AOI 1: Recovery of Rare Earth Elements (REEs) from Coal Mine Drainage

NATIONAL ENERGY TECHNOLOGY LABORATORY

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NETL REE Review
Pittsburgh PA
9apr19
1130h

Project Objectives

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1. **Primary objective:** demonstrate the technical and economic feasibility of extracting a 2% purity total rare earth element (TREE) product from AMD precipitates.

2. **Secondary objective** Identify process improvements and develop a final design for a commercial scale operation.

3. **Sub objectives**:

   A. Develop a testing plan and a chemical hygiene plan for mini-pilot plant operation in the WVU High Bay research facility.

   B. Design, construct and operate the REE recovery system while optimizing system design parameters

   C. Assess capital and operating costs based on the following criteria:

      a. System REE Recovery

      b. Concentrate Purity

      c. Reagent Recycle rates and losses

      d. Overall consumable costs

   D. Prepare a techno-economic analysis (TEA) based on the above criteria

   E. Prepare a Technology Development and Commercialization Assessment based on the results of the Phase 2 testing and TEA.

USDOE/NETL Program Goals

To quickly develop bench-scale and pilot-scale projects for recovering REEs from coal and coal byproducts as follows:

Area of Interest (AOI) 1 - Bench-scale Technology to Economically Separate, Extract, and Concentrate Mixed REEs from Coal and Coal Byproducts including Aqueous Effluents.

Our USDOE/NETL REE Projects

FOA 1202: Feedstock TREE > 300 mg/kg

- Concentrate TREE > 2%
- Small scale demonstration

SOL 9067: Prove significant supply to the domestic REE market

- Characterize and quantify the reserve base

FOA 1718: At Source TREE recovery from AMD

- Concentrate TREE> 90%

Acid Mine Drainage: AMD

1. H_2SO_4 leaches REE from shale
2. REE precipitate with $Fe(OH)_3$

Pyrite + O_2 + H_2O

= Fe^{2+} + H_2SO_4

Fe^{2+} + O_2 + OH^-

= $Fe(OH)_3$

Typical AMD treatment facility

AMD from refuse pile in background

Sludge production and drying

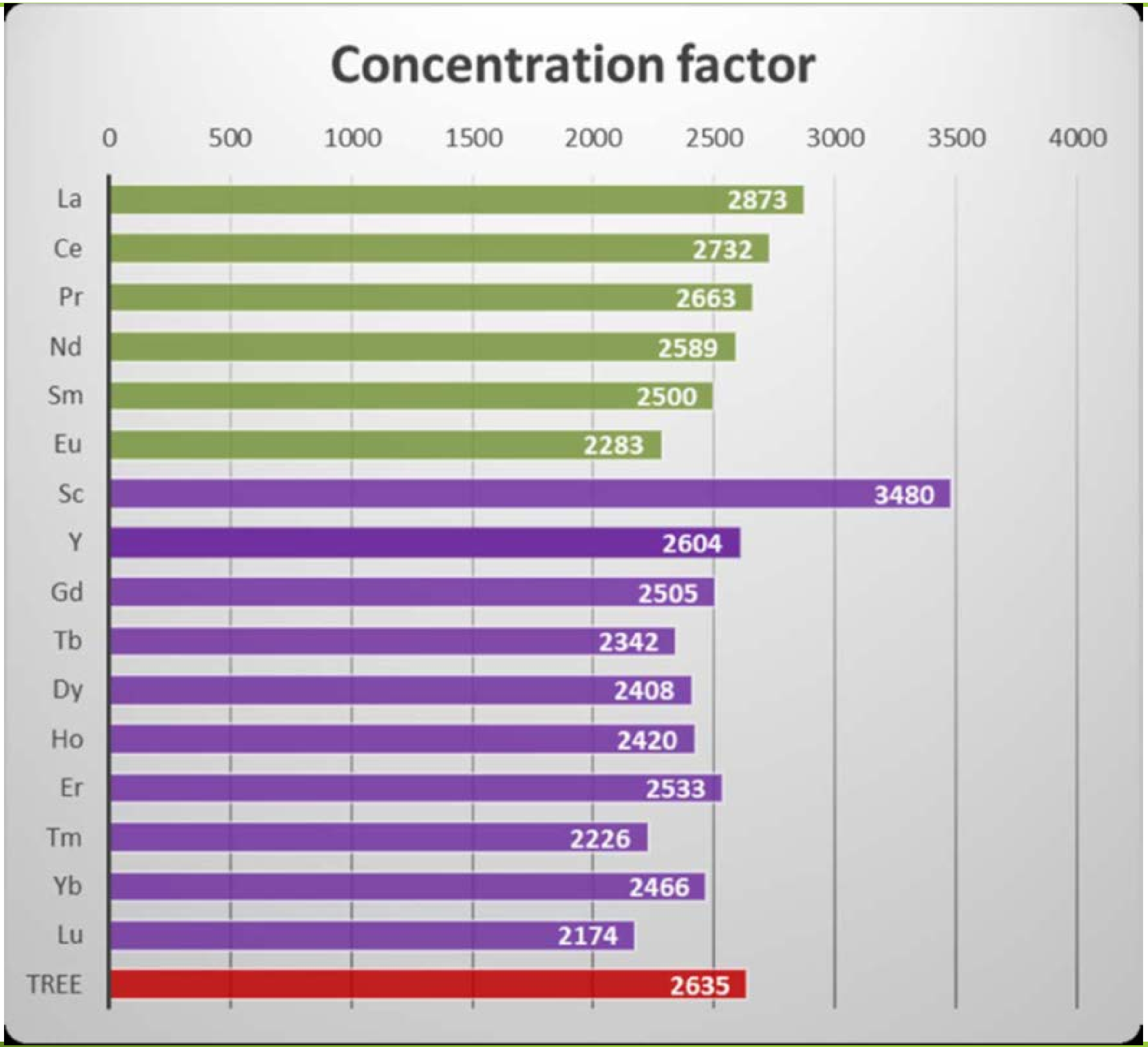
Contained value=market value of REEs excluding transport and processing

