VG-2017-018

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

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DOE Award #: DE-FE0027167
Period of Performance: 3/1/2016 – 8/31/2017

*Presentation to:*
2017 Rare Earth Elements Portfolio Review (DOE/NETL)
Pittsburgh, PA

22 March 2017

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# Project Goals and Objectives

Physical Sciences Inc.



- **Overall Project Goal (Phases 1 and 2)**
  - Develop a pilot scale plant to demonstrate feasibility of economically producing from coal ash
    - High-yield REYSc concentrates, and
    - Commercially viable byproducts and co-products, using
    - Environmentally safe physical and chemical enrichment processes

- **Phase 1 Project Objectives:**

  *Phase 1 performance metrics:*
  - Threshold Values > 2 wt% requirements of the solicitation
  - Threshold values will be used for the GO/NOGO evaluation criteria

| Parameter | Proposed Performance Range | Phase 1 Results and Values Used |
|---|---|---|
| Wt% of REY in dry nitrate concentrate final product | ~ 5 wt%, threshold<br>> 10 wt%, objective | > 10 wt%; Prop. Prod.<br>> 30 wt%; Product 1 |
| Ash feedstock REY Content | ~ 300 ppm threshold<br>> 500 ppm objective | 556 ppm |

| Milestone | Program Month | Planned Completion Date |
|---|---|---|
| Kickoff Meeting @ DOE/NETL | 1 | 10 March 2016 |
| Sampling and Characterization Plan | 1 | 29 March 2016 |
| Technical Interchange Mtg. (TIM) #1 @UK/CAER | 3 | 31 May 2016 |
| Interim Review # 1 @PSI | 6 | 31 August 2016 |
| TIM #2 @ ECL | 9 | 08 December 2016 |
| Phase 1 Feasibility Study Results | 11 | 31 January 2016 |
| GO/NOGO | 12 | 21 February 2017 |
| Interim Review #2 @ DOE/NETL | 12 | 21 February 2017 |
| Phase 1 Design Package | 14 | 31 May 2017 |
| Phase 1 Summary Report | 14 | 31 May 2017 |
| Phase 2 Proposal | 14 | 31 May 2017 |
| TIM#3 Teleconference | 15 | 31 May 2017 |
| Phase 1 Final Briefing @DOE/NETL | 18 | 31 August 2017 |

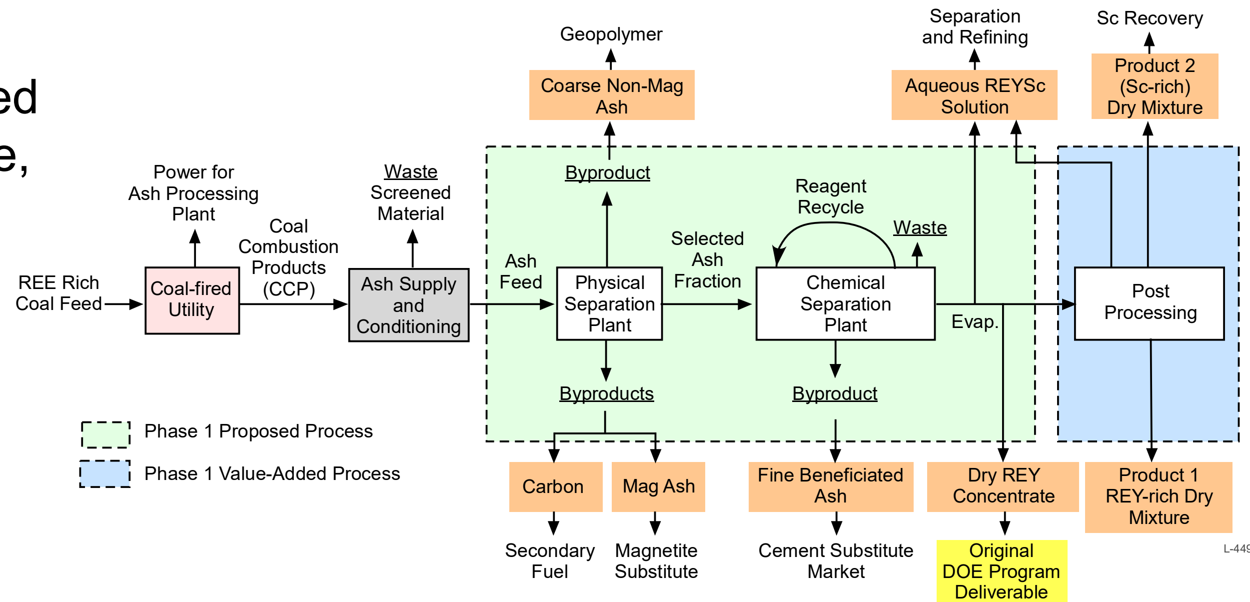
# Outline



- **Process Overview**
- **Project Specific Objectives**
- **Ash Source: Selection and Characterization**
- **Physical Processing**
- **Chemical Processing**
- **Techno-Economic Model**
- **Summary**

