Rare Earth Elements

RIC Portfolio Overview & Recent Successes

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U.S. DEPARTMENT OF ENERGY

RIC Portfolio Strategy

How We are Approaching the Problem

- **Understanding & Finding the Best Resources**
  - Understanding REE occurrences in coal and related measures
  - Finding the high-quality resources: high concentration, easily extractable, abundant quantity
- **Making the Numbers Work**
  - Discovering Production Pathways
  - Identifying the Barriers Holding Industry Back
- **Enabling Domestic Innovation**
  - Developing the cutting edge CFD models to help drive commercialization and scale up
  - Identifying process bottlenecks, research targets, and market opportunities through systems analysis

Understanding the Resource

Important to see both the Forest and the Trees

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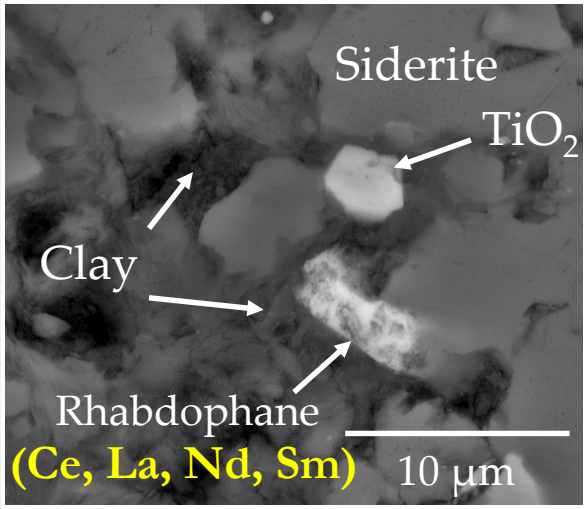
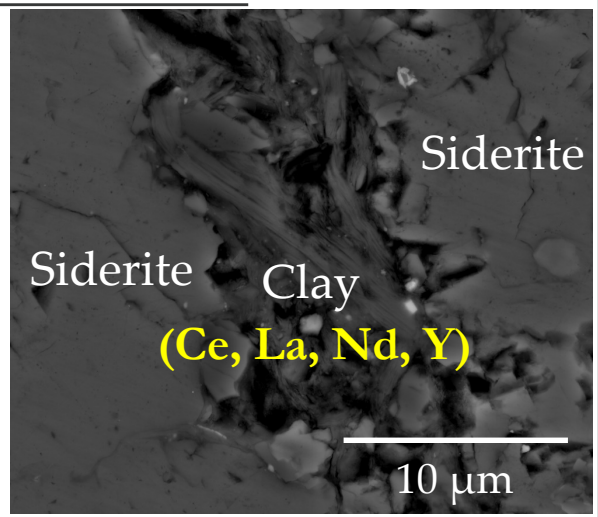
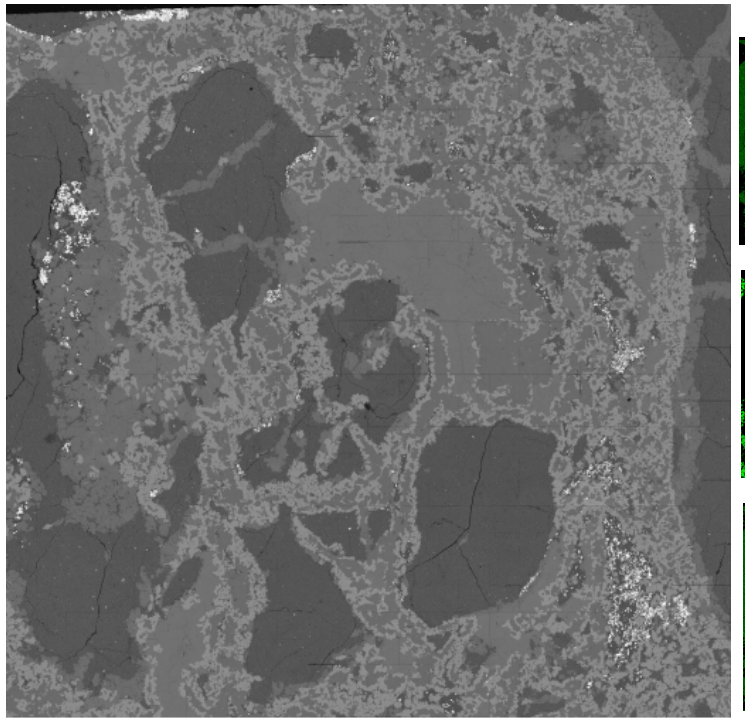
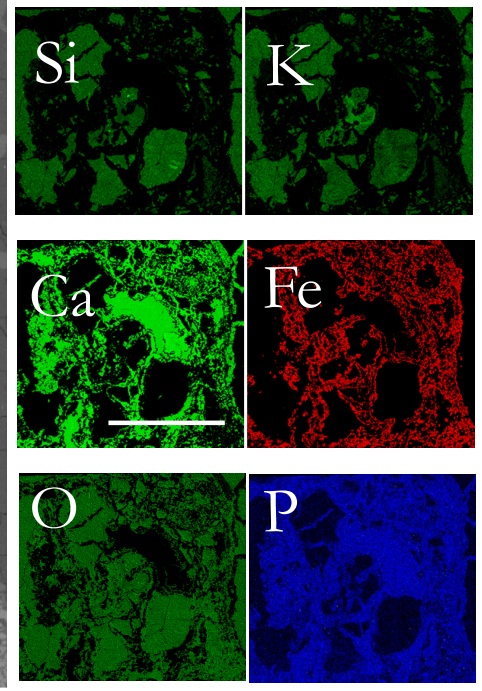
Individual Minerals