Passive AMD sludge dewatering

Omega AMD plant, WVDEP

Geotube cell

AMD treatment concentrates AMD by 2600x



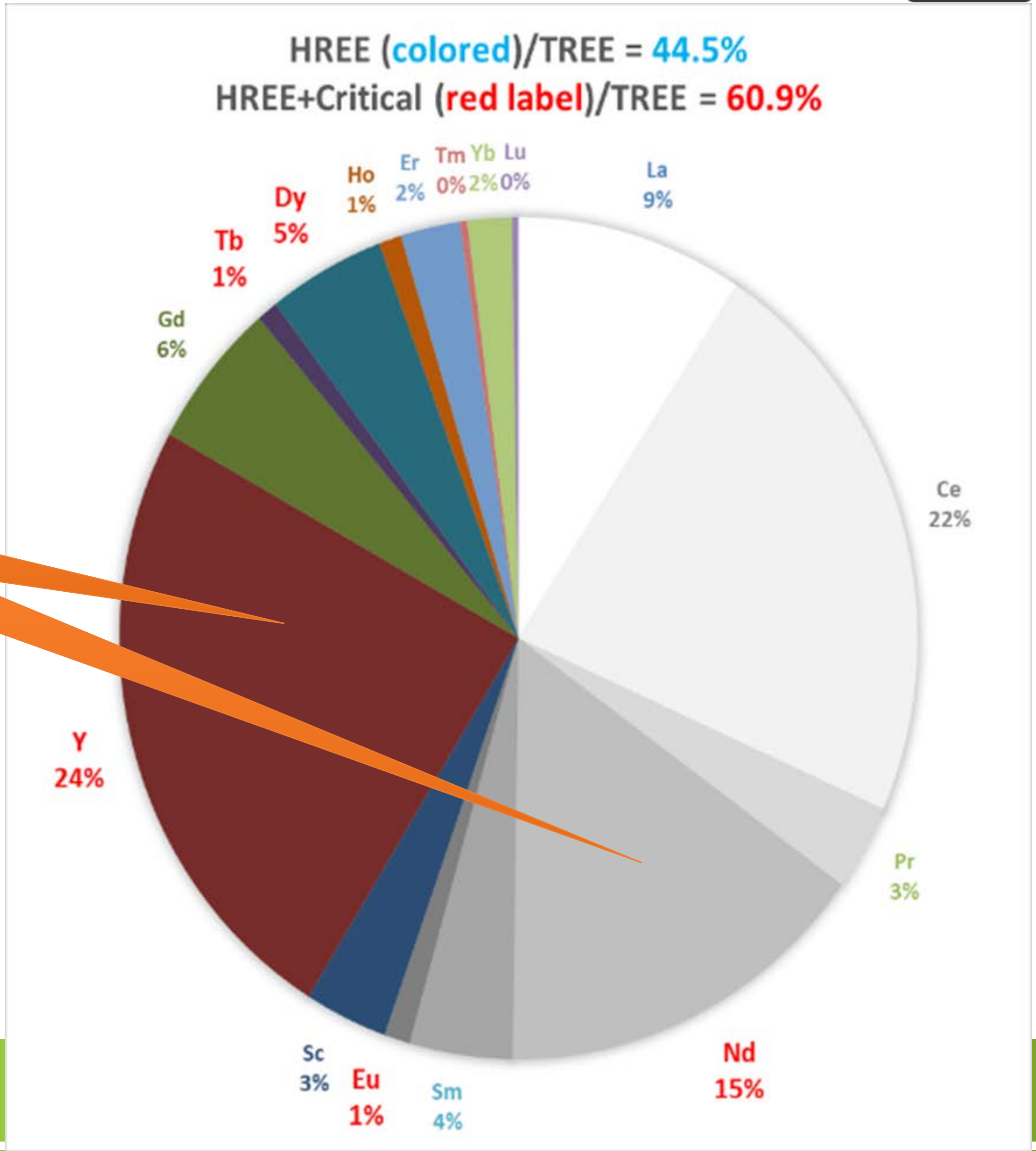
- Typical AMD:
  400 µg/L
- Typical Sludge:
  700 g/t

Results of field sampling

n = 155

Heavy and Critical REEs
in Acid Mine Drainage

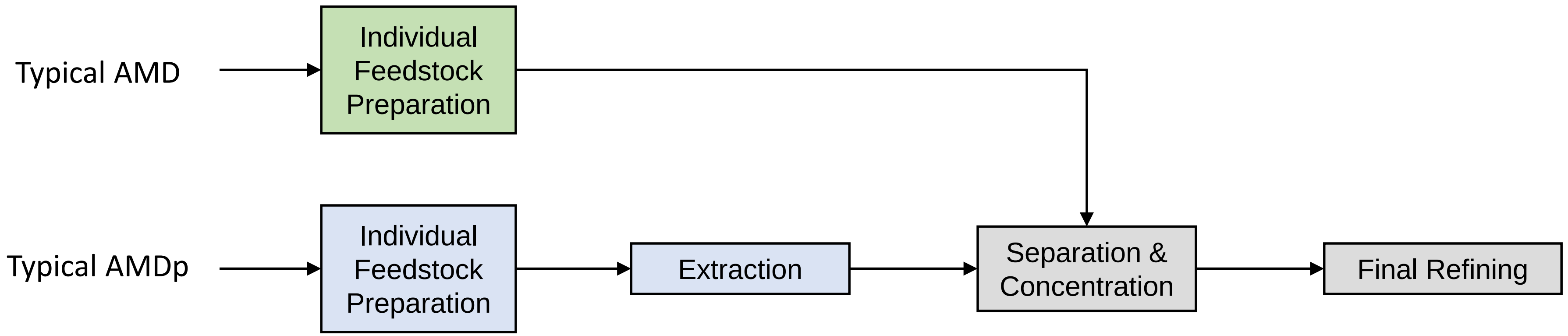
High Y, Nd, both
used in Nd:
YAG lasers



Cobalt is present in all samples.
TREE x 0.75 = Co

General Approach

- To date, our process design has followed two independent tracks:
  - Treatment of AMD Sludge (this project)
  - Treatment of Raw AMD (tomorrow's presentation)
- Each requires a unique pre-treatment, strategy but they eventually coalesce around a central processing train



Process Highlights

- Extraction of REEs from AMD sludge is much easier than extraction from hard rock type deposits. It's pre-digested

