry to extract REE and CM from dilute liquid sources.	Acid Mine Drainage Process Leachate Solutions from other Extraction Processes	96+ percent MREO 22 percent, 47 percent, 95 percent purity MREO "Baskets" 40-95+ percent other CM (Al, Mn)	>95 percent	Phase 3 Field Test	Pittsburgh Botanic Gardens Hedin Environmental Somerset Environmental PQ, Inc. WV Department of Env. Protection
Sequential Acid Extraction for Ash & AMD Wastes Approach: Sequential extraction process minimizes cost and environ-mental impact to extract REE from certain ash by dissolving a portion of the host material.	Calcium-rich Coal Ash Acid Mine Drainage Sludge	95+ percent MREO 15+ percent other CM (Co)	>85 percent	Pilot Facility Under Development	University of Wyoming School of Energy Resources City of Gillette, Wyoming Campbell County, Wyoming Energy Capital and Economic Development (ECED), WY
Mild Acid Extraction for Ion-Absorbed REE Materials Approach: Extraction process leverages mild acid cocktail to extract REE found in	Coal Refuse Underclays associated with Coal Strata	TBD (solvent extraction tests underway)	33 percent	Pilot Scale Testing Underway	WV Geologic and Environmental Survey Several WV Coal Companies

[19] Conventional ore processing operations often operate at intense process conditions (e.g., elevated temperature and pressure) and use very caustic or acidic chemicals, requiring expensive process equipment, higher energy inputs, and having potential environmental impact implications. NETL-RIC led research is focused on operating at or close to ambient conditions (atmospheric temperature and pressure), minimizing chemical use, and using less intense chemicals, all as a means of reducing costs and environmental impacts.

the ion- and colloidal-absorbed states within legacy waste product from coal mining.					

2. Developed and validated advanced separation and optimization of current state-of-the-art technologies (a) to assess commercial viability of the approaches and (b) to enhance and improve technologies that appeared to have commercial potential.

   These results strongly support the potential for this technological approach to serve as both a source of REEs and the CMs that are typically found in analyses of coal seam cores (including complete coal measures); and to use co-production of multiple product streams to remediate coal waste piles, settling ponds such as those for AMD, and potentially other non-carbonaceous ore wastes.

   Research was conducted to improve processes to achieve a smaller environmental footprint or for process intensification to reduce characterization or for the size and complexity of an extraction and recovery system. In some cases, the project focused on a pre-separation process that concentrated the REEs in the process stream by removing other constituent materials or on a novel means to treat the whole sample, which provided improved recovery of the REEs. In addition, research was performed by National Laboratories, that focused on improved instrumentation, for lower-cost, rapid field techniques or that could be applied for process control.

   The projects summarized in Table 4 sought to improve the portfolio of transformational technologies that could be deployed in the next phase of small-scale pilots. Individual projects often focused on one source-type (fly ash, coal refuse, lignite, AMD) but the information developed might be transferrable to other coal-related sources and, perhaps, to other non-coal sources. Additionally, other Offices within DOE are engaged in work that offers potential to provide transformational insights and concepts in separation science that will benefit processes being developed to extract REEs and CMs from unconventional and secondary sources.

Table 4: Synopsis of transformational and novel separations or advanced sensor activities

Organization	Partners	Project Objectives	Outcomes
Transformational Technology Projects			
Battelle Memorial Institute:	Rare Earth Salts	Recovery of High Purity Rare Earth Elements (REE) from Coal Ash via a Novel Electrowinning Process	RES's electrowinning process can recover a concentrated rare earth oxide (REO) product. BMI & RES delivered a sample of lanthanum oxide with a purity of ~ 90 wt% to NETL.
University of Kentucky Research Foundation	Virginia Polytechnic Institute and State University	Low Temperature Plasma Treatment for Enhanced Recovery of Highly Valued Critical Rare Earth Elements from Coal-Based Resources	Plasma treatment showed benefits for leaching HREEs from WKy. and Fire Clay coal specific gravity cuts.
National Energy Technology Laboratory – Research and Innovation Center	Several Licensing Applications and CRADA agreements are pending	Lithium and Rare Earth Element Recovery from Brines and Produced Water	Technology to extract lithium, REE, and other CM from waste streams such as geothermal brines and produced water from oil and gas operations. Pathway represents advance over current methods leveraged to produce lithium in South America and consumes carbon dioxide in the process.
National Energy Technology Laboratory – Research and Innovation Center		Rare Earth Element and Critical Mineral Detection in Liquids using Metal Organic Framework Sensitizers	Advanced sensors for real-time measurements of REE and CM in liquids down to the 10s of parts per billion concentration. Sensors will enable real-time process control in extraction and enrichment facilities, enabling innovation and process intensifications not previously possible, along with the attendant cost reductions. Allows prospecting of remote mine drainage locations.
National Energy Technology Laboratory – Research and Innovation Center	Washington Mills	Rare Earth Element Recovery from Ash and Slag via High Temperature Fusion and Controlled Cooling	Novel process that leverages electricity to convert ash into a material similar to a conventional REE ore (e.g., REE phosphate or synthetic monazite) of substantially higher concentration (enrichment up to 58 percent purity). Acid use greatly reduced or eliminated.
University of North Dakota Energy and Environmental Research Center	Pacific Northwest National Laboratory	Economic Extraction and Recovery of REE and Production of Clean Value-Added Products from Low-Rank Coal Fly Ash	Identified unique pathways and pretreatments to extract rare earth elements (REE) from low-rank coal (LRC) ash.
Ohio State University		Concentrating Rare Earth Elements in Acid Mine Drainage Using Coal Combustion Products through Abandoned Mine Land Reclamation	Demonstrated a conceptual three-stage trap-extract-precipitate (TEP) process can successfully extract REE from coal mine drainage.
Research Triangle Institute	Cerahelix and Veolia Water Technologies	Low-Cost Rare-Earth-Element (REE) Recovery from Acid Mine Drainage Sludge	Membranes shown to concentrate desirable elements (e.g., lanthanum and praseodymium, etc.) & remove bulk of the low-value ions (e.g., sodium, potassium, heavy metals, divalent metal salts) to improve downstream recovery of REEs.
University of Utah	Virginia Polytechnic Institute and State University	Economic Extraction, Recovery, and Upgrading of Rare Earth Elements from Coal-Based Resources	Evaluated a low-cost technology, partly based on heap leaching, to extract & recover enriched, mixed REE oxide (MREO) product from coal-based wastes. Successful produced sample with 36.7 wt% MREO.
Virginia Polytechnic		Development of a Cost-Effective Extraction Process for the Recovery of Heavy and Critical	Findings verified novel leaching lixiviants outperformed industry standards, effectively isolating and concentrating REE-enriched clays.

Institute and State University		Rare Earth Elements from the Clays and Shales Associated with Coal	Project offers environmental benefits because modified leaching lixiviants would potentially be less hazardous than current practices.
Wayne State University	University of California-Los Angeles and Los Alamos National Laboratory	Coupled Hydrothermal Extraction and Ligand-Associated Swellable Glass Media Recovery of Rare Earth Elements from Coal Fly Ash	New sorbent medium concentrated REE in a coal fly ash sample resulting in a mixed rare earth oxide (MREO) powder of more than 13 wt percent. This medium eliminated the use of potentially hazardous organic solvents.
West Virginia University Research Corporation	West Virginia Department of Environmental Protection	At-Source Recovery of Rare Earth Elements from Coal Mine Drainage	Evaluated extracting REE from acidic AMD and net-alkaline AMD streams using electro-membrane extraction and other methods. Results showed that nearly 100 percent of the REE in the raw AMD or sludge can be recovered.
Novel Rare Earth Element Separation & Advanced Sensor Development			
National Energy Technology Laboratory – Research and Innovation Center		Rare Earth Element and Critical Mineral Detection in Solid and Liquid materials using Laser Induced Breakdown Spectroscopy (LIBS)	Advanced sensors for real-time measurements of REE and CM in liquids down to single parts per million or in solids to the 10s of parts per million concentration. Sensors will enable real-time process control in extraction and enrichment facilities, enabling innovation and process intensifications not previously possible, along with the attendant cost reductions. Allows prospecting of remote locations and potential enables advances in solids processing and screening.
Los Alamos National Laboratory		Evaluation of Novel Strategies and Processes for Separation of Rare Earth Elements from Coal-Related Materials	Effort consisted of two tasks: (a) Evaluate existing actinide/lanthanide separation methods developed for nuclear materials & assess potential for REE extraction; and (b) evaluate merits of developing processes and separations offered by 3 emerging technologies that might lower cost and/or reduce environmental impacts.
Lawrence Livermore National Laboratory		Application of Biosorption for REE Separation from Coal Byproducts	Develop a biofilm-based, continuous flow-through, system in an airlift bioreactor to evaluate whether the approach can lead to an inexpensive & cost-effective means for REE recovery from leachates of pre-combustion and post-combustion coal by- products.
Los Alamos National Laboratory		Evaluation of Laser-Based Analysis of Rare Earth Elements in Coal-Related Materials	Effort consisted of two tasks: (a) construct and evaluate a field-portable unit for LIBS-Raman analysis of REE in coal-related materials; and (b) develop analytical methods specific to the quantification of REE in coal-related materials, leading to creation of broader databases of REE concentrations and physical forms.
Idaho National Laboratory		New Sensing Mechanisms for Rare Earth Detection in Coal and Coal Byproducts	Evaluate novel complexation chemistries for development of innovative sensing technologies for REEs. Complexation of lanthanides by peptides, coupled with the unique spectroscopic properties of lanthanides, is the underpinning for the use of lanthanide binding tags (LBT).

Additional research across DOE is helping advance fundamental separation science and novel technologies useful for extraction from coal and coal byproducts. Basic Energy Sciences (BES) is conducting research in separation science that targets fundamental understanding, including molecular-level mechanisms underlying macroscopic separation processes. The goal of the research is the discovery of new concepts and the development of new separation approaches that are energy efficient and environmentally benign. This research builds the scientific foundations needed to improve existing separation technologies and conceive new ones for the extraction and recovery of critical elements from coal, coal byproducts, mines, and other natural and anthropogenic sources, particularly when the critical elements are very dilute.

BES researchers utilize the latest advances in synthesis science, in situ and operando characterization at DOE user facilities, and theoretical, computational, and data science methods. Recent research areas include efforts to elucidate how tailoring solvent media and binding sites in novel ligands and materials regulate kinetics and selectivity of separations, to manipulate oxidation states of the critical elements through redox chemistries and external fields to enhance selectivity, and to employ photo-chemical switching and electromagnetic fields to trigger capture and release of critical elements such as through phase transitions including crystallization.

Within EERE, work is on-going to use and further develop biosorption technology from the Critical Materials Institute (CMI) for scandium (Sc) and lanthanide extraction from coal byproducts. The project[20] is a 3-year ~$1M LLNL-led collaboration that includes Duke University and the University of Arizona. Significant progress has been made on salability of the biosorbent synthesis as well as testing the performance with unconventional and secondary feedstocks using this platform.[21] The main accomplishment is the scalable cell-based biosorption columns for Sc recovery and purification from coal byproducts. In Phase 1, the focus was on engineering REE-adsorbing microbes and synthesizing REE biosorbents that were used for bulk REE extraction from electronic wastes. The CMI concept was extended and adapted for coal byproducts for bulk TREE and Sc extraction. In CMI Phase 2, the work pivoted to the use of protein-based (lanmodulin) material for separation of individual REEs. This work ended September 2021.

