Rare Earth Elements

FROM COAL & COAL BY-PRODUCTS PROGRAM OVERVIEW | March 22, 2017

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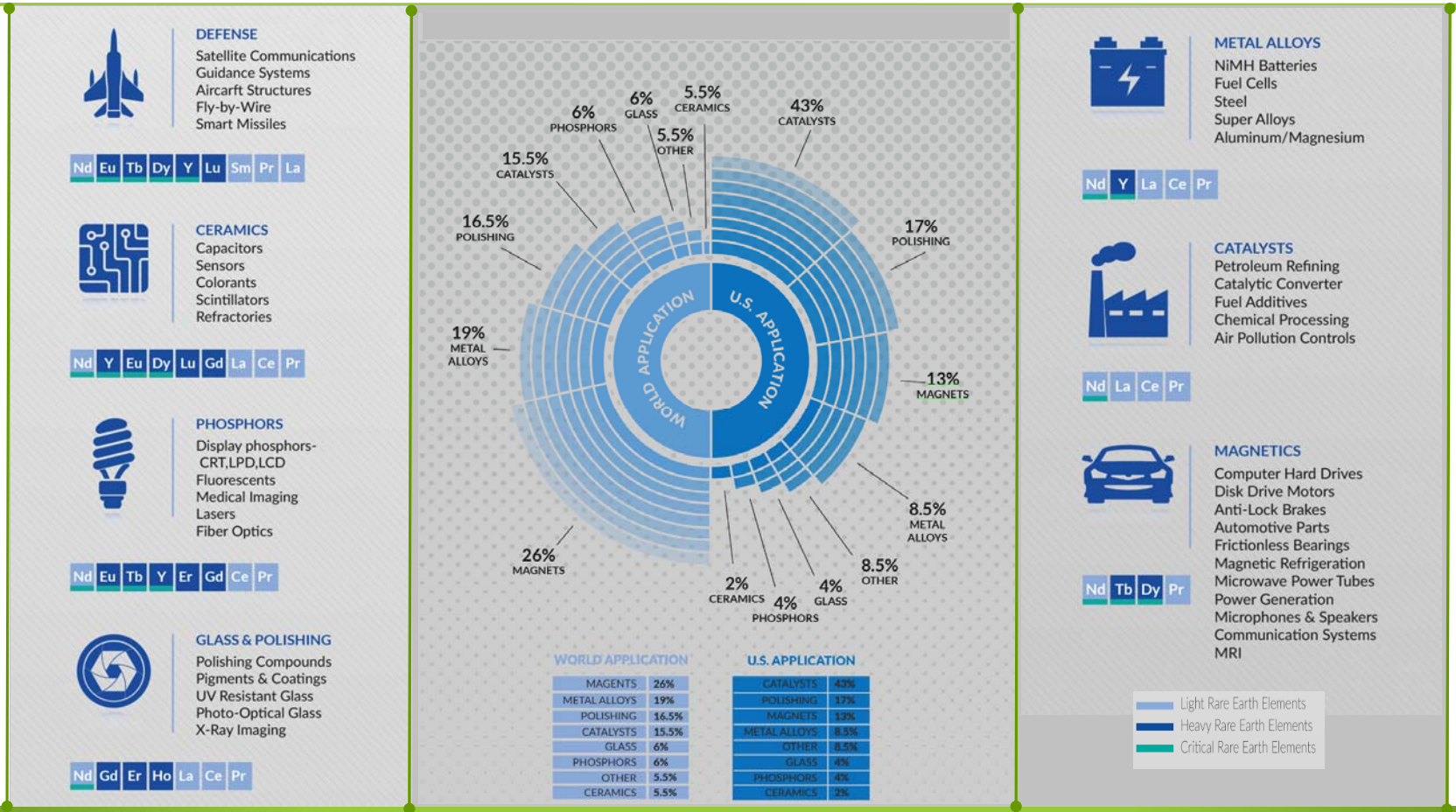
Solutions for Today | Options for Tomorrow