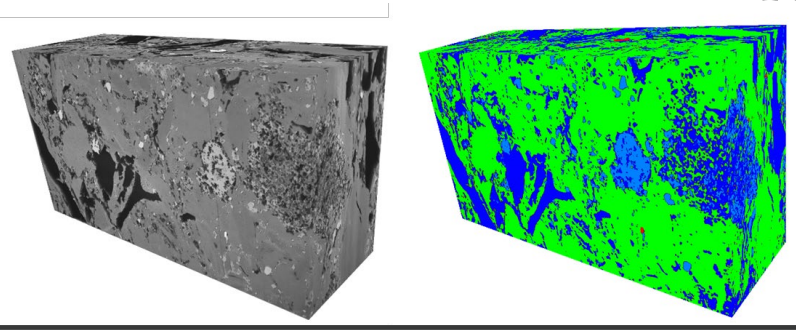


Bulk Material & Phases (650 images)





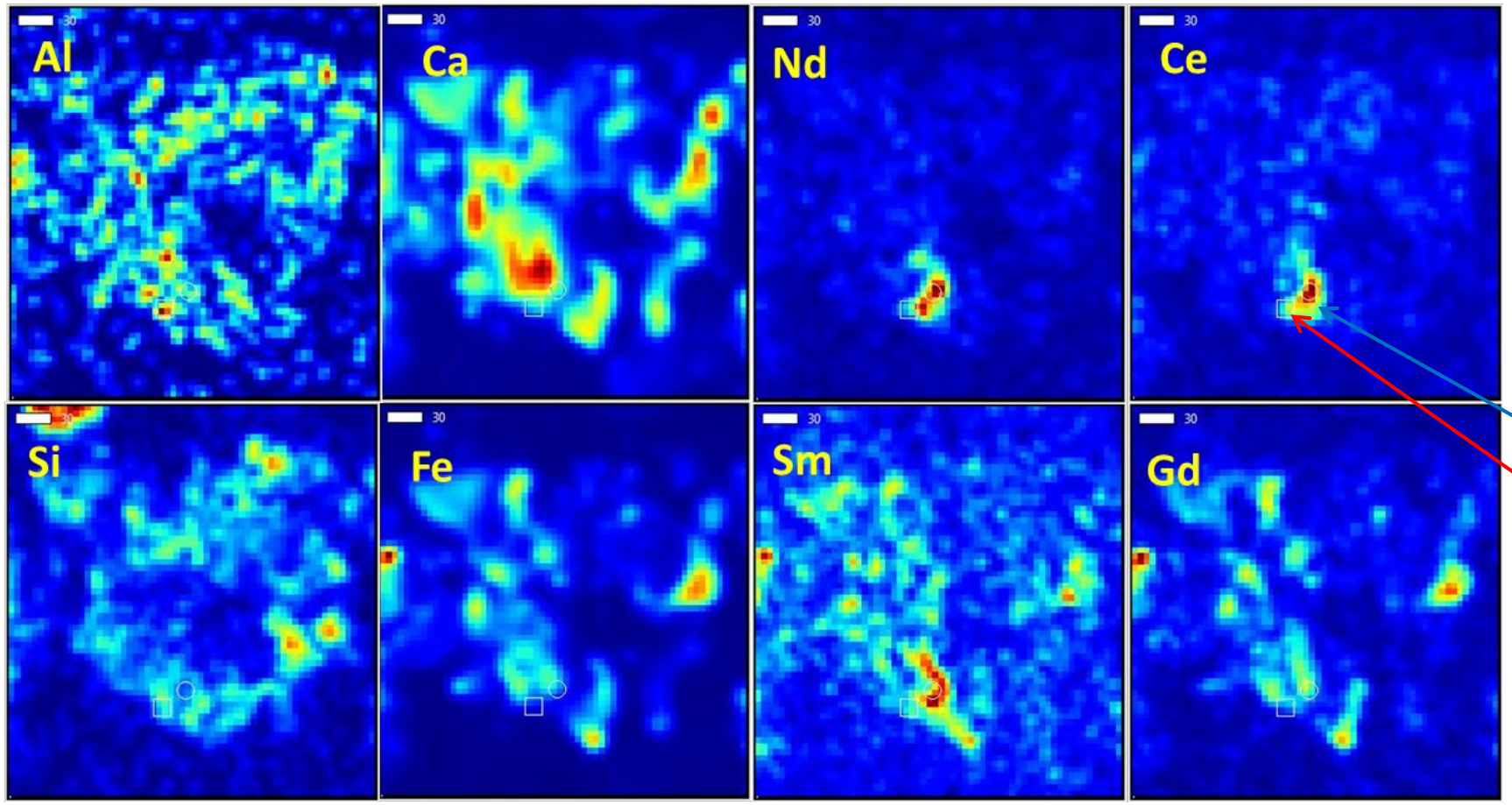
3-D Pore Volume & Density Mapping

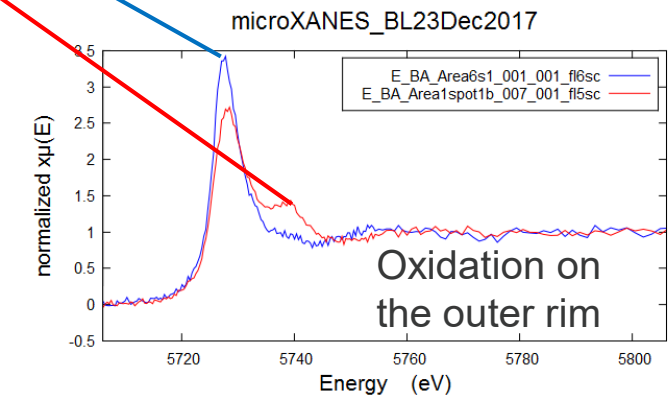


Understanding the Resource

Identifying REE Phases to Target Using the Synchrotron

Analysis informs which REE to target based on oxidation state & binding environment





Light REEs (e.g. Ce, Nd) w/ Ca-rich AlSi, and heavy REEs (e.g., Sm, Gd) w/ Fe-rich AlSi

