

Preliminary Techno-Economic Evaluation of a Novel Membrane Based Separation and Recovery Process for Rare Earth Elements from Coal Combustion Residues

Zachary Hendren¹, Young Chul Choi¹, Helen Hsu-Kim², James C. Hower², Desiree Plata⁴, and Mark Wiesner³

¹RTI International – Energy Technology Division, 3040 Cornwallis Rd, Research Triangle Park, NC 27709; ²Duke University, Department of Civil and Environmental Engineering, Hudson Hall, Durham NC 27701; ³University of Kentucky, Center for Applied Energy Research, 2540 Research Park Drive, Lexington, KY 40511; ⁴Yale University, School of Engineering and Applied Science, New Haven CT 06520

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Abstract

Rare earth elements (REEs) recovery from coal combustion residues (CCRs) is of increasing economic interest. We utilize hydrometallurgical-based methods, including nanotechnology-enabled filtration and electrodeposition methods, to separate rare earth ions from acid leachates of CCRs. We examined an existing collection of CCR samples from a wide variety of U.S. power utilities, representing every major coal source and more than 20 states in the U.S. Subsequent efforts have focused on obtaining lab-scale experimental data for the performance of each of the processing steps proposed. This presentation will detail the techno-economic analysis based a preliminary design of a full-scale treatment operation designed for a basis of 1 ton/hr of ash on a dry basis. A process spreadsheet was developed to represent the performance of each of the unit operations required for REE dissolution, concentration, and recovery into a salable product. The process performance was linked to a financial analysis that incorporates equipment sizing, capital costs, operational costs, product recovery, as well as residual disposal costs. The approach is a powerful tool that allows the customization of the recovery method, so that performance can be assessed by varying material inputs as well as variation of unit operations selected for REE recovery.

Introduction

This project is developing methods to recover rare earth elements (REEs) from coal combustion residues (CCRs). The technology utilizes hydrometallurgical-based methods, including nanotechnology-enabled filtration and electrodeposition methods, to separate rare earth ions from acid leachates of CCRs. At the start of this project, we

examined an existing collection of CCR samples from a wide variety of U.S. power utilities, representing every major coal source and more than 20 states in the U.S. Subsequent efforts have focused on obtaining lab-scale experimental data for the performance of each of the processing steps proposed. An overview of the proposed processes under consideration are shown in **Figure 1**.

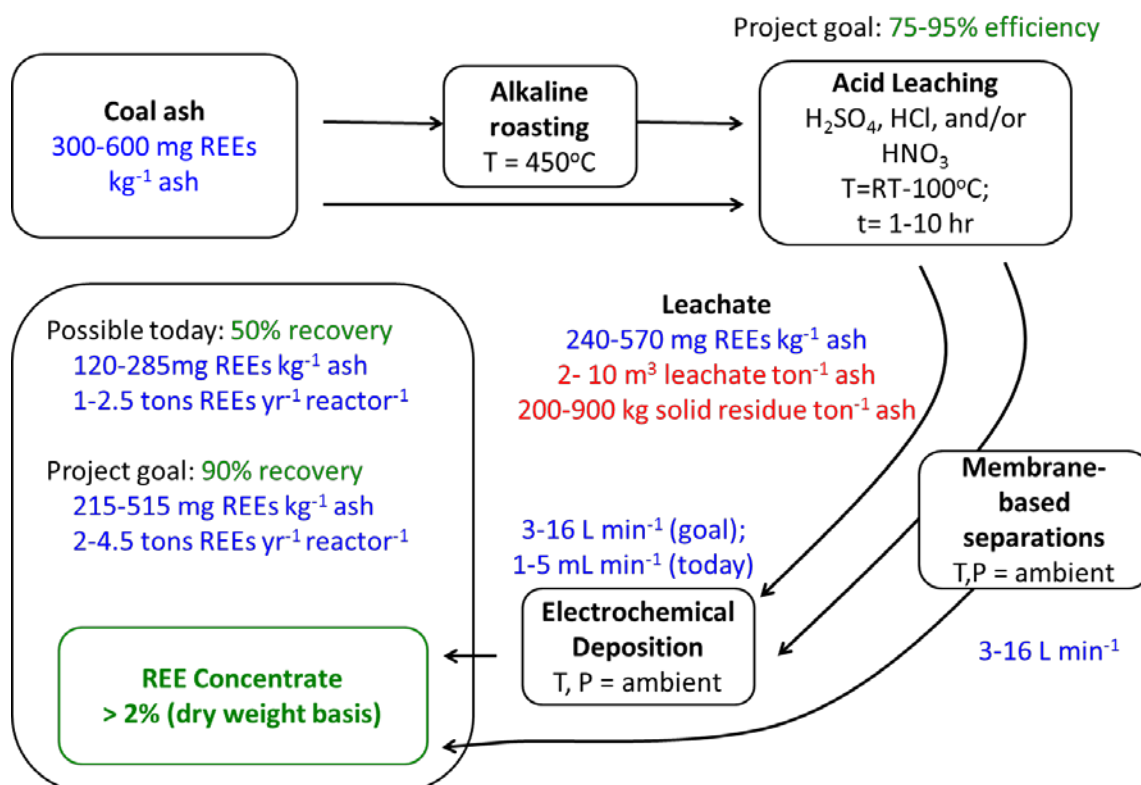


Figure 1. Flow chart of the overall proposed process. Flow rates and REE contents are given in blue; waste stream generation is indicated in red (note that the leachate volume waste is equal to the electrochemical deposition eluent waste volume, as it is the same stream; omitted for clarity); recoveries and products are shown in green. The feasibility study developed assumed a mass basis of 1000 kg/hr of CCR.

This paper details the techno-economic analysis based a preliminary design of a treatment operation designed for a basis of 1 ton/hr of ash on a dry basis. A process spreadsheet was developed to represent the performance of each of the unit operations. The process performance was link to a financial analysis that incorporates equipment sizing, capital costs, operational costs, product recovery, as well as residual disposal costs. The included spreadsheet is a powerful tool that allows the customization of the recovery method, so that performance can be assessed by varying material inputs as well as variation of unit operations selected for REE recovery.

Sampling and Characterization Summary

At the start of this project, we examined an existing collection of coal combustion residuals (CCR) samples from a wide variety of U.S. power utilities, representing every major coal source and more than 20 states in the U.S. From this collection, we selected

12 CCR samples for further characterization and evaluation of REE recovery methods for this project. These samples were collected from 9 different coal fired power plants and represent coal ash stocks burned from coals mined from the three major basins in the U.S. (Central Appalachia, Illinois, and Powder River Basins). Total REE contents of these samples range from 233 to 1180 mg kg⁻¹. The major element contents of the samples demonstrate a wide variety of sample types, including Class C and Class F fly ashes. The samples are dominated by amorphous glass phases with some crystalline fractions that are primarily quartz. Iron oxide and mullite phases were also detected in a subset of samples (primarily those originated from Illinois and Appalachian coals). In a subset of the samples, distinct REE-bearing mineral phases were observed, but the abundance of these chemical forms remains unknown. Further work with microscopy and spectroscopy will be pursued for more quantitative analysis of the REE forms in the samples. **Table 1** provides the summary of coal ash samples selected for the experiments and modeling that inform this Feasibility Study. A detailed discussion of the characterization methods, including mineralogy and analysis methods as well as a more detailed discussion of the variation in species concentration by geography and ash samples can be found the *Sampling and Characterization Report* Submitted September 6th 2016.

