Recovery of Rare Earth Elements from Acid Mine Drainage

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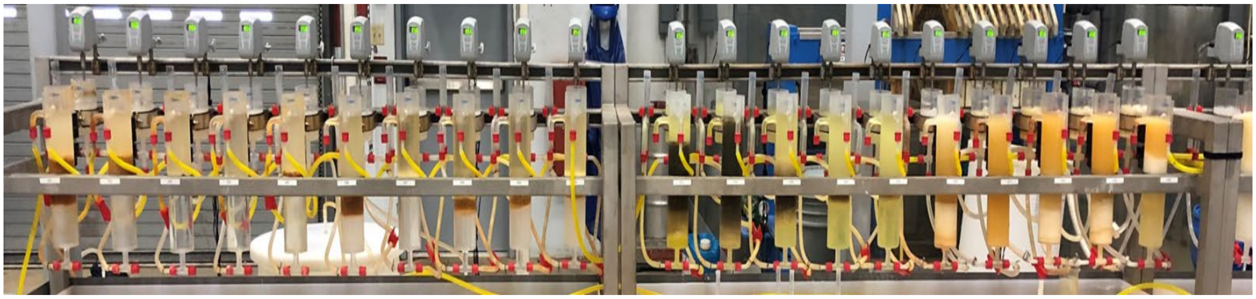

Rare earth elements in acid mine drainage become high-grade concentrates at WVU's Rare Earth Extraction Facility

<u>Written Testimony of Paul F. Ziemkiewicz to the U.S. Senate Committee on Energy and Natural Resources</u> 31 March 2022

Chairman Manchin, Ranking Member Barrasso and members of the Committee, thank you for the opportunity to offer relevant testimony and to answer your questions in my areas of experience and expertise.

I am the Director of the West Virginia University Water Research Institute, a component of WVU's Energy Institute. The Institute serves to facilitate collaborative and innovative solutions for the energy and environmental future of West Virginia and the United States.

West Virginia University is a public, land-grant, research-intensive university founded in 1867. It is designated an "R1" Doctoral University (Very High Research Activity) by the Carnegie Classification of Institutions of Higher Education.

The Water Research Institute conducts sponsored and grant-funded research programs in the areas of watershed restoration, acid mine drainage treatment, mitigation of mining and gas development impacts on water and land. Most recently we developed a research initiative around recovery of critical minerals (CM) and rare earth elements (REE) from acid mine drainage (AMD).

Introduction: **Rare Earth Elements or REE are essential for advanced technologies from smart phones and robots to top-secret national defense systems. The REE metals have remarkable chemical properties but are so evenly dispersed throughout the earth's crust that economically attractive concentrations are extremely rare.** Also, nearly all conventional sources of REE occur with the radioactive elements thorium and uranium and they are concentrated by the same processes used to release REE from their host minerals. **The result is commonly a mildly radioactive tailings stream that must be managed in perpetuity. As a result, the U.S. imports nearly all its rare earth elements from China, which supplies about 89 percent of the world's rare earth needs**. India and Russia provide most of the balance of these strategically important materials. **However, researchers at West Virginia University found that treating one of the biggest sources of pollution in the United States, acid mine drainage or AMD is a rich source of rare earth elements, or REEs (figure 1) without the problems of radioactive tailings or additional mine waste.**

The U.S. has one operating REE mine, at Mountain Pass, CA. It ships its REE concentrate to China for refining to metal where companies often use it to manufacture advanced electronic products for export. With no domestic supply chain, the U.S. is vulnerable to interruptions in the international market. To address this issue, the U.S. Department of Energy's National Energy Technology Laboratory, in 2015, solicited ideas across the U.S. for extracting rare earth elements from coal and related byproducts. Our research team at West Virginia University, was awarded the first of nine grants in early 2016 to study the potential of extracting rare earth elements from AMD.

Figure 1. Typical AMD sludge settlement cells at a Pennsylvania coal mine. The orange material in the foreground is enriched with rare earth elements. After the metals precipitate, the clear water in the far cells is discharged via a regulated discharge point.