Recovery from Acid Mine Drainage

Field Test at Pittsburgh Botanic Garden, formerly an Abandoned Mine

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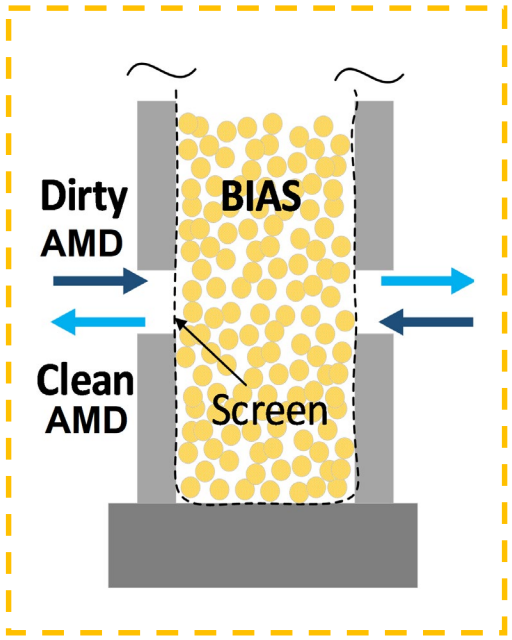
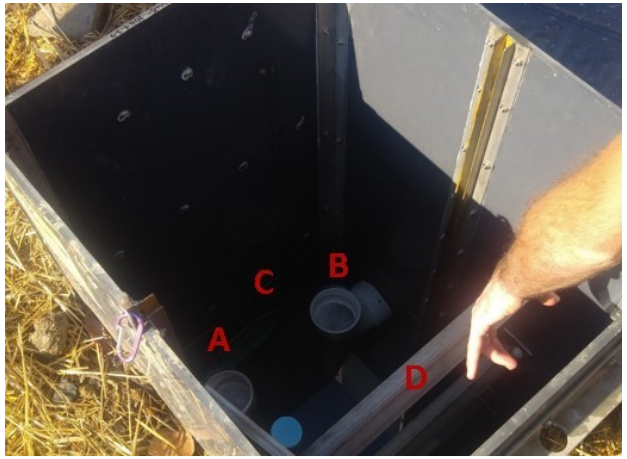
BIAS Sorbent "Reactor"



Reactors Placed in AMD Treatment System Inlet



AMD Enters Passive Treatment System (after REE removal)

Recovery from Calcium-rich Ash

Targeting Powder River Basin (PRB) Ashes to Reduce Extraction Steps & Conditions

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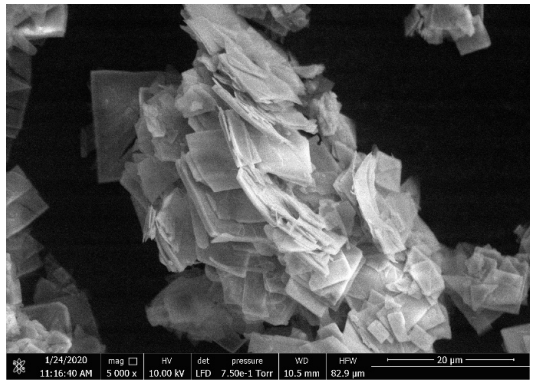
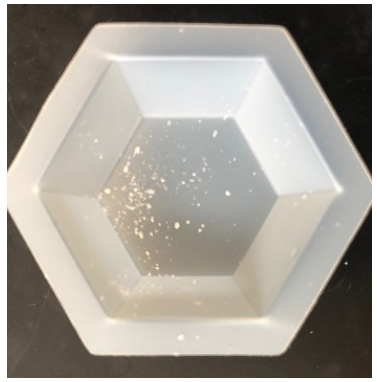
PRB Fly Ash

96wt% Pure Rare Earth Oxide (REO)





From Bench to Pilot: $1.6 million TCF Project

Wyoming partners committed to technology maturation:

- University of Wyoming School of Energy Resources
- Campbell County
- City of Gillette

State, Campbell County pursue rare earth opportunities

By Greg Johnson, Gillette News Record | Via Wyoming News Exchange Jul 5, 2020 Comments OPEN ACCESS

Rare Earth Elements Project Receives Federal Funding

NEWS DIRECTOR | Article Updated: June 23, 2020 | COMMENTS OFF

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Recovery from Ash via Controlled Fusion