The FOAK pilots demonstrated the technical feasibility to produce mixed rare earth oxides/salts from low concentration material. Process scale-up, optimizations and efficiency improvements in the recovery of REEs and other CMs are included in the next phase of these FOAK pilots. Some of the projects (TRL 3-TRL 5) in Table 4, such as bio-oxidation were integrated into the small-scale pilots for optimization and cost reduction. Other technologies in Table 4 have the potential to be used in future projects for other unconventional and secondary source materials.

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[20] See: *Environmental Science & Technology, 2021 (10.1021/acs.est.0c08632). (*Sc extraction from coal byproducts); *ACS Sustainable Chem. Eng.* 2020, 8, 49, 17914–17922. (TEA for 2-stage Sc/REE recovery from coal byproducts); *International Journal of Coal Geology.* 2020, 227, 103532. (Drivers of REE solubility during leaching); and *Separation and Purification Technology*. 2020, 241, 116726. (Cell-based REE extraction from coal byproducts)

[21] Scandium separation from rare earth element containing material (U.S. Provisional Patent Application No. 63/015,354)

Although the work to date has achieved significant progress, more RD&D needs remain:

- Build and operate engineering prototype facilities of sufficient size to (a) allow continuous operation to be demonstrated; and (b) collect data that can be used to perform sound techno-economic analysis (TEA) and life cycle (LCA) analyses.
- Expand the studies of critical mineral concentrations found in the source materials being tested and coal fly ash to begin development of a more complete map of CMs (including REEs) that may be sourced from coal, coal processing residue, coal fly ash, and/or AMD wastes.

C. Environmentally sustainable pathways to commercial production of high purity critical minerals, including rare earth elements from unconventional and secondary sources

DOE initiated several small pilot projects to further validate the feasibility of CM production from unconventional sources. These projects build upon the successes of previous small scale FOAK projects, which demonstrated production of high purity REE and CM, while integrating lessons learned. These projects aim to improve both recovery of CMs and environmental performance and to overcome cost hurdles associated with processing. Ultimately, these projects provide the data and operating experience required to design larger scale projects, guiding process scale-up, optimization, and commercialization.

Developing environmentally responsible technologies and moving toward sustainable supply chains are an essential aspect of this program. The program began demonstrating the technical feasibility of producing small quantities of high purity—approximately 98 wt percent (980,000 ppm) and greater—MREO in these domestic first-of-a-kind small bench/pilot-scale facilities. Subsequently, the focus turned to evaluating innovative processes, instrumentation or methodologies to reduce environmental impacts and costs. Research to reduce the environmental footprint has included such improvements as evaluating the use of less acid or to producing acids from locally available materials, employing alternative and innovative technologies, or seeing to take advantage of the unique form of occurrence of REE in some unconventional sources.

In addition, funding was made available to support developments that led to performance optimization (in terms of recoveries and selectivity) and to efficiency improvement of conventional REE separation systems. Both of these approaches could improve economic viability of processes currently being used as well as to development of transformational REE and CM separation processes. Notably, all conventional and transformational REE and CM separation process designs have undergone rigorous TEA prior to bench/small-pilot-scale facility construction and operation. In addition, gathering information relevant to performing life cycle assessment studies thorough the developmental cycle is on-going in parallel with the experimental activities.

FOA 2003 (topic area AOI 2) aims to optimize and improve the processing efficiency of the three systems established in FOA 1202 that was issued in 2016. This work enables a transition toward scale-up and validation of conventional extraction/separation processes from bench-scale to pilot-scale facilities for CM/REE production as the projects were to improve the purity of the MREO produced and to increase the quantity of MREO produced. Specifically:

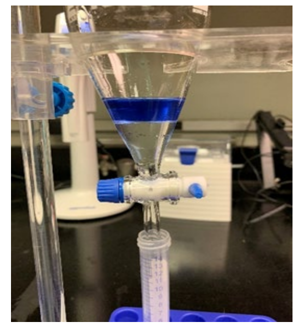
- The University of Kentucky upgraded their small pilot facility. This activity also is seeking to reduce the cost of producing REE concentrates by recovering and using naturally occurring coal pyrite in bioreactors to produce the acid needed for leaching;
- The University of North Dakota is scaling their process up from bench scale (semi-batch) to small pilot scale; and
- West Virginia University is developing a pilot-scale continuous, integrated process for simultaneously and efficiently treating up to 1,000 gpm of AMD while producing an enriched CM/REE concentrate. This project takes advantage of Rockwell Automation as a project partner to achieve a continuous process as compared to their previously used batch process.

ACCOMPLISHMENTS

1. Several small-scale pilot projects have integrated new technologies and innovative process designs to reduce the cost of production, while maintaining environmentally sustainable processes.

   The small-scale projects have expanded their designs to produce not only REEs but also other CMs that are specific to their individual feedstocks. These small-scale projects are assessing the potential for co-production of other CMs, where appropriate, such as cobalt (Co), manganese (Mn), lithium (Li) aluminum (Al), zinc (Zn), germanium (Ge), and gallium (Ga). Co-production is key to developing a sound business case that can provide some insulation from the REE price volatility in the international market. However, to be competitive, the cost of producing CM/REE from unconventional and secondary sources, will still need to be reduced. This is the greatest challenge to overcome, and creative solutions are being applied to meet it:

- The University of Kentucky small-scale pilot has consistently produced rare earth oxide mix concentrates with a purity > 90 percent from multiple coal sources (seams, coarse refuse, and AMD). The project has developed successful innovated processes to address both technical and economic challenges of production from low-grade source material. Acid for processing is a significant cost component. To decrease this cost, a bio-oxidation circuit was developed that reduced acid costs by approximately 75 percent of commercial grade. This produced acid has shown to be just as effective to leach REEs and other CMs from coal refuse. In addition, the project has demonstrated that roasting the feedstock before the leaching process will improve leach recovery and reduce the acid consumption. Acid baking after the roasting provides leach recoveries of HREE and LREE greater than 80 percent. Additional circuits have been developed for scandium, cobalt, nickel, zinc, and manganese production.



- West Virginia University's Water Research Institute (WVUWRI) and its partners are constructing an integrated AMD treatment and CM/REE extraction facility. This 500 gallon per minute (gpm) pilot has been designed to produce approximately 1 metric ton per year each of REE, cobalt, and nickel. If economic, the project could also produce up to 27 metric tons per year of manganese. Operational in late 2021 or early 2022, the facility will include a fully hydraulic processing train with controls provided by project partner Rockwell Automation Inc. and dewatering media provided by TenCate Corp. Some additional process innovations included grade improvement (1-3 percent REE+Co) and continuous hydraulic pre-concentrate (HPC) dewatering for transport. Also, clarifier performance was optimized by constructing a 1:10 scale mini-clarifier for processing actual site water. HPC is then processed into a high-grade pregnant leach solution suitable for processing to mixed rare earth oxides exceeding 95 percent purity. WVUWRI is integrating standard AMD remediation

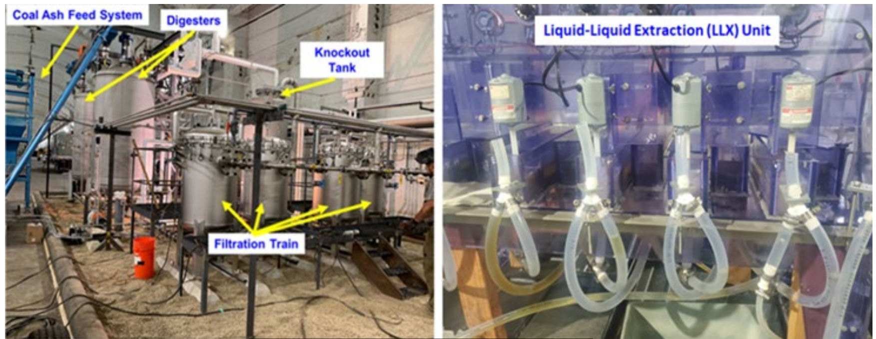
practices with innovation to create a successful business model for CM/REE production while cleaning up the environment. These processes are being evaluated for other hard rock AMD, such as copper mine drainage. The WVUWRI process yields concentrates with nearly identical REE distributions with both coal and hard rock AMD. Both have approximately 45 percent heavy REE. Therefore, a central processing facility could take material from various types of AMD, as part of a hub-spoke model.

- The University of North Dakota small-scale pilot project is focused on production from lignite coal that is low rank, younger, and less carbonized than other types of coal. As previously mentioned, one of the challenges is the need to reduce production costs. This project is integrating innovative processes to decrease costs. The organic associations with lignite coals allow for simple dilute acid leaching, which is a significant cost savings comparted to using feedstocks from other coal ranks. This aspect also minimizes the leaching required to remove any radioactive elements. Advanced software has been developed with process area emergency shutdowns (plant-wide) and manage all programming almost instantaneously.

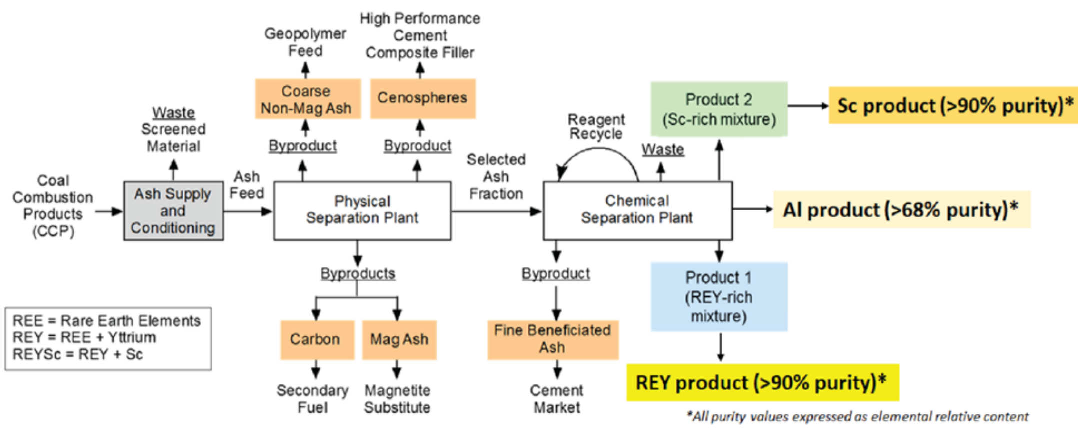
University of North Dakota
Pilot facility began shakedown in the Fall of 2021

As part of this project's business model, higher-value coal products will be produced, such as activated carbon for water purification and humic acid used as organic fertilizer. Lignite coals have a relatively high heavy rare earth elements (HREE) content. This project designed its processing to target HREE for magnets, germanium and gallium, both of which will improve project economics.

