Recovery of Rare Earth Elements (REEs) from Coal Ash with a Closed Loop Leaching Process

2017 Rare Earth Elements Portfolio Review

DE-FE-0027012

Period of Performance March 1, 2016 – August 31, 2017

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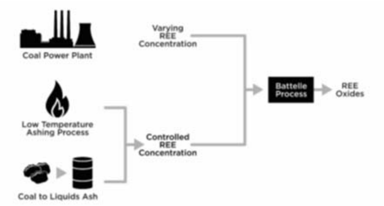
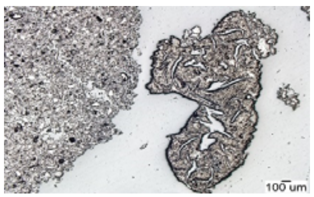
Project Goals and Objectives

- Validate economic viability of recovering Rare Earth Elements (REE) from coal byproducts using Battelle's closed loop Acid Digestion Process
  - Analyze and assess potential sources of coal byproducts as process feedstocks
  - Perform a techno-economic assessment based upon preliminary laboratory testing and process modeling
- Design a bench scale closed loop process for REE recovery from coal byproducts

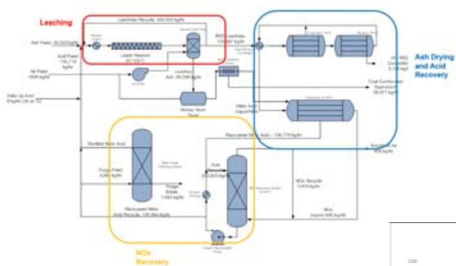
Presentation Outline



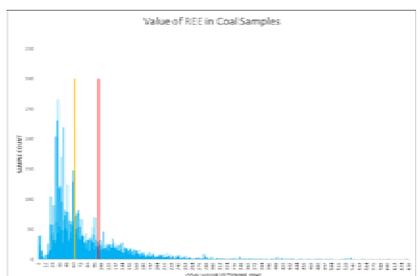
Project Overview



Sampling and Characterization Results



Preliminary Laboratory Testing Results



Feasibility Study Results

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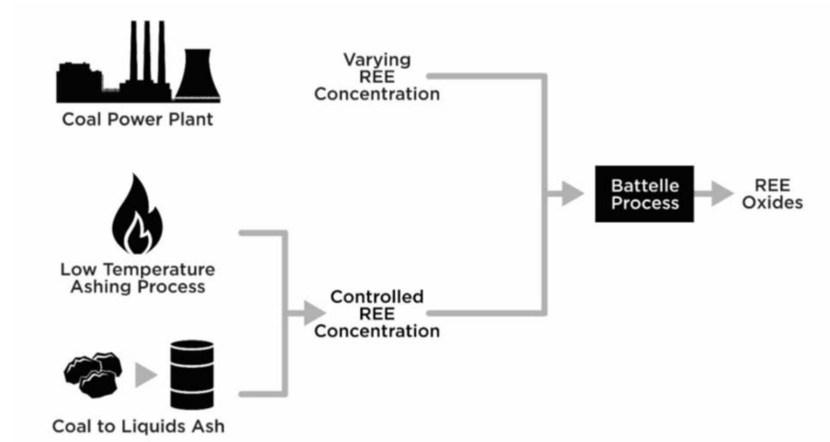
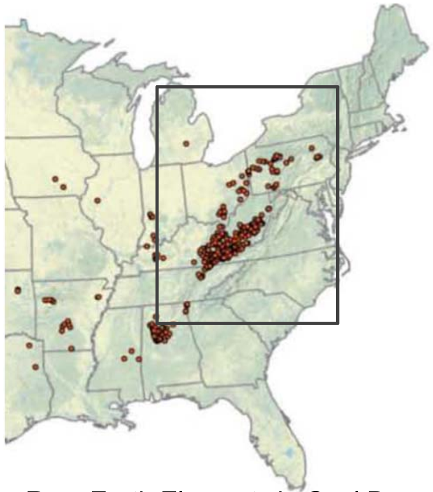
Project Overview

- Battelle proposed demonstration of a bench-scale technology to economically separate, extract, and concentrate mixed REEs from coal and coal byproducts (AOI 1)
  - Uses a closed loop acid leaching process incorporating the Acid Digestion Process for acid recovery
  - Targets coal sources with >300 ppm REE by weight
  - Target concentration of >2% by weight for recovered REEs
- Award No. DE-FE0027012
  - $900,014 ($710,000 Federal; $190,014 OCDO)
  - PoP = March 1, 2016 to August 31,2017



Project Partners

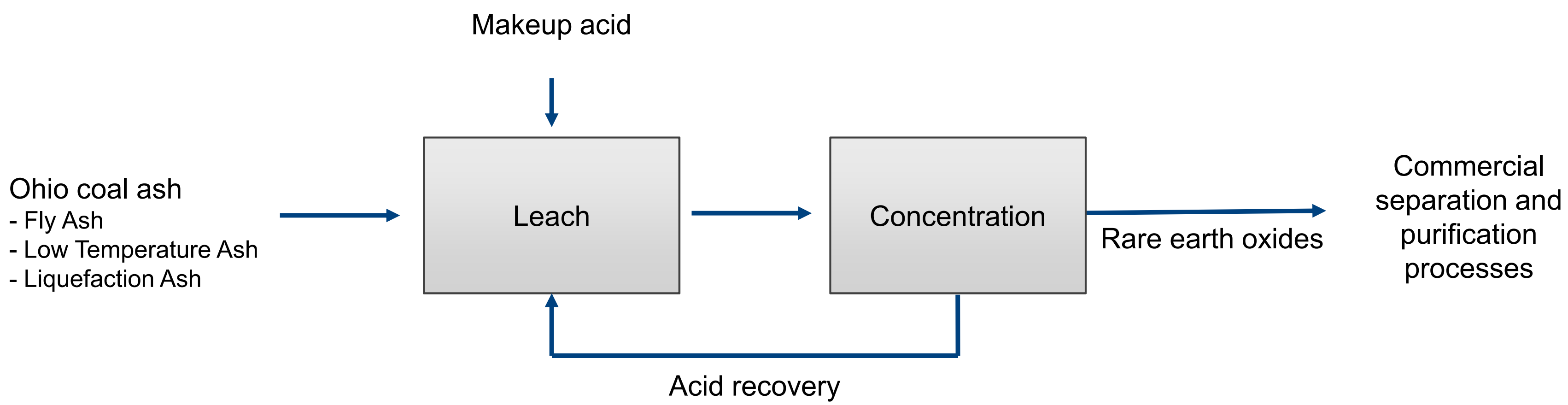
- Battelle has identified project partners with the ability to support identification and procurement of high REE content coal samples
  - The Ohio Coal Development Office includes key strategic partners such as AEP and can provide access to coal ash samples and critical information for the economic feasibility assessment
  - Pennsylvania Bureau of Topographic and Geologic Survey will provide coal samples from their inventory for characterization
  - West Virginia Geological and Economic Survey will similarly provide coal samples from their inventory for characterization



Source: Rare Earth Elements in Coal Deposits – a Prospectivity Analysis

Technical Approach

- Proposed technology: concentration of rare earth oxides and recovery of leach acid
- Patented Acid Digestion Process previously demonstrated for metal leaching and acid recovery at 70 lb/hr
- Synergistic with current DOE/OCDO Project for direct coal liquefaction