AMD forms when pyritic waste rock from coal mines is exposed to air. This acid then leaches rare earth metals out of the rock. We then recover the concentrates and refine them into marketable products. Recovery of value from AMD will also help stimulate AMD treatment at abandoned mines and allow operators to offset treatment costs.

We found that REE concentrations in AMD treatment solids exceed many of the world's best commercial deposits. And, whereas most conventional rare earth deposits are encased in hard rock and located in remote wilderness, AMD sludge is already extracted from the host rock and easily accessible, resulting in modest processing costs. In the near future the AMD treatment systems at both operating and former mine sites could be managed as rare earth production facilities.

The WVU researchers evaluated the reserves at 140 acid mine drainage treatment sites throughout West Virginia, Pennsylvania, and Ohio. We are also developing commercially viable refining methods. If successful, the project could lead to economic diversification and new economic development opportunities for Appalachia's coal towns. While the coal market may fluctuate over time, acid mine drainage is constant. Long after mining is done, the mines still generate AMD and REE. Some of the richest AMD comes from sites where mining ceased 30 years ago. Our strategy involves extracting a REE concentrate from AMD at the mine for refining at a central facility. This involves treatment of the AMD for compliance with regulatory requirements while leaving the bulk of the waste stream for disposal at the mine under its currently permitted conditions. **We've also started to look at acid mine drainage in other states, including western states with AMD from hardrock mining – and early results show that our work could benefit those states as well.**

We have integrated our recovery method with acid mine drainage treatment so that our two main products are valuable mineral concentrates and clean water. The process takes all the metals out of the water so efficient recovery of the rare earths is not possible without treating the mine water to compliance with the Clean Water Act. The concentrates would then be shipped from the AMD treatment units to a central refinery for processing into market-ready metals.

We still need to fully demonstrate the technology and build a domestic refinery but once completed and operated, we will have a market for rare earths and production could begin almost immediately with modest investments at the mine site. Compare this to trying to startup a new rare earth mine. A potential developer would need to spend a great deal of money and time proving the reserve and acquiring permits to operate. That can take five to 10 years.

We (West Virginia University and our colleagues at Virginia Tech) pioneered the idea of using acid mine drainage as feedstock and we've developed a process for economically recovering the rare earths and critical materials in an environmentally-benign way. No additional mining is needed, and the process does not produce radioactive byproducts like most conventional rare earth mines. Also, acid mine drainage provides the rare earths in a form that is easily recovered, requiring no rock grinding nor intensive processing. As a result, our carbon footprint is about one half as much as a conventional mining and milling operation.

