High Yield and Economical Production of Rare Earth Elements from Coal Ash

DOE Contract DE-FE0027167 – Phase 2

NATIONAL ENERGY TECHNOLOGY LABORATORY

VG-2020-105

Physical Sciences Inc., Andover, MA
Center for Applied Energy Research, Lexington, KY
Winner Water Services, LLC, Sharon, PA

Presentation to:

Rare Earth Elements (REE) Program Portfolio,
2020 Annual Review Meeting (Virtual)
15 September 2020

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Presentation Outline

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- Phase 2 Project Description and Objectives
- Project Updates
- Next Steps and Concluding Remarks

Phase II Team

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- The PSI, CAER, WWS team provides a complete integrated science, technology, engineering, technology transition, and commercialization solution for DOE/NETL

Key Personnel:

- Physical Sciences Inc (PSI):
  - Dr. Dorin Preda: PI/PM, Lead Chemist
  - Dr. David Gamliel: Lead Chemical Engineering/Process Modeling/TEA
  - Dr. Prakash Joshi: Consultant
- University of Kentucky Center for Applied Energy Research (CAER):
  - Dr. James Hower: Coal Geochemistry, Ash Source Selection, Materials Characterization
  - Dr. John Groppo: Mineral/Ash Processing, Feedstock Logistics, Site Qualification
- Winner Water Services (WWS):
  - Mr. Todd Beers: Chemical & Pilot Plant Engineering, and Technology Commercialization
  - Mr. Michael Schrock: Plant Design, Pilot Plant Operations

Phase 2 Project Description

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- Area Of Interest (AOI) 2 program: Pilot Scale Technology
  - Phase 1 – Separation technology demonstrated successfully on bench scale
  - Phase 2 – Design, construction and operation of physical and chemical pilot plants to extract rare earth elements (REEs) from coal ash

- 30-month Phase 2 program: 9/29/2017 – 10/31/2020

- Team: - Physical Sciences Inc. (PSI), Andover, MA
  - Center for Applied Energy Research (CAER), Lexington, KY
  - Winner Water Services, LLC (WWS), Sharon, PA

- Total Contract Value ~$7.5M = $6M DOE funds + $1.5M Cost Share

Phase 2 Project Objectives

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Overall Objective: Demonstrate Phase 1 REYSc separation/enrichment technology at pilot scale in a plant(s) with *decoupled* operating capacities of ~ 0.4 tpd physical processing, and ~ 0.5 tpd chemical processing.

- Both pilot designs are *modular* and *transportable*

Performance Parameter	Threshold Value	Objective Value
Feedstock REYSc Content	>300 ppm (Whole Mass Basis)	>500 ppm (Whole Mass Basis)
Total REYSc Enrichment in Final Concentrate	>10 wt% (Elemental Basis)	>20 wt.% (Elemental Basis)
Return on Investment	<12 yr	<10 yr
Delivered Concentrate Quantity	~50 g	~0.5 kg

Current Program Status

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- Collected ~15 tons of coal ash from two different KY plants for physical processing
  - 475 – 550 ppm ash REYSc content
- Physical processing of ash completed 8/2019
- Chemical plant construction, shakedown and start-up completed 11/2019. Chemical processing operations ongoing:
  - ~5 tons of coal ash processed to date
  - ~0.5 kg of REE concentrate produced
  - REYSc content of 10-66 wt.% (elemental basis)
- Techno-economic analysis indicates payback period of <10 years for commercial venture

REY Product

Phase II Status

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Performance Attributes	Commercial Target Performance Requirements	Current Status
Feedstock REYSc Content	>300 ppm (whole mass basis)	Feedstock REYSc content >500 ppm has been achieved by CAER.
Total REYSc content in final concentrate	>10 wt.% (elemental basis)	REYSc final content of 10 – 20 wt.% has been recorded at Micropilot scale. Enrichment at chemical pilot scale TBD.
Return on Investment	<12 years	Detailed economic forecasts ongoing. Cost and revenue drivers, potential plant locations, and potential suppliers and purchasers identified and quantified.
Delivered Concentrate Quantity	0.05 kg	Achieved ~0.5 kg of concentrate production to date.
Final REE Yield	>10 wt.%	REYSc yields of 10-30 wt.% recorded in Micropilot and Chemical pilot.
Cement Substitute Yield	>90 wt.%	Consistent cement substitute yields of 90-93 wt.% recorded in the Micropilot. Similar yield at pilot scale. Cement substitute utility confirmed via standardized testing.
Solvent/ Reagent Recycling	Solvent >98.5 wt.% Reagent >90 wt.%	Solvent recovery of ~97 wt.% & reagent recovery of 93 wt.% recorded in Micropilot. Solvent recycling efficiency expected to increase at pilot scale (ongoing).

PSI team anticipates that all target performance requirements will be met.

