Generating rare earth element and critical mineral hydraulic pre-concentrate from acid mine drainage at remote sites: A case study at Fola job 5, Clay County, WV

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Abstract

The need for a national supply of rare earth elements (REEs) and critical minerals (CMs) motivated the research of REE/CM feedstocks alternative to mining. Research on hard and soft rocks has demonstrated concentrations of REE/CM, yet the cost-effectiveness of processing these rocks directly for REE/CM mining remains a challenge. Therefore, the West Virginia Water Research Institute (WVWRI) began investigating recovering REE/CM from mining byproducts, including sludges generated by the treatment of acid mine drainage (AMD). This investigation was successful and is now patented; WVWRI is expanding operations to create a national REE/CM feedstock supply chain.

The first step in this supply is generating REE/CM-enriched sludge, referred to as hydraulic pre-concentrate (HPC), by treating AMD. In Appalachia, a large portion of AMD is generated at remote sites, where AMD must be treated passively with no power supply. This research investigated the feasibility of producing HPC following the Ziemkiewicz et al. patented process at a remote AMD site with a flow rate of less than 50 gpm (190 L/min). This research intended to design, deploy, and operate a system capable of treating AMD in compliance with NPDES limits while generating HPC in a remote site. The process was demonstrated by constructing a system at a remote site in Clay County, WV.

The deployed system achieved steady-state flow with effective pH control. Samples were collected to assess the system's performance in terms of REE/CM recovery in the resulting HPC product. Analytical results revealed an impressive REE recovery rate of 85% and CM recovery rate of 83%, indicating substantial potential for profitability. Operations were paused for the winter season, with plans to resume in spring 2024, incorporating enhancements to system control and operation.

Keywords: Rare earth elements, critical minerals, selective precipitation, remote sites

Introduction

Rare earth elements (REEs) and critical minerals (CMs) are in high demand due to technological advancement. Most REE/CMs consumed in the US are imported (USDOE 2017). Vass et al. (2019 a,b) studied the REE concentration in coal by-products, specifically in acid mine drainage (AMD) in the US's Northern and Central Appalachian regions, identifying an average concentration of REE of 282 µg/L; the study estimated an REE production of 13,000 kg/a from AMD precipitate. Ziemkiewicz et al. (2018) estimated a potential REE extraction rate of approximately 1,000 tons of REE oxides per year in the referred region.

To implement reliable and environmentally friendly REE/CM recovery from AMD, this research investigated the design, construction, and deployment of a passive system able to treat AMD in accordance with the National Pollutant Discharge Elimination System (NPDES) while increasing the concentration of REE/CM in the precipitate to generate an economically feasible production chain. REE/CM enriched sludge is referred to as hydraulic pre-concentrate (HPC) in this manuscript. The project team partnered with Continental Heritage (Fola, WV) to implement and investigate a field test of the Ziemkiewicz et al. (2021) REE/CM recovery process at a remote AMD source in Clay County, West Virginia. The process consists of selective precipitation with two set pH points for an in-series treatment. The first pH cut precipitate is a typical AMD sludge to be disposed of, while the second pH cut precipitate is the HPC.

The project's goals were to 1) investigate the feedstock for REE/CM concentration, 2) design and implement a system to conform to the site conditions and limitations, and 3) operate and optimize the system to achieve the desired REE/CM recovery to HPC.

Site description

Fola Job 5, a reclaimed surface mine, feeds into a point source, forming a creek that undergoes treatment using an AquafixTM system with hydrated lime. Following treatment, the water is directed to a polishing pond before its final discharge at an NPDES-designated point. The watershed area responsible for draining Acid Mine Drainage (AMD) into this site spans 154.8 ac (0.63 km²). Due to its lack of access to power, this site falls under the category of remote locations.