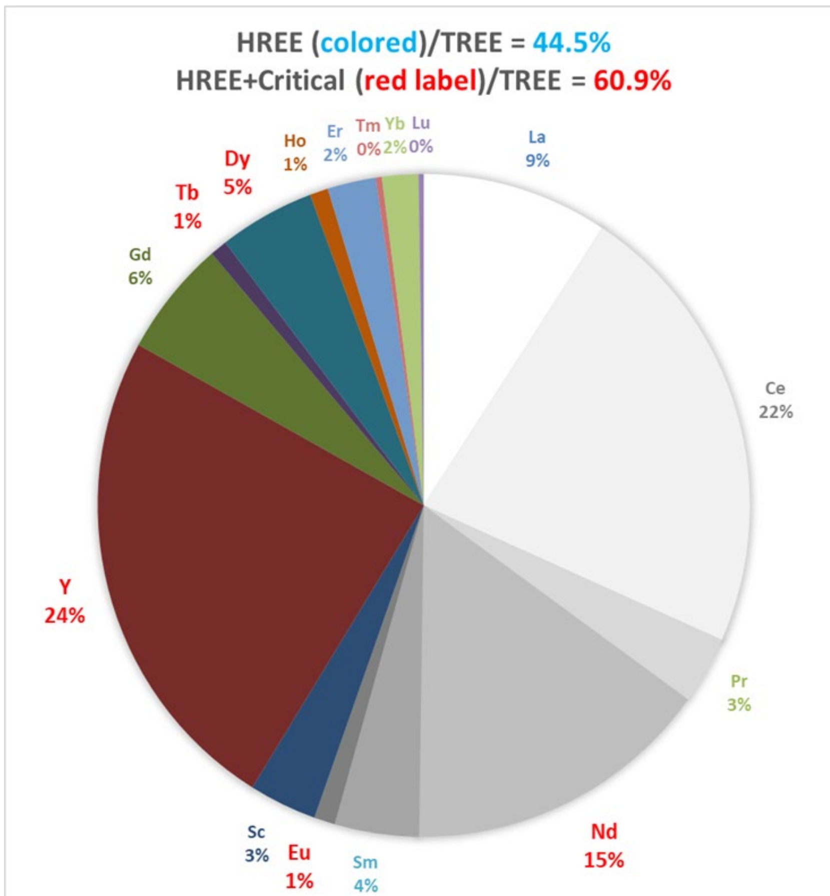

Figure 2. AMD contains a high proportion of the valuable critical and heavy rare earth elements (HREE). Together they comprise about 60% of the total rare earths in Appalachian acid mine drainage.

To make this a commercial reality, WVU is partnering not only with USDOE/NETL but also members of the coal industry, Rockwell Automation, Inc., TenCate Corp. and WVDEP. The support received has been tremendous. **Success will turn an environmental liability into become an economic opportunity while cleaning up the environment.**

Rare earths and critical materials are the building blocks of advanced technologies. Without a domestic supply chain, we will lose the ability to sustain commercial and defense related industries. At that point, we will be at the mercy of foreign powers.

Program Status: Our approach takes advantage of autogenous processes that occur in coal mines and associated tailings which liberate then concentrate REEs. **In addition, we've found that AMD feedstock yields a favorable mix of valuable heavy and critical REE relative to many REE projects (figure 2).** It is important to note that the Mountain Pass REE mine in California and China's largest REE mine at Bayan Obo, both produce largely light REEs while China's heavy REE supply is said to be depleting rapidly (figure 3). REE sourced from coal AMD is non-radioactive, unlike conventional, hardrock sources. A typical, recent sample of our concentrate contained 62% REE oxide with only 0.01% uranium + thorium.