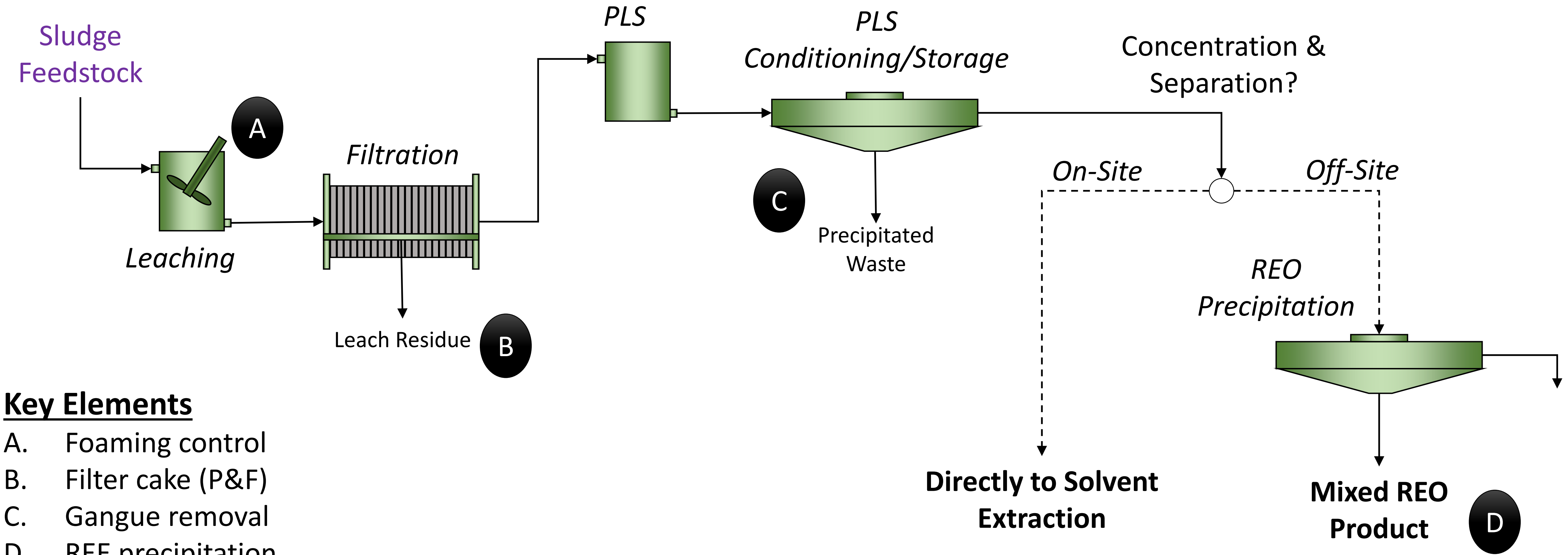
- A process pathway has been tested and proven at the laboratory scale.

- This process is currently being developed in a continuous bench unit. Initial runs with this process have successfully generates high grade products.

- Ongoing efforts are identifying process parameters that influence performance and refining process cost estimates.