REE Markets

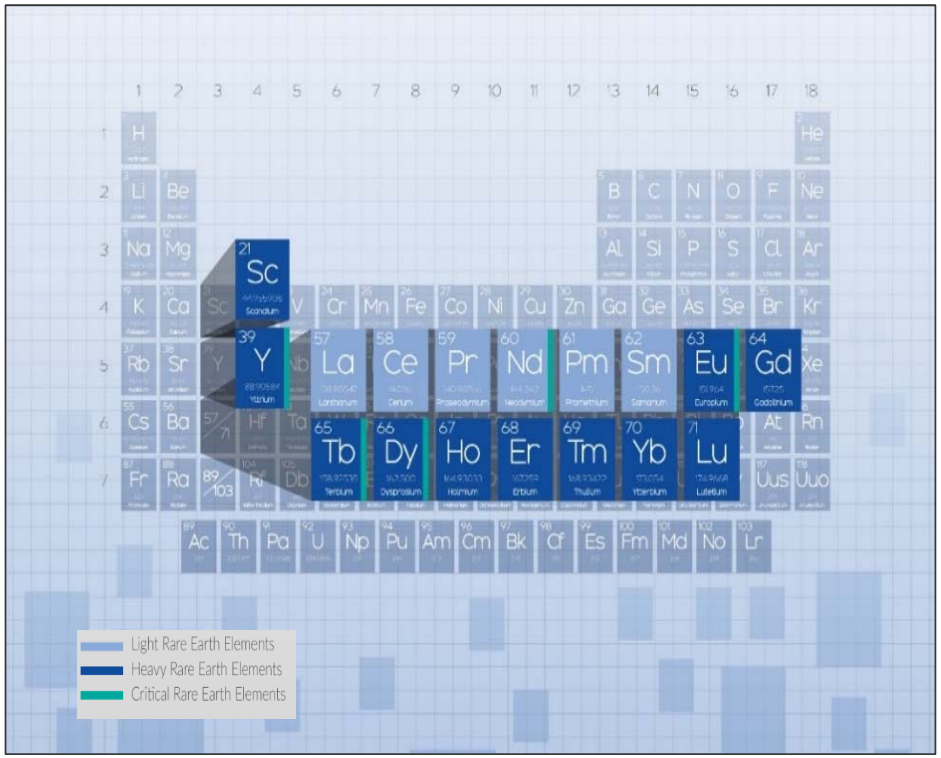
- The Annual Global Rare Earth Market was ~$5B in 2015 (~149,000 tonnes/yr)
- The U.S. consumes around 11% ($550M) or ~16,000 tonnes/yr in 2015
  - The U.S. rare earth industry intermediate products (e.g., magnets, catalysts, ceramics, etc.) generated nearly $40B in revenue and 101,000 jobs (2013)
  - The U.S. rare earth industry end-market products (e.g., healthcare, communications systems, and defense technologies) generated nearly $260B in revenue and 433,000 jobs (2013)

- The Majority of REE's Imported into the U.S. Comes in As Finished Goods, and Not As a Raw Material
  - The U.S. imported $2.3T finished products containing REEs in 2015
  - The top 4 product groups – electronic equipment, machines, engines, pumps, vehicles, oil – account for ~50% of the imported value

REE Applications



Congressional Language



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

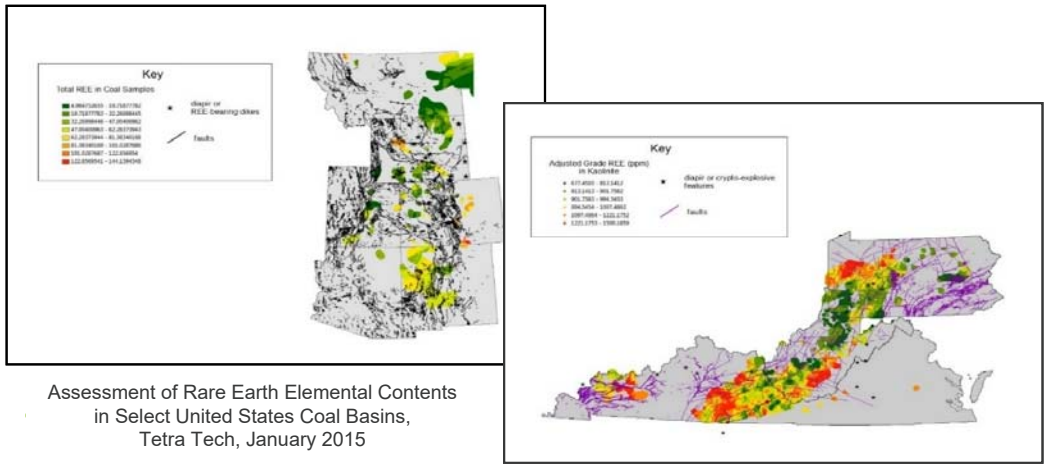
FY16-FY17 to expand its external agency activities to develop and test commercially viable advanced separation technologies at proof-of-concept or pilot scale that can be deployed near term for the extraction and recovery of rare earth elements and minerals from U.S. coal and coal by-product source showing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