Project Update

Rare Earths Recovery Process Overview

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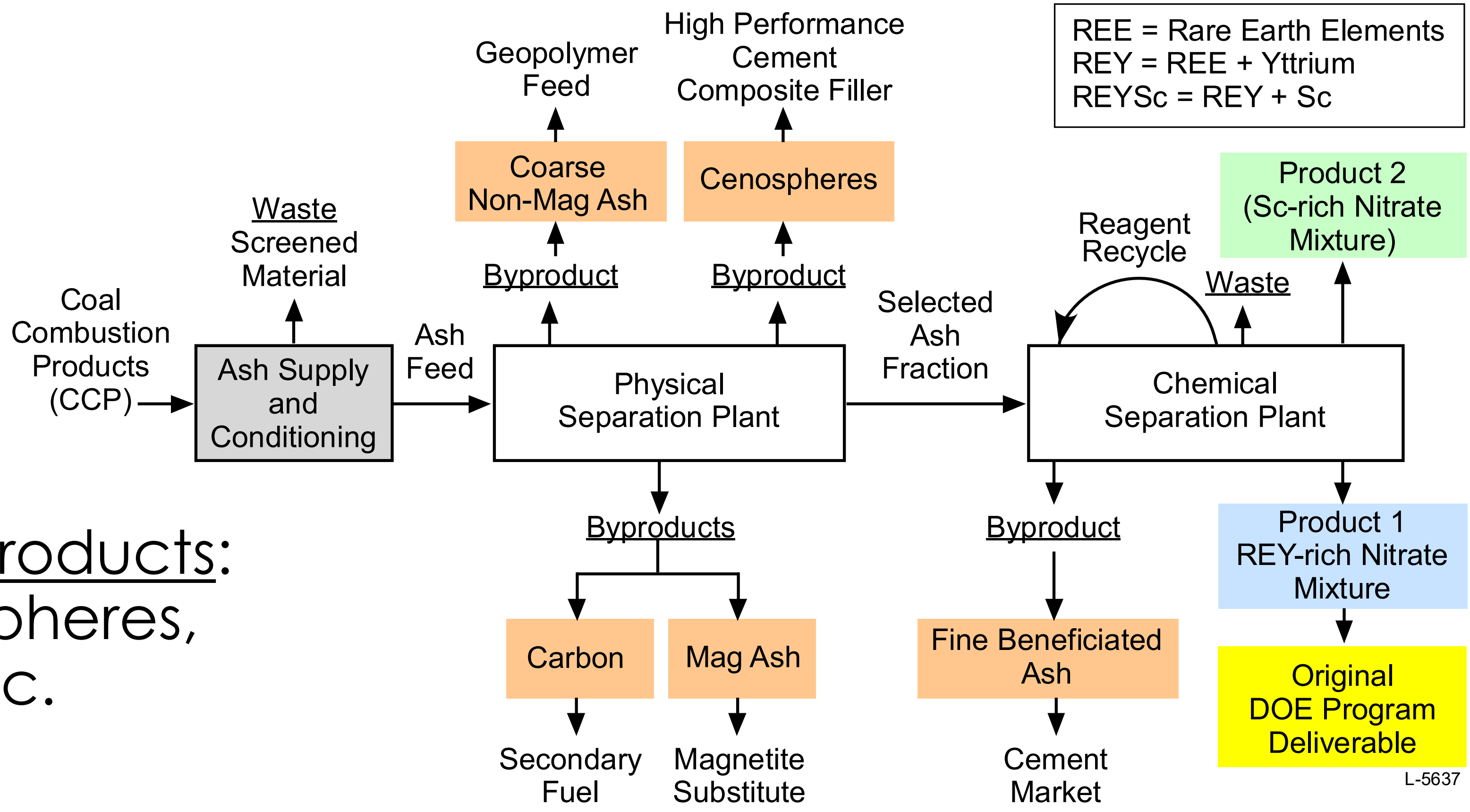
- Physical separation stage, followed by a chemical separation stage, followed by a post-processing stage

- Proposed Product:
  REYSc-enriched mixture (dry concentrate)

- Higher Value Products:
  REY-rich & Scandium-rich concentrates

- Commercially Viable By-products:
  Cement substitute, cenospheres, secondary fuel carbon, etc.