Acid Leaching

PLS Preparation



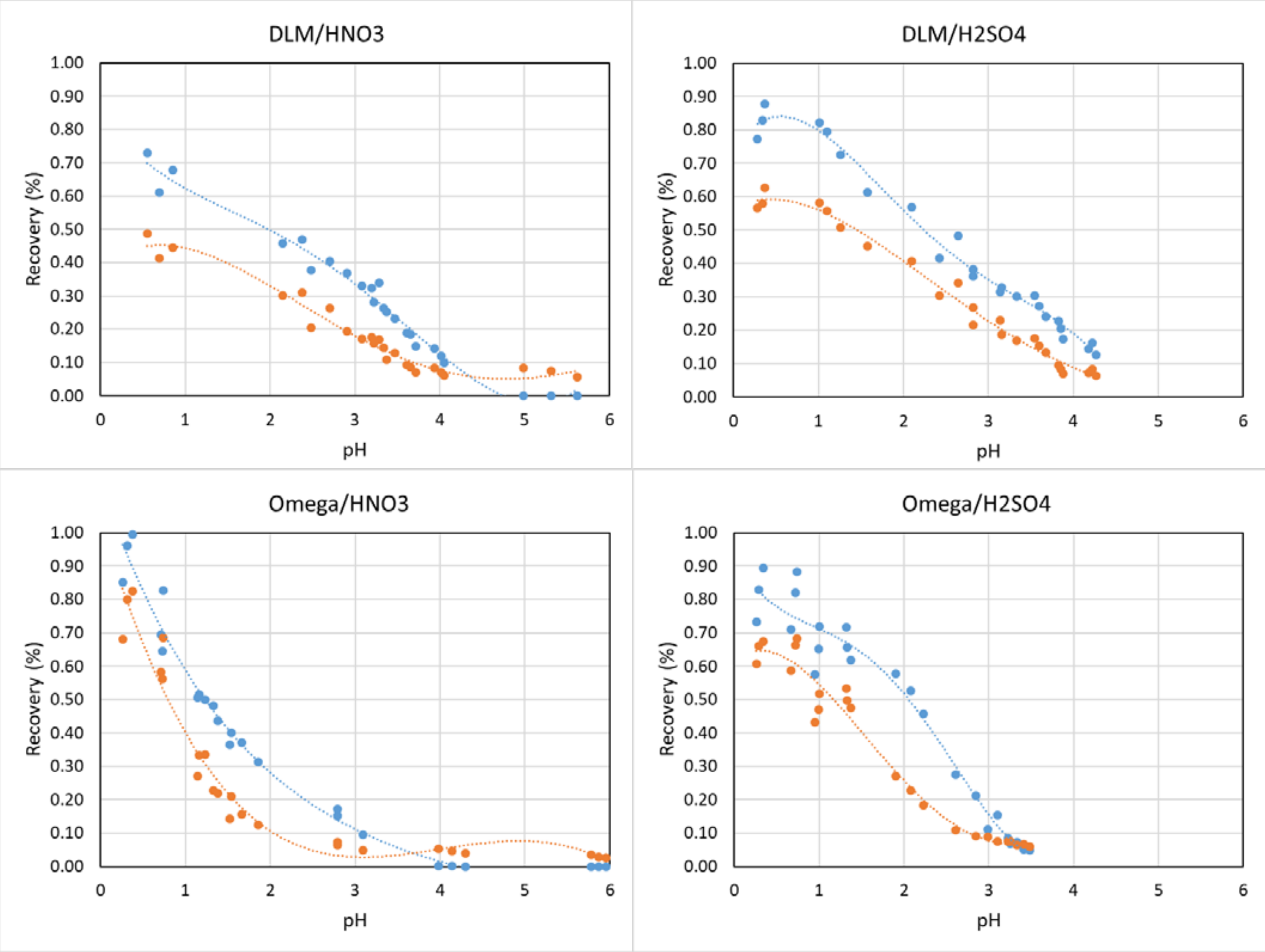
Key Elements

A. Foaming control
B. Filter cake (P&F)
C. Gangue removal
D. REE precipitation

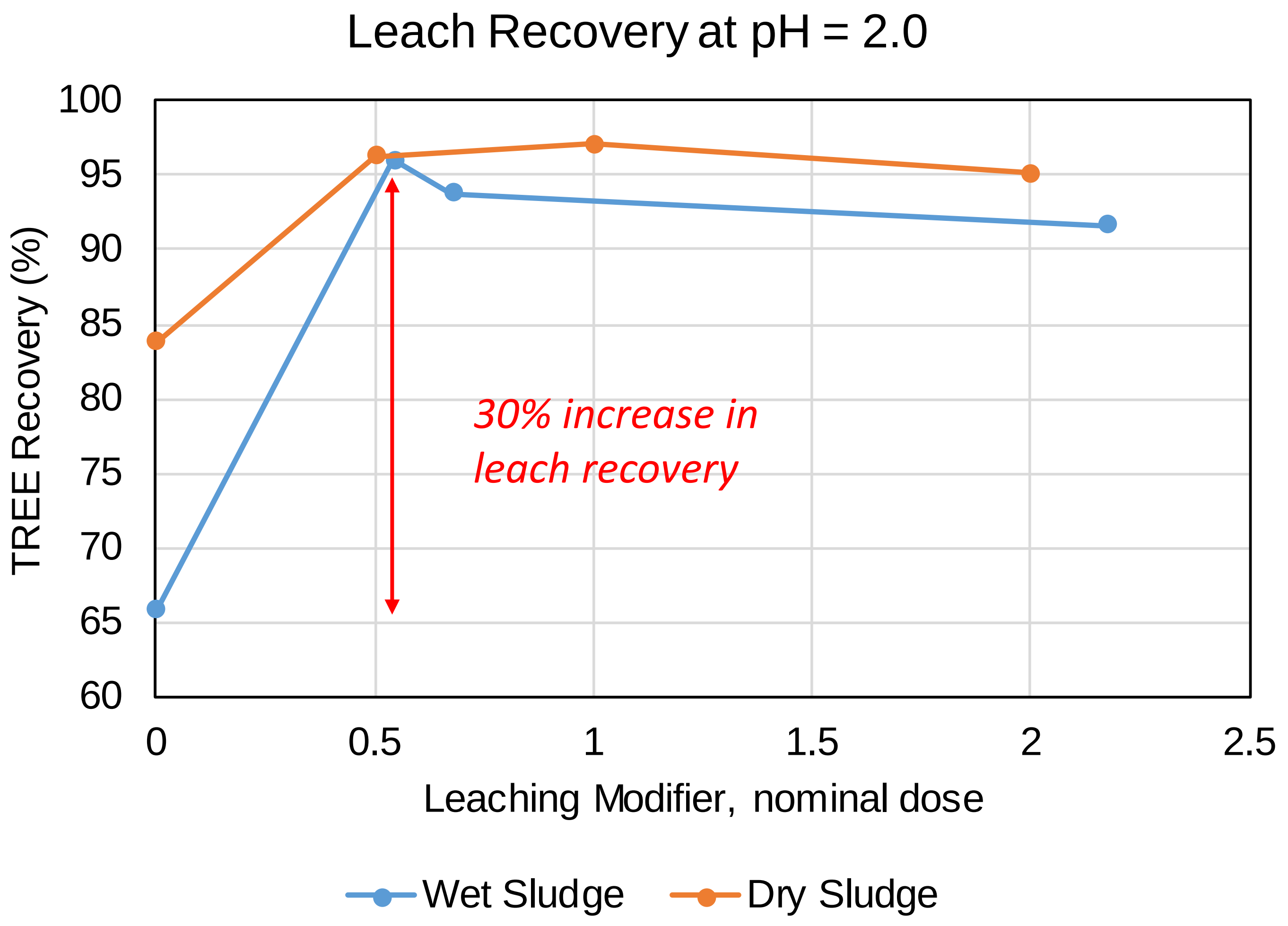
Parametric Sludge Leaching Tests

- Initial leaching survey.
- Two different samples, two different acid types.
- Ambient temperature and pressure.
- Conditions show high leach recoveries are possible >80-90%.