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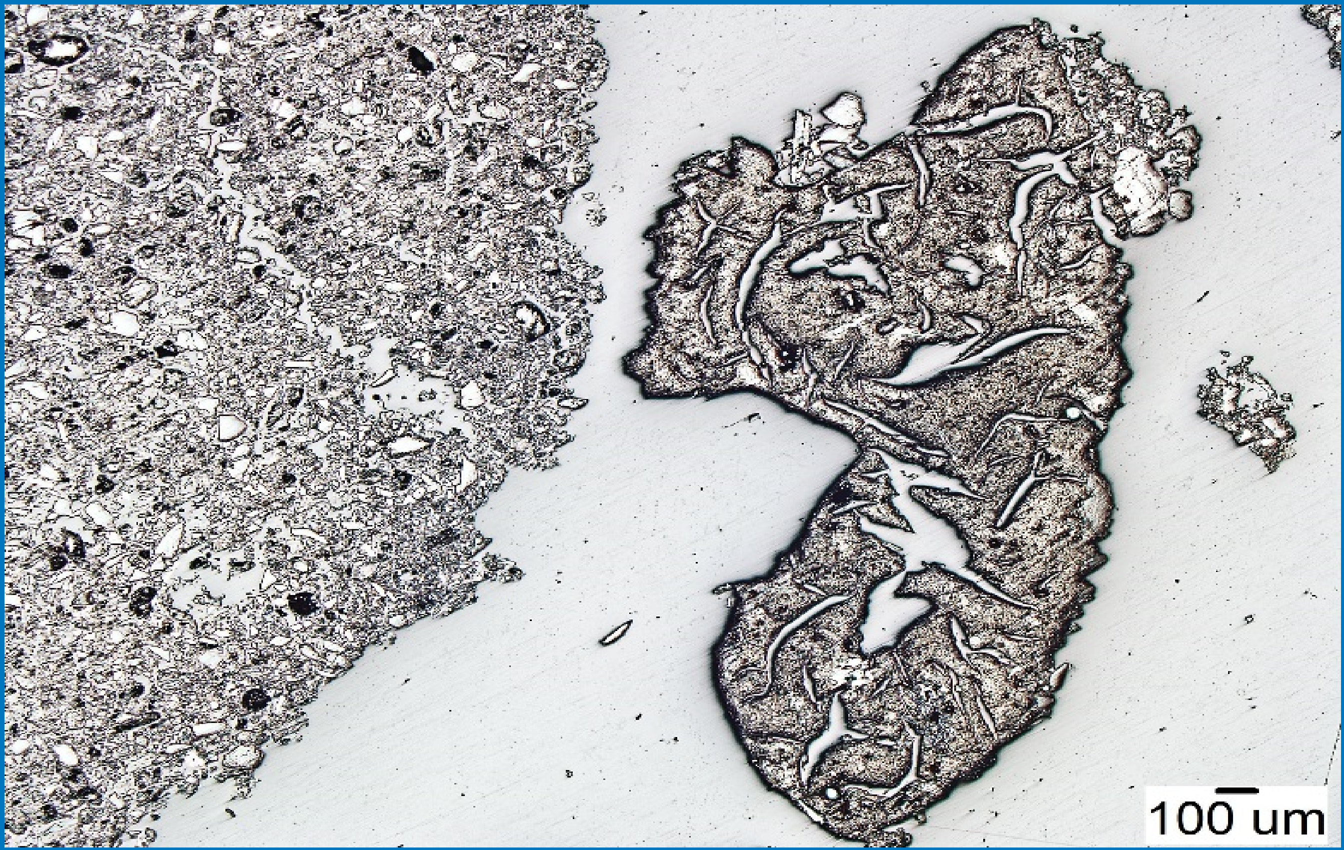

Sampling and Characterization Results

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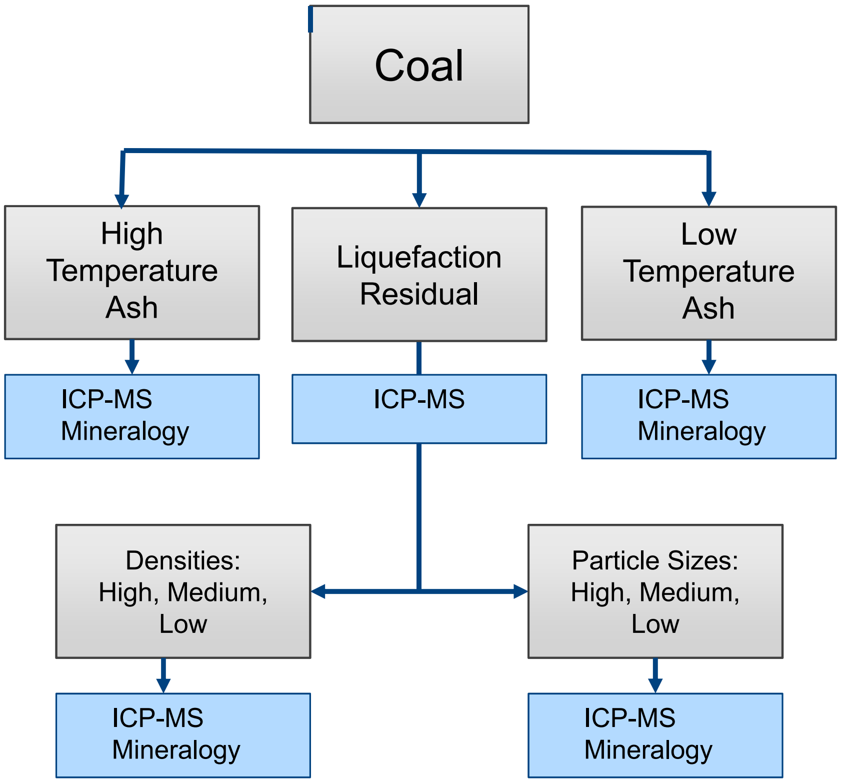
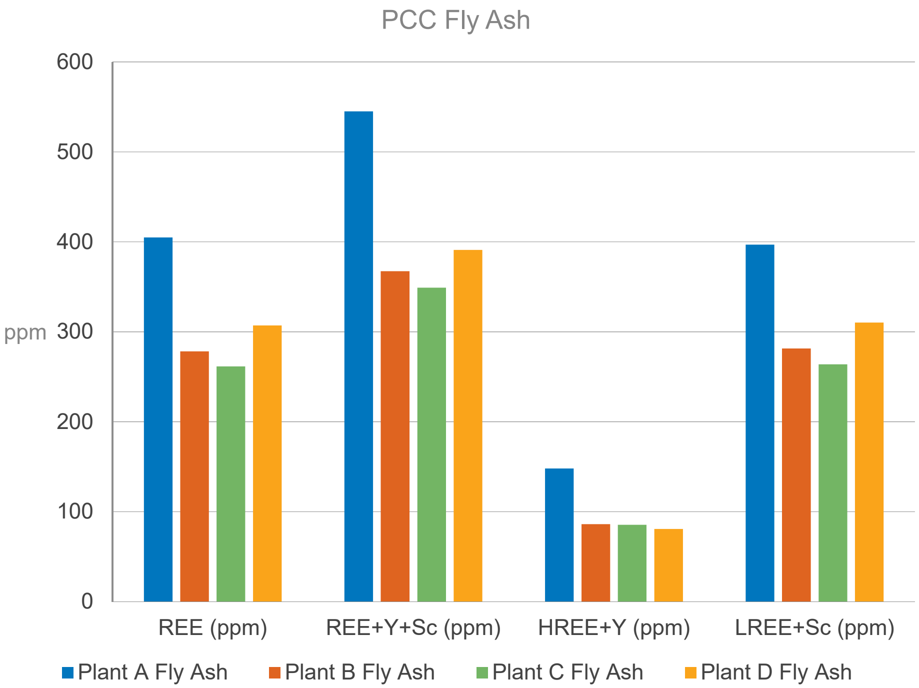
Three Coal Ash Sources were Investigated