Feed Ash Material

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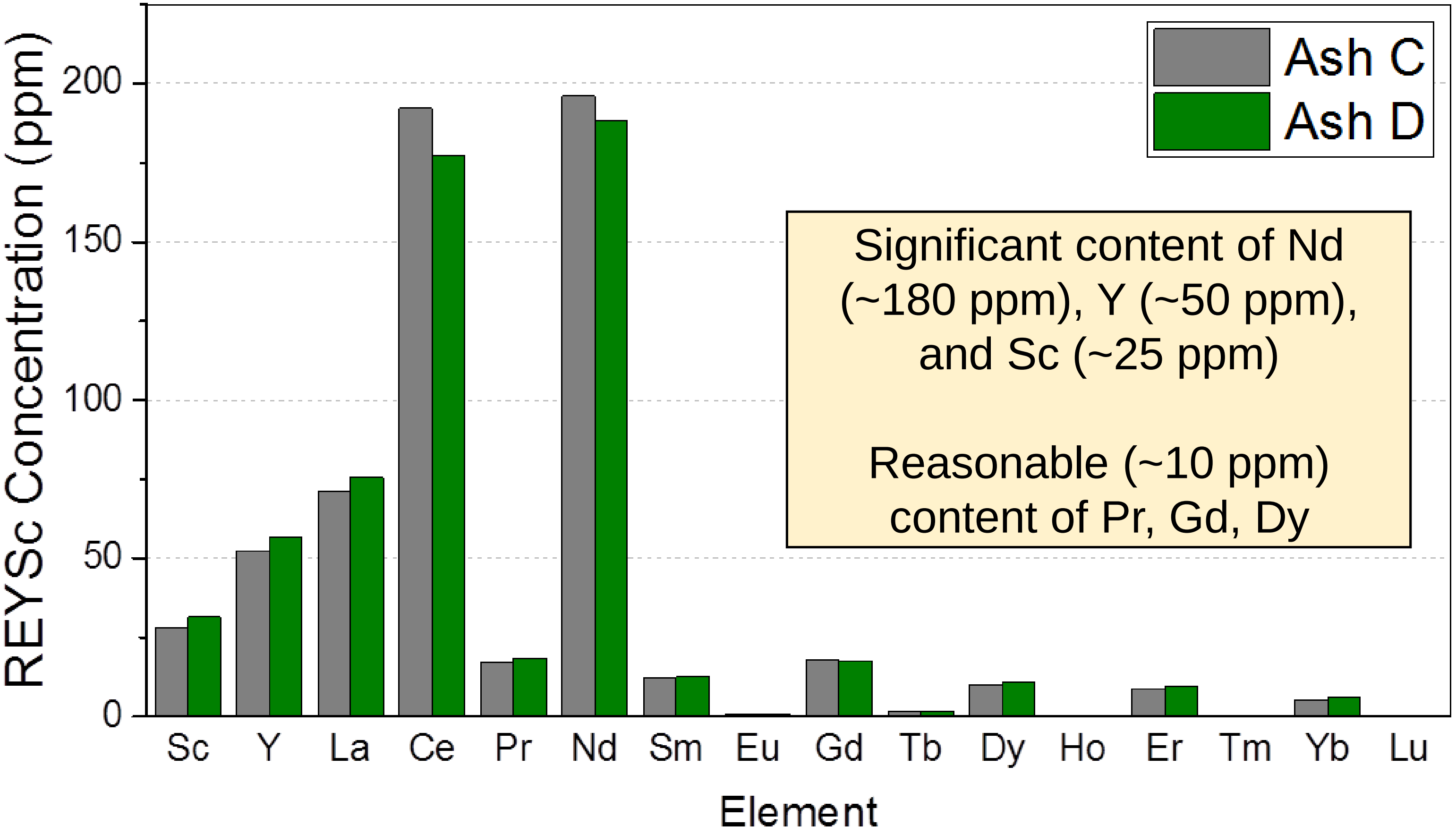
- Ash from 2 KY coal fire power plants was recovered and used as process feed



Physical Processing Pilot

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CAER physical pilot plant operational and >15 tons of coal ash processed to date; >50% yield for ash mass fraction for chemical processing

Output of Physical Processing

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- Physical processing creates an ash that is a suitable feed to chemical pilot
    - Low carbon content
    - Low magnetics content
    - Small particle size
- Processed ash collected in super sacks and shipped to chemical pilot in Sharon, PA

Chemical Processing Overview

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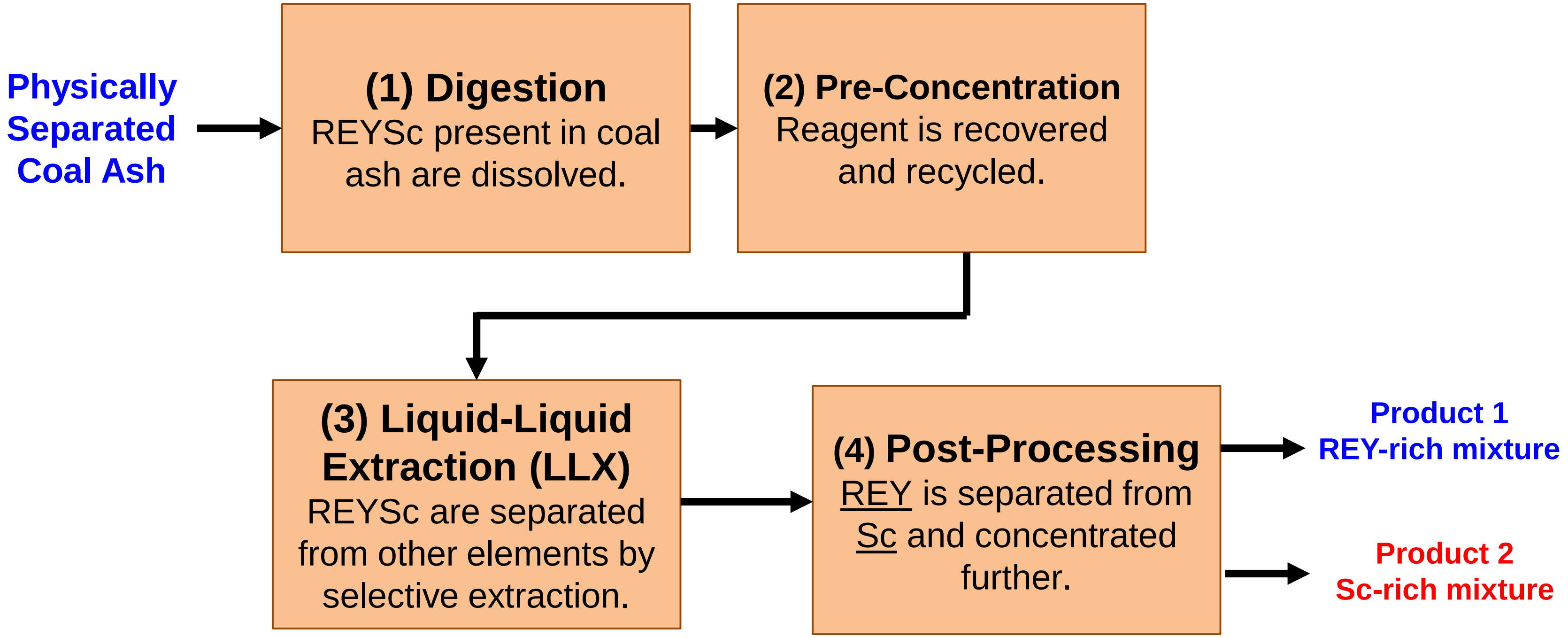