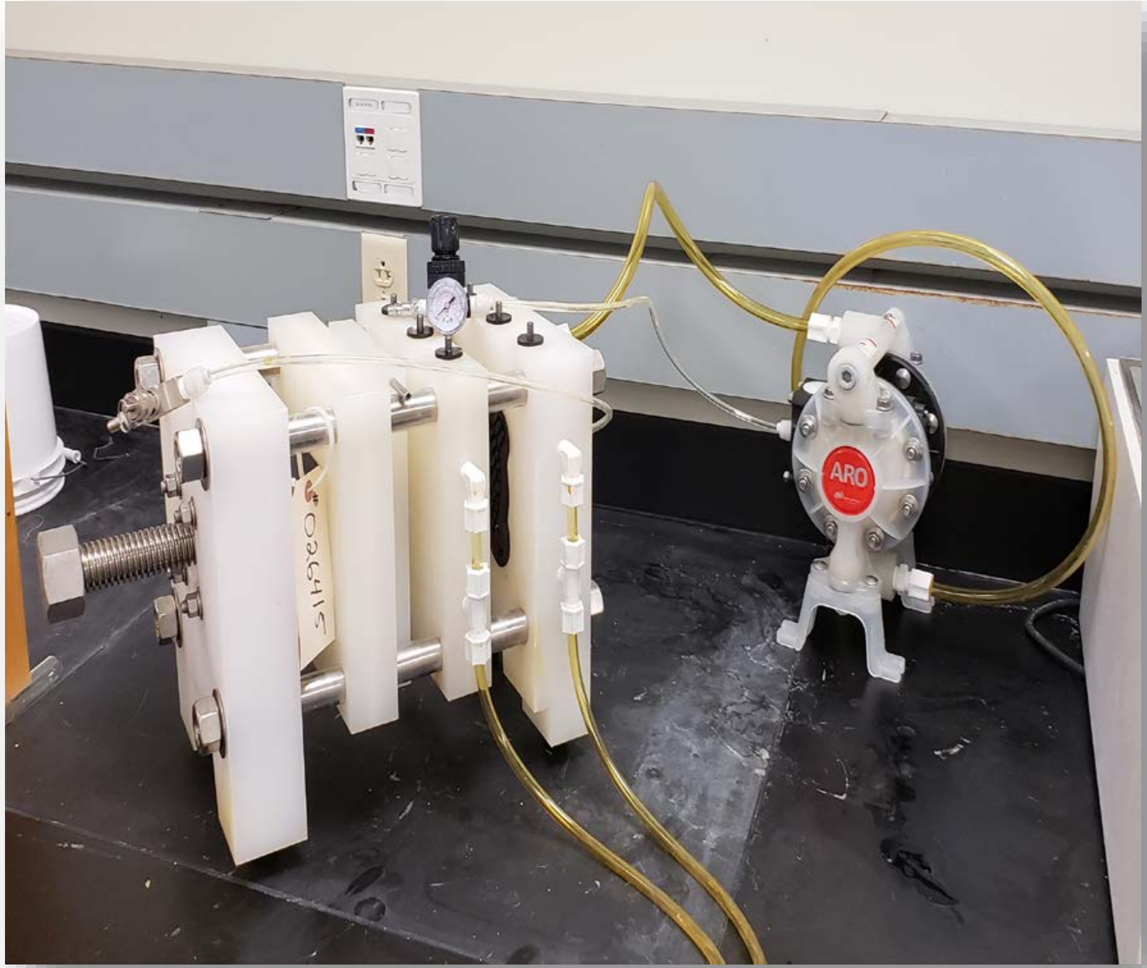
REE / Major ions



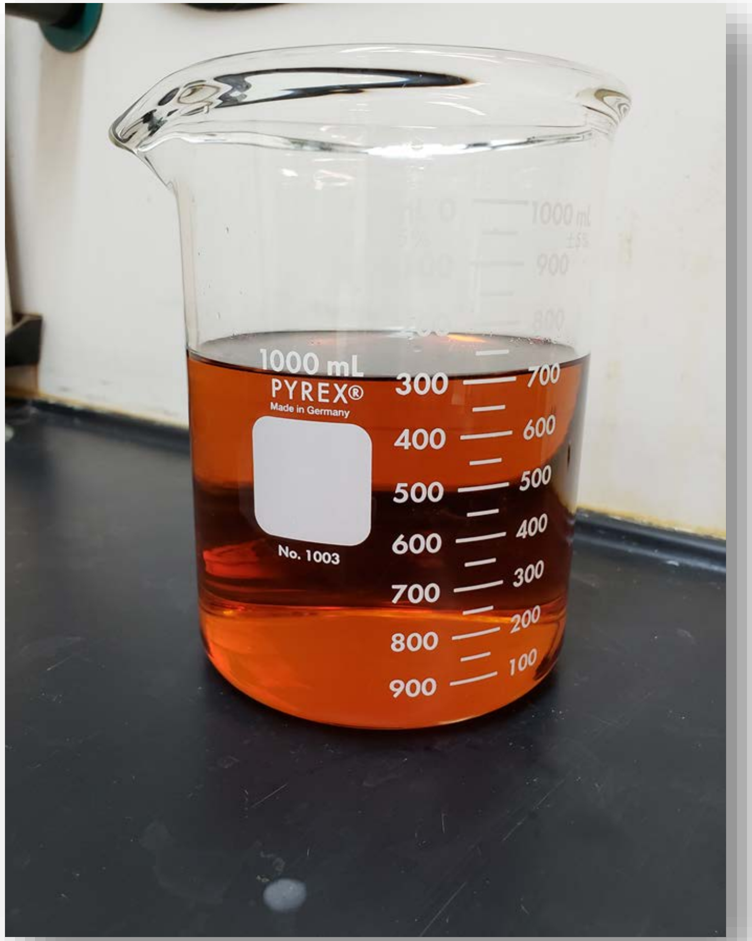
REE Recovery from AMD Sludge



Leach Residue Filtration

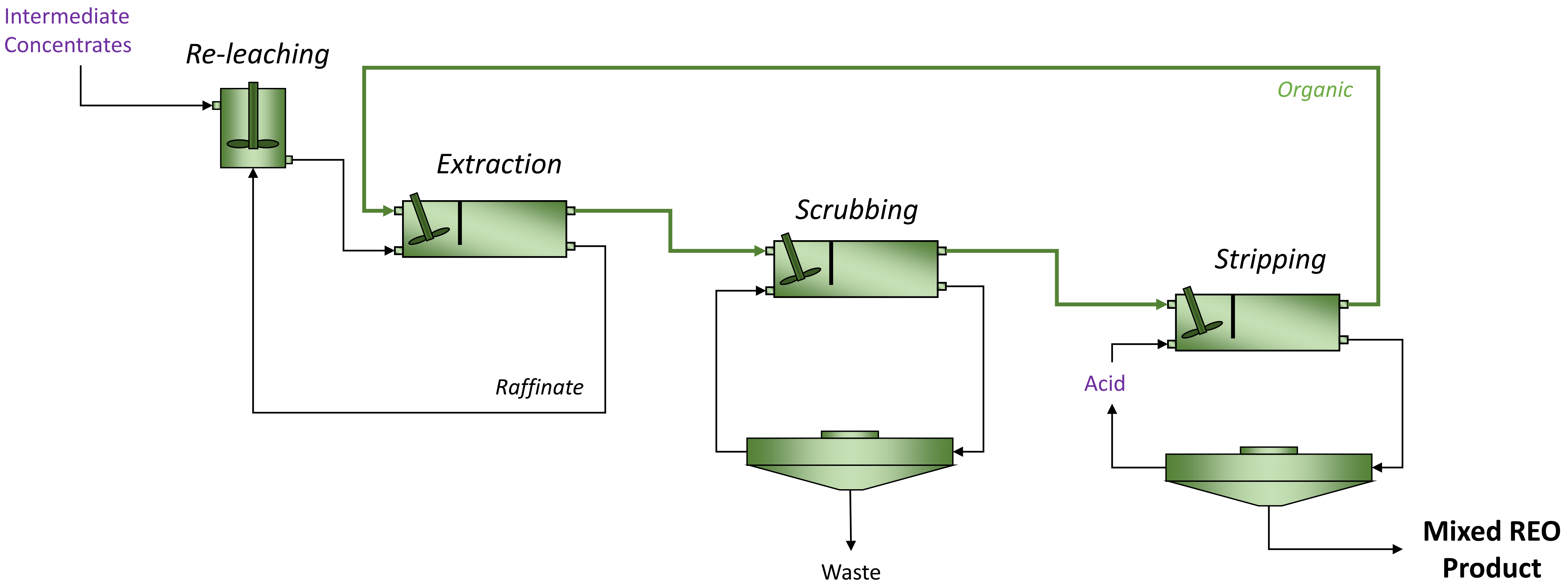


Leach Residue Filtration



Solvent Extraction

Concentration and Separation



Solvent Extraction

Bench-Scale, Continuous Flow Plant

100 mixer/settlers

Rockwell's Support

Recovery of REOs from Simulated Solutions

ID	Leachate (mg, in 100 mL)	REO (mg, in 0.5 g)	**Recovery (%)**	**Selectivity** (REE/Fe)
Y	62.4	58.6	94.0	183
Sc	2.4	2.2	88.8	173
Nd	339.2	350.3	103.3	202
Dy	144.6	148.5	102.7	201
Fe	302.4	1.5	0.5	
Mg	58.5	0	0.0	

- Precipitation of REEs from artificial strip solutions is very efficient and selective.
- High selectivity over Fe and Mg

Concentrates from two sites

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DLM

total oxides	889,519.2	89.0%
unaccounted	110,480.8	11.0%

