Rare Earth Element Recovery from Coal-Based Materials

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Mine Design, Operations & Closure Conference
– Nontraditional Commodities Session –

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Rare Earth Elements (REEs)
REE Applications

MAGNETICS
- Computer Hard Drives
- Disk Drive Motors
- Anti-Lock Brakes
- Automotive Parts
- Traction Motors
- Refrigeration
- Microwave Power Tubes
- Power Generation
- Microphones & Speakers
- Communication Systems
- MRI

CATALYSTS
- Petroleum Refining
- Catalystic Converter
- Fuel Additives
- Chemical Processing
- Air Pollution Controls

METAL ALLOYS
- NiMH Batteries
- Fuel Cells
- Steel
- Super Alloys
- Aluminum/Magnesium

PHOSPHORS
- Display phosphors
- CRT/LCD
- Fluorescents
- Medical Imaging
- Lasers
- Fiber Optics

CERAMICS
- Capacitors
- Sensors
- Refractories

Nd | Tb | Dy | Pr
---|----|----|----
Eu | Y  | Lu | Sm | Pr | La
Nd | La | Ce | Pr

Nd | Gd | Er | Ho | La | Ce | Pr

Nd | Eu | Tb | Y  | Er | Gd | Ce | Pr

Nd | Y  | La | Ce | Pr

Nd | Y  | La | Ce | Pr

Nd | Tb | Dy | Y  | Eu | Gd | La | Cr | Pr

6% PHOSPHORS
6% GLASS
5.5% CERAMICS
43% CATALYSTS
15.5% CATALYSTS
16.5% POLISHING
19% METAL ALLOYS
26% MAGNETS
2% CERAMICS
4% PHOSPHORS
8.5% METAL ALLOYS
13% MAGNETS
17% POLISHING
Top Suppliers in the World
Approximately 750M Tons of Coal Burned in U.S. Annually

- ~75M tons of coal ash generated
- Average concentration of ~470 ppm REE+Y, yields ~35,250 tons (~31,980 tonnes) of REE+Y annually
- If completely extracted, potential for generation of REEs from coal exceeds U.S demand

Challenges & Opportunities
Material Reserves
Environmental & Economic Impact

Annual Global Rare Earth Market
- ~$5B in 2015 (~149,000 tonnes/yr)

U.S. Consumes
- 11% ($550M) or ~16,000 tonnes/yr in 2015

REE Market – REEs from Coal
REE Active Mines

[Map showing locations of REE mines and projects worldwide]

EXPLANATION
- Acia mines
- Carbonate
- Ferrophosphate deposits
- Heavy-mineral sands
- Clays
- Advanced projects
- Carbonate
- Ferrophosphate deposits
- Heavy-mineral sands
- Clays

Rare Earth Elements – Coal Basins, REE Deposits, Mines

Coal Basin
- Central Appalachia
- Central Interior
- Gulf Lignite
- Illinois Basin
- Lignite
- Northern Appalachia
- Powder River Basin
- Rocky Mountain
- Southern Appalachia
- West/Northwest

Known Deposit of REEs
REE Mine in Operation
Past REE Mine Location

Peralkaline Igneous Deposits

Bear Lodge
Mountain Pass
Elk Creek
Round Top
Bokan Mountain

Congressional Language
– Feasibility of Recovering Rare Earth Elements (REEs) –

**FY14** to perform an assessment and analysis of the feasibility of economically recovering rare earth elements from coal and coal by-product streams, such as fly ash, coal refuse, and aqueous effluents

**FY15** to continue activities to economically recover rare earth elements from coal and coal by-product streams, such as refuse, and aqueous effluents

**FY16-FY17** to expand its external agency activities to develop and test commercially viable advanced separation technologies at proof-of-concept or pilot scale that can be deployed near term for the extraction and recovery of rare earth elements and minerals from U.S. coal and coal by-product source showing the highest potential for success