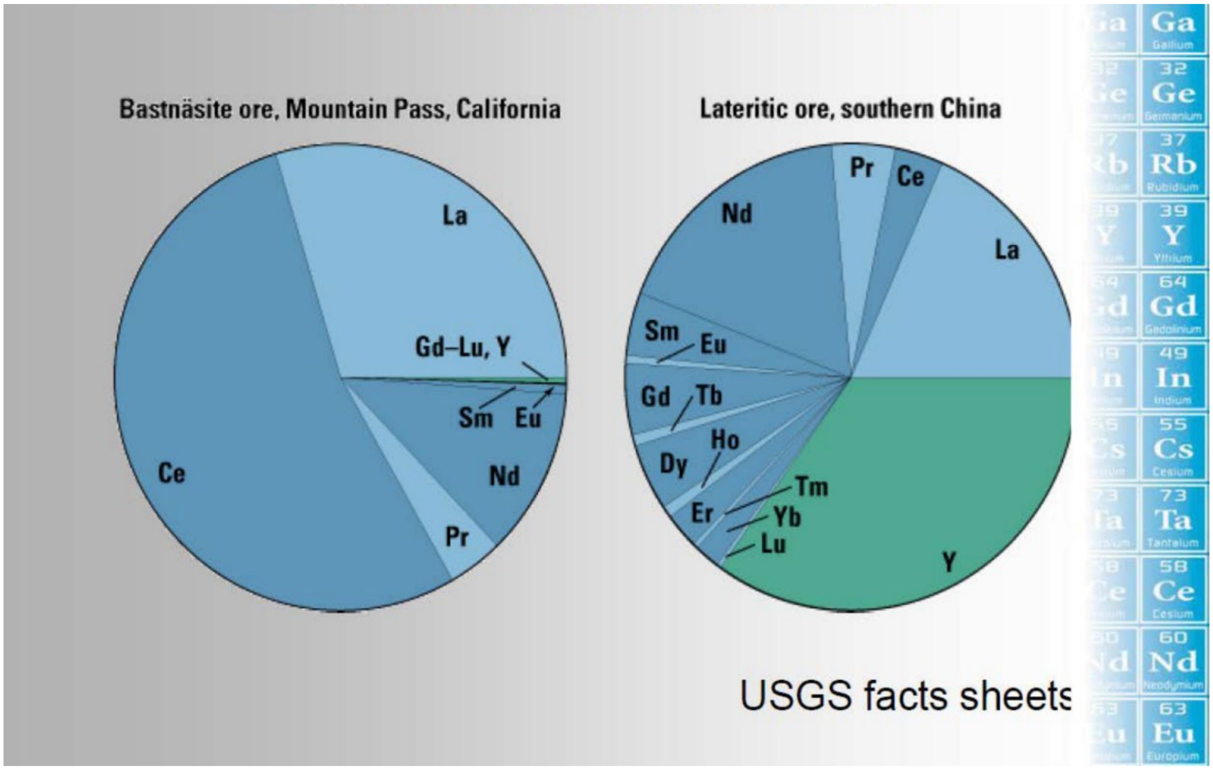

Figure 3. Bastnasite ores are mined at Mountain Pass CA and China's largest REE mine at Bayan Obo (left), they contain less than 12% heavy REE. Nearly all of China's heavy REE come from their laterite deposits (right) which contain about 50% heavy REE.

A recent techno-economic analysis found that REE extraction from AMD feedstock is economically attractive with a refining facility projected to generate positive cash flow within five years. In 2021 we and the West Virginia Department of Environmental Protection began construction of a full scale plant to demonstrate continuous of an integrated AMD treatment plant that will recover high grade (90%+) mixed REE oxide concentrate. Rockwell Automation is providing technical expertise as well as its sensor and control technology to accelerate market readiness. TenCate Corp. is providing filtration media to capture and dewater concentrates prior to shipment.

Thus far, we have produced pre-concentrates from acid mine drainage with 5% REE. Using hydrometallurgical methods at the bench scale, we produced a concentrate with 95% Rare Earth Oxides from AMD treatment sludge (figure 4).

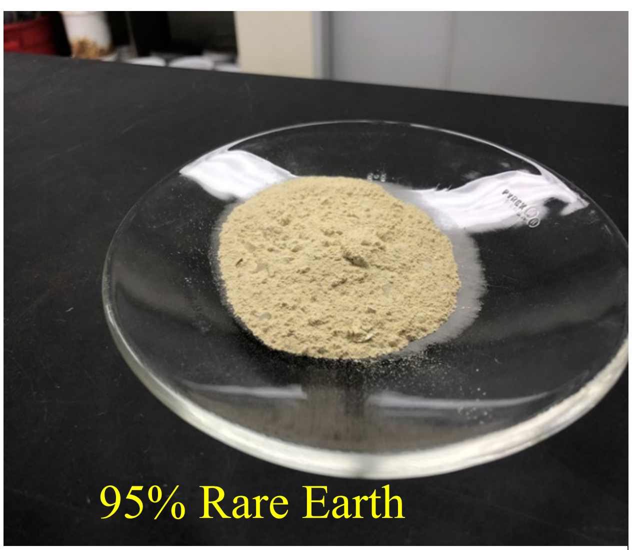

Figure 4. High-grade rare earth concentrate produced by the WVU research team.

Next steps will involve a pilot plant and scaleup of our REE oxide technology to commercialization. Success will support the base of a domestic supply chain but that is only the start of a broader need to stimulate refining to REE metal and transitioning of domestic REE users to domestic supplies.