Creating Synthetic Monazites and Sands from Coal Ash and Slag

Monazite: A Naturally Occurring Source of REE

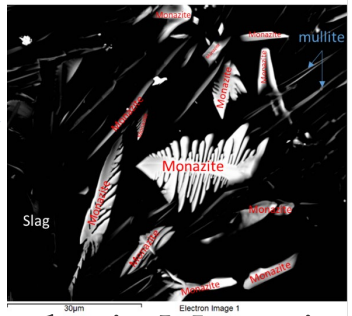
Monazite ore

Monazite sand

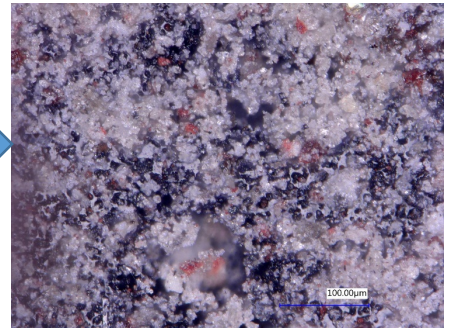
Monazite mine in Australia

Coal Ash "sand": Synthetic Monazites & REE Phosphates

Fusion & Controlled Cooling



Synthetic Monazite or REE Phosphate



Coal "Sand"

Conventional Monazite Processing Stages

Natural monazite image: Indian Journal of Marine Science, Vol. 33(2), June 2004, pp. 138-149
Monazite mine image: Krakatoa Resources, LTD. Website, accessed August 20, 2020.

Recovery from Underclays & Coal Waste

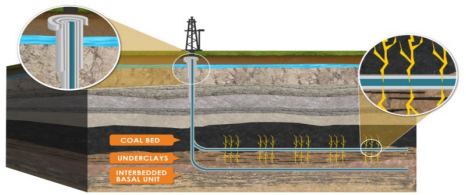
Washing with Benign Acid to Reduce Chemical Consumption and Costs

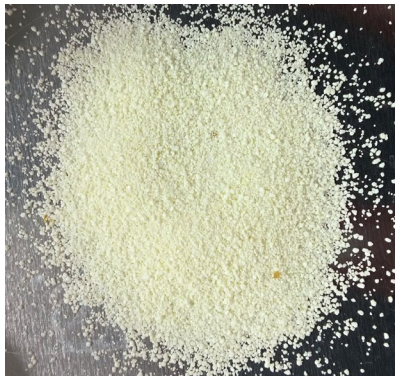
Clays, Coal Refuse, etc.

~40 gal Batch Extractions

15 kg columns to simulate heap leaching

Down-hole Applications





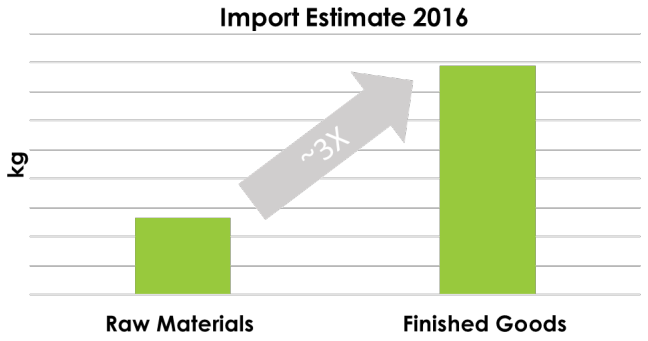
BIAS Sorbent to Enable Solution Recycling

Making the Numbers Work

Analysis to Understand Markets, Process Economics, and Potential "Gotchas"

Understanding REE Markets & Imports

- US REE imports in 2018[1]: ~$160 million
- Distribution by end use:
  - Catalysts: 60%
  - Ceramics & glass: 15%
  - Metallurgical applications & alloys: 10%
  - Polishing: 10%; and
  - Other: 5%.
- Majority (3x) of REE imported as finished goods, and not as a raw material: ~$1.5 B