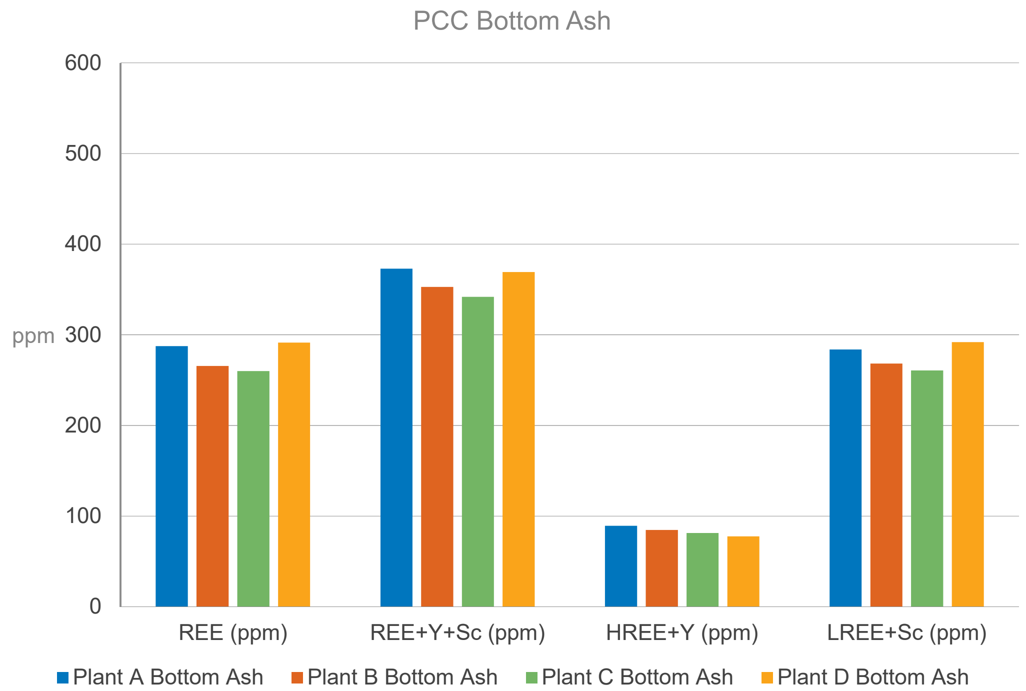


Sample Sources:

- Pulverized Coal Combustor (PCC) – 4 operating plants
- Fluidized Bed Combustor (FBC) – 1 plant
- Direct Coal to Liquids (CTL) – 1 pilot run

PCC Fly Ash Tended to Have Higher REE+Y+Sc Concentrations than Bottom Ash



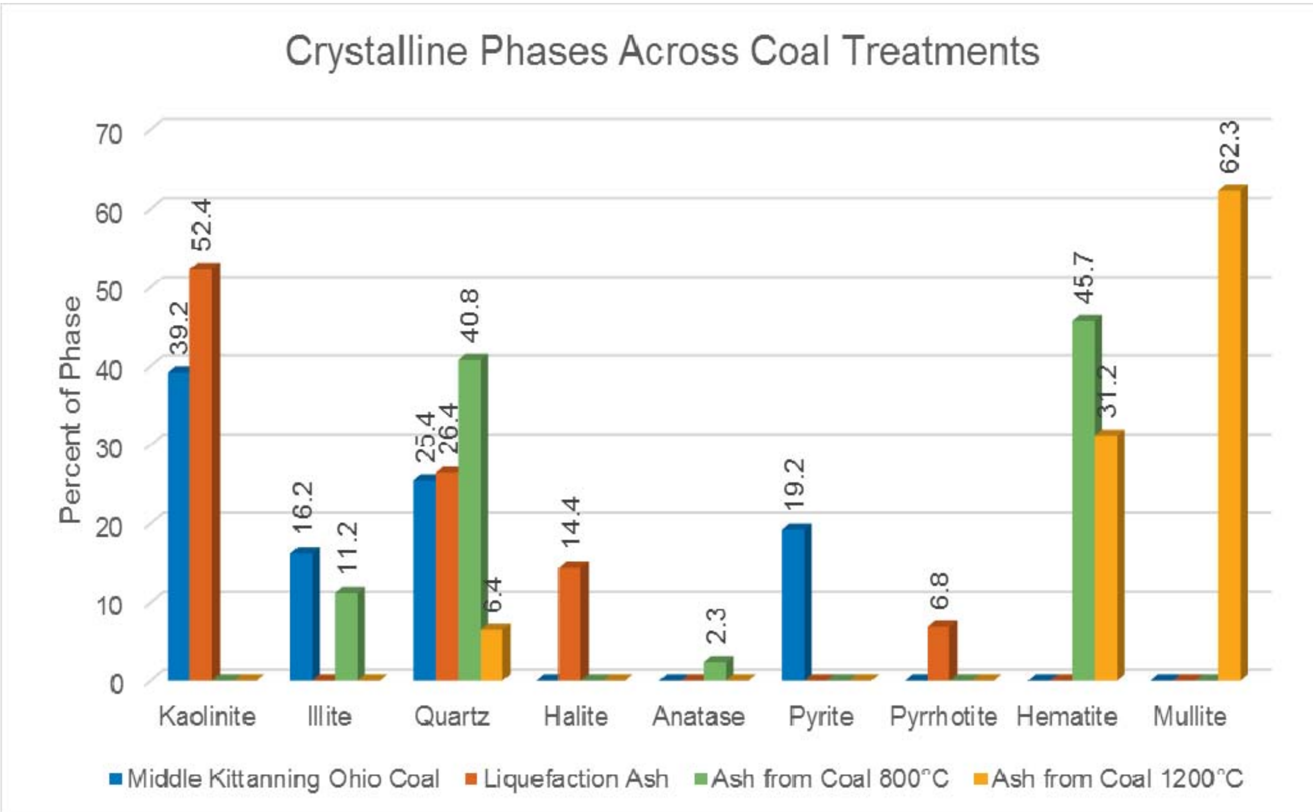


Fluidized Bed Combustor Ash was Diluted in Calcium

	Calcium	Total REE	Total REE+Y+Sc	HREE +Y	LREE +Sc	HREE/LREE
	Weight Percent (%)	ppm	ppm	ppm	ppm	Ratio
Fluidized Bed Combustor Fly Ash	18.1%	147.5	188.1	38.6	149.5	0.26
Fluidized Bed Combustor Bottom Ash	13.7%	121.4	153.2	30.5	122.7	0.25