U.S.DOE Critical Materials Strategy, December 2010
FY14 https://www.congress.gov/congressional-record/2014/1/15/house-section/article/H475-2
FY15 https://www.congress.gov/crec/2014/12/11/CREC-2014-12-11-pt2-PgH9307.pdf
FY16 https://www.congress.gov/114/crpt/hrpt91/CRPT-114hrpt91.pdf

Challenges & Opportunities

- **Currently U.S. does not produce REEs**
  - Lack of a secure supply of domestic REEs results in risk to the U.S. economy and defense
- **Off-shore production**
  - Lower labor costs and lax environmental regulations
  - Production of primarily low commercial value, light REEs (L-REEs)
- **What are the Barriers?**
  - Relatively low concentration of REEs in coal and coal by-products, 100 – 1300 ppm (0.01-0.13 wt%) vs. commercial ores (monazite, bastnasite, etc.) which are typically 2 – 20 wt% (2,000-20,000 ppm) total REEs, makes recovery from coal-based sources technically challenging

- **U.S. coal contains significant amounts of REEs**
  - Appalachian coals represent the richest REE resources in the country
  - 208 coal preparation plants in WV, KY, P, VA, AL, TN with an installed capacity of 166,495 tons per hour, or more than one billion tons annually
  - Retrofitting only a portion of these plants with advanced REE separation processes would suffice the U.S. domestic need



Assessment of Rare Earth Elemental Contents in Select United States Coal Basins, Tetra Tech, January 2015

DOE-NETL Rare Earth Element Program

Key Drivers

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

2014	2015	2016	2017	2018	2019	2020	2021	2022

Δ **Feasibility Assessment**

Δ **Report to Congress; Issued** Δ

Δ **Initiated NETL R&IC FWP (July 15, 2015)**

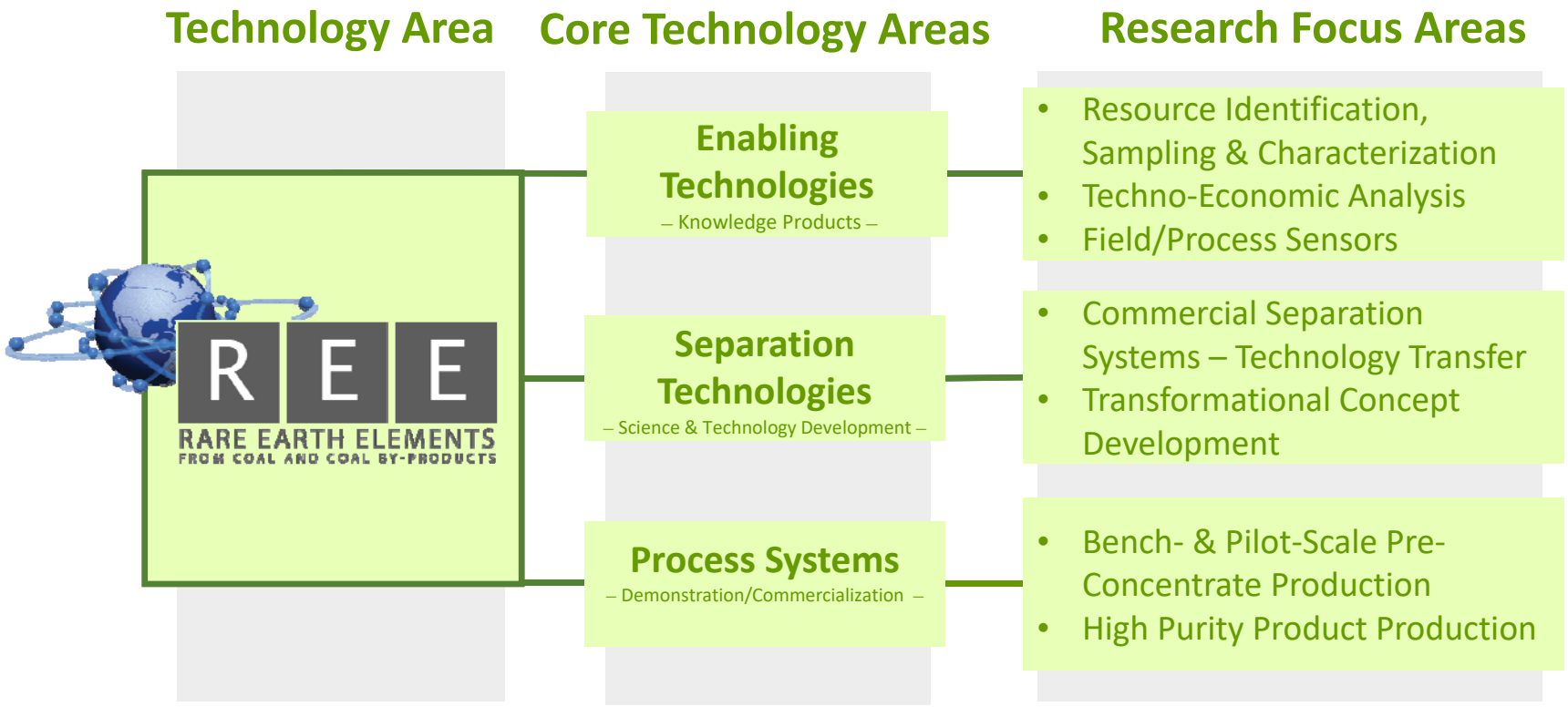
Δ **Initiated FOA-1202 (March 1, 2016)** – **Bench-Scale & Pilot-Scale REE Separation**