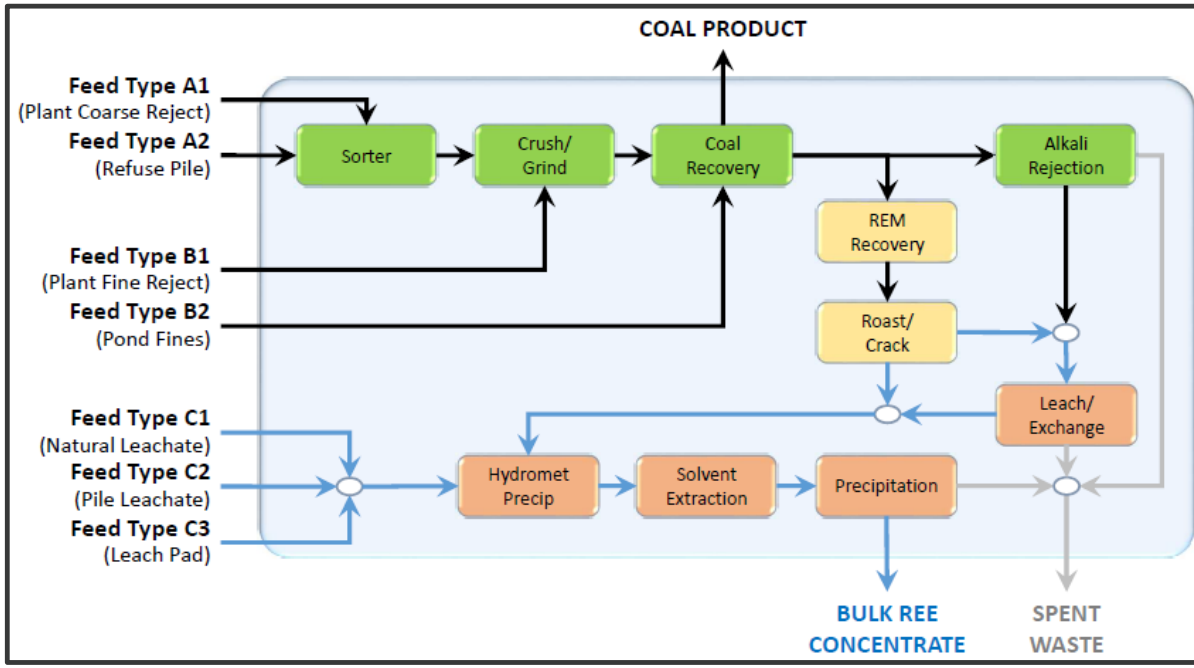


Estimated REE Value[2]

~$120 million (excluding Y & Sc)

>$1.5 billion (excluding Sc)

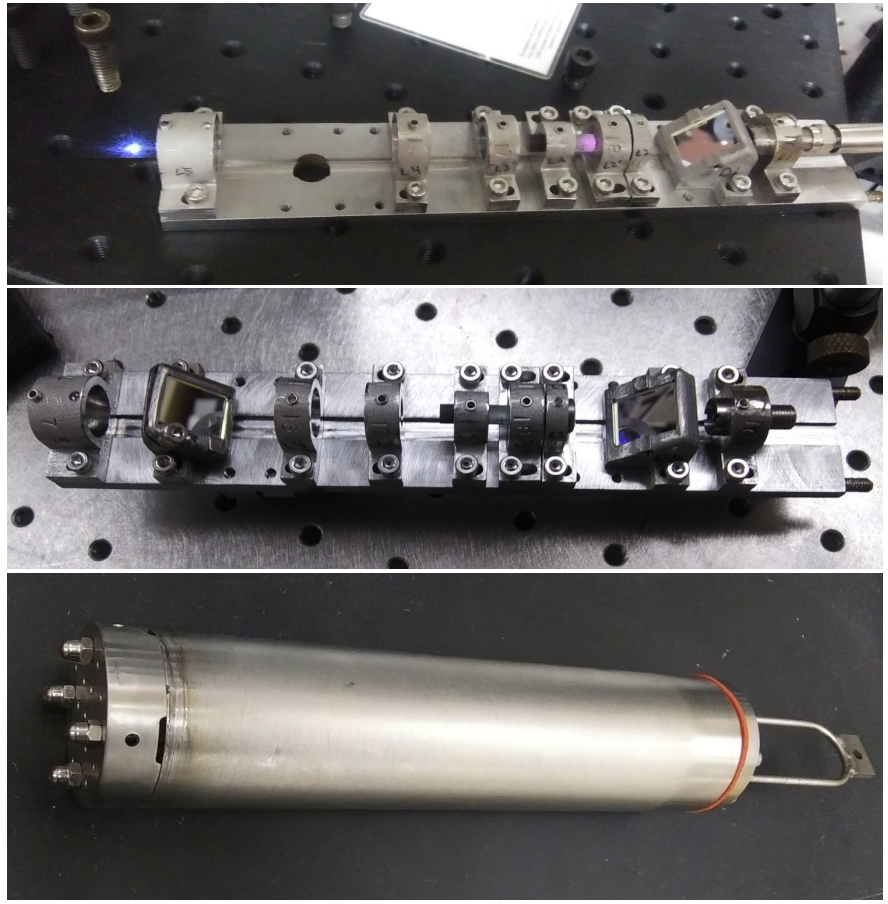
…and Process Economics/Performance[3]