LREE	186,118.4	23.2%
HREE	615,661.7	76.8%

TREO	801,780	80.2%
TMM	87,739	8.8%
TAc	0.09	0.000009%
Total oxides	889,519	89.0%

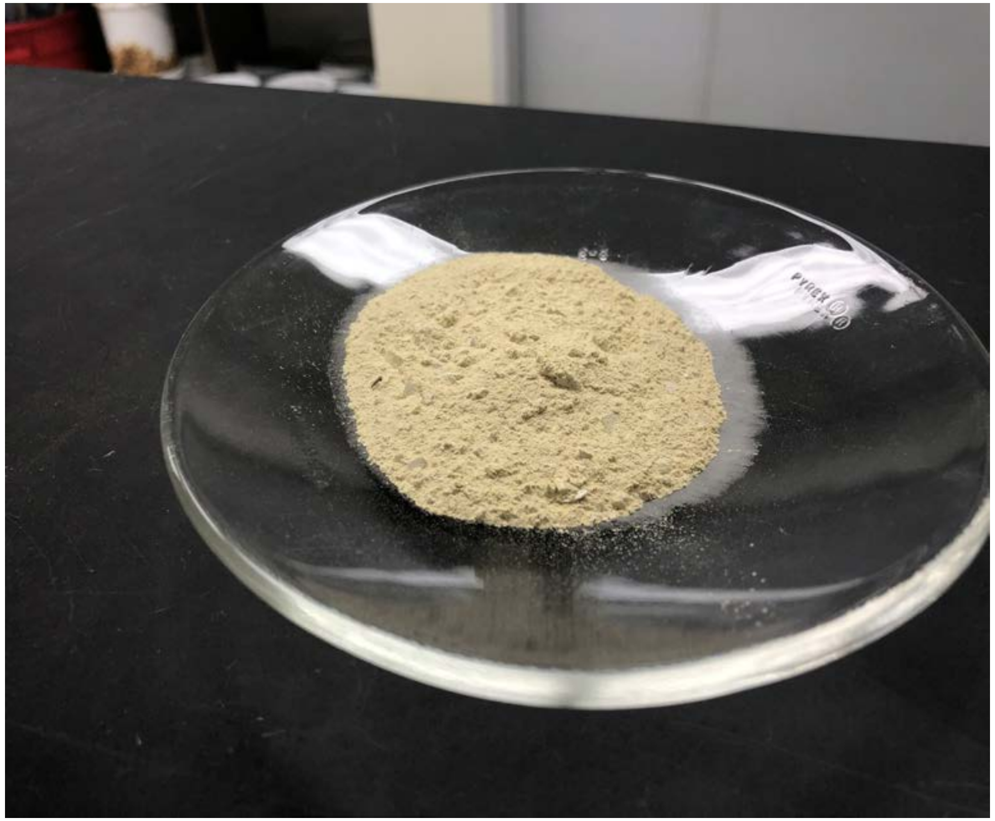
OM

total oxides	665,728.7	66.6%
unaccounted	334,271.3	33.4%

LREE	121,501.3	25.9%
HREE	346,714.0	74.1%

TREO	468,215	46.8%
TMM	197,513	19.8%
TAc	0.30	0.0000%
Total oxides	665,729	66.6%

Purified Product: AL/SX 80% TREO



OUTPUT: w/oxides			
Rare Earth Concentrate sample 283, 25 jan 19			
	mg/kg		mg/kg
Sc	740.5	Al	17,596.3
Y	423,961.4	Ca	670.8
La	5,578.8	Co	34.5
Ce	108,052.4	Fe	59,229.9
Pr	8,218.8	Mg	104.4
Nd	39,093.4	Mn	294.2
Sm	19,149.2	Na	6,242.7
Eu	6,025.8	Si	2,785.2
Gd	37,269.4	SO4	88.1
Tb	10,983.6	Cl	692.9
Dy	73,637.8	TMM	87,739.0
Ho	14,861.2		8.8%
Er	38,392.2	%Tot ions	9.9%
Tm	3,786.3		
Yb	11,007.3	Th	0.091
Lu	1,021.9	U	0.000
TREO	801,780.1	Th+U	0.0913289
	80.2%		0.0%
%Tot ions	90.1%	%Tot ions	0.00001%