The flow of AMD at this site typically exceeds 50 gpm (190 L/min), with a pH value around 3.61. A laboratory analysis was conducted on the feedstock to determine mineral distribution, as presented in Fig. 1; the total rare earth (TREE) concentration is illustrated in Fig. 2. The total concentration of Rare Earth Elements (REE) for the site measures 0.5 mg/L (Table 1). This concentration aligns relatively closely with similar feedstocks found in the Appalachian region, as reported by several studies: Vass et al. (2019a) documented concentrations ranging from 0.088 to 0.3 mg/L, Vass et al. (2019b) found an average of 0.282 mg/L, and Middleton et al. (2024) reported levels between 0.12 and 1.5 mg/L. Concentrations at Fola Job 5, and for coal-based AMD in general, are lower than hard rock sources in Colorado, as reported by Goodman et al. (2023) with concentrations ranging from 0.037 to 1.275 mg/L. Furthermore, concentrations at Fola Job 5 are notably lower than coal-derived AMD in the Iberian Pyrite Belt (Spain), reported by Ayora et al. (2016) ranging from 3.5 to 7.9 mg/L and Leon et al. (2021) with an average of 2.248 mg/L.

System design

The proposed 2-split treatment system was designed to handle flows below 50 gpm (190 L/min) and was seamlessly integrated into the existing treatment setup with minimal changes.

Flow Collection:

Raw Acid Mine Drainage (AMD) is collected at the source using a weir box. The weir box features a 2-in (5 cm) pipe exit set at a depth of 4 in (10 cm) with a grate to prevent debris.

AMD Treatment and HPC production:

AMD is routed through schedule 40 PVC pipes into two 1,600-gal (6,056-L) settling cone tanks. Before entering each tank, pH is adjusted using liquid sodium hydroxide ("caustic"). Sodium hydroxide is introduced via a 0.5-in tubing (1.9 cm), with dosing controlled by a solar panel-fed peristaltic pump. A programmable automatic valve, powered by a solar panel-fed battery, regulates discharge from each tank. Sludge from Tank 1 is directed to the existing treatment system for disposal. Supernatant (treated water) from Tank 1 is sent to Tank 2. In Tank 2, a second pH adjustment is performed to generate Hydraulic Pre-Concentrate (HPC), which is then routed to filtration and retention processes. A specially designed "Y" fitting is incorporated to accommodate a floc log for enhanced filtration efficiency. Additionally, a static mixer is utilized to ensure thorough mixing of the caustic within the system.

Filtration System:

Two geotextile bags are used for filtration and retention. Each bag has a two-ply filtration geotextile system. A wicking geotextile in the center of each bag improves moisture distribution and dewatering.

Cost Estimate:

Materials and installation costs are estimated at $23,075 (excluding operational and maintenance labor). This system allows for

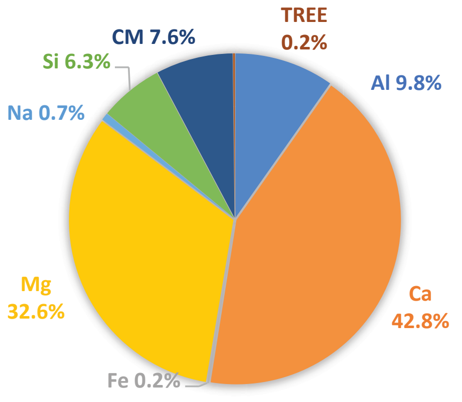

Figure 1 *Metal concentration in AMD feedstock at FOLA Job 5. Critical Materials (CM) account for 7.6% of the total solution concentration while Total Rare Earth Elements (TREE) account for 0.2%. Note this chart only accounts for cationic species*

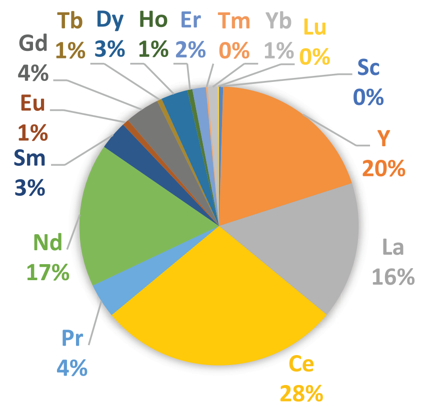

Figure 2 *TREE distribution – Fola Job 5 feedstock*

efficient treatment of AMD at Fola Job 5, meeting the site's needs while minimizing costs and environmental impact.