REY-rich material and Sc-rich material are produced from coal ash using simple and efficient process steps.

PSI Micropilot Facility

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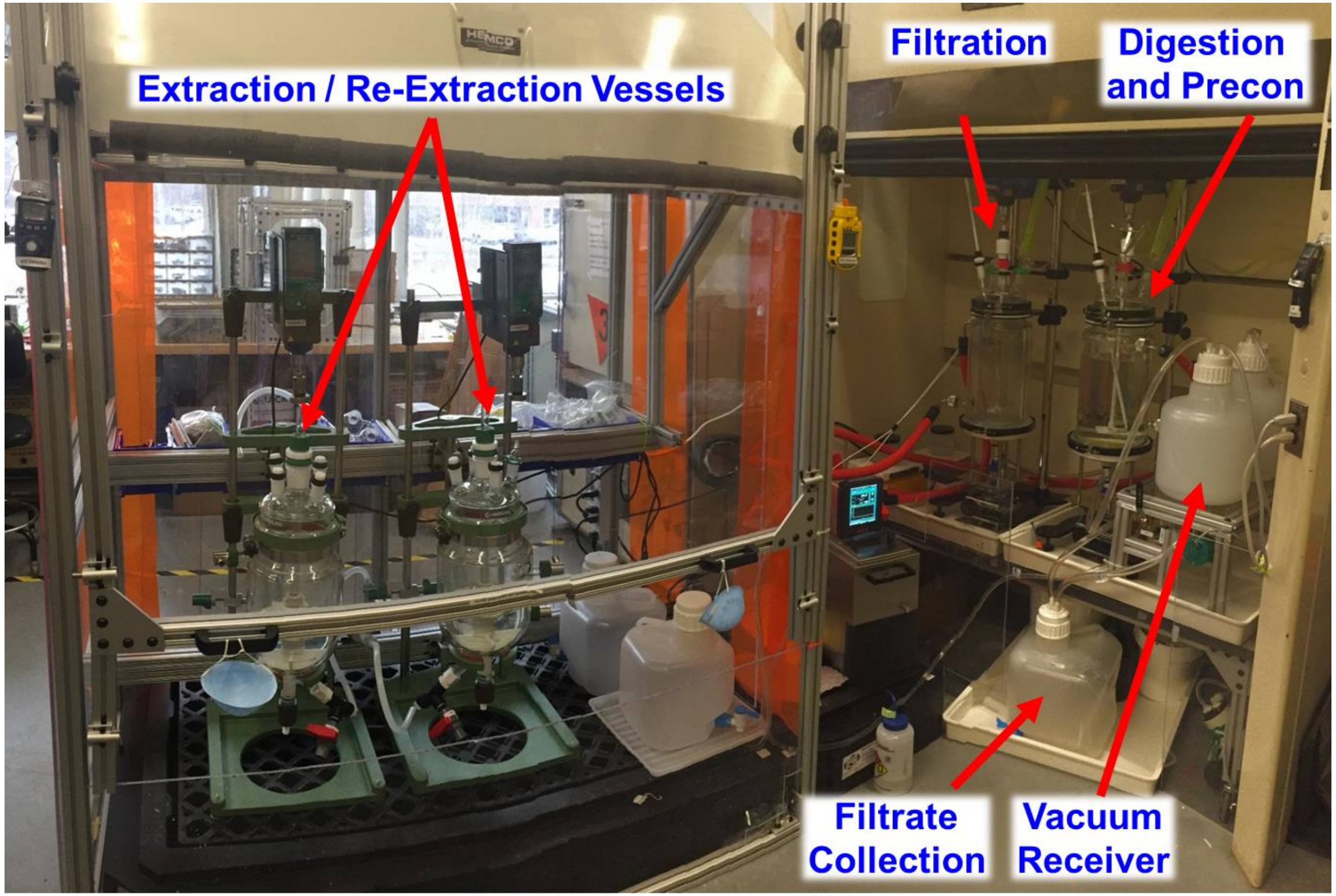
- Feed ash was first processed in PSI micropilot facility to:
  - Demonstrate target yields and enrichment
  - Determine ash suitability
  - Identify processing challenges and bottlenecks