- Physical Science, Inc (PSI) – Winner Water Services small pilot facility has not only provided the capability to produce REEs and other CMs, but the project demonstrated how co-production could be integrated throughout an environmentally sustainable project. The project uses physical and chemical processing of ash feedstock and designed an innovative modular system that could process the ash material on-site. The fine non-magnetic fraction of the ash was then transported to the central processing facility for chemical processing. The beneficiated ash fraction left at the physical beneficiation site can be used in commercially viable products, such as cement substitute, cenospheres, and secondary fuel. Optimizations at the pilot plant have identified key parameters of the liquid-liquid solvent extraction process (LLX) to achieve a REE yield greater than 90 percent, while recycling major reagents, at high efficiency, significantly reducing quantities of chemicals, waste disposal needs, and costs. Co-production of scandium and aluminum, at high purity, with the REE is also being achieved and again can provide additional revenue to offset costs of producing REEs.



Physical Sciences, Inc (PSI)



2. Supporting the establishment of technically sound, environmentally sustainable domestic standards for production of CM/REE from legacy material and other sources.

   It is worth recalling that these projects are often primarily with wastes from coal fly ash to coal preparation plant and mine wastes to acid mine drainage liquids and sludges. The UND project is processing lignite. Furthermore, the projects have included source materials from a number of major U.S. coal basins from the Appalachians to the Rocky Mountains. The dual benefit of these activities is the potential for remediation of legacy material—cleaning up legacy material by manufacturing commercially valuable products from past mining of coal/coal byproducts and possibly from hard rock mining.

   Furthermore, careful separations of the organic and inorganic parts of these wastes could leave two highly concentrated, low in contaminants, streams that could feed respective sustainable supply chains. Truly responsible environmental stewardship would seek to separate and reuse as many constituents of the source material as possible to move toward zero wastes possessing environmentally deleterious material. A significant number of new technologies make substantial use of many forms of carbon. The organic stream developed by these separations can make a quality feed material for production of products like carbon fiber, activated carbon, and graphene.

   As a key tool to support both domestic development of sustainable supply chains and to encourage other nations to embrace these same concepts, the Critical Mineral Program (through FECM) has become involved with the International Standards Organization (ISO). This engagement can encourage development of international standards, which can support responsible mining (including social responsibilities) and reduce use of raw materials that could damage the environment in products (for example, conflict minerals). FECM has become involved in two ISO committees, ISO TC298 (rare earth) and ISO TC333 (Lithium) to take advantage of global interest in environmentally responsible mining. The long-term goal of international engagement is to create enduring competitiveness for a domestic industry and to provide time to create sustainable supply chains.

Although the work to date has achieved significant progress, more RD&D needs remain:

- Build and operate large-scale pilot facilities of sufficient size to (a) allow continuous operation to be demonstrated and to de-risk and accelerate deployment; and (b) collect data that can be used to validate economic and environmental performance.

- Develop, modify, and validate sound TEA and life cycle assessment (LCA) approaches for CM production, which will require data that can be gathered from large scale pilots.

- Evaluate unique qualities of REEs and CMs derived from unconventional sources to determine if they possess properties beneficial to new products being evaluated and/or alloys being created. Co-production of a number of constituent minerals may have important benefits to the overall economics and to the environmental footprint of production units.

- Expand the studies of critical mineral concentrations found in the source materials being tested to begin development of a more complete map of CMs (including REEs) that may be sourced from coal, coal processing residue, coal fly ash, and AMD wastes. This information can support development of tools to inform the creation of optimized regional supply chains based on extraction performance data and regional resource assessments.

D. Enabling early commercial production of critical minerals, including REEs, from unconventional and secondary sources

DOE's efforts to date have unequivocally established that unconventional and secondary sources are a viable domestic source of critical minerals, demonstrating the production of high purity materials and establishing a multi-decade supply of the resource exists. The design of larger scale engineering prototype facilities which produce individual REOs and other CMs for immediate use by industry (compared to mixtures of REOs, e.g., MREOs, which require future processing) has been initiated. A complementary effort to characterize regional resources and build a CM development ecosystem is underway to establish a foundation for regional CM industries and enable rapid technology deployment.

Subsections A, B and C, above, demonstrate significant progress in the development of advanced separation technologies for the extraction and recovery of REEs and other CMs from unconventional and secondary (coal and coal byproducts) sources. These sources represent a near-term solution for production of a number of critical minerals, including the rare earth elements. The bench- and small-scale pilot units (TRL 5-7) produced small quantities of concentrated REEs (>90 percent) and are evaluating production of Co, Mn, Li, and potentially Al, Zn, Ge, and Ga. Engineering pilot-scale projects (TRL 7-8), or large-scale pilots, are the critical path to enable sustainable domestic supply chains from these sources.

The technological systems being developed for extracting and processing CMs from coal, coal wastes, and coal byproducts (including AMD) may also be successful when used for other unconventional and secondary sources. Opportunities may exist to recover CMs complementarily from sources associated with oil and natural gas production (e.g., produced water), hard rock mining (e.g., mine tailings), and other waste material and byproducts from industrial processes (e.g., aluminum refining and steel production) using the same or similar technologies described above. Utilizing any of these source materials could be part of the solution, depending on resources available within various different basinal regions.

To enable timely commercial production from unconventional and secondary sources, both technical and non-technical challenges throughout the supply chain need to be addressed. Domestic unconventional and secondary sources of CM/REE tied to historic coal production can contribute to enabling U.S. industries to develop resilient domestic supply chains. However, other components of the supply chains (i.e., processing, refining, and manufacturing) will be required.

ACCOMPLISHMENTS

1. Design of "first-mover" engineering pilot-scale projects (TRL 7-8), or large-scale pilots has been initiated.

   Pre-front end engineering and design (pre-FEED) studies are underway for engineering-scale prototype facilities (TRL 7–8). These studies further improve economic assumptions and provide cost-estimates that can be used to assess the feasibility of developing facilities capable of producing 1–3 metric tons per day of a minimum of 75 wt percent mixed rare earth oxides or salts (MREO/MRES). Such units can also produce select CMs based on the composition of each source material. Each study includes the design basis, performance results, cost results, and technology gap analysis. In addition, the studies are assessing technologies, business models and modular circuits for individual separation and reduction to metals.

   In 2020, thirteen projects were selected for conceptual design and eight of these projects have begun to develop a comprehensive pre-FEED study. To explore what technologies might improve the economic performance, these studies include optimization and innovative processes combined with appropriate transformational technology for cost reduction. The results from these pre-FEED studies will inform the detailed design and construction of future "first mover" large-scale pilots that could be ready to begin in the 2025-2026 timeframe, pending availability of funding. Optimization and cost reduction efforts of the existing facilities will be combined with appropriate transformational technology developments to enable the potential operation of domestic commercial-scale facilities across the United States, where the goal of producing approximately 10,000 tonnes MREO/yr—equivalent to approximately 50 percent of the 2015 U.S. REE demand—can be realized early in the next decade.

2. The Carbon Ore, Rare Earth and Critical Mineral (CORE-CM) initiative has been started to assess and develop the regional infrastructure needed for this emerging industry.

In 2021, DOE-NETL's REE-CM program initiated more than a dozen regional coalition efforts through the Carbon Ore Rare Earth and Critical Minerals (CORE-CM) Initiative to help assess the full economic potential value of U.S. natural resources for producing REEs, CMs, and high-value, nonfuel, carbon-based products within these regions. The CORE-CM Initiative has been designed as a multi-year effort which focuses on regional economic growth and job creation by realizing the full potential value of CMs/REEs from unconventional and secondary sources (e.g., coal and coal byproducts, AMD, produced water), across many basins throughout the United States. It has been designed to address the upstream and midstream critical minerals supply chain and downstream manufacturing of high-value, nonfuel, carbon-based products, to accelerate the realization of full potential for carbon ore and critical minerals within U.S basins, and including facilities, infrastructure, and workforce resources and gaps. Regional coalitions, consisting of private industry, university, state, local, Federal, and tribal government personnel, will develop and implement strategies.

CORE-CM is envisioned as a multi-year effort to be implemented in three phases. Thirteen projects, in traditionally fossil-energy producing basins, have begun Phase 1, which is focus on completing initial assessments and drafting plans to form a foundation for subsequent formulation. The foundation will include a Characterization and Data Acquisition Plan that addresses and justifies the need for acquiring, characterizing and analyzing additional field samples in order to provide an accurate account and future prediction of the REE, CM and carbon resource within the basin for future commercial use. The later phases will implement those plans throughout the United States. With an emphasis on unconventional and secondary sources, regional assessments are an essential link between the resource characteristics within a region and opportunities to develop robust supply chains. In between this link is transportation costs for raw materials. By regionally co-locating smaller vertically integrated supply chains, there will be a significant reduction in transportation costs and impact the carbon footprint of any commodity. CORE-CM will perform the following:

- Basinal assessments of CORE-CM resources
- Basinal assessments of reuse of waste streams
- Basinal strategies for infrastructure, industries, and business
- Technology assessment, development, and field testing
- Technology Innovation Centers
- Stakeholder outreach and education

These projects will be the foundation for bringing together the various components needed to develop the regional infrastructure from characterization of resources, through separation and refining, that are needed to enable industries to invest and bring jobs back to regions that are economically distressed.

In addition, to fully enable the potential for producing rare earth elements from coal, coal wastes, and coal byproducts, additional research, development and perhaps demonstration work is needed:

- Holistic assessment of potential mineral resources from unconventional and secondary feedstocks (such as planned in the CORE-CM Initiative), and characterization of specific resources at a detail to inform the selection and design of extraction technologies is needed.
- Transformational next-generation extraction and processing technologies that incorporate feedstock-based approaches and improve environmental, safety, and cost performance will need to be developed to take advantage of the wealth of CM resources available in coal, coal byproducts, produced water, and other unconventional and secondary resources.
- If the "first mover" pre-FEED studies suggest economic viability for environmentally sustainable large-scale demonstration pilots, then such pilot plants can serve as first-of-a-kind units to produce high quality rare earth oxides to support development of processing and refining facilities to further separate mixed rare earths into individual elements.
- Financial models of conceptual commercial production operations should be developed and refined to verify whether on-going test programs are meeting cost and performance goals. This work will evaluate the economic feasibility of building supply chain sources with CM co-produced from coal and coal byproducts. Success in this area would rely on continued engagement by the U.S. stakeholder base (academic and industrial) with specialized knowledge in this area.

VI. Concluding Remarks with Key Insights

As described above, DOE has made many advancements toward the recovery of REE and CM from coal and coal byproducts—identifying significant REE resources in coal and coal byproducts and in what quantities and combinations, demonstrating that they can be extracted from coal, coal measures, coal ash, coal refuse, and acid mine drainage, and establishing first-of-a-kind pilots that produce high purity REE from these feedstocks. Nonetheless, there is much more work to be done before coal and coal byproducts can become part of the foundational supply for domestic critical mineral supply chains. Additional research activities have been initiated to address these research needs and technical challenges.

Furthermore, the program has generated several key insights while making progress in the development of advanced separation technologies for the extraction of CM/REE from unconventional and secondary sources (coal and coal byproducts), improving the understanding of multi-faceted complex issues with establishing domestic CM/REE supply chains.