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

Δ **Issued FOA-1627 (Sept 28, 2016)** – **Salable High Purity REE Separation**

GOAL: ***Validate Technical & Economic Feasibility of Prototype Salable High Purity Systems – 2020*** Δ

DOE-NETL REE Program Portfolio



DOE-NETL REE Program Portfolio

15 ACTIVE PROJECTS

- **FY15-FY17 Research & Innovation Center (R&IC) Field Work Proposal (FWP)** – Rare Earth Elements for Coal and Coal By-Products

- FY15 FOA DE-FE-0001202 – Opportunities to Develop High Performance, Economically Viable, and Environmentally Benign Technologies to Recover Rare Earth Elements (REEs) from Domestic Coal and Coal Byproducts

- FY16 RFP DE-SOL-0009067 – Identification and Characterization of Domestic U.S. Coal and Coal By-Products Containing High Rare Earth Element (REE) Concentrations

PROJECTS UNDER REVIEW FOR SELECTION

- FY16-FY17 FOA DE-FE-0001627 – Production of Salable Rare Earth Elements from Domestic U.S. Coal and Coal By-Products

Separation & Extraction Processes

Embryonic New/Novel Advanced Concepts

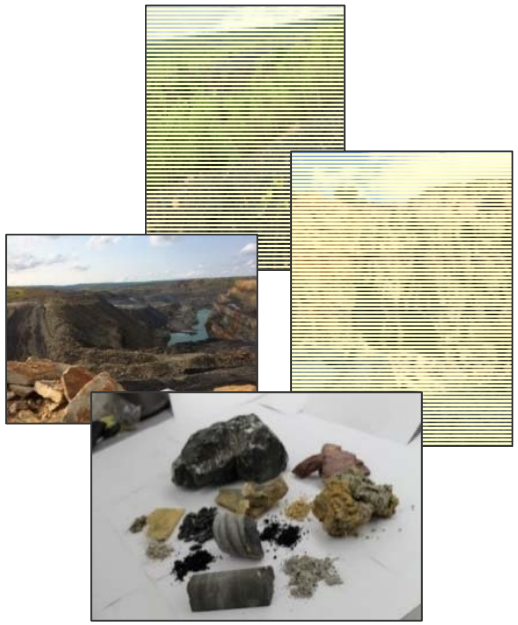
Bench-Scale & Pilot-Scale

Small-Scale Proof-of-Concept Salable

Transformational Concept Development

Demonstration & Commercialization

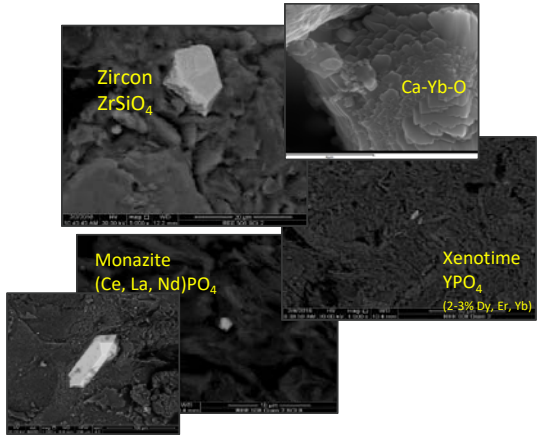
REE Separation & Extraction



Feedstock Materials

Run-of-Mine Coal
Overburden & Underlying Clays/Shales/Sediments
Coal Prep Plant Refuse
Power Generation Ash
Acid Mine Drainage Sludge

Mining	•Ore •Coal •Shale	•Clay •Fly Ash	•Recycled Materials	Rougher Circuit