Growth Strategy. AMD is unlikely to supply all domestic REE/CM needs. It would, however, allow rapid development of a domestic supply and processing industry. While conventional mines might require 5 to 10 years and hundreds of millions of dollars for exploration, permitting and infrastructure development, **the AMD strategy could be initiated almost immediately at operating, already permitted sites. High-value, AMD derived feedstock would sustain a profitable, national refinery that could accept suitable feedstock from other sources and, thus grow organically as the supply side of the industry comes on line in future years.** This would support technical advancement and, in conjunction with U.S. mining schools, re-establish our former dominance in the field of rare earth mineral processing. Ultimately, we anticipate a resilient supply chain with multiple feedstock sources from waste recovery such as AMD and other mineral processing byproducts to greenfield mines. Further, resilience at the downstream, processing end of the supply chain will create a robust domestic industry that will be resistant to foreign interference.

Additional Matters:

The Bipartisan Infrastructure Law support for AMD remediation has the potential to restore whole watersheds by installing centralized treatment plants that treat AMD from both AMLs and post 1977 bond forfeitures. These central plants could also recover rare earths and critical materials on a large scale. However, AMLs and bond forfeiture sites are often subject to different and inconsistent regulatory compliance regimes. In order to jointly manage AMD loadings to these watersheds, unified policy guidance is needed to define common regulatory compliance endpoints. This would, for example, bring watershed treatment entirely under the Total Maximum Daily Load reduction plans under the Clean Water Act.

Also, **AMD treatment facilities require long term maintenance. Policy guidance allowing states to set aside a portion of their BIL/AML funds for long term maintenance and operations would be extremely helpful.**

Finally, the Nation's mining schools have suffered from declining enrolment as the conventional mining and mineral processing industries have contracted. Processing unconventional feedstocks for REE/CM recovery will require new, specialized skills for designing and operating domestic processing facilities and to re-grow U.S. dominance in this critical field.

APPENDIX: Supplemental Information

Introduction:

Rare Earth Elements and Critical Materials (REE/CM) are needed to support domestic manufacturing of advanced technology needed for industrial and defense production. Without them the U.S. is almost entirely dependent on China for not only REE/CM but strategically important, manufactured products. In order to rebuild a domestic supply chain, the USDOE began, in 2016 to explore domestic feedstocks derived from coal and coal related waste products to create an environmentally benign, domestic supply of REE/CM. With USDOE support, the Water Research Institute at West Virginia University has successfully advanced the extraction of REE/CM from acid mine drainage (AMD). Its extraction has proven economically advantageous, it yields the high demand heavy REEs and the critical materials cobalt, nickel and manganese. The program is now building, in conjunction with the WV Department of Environmental Protection, an integrated AMD treatment/REE/CM recovery pilot plant near Mt. Storm WV to demonstrate that technology. The next step would be construction of a regional/national concentrator and refinery. A conceptual study was completed for USDOE in December 2020. It was approved and a detailed feasibility study was completed in November 2021. It includes a refinery to be completed in West Virginia that would process approximately 400 tons of REE/CM annually. The conceptual study indicates highly favorable economics estimating a profit of $10/kg of production. The base capital cost estimate is $105. However, this would be a first of its kind facility and the technology, while demonstrated in a continuous pilot plant has not been scaled and operated in large-scale fully automated mode. To accommodate that uncertainty, an additional $35M contingency is included, totaling $140M. This may be needed to allow adjustments as the facility ramps up to full scale, commercial production. The following analysis draws from the executive summary of our USDOE funded conceptual study.

1. Business Case

1.1. Market Scenario

Coal Based Resources. Acid mine drainage (AMD) is produced in vast quantities at both abandoned and current coal and hard rock mines. It forms when pyritic rock is exposed to oxidizing conditions and produces sulfuric acid. AMD forms when the accompanying rock units lack sufficient neutralizing minerals such as calcite. The resulting acids leach a complex suite of metal ions, which often pollute receiving streams or groundwater. Typical AMD treatment uses acid neutralization, mechanical oxidation and metal hydroxide precipitation to achieve compliance discharge levels of Fe, Al, Mn and other pollutants[i].