Techno-Economic Model Overview

The aim of the modeling approach is to develop a technical and economic feasibility tool that allows the various groups involved in the project to evaluate the feasibility of various process configurations and process efficiencies. The objective is to analyze various process layouts for concentrating the Rare Earth Element (REE) concentration from 300-600 mg REE/kg coal ash to an REE concentrate stream containing 2 wt% REE on dry basis. The basic process layout is shown in **Figure 2**.

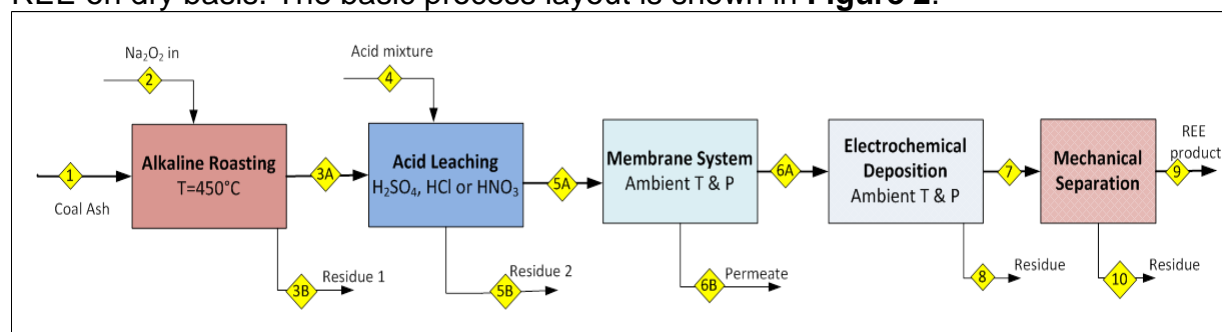


Figure 2. Basic process block diagram for REE recovery

The tool is designed with the objective of customizing the process layout that can include or exclude a processing step for recovering REE. The first step entails inputs parameters such as the coal ash composition including both REE and non-REE content in the coal ash available. In the analysis performed for this study, three representative concentration lists for both REE and non-REE content were selected to represent fly ash produced from coals derived from the Appalachian Basin (App), Illinois Basin (IL), and Powder River Basin (PRB) geographical regions. Once the composition of the inlet stream is entered, if the alkaline roasting step is considered in the layout, the mass and

energy balances for this step are calculated. Depending on the amount and type of roasting agent used in the alkaline roasting step and the temperature maintained, the capital cost for the rotary kiln and the energy input and material costs involved for this treatment step are calculated.

Table 1. Coal ash samples selected for testing of REE recovery technologies.

Sample ID #	Power Utility (Location)	Type	Feed Coal Source	Sampling Date	Total lanthanides (mg kg ⁻¹)	Total REE: (Lanthanides + Y +Sc) (mg kg ⁻¹)	Specific surface area (m ² g ⁻¹)	Crystalline minerals via XRD		
								Major	Minor	Trace
93932	Power plant W (South Carolina)	Fly ash	Appalachian	2014	519	669	2.786	Quartz	Mullite, Hematite	Magnetite?
93938	Plant Plant I (Kentucky)	Fly ash silo	Appalachian	2014	570	703	7.781	Quartz	Mullite, Hematite, Gypsum	C ₂₅ (SiO ₄) ₂ F ₂
93962	Power Plant KS (Kentucky)	Stoker ash	Appalachian	2015	961	1222	3.104	Mullite, Quartz	Cristobalite, Hematite	Magnetite?
93965	Power Plant C (Kentucky)	Pond ash	Appalachian	2015	422	531	15.10	Quartz	Mullite, Hematite	
93963	Power Plant H, Unit 2 (Kentucky)	Fly ash	Appalachian	2015	511	655	3.171	Quartz	Mullite, Hematite	Magnetite
93895	Power Plant H (Kentucky)	Fly ash, rows 2	Illinois	2013	422	553	1.387	Quartz, Magnetite	Mullite, Hematite	
93899	Power Plant H (Kentucky)	Fly ash, rows 3	Illinois	2013	306	388	3.661	Quartz	Mullite, Hematite, Magnetite, Anhydrite, Calcite, Portlandite	
93964	Power Plant H, Unit 3 (Kentucky)	Fly ash	Illinois	2015	408	524	1.492	Quartz	Mullite, Hematite, Magnetite	
93966	Power Plant DE (Texas)	Fly ash	Powder River	2015	332	406	1.434	Quartz	Hematite, Periclase	Anhydrite
93973	Power Plant SC (GA)	Fly ash	Powder River	2015	309	383	1.099	Quartz	Anhydrite, Hematite, Periclase	Lime
93927	Power Plant LA (Missouri)	Fly ash	Powder River	2013	211	265	1.216	Quartz, Tricalcium aluminate, Periclase	Anhydrite, Lime	
93971	Power Plant RI	Fly ash	Powder River	2015	180	233	2.451	Quartz	Anhydrite, Lime, Tricalcium Aluminate, Periclase, Ye'elimite	Fluoroapatite, Sodalite-Nosean?, C ₁₀ Al ₁₂ Cl ₂ Si ₅ O ₃₇ ?

Based on the experimental results observed, the amount of REE recovered in this step is determined. The REE recovered in the Alkaline Roasting step is subjected to acid leaching depending on the process layout. Based on the acid concentration and volume, the capital cost for a mixer to facilitate leaching as well as the cost of acid required can be determined in this step. The recovered REE slurry is sent to a membrane-based system for concentration. Three types of membrane systems are being evaluated at this stage: nanofiltration (NF), micelle enhanced ultrafiltration (UFM), and liquid emulsion membrane recovery (LEM). The user determines which, if any, concentration step is used in the process. The recoveries for the membrane systems evaluated are used to calculate the volume and REE concentration of the retentate and permeate. The REE enriched membrane stream then flows to the electrodeposition stage for final capture via mechanical separation. For each of the units, the costs were estimated based on sizing data from the process assessment as well as a range of sources, including manufacturer quotes and engineering estimation tools. This report details the assumptions and results generated from the techno-economic spreadsheet tool.

Quality of Cost Estimate & Assumptions

The accuracy of a cost estimate is a function of the stage or definition of a project. As a project progresses towards completion the cost estimate becomes more accurate. This progression has been defined by a cost estimate classification system ranging from 5 (>0% to 2% project definition) to 1 (50% to 100% project definition). Based on the current stage of this project, a Class 5 estimate was deemed appropriate and is defined as:

CLASS 5 ESTIMATE: Concept screening (AACE 2016)

Typical level of project definition required: 0% to 2% of full project definition.)

(Accuracy Range: L=-20% to -50%, H=+30% to +100%) [AACE 2016]

Although the design package includes process flow diagrams (PFDs), mass and energy balances, and equipment appropriately sized for the proposed mass throughput are typically enough detail for the project to meet a Class 4 estimate, the novelty of combining a lab based electrochemical membrane REE recovery system and a range of potential membrane treatment system options that are being evaluated for REE concentration brings a higher level of uncertainty to the final performance and pricing of a full scale system, and thus a Class 5 estimate is deemed appropriate. Class 5 estimates are generally prepared based on limited information and subsequently have fairly wide accuracy ranges. They are useful for concept screening, determination of feasibility, concept evaluation, and preliminary budget approval. Class 5 estimates are prepared for a number of purposes such as, but not limited to, detailed strategic planning, business development, project screening at more developed stages, alternative scheme analysis, confirmation of economic and/or technical feasibility, and preliminary budget approval or approval to proceed to next stage.