- **Technologies developed for CM/REE production from coal and coal byproducts could be used for other source material within a regional area.** Assessment and inclusion of all unconventional/secondary sources, including hard-rock mining and industrial byproducts, with similar coal and coal-byproducts sources could optimize operations through experiential learning and thereby help decrease the cost of the project. The technologies, innovated processes, and field characterization best practices developed may prove transferrable to these other reclamation opportunities. To date, the program is only beginning to understand if/how technologies being developed for coal and coal byproducts may be used for other sources such as hard rock mining. Significant technology transfer opportunities may be created by these developments particularly if limited, preliminary examination of the other source materials can be done.
- **Integrated data management and data analytical capabilities could benefit many Federal agencies.** Between the data systems maintained by DOE (e.g., EDX), the Bureau of Land Management (BLM), USGS, and the Office of Surface Mining Reclamation and Enforcement (OSMRE), tens of thousands of abandoned mine sites or related features have been identified, but these data cannot all be coordinated with existing tools.
- **Commercial projects will vary based on individual business models.** Business models will evaluate horizontal, vertical, and local co-production (hub and spoke model). These models will verify whether cost and performance goals are being met for inclusion of modular individual separation and reduction circuits. Assessment studies that are now being (and will continue to be) conducted can evaluate the metrics of each for the materials being produced from widely distributed deposits.
- **Co-production is an essential part of the opportunity**. Designs that use as much of the source(s) material in their concept (and reflect that in the TEAs and LCAs that are required) can enhance the economics by co-processing to recover CMs and spread both technical and financial risks across a number of commodities. This also will reduce waste management costs. The potential for co-production is an essential part of the opportunity presented by the focus on unconventional and secondary sources.
- **Sustainable domestic production is possible while remediating legacy waste.** Advanced environmentally benign and economically effective extractive metallurgy, separation, reduction and alloying technologies and innovated processing designs are being developed. Co-producing quantities of several CMs can result in a significantly reduced environmental footprint and lower costs. The CM demand could be supported by a few central processing facilities to allow product materials to be shipped a modest distance from various reclamation sites. The opportunity for co-production, combined with reclamation may partially fund the cost of reclamation due to the economic value of the materials recovered.

- **End-users of materials being developed should be integrated with extraction projects as soon as possible.** Custom separations should be a target for development if the specification of the material produced by this method matches the requirements for manufacture of a particular product. Linking the downstream supply chain to upstream and midstream processes could be an important tool in building a sustainable, domestic supply chain that is economically, environmentally, and socially sustainable.

Appendix A: Additional Information

For detailed information on the DOE Rare Earth and Critical Minerals Program, Goals, Accomplishments, and Funding Opportunities, go to:

https://www.netl.doe.gov/coal/rare-earth-elements

Appendix B: Recent Publications, Presentations, and Patents

For the latest list of publications, use the following links:

https://www.netl.doe.gov/research/coal/rare-earth-elements/publications_extramural

https://www.netl.doe.gov/research/coal/rare-earth-elements/publications

Author(s)	Title	Journal or Conference	Date	Document description
Mary Anne Alvin	Critical Minerals Sustainability	2021 Virtual International Pittsburgh Coal Conference	2021	Conference Presentations
Principal investigators, federal project managers, REE technology manager, supervisors, and National Energy Technology Laboratory site-support contractors	Carbon Ore to Products Project Portfolio	Critical Minerals Sustainability Program	2021	Portfolio
Principal investigators, federal project managers, REE technology manager, supervisors, and National Energy Technology Laboratory site-support contractors	Critical Minerals Sustainability Program Project Portfolio	Critical Minerals Sustainability Program	2021	Portfolio
Mary Anne Alvin	Rare Earth Elements and Critical Minerals from	ACS Fall 2020 Virtual Meeting & Expo	2020	Conference Presentations

	Coal-Based Resources			
Jain, J., Hartzler, D., McIntyre, D., Moore, J., and Crandall, D.	Geochemical Characterization of Shale Rocks by Laser Induced Breakdown Spectroscopy (LIBS)"	URTeC Workshop	2019	Conference Presentations
Scott E. Crawford, Xing Yee Gan, Peter C. K. Lemaire, Jill E. Millstone, John P. Baltrus, and Paul Ohodnicki, Jr.	Zinc-Adeninate Metal–Organic Framework: A Versatile Photoluminescent Sensor for Rare Earth Elements in Aqueous Systems	ACS Sens.	2019	Journal Articles
Baltrus, J.P. and Keller, M.J.	Rare Earth Oxides Eu_2O_3 and Nd_2O_3 Analyzed by XPS	Surface Science Spectra, vol 26, p. 014001	2019	Journal Articles
Hartzler, D.A., Jain, J.C., and McIntyre, D.L.	Development of a Subsurface LIBS Sensor for In Situ Groundwater Quality Monitoring with Applications in CO_2 Leak Sensing in Carbon Sequestration	Scientific reports, 9(1), p.4430	2019	Journal Articles

Hedin, B., Capo, R., Stewart, B., Hedin, R., Lopano, C., and Stuckman, M.	The Evaluation of Critical Rare Earth Element (REE) Enriched Treatment Solids from Coal Mine Drainage Passive Treatment Systems	International Journal of Coal Geology, 208, pp.54-64	2019	Journal Articles
Jinichiro Nakano, Anna Nakano, and James Bennett	System and Method for Concentration Rare Earth Elements from Coal Byproducts/slag	U.S. Patent 10,358,694 B2	2019	Patents
Principal investigators, federal project managers, REE technology manager, supervisors, and National Energy Technology Laboratory site-support contractors	2019 Project Portfolio	Feasibility of Recovering Rare Earth Elements	2019	Portfolio
Peter. L. Rozelle, Thomas J. Tarka, and Ned Mamula	The Application of Current Mineral Processing and Extractive Metallurgy Technologies to Potential Rare Earth Ores in the U.S. Coal Measures: Near-Term Opportunities to Fill Out the	https://doi.org/10.2172/1595955	2019	Technical Report

	U.S. Value Chain			
Evan Granite, Elliot Roth, Tracy Bank, Mary Anne Alvin, Ken Ladwig	Determination of Rare Earths in Coal Combustion Byproducts	Energy, Utility & Environment Conference (EUEC) 2018 (San Diego, CA)	2018	Conference Presentations
Megan Macala, Elliot Roth, Tracy Bank, Phillip Tinker, Bret Howard, Evan Granite	Microwave-Assisted Recovery of REES from Coal Combustion Products	Energy, Utility & Environment Conference (EUEC) 2018 (San Diego, CA)	2018	Conference Presentations
Elliot Roth, Megan Macala, Ronghong Lin, Bret Howard, Tracy Bank, Yee Soong, Evan Granite	Rare Earth Elements in Coal and Coal Combustion Products	Energy, Utility & Environment Conference (EUEC) 2018 (San Diego, CA)	2018	Conference Presentations
Montross, S., Guan, K., and Verba, C	Mineralogical Analysis of Recovery of Rare Earth Elements From U.S. Domestic Coal Resources	2018 Geological Society of America 130th Annual Meeting, (Indianapolis, Indiana), November 4-7, 2018. Element 3.6.1	2018	Conference Presentations
Verba, C., Montross, S., and Plechacek, A	The Search for Rare Earth Element and Critical Metals in Underclay Deposits	2018 American Geophysical Union, (Washington, D.C.) December 10-14, 2018, Abstract #355116	2018	Conference Presentations
Plechacek A., Montross, S., and Verba, C	Petrophysical Properties of Underclay	2018 American Geophysical Union, (Washington, D.C.)	2018	Conference Presentations

	Deposits Associated with the Pittsburgh and Brookville Coal Seams	December 10-14, 2018, Abstract #356141		
Granite, E.	Rare Earth Elements from Coal Burning Plants	Invited Plenary Talk, 42nd International Activated Carbon Conference, (Pittsburgh, PA,) September 21, 2018	2018	Conference Presentations
Murphy J Keller, III, Ward Burgess, Bret Howard, Evan Granite,	Reaction Pathways Observed During Roast of RE Phosphates with Calcium Halides	45th Annual NOBCChE Conference (ORLANDO, FL)	2018	Conference Presentations
Mary Anne Alvin	Recovering Rare Earth Elements from Coal-Based Materials	AIChE National Meeting (Pittsburgh, PA)	2018	Conference Presentations
Ward Burgess, Murphy Keller, Elliot Roth, Bret Howard, Jonathan Lekse, Evan Granite	Effect of Calcium Halide Salt Addition on the Fate of Rare Earth Compounds During Coal Combustion Process	AIChE National Meeting (Pittsburgh, PA)	2018	Conference Presentations
Ronghong Lin, Yee Soong, Evan Granite	Evaluation of Critical Trace Elements Including Rare Earth Elements in U.S. Coals	AIChE National Meeting (Pittsburgh, PA)	2018	Conference Presentations

Evan Granite, Ken Ladwig, Elliot Roth	Determination and Recovery of Rare Earths from Coal Combustion Byproducts	AIChE National Meeting (Pittsburgh, PA)	2018	Conference Presentations
Ronghong Lin, Yee Soong, Bret Howard, Elliot Roth, Evan Granite	Recovery of Rare Earth Elements and Yttrium from U.S. Domestic Coals and Coal Byproducts	International Conference on Renewable and Non-Renewable Energy (Las Vegas, NV)	2018	Conference Presentations
F. Shi, Y. Soong, M.L. Gray	Enrichment of Rare Earth Elements (REEs) from Coal and Coal Byproducts	256th ACS National Meeting (Boston, MA)	2018	Conference Presentations
Y. Soong, R. Lin, B. Howard, E.J. Granite, C. Lopano, E. Roth, M. Stuckman	Extracting the Rare Earth Elements (REE) From Coal Fly Ash via the Combination of Physical Separation and Chemical Extraction Techniques	256th ACS National Meeting (Boston, MA)	2018	Conference Presentations
Jinesh Jain, Dustin McIntyre	LIBS Sensor for a Rapid Source Characterization of Rare Earth Elements	43rd International Technical Conference on Clean Energy (Clearwater, FL)	2018	Conference Presentations
Evan Granite, Elliot Roth, Ken Ladwig	Determination and Recovery of Rare Earths	43rd International Technical Conference on	2018	Conference Presentations

	from Coal Combustion Byproducts	Clean Energy (Clearwater, FL)		
Mary Anne Alvin	Rare Earth Elements from Coal-Based Resources	43rd International Technical Conference on Clean Energy (Clearwater, FL)	2018	Conference Presentations
Evan J. Granite	R&IC Rare Earth Overview	American Coal Ash Association 2018 Winter Meeting (Sarasota, FL)	2018	Conference Presentations
Ward A. Burgess, Murphy J. Keller, Jonathan W. Lekse, Bret H. Howard, Elliot A. Roth, and Evan J. Granite	Effect of Pre-Reaction Ball Milling on Kinetics of Lanthanum Phosphate Roasting with Sodium Carbonate	Industrial & Engineering Chemistry Research, 57, (6088–6096)	2018	Journal Articles
Ronghong Lin, Mengling Stuckman, Bret H. Howard, Tracy L. Bank, Elliot A. Roth, Megan K. Macala, Christina Lopano, Yee Soong, Evan J. Granite	Application of Sequential Extraction and Hydrothermal Treatment for Characterization and Enrichment of Rare Earth Elements From Coal Fly Ash	Fuel, volume 232, (124-133)	2018	Journal Articles
Mengling Stuckman, Christina Lopano, Evan Granite	Distribution and Speciation of Rare Earth Elements in Coal Combustion	International Journal of Coal Geology, volume 195, pages (125–138)	2018	Journal Articles