Physical Beneficiation	•Crushing •Screening •Regrinding	• Magnetic, gravity, electrostatic Separation	•Froth Flotation	Rougher Circuit
Leaching	•Hydrochloric Acid •Sulfuric Acid •Nitric Acid	•Caustic Cracking •Acid Bake •Calcination		Midstream
Impurities Removal	•Thorium Precipitation •Uranium Extraction •Iron Extraction			Midstream
Concentration of REO	•Ionic Liquid •Solvent Extraction •Carbonate Precipitation			Midstream
Separation of REO	•Solvent Extraction •Affinity Chromatography •Electrophoresis	•Ion Exchange •Rare Earth Salts •Carbonate Precipitation		Down-stream
Reduction to a Metal	•Concentrated REO to Rare Earth Metal			Finishing
Alloying, Products & Component Production	•Glass Production •Permanent Magnets •Battery Production	•Automobile Manufacturing •Ceramics, etc…		Application Specific
Final Technology				



Courtesy of NETL R&IC

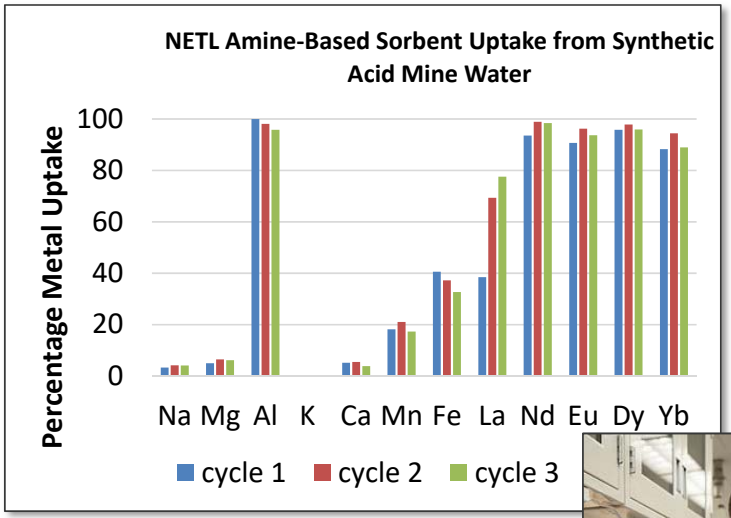
FY15-FY17 NETL R&IC FWP Accomplishments

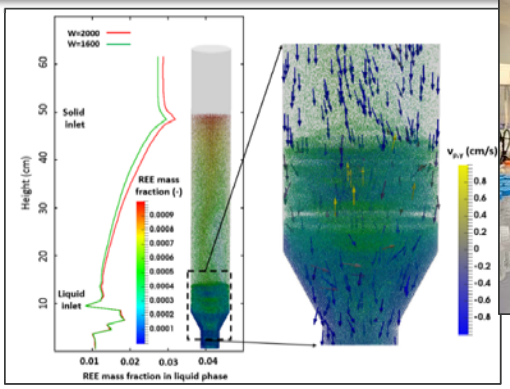
- **Field Resource Assessment**
  - 768 field samples from PA & WV were collected in collaboration with FE-HQ and analyzed
  - Thorium spectral gamma-ray indicated the presence of REE-rich zones
  - H-REE association with Zr, Y, Hf
  - L-REE correlation with Th
  - Samples with high REEs appear to contain physically weathered monazite grains
  - Ti/Al correlates strongly with REE and indicates REEs were concentrated during periods of high erosion
  - Expanded field sampling: EPRI & USGS (MOAs); Consol
  - Luminescense-based fiber optic probe detects REEs at ppm levels *(Patent Application)*