Inputs and Assumptions

Key inputs from partners Duke and Yale as well as RTI were utilized in developing the requisite membrane area needed for treatment, pump capacities, energy consumption for the full scale design include:

- REE Recovery in 1st stage 100%
- Non-REE recovery in 1st stage for metals with $E^0 < 1.7V = 100\%$
- REE recovery for REE in 2nd stage = 95%
- Non-REE recovery in 2nd stage for metals with $E^0 > 1.7V = 10\%$
- NF nominal flux = 20 LMH
- Electrodeposition nominal flux = 12 LMH

Process equipment was sized on the design flow basis of 1000 kg/hr ash. Equipment was sized using empirical factors based on calculated size from The Process Design Handbook (Walas 2010), which uses 1985 costs that have been updated to 2015 dollars. Other equipment costs were generated from direct vendor quotes or from www.matche.com/equipmentcost. Project partner Duke University evaluated the costs for the LEM and UFM systems using cost curves for each system scaled to the required flow rate. A detailed presentation of the methodology used for these curves is provided in Appendix B. The membrane-based electrodeposition step is the process with the highest level of uncertainty because it is not yet developed to the commercial scale. The approach used to estimate the cost of the system was to base membrane costs of vendor quotes for UF membrane modules, but since the membranes are coated with CNT, a cost factor was introduced to account for the price increase. DeLannoy et al (2013) estimated the increased capital cost of the CNT-fabricated membranes (~\$2.50/m², or ~1.5% of total membrane costs), so this was used as a basis for the cost factor. In addition, the mechanical separator was assumed to be incorporated to the external pressure vessel, so the costs of such a unit were assumed to be 2x the cost of quoted pressure vessels. In addition, we did not include a cost for acquisition and transportation of coal ash. This cost will be site dependent, with the possibility that a site may pay to have the ash removed to limit their own disposal costs.

The total capital cost is the sum of material equipment costs, the installation cost for the process equipment, and the total indirect capital costs. The total indirect capital costs account for the construction overhead costs, contingency, project management fees and the working capital required for the project. The operational costs include energy consumption such as heating fuel/electricity, chemical consumables that are key to the process, and maintenance/repairs, as well as factor for labor. The assumptions made for estimating other key operational and capital costs are listed below in **Table 2**.

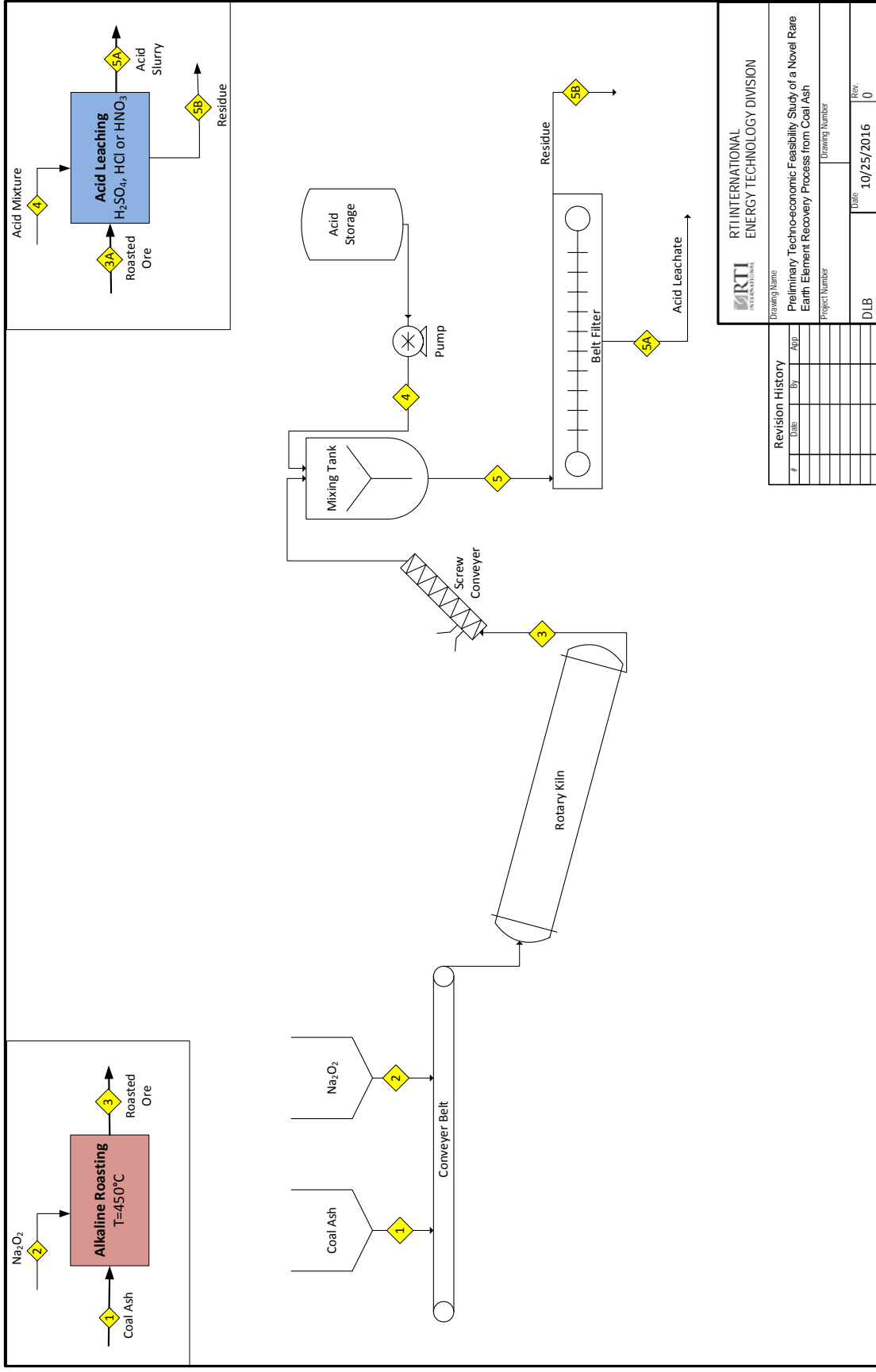
Table 2. Cost and design assumptions used in the CAPEX and OPEX economic analysis developed for the REE recovery system.