	Byproducts via Synchrotron Microscopy and Spectroscopy			
Esmail Monazam, Ranjani Siriwardane, Duane Miller, Dustin McIntyre	Rate Analysis of Sorption of Ce^{3+}, Sm^{3+}, and Yb^{3+} Ions From Aqueous Solution Using Dowex50w-x8as a Sorbent in a Continuous Flow Reactor	Journal of Rare Earths Volume 36, Issue 6, June 2018, Pages (648-655)	2018	Journal Articles
Elliot Roth, Tracy Bank, Evan Granite	Investigation of Thulium and Other Rare Earth Element Mass Fractions in NIST SRM 1632a Bituminous Coal Reference Material by Quadrupole ICP-MS	Geostandards and Geoanalytical Research 42.2 2018: (263-269)	2018	Journal Articles
Scott N. Montross, Circe A. Verba, Han Ling Chan, Christina Lopano	Advanced Characterization of Rare Earth Element Minerals in Coal Utilization Byproducts Using Multimodal Image Analysis	International Journal of Coal Geology 195 2018: (362-372)	2018	Journal Articles
Ronghong Lin, Yee Soong, Evan J. Granite	Evaluation of Trace Elements in U.S. Coals	International Journal of Coal	2018	Journal Articles

	Using the USGS COALQUAL Database Version 3.0. Part I: Rare Earth Elements and Yttrium (REY)	Geology, vol. 192, (1–13)		
Robert L. Thompson, Tracy Bank, Scott Montross, Elliot Roth, Bret Howard, Circe Verba, Evan Granite	Analysis of Rare Earth Elements in Coal Fly Ash Using Laser Ablation Inductively Coupled Plasma Mass Spectrometry and Scanning Electron Microscopy	Spectrochimica Acta Part B, vol. 143, (1-11)	2018	Journal Articles
Ronghong Lin, Yee Soong, Evan J. Granite	Evaluation of Trace Elements in U.S. Coals Using the USGS COALQUAL Database Version 3.0. Part II: Non-REY Critical Elements	International Journal of Coal Geology, vol. 192, (39-50)	2018	Journal Articles
Miller, D.D.; Siriwardane, R.; Mcintyre, D.	Anion Structural Effects on Interaction of Rare Earth Element Ions with Dowex 50W X8 Cation Exchange Resin	Journal of Rare Earths, Volume 36, Issue 8, Pages (879-890)	2018	Journal Articles

Monazam, E.; Miller, D.D.; Siriwardane, R.; Mcintyre, D.	Rate Analysis of Sorption of Ce^{3+}, Sm^{3+}, and Yb^{3+} Ions from Aqueous Solution Using Dowex 50W-X8 as a Sorbent in a Continuous Flow Reactor	Journal of Rare Earths, Volume 36, Issue 6, Pages (648-655)	2018	Journal Articles
Bhatt, C.R., Jain, J.C., McIntyre, D.L.	Investigating the CO_2 Pressure Effect on Underwater Laser-induced Plasma Emission of Eu and Yb	Spectrochimica Acta - Part B Atomic Spectroscopy, 149, pp. (42-47)	2018	Journal Articles
Bhatt, C.R., Jain, J.C., Goueguel, C.L., McIntyre, D.L., Singh, J.P.	Determination of Rare Earth Elements in Geological Samples Using Laser-Induced Breakdown Spectroscopy (LIBS)	Applied Spectroscopy, 72,1, pp. (114-121)	2018	Journal Articles
McIntyre, D.L.	“Laser Induced Breakdown Spectroscopy (Libs) Probe for Simplified Light Collection and Laser Operation,”	U.S. Patent Application 10/145,737	2018	Patents
Principal investigators, federal project managers, REE technology	2018 Project Portfolio	Feasibility of Recovering Rare Earth Elements	2018	Portfolio

manager, supervisors, and National Energy Technology Laboratory site-support contractors				
Evan J. Granite, Elliot Roth, Tracy Bank, Bret Howard, John Baltrus, Sofiane Benyahia, Morgan Summers, and Mary Anne Alvin	R&IC Rare Earth Overview	Rare Earth Research Portfolio Review Meeting (Pittsburgh, PA)	2017	Conference Presentations
Tracy Bank, Elliot Roth, and Evan Granite	Evidence of Mobilization of REE: Geological Aspects of REE Formation in the United States	Rare Earth Research Portfolio Review Meeting (Pittsburgh, PA)	2017	Conference Presentations
Sofiane Benyahia and Liqang Lu	Development of a Novel CFD Model for Large-Scale REE Extraction Process	Rare Earth Research Portfolio Review Meeting (Pittsburgh, PA)	2017	Conference Presentations
Morgan Summers	Systems Perspective on REE from Coal	Rare Earth Research Portfolio Review Meeting (Pittsburgh, PA)	2017	Conference Presentations
Elliot Roth, Tracy Bank, Ronghong Lin, Megan Macala, Bret Howard, Aaron Walsh, Robert Thompson, Evan Granite, Yee Soong	Distributions and Extraction of Rare Earth Elements from Coal and Coal Byproducts	World of Coal Ash (Lexington, KY)	2017	Conference Presentations

Elliot Roth, Megan Macala, Ronghong Lin, Tracy Bank, and Evan Granite	Rare Earth Element Distributions and Extraction from Coal Ash	28th Rare Earth Research Conference (Ames, IA)	2017	Conference Presentations
Tracy Bank, Bret Howard, Elliot Roth and Evan Granite	Evidence of REE Mobility and Fossil Ion Adsorbed REE Deposits in Pennsylvania	28th Rare Earth Research Conference (Ames, IA)	2017	Conference Presentations
Mary Anne Alvin	Feasibility of Recovering Rare Earth Elements from Coal and Coal Byproducts	34th International Pittsburgh Coal Conference (Pittsburgh, PA)	2017	Conference Presentations
Evan Granite	Trace Elements in Coal – A Magical Journey Across the Periodic Table	34th International Pittsburgh Coal Conference (Pittsburgh, PA)	2017	Conference Presentations
Mengling Stuckman, Christina Lopano, Evan Granite	Elucidating Distribution and Speciation of Rare Earth Elements in Coal Utilization Byproducts Utilizing Synchrotron Microscopy and Spectroscopy	34th International Pittsburgh Coal Conference (Pittsburgh, PA)	2017	Conference Presentations
Ward Burgess, Murphy Keller, Elliot Roth, Jonathan	Effect of Pre-Reaction Ball Milling of	34th International Pittsburgh Coal	2017	Conference Presentations

Lekse, Bret Howard, and Evan Granite	$LaPO_4$*H_2O + Na_2CO_3 on Kinetic Parameters of the $LaPO_4$ Roasting Reaction	Conference (Pittsburgh, PA)		
Evan Granite, Elliot Roth, Tracy Bank, Ronghong Lin, Bret Howard, Yee Soong, Mac Gray, Chris Wilfong, Ranjani Siriwardane, James Bennett, Jin Nakano, Mary Anne Alvin, Kurt Rothenberger	Brief Overview of Rare Earth Research at NETL R&IC	34th International Pittsburgh Coal Conference (Pittsburgh, PA)	2017	Conference Presentations
Evan Granite, Elliot Roth, Tracy Bank, Mary Anne Alvin, Ken Ladwig	Determination of Rare Earths in Coal Combustion Byproducts	34th International Pittsburgh Coal Conference (Pittsburgh, PA)	2017	Conference Presentations
Ronghong Lin, Tracy L. Bank, Evan J. Granite, Yee Soong	Organic and Inorganic Association of Rare Earth Elements in Coal	34th International Pittsburgh Coal Conference (Pittsburgh, PA)	2017	Conference Presentations
Allan Kolker, Clint Scott, James Hower, Christina Lopano	Grain Scale Rare Earth Element Distribution in Coal Fly Ash	34th International Pittsburgh Coal Conference (Pittsburgh, PA)	2017	Conference Presentations
Scott N. Montross, Circe A. Verba, Amy Falcon, James Poston, Mark McKoy	Characterization of Rare Earth Element Minerals in Coal Utilization	34th International Pittsburgh Coal Conference (Pittsburgh, PA)	2017	Conference Presentations

	Byproducts and Associated Clay Deposits from Appalachian Basin Coal Resources			
Evan Granite	Trace Elements in Coal – A Magical Journey Across the Periodic Table	40th International Activated Carbon Conference (Pittsburgh, PA)	2017	Conference Presentations
Scott Montross	Characterization of Rare Earth Elements in Clay Deposits Associated with Central Appalachian Coal Seams	AGU Fall Meeting, (New Orleans, LA)	2017	Conference Presentations
Scott Montross	Characterization of Rare Earth Elements in Clay Deposits Associated with Central Appalachian Coal Seams	New Orleans	2017	Conference Presentations
Evan Granite, Elliot Roth, Tracy Bank, Ronghong Lin, Bret Howard, Yee Soong, Mac Gray, Chris Wilfong, Ranjani Siriwardane, James Bennett, Jin Nakano, Tom Tarka, and Mary Anne Alvin	Brief Overview of Rare Earth Research at NETL R&IC	AIChE Annual Meeting (Minneapolis, MN)	2017	Conference Presentations

Elliot Roth, Megan Macala, Ronghong Lin, Tracy Bank, Bret Howard, and Evan Granite	Extraction of Rare Earth Elements from Fly Ash Using NaOH Hydrothermal and Ultrasound Pretreatment	AIChE Annual Meeting (Minneapolis, MN)	2017	Conference Presentations
Hani Abu El Hawa, Jinichiro Nakano, Anna Nakano, and James Bennett	The Influence of Phosphorous Additions on Phase Evolution in Molten Coal Slag	TMS 2017 Conference (San Diego, CA)	2017	Conference Presentations
H.A.E. Hawa, J. Nakano, A. Nakano, and J. Bennett	The Influence of Phosphorous Additions on Phase Evolution in Molten Coal Slag	Applications of Process Engineering Principles in Materials Processing, Energy and Environmental Technologies, ed. S. Wang, et al., Springer, 2017, pp 221-229	2017	Books and Book Chapters
Elliot Roth, Tracy Bank, Evan Granite	Investigation of Thulium and Other Rare Earth Element Concentrations in NIST 1632a Bituminous Coal Standard Reference Material	Geostandards and Geoanalytical Research, volume 42, issue 2, (263-269)	2017	Journal Articles
John C. Ahern, Zsolt L. Poole, John Baltrus, and Paul R. Ohodnicki, Jr.	Portable Luminescence Based Fiber Optic Probe for REE Detection	IEEE Sensors Journal Volume: 17 Issue: 9, May 2017 (2644 – 2648)	2017	Journal Articles

	and Quantification			
Allan Kolker, Clint Scott, James C. Hower, Jorge A. Vazquez, Christina L. Lopano, Shifeng Dai	Distribution of Rare Earth Elements in Coal Combustion Fly Ash, Determined by SHRIMP-RG Ion Microprobe	International Journal of Coal Geology; Volume 184, 1 November 2017, Pages (1-10)	2017	Journal Articles
Ronghong Lin, Tracy Bank, Bret Howard, Yee Soong, Elliot Roth, and Evan Granite	Enrichment of Rare Earth Elements from Coal and Coal Byproducts by Physical Separations	Fuel, Volume 200, (506-520)	2017	Journal Articles
Elliot Roth, Tracy Bank, Bret Howard, and Evan Granite	Rare Earth Elements in Alberta Oil Sand Process Streams	Energy & Fuels, Volume 31, (4714-4720)	2017	Journal Articles
John C. Ahern, Zsolt L. Poole, John Baltrus, and Paul R. Ohodnicki, Jr.	Portable Luminescence Based Fiber Optic Probe for REE Detection and Quantification	IEEE Sensors Journal, 17(9), (2644-2648)	2017	Journal Articles
Wilfong, W.C., Kail, B.W., Bank, T.L., Howard, B.H., and Gray, M.L.	Recovering Rare Earth Elements from Aqueous Solution with Porous Amine-Epoxy Networks	ACS Applied Materials and Interfaces, 9, 21, (18283-18294)	2017	Journal Articles