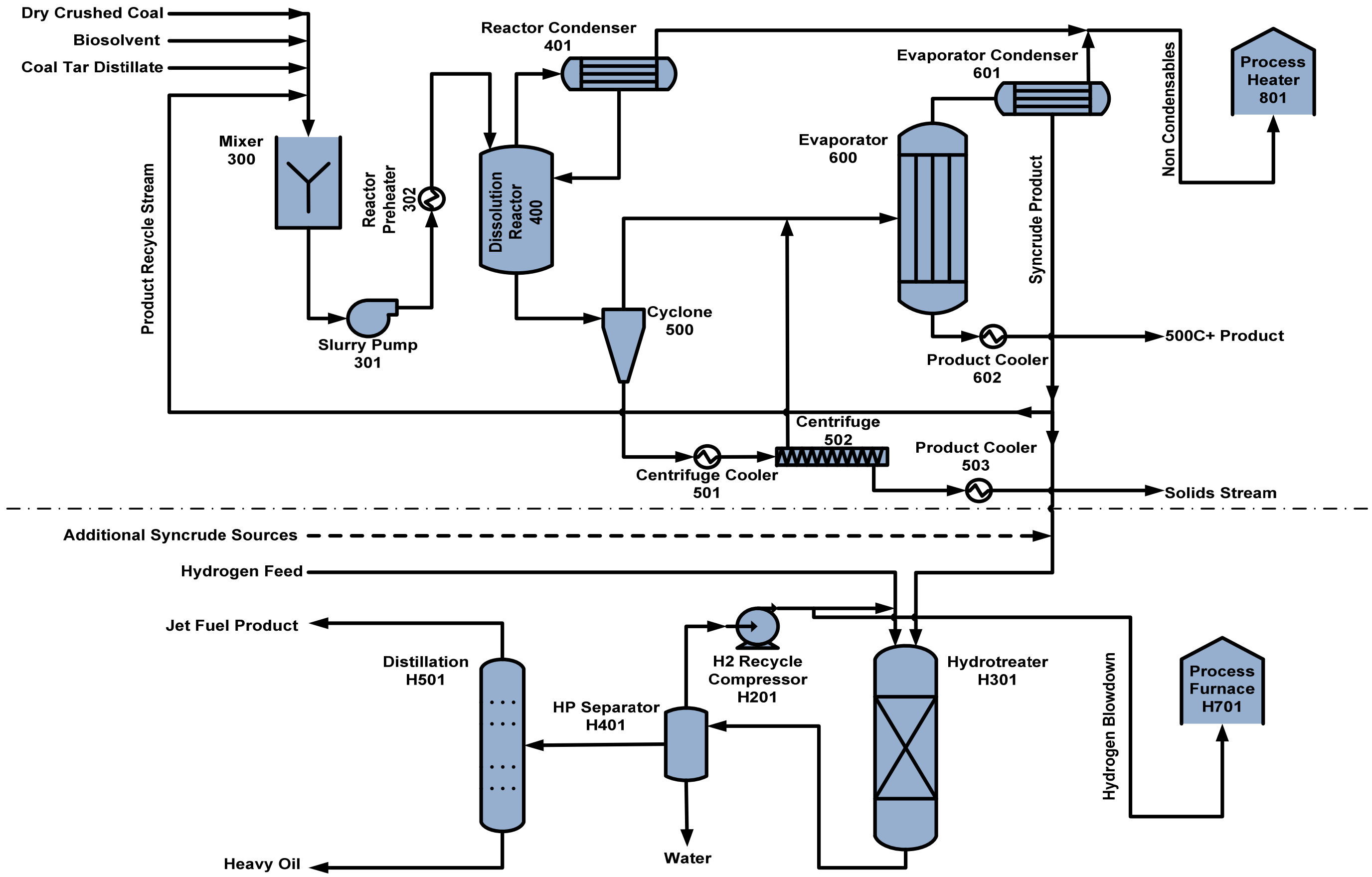
The low REE concentration in FBC is diluted in Limestone used to precipitate SO_2, Reduce NOx and improve the heat transfer

Higher Temperatures Lead to Formation of Refractory Phases



Sample	Percent Crystallinity
Middle Kittanning Coal	5%
Liquefaction Residual	7%
800°C Ash	35%
1200°C Ash	42%

Battelle's Direct Coal To Liquids (CTL) Separates Organic and Mineral Material



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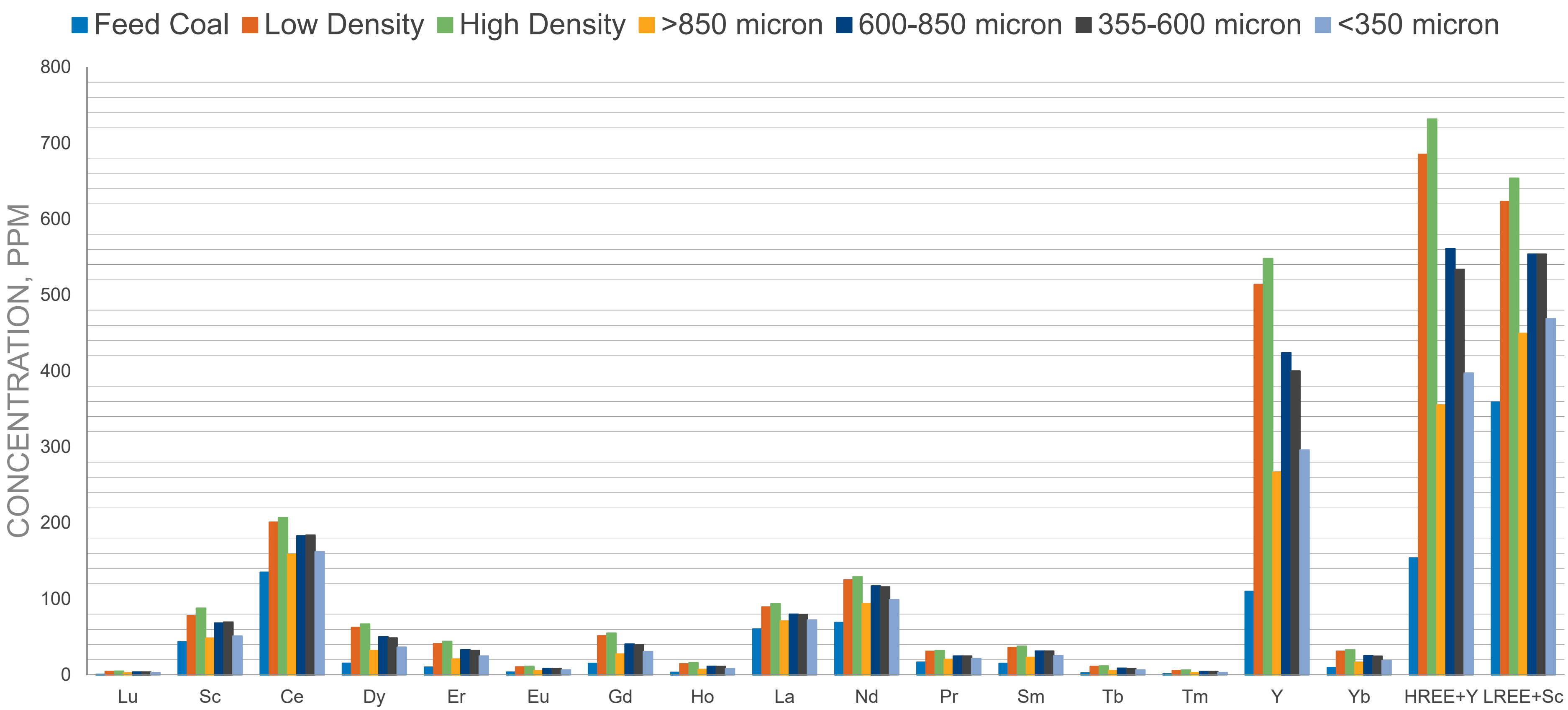
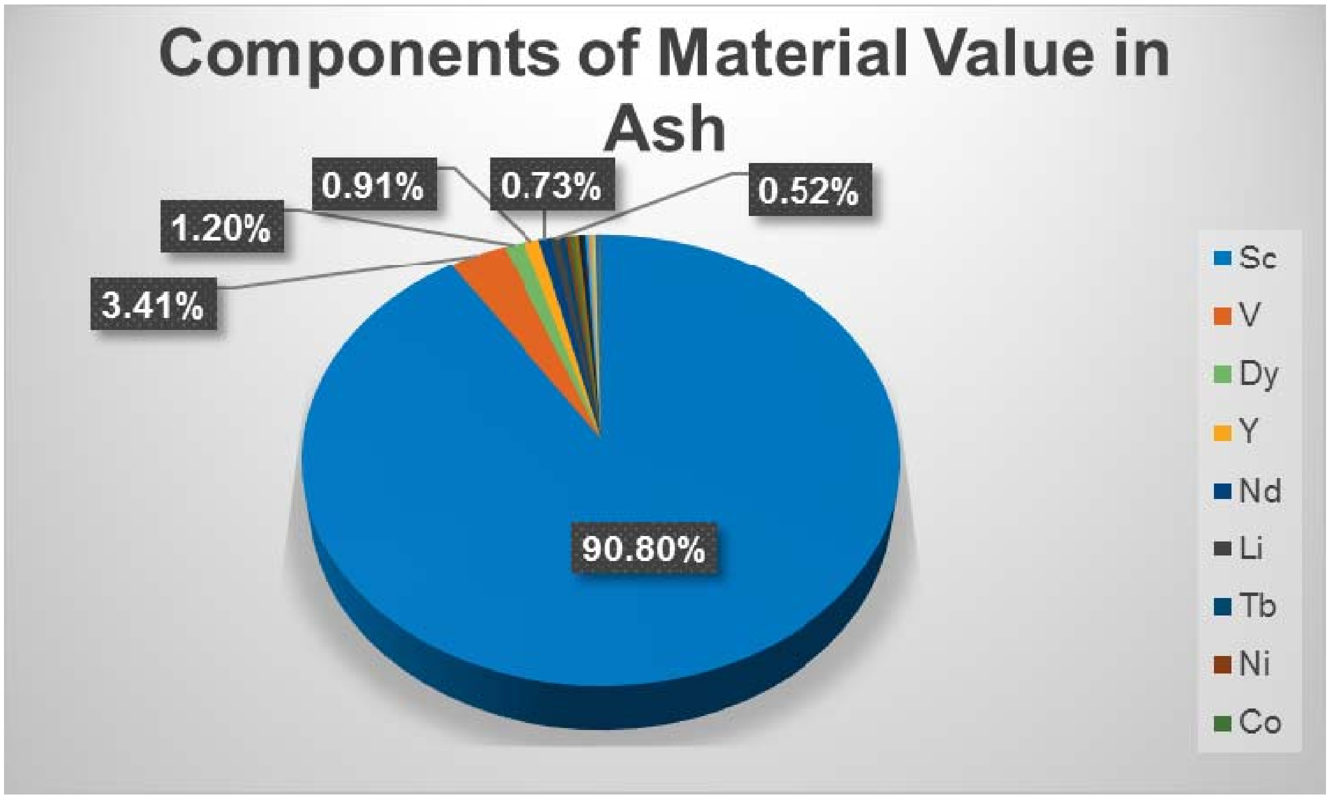
Coal Liquefaction Increased TREE Concentration Over the Feed Coal on an Ash Basis