Recent results

DLM sludge

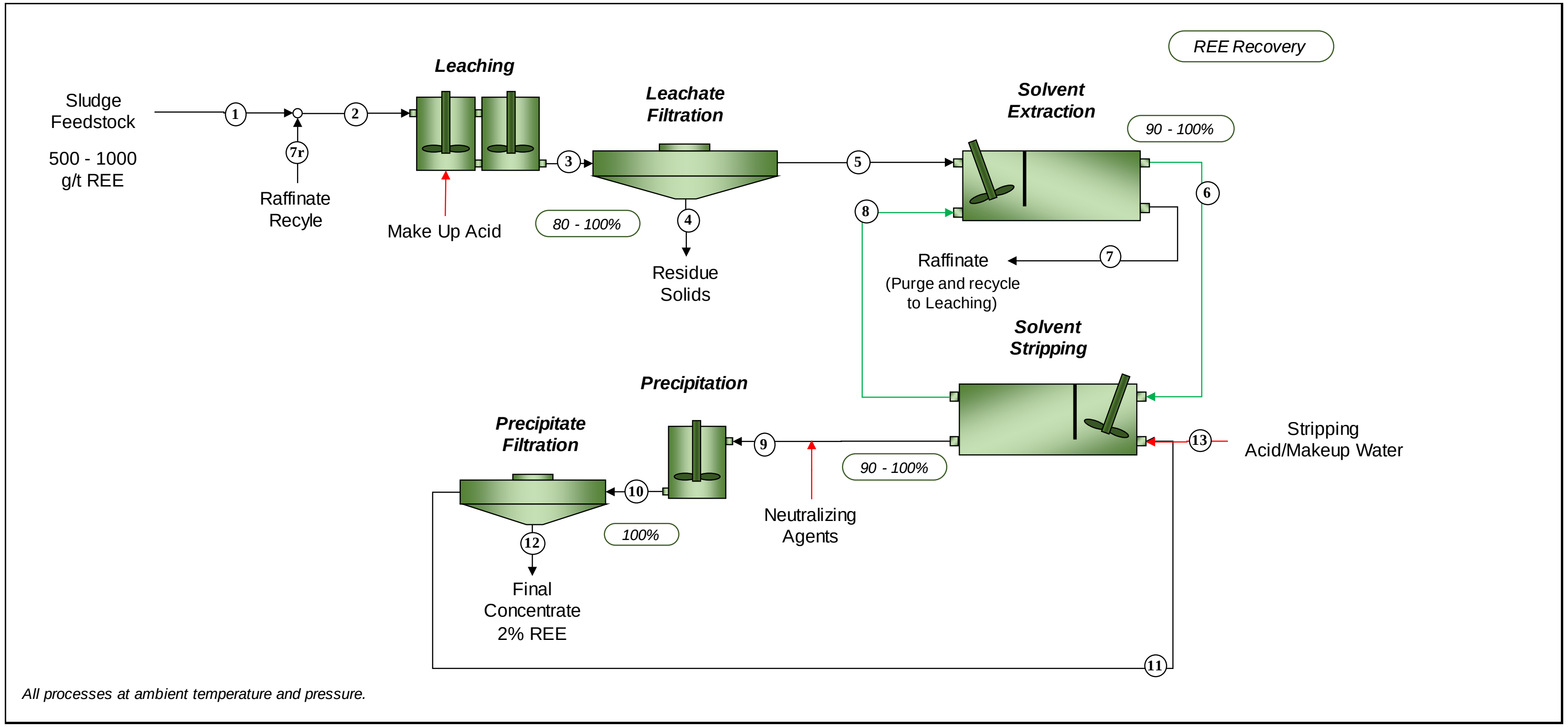
	phase	TREE (%) Conc.	TREE (%) Ion Recovery	TREE (%) HREE/TREE	TREO (%) Conc.	TREO (%) Ion Recovery	TREO (%) HREE/TREE
Strip Solution	AQ	**0.026**					
Trt A Precipitate	SL	**14.7**			**17.3**		
Calcination	SL	**41.5**	74.9	78.0	**48.1**	91.7	77.2
Trt B Final	SL	**69.2**	75.7	77.6	**80.2**	89.0	76.8

Systems Evaluation

Economic Modeling

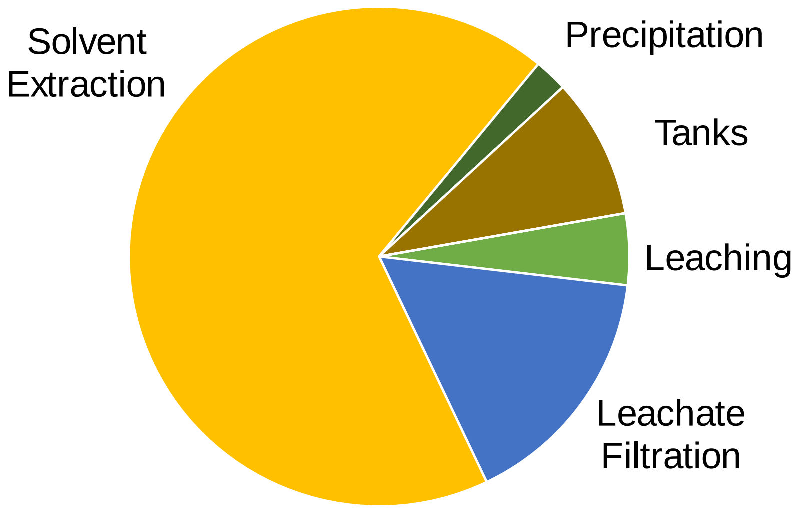
Initial TEA analysis

- Prior to Phase 2, a detailed techno-economic analysis was conducted using the laboratory data conducted from the initial beaker-scale tests.
- Assumptions:
  - 115 TPH central plant; 20 year operation
  - Composite Feed Grade : 610 g/t
  - NETL-provided REE prices and financial assumptions