Ronghong Lin, Tracy L. Bank, Elliot A. Roth, Evan J. Granite, and Yee Soong	Organic and Inorganic Associations of Rare Earth Elements in Central Appalachian Coal	International Journal of Coal Geology, Volume 179, (295-301)	2017	Journal Articles
Chet R. Bhatt, Jinesh C. Jain, Christian L. Goueguel, Dustin L. McIntyre, Jagdish P. Singh	Measurement of Eu and Yb in Aqueous Solutions by Underwater Laser Induced Breakdown Spectroscopy	Spectrochimica Acta Part B, volume 137, p. (8–12)	2017	Journal Articles
Bhatt, C.R., Jain, J.C., Goueguel, C.L., McIntyre, D.L., Singh, J.P.	Measurement of Eu and Yb in Aqueous Solutions by Underwater Laser Induced Breakdown Spectroscopy	Spectrochimica Acta - Part B Atomic Spectroscopy, 137, pp. (8-12)	2017	Journal Articles
Qiuming Wang, Walter C. Wilfong, Brian W. Kail, Yang Yu, and McMahan L. Gray	Novel Polyethylenimine–Acrylamide/SiO_2 Hybrid Hydrogel Sorbent for Rare-Earth-Element Recycling from Aqueous Sources	ACS Sustainable Chem. Eng., 5, 11, pp (10947-10958)	2017	Journal Articles
Allan Kolker, Clint Scott, James C. Hower, Jorge A. Vazquez, Christina L.	Distribution of Rare Earth Elements in Coal	International Journal of Coal Geology, 184, (1-10)	2017	Journal Articles

Lopano, and Shifeng Dai	Combustion Fly Ash, Determined by SHRIMP-RG Ion Microprobe			
Mary Anne Alvin, Evan Granite and Charles Miller	The Future of Rare Earth Elements May Lie with Coal	American Coal, 2, (28-32)	2017	Journal Articles
Principal investigators, federal project managers, REE technology manager, supervisors, and National Energy Technology Laboratory site-support contractors	2017 Project Portfolio	Feasibility of Recovering Rare Earth Elements	2017	Portfolio
Ronghong Lin, Elliot Roth, Tracy Bank, Bret H. Howard, Yee Soong and Evan J. Granite	Enrichment of Rare Earth Elements from Coal and Coal Byproducts by Physical Separations	2016 AIChE National Meeting, Rare Earths in Fossil Energy Session (San Francisco, CA)	2016	Conference Presentations
Yee Soong, Fan Shi, McMahan L. Gray and Yungchieh Lai	Frother Performance and Its Influence on Flotation Process	2016 AIChE National Meeting, Rare Earths in Fossil Energy Session (San Francisco, CA)	2016	Conference Presentations
Elliot Roth, Robert Thompson, Ronghong Lin, Tracy Bank and Evan J. Granite	Distributions and Associations of Rare Earth Elements in Fly Ash Using Laser	2016 AIChE National Meeting, Rare Earths in Fossil Energy Session (San Francisco, CA)	2016	Conference Presentations

	Ablation High Resolution Mass Spectrometry			
Elliot Roth, Ronghong Lin, Tracy Bank and Evan J. Granite	Reactive Grinding of Coal Ash for Enhanced Rare Earth Extraction	2016 AIChE National Meeting, Rare Earths in Fossil Energy Session (San Francisco, CA)	2016	Conference Presentations
Evan J. Granite, Elliot Roth and Mary Anne Alvin	Characterization and Recovery of Rare Earths from Coal and Byproducts	2016 AIChE National Meeting, Rare Earths in Fossil Energy Session (San Francisco, CA)	2016	Conference Presentations
J. Jain and H.M. Edenborn	Studies on the Use of Alginate Gel Polymers as Selective Adsorbents of Rare Earth Elements from Aqueous Solutions (Poster Presentation)	GSA Northeastern Section Meeting (Albany, New York)	2016	Conference Presentations
Robert Thompson, Tracy Bank, Elliot Roth, and Evan Granite	Resolution of Ba Interferences on Eu and Lu in Residue Samples using Sector Field ICP-MS	2016 Winter Conference on Plasma Spectrochemistry (Tucson, AZ)	2016	Conference Presentations
Robert Thompson, Tracy Bank, Bret Howard, Elliot Roth, and Evan Granite	The Search for Rare Earth Elements in an Eastern Shale	2016 Winter Conference on Plasma	2016	Conference Presentations

		Spectrochemistry (Tucson, AZ)		
Robert Thompson, Elliot Roth, and Evan Granite	Resolution of Ba Interferences on Eu Peaks in Residue Samples Using Sector-Field ICP-MS	2016 Winter Conference on Plasma Spectrochemistry (Tucson, AZ)	2016	Conference Presentations
Dr. Grace Bochenek	Backbone of the Energy Future	American Coal Ash Association 2016 Winter Meeting	2016	Conference Presentations
Evan Granite, Elliot Roth, and Mary Anne Alvin	Characterization and Recovery of Rare Earths from Coal and Byproducts (Poster Presentation)	2016 Enabling Technologies and Partnerships & Rare Elements Conference	2016	Conference Presentations
Evan Granite, Mary Anne Alvin, and Elliot Roth	Brief Overview of NETL RIC Rare Earth Research	National Association of Regulatory Utility Commissioners (NARUC) (Nashville, TN)	2016	Conference Presentations
Emma Keegan, Elliot Roth, and Evan Granite	Use of Portable X-Ray Fluorescence for Determination of Rare Earths in Coal Byproducts	2016 Mickey Leland DOE Technical Forum (Pittsburgh, PA)	2016	Conference Presentations

Andre Gilchrist, Murphy Keller, Elliot Roth, and Evan Granite	Extraction of Rare Earths from Coal Ash by Reactive Grinding	2016 Mickey Leland DOE Technical Forum (Pittsburgh, PA)	2016	Conference Presentations
Ronghong Lin, Elliot Roth, Evan Granite, Bret Howard, Yee Soong, and Tracy Bank	Size, Density and Electromagneti c Separations of Coal Ashes for Rare Earth Element Enrichment	252nd American Chemical Society National Meeting (Philadelphia, PA)	2016	Conference Presentations
Scott N. Montross, Circe Verba, Christina Lopano, Mengling Stuckman, and Keith Collins	Microanalysis of Rare Earth Elements in Coal Utilization Byproducts	2016 Microscopy & Microanalysis Meeting (Columbus, OH)	2016	Conference Presentations
Mengling Stuckman, Christina Lopano, Emily Dixon, and Evan Granite	Distribution Speciation of Rare Earth Elements in Coal Combustion Byproducts	18th International Conference on Heavy Metals in the Environment (Ghent, Belgium)	2016	Conference Presentations
Elliot Roth, Emma Keegan, Tracy Bank, and Evan Granite	Using Portable X-Ray Fluorescence to Detect Rare Earth Elements in Coal and Surrounding Rock	Geological Society of America Annual National Meeting (Denver, CO)	2016	Conference Presentations
Tracy Bank, Elliot Roth, Bret Howard, and Evan Granite	Evidence of Rare Earth Element Enrichment in Sedimentary	Geological Society of America Annual National Meeting (Denver, CO)	2016	Conference Presentations

	Rocks from Pennsylvania			
Evan Granite, Elliot Roth, and Mary Anne Alvin	Brief Overview of NETL RIC Rare Earth Efforts	38th International Activated Carbon Conference (Pittsburgh, PA)	2016	Conference Presentations
Allan Kolker, Clint Scott, James C. Hower, Jorge A. Vazquez, Christina L. Lopano, and Amrika Deonarine	Grain Scale Distribution of Rare Earth Elements in Coal Ash by SHRIMP-RG Ion Microprobe	Geological Society of America Annual National Meeting (Denver, CO)	2016	Conference Presentations
Tracy Bank, Elliot Roth, Phillip Tinker, and Evan Granite	Analysis of Rare Earth Elements in Geologic Samples using Inductively Coupled Plasma Mass Spectrometry	US DOE Topical Report DOE/NETL-2016/1794	2016	DOE Topical Reports
Tran X. Phuoc, Ping Wang, and Dustin McIntyre	Detection of Rare Earth Elements in Powder River Basin Sub-Bituminous Coal Ash Using Laser-Induced Breakdown Spectroscopy (LIBS)	Fuel, Volume 163 (129-132)	2016	Journal Articles
James C. Hower, Evan J. Granite, David B. Mayfield, Ari S. Lewis, and Robert B. Finkelman	Notes on Contributions to the Science of Rare Earth Element Enrichment in	Minerals, 6(2), 32	2016	Journal Articles

	Coal and Coal Combustion Byproducts			
Evan J. Granite, Elliot Roth, and Mary Anne Alvin	Characterization and Recovery of Rare Earths from Coal and Byproducts	EM	2016	Journal Articles
Evan J. Granite, Elliot Roth, and Mary Anne Alvin	Recovery of Rare Earths from Coal and Byproducts - A Paradigm Shift for Coal Research	National Academy of Engineering - The Bridge, Fall 2016 46,3, (56-57)	2016	Journal Articles
Robert Thompson, Tracy Bank, Elliot Roth, and Evan Granite	Resolution of Rare Earth Element Interferences in Fossil Energy Byproduct Samples Using Sector-Field ICP-MS	Fuel, Volume 185, (94-101)	2016	Journal Articles
Liqiang Lu, Kisoo Yoo, and Sofiane Benyahia	Coarse-Grained-Particle Method for Simulation of Liquid-Solids Reacting Flows	Industrial & Engineering Chemistry Research, 55,39, (10477-10491)	2016	Journal Articles
Clinton W Noack, Jinesh C Jain, John Stegmeier, J Alexandra Hakala, and Athanasios K Karamalidis	Rare Earth Element Geochemistry Of Outcrop And Core Samples From The Marcellus Shale	Geochemical Transactions,16:6	2015	Journal Articles

