Feasibility of Recovering Rare Earth Elements

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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.
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

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

Feasibility Assessment

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

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 FOA-1718 (Nov 15, 2017) — Advanced Separation – Up-Stream: 2wt% REE; Mid-Stream: 2-10wt% REE; Down-Stream: 90-99wt% REO
Initiated NL FWP (March 12, 2018) — Biosorption Technology Development
Initiated RFP-9067 (Sept 1, 2017) — Field Sensors & Technology Transfer REE Separation
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

U.S. DEPARTMENT OF ENERGY

REE Program – Project Portfolio
REE Program Portfolio

FY16-FY17 FOA DE-FE-0001627 Phase 1 – Production of Salable Rare Earth Elements from Domestic U.S. Coal and Coal By-Products
  • Marshall Miller & Associates
    • Arch Coal, Mineral Refining Co., Outotec, Blue Line Corp., Anchor House, Cumberland Mine Services, Virginia Tech, University of Kentucky, West Virginia University
  • Inventure Renewables Inc.
    • Texas Minerals Resources Corp. (TMRC), K-Technologies, Inc., Penn State University

FY15 FOA DE-FE-0001202 Phase 2 – Opportunities to Develop High Performance, Economically Viable, and Environmentally Benign Technologies to Recover Rare Earth Elements (REEs) from Domestic Coal and Coal Byproducts
  • AOI-1 Bench-Scale (18 Months)
    • West Virginia University (March 2019)
    • University of North Dakota (September 2019)
  • AOI-2 Pilot-Scale (30 Months)
    • University of Kentucky (March 2020)
    • Physical Sciences Inc. (March 2020)
FY17-FY18 FOA DE-FE-0001718 — Development of Transformational Separations and Extraction Processes for Production of Rare Earth Elements from Domestic U.S. Coal and Coal By-Products (3 AOIs)

2wt% REE Pre-Concentrates (AOI-1)
- University of Kentucky, Virginia Tech, Blackhawk Mining, and Alliance Coal
- Virginia Tech
- Cerahelix, Veolia Water Technologies
- University of North Dakota, Pacific Northwest National Laboratory
- The Ohio State University

2-10wt% REE Pre-Concentrates (AOI-2)
- University of Utah, Virginia Tech
- Wayne State University, Los Alamos National Laboratory, UCLA

90-99wt% High Purity REE (AOI-3)
- Battelle Memorial Institute, Rare Earth Salts
- West Virginia University, Virginia Tech
REE Program Portfolio

National Labs
- FY15-FY19 NETL R&IC FWP – Rare Earth Elements from Coal and Coal By-Products
- FY17 LANL FWP – Evaluation of Laser-Based Analysis of REE in Coal-Related Materials
- FY17 LANL FWP – Evaluation of Novel Strategies and Processes for Separation of REE from Coal-Related Materials (Actinide Technology Transfer)
- FY17 INL/LLNL/Rutgers/OLI/Univ. California-Davis FWP – Bio-Illuminescence REE Sensor Development
- FY17 LLNL/Duke Univ/Purdue Univ FWP – Application of Biosorption for REE Recovery from Coal Byproducts

Technology Commercialization Fund (TCF) – Completed
- FY17 LLNL – Rare Earth Metal Extraction for Clean Technologies

FY17 Small Business (SBIR) Projects – Completed
- Physical Optics Corp – REE Mass Analyzer
- Physical Sciences Inc. – Spectro-chemical Detection/Monitoring of REE during Extraction
- Adelphi Technology – Nondestructive Bulk REE Measurement System from Coal
- Applied Spectra, Inc. – Sensor for Direct, Rapid and Complete Elemental Analysis of Coal

FY18 Small Business (SBIR) Projects – Completed
- Skyhaven Systems, LLC – Rare Earth Extraction from Coal Fly Ash
- Wyonics LLC – Ionic Liquids as Advanced Solvents for the Extraction of Rare Earth Elements from Coal Products
- Anactisis LLC – Coal Ash Beneficiation through Critical Material Extraction and Recovery

FY19 Small Business (SBIR) Projects
Topic: Production of Rare Earth Metals
**REE Program Portfolio**

- **FY16 RFP DE-SOL-0009067 — Domestic Field Sampling & Characterization (Contracts Completed)**
  - University of Kentucky: Western Kentucky bituminous coal in the Illinois Coal Basin
  - West Virginia University: Acid mine drainage (AMD) from bituminous coal mines in Northern and Central Appalachian Coal Basins
  - TetraTech, Inc. (PA, CO): Bituminous, subbituminous, and anthracite coals in Northern and Central Appalachian Coal Basins; Rocky Mountain
  - XLight Corporation: Coals in the Eastern Pennsylvania Anthracite Region

- **FY17 RFP DE-SOL-0010982 — Domestic Field Sampling & Characterization; Round Robin Analyses (Sept 2019)**
  - University of North Dakota, Energy & Environmental Research Center, North Dakota Geological Survey, University of Kentucky, Kentucky Geological Survey, North American Coal Corporation (NACoal), Westmoreland Coal Company, Kiewit Mining Company, BNI Coal Company:
    - Coals from Fort Union Group within the Lignite/Williston Basin and Powder River Basin; Gulf Coast lignite and Appalachian Basins

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

**REE Program Portfolio**

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Dry Ash Basis

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Dry Ash Basis
**REE Program — Major Accomplishments: 2016-2017**

**FEASIBILITY ASSESSMENT**

- **2014**
  - **NETL RIC** fiber optic sensor development for detection of ppm levels of REEs in liquid samples

- **2015**
  - **University of Kentucky, University of Wyoming,** and others achieved $>30$ wt% (300,000 ppm) mixed REE pre-concentrates from coal-based materials

- **2016**
  - **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
  - **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 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

- **2017**
  - **NETL RIC** immobilized amine and organo-clay sorbents development for REE recovery from liquid sources

- **2018**

- **2019**

- **2020**

- **2021**

- **2022**
**Major Accomplishments: 2018-2019**

**Feasibility Assessment**

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

- **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

- **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

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

**NETL RIC** (September 2018)
- Production of 2wt% REE (20,000 ppm) Pre-Concentrates (Lab-Scale Facility)

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

Prospecting → Processing → Production

Technology Development Pathway

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

Heavy-Light vs Critical REEs – Product Impacting Process Economics
Critical Materials – EO-13817
Process Operation – Resources & Fuel Flexibility

NETL REE Website
REED Program – Summary

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 **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 Re-Cycling
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