Courtesy of NETL R&IC

FY15-FY17 NETL R&IC FWP Accomplishments

- **Separation & Extraction Technologies**
  - Regenerable immobilized amine sorbents for REE and heavy metals recovery from liquid sources – near 100% removal *(Patent Application)*
  - Organo-clays for recovery of rare earth elements – ~ 100% removal *(Patent Application)*
  - Physical separations – Achieved ~ 6,000 ppm REE pre-concentrate from 300-500ppm REE coal-based material
  - Thermal – ~ 100% removal from synthetic slags *(Patent Application)*
  - Development of multiphase CFD tools to simulate and optimize REE ammonium sulfate separation processes
- **Techno-Economic Analyses**
  - Models developed for assessing the performance and economics for REE separation & extraction
  - Established an in-house resource for global REE processing and market information
  - Identification of system and market knowledge gaps in coal-based REE recovery processes





Courtesy of NETL R&IC

FY15 FOA DE-FE-0001202

Opportunities to Develop High Performance, Economically Viable, and Environmentally Benign Technologies to Recover Rare Earth Elements (REEs) from Domestic Coal and Coal Byproducts

- Identify innovative processes using **existing separation technologies for recovery of REEs from coal and coal by-products**
- The resulting total concentration of mixed REEs in the final product from the proposed recovery process should approach **2wt% total REE**
- The process designs proposed should **minimize or reduce the environmental**, safety, and health impact of radioactive and other byproducts, and **optimize the overall economics** of the separation and recovery process

5 Bench-scale projects &
4 Pilot-scale projects

Effort initiated March 1, 2016
Phase 1: 18 months
Competitive down-select
Phase 2: 18 month bench-scale
Phase 2: 30 month pilot-scale

– Accomplishment –

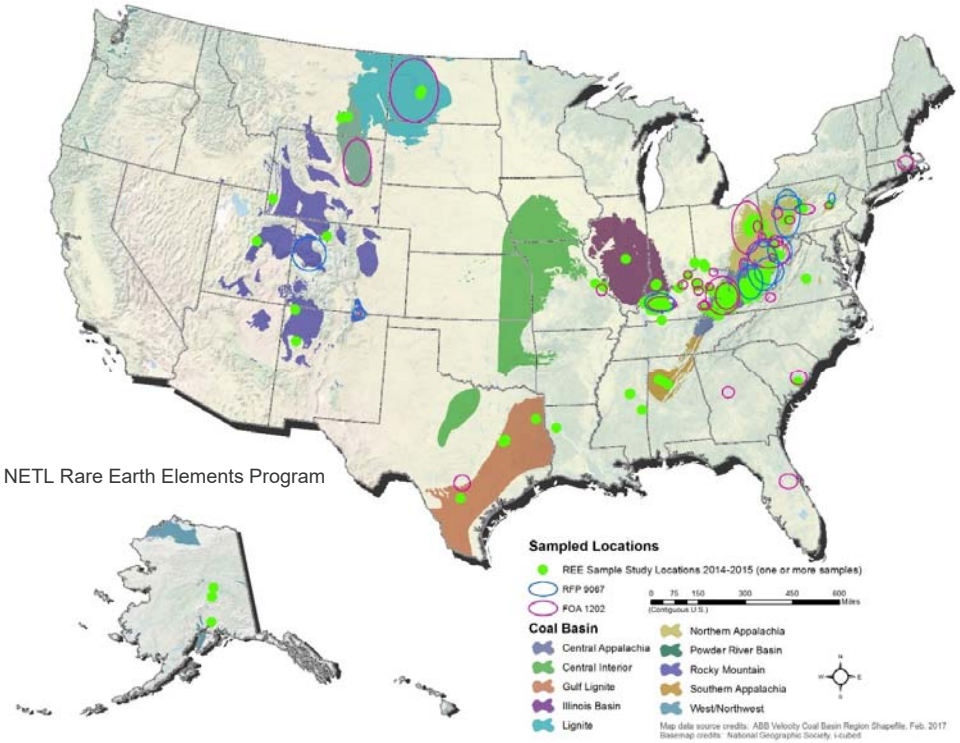
Within the first 6 months of project initiation, production of ≥2wt% REE pre-concentrates from coal-based materials was achieved
– TEAs being addressed –