Scandium Represents the Bulk of Material Value in the Fly Ash



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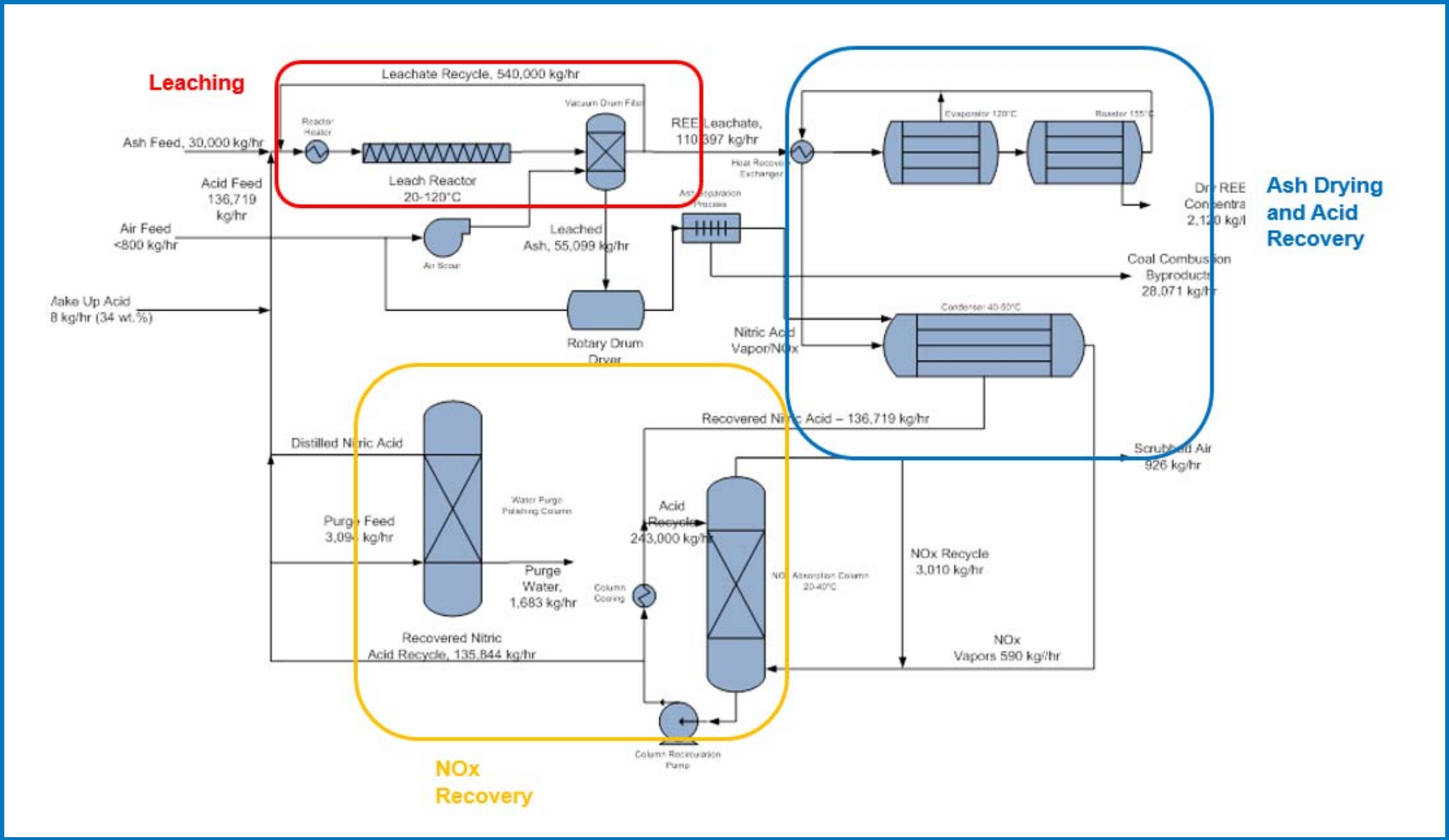

Preliminary laboratory testing

Leaching Efficiencies Appear to Decrease at High Nitric Acid Concentrations

Element	Starting Nitric Acid Concentration in PCC Fly Ash Leaches						
	17%	17%	17%	34%	51%	68%	34% (milled)
Sc	19.2%	20.8%	21.5%	21.5%	N/A	N/A	55.3%
Y	24.6%	26.7%	28.0%	28.0%	14.9%	13.0%	46.9%
La	19.0%	19.3%	20.0%	19.0%	9.9%	8.2%	35.4%
Ce	21.0%	21.5%	21.7%	27.0%	11.9%	9.9%	34.0%
Pr	20.3%	21.7%	22.4%	22.9%	11.6%	10.0%	36.3%
Nd	20.8%	22.6%	23.4%	23.9%	12.3%	10.5%	39.5%
Sm	22.5%	24.0%	25.0%	25.4%	13.7%	11.8%	40.5%
Eu	22.7%	24.5%	25.4%	26.4%	14.8%	12.7%	42.4%
Gd	25.0%	27.2%	28.5%	28.8%	15.7%	13.7%	45.2%
Tb	23.3%	25.5%	26.9%	28.1%	15.4%	13.4%	44.3%
Dy	24.1%	26.2%	27.6%	28.6%	15.5%	13.0%	41.9%
Ho	24.6%	26.8%	28.0%	28.6%	15.2%	13.3%	41.8%
Er	23.8%	26.2%	27.5%	27.8%	14.8%	12.6%	43.8%
Tm	23.0%	25.2%	26.4%	26.9%	14.4%	12.0%	42.2%
Yb	21.2%	23.1%	24.7%	24.8%	12.9%	10.6%	36.3%
Lu	21.2%	22.6%	23.9%	24.3%	13.0%	10.2%	34.6%