PARAMETER	UNITS	VALUE
Equipment life	Years	20
Operating hours	Hours/day	24
Operating days	Days/year	365
Power Cost	\$/kWh	0.1

Thermal heating cost	\$/100,000 BTU	1.1
MREO ore value (100%)	\$/kg	7
Acid Cost (HCl, 37%)	\$/kg	0.15
Base membrane element cost for	\$/element	1484
Base pressure vessel cost for electrodepos.	\$/unit	2120
Membrane Replacement Frequency	years	3
Maintenance and Repair Allowance	% of equipment cost	3
Project + Process Contingency	%	30
Engineering, LM	%	20
Offsite waste transport & disposal (liquid)	\$/kg	0.59
Roasting agents: (Na₂O₂, NaOH, CaO,	\$/kg	1.8, 0.30, 0.10,
Specific heat CCR (all types)	kJ/kg C	1.15
Surfactant Loss Rate	%	10
Oil Phase Loss Rate	%	10
NF monovalent rejection	%	25
Membrane water recovery	%	80

Process Flow Diagram

material flows in a process. For the novel REE recovery process, a PFD is presented in **Figures 3-7** below. The first step (stream 1) of the overall process is the Alkaline Roasting, which is a pretreatment step that ensures a more complete dissolution of the REE from the ash during the acid leaching step. The major equipment include hoppers for the ash and roasting agent, a conveyer belt, a rotary kiln, and a screw conveyer to take the roasted ash to the acid leaching unit (stream 3). Major equipment in the acid leaching step includes a storage tank for HCl, a mixing tank, and a belt filter to remove any undissolved residue. The acidified ash (stream 5A) can then flow directly to the electrodeposition REE collection step or to one of three membrane based concentration steps. The major equipment in the NF step includes feed pumps, UF pretreatment membranes, NF membranes, and chemical dosing pump. The UFM step includes a mixing tank, ultrafiltration membrane modules, feed pump, and surfactant recovery membranes. The major equipment in the LEM step includes a mixing tank, settling tank, emulsion settling tank, and surfactant removal membrane. The REE is ultimately recovered (stream 6A) in the electrodeposition step, which includes a feed pump and two stages of electrodeposition membranes. For this preliminary analysis, the mechanical separation was assumed to take place as part of each module. Since this unit process is under proof-of-concept development and is not available at commercial scale, it is envisioned in this design as a type of module that incorporates mechanical scraping, agitation, sonication, or something similar. Screenshots of the TE spreadsheet and stream tables for a specific scenario are provided in the supplementary appendix. A.



Revision History		Drawing Name	
#	Date	By	App

Date: 10/25/2016
 Rev: 0

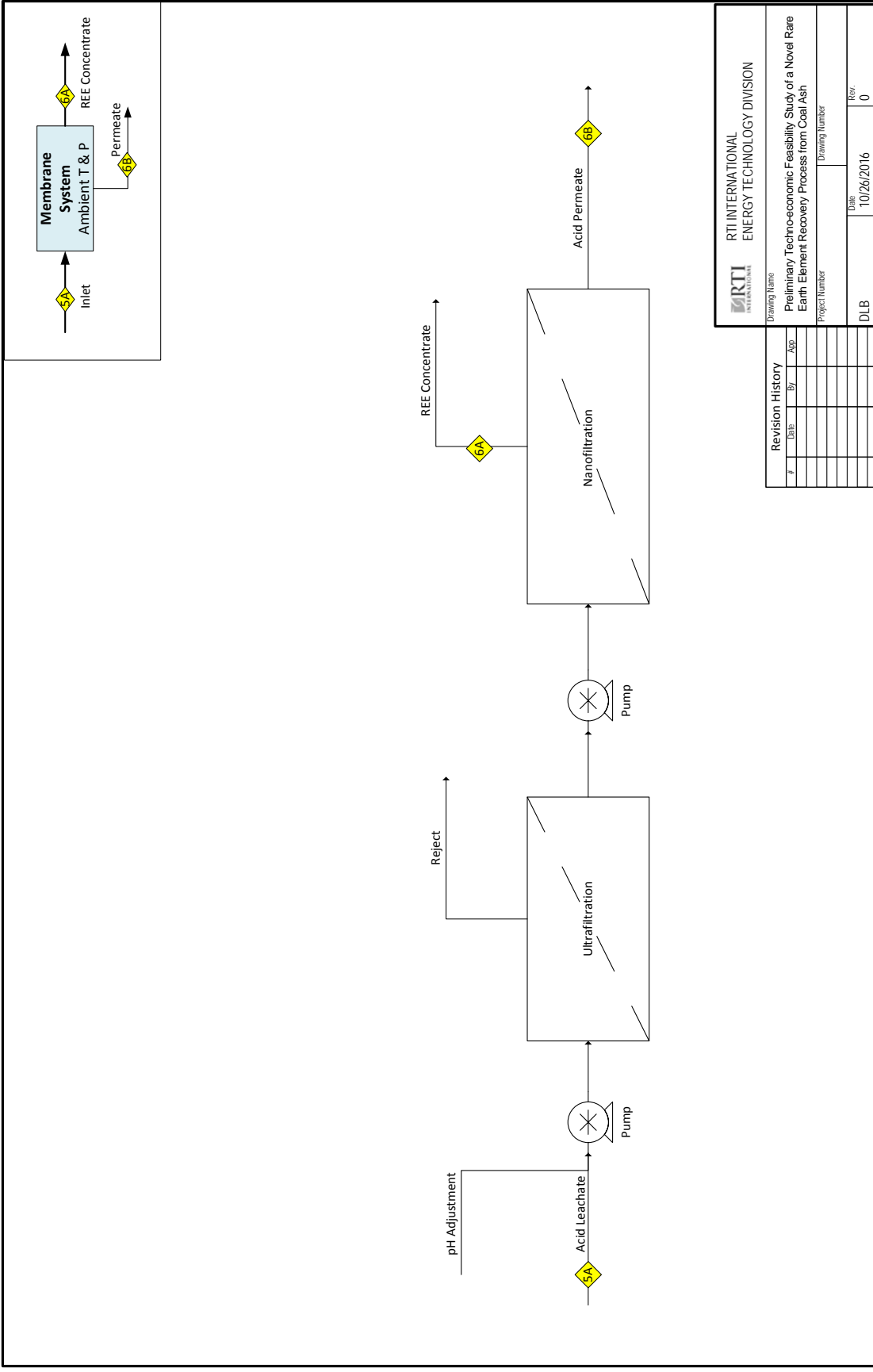
RTI INTERNATIONAL
 ENERGY TECHNOLOGY DIVISION

Drawing Name
 Preliminary Techno-economic Feasibility Study of a Novel Rare Earth Element Recovery Process from Coal Ash

Project Number
 Drawing Number

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Figure 3. PFD representation of alkaline roasting and acid leaching steps of the REE recovery process.



RTI INTERNATIONAL ENERGY TECHNOLOGY DIVISION	
Revision History	Drawing Name
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Preliminary Techno-economic Feasibility Study of a Novel Rare Earth Element Recovery Process from Coal Ash	
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Figure 4. PFD representation of nanofiltration (NF) concentration step of the REE recovery process.