Micropilot Campaign Demonstrated REE Enrichment

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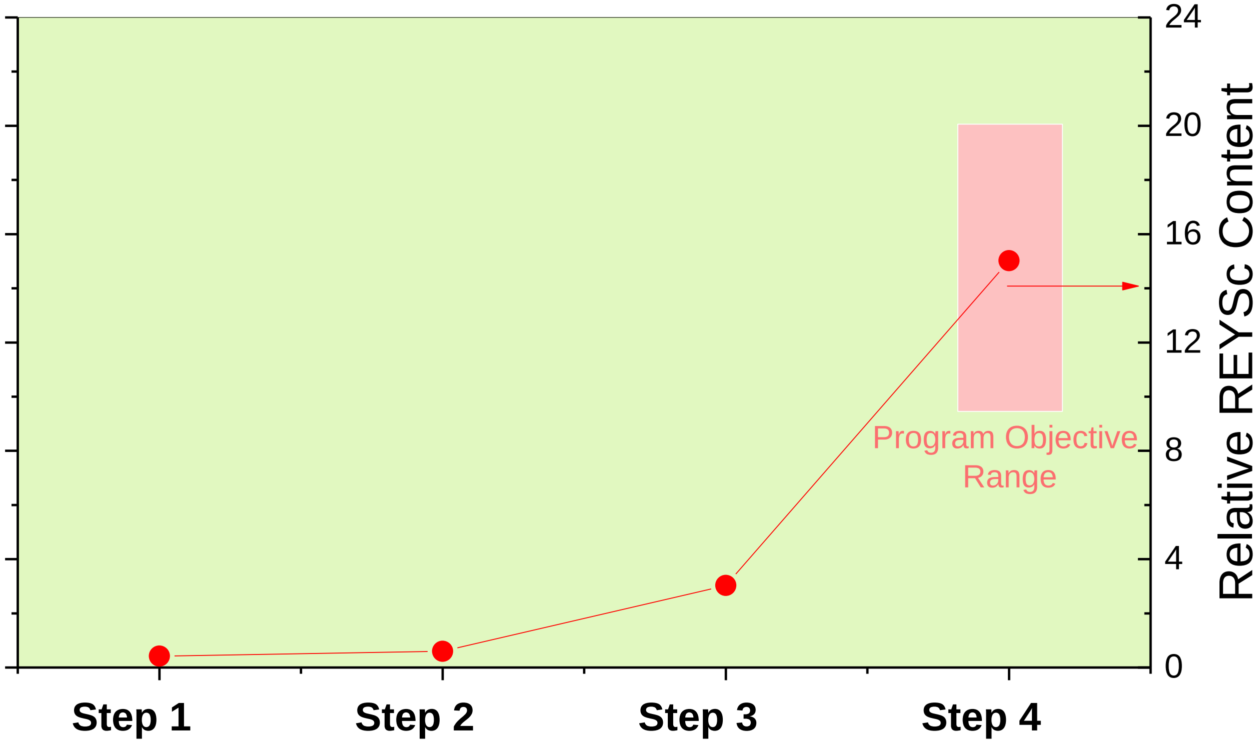

- REYSc concentration sequentially increased as material moves through chemical processing stages

Total REYSc relative content in final micropilot concentrate is >10 wt.%, meeting threshold program objective.

Chemical Pilot Operations

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- Chemical pilot designed to process 0.5 tons/day of coal ash
- Situated on the floor of a former torpedo factory
- All unit modules are currently operational