Elliot Roth, Tracy Bank, and Evan Granite	Analysis of Twenty Coal Ashes for Rare Earth Element Content Using Inductively Coupled Plasma Mass Spectrometry (ICP-M)	2015 AIChE Annual Meeting (Salt Lake City, UT)	2015	Conference Presentations
Tran X. Phuoc, Ping Wang, and Dustin McIntyre	Profiling Rare Earth Elements In Power River Basin Sub-Bituminous Coal Ash Using Laser-Induced Breakdown Spectroscopy (Libs)	2015 World of Coal Ash Conference (WOCA) (Nashville, TN)	2015	Conference Presentations
Tracy Bank, Elliot Roth, and Evan Granite	Detection of Metals and Rare Earth Elements in Deep Eutectic Solvents and Ionic Liquids Using ICP-MS	2015 International Association of Geoanalysts Meeting (Leoben, Austria)	2015	Conference Presentations
Tracy Bank, Elliot Roth, and Evan Granite	Optimization of Rare Earth Analyses in Geologic Material using Universal Cell Technology and ICP-MS	2015 International Association of Geoanalysts Meeting (Leoben, Austria)	2015	Conference Presentations
Mengling Stuckman, Christina Lopano, Christine Thomas,	Geochemical Characterization of Rare Earth Elements in	2015 GSA Annual Meeting, (Baltimore, MD)	2015	Conference Presentations

Jinesh Jain, and Evan Granite	Coal Combustion Byproducts Utilizing Synchrotron Technology			
Janesh Jain, and Hank Edenborn	Selective Cation Removal via Gel Polymerization in Marcellus Flowback Water	Geological Society of America Southeastern Annual Meeting,(Chattanooga, TN)	2015	Conference Presentations
Ashley LeDonne, Elliot Rith, J.Leske, and Evan Granite	Synthesis of Layered Double Hydroxides Intercalated with Chelating Agents for Rare Earth Element Capture from Aqueous Streams	2015 AIChE Annual Meeting (Salt Lake City, UT)	2015	Conference Presentations
Elliot Roth, Tracy Bank, and Evan Granite	Characterization of Rare Earth Elements in Canadian Oil Sand Process Streams	2015 AIChE Annual Meeting (Salt Lake City, UT)	2015	Conference Presentations
Elliot Roth, Tracy Bank, and Evan Granite	Uncertainties and Optimum Detection Modes for Rare Earth Analysis in Coal and Coal Ash Using Coupled Plasma Mass Spectroscopy (ICP-MS)	2015 AIChE Annual Meeting (Salt Lake City, UT)	2015	Conference Presentations

Elliot Roth, Murphy Keller, Tracy Bank, and Evan Granite	Fate of Rare Earth Elements during Lab-Scale Combustion of Lignite Coal	2015 AIChE Annual Meeting (Salt Lake City, UT)	2015	Conference Presentations
Elliot Roth, Megan Macala, Tracy Bank, and Evan Granite	Deep Eutectic Solvents and Ionic Liquids for Extraction of rare Earth Elements from Coal Ash	2015 AIChE Annual Meeting (Salt Lake City, UT)	2015	Conference Presentations
Elliot Roth, Tracy Bank, and Evan Granite	Analysis of Twenty Coal Ashes for Rare Earth Element Content using Inductively Coupled Plasma Mass Spectrometry (ICP-MS)	32nd International Pittsburgh Coal Conference (Pittsburgh, PA)	2015	Conference Presentations
Elliot Roth, Tracy Bank, and Evan Granite	Characterization of Rare Earth Elements in Canadian Oil Sand Process Streams	32nd International Pittsburgh Coal Conference (Pittsburgh, PA)	2015	Conference Presentations
Elliot Roth, Megan K. Macala, Tracy Bank, and Evan Granite	Deep Eutectic Solvents and Ionic Liquids for Extraction of Rare Earth Elements From Coal Ash	32nd International Pittsburgh Coal Conference (Pittsburgh, PA)	2015	Conference Presentations
Ashley LeDonne, Elliot Roth, Jonathan	Layered Double Hydroxides	DOE Mickey Leland Conference	2015	Conference Presentations

Lekse, and Evan Granite	Intercalated with Chelating Agents for Rare Earth Element Capture From Aqueous Streams			
Elliot Roth, Tracy Bank, and Evan Granite	Uncertainties and Optimum Detection Modes for Rare Earth Analysis in Coal and Coal Ash Using Inductively Coupled Plasma Mass Spectrometry (ICP-MS)	32nd International Pittsburgh Coal Conference (Pittsburgh, PA)	2015	Conference Presentations
Tran X. Phuoc, Ping Wang, and Dustin McIntyre	Discovering the Feasibility of Using the Radiation Forces for Recovering Rare Earth Elements from Coal Power Plant Byproducts	Advanced Powder Technology, 26 (1465-1472)	2015	Journal Articles
Edgar Klunder	Method for enhancing selectivity and recovery in the fractional flotation of particles in a flotation column	US Patent 7,992,718	2011	Patents

James C. Hower, John G. Groppo, Prakash Joshi, Dorin V. Preda, David P. Gamliel, Daniel T. Mohler, John D. Wiseman, Shelley D. Hopps, Tonya D. Morgan, Todd Beers and Michael Schrock	Distribution of Lanthanides, Yttrium, and Scandium in the Pilot-Scale Beneficiation of Fly Ashes Derived from Eastern Kentucky Coals	Minerals 2020, 10(2), 105, https://doi.org/10.3390/min10020105	2020	Journal Articles
Honaker, R.Q., Werner, J., Zhang, W., Yoon, R.-H., Luttrell, G.H. and Noble, A.	Design, Development and Testing of a Pilot Plant for Rare Earth Recovery from Coal-Based Sources	Society for Mining, Metallurgy and Exploration Annual Meeting, Denver, Colorado (February 2019)	2019	Conference Presentations
Tang. H., Honaker. R.Q., and Werner, J.	Investigation into the Recovery of Rare Earth Elements from Illinois Basin Coarse Refuse by Heap Leaching	Society for Mining, Metallurgy and Exploration Annual Meeting, Denver, Colorado (February 2019)	2019	Conference Presentations
Morgen Leake and Aaron Noble	Enrichment of Rare Earth Element-bearing Coarse Coal Refuse by X-ray Transmission Sorting	Mineral Processing Division – Student Session: 2019 SME Annual Meeting & Exhibit. Denver, CO. February 27, 2019	2019	Conference Presentations

Zhang, W. and Honaker, R. Q.	Effects of Calcination Pretreatment on Rare Earth Element Recovery from Bituminous Coal Sources	Society for Mining, Metallurgy and Exploration Annual Meeting, Denver, Colorado (February 2019)	2019	Conference Presentations
Gupta, T., Zhang, W. and Honaker, R. Q.	Low Temperature Plasma Treatment for Enhanced Recovery of Rare Earth Elements from Coal	Society for Mining, Metallurgy and Exploration Annual Meeting, Denver, Colorado (February 2019)	2019	Conference Presentations
Addo, D., Werner, J., and Honaker, R.Q.	Operation and Process Control Development for a Leaching and Solvent Extraction Circuit Recovering Rare Earth Elements from Coal-Based Sources	Society for Mining, Metallurgy and Exploration Annual Meeting, Denver, Colorado (February 2019)	2019	Conference Presentations
Noble, A., Sechrist, C.M., Keles, S., Luttrell, G.H., and Honaker, R.Q.	Utilization of X-ray Sorter Technology to Enhance the Economic Viability of Recovering Rare Earth Elements from	Society for Mining, Metallurgy and Exploration Annual Meeting, Denver, Colorado (February 2019)	2019	Conference Presentations

	Coal-Based Feedstocks			
Benson, S., Theaker, N., Laudal, D.	Rare Earth Element Recovery from North Dakota Lignite	2019 Energy Generation Conference. January 31, 2019. Bismarck, ND.	2019	Conference Presentations
Theaker, N., Laudal, D., Benson, S., Rew, B., Lucky, C.	Extraction of Rare Earth Elements from Lignite Coal – Kinetics of Extraction and Bench-Scale Updates	19 SME Annual Conference. February 25, 2019. Denver, CO.	2019	Conference Presentations
Zhang, W. and Honaker, R.Q.	Calcination Pretreatment Effects on Acid Leaching Characteristics of Rare Earth Elements from a Bituminous Coal Source	Fuels, accepted March 12, 2019	2019	Journal Articles
Zhang, W. and Honaker, R.Q.	Enhanced leachability of rare earth elements from calcined products of bituminous coals	Minerals Engineering 142 (2019) 105935	2019	Journal Articles

Honaker, R.Q., Yang, X., Chandra, A., Zhang, W. and Werner, J.	Hydrometallurgical Extraction of Rare Earth Elements from Coal	Proceedings of Extraction 2018, Ottawa, Canada, DOI: 10.1007/978-3-319-95022-8_193	2018	Conference Presentations
Luttrell, G.H., A. Noble, C.M. Sechrist, S. Keles and R. Q. Honaker	Preconcentration of Coal-Based Rare Earth Element Feedstocks Using X-Ray Sorter Technology	Proceedings of the Clearwater Clean Energy Conference, Clearwater, Florida (June 2018)	2018	Conference Presentations
Honaker, R. Q., Werner, J., Yang, X, Chandra, A, and Zhang, W.	Hydrometallurgical Circuits for the Recovery of Rare Earth Elements from Coal Sources	American Institute of Chemical Engineers Annual Meeting, Pittsburgh, Pennsylvania (October 2018).	2018	Conference Presentations
Michael Free, Prashant Sarswat, Landen Allen, X. Hu, Aaron Noble, Gerald H. Luttrell, and Daejin Kim	Economic Extraction, Recovery and Upgrading of Rare Earth Elements from Coal-Based Resources	Oral Presentation, 2018 AIChE Annual Meeting. Pittsburgh, PA, November 1, 2018	2018	Conference Presentations
Michael Free, Prashant Sarswat, Aaron Noble, and Gerald Luttrell	Efficient Recovery of Rare Earth Elements from	Oral Presentation, Extraction 2018, Ottawa, Canada, August 29, 2018	2018	Conference Presentations

	Coal Based Resources			
Laudal, D., Benson, S., Theaker, N.	Investigation of Rare Earth Element Extraction From North Dakota Coal-related Feed Stocks	2018 NETL Rare Earth Elements Review Meeting. April 10, 2018. Pittsburgh, PA.	2018	Conference Presentations
Laudal, D., Benson, S., Theaker, N., Rew, B.	Examination of an REE-Rich Lignite by Combined Density Separations and Leaching	2018 Clearwater Clean Energy Conference. June 6, 2018. Clearwater, Fl.	2018	Conference Presentations
Rew, B., Theaker, N., Laudal, D., Benson, S., Holden, J.	Determination of Rare Earth Element Modes of Occurrence in Lignite Coal	2018 AIChE Conference. November 1, 2018. Pittsburgh, PA	2018	Conference Presentations
Zhang, Wencai and Honaker, R.Q.	Flotation of Monazite in the Presence of Calcite Part Ii: Enhanced Separation Performance Using Sodium Silicate and EDTA	Minerals Engineering, Volume 127, pp. 318-328 (2018)	2018	Journal Articles