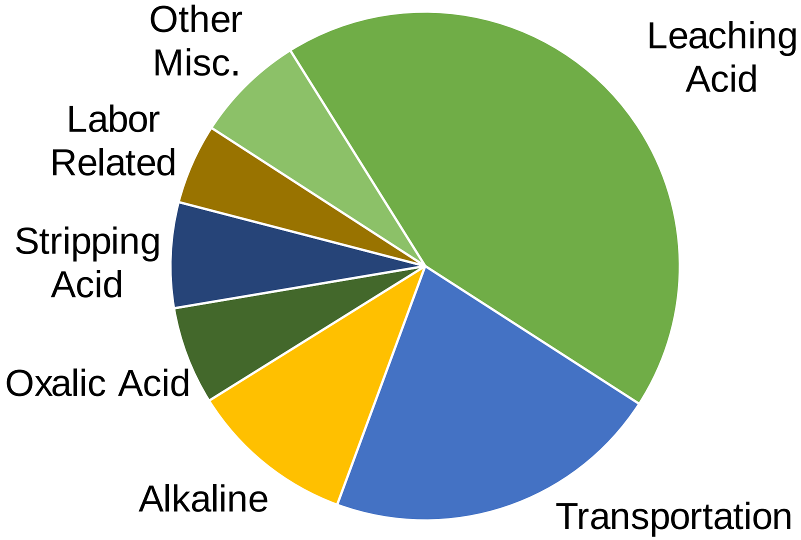


Economic Modeling

Total CAPEX = $46 million



Total OPEX = $141 / kg



Final Indicators:

- NPV = $80 million
- IRR = 37%

Very sensitive to consumable costs.
(Need bench and pilot-scale data)

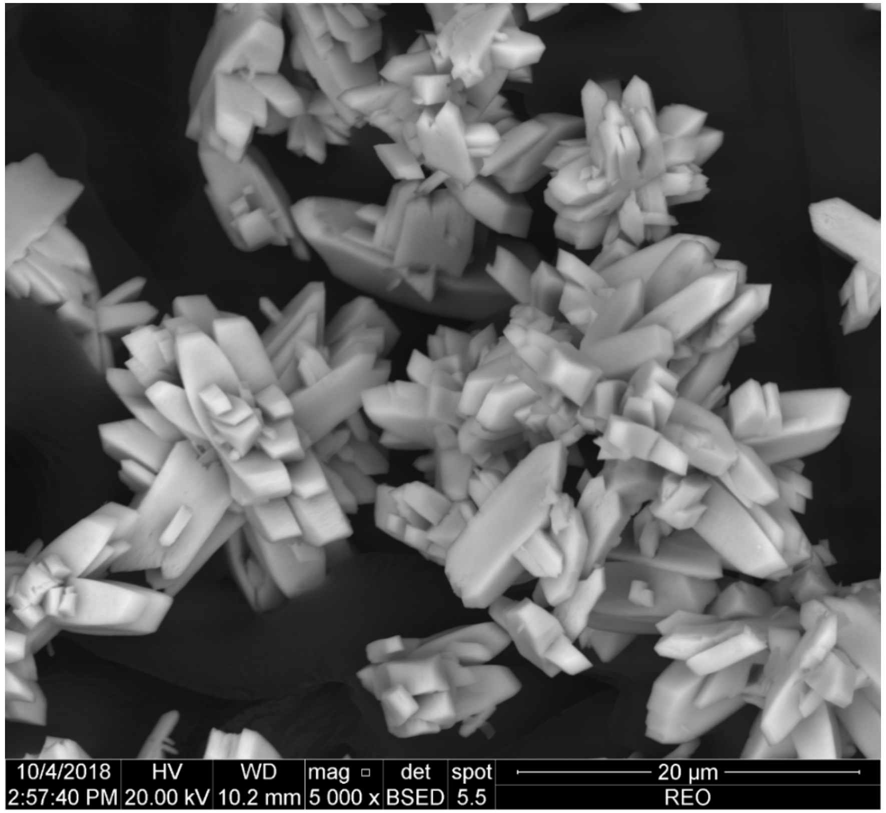
Directions for the Future

Upcoming Plans

1. Continue parametric testing with RS feedstock.
2. Work with DLM and OM feedstocks to reduce Fe content in PLS.
3. Bring Rockwell side of plant online and start processing PLS while training automation system.
4. Work on precipitation process to increase grade of REE product.
5. Incorporate more mixer-settlers in parallel testing and further REE refinement.

Questions?

REO crystals



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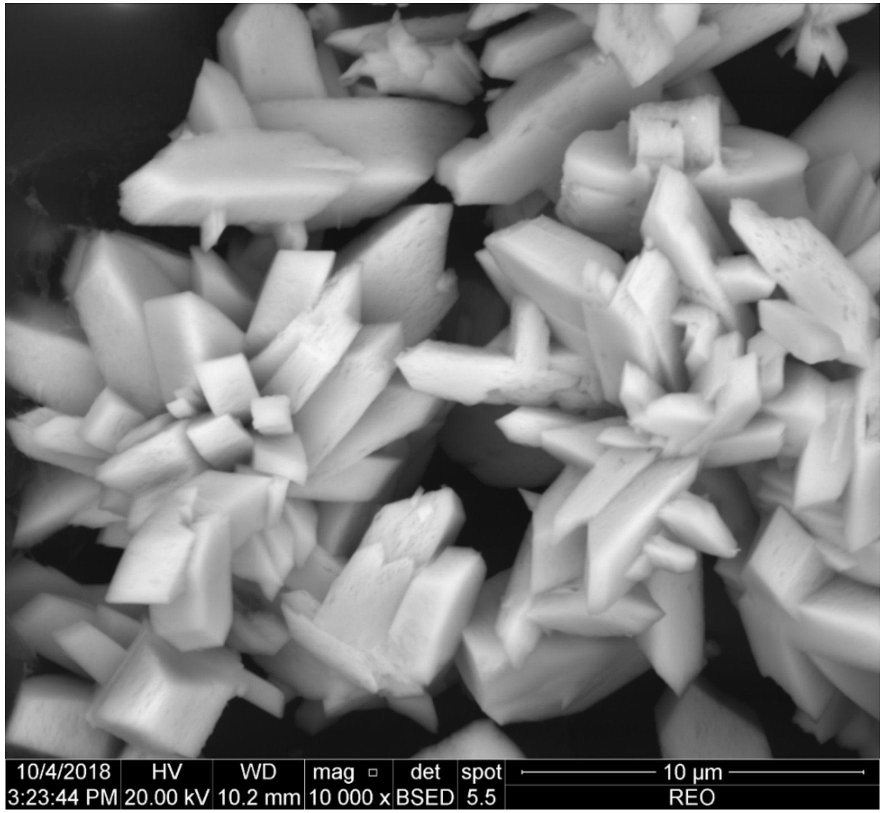

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