System operation

The system operation was divided into three stages: 1) establishing the water flow and hydraulics, 2) HPC production, and 3) HPC collection.

Stage 1 – Establishing water flow and hydraulics

The first stage comprised system installation and establishment of water flow through the system. As the main flow driver was gravity, the team intended to obtain steady-state flow before attempting HPC production. The collection box weir was enclosed by rocks, creating a dam around it and allowing water to be collected and routed in the pipeline. The flow was not pressurized until the elevation of the first tank overflow port. From the first settling tank, water flowed to the second tank, then to the supernatant discharge port, and then back to the existing treatment system inflow. After several modifications to the system alignment, steady flow was reached at 40 gpm (151 L/min). During operation, the system clogged due to sediments and algae. Cleaning ports were installed along the line to allow flushing via pumping if clogging issues occurred in the future.

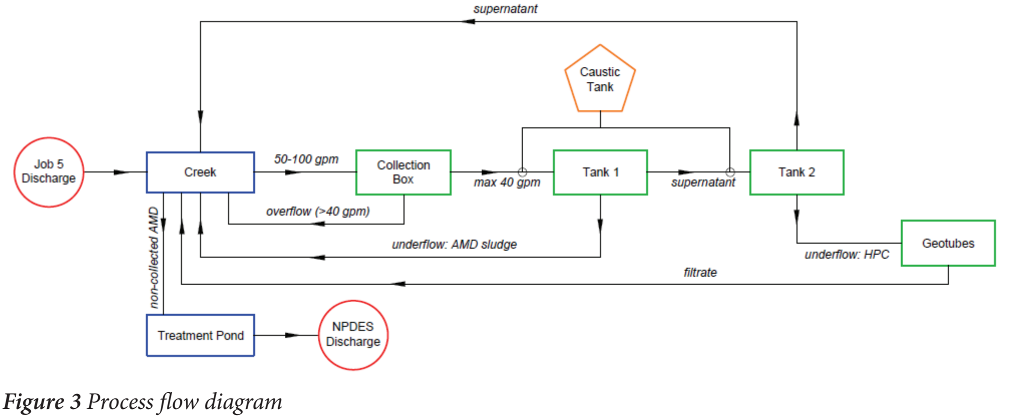

Figure 3 *Process flow diagram*

Stage 2 – HPC production

The second stage of the system operation consisted of running AMD through the system to produce HPC and lasted approximately eight weeks. Initially, the pH points were attempted by dosing sodium hydroxide via gravity into the system and controlling dosing with ball valves. This method proved unsuccessful. The second attempt included peristaltic pumps for more deliberate dosing. The peristaltic pump for the first split successfully kept the pH within +/- 0.1 throughout the operation. The peristaltic pump on the second split had issues achieving the desired pH set point due to battery overconsumption resulting in pump shutoff during operation. To achieve system operability without the delay of replacing the pump and/or ordering and installing a new power source for the pump, the second split pump was disconnected from the solar panel, and a ball valve was used for pH control via gravity feed of caustic. The pH was maintained with this method within +0.5/-1.5 of the pH target for isolated periods. Samples of the second pH split were tested for settling velocity, averaging 0.65 in/min (1.65 cm/min). There was little to no accumulation of precipitate at the bottom of both pH split cone tanks. It was hypothesized that the flow in the tank was elevated enough to drive the flocs with the supernatant discharge. Larger tanks or lower flow would be needed to promote the settling of solids. Additionally, no flocculant was used at this point, which could have aided the settling issue.

Stage 3 – HPC collection

Two bags were set to collect the HPC flushed from the second settling tank. During the initial testing of the bags in the 8-week operation, clear water was flowing out, indicating filtration effectiveness. No quantitative measurement of filtration efficiency was made at this stage. After one week of operation with the automatic discharge valve set to flush for 30 s every 24 h, no considerable amount of solids was identified in the bags. This was attributed to the limited stability and settling of the second pH split. The system was disconnected and flushed for the winter in November 2023 and will be re-connected in the spring of 2024.