Feedstock Reserves. Many of the coal seams in the Northern and Central Appalachian Coal Basin (N/CAPP) produce AMD. Its steady production of rare earth elements (REE) in soluble form presents an attractive feedstock capable of yielding a minimum 365 metric tons per year (tpy) of REE oxide (REO). Also, in coal AMD the ratio of cobalt, a critical mineral (CM) CoO:REO is roughly 1.12:1.

AMD discharges range from tens to thousands of gpm over a broad pH range and are an ongoing source of REE/CM [ii] [iii]. Thus, they represent a continuous flux versus a static in-place reserve. REE, cobalt, discharge rate and thus load (mass/unit time) were determined under USDOE project DE FE0026444 at 140 AMD treatment sites across the N/CAPP. Representing a small fraction of the total AMD generated in the basin, the study identified pH as the most important single correlate with REE. It occurs within two distributions: one above and the other below pH 5. Owing to the acid solubility of REE-containing materials, discharges above pH 5 contained insignificant REE while those below pH 5 were significantly enriched. Within the lower pH range, REE concentration was independent (R^2 = 0.0529) of pH allowing use of the mean value (368 µg/L, 95% Confidence Interval = 49.7). These results informed a model that predicts REE yield based on pH as a quantitative variable and flow as a continuous variable. The model was applied to a large dataset consisting of state and in-house records. Ultimately, over 1,200 discharges with pH<5 were evaluated, while sites with pH>5 were discarded. The resulting cumulative load analysis indicated that REO recovery from 276 N/CAPP discharges would be required to generate 365 tpy. If CoO was included, yield would increase to 885 t REO/CM per year.

Business Case. Our Business Case includes both N/CAPP AMD as well as AMD from the Berkeley Pit copper mine in Butte MT. The latter site consists of two large discharges and was sampled directly to determine the REE content. Table 1 summarizes the projected resource base given these analyses. It is clear that coal AMD represents a distributed resource base, containing thousands of potential albeit, low-yielding, sites. Our reserve analysis arbitrarily includes only enough sites to produce 365 tpy per the USDOE's requirements. Nonetheless, adding additional sites within our database would bring the total production to over 800 tpy. In the next year we will demonstrate recovery methods suitable for small, remote sites that operate passively while producing a pre-concentrate suitable for central processing. On the other hand, large, discharges such as the Berkeley Pit alone would generate 50 tpy of total REE Oxides (TREO) and an additional 18 tpy cobalt. There are perhaps a dozen large metal mine discharge sites like the Berkeley Pit in the U.S. Collection of feedstock from these sources will provide the volumes needed to profitably sustain a small capacity domestic AMD-based REE/CM supply chain.

Table 1. Number of treatment sites in the N/CAPP and the Berkeley Pit needed to yield 817 and 68 tpy REO/CM respectively.

	N/CAPP	Berkeley Pit	Total
# treatment sites	276	1	277
Water treated (gpm)	360,000	9,500	369,500
TREO Yield (tpy)	365	50	415
TREO/CM Yield (tpy)	452	18	470
Total (tpy)	817	68	885

Feedstock Characterization. While TREO concentrations in Berkeley Pit AMD were nearly 10x higher than that in the N/CAPP (4,289 vs. 462 µg/L, both had similar REE chemistries (Figure 2) Both contain about 45% heavy REE. This finding suggests that downstream processing and refining methods such as those currently being developed by the project team would be suitable for either feedstock.

Rare Earth Element Pricing. Pricing for the project is presented in Appendix A. Baseline prices supplied by USDOE have been adjusted for specific products. For metal powders, the adjustment factor of 113.6% was established based on a February 2020 confidential market study update by T. Larochelle commissioned by Hela Novel Metals. For mixed rare earth oxide concentrates, basket pricing was derived from individual oxides pricing adjusted using a discount factor of 35% to account for separation costs.