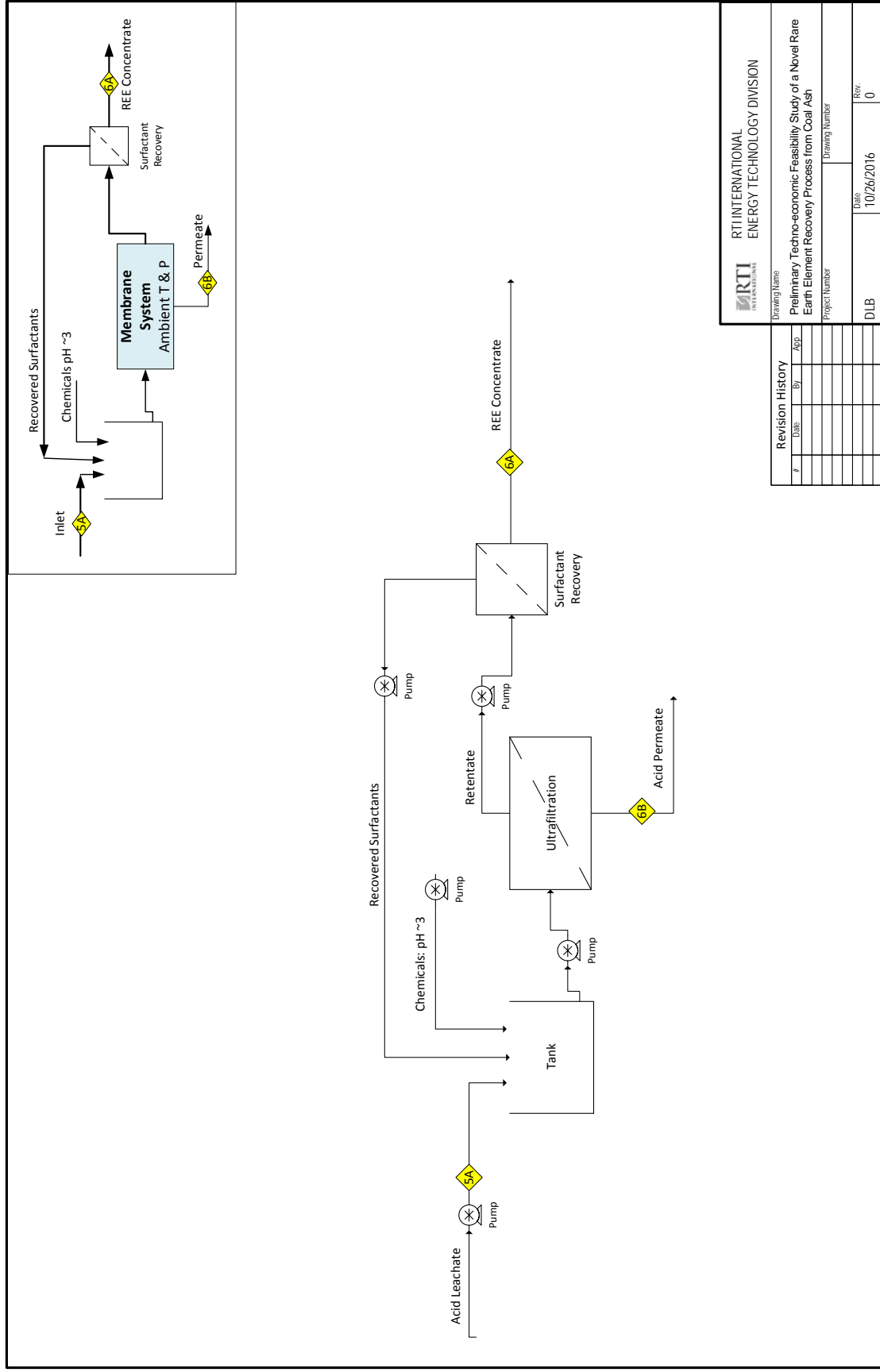
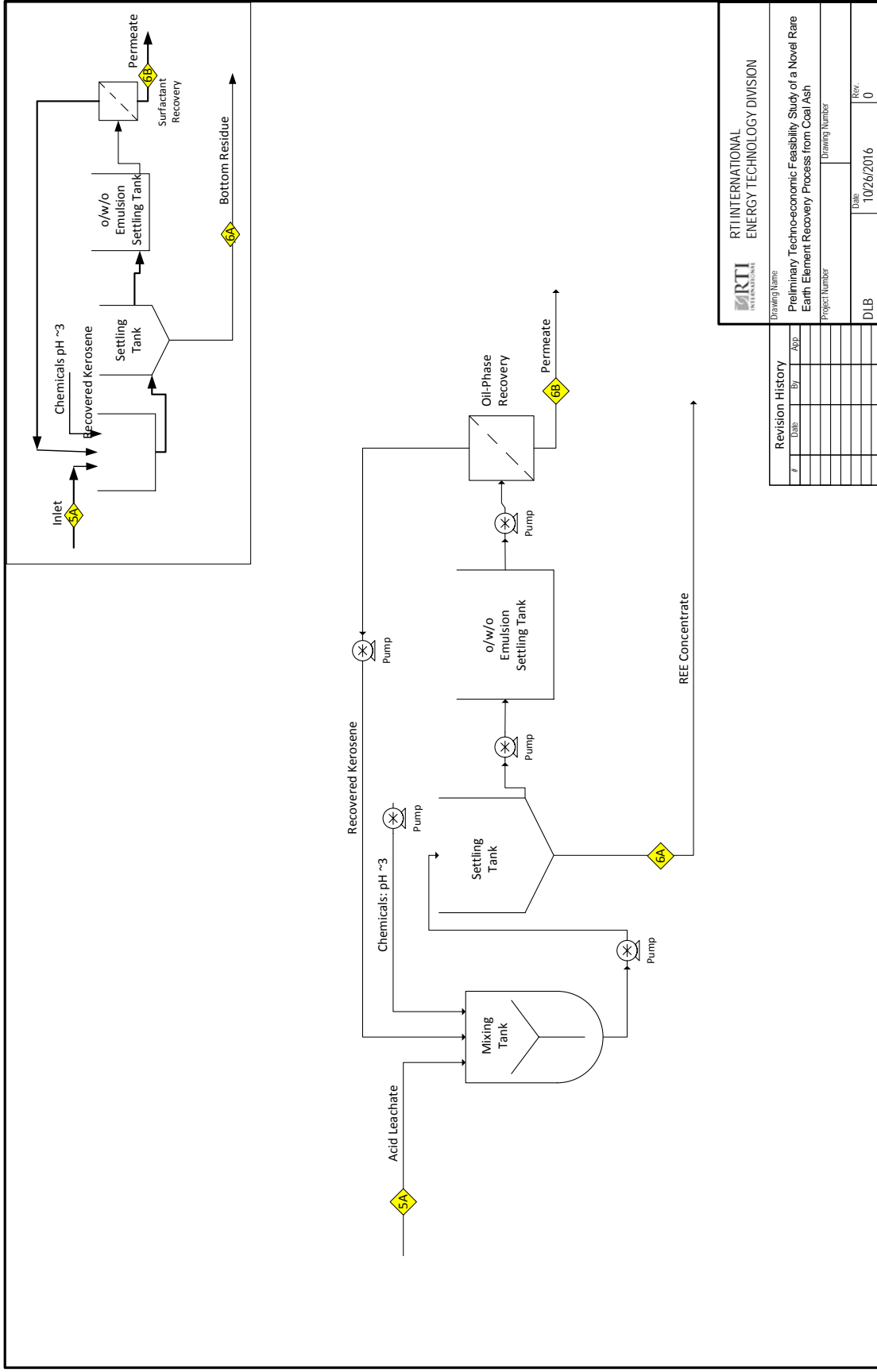


Figure 5. PFD representation of micelle enhanced ultrafiltration (UFM) concentration step of the REE recovery process.

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Drawing Name: Preliminary Techno-economic Feasibility Study of a Novel Rare Earth Element Recovery Process from Coal Ash	
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Figure 6. PFD representation of the liquid emulsion membrane concentration step of the REE recovery process.