**FY18** to continue its external agency activities to develop and test advanced separation technologies and accelerate the advancement of commercially viable technologies for the extraction and recovery of rare earth elements and minerals from U.S. coal and coal by-product sources
Mission
Development of an economically competitive and sustainable domestic supply of rare earth elements (REEs) and critical materials (CMs) to assist in maintaining our Nation’s economic growth and National Security

Objectives
• Recovery of REEs from coal and coal by-product streams, such as coal refuse, clay/shale over/under-burden materials, aqueous effluents, power generation ash
• Advance existing and/or develop new, second-generation or transformational technologies to improve process systems economics, and reduce the environmental impact of a coal-based REE value chain

Goals
• By 2020, validate the technical and economic feasibility of small, domestic, pilot-scale, prototype facilities to generate, in an environmentally benign manner, 10 lbs/day, 1,000 pounds, high purity 90-99 wt% (900,000-990,000 ppm), salable, rare earth element oxides (REOs) from 300 ppm coal-based resources.
REE Program – Overview: Value Chain

Current Program Focus: Economically viable recovery of REEs from coal and coal by-products

- Exploration
- Mining
- Processing
  - Resource: >300 ppm
- Separation and Purification
- Metals Processing/Making
- Alloying
- Manufacturing

Mining Ore

Crushing to separate monazite and/or bastnasite

Milling to grind into fine particles less than 1mm in size

Floatation to separate and obtain stable concentrations of REE

REE Concentrate

Product: ~4,000 ppm

Leaching

Impurity Removal

Separation Through ion-exchange or solvent extraction

REE (Rare Earth Oxide)

Product: 90-99% w/w

Electrolysis

Metallothermic Reduction

“Super Alloys” or Permanent Magnet Alloys

End Use Alloys Making

Renewable Energy, Consumer and National Defense Products

Courtesy of NETL-LTI, 2015
REE Program – Structure

Technology Area

Key/Core Technology Areas

Enabling Technologies
- Knowledge Products

Separation Technologies
- Science & Technology Development

Process Systems
- Validation / Demonstration / Commercialization

Research Focus Areas

- Resource Identification, Sampling & Characterization
- Techno-Economic Analysis
- Field/Process Sensors

- Commercial Separation Systems – Technology Transfer
- Transformational Concept Development

- Bench- & Pilot-Scale Pre-Concentrate Production
- High Purity Product Production
## REE Program – Metrics

<table>
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<th>2014-2018</th>
<th>2020 Target</th>
<th>2025 Target</th>
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<td><strong>REE Pre-Concentrates</strong></td>
<td>&gt;2wt% Laboratory/Bench-Scale Production</td>
<td>90-99wt%</td>
<td>90-99wt%</td>
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<td><strong>Economic Targets for Domestic REE Production</strong></td>
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<td>Near Commercial Market Pricing</td>
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<td>Non-Hazardous</td>
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<td><strong>Developmental Scale</strong></td>
<td>Laboratory-Scale Concepts; Transitioning of Conventional Separation Technologies (TRL 2-3)</td>
<td>Validate Technical &amp; Economic Feasibility of Prototype Salable High Purity REE Systems (TRL 5-7)</td>
<td>Integration of Transformational Technologies in Pilot-Scale Systems (TRL 7-9)</td>
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Key Drivers

• National Security & Economy
• Environmental Impact
• Economic Targets
• Build U.S. Domestic Infrastructure for On-Shore Production

Report to Congress; Issued 2017
Initiated NETL RIC FWP (July 15, 2015)
~300 to >1,000 ppm; 2wt% REEs

Initiated FOA-1718 (Nov 15, 2017) – Advanced Separation – Up-Stream: 2wt% REE; Mid-Stream: 2-10wt% REE; Down-Stream: 90-99wt% REO

Initiated FOA-1202 (Oct 1, 2017) – Bench & Pilot-Scale REE Separation (Phase 2– 2wt%)