# Process Overview

- **Physical separation stage, followed by a chemical separation stage, followed by a post-processing stage**
- **<u>Proposed Product:</u> REYSc-enriched mixture (dry concentrate)**
- **<u>Higher Value Products:</u> REY-rich & Scandium-rich concentrates**
- **<u>By-products:</u>**
  - Conventional/beneficiated ash as cement substitute, carbon as supplementary fuel, magnetic ash (magnetite substitute), geopolymer



# Project Specific Objectives

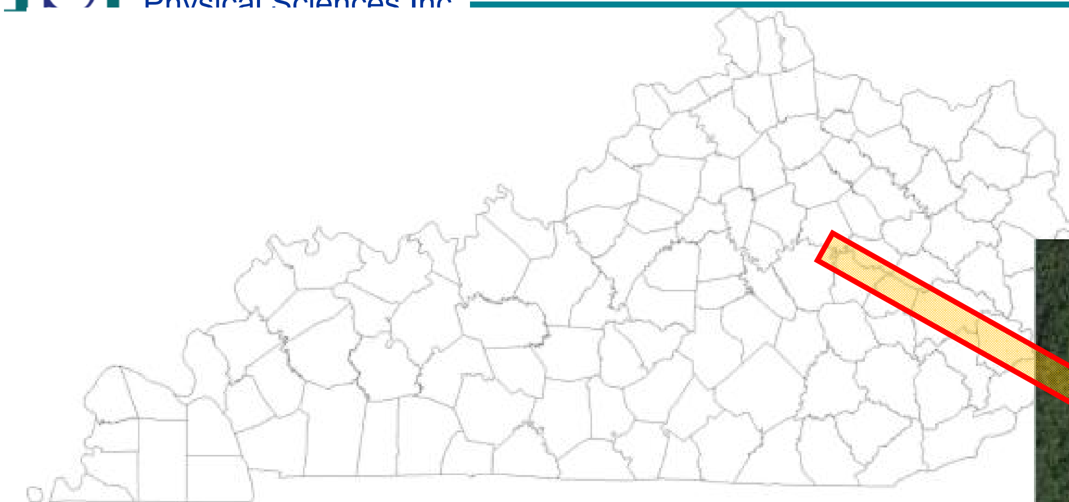


- **Characterize ash feedstocks for total REYSc (REE + Y + Sc) content as well as distribution of the REE within ash particle morphologies**
  - Measurement protocol: ASTM D6357-11-1
- **Optimize the bench scale processes for REYSc enrichment already developed by PSI**
  - REE Enrichment Metric: ~ 5%
- **Perform key process experiments to anchor model below**
- **Develop a techno-economic process model that includes:**
  - Ash feedstock and reagent inputs, recycling of reagents, REYSc and by-product outputs of commercial value, accounting for market forecasts, mass balances and energy expenditures, and capital and operating expenses
- **Use above model to design a pilot scale REE enrichment plant**
  - Nominal capacity 1-5 tons (0.5-2.5 $m^3$) of ash processed per day
  - Identify parameters for economical operation of plant

# Ash Source: Selection and Characterization

# Selected Ash Source: Dale Location






- Plant located near Ford, KY

# Selected Ash Source:
# Dale Ponds and Power Plant





*July 2014 sampling trip*

- 20 samples collected from several locations; a composite sample created for analysis and experimental work