Sources: [1] USGS, [2] Adamas International and Argus Media, [3] "Pilot-Scale Testing of An Integrated Circuit for the Extraction of…", R. Honaker, University of Kentucky, Annual REE Review Meeting, Pittsburgh, PA, April 2018.

Enabling Domestic Innovation

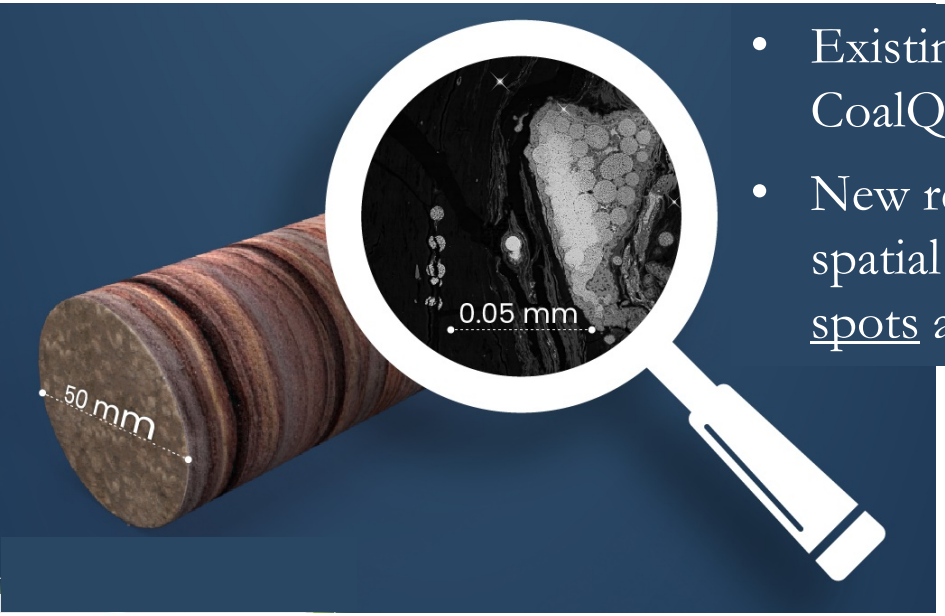
REE Detection Prototype Enables Next-Generation Separations Plants



"Process Ready" LIBS probe enables precise process control by providing REE measurements in minutes (compared to hours) for liquids and solids. Fiber optic probes under development offer ppb-detection limits.