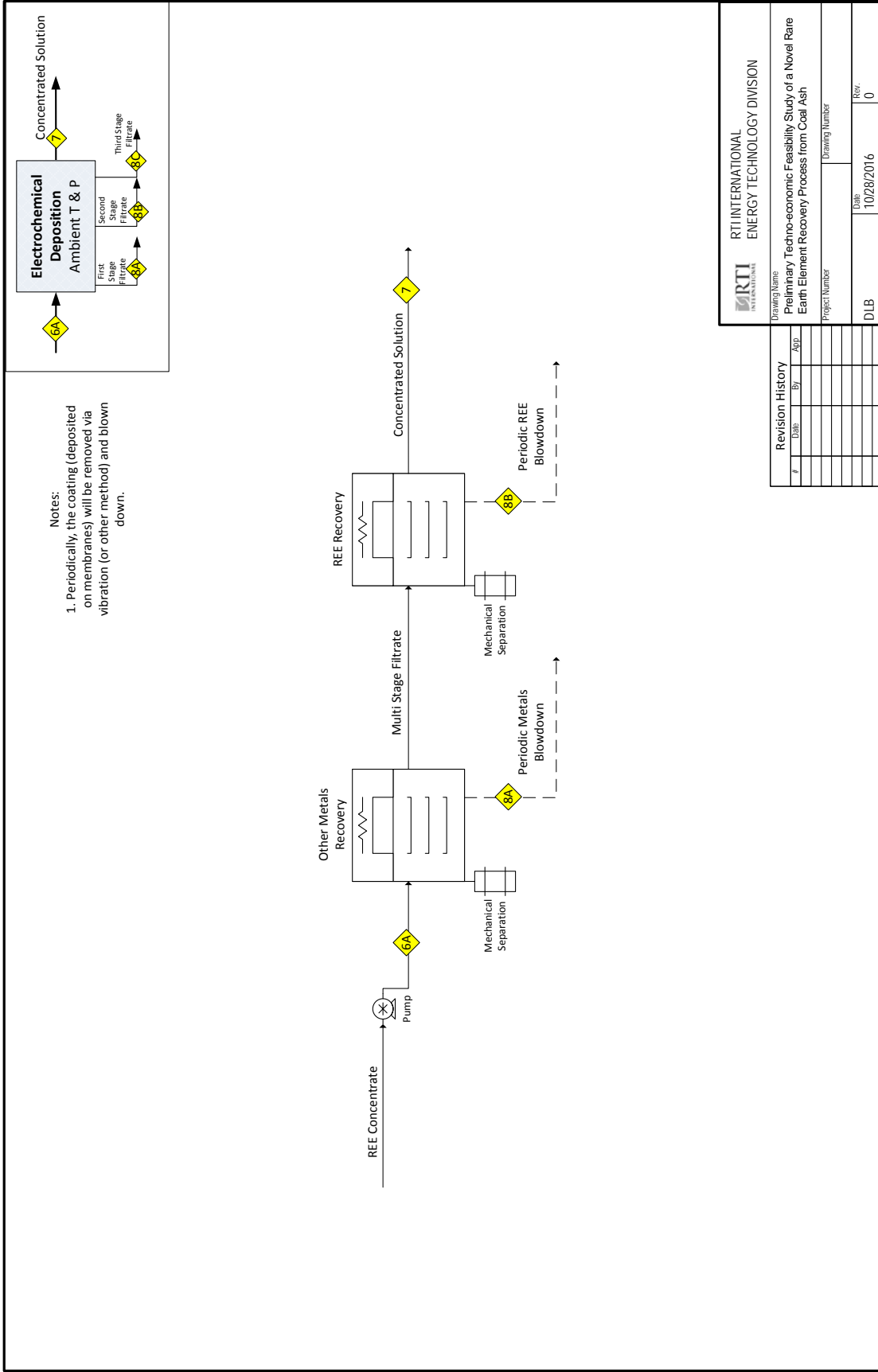


Figure 7. PFD representation of the membrane based electrodeposition REE recovery step.

Techno-Economic Analysis Results

The TE-spreadsheet allows for the rapid assessment and comparison of factors such as the CCR input source (App, IL, or PRB), unit process configuration and material feedstock (roasting agent types). In addition, the spreadsheet can be used to assess the individual performance and economic impact of each of the unit operations and identify areas of high cost/low performance that can be addressed with further R&D efforts. The TE-spreadsheet provides an analysis summary sheet for a given scenario run in the “Results Summary” tab. A discussion for selected scenarios of interest are used to highlight areas for process improvement and to highlight future R&D efforts.

Scenario 1: NF as REE Concentration Step

This scenario assumes the default recoveries for each unit operation and uses sodium carbonate as the roasting agent. **Table 3** shows the output for each of the three CCR sources using NF as the REE concentration step.

Table 3. TE output summary assuming NF concentration, and other divalent ions collected at 10% in the final electrodeposition step.

Ash type	Ore production [kg/yr]	%REE by wt.	Overall yield [%]	CAPEX [\$ /yr]	OPEX [\$ /yr]	Annual ore value ^a [\$ /yr]	REE ore value [\$ /ton]	Potential REE value ^b [\$ /yr]
App	55849	9.3%	81%	\$98,691	\$2,148,031	\$36,215	\$648	\$2,414,436
IL	34720	9.0%	81%	\$98,704	\$2,148,534	\$21,987	\$633	\$1,737,164
PRB	130260	2.2%	81%	\$85,931	\$474,709	\$20,245	\$155	\$1,483,790

^a Assuming \$7/kg mishemetal for 100% MREO

^b Assuming 2013 prices for individual REE elements

The results provide a number points for discussion and comparison. The spreadsheet is set to default REE recovery values of 100%, 95%, 95%, 95%, and 100% for the alkaline roasting, acid leaching, membrane concentration, electrodeposition, and mechanical recovery steps, respectively, so the overall yield does not vary by coal ash type.

Scenarios 2, 3, and 4: Selection of UFM, LEM, or Eliminating the Concentration Step:

The TE spreadsheet was run for each of the coal types and each of the options for REE concentration after acid leaching. The results summaries are presented in **Tables 4-6** below.

Table 4. TE output summary assuming UFM concentration, and other divalent ions collected at 10% in the final electrodeposition step.

^a Assuming \$7/kg mishemetal for 100% MREO

Ash type	Ore production [kg/yr]	%REE by wt.	Overall yield [%]	CAPEX [\$ /yr]	OPEX [\$ /yr]	Annual ore value ^a [\$ /yr]	REE ore value [\$ /ton]	Potential REE value ^b [\$ /yr]
App	16776	32.6%	86%	\$140,121	\$2,935,084	\$38,227	\$2279	\$2,548,571
IL	10349	32.0%	86%	\$139,983	\$2,934,474	\$23,208	\$2243	\$1,833,673
PRB	31360	9.7%	86%	\$90,205	\$981,187	\$21,369	\$681	\$1,566,222

^b Assuming 2013 prices for individual REE elements

Table 5. TE output summary assuming LEM concentration, and other divalent ions collected at 10% in the final electrodeposition step.