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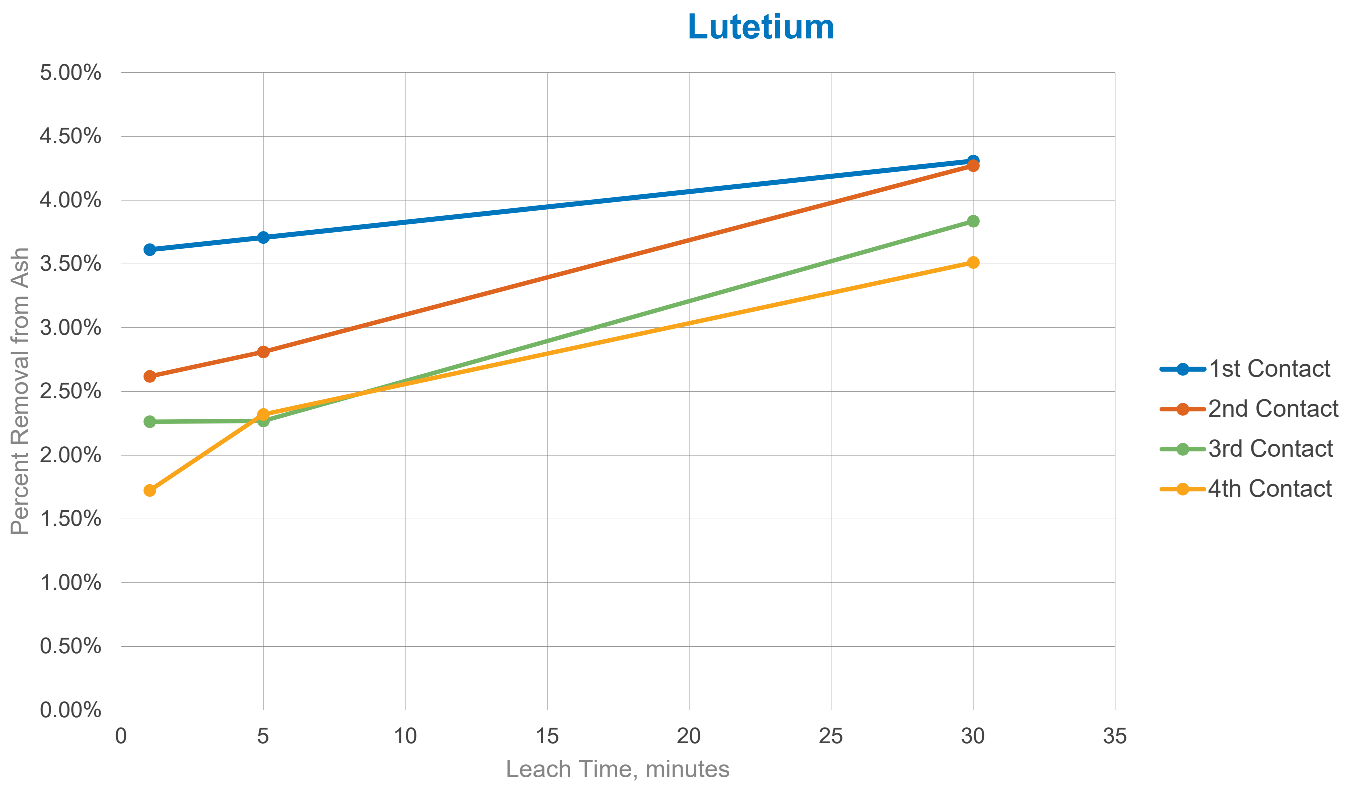
Serial Acid Contacts with Ash Decrease Leaching Rates



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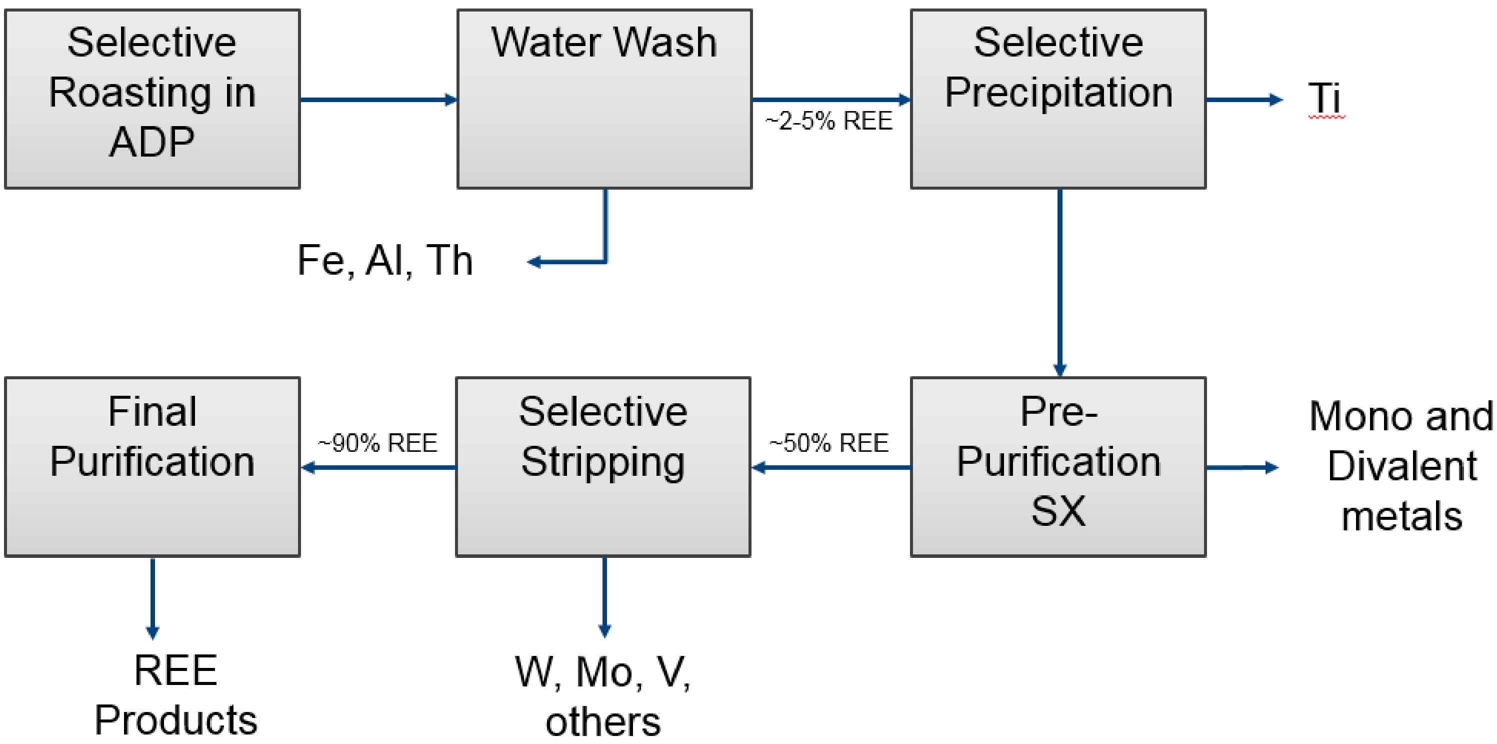
Conceptualization of REE purification train.



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Compressive Strength Testing of Concrete Suggests Leached Ash Pozzolan Does not Adversely Affect Concrete Strength.