The "Where": Finding High Concentration Deposits

New measurements show REE concentrations vary with geology



- Existing REE assessments databases (e.g. CoalQual) are not suited for this need
- New research collects data to capture spatial heterogeneity to detect vertical hot spots and inform REE prospecting tools

Recently published 2019 study[1] demonstrated this heterogeneity, higher REE concentrations (hot spots) in clays above & below coal

Thirty-Sixth Annual INTERNATIONAL PITTSBURGH COAL CONFERENCE
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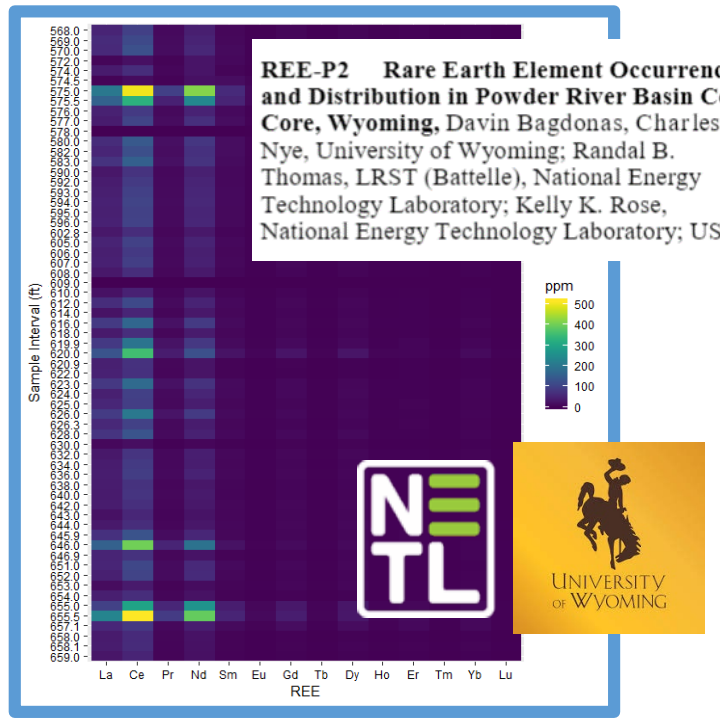

- 2nd study using industry cores documented similar geologic trends
  - Findings include a *~10' thick ore horizon with REE ranging from 500 to over 2700 ppm*
- New efforts with USGS & WVGES will expand data collection to add'l cores

[1] Bagdonas et al., 2019, performed by the University of Wyoming's School of Energy Resources and NETL.

Selected Patents

- **Separations**
  - M. Gray, B. Kail, W. Wilfong, Q. Wang, "Stable Immobilized Amine Sorbents for REE and Heavy Metal Recovery from Liquid Sources," U.S. Non-Provisional Patent, No. 15/782,315, March, 2018.
  - Nakano, A. Nakano, and J. Bennett, "**System and method for concentrating rare earth elements from coal byproduct/slag**," U.S. Non-Provisional Patent, US10,358,694 B2, July, 2019
  - J. Nakano, A. Nakano, and J. Bennett, "**Method for recovering target materials from source materials**," U.S. Non-Provisional Patent, US 10,323,298 B2, June, 2019 – targets Ni and V recovery from molten slag.
  - Nakano, A. Nakano, and J. Bennett, "**Selective lithium recovery as lithium carbonate from natural brines**," U.S. Non-Provisional Patent, US 10,315,926 B2, June, 2019
  - J. Nakano, A. Nakano, and J. Bennett, "**Selective material recovery from natural brines**," U.S. Non-Provisional Patent Application, US16/537,985, filed, August, 2019
  - C. Lopano, M. Stuckman, and T. Tarka, "**Step-Leaching Process of REE from Select Coal Combustion Fly Ashes Using Mild Inorganic Acids at Ambient Conditions,**" U.S. Provisional Application Serial No. 63053,925, July 2020.
  - F. Shi, C. Matranga, M. Gray, T. Ji, "**Production of Graphene-structured Products from Coal Using Thermal Molten Salt Process,**" Patent Pending (non -Provisional Application filed), March, 2019.
- **Sensors & Characterization**
  - D. McIntyre, "**Laser Induced Breakdown Spectroscopy (Libs) Probe for Simplified Light Collection and Laser Operation**,", U.S. Patent Application 10/145,737, 2018.
  - D. McIntyre, D. Hartzler, and J. Jain, "**Downhole Laser System with an Improved Laser Output Production and Data Collection**", Patent Pending (non -Provisional Application filed), 2019.

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PIs

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