Ash type	Ore production [kg/yr]	%REE by wt.	Overall yield [%]	CAPEX [\$ /yr]	OPEX [\$ /yr]	Annual ore value ^a [\$ /yr]	REE ore value [\$ /ton]	Potential REE value ^b [\$ /yr]
App	16776	32.6%	86%	\$140,121	\$5,786,399	\$38,227	\$2282	\$2,548,571
IL	10349	32.0%	86%	\$139,983	\$5,782,617	\$23,208	\$2243	\$1,833,673
PRB	31360	9.7%	86%	\$90,205	\$2,627,604	\$21,369	\$681	\$1,566,222

^a Assuming \$7/kg mishemetal for 100% MREO

^b Assuming 2013 prices for individual REE elements

Table 6. TE output summary assuming no concentration step, and other divalent ions collected at 10% in the final electrodeposition step.

Ash Type	Ore production [kg/yr]	%REE by wt.	overall yield [%]	CAPEX [\$ /yr]	OPEX [\$ /yr]	Annual ore value ^a [\$ /yr]	REE ore value [\$ /ton]	Potential REE value ^b [\$ /yr]
App	62322	9.2%	90%	\$136,393	\$2,126,097	\$40,239	\$646	\$2,682,707
IL	38660	9.0%	90%	\$136,322	\$2,126,683	\$24,430	\$632	\$1,930,182
PRB	144747	2.2%	90%	\$94,434	\$462,426	\$22,494	\$155	\$1,648,655

^a Assuming \$7/kg mishemetal for 100% MREO

^b Assuming 2013 prices for individual REE elements

The results show that the order of process configurations from highest to lowest total costs are LEM > UFM > NF > no concentration step. The main cost driver for the LEM process is the consumption of organic solvent (such as kerosene), which results in an estimated operating cost of more than double any other process. Similarly, the consumption of the surfactant for the UFM process drives the operational costs for that process. For both of these processes, the loss rate was assumed to be 10%, and we note that the likelihood for cost variation will remain high until rigorous experimental testing is used to determine loss rates with greater confidence. Figure 8 shows the calculated impact of assuming different loss rates for the chemicals used in the LEM and UFM processes. It is clear that key factor in choosing between different prospective surfactant and oil phase options will be loss per cycle. The impact of The NF and no concentration step scenarios provide roughly equivalent cost values, since although eliminating the NF concentration step decreases the operational costs associated with the NF system, there is corresponding increase in the cost of the electrodeposition step due to the requirement for more membrane area from the increased feed volume fed to the final REE recovery system. The tradeoff in costs being roughly equivalent, any value provide by NF concentration will be in its performance in separating REE from non-REE.

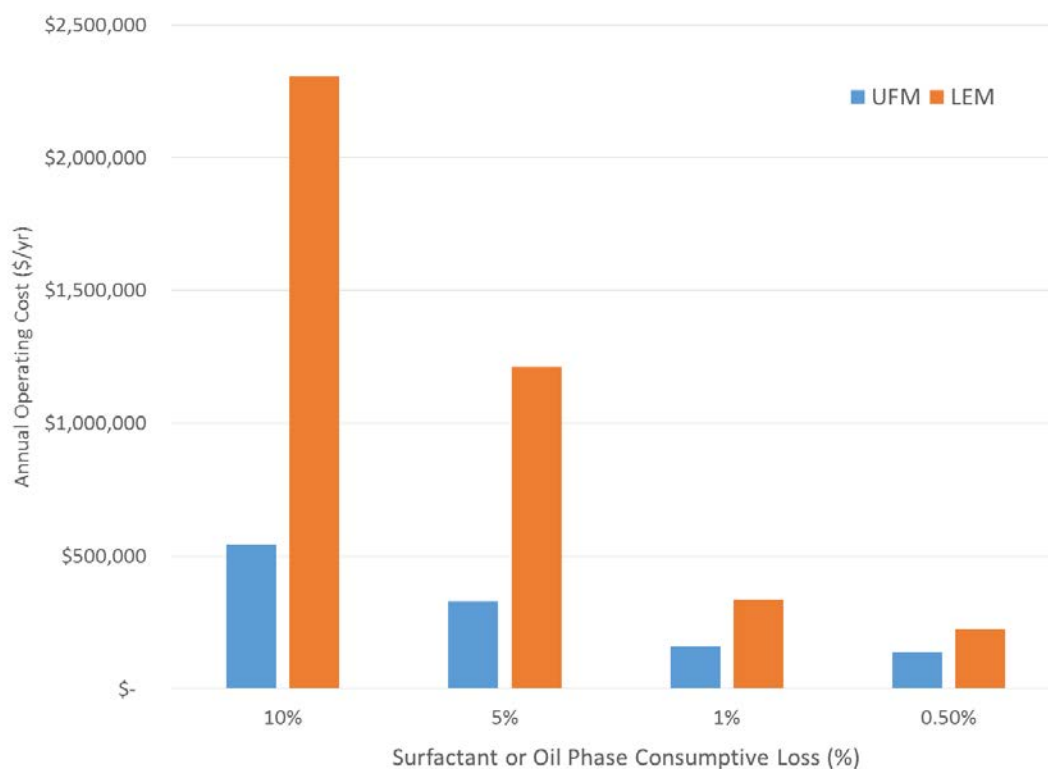


Figure 8. Projected annual operating costs for the UFM and LEM processes assuming different values of either surfactant or oil phase consumptive losses. App CCR scenario used for data generation.

Impact of Coal Source

The most obvious result is that the App and IL CCRs have operating costs >450% that of the PRB CCR. This is because experimental results showed that PRB CCRs do not require alkaline roasting for complete release of mineral content, they require only the acid dissolution step. (Ross et al 2016). The other CCRs are roasted first and the consumption of the alkaline roasting agent is dominant operational cost factor (see **Figure 9**)

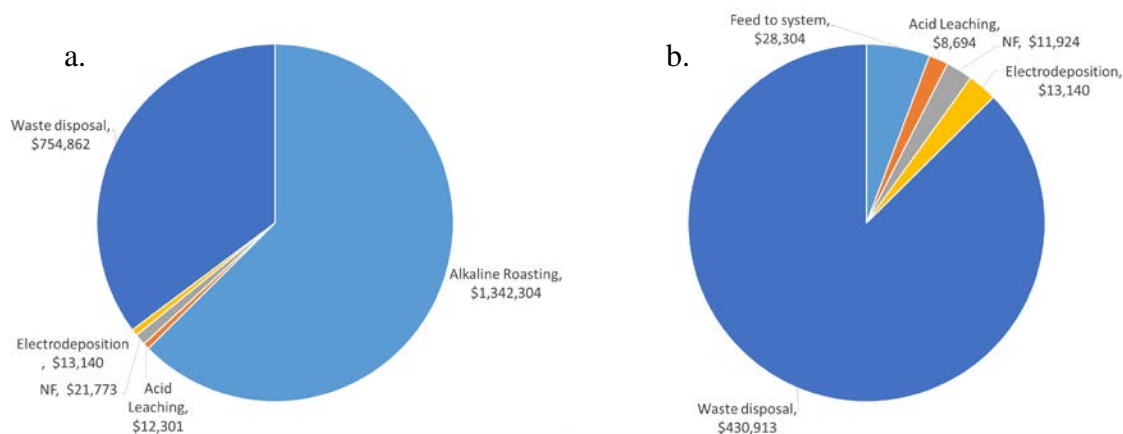


Figure 9. Operational annual cost breakdown for (a) Appalachian CCR and (b) Powder River Basin CCR. The alkaline roasting step consumes more than \$1.3M worth of sodium carbonate on an annual basis.