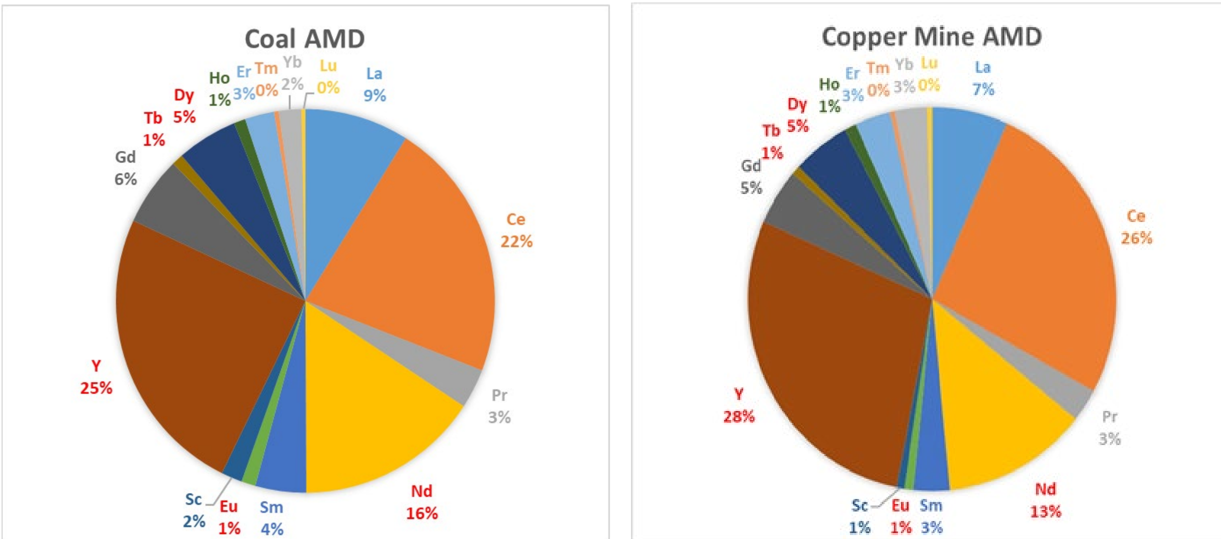

Figure 2. Distribution of REE in coal and copper mine AMD. The coal results represent 140 samples from northern and central Appalachian mines. The copper AMD represents two samples from the Berkeley Pit, Butte MT. Red labels represent critical REEs.

Permitting. AMD treatment plants are routinely permitted under the Federal Clean Water Act. Coal AMD wastes are non-hazardous and generally disposed on site as a condition of the mining permit. AMD treatment wastes from hardrock mines will require site specific characterization.

Mineral Rights Engagement. A legal assessment of AMD/REE/CM mineral rights was undertaken in an earlier USDOE project DE FE0026937. It concluded that, in the event that mineral rights and AMD treatment liabilities are under a single entity, the operator of the AMD plant would have control of the REE/CM resource. Otherwise, the mineral rights owner and the operator of the AMD treatment/REE/CM recovery operation would jointly agree on a mineral royalty or exchange of REE/CM marketing rights for assumption or AMD treatment liability.

Waste Treatment Costs. The bulk of liquid and solid wastes would be treated and disposed of at the AMD treatment site. Solid waste would be identical to AMD treatment solids without the REE/CM component. The bulk of solid wastes would be incorporated into the currently permitted disposal system at each AMD treatment site. Likewise, aqueous discharges would consist of treated AMD discharge which would meet the site's discharge limits under its Section 402, Clean Water Act permit. Thus, additional waste disposal costs would be negligible. This strategy would also apply to a centralized processing facility that would, most likely, be located at an existing, permitted AMD treatment facility. Fortunately, coal AMD contains low, essentially background levels of Th and U, negating any issues associated with radioactivity.