Hot and Cold Side Operations

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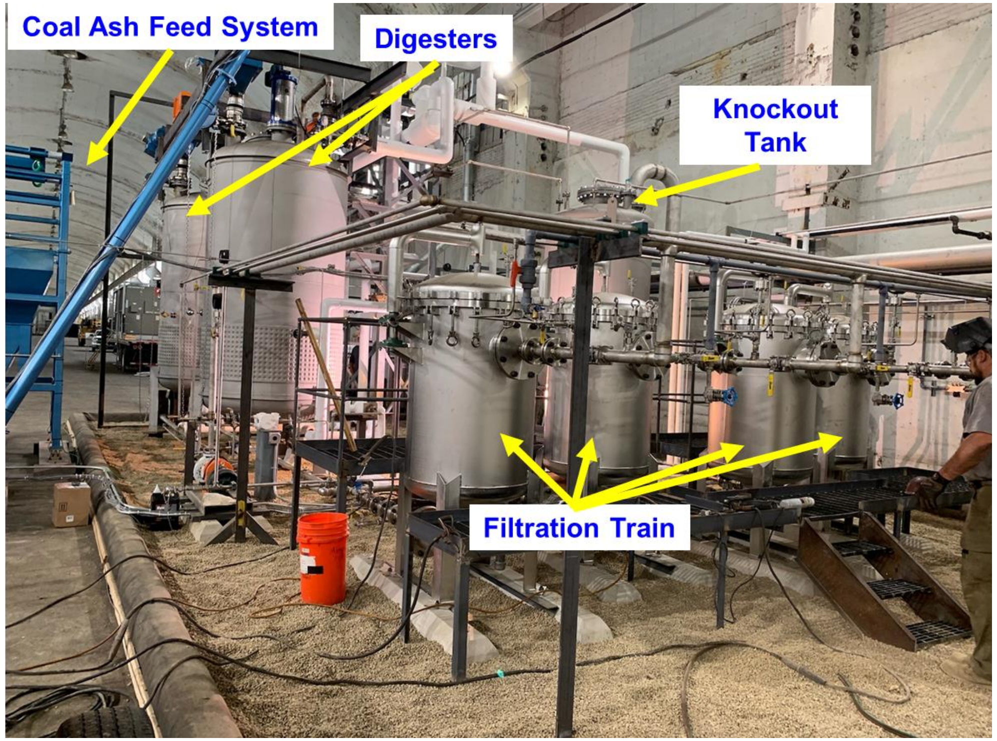
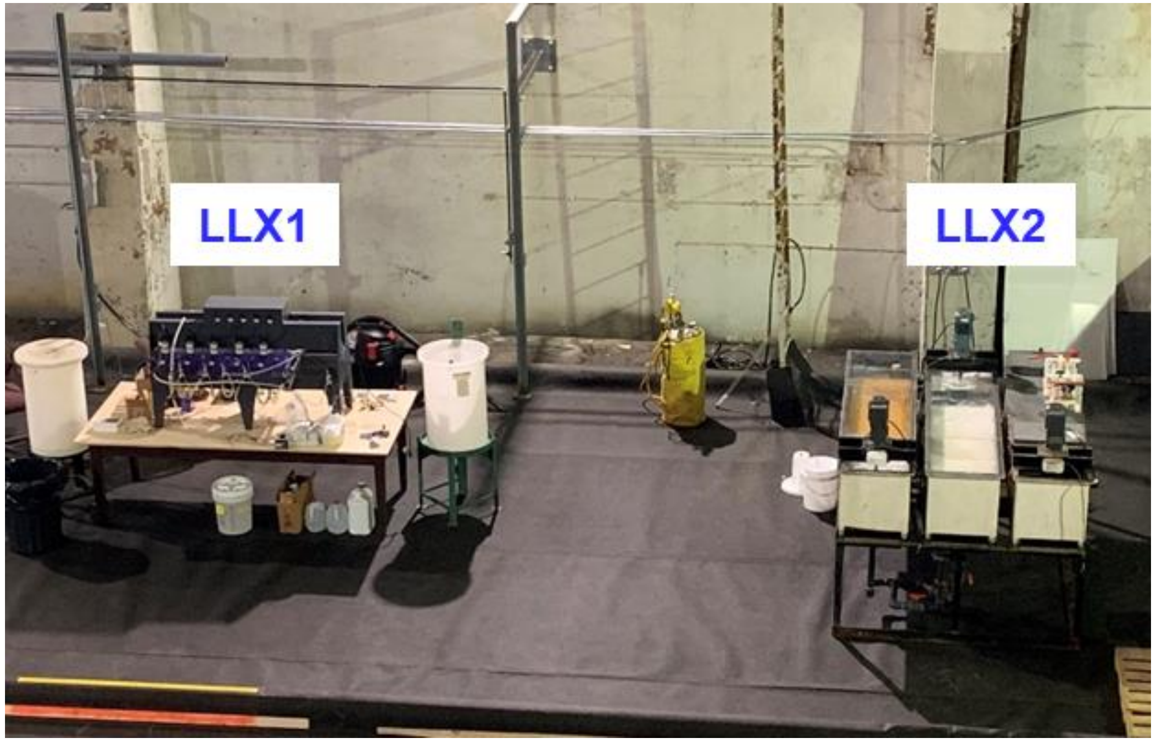


Hot Side Operation



Cold Side Operation

WWS chemical pilot plant operational and ~5 tons of coal ash processed to date; >20% yield for REYSc concentrate, >50% purity (elemental basis). Deliverable REYSc concentrate production ongoing

Plant can process various pulverized feedstocks: coal ash, coal, refuse

Chemical Pilot Plant Status Update

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- Multiple ash batches processed from different sources (Ash C, Ash D)
- Materials sampled at various process stages analyzed via ICP-OES/MS
- Final product has REE concentration of up to 66.7% (elemental basis)
  - Further optimization expected to increase final concentrate REE content

Pilot Plant Data	Run 1	Run 2	Run 3	Run 4
REYSc Elemental Content	14%	11.9%	66.7%	29.1%
Ash	Ash D	Ash C	Ash C	Ash C