Initiated RFP-10982 (Sept 15, 2017) – Field Sampling & Characterization/Round Robin

Initiated FOA-1627 (Sept 1, 2017) – Salable High Purity REE Separation (Phase 1 – 90-99wt% REO)

*Initiated NL FWPs (July-Sept 2017) – Field Sensors & Technology Transfer

Initiated RFP-9067 (Sept 1, 2016) – Field Sampling & Characterization

Initiated FOA-1202 (March 1, 2016) – Bench & Pilot-Scale REE Separation (Phase 1– 2wt%)

Initiated OTT TCF Project (Sept 2017) — LLNL EERE CMI REE Biosorption Extraction

Initiated OSC SBIRs (June 2017) — Field Sensors; (May 2018) — REE Extraction

2020 GOAL
Validate Technical & Economic Feasibility of Prototype, Salable, High Purity (90-99%) REE Systems

FY17: 15 Active Projects
FY18-FY19: 25-30 Active Projects
Budget: $15M/FY; $18M/FY19

Feasibility Assessment
REE Program – Prospecting

Northern Appalachia
Northern Appalachia WVU AMD Solids
Central Appalachia
Central Appalachia WVU AMD Solids
Illinois Basin
Rocky Mt Basin
Gulf Lignite
Southern Appalachia
West/Northwest

Dry Ash Basis
FOA DE-FE-0002012 – Opportunities to Develop High Performance, Economically Viable, and Environmentally Benign Technologies to Recover Rare Earth Elements (REEs) from Domestic Coal
FOA-1202 Phase 2: REE Extraction System – Conventional Technologies (Minimum 2wt%)

Small AMD sludge drying cell
0.5 ac, 10 ft deep, 80% moisture
Sludge DW 1,300 t
$190/ton of sludge DW
In situ REE value = $247,000

AOI-1 Bench-Scale Facilities
West Virginia University
Schematic of an acid mine drainage (AMD) treatment system
~100% REE Recovery from Feedstocks
Production of 5-6 wt% concentrates prior SX

Courtesy of Paul Ziemkiewicz, WVU
FOA-1202 Phase 2: REE Extraction System – Conventional Technologies (Minimum 2wt%)

Feedstock: Coal Refuse
Central Appalachian & Illinois Coal Basins – Kentucky
System: Modular
REE Product: Minimum 2wt% Pre-Concentrate

AOI-2 – Pilot-Scale Facilities University of Kentucky

Initiated operation in June 2018
Production of REEs in October/November 2018
80-90% REE concentrate produced prior to SX

Courtesy of Rick Honaker, Univ Kentucky, Roe-Hoan Yoon, Virginia Tech
**REE Program — Major Accomplishments: 2016-2017**

**NETL RIC** fiber optic sensor development for detection of ppm levels of REEs in liquid samples

**NETL RIC** immobilized amine and organo-clay sorbents development for REE recovery from liquid sources

- **2014**: Feasibility Assessment
- **2015**: Feasibility Assessment
- **2016**: Fiber optic sensor development
- **2017**: Fiber optic sensor development
- **2018**: Immobilized amine and organo-clay sorbents development
- **2019**: Immobilized amine and organo-clay sorbents development
- **2020**: Immobilized amine and organo-clay sorbents development
- **2021**: Immobilized amine and organo-clay sorbents development
- **2022**: Immobilized amine and organo-clay sorbents development

**Physical Sciences Inc. (PSI), University of Kentucky, University of Wyoming**, and others achieved >30 wt% (300,000 ppm) mixed REE pre-concentrates from coal-based materials.

**West Virginia University** achieved recovery of nearly 100 percent REEs from coal acid mine drainage (AMD) sludge.

**University of Kentucky** produced small quantities of 80 percent (800,000 ppm) total REEs on a dry whole mass basis and more than 98 percent (980,000 ppm) REOs. Critical elements such as neodymium and yttrium — used in national defense technologies and the high-tech and renewable energy industries — represented more than 45 percent of the total REE concentrate.