# REE in Selected Ash Fraction: HRTEM Analysis



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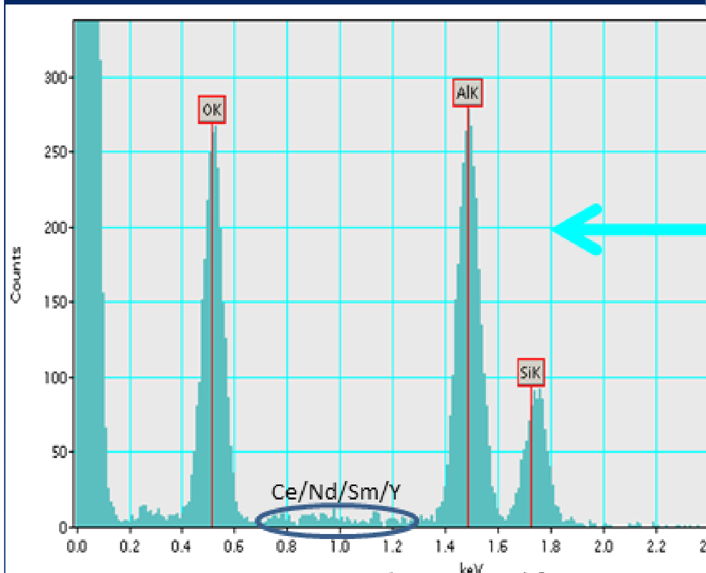
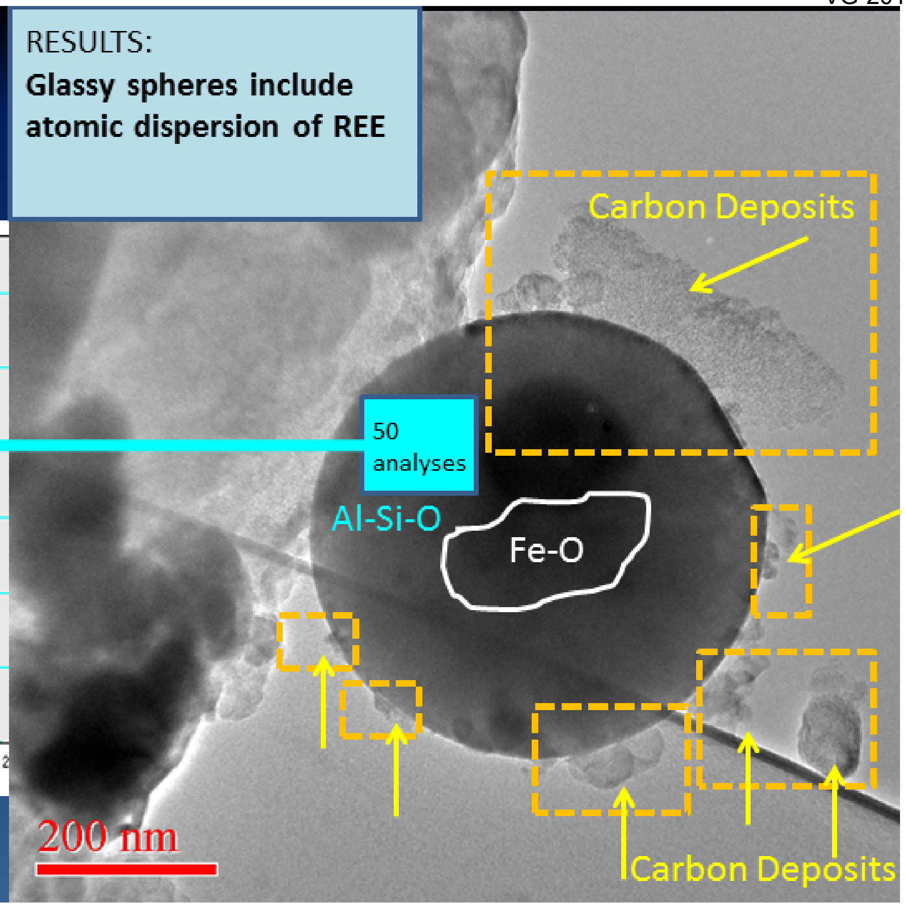
## 75805: <200 mesh:

Nd (173) Ce (152) La (70) Y (38)

RESULTS:
**Glassy spheres include atomic dispersion of REE**




Representative EDS Spectrum (50 analyses) for Al-Si-O glassy sphere: REE peaks correspond to Atomically dispersed Ce/Nd/Sm and Y.