Process effectiveness

The Hydraulic Pre-Concentrate (HPC) capture system encountered challenges, resulting in a lack of high enough amounts of solid precipitates for analysis. Nevertheless, liquid samples obtained during steady-state conditions allowed for system evaluation (Table 1).

Operational observation indicates that no relevant precipitation occurred in the first split. This is possibly due to the high flow limiting retention time for the solids to precipitate from the solution. Additionally, the operation produced 14% recovery of TREE to the first split. While it should be noted that this AMD source is low in iron compared to other Appalachian AMD sources, previous results from this research group indicate that iron precipitation can be improved while reducing REE/CM precipitation in the first split reject sludge. Further investigation into the system stabilization delay, pH control, and pH measurement location is needed.

Furthermore, results indicated recovery rates of 85% TREE and approximately 83% of the Critical Materials (Co, Mn, Ni, and Zn) precipitated to the HPC solid. It should be noted that the high recovery of major metals such as Aluminum and Silica to the HPC solid coincides with data from treatment at previous sites and can be further handled in metallurgic processes. While no HPC solid was captured for assay, the treatment using its current pH splits will be sufficient to generate Rare Earth Enriched HPC as designated by the aqueous data.

Conclusions and future work

A remote site (Fola Job 5) in Clay County, WV was evaluated for REE/CM feedstock, and an AMD treatment system was designed, deployed, and operated. The system utilized selective precipitation to generate REE/CM enriched precipitate (HPC). The following conclusions are made from this project:

- Feedstock investigation demonstrated REE/CM contents at 7.8% of the solution, indicating potential for profitable operation.
- The system was designed, deployed, and operated over an 8-week period, achieving a successful steady-state flow of

Table 1 Analytical assays of treatment process and recoveries. Note: "ND" is a non-detected element. Negative Recoveries are usually indicative of analytical error

Element	Concentration per treatment stage Raw Job 5 AMD mg/L	First Split mg/L	Second Split mg/L	% Recovery to Solid First Split	% Recovery to Solid Second Split
Al	27.3	24.9	1.3	9%	86%
Ca	119.4	110.1	107.5	8%	2%
Co	0.4	0.4	ND	15%	85%
Fe	0.5	0.6	ND	-33%	100%
Mg	91.0	82.4	69.7	9%	14%
Mn	19.2	16.4	5.4	14%	58%
Ni	0.5	0.4	ND	12%	88%
Si	17.5	17.8	ND	-2%	100%
Zn	1.1	1.4	ND	-28%	100%
TMM	276.8	254.3	183.8	8%	25%
Sc	0.00	0.0	0.0	0%	97%
Y	0.10	0.1	0.0	13%	87%
La	0.08	0.1	0.0	18%	81%
Ce	0.15	0.1	0.0	13%	86%
Pr	0.02	0.0	0.0	16%	84%
Nd	0.09	0.1	0.0	14%	86%
Sm	0.02	0.0	ND	14%	86%
Eu	0.00	0.0	ND	16%	84%
Gd	0.02	0.0	ND	15%	85%
Tb	0.00	0.0	ND	16%	84%
Dy	0.02	0.0	0.0	14%	86%
Ho	0.00	0.0	ND	13%	87%
Er	0.01	0.0	0.0	11%	89%
Tm	0.00	0.0	ND	12%	88%
Yb	0.01	0.0	ND	9%	91%
Lu	0.00	0.0	ND	11%	89%
TREE	0.5	0.5	0.0	14%	85%

40 gpm (151 L/min) with very stable pH control (±0.1) on the first split through the operation. A moderately stable (+0.5/ -1.5) second pH split was achieved over isolated periods. These operational results indicate that a passive system to generate REE/CM preconcentrate can overcome remote site constraints.

- Analytical Data from the aqueous pH splits indicates an acceptable recovery of TREE to the HPC solid phase.

Further investigation is needed to optimize the HPC collection and filtration. Continued research in the spring of 2024 will enhance the system for better pH control, HPC settlement, and filtration.

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