**University of North Dakota** identified that approximately 80 to 95 percent of the REE content in lignite coals is organically associated, primarily as coordination complexes as opposed to mineral forms typically found in the older/higher-rank coals.
**REE Program — Major Accomplishments: 2018-2019**

### Feasibility Assessment

- **2014**: West Virginia University (July 2018)
  - Commissioning of the Rare Earth Extraction (REEF) Facility
  - Bench/Pilot-Scale Facility
  - Acid Mine Drainage Feedstock

- **2015**: University of Kentucky (November 2018)
  - Pilot-Scale Facility Currently Producing a Few Grams/Day of a Rare Earth Oxide Concentrate Containing Greater than 90% (900,000 ppm) Total RE Oxide (Dry Basis)
  - Products Were a Result of Processing Leachate Collected from the Coarse Refuse Area at Dotiki

- **2016**: Physical Sciences Inc., (July 2018)
  - Micro-Pilot Facility Produced >15 wt% (150,000 ppm) Concentrate of Mixed Rare Earths from Post-Combustion Ash Resulting from Burning East Kentucky Fire Clay Coal in a Power Plant Boiler
  - Pilot Facility (Sharon, PA) to be Operational June/July 2019

- **2017**: University of Kentucky (September 2018)
  - Production of 40wt% REE-Y (400,000 ppm) Pre-Concentrates – CaMg-Fly Ash; 2.7wt% (27,000 ppm) CaCO₃/Mn-AMD (Co-Enriched) (Lab-Scale Facility)

- **2018**: NETL RIC (September 2018)
  - Production of 40wt% REE-Y (400,000 ppm) Pre-Concentrates – CaMg-Fly Ash; 2.7wt% (27,000 ppm) CaCO₃/Mn-AMD (Co-Enriched) (Lab-Scale Facility)

### Production Facilities

- **2019**: Three domestic bench/pilot-scale operating facilities will domestically be producing REEs from coal and coal-based resources in the July-August 2019 timeframe

- **2019**: West Virginia University (February 2019)
  - Bench/Pilot-Scale Facility Production of 69% TREE (80% TREO) from Acid Mine Drainage

**U.S. Department of Energy**
REE Program – Summary

Prospecting → Processing → Production

Technology Development Pathway

- Technical Feasibility
- Process Scale-Up
- Economic Viability
- Production Demand
- Market Impact

Where We Are Today

- Technical Feasibility of Extracting REE from Coal-Based Resources Demonstrated at Laboratory/Bench-Scale
- Three Domestic, First-of-a-Kind, Extraction/ Separation Test Facilities, Producing REEs from Coal- Based Materials, Are Targeted to be Operational in the June-July 2019 Timeframe
- Fully Integrated REE Program
  - Spanning Basic/Fundamental Technology Development (TRL 1-3) through to Small Pilot-Scale Facility Validation (TRL 5-7)
  - Maintaining Broad Feedstock Base – Coal Refuse/Tailings, Clays/Shales, Power Generation Ash, Acid Mine Drainage

What Is Needed for Tomorrow

- Process Scale-Up & Economic Feasibility Need to be Demonstrated
- Impact of REE Production on International Market Needs to Be Addressed
- Commodity-to-Product Integration: REE Metallization through On-Shore Manufacturing Supporting Entire Supply Chain

Overall Benefits & Impact

- National Independence from Off-Shore Production
- Impact of REE Production on Ash Pond, AMD, Coal Refuse Wastes Remediation
- REE Processing & Critical Materials Production
- REEs & Advanced Materials Development: Advanced High Temperature Alloys & Coatings, etc.
- Product Development of Dual Use REEs: Incorporation into Advanced Defense and Energy Equipment
- Technology Transfer to Alternate Separation Industries: Battery/Magnet Recycling
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http://www.netl.doe.gov/research/coal/rare-earth-elements/
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