This operational cost is based on a 1:1 mass ratio of roasting agent (Na_2O_2 , NaOH , CaO , Na_2CO_3) to dry ash. CaO was determined to be the lowest cost roasting agent (\$0.15/kg), and this low cost was more than enough to offset the increased heating costs 900°C for CaO vs 450°C . However, in all cases that incorporate alkaline roasting the cost is prohibitive using a 1:1 ratio. This highlights a need to experimentally determine the minimum possible roasting agent to CCR ratio and/or explore methods for REE release that do not require roasting. The impact of coal source is also evident in the final wt% concentration for each of the recovered MREO ores. Here the PRB ash generates a final product that is significantly lower than in REE concentration than either APP or IL. This final concentration is a product of the initial species distribution of the ash. The characteristic PRB ash used as input to the TE spreadsheet has a calcium concentration of 142,710 mg/kg, whereas the App and IL ashes have Ca concentrations of 18,604 mg/kg and 36,186 mg/kg, respectively. In the electrodeposition step, the assumption of 10% recovery for other divalent ions in stage 2 was used and this determines the final make up of which impurities are present in the final product ore. If experimental results show that the electrodeposition recovers no Ca, the final REE purity concentration would increase significantly for all coal types.

Figure 8b also shows that the second highest operational cost is waste disposal. The spreadsheet currently assumes a disposal cost of \$0.59/kg cost for non-hazardous liquid waste disposal. This is based on the conservative assessment that zero recovery is possible from each of the waste streams of the unit processes. In practice, reuse of the acidified wastewater followed by onsite dewatering could significantly reduce or

eliminate the costs of waste disposal, which would also lessen operational costs by reducing acid consumption.

Economic Viability

Reduction in waste disposal via reuse and onsite treatment that reduces the disposal costs and consideration of additional valuable materials easily demonstrate the potential for reasonable economic recoveries. For example, assuming a reduction in disposal costs of 95% of current conservative estimations and that 90% aluminum present in the input ash would make the PRB CCR return a profit of \$81,500/yr. Greater economic value is also possible by further processing the REE to individual elements, which may be possible by the electrodeposition approach and/or modified solvent recovery approaches. Additional value can be recovered not only through complete separation of all REE species, but also by targeting one or two high value components. In the case of the CCRs evaluated, the recoverable scandium oxide content accounts for approximately 90% of the total recoverable value of the REEs present in the CCR.

Table 7 shows a summary of potential revenue for a range of final target materials for sale from a prospective CCR recovery operation. It is clear that since Sc would make a primary target for extraction, given its occurrence at high concentrations in all type of CCR evaluated as well as its high value (\$3100-\$5500/kg from 2011 to 2016).

Table 7. Comparison summary of potential extractable value for different target materials for recovery. TE assumptions: divalent ions collected at 10% in the final electrodeposition step, no concentration step, 90% overall recovery for all valuable materials.

Target Material for Recovery	Recoverable value - App CCR [\$/yr]	Recoverable value - IL CCR [\$/yr]	Recoverable value - PRB CCR [\$/yr]
MREO only	\$40,219	\$24,430	\$27,494
MREO + Al	\$262,956	\$257,711	\$253,291
Sc ₂ O ₃ + Al only	\$2,176,372	\$1,673,688	\$1,451,997
Individual REEs + Al	\$2,905,423	\$2,163,464	\$1,879,452

Costing the capital and operating costs required to recovery aluminum and individual elements is beyond the scope of this assessment. However, the wastewater disposal costs are reduced by 95% and that ore roasting is feasible with a 1:10 ratio of agent to ash, the average minimum required value that must be recovered across all three CCR types is ~\$262,000/yr. This places MREO + Al as target recovery materials that are in the range of economic feasibility, and recovery scenarios that target Sc only or Sc + other individual REEs very likely economically viable. The results point to the need to utilize strategies that target multiple recoverable materials to ensure economic viability and buffer against market price swings.

Conclusions and Technology Outlook

In this effort, the goal was to determine the feasibility of recovering ore at minimum 2% MREO composition using a range of metallurgic concentration, separation and recovery processes. The potential for economic viability with MREO as the only product was determined to be highly unlikely based on the expected capital and operating costs of several evaluated range of conditions. This is not due to the technology options considered, since based on the low prices for MREO (~\$50,000/yr value of MREO for a feed rate of 1000 kg/hr), it is highly unlikely that any process outside of those under consideration by the team would achieve sustainable economic feasibility. The assessment did show that aluminum is a potential secondary by product, and that at more than 80% of the total recoverable REE value could be recovered by targeting scandium alone. In addition, this analysis highlighted areas for cost reduction for each of the process technologies under consideration. Based on the results from the TE analysis, the following recommendations are presented to inform our continuing work:

1. **Assess technologies and separation methods to individually recover REE elements.** Continuing efforts should be made to evaluate the potential of the electrodeposition process to separate individual REE elements and conduct a technology review to determine the feasibility of co-locating existing REE separation methods. Due to the likely low value of MREO ore independent of the final concentration, any successful REE recovery approach will very likely need to produce a high quality salable product consisting of >99% pure separated REE or REO. This approach is also common in China, which further supports the need for a complete REE product recovery to ensure economic viability.
2. **Investigate the approaches to reduce the highest cost driver and/or maximize overall value to the final separation scheme for each of the unit processes:**
 - Alkaline roasting – minimize the roasting agent to ash ratio
 - Acid leaching – minimize acid to CCR ratio
 - NF – multivalent and monovalent separation factors
 - UFM – minimize surfactant consumption, evaluate alternatives for cost
 - LEM – minimize solvent consumption, evaluate alternative for cost
 - Electrodeposition – (1) evaluate the final recovery of REE relative to non-REE constituents for complex mixtures, (2) assess the potential for individual REE separation, and (3) experimentally determine the minimum required REE feed concentration for recovery.
3. **Evaluate the LEM and UFM processes as potential options for final stage REE recovery in addition to assessment as concentration steps.** Both the LEM and UFM processes have potential for high REE recovery and could serve as a terminal collection step for MREE or individual element recovery. Screening and further experimental evaluation of a range of solvent/surfactant consumables with final costs as part of the selection criteria should also be incorporated in continuing efforts.
4. **Characterize the residual material from each of the lab-scale experiments.** The TE analysis highlighted the potential high costs of waste disposal for the assumed offsite transport and disposal option. This is an area of the process

where operational costs can be greatly reduced by incorporating high levels of reuse and/or onsite treatment to ensure volume reduction. In addition, the presence of radioactive elements such as thorium in the feed coal ash was not extracted to the same efficiency as the REEs. This suggests that thorium might be separating into various waste streams in the process and become diluted rather than concentrated. However as the process is refined, the concentration of potential hazardous components will require monitoring to ensure this remains to be the case.

5. **Perform a review of potential Al and Sc recovery technologies that could be incorporated as part of the overall process scheme.** Aluminum and Sc was shown to be present in high concentrations in CCR samples from all regions evaluated. Efficient recovery of Al/Sc has the potential to increase the overall feasibility of the MREO process.

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