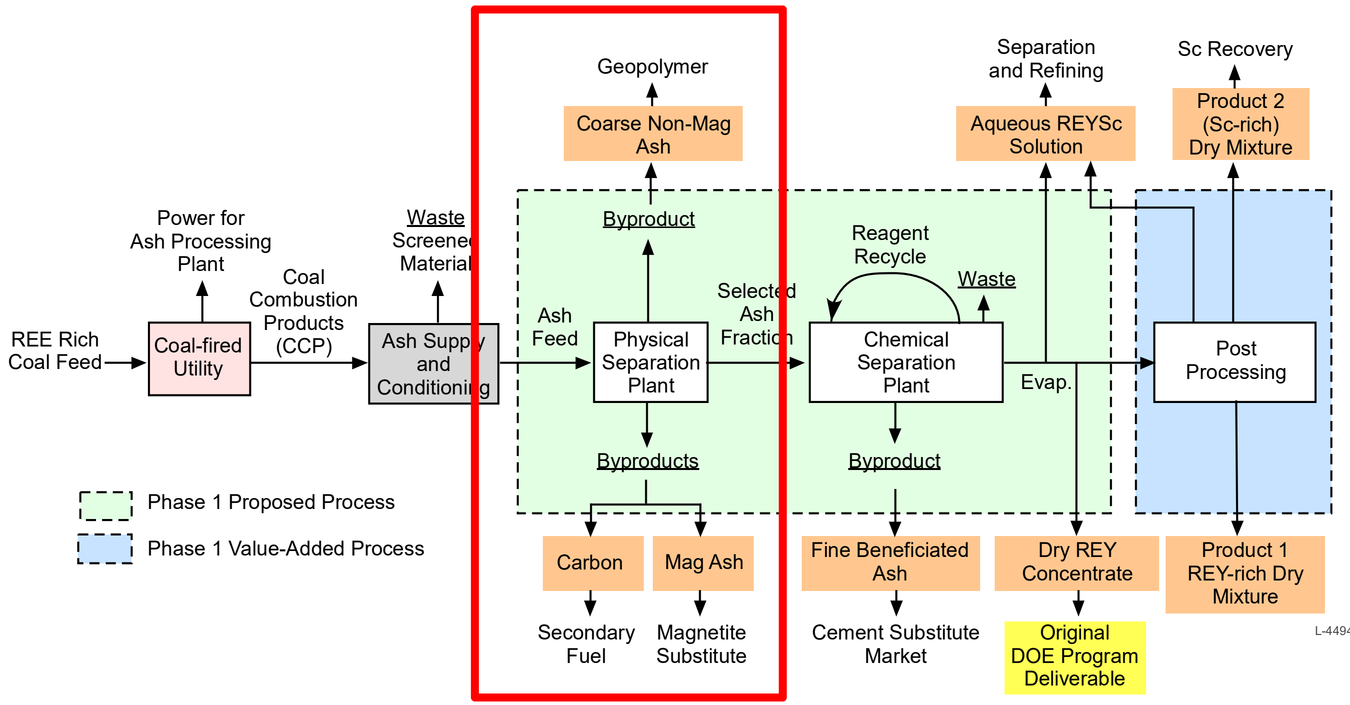


# Ash Selection and Characterization



- **Ash source analyses and selection completed**
  - Analyzed four PCC power plant ash sources that use primarily Eastern KY coal & one FBC power plant ash source that uses anthracite/culm from Central PA
    - Cooper, Williams, Brown, and Dale (PCC), plus Northampton (FBC)
  - All ash sources analyzed via ICP-MS; REYSc content > 500 ppm
- **Ash from Dale power station, Ford, KY was selected as ash source for plant demonstration on Phase 2 of this program**
  - REYSc = 556 ppm, exceeding 500 ppm objective requirement
  - ~ 2Mt of ash reserve; ~1200 tons REYSc reserve (~10% of US annual demand)
  - Adequate for 1200 tpd commercial scale plant (~1.5% annual demand for ~ 7 y)
  - A vast reserve for an envisioned 1-5 tpd pilot plant
- **Feed ash, physically separated ash, and chemically pre-treated ash characterized via various optical/other techniques**
  - REE concentrates present in glassy ash particles in feed ash
  - REE also present in carbon deposits around glassy particles