Huang, Q., Noble, A., Herbst, J. and Honaker, R.Q.	Liberation and Release of Rare Earth Minerals from Middling Kittanning, Fire Clay, and West Kentucky No. 13 Coal Sources	Powder Technology, Volume 332, pp. 242 – 252. (2018)	2018	Journal Articles
Honaker, R. Q., Zhang, W., Yang, X. and Razaee, M.	Conception of an Integrated Flowsheet for Rare Earth Elements Recovery from Coal Coarse Refuse	Minerals Engineering, Vol. 122, pp. 233 – 240 (2018)	2018	Journal Articles
Zhang, W. and Honaker, R.Q.	Rare Earth Elements Recovery Using Staged Precipitation from a Leachate Generated from Coarse Coal Refuse	International Journal of Coal Geology, Vol 195, pp. 189 – 199 (2018)	2018	Journal Articles
Yang, X., Werner, J., and Honaker, R.Q.	Leaching of Rare Earth Elements from an Illinois Basin Coal Source	Journal of Rare Earths, https://doi.org/10.1016/j.jre.2018.07.003; (2018)	2018	Journal Articles

Taggart, R.K., Rivera, N.A., Levard, C., Ambrosi, J.P., Borschneck, D., Hower, J.C., Hsu-Kim, H	Differences in Bulk and Microscale Yttrium Speciation in Coal Combustion Fly Ash: Environmental Science	Processes & Impacts, v. 20, p. 1390-1403	2018	Journal Articles
Taggart, R.K., Hower, J.C., Hsu-Kim, H.	Effects of Roasting and Leaching Parameters on Extraction of Rare Earth Elements From Coal Fly Ash	International Journal of Coal Geology, v. 196, p. 106.114. ,10.1016/j.coal.2018.06.021	2018	Journal Articles
Laudal, D., Benson, S., Palo, D., Addleman, R.S.	Rare Earth Elements in North Dakota Lignite Coal and Lignite-Related Materials	*Journal of Energy Resource Technology 140*(6). doi: 10.1115/1.4039738	2018	Journal Articles
Laudal, D., Benson, S., Addleman, R.S., Palo, D.	Leaching Behavior of Rare Earth Elements in Fort Union Lignite Coals in North America	*International Journal of Coal Geology 191*, 112-124. doi.org/10.1016/j.coal.2018.03.010	2018	Journal Articles

Zhang, W., Honaker, R.Q., and Groppo, J.	Concentration of Rare Earth Minerals from Coal by Froth Flotation	SME 2017, Denver, Colorado (February 2017)	2017	Conference Presentations
Chandra, A., Honaker, R. Q. and Han, K.	Recovery of Rare Earth Elements from Dilute Leachates Generated from Coal	SME 2017, Denver, Colorado (February 2017)	2017	Conference Presentations
Benson, S., Laudal, D., Palo, D., Addleman, R.S.	Investigation of Rare Earth Element Extraction from North Dakota Coal-Related Feed Stocks	2017 NETL Crosscutting Research & Analysis Portfolio Review. March 2017. Pittsburgh, PA.	2017	Conference Presentations
Laudal, D., Benson, S., Palo., D., Addleman, R.S.	Rare Earth Elements in North Dakota Lignite-Related Materials	Clearwater Energy Conference. June 2017. Clearwater, FL	2017	Conference Presentations
Laudal, D., Benson, S., Palo., D., Addleman, R.S.	Recovery of Rare Earth Elements from North Dakota Lignite-Related Feedstocks	34th Annual International Pittsburgh Coal Conference. September 2017. Pittsburgh, PA	2017	Conference Presentations

Laudal, D., Benson, S., Palo., D., Addleman, R.S.	Recovery of Rare Earth Elements from North Dakota Lignite-Related Feedstocks	Annual AIChE Conference. November 2017. Minneapolis, MN.	2017	Conference Presentations
Zhang, Wencai, Honaker, R.Q. and Groppo, J.	Flotation of Monazite in the Presence of Calcite Part I: Calcium Ion Effects on the Adsorption of Hydroxamic Acid	Minerals Engineering, Volume 100, pp. 40 – 48 (2017).	2017	Journal Articles
Honaker, R.Q., Groppo, J., Yoon, R.-H., Luttrell, G.H., Noble, A. and Herbst, J.	Process Evaluation and Flowsheet Development for the Recovery of Rare Earth Elements from Coal and Associated Byproducts	Minerals & Metallurgical Processing Journal, Vol. 34, No. 3, pp. 107-115 (2017)	2017	Journal Articles
Zhang, Wencai, Honaker, R.Q. and Groppo, J.	Concentration of Rare Earth Minerals from Coal by Froth Flotation	Minerals & Metallurgical Processing Journal, Vol. 34 No. 3, pp. 132 – 137 (2017)	2017	Journal Articles

Zhang, Wencai and Honaker, R.Q.	Adsorption of Octanohydroxamic Acid on Monazite Surfaces	International Journal of Mineral Processing, Vol. 164, pp. 26 – 36 (2017)	2017	Journal Articles
Zhang, Wencai and Honaker, R.Q.	Surface Charge of Monazite in Aqueous Solutions	Powder Technology, Vol. 318, pp. 263 – 271 (2017)	2017	Journal Articles
Zhang, Wencai, Xinbo, Y. and Honaker, R.Q.	Association Characteristic Study and Preliminary Recovery Investigation of Rare Earth Elements From Fire Clay Seam Coal Middlings	Fuel, Vol. 215, pp. 551-560 (2017)	2017	Journal Articles
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Hower, J.C., Hood, M.M., Taggart, R.K., Hsu-Kim, H.	Chemistry and Petrology of Paired Feed Coal and Combustion Ash	Fuel, vol. 199, p. 438-446. http://dx.doi.org/10	2017	Journal Articles

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Hower, J.C., Groppo, J.G., Henke, K.R., Graham, U.M., Hood, M.M., Joshi, P., Preda, D.V., 2017	Ponded and Landfilled Fly Ash as a Source of Rare Earth Elements from a Kentucky Power Plant	Coal Combustion & Gasification Products, vol. 9, p. 1-21. doi:10.4177/CCGP-D-17-00003.1	2017	Journal Articles
Hood, M.M., Taggart, R.K., Smith, R.C., Hsu-Kim, H., Henke, K.R., Graham, U.M., Groppo, J.G., Unrine, J.M., Hower, J.C.	Rare Earth Element Distribution in Fly Ash Derived From the Fire Clay Coal, Kentucky	Coal Combustion & Gasification Products, vol. 9, p. 22-33. doi:10.4177/CCGP-D-17-00002.1	2017	Journal Articles
Zhang, Wencai, Honaker, R.Q. and Groppo, J.	Fundamental Study of the Monazite-Calcite Flotation Separation	Proceedings of the International Minerals Processing Congress, ISBN: 978-1-926872-29-2, Paper ID 340, 2016	2016	Conference Presentations
Luttrell, G.H., Kiser, M.K., Yoon, R.-H., Bhagavatula, A., Rezaee, Honaker, R.Q.	Rare Earth Element Concentrations in Product Streams of Coal Preparation Plants in the Eastern United States	Proceedings, SME Annual Meeting, Phoenix, Preprint 16-144	2016	Conference Presentations

Luttrell, G. H., Noble, A., Honaker, R.Q., and Yoon, R.-H.	Rare Earth Opportunities for Coal	International Technical Conference on Clean Coal & Fuel Systems, Clearwater, Florida, June 5 - 9	2016	Conference Presentations
Honaker, R., Groppo, J., Bhagavatula, A., Rezaee M. and Zhang, W.	Recovery of Rare Earth Minerals and Elements from Coal and Coal Byproducts	International Coal Preparation Conference, Louisville, Kentucky, pp. 43 – 54	2016	Conference Presentations
Luttrell, G.H., Kiser, M. J., Yoon, R.-H., Bhagavatula, A., Rezaee M. and Honaker, R. Q.	Concentrations of Rare Earth Elements Generated by U.S. Coal Preparation Plants	Coal Preparation Conference, Louisville, Kentucky, pp. 35 – 41	2016	Conference Presentations
Zhang, W., Rezaee, M., Bhagavatula, A., Li, Y., Groppo, J. and Honaker, R.Q.	Review of the Occurrence and Promising Recovery Methods of Rare Earth Elements from Coal and Coal Byproducts	Int. Journal of Coal Preparation and Utilization, Vol. 35, 1 - 36, 2015	2015	Journal Articles
Hower, J.C., Groppo, J.G., Henke, K.R., Hood, M.M., Eble,	Notes on the Potential for the Concentration of Rare Earth	Minerals 5, 356-366. doi:10.3390/min50x000x	2015	Journal Articles

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Appendix C: Glossary of Terms

(See notes at end of Glossary for sources of the definitions)

Unconventional Secondary Resources (UAR) non-coal-based materials: Remediation and reclamation materials, such as mineral/metal acidic mine drainage, legacy impoundment materials, tailings, produced waters, and associated chemical wastes or waste streams.

Unconventional Resources (UR) coal feedstocks and coal byproducts: Run-of-mine coal, coal refuse, over/under-burden, ash, aqueous effluents (e.g., AMD), associated treatment solids and precipitates, and remediation/reclamation materials.

Mineral Processing is the field of engineering concerned with the separation of valuable minerals from ores into concentrates usually without chemical change.

Beneficiation involves process technologies that reduce rock (ore) particle size by crushing, grinding, and separating ore particles according to particle size and mineral properties, and can also include dewatering and drying components. These steps include:

- **Comminution** is crushing and grinding of ore from the mine to achieve particle size reduction.
- **Sizing** is separation of crushed ore particles according to their size.
- **Concentration** is increasing the amount of the wanted minerals through various techniques, such as gravity, froth floatation, electrostatic, or magnetic separation.

With respect to conventional REE production, a mineral processing system is fed ore from the mine and produces a mineral concentrate that is enriched in rare earth content. Those steps include:

- **Liberation** is separating rare earth minerals from the host ore rock/material.
- **Enrichment** is accumulating rare earth-bearing minerals to increasingly higher concentrations.
- **Separation** is partitioning of rare earths into individual elements or oxides.

Upgrading are the steps used to increase the concentration of an element or elements of interest.

Extractive Metallurgy is the field of engineering concerned with the extraction of valuable metals from ores or concentrates usually with chemical change.

Extractive metallurgy involves inducing chemical changes to ores and then recovering the metal value. Two types of extractive metallurgy include:

- **Hydrometallurgy** is used in the presence of liquid water; the primary property being exploited to accomplish extraction is solubility.
- **Pyrometallurgy** is used in the absence of liquid water; the primary property being exploited to accomplish phase extraction is phase change. Production of metal from a rare earth compound is typically a pyrometallurgical operation involving reduction.

Reduction is conversion of rare earth compounds (oxides) into pure metals or alloys using chemical reduction reactions. The reduction of metals such as the rare earths or other metals was originally understood to be the reactions used to obtain those metals from their oxides by using substances having greater affinity for oxygen than the metal.

Notes:

Specific processing steps used to produce rare earth-bearing minerals or other critical mineral commodities from a host ore/material, fall under two disciplines: Mineral Processing and Extractive Metallurgy. The Mineral Processing and Extractive Metallurgy Handbook (2019) published by the Society of Mining, Metallurgy and Exploration (SME) provides authoritative definitions for these disciplines and related processes.