Sample	Description	Cement (wt%)	Ash (wt%)	Sand (wt%)	Water/Cement weight ratio	Failure Pressure
A	Concrete with post leached fly ash	77	19	4	0.5	3,420 psi
B	Concrete with fly ash	77	19	4	0.5	3,420 psi
C	Concrete without addition of fly ash	77	0	23	0.5	3,250 psi

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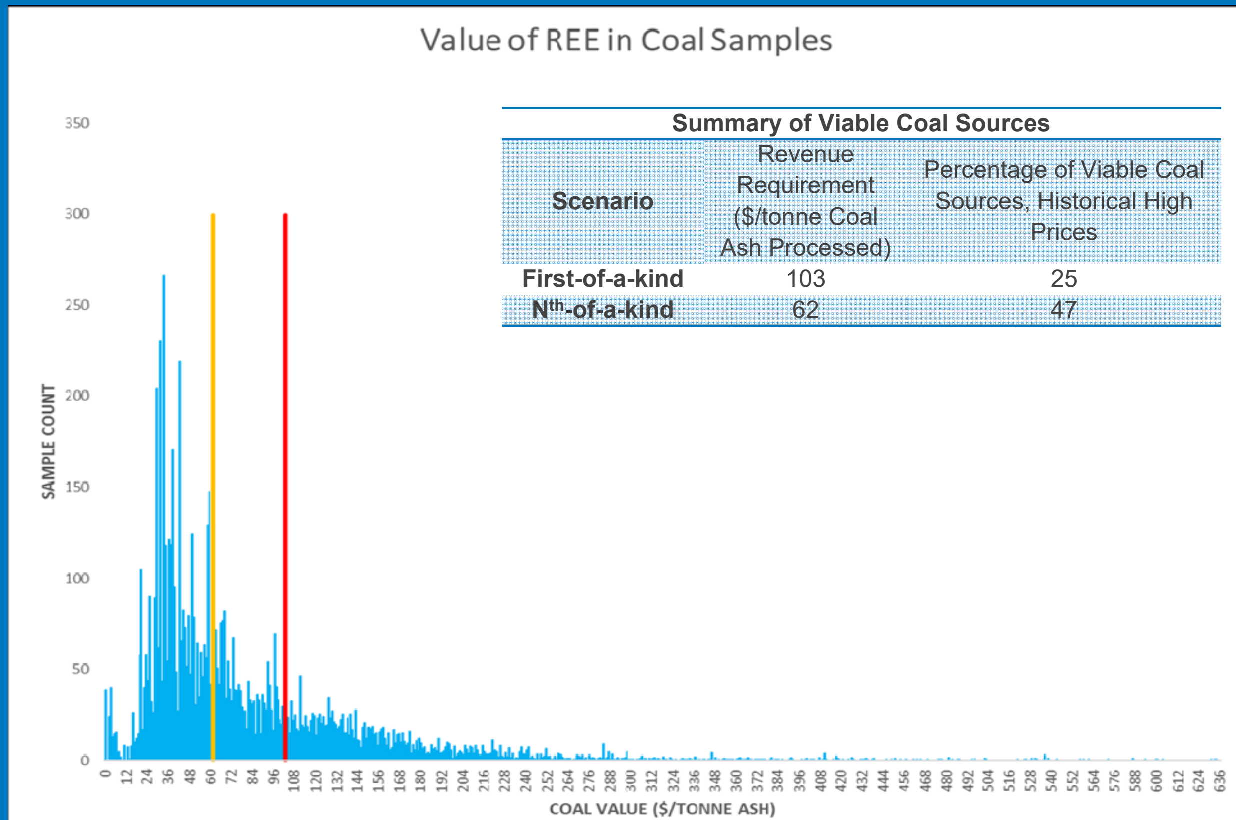

Summary of Viable Coal Sources

Scenario	Revenue Requirement ($/tonne Coal Ash Processed)	Percentage of Viable Coal Sources, Historical High Prices
First-of-a-kind	103	25
Nth-of-a-kind	62	47

Feasibility study

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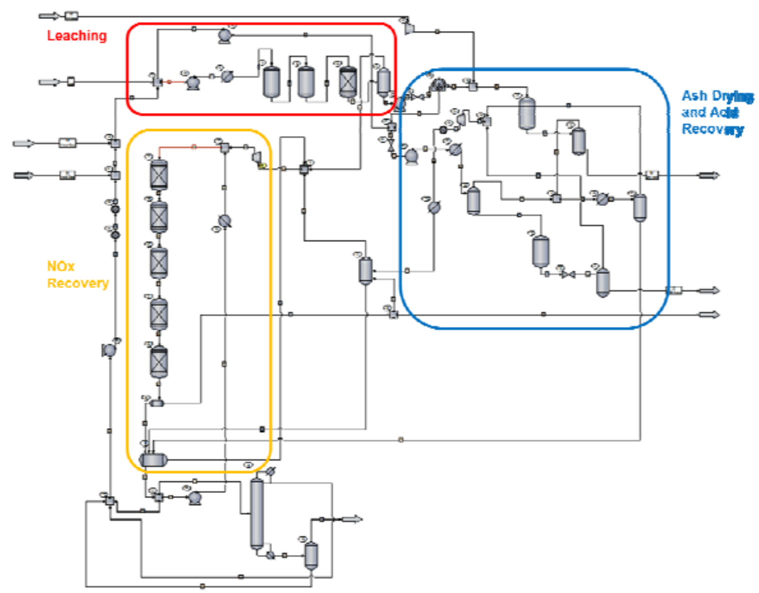
CHEMCAD Simulation Has Been Developed to Model Proposed Plant

- Model simulates a 30 tonne/day process.
  - Sized to reflect full capacity of a typical coal plant.
- Laboratory testing results incorporated into process model:
  - Species leaching efficiency
  - Acid loading capability
  - NOx generation rates
  - Acid roasting recovery estimates
- Model results used to inform equipment sizing parameters within TEA.



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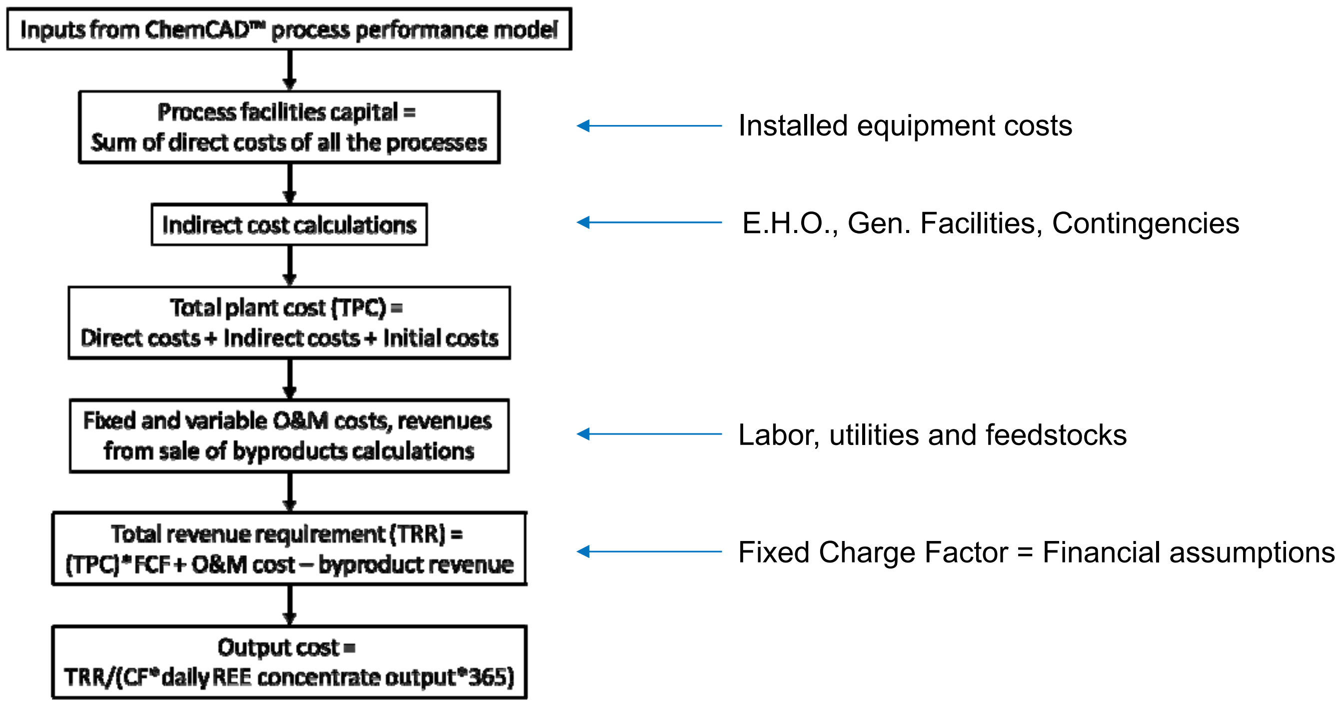
Approach to TEA follows EPRI's TAG® method