# Physical Processing



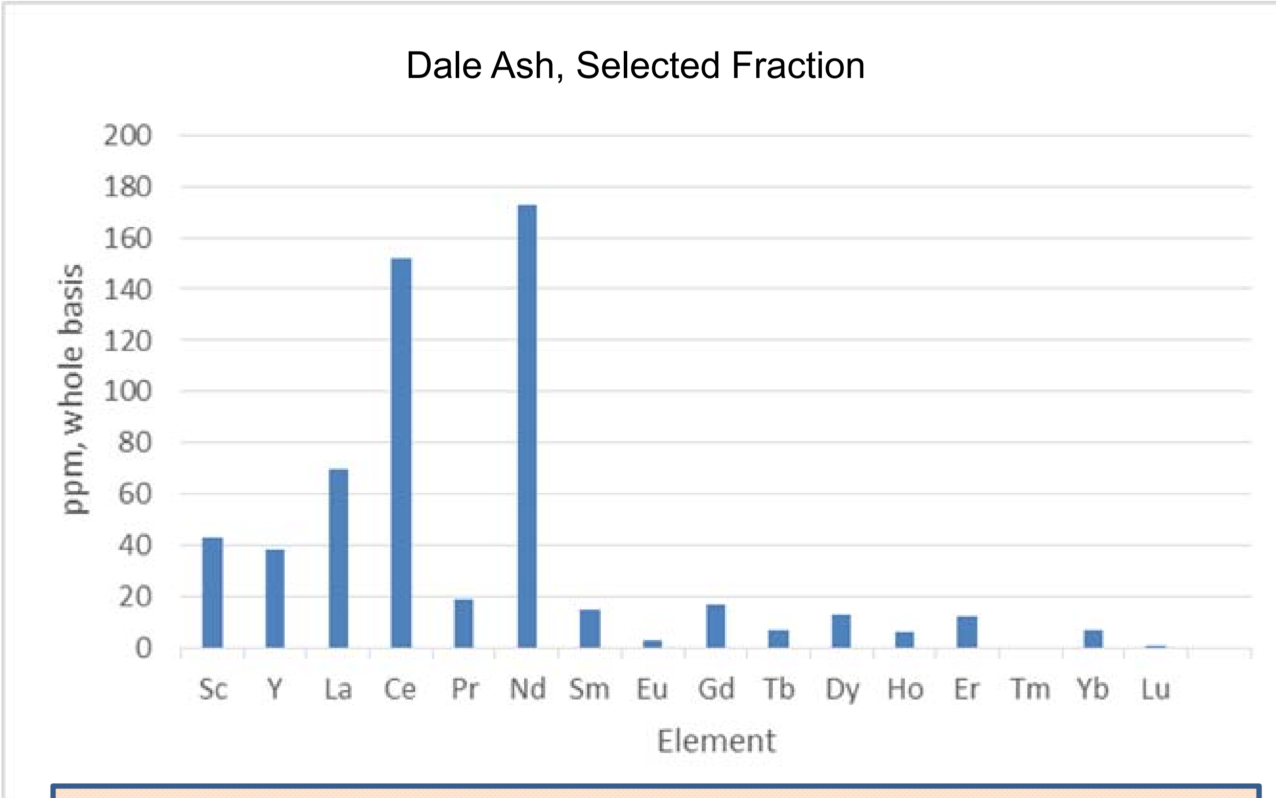
# Summary of Results



- **Each of the five ash sources were separated into five fractions**
  - +60 mesh (>250 µm): Oversize, discarded
  - Froth product (principally C): Use as supplementary fuel, higher C products
  - Magnetic: Use as cheap magnetic substitute
  - Non-magnetic:
    - +200 mesh (>75 µm): Use as conventional cement substitute
    - -200 mesh (<75 µm): High REY content fraction for chemical processing
- **Developed flowsheets for physical separation process**
- **Developed a spreadsheet economic model of the process**
- **Integrated physical processing with the chemical process model, and used for techno - economic assessment**

# Individual Rare Earth Elemental Content for Selected Ash Fraction






Significant content of Nd (~170 ppm), Y (~70 ppm), and Sc (~40 ppm)
Reasonable (>~10 ppm) content of Pr, Gd, Dy, Er, Tb