Dried Product Composition

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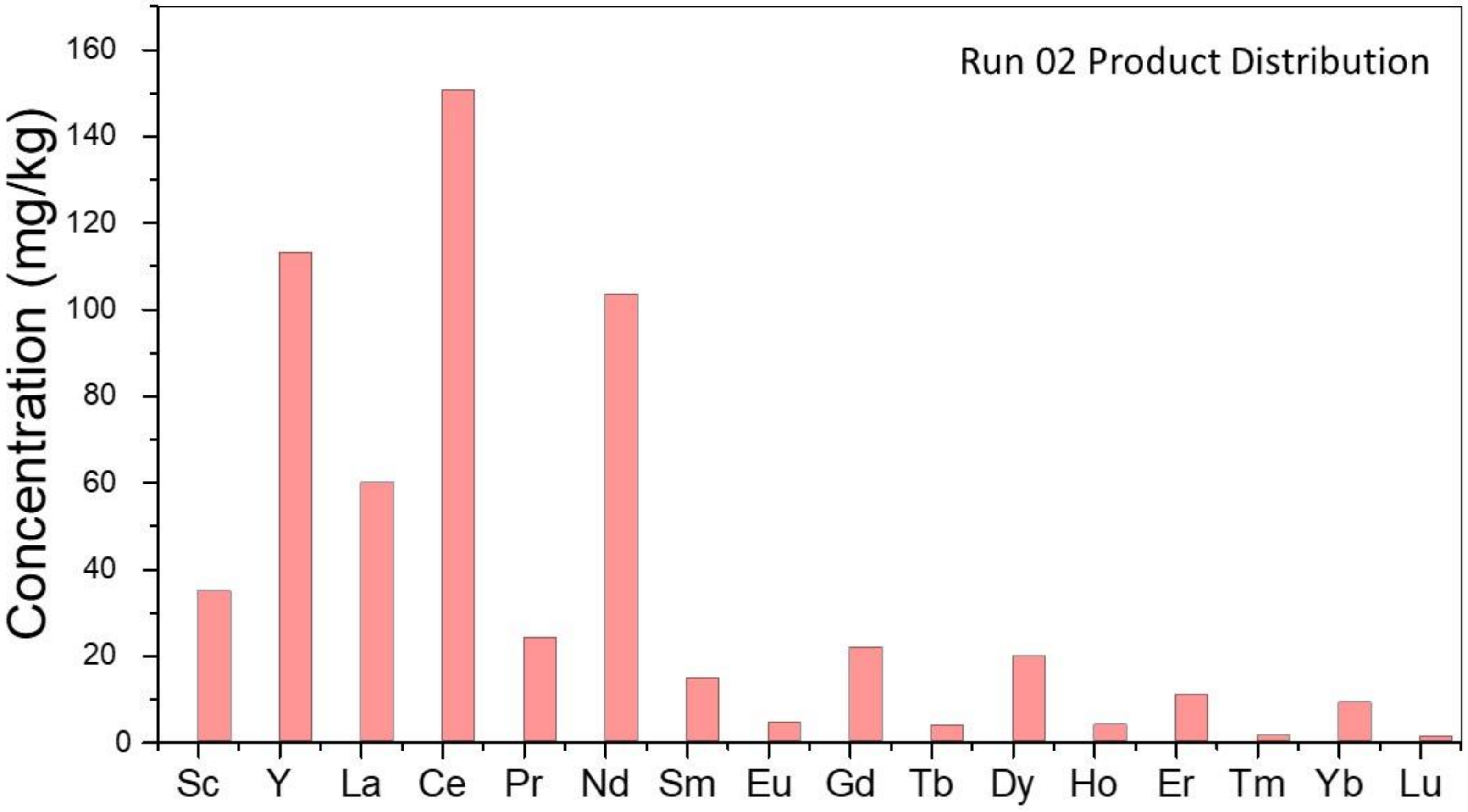

Product compositions are above objective key performance parameter (>20 wt.%).

Significant quantities of Nd, Y, Sc and HREE in product material.

Pozzolanicity Testing – Strength Activity Index

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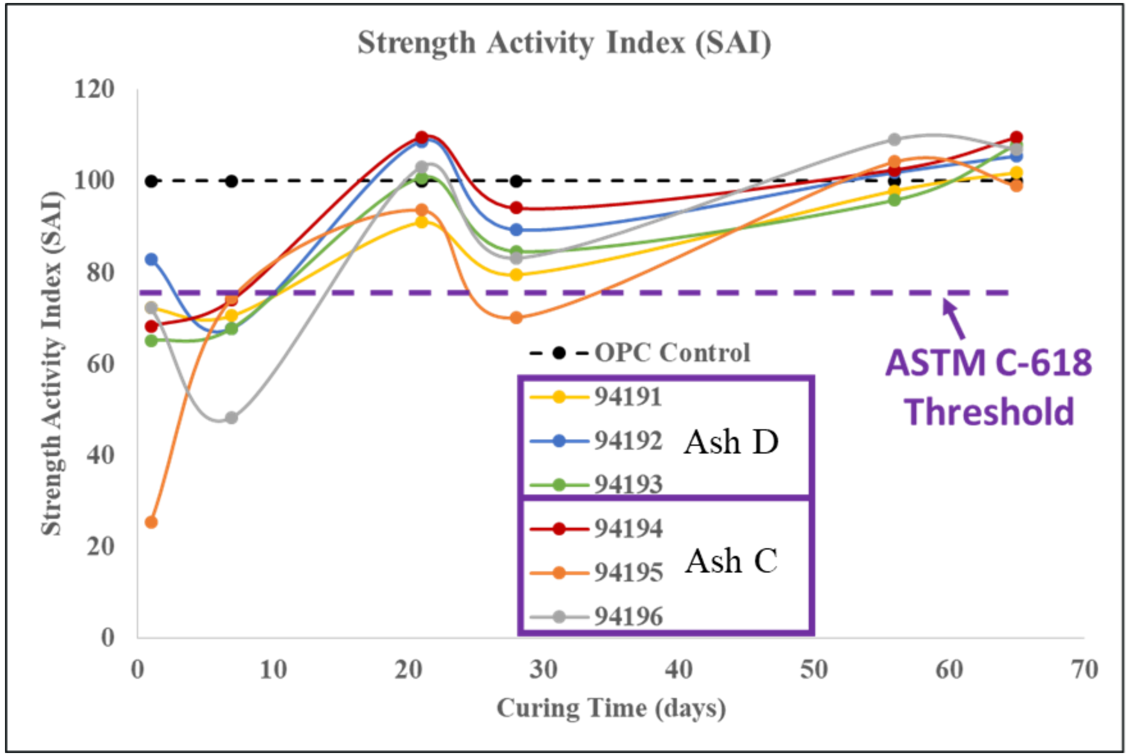
- Strength Activity Index or SAI: how the coal ash contributes to the strength of concrete.
- Typically measured as the compressive strength of a standard mortar mix with fly ash substituting for 20 wt% Portland cement; a defined period of curing.
- SAI is then compared as a ratio (percent) to a mortar with 100% Ordinary Portland Cement (OPC).
- ASTM C-618 SAI threshold passing criterion is 75% at 7 days or 28 days (Purple line).
- The processed fine ash utilized at 20% replacement of OPC achieved a strength index greater than 75 by 28 days of curing in 5/6 cases.