1.2. Rare Earth Industry Overview

Rare Earth Industry Overview. The Peoples Republic of China (PRC) has successfully consolidated the rare earth industry in vertically integrated conglomerates. As such, intermediate products such as mixed-oxide concentrates are not available for purchase by companies outside these vertically integrated conglomerates, and to a greater extent, non-Chinese companies. Major non-Chinese refiners and consumers of rare earth products, such as Solvay Rhodia and Shin-Etsu, are all involved with Chinese companies, having operations in China to secure their supply chain. The vast majority of rare earth element end users are now also located in China. After the market shock of 2010 when China dramatically decreased its exports and prices outside China many end users that had operations outside of China relocated to China.

The U.S. has only one REE producer, the Mountain Pass mining and concentration facility in California. It currently ships all of its mineral concentrate to China for refining and manufacturing. A few projects have been advanced to join Mountain Pass as a potential domestic source of rare earth elements, but none has yet advanced to production. Of these few dedicated rare earth companies, UCore and Rare Element Resources have shown the greatest potential to date.

Market Advantage of the Concept. The proposed conceptual supply chain addresses many of the entrance barriers in the market by integrating a low-cost supply source, a separation facility and a metals production facility using a combination of state of the art technology with innovative technology. This novel approach will allow for the production of a suite of products with a domestic market as opposed to foreign markets for mixed-oxides and separated oxide materials. The proposed, conceptual supply chain also minimizes the time and barriers to production since the feedstock is already available at permitted sites minimizing exploration and investment uncertainty. AMD is treated at sites that already have the required power, transportation and workforce infrastructure. Lastly, AMD-based REE/CM occurs in aqueous form, minimizing processing plant capital requirements.

1.3. Risk Identification and Mitigation

The most important risk to the project is related to the capability of the project team to finance the project throughout the design, construction and startup phases i.e. until production has been qualified with enough downstream purchasers. Many critical mineral extraction and refining projects fail at the financing stage, often for non-technical considerations.

A second but related risk is the predatory commercial practices of the PRC, which controls the world REE industry. A typical strategy is to flood the market and artificially lower prices until all foreign competitors are out of business or have been acquired by Chinese interests before raising prices and profiting from their dominant position. As an initially minor player, the proposed supply chain will need to secure outlets for its products in an opaque market. Without government support, any small-scale entrant will be at a significant disadvantage compared to established producers. To address this risk, the study team has considered the potential for future feedstock diversification in the process design.

Appendix A-1: Estimates and Pricing

Rare Earth Elements and Cobalt Product Pricing

Element	Metal	Source	Oxide	Source
La	-	-	$ 2.00	1
Ce	-	-	$ 2.00	1
MischMetal	$ 20.45	1.1	-	-
Pr	-	-	$ 50.00	1
Nd	-	-	$ 42.00	1
Nd/Pr	$ 69.65	1.1	-	-
Sm	$ 18.40	3	$ 1.75	2

are Earth and Critical Pricing

Elements Materials

Eu	-	-	$ 30.00	1
Gd	$ 56.81	1.1	$ 23.00	1
Tb	$ 738.58	1.1	$ 500.00	1
Dy	$ 340.88	1.1	$ 250.00	1
Ho	$ 695.03	4	$ 68.48	2
Er	$ 107.95	1.1	$ 22.00	1
Tm	$ 857.29	4	-	-
Yb	$ 228.28	4	$ 15.54	2
Lu	$ 3,298.76	4	$ 638.36	2
Y	$ 39.77	1.1	$ 6.00	1
Sc	$ 3,976.99	1.1	$ 1,000.00	1
Co	$ 41.67	3	-	-

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[iii] Vass, C.R., Noble, A. and Ziemkiewicz, P.F. 2019. The occurrence and concentration of rare earth elements in acid mine drainage and treatment by-products: Part 2: Regional Survey of Northern and Central Appalachian Coal Basins. Mining, Metallurgy & Exploration. HTTPS://doi.org/10.1007/s42461-019-00112-9