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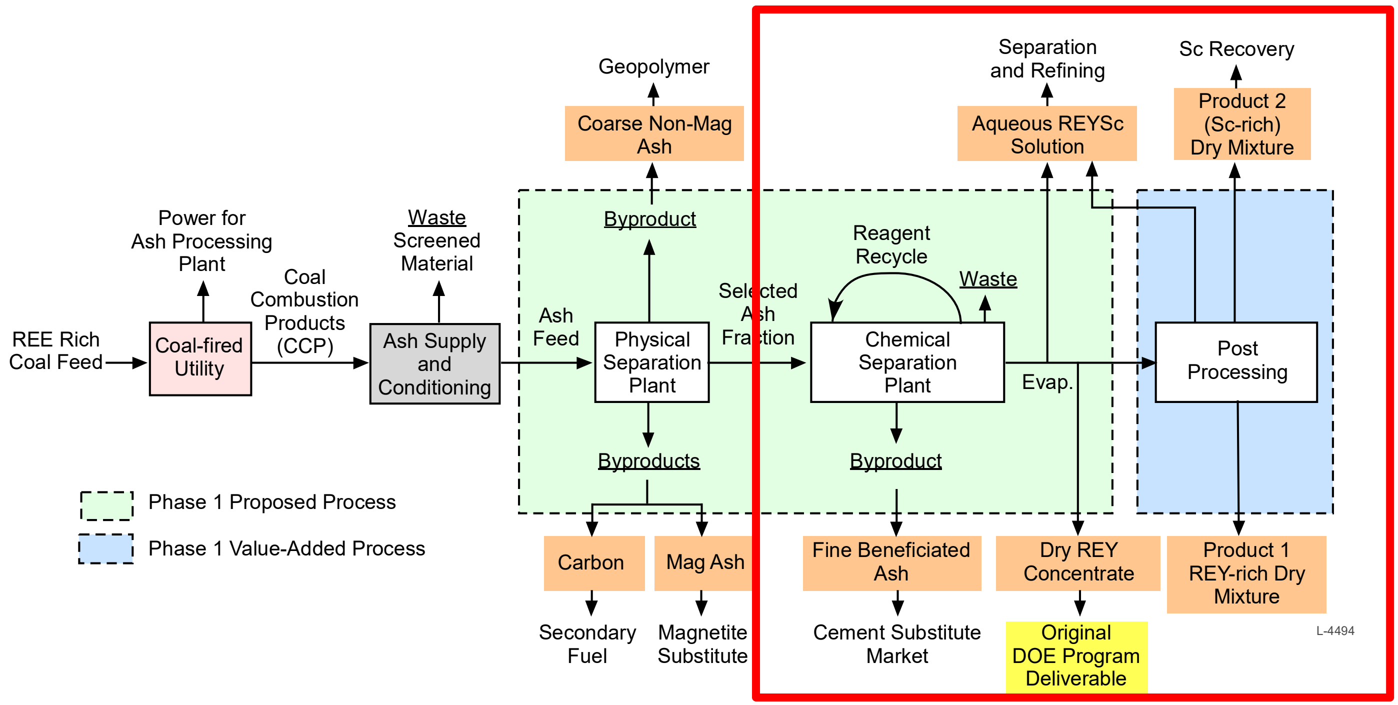
# Chemical Processing