Techno-economic Modeling Approach – Phase 1

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- Chemical processing and economics modeled in Aspen Plus
  - Capital and operating expenses per model
    - Modified per our team’s experience
  - Result: Pro forma spreadsheet model
- Physical processing economics modeled
  - Capital and operating expenses per CAER and WWS experience
  - Result: Pro forma spreadsheet model
- Integrated process economics modeled
- Added capital expenditures of physical and chemical processes
- Modular, transportable physical and chemical processing plants
- Phase I Model: AACE Level 3

Phase 2 model improves fidelity.
Currently AACE Class 2-3

Capacity, Products and Annual Production

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Plant Size: 1200 tpd ash physical processing plant and 600 tpd chemical processing plant
Plant Attributes:
- Co-located at ash source to significantly reduce transportation costs; Decoupled operations
- Modular designs for operational flexibility and transportability

Ash fractions shipped to local markets
- Carbon, magnetic ash, > 200 mesh non-magnetic ash

Annual production of major REE salts, Sc salt, and byproducts:

Component	Quantity Produced* tons/year	Portion of Revenue (%) 2020 REE Pricing	2011 REE Pricing	Worldwide Market tons/year	Market Application
REEs	38.2	2.0	10.8	170K	Batteries, Magnets, Alloys, Catalysts
Scandium	5.8†	20.4	35.0	10-15	Alloys, Catalysts
Carbon	96K	6.7	4.6		Low-grade Fuel
Magnetic	20K	7.0	4.0		Magnetite Substitute
Non-Magnetic >200 Mesh	48K	1.1	0.8		Geopolymer Feed
Non-Magnetic <200 Mesh	186K	23.5	17.8	71.8M	Cement Substitute (Pozzolan)
Cenosphere Product	2K	39.3	27.1	~51K	Concrete Additive

- Non-REE products significantly offset effects of REYSc commodity price fluctuations
  - Pricing of non-REYSc products varies with general economic conditions

†Sc_2O_3 market demand expected to reach 25,000 kg by 2023**

Preparing Project for Next Steps

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- Our process and equipment are designed to be flexible: modular and transportable.
- Pilot project utilizes standard commercial equipment that lends itself to scaling up via sizing and/or multiple parallel modular units.
- A team experienced in FEED studies, A/E design, and commercial scale plant design and implementation has been assembled.
- Commercial scale REY and CM production from coal ash possible in 2023-2024 timeframe.

Project develops a technology that will provide a domestic supply of REE-rich concentrate for downstream separation and refinement into individual REE, and for recovery of other critical elements.

Concluding Remarks

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- **U.S. fly ash is an attractive feedstock with rare earths content sufficient for economical recovery of REYSc, particularly, the heavy rare earth elements**

- **Demonstrated operational pilot plant (0.4 tpd) for physical separation processes**
  - Optimized processes to produce selected ash fraction as feedstock for the chemical processing
  - Valuable by-products: cement substitute, cenospheres, secondary fuel carbon

- **Pilot plant for chemical processing (0.5 tpd) now operational**
  - Optimized processes validated in micropilot plant operations
  - REYSc concentrates as main products (~66% content achieved on elemental basis)
  - Beneficiated ash as valuable by-product

- **Commercially viable processes demonstrated by techno-economic analysis**
  - Currently AACE Class 2/3

- **Next steps include increase in product purity and production of additional CMs**

Thank you!

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Backups

AACE Estimate Classes

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	Primary Characteristic	Secondary Characteristic		
ESTIMATE CLASS	**MATURITY LEVEL OF PROJECT DEFINITION DELIVERABLES** Express as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges[a]
Class 5	0% to 2%	Concept screening	Capacity factored, parametric models, judgment, or analogy	L: -20% to -50% H: +30% to +100%
Class 4	1% to 15%	Study or feasibility	Equipment factored or parametric models	L: -15% to -30% H: +20% to +50%
Class 3	10% to 40%	Budget authorization or control	Semi-detailed unit costs with assembly level line items	L: -10% to -20% H: +10% to +30%
Class 2	30% to 75%	Control or bid/tender	Detailed unit cost with forced detailed take-off	L: -5% to -15% H: +5% to +20%
Class 1	65% to 100%	Check estimate or bid/tender	Detailed unit cost with detailed take-off	L: -3% to -10% H: +3% to +15%

Notes: [a] The state of process technology, availability of applicable reference cost data, and many other risks affect the range markedly. The +/- value represents typical percentage variation of actual costs from the cost estimate after application of contingency (typically at a 50% level of confidence) for given scope.