TEA results for FOAK and NOAK REE Recovery Plant

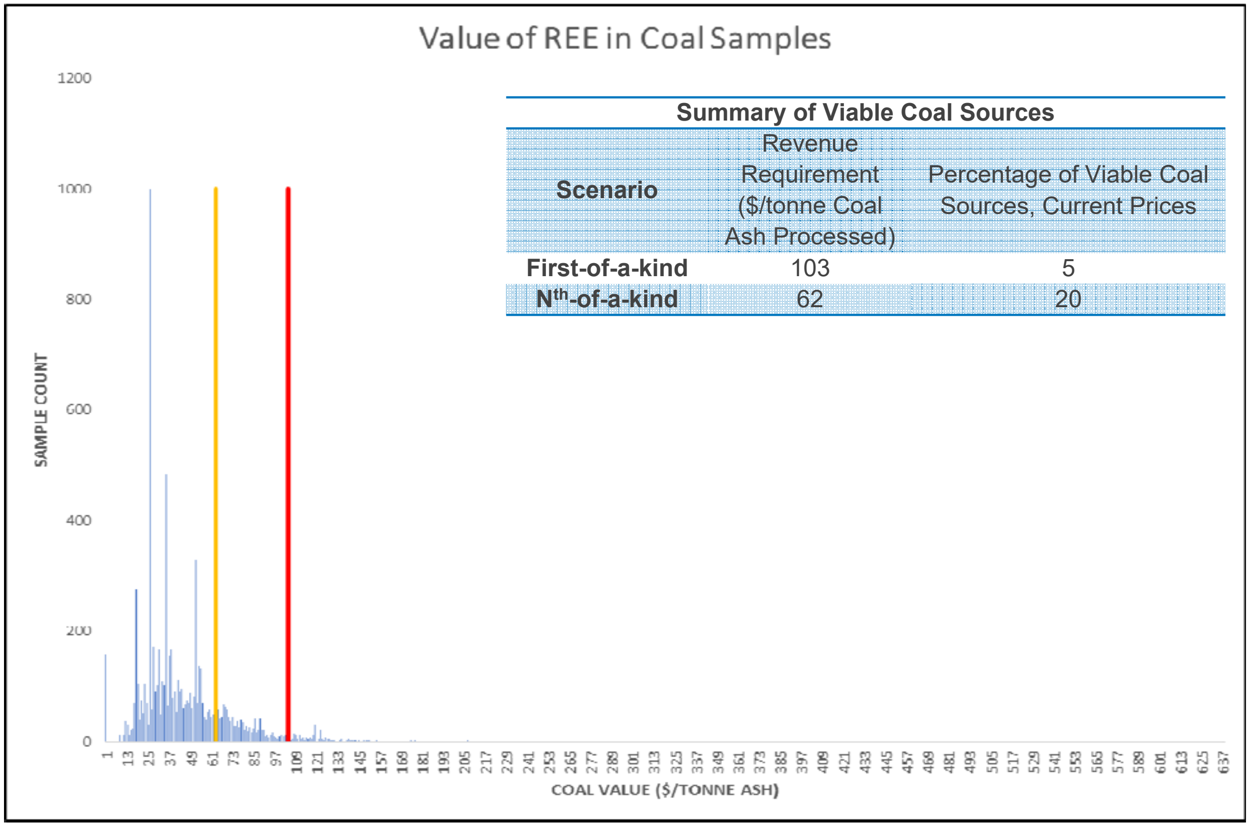
First-of-a-Kind Plant

Cost Component	$Million per year (2015)	$/tonne Coal Ash Processed
Annual Fixed Cost	$5.4	$29
Annual Variable Cost	$5.2	$28
Annualized Capital Cost	10.0	$56
By-Product Credits	$(2.1)	($11)
Total Annual Revenue Requirement	$19.1	$103

Nth-of-a-Kind Plant

Cost Component	$Million per year (2015)	$/tonne Coal Ash Processed
Annual Fixed Cost	$3.6	$20
Annual Variable Cost	$5.2	$28
Annualized Capital Cost	4.7	$26
By-Product Credits	$(2.0)	($11)
Total Annual Revenue Requirement	$11.6	$62

Revenue requirement for FOAK and NOAK plants compared favorably to value present in coal ash.



Summary of Viable Coal Sources

Scenario	Revenue Requirement ($/tonne Coal Ash Processed)	Percentage of Viable Coal Sources, Current Prices
First-of-a-kind	103	5
Nth-of-a-kind	62	20

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Next Steps

- Integrated Process Design
  - Generation of Laboratory Test Plan
  - Laboratory testing to inform process design
  - Generation of design package for 100 lb/day system

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It can be done

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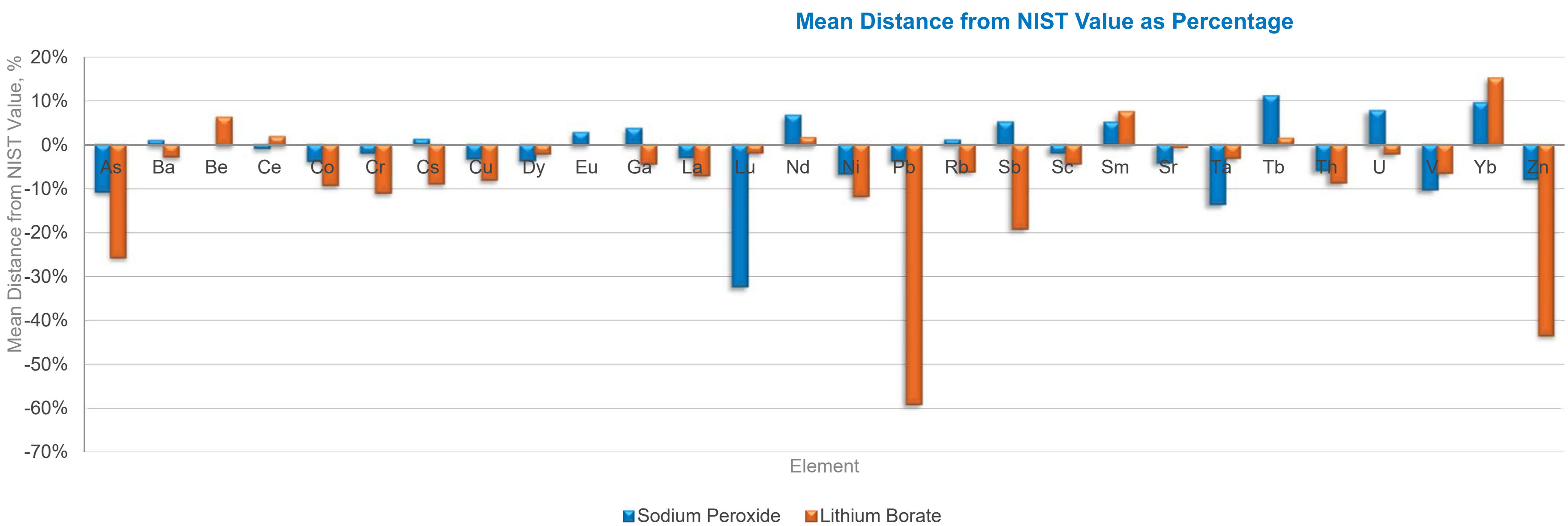
Selection of Analytical Method for Sample Characterization



Comparison of Sodium Peroxide vs. Lithium Borate digestion using NIST sample
Sodium Peroxide digestion method gives a closer result to the NIST reference material than Lithium Borate digestion

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