# Summary of Results

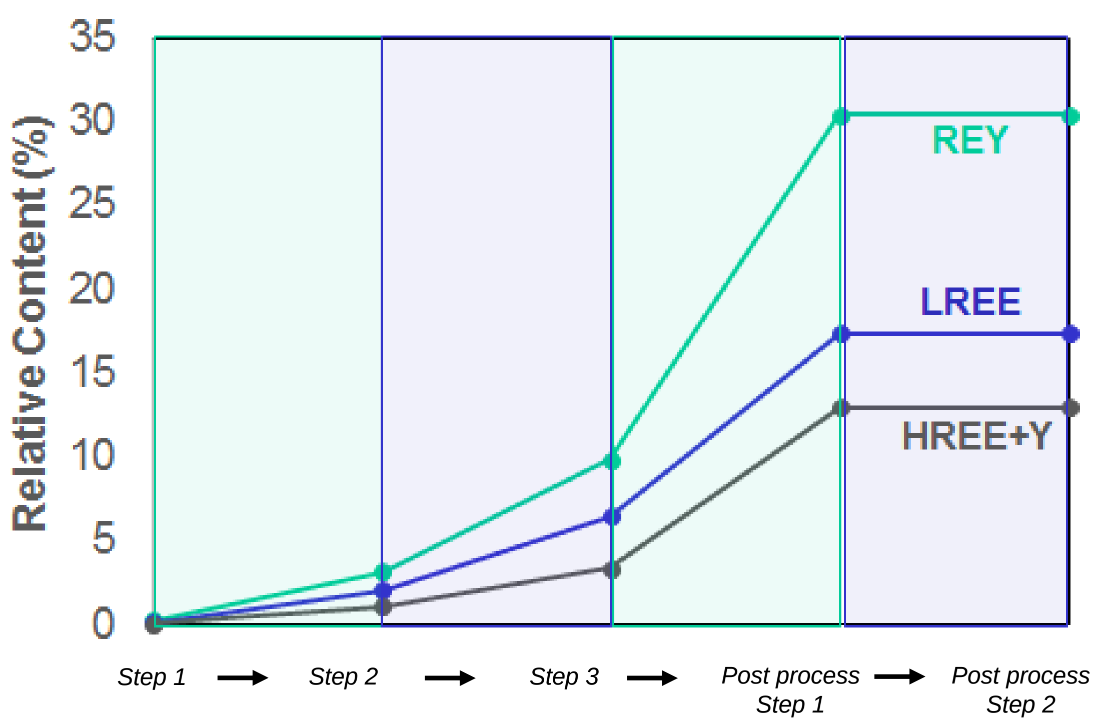


- **Determined optimal parameters for each process step to recover REE from Dale ash at high yield consistent with high enrichment**
- **Developed post-processing steps that yield two higher value product streams**
  - REY-rich: REY Yield > 18%, Conc > 30 wt%; Sc Yield ~ 18%, Conc ~ 0.5 wt%
    - REE conc >> objective target (10 wt%)
  - Sc-rich: Sc Yield ~ 18%, Conc ~ 1.5 wt%; REE Yield > 4%, Conc ~ 6 wt%
    - REE conc >> threshold target (5 wt%)
- **Reduced process time for individual steps and avoided elevated temperatures**
- **Experimental development of process scale up**
- **Process implementable on commercial scale; requires different optimization parameters for project economics**
  - Tradeoff some of the high REYSc yield/enrichment to achieve better economics

# REY and Sc Relative Content (Enrichment wt%)



- **Post-processing step 1 leads to:**
  - 3X increase in REY enrichment
  - Efficient separation from other contaminants
  - Product well-suited for REY separation



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# Techno-Economic Modeling

# Techno-Economic Modeling Approach



- **Chemical processing and economics modeled in Aspen**
  - Capital and operating expenses per model
    - Modified per Equinox experience
  - Result: Pro forma spreadsheet model

- **Physical processing economics modeled**
  - Capital and operating expenses per CAER experience
  - Result: Pro forma spreadsheet model

- **Integrated process economics modeled**
  - Added capital expenditures of physical and chemical processes
  - Physical process <u>decoupled</u> from chemical
  - Physical *and* chemical processing performed on-site at Dale pond
    - Save transportation costs

# Techno-Economic Modeling Results

## *Capacity, Products and Annual Production*



- **A nominal 1200 tpd physical processing plant and 600 tpd chemical processing plant needed for**
  - Return on Investment (ROI) of < 5 years
- **Both physical and chemical processing plants**
  - Collocated at ash source to eliminate transportation costs; Decoupled ops
  - 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, Sc, and Y nitrate concentrate (kg)**

| | LREE | | | | H | R | E | E | | Other HREE |
|---|---|---|---|---|---|---|---|---|---|---|
| Sc | La | Ce | Pr | Nd | Eu | Gd | Tb | Dy | Y | Ho, Er, Tm, Yb, Lu |
| 11K | 11K | 9K | 300 | 10K | 350 | 2K | 300 | 2K | 14K | 300-800 |

  - $Sc_2O_3$ production worldwide (2013) ~ 10K kg, Our oxide equivalent ~ 3000 kg
- **Annual production of byproducts (kg)**

| Carbon | Magnetic | Non-mag > 200 mesh | Non-mag < 200 mesh |
|---|---|---|---|
| 100K | 21K | 50K | 124K |

# Summary





- **The PSI team has effectively addressed the technical and economic aspects of recovery of trace REYSc elements from coal ash for our proposed physical and chemical separation processes**
- **Ponded ash from Dale power plant in Ford, KY was selected as the ash source for demonstration of key process elements on pilot scale as well as a potential source for a commercial scale plant**
  - > 500 ppm REYSc
- **Both physical and chemical processing plants are collocated at ash source for process economy; their modular designs will permit transportability from one ash source to another**
  - 1200 tpd (~ 500 $m^3$/d) physical processing, 600 tpd (~ 250 $m^3$/d) chemical processing
- **For our processes with the 600 tpd throughput, reagent costs have the most significant influence on Return On Investment (ROI)**
  - High efficiency recycling/re-use of reagents is required