FY16 RFP DE-SOL-0009067

Identification and Characterization of Domestic U.S. Coal and Coal By-Products Containing High Rare Earth Element (REE) Concentrations

- The objective is to identify, locate, field sample, and chemically analyze U.S. domestic coal and coal by-product solid and/or liquid materials that contain high rare earth element (REE) concentrations (i.e., ≥300 ppm total REE)
- Materials from the Illinois Coal Basin, Northern Appalachian Coal Basin in Pennsylvania and West Virginia, Central Appalachian Coal Basin in West Virginia, and the Raton Basin in Colorado and New Mexico

5 projects
Effort initiated October 1, 2016
Period of performance: 18 months



UK University of Kentucky | WestVirginiaUniversity | TETRA TECH

XLight Corporation

FY16-FY17 FOA DE-FE-0001627

Production of Salable Rare Earth Elements from Domestic U.S. Coal and Coal By-Products

- Achieve **small-scale production of salable REEs** in the form of final products such as individual rare earth oxides (REO) and/or other individual rare earth compounds
  - Small-scale is defined as a minimum composite rare earth output of **10 pounds per day** (reported as oxides)
- REE production is at **least three individual rare earth** elements (REEs), preferably heavy REEs, as compounds with sufficient purity to render them salable in the marketplace, at a **minimum 90%-99% purity**
- Process feedstocks **(pre-combustion coal and coal by-products)** may include run-of-mine coal, overburden and underlying materials and partings/sediments associated with coal seams, coal preparation plant refuse and other by-products, and acid mine drainage sludges

FOA Issued – September 28, 2016
Tentative Award – FY17-Q3
Phase 1: 18 months; Competitive down-select
Phase 2: 18 months

Rare Earth Element	Metal Market Price $/kg	Oxide Market Price $/kg	Major Use	Application
Pr	$80.00	†$50.06	Permanent Magnets, LaNiH Batteries, Phosphors	Magnets for Wind Turbines Hybrid Vehicle Batteries Computer Hard Drives Mobile Phones Medical Scanners Power Tools
Nd	$50.00	†$39.05	Permanent Magnets, LaNiH Batteries, Catalysts, Glass Additive	
Eu	*$1,600.00	$66.00	Phosphors, Fiber Optics	LCD's LED's Fluorescent Lights
Tb	$564.00	$425.00	Permanent Magnets, Phosphors, Fiber Optics	Fiber Optics for Signal Amplification
Dy	$259.00	$187.00	Permanent Magnets, Phosphors	Magnets Phosphors
Sc	**$15,000.00	*$4,200.00	Phosphors, Alloying Agent	Aerospace & Air Transportation Industries
Y	$34.00	†$3.67	Phosphors, Coatings	Gas Turbine Thermal Barrier Coatings

*2003 Market Prices per Rare Elements Resources 2004 Report
** September 2016 Market Prices per mineralprices.com
† Converted from tonnes to kg
‡ 2013 Cumulative Revenues per Rare Earth Technological Alliance 2014 Report

FY16-FY17 Review Meetings & Workshops

2016 Project Review Meeting
for
Crosscutting Research and Analysis
and
Rare Earth Elements

REE Project Portfolio Poster Session

Station Square, Pittsburgh, PA
April 18, 2016

2017 Project Review Meeting
for
Crosscutting Research and Analysis,
Gasification Technologies,
Rare Earth Elements Research Portfolios

Omni William Penn, Pittsburgh, PA
March 22, 2017

NETL-HQ REE Workshop
NETL Morgantown
August 8-9, 2016

Purpose:

- To accelerate REE technology research development, demonstration and deployment for separation of REEs from coal and coal by-products, the REE Workshop was hosted by NETL in support of DOE FE-HQ.
- Provide an open forum for industry, university, government agencies to discuss potential opportunities and/or research requirements to address accelerated achievement of REE recovery in a techno-economic and benign manner by 2023-2025.
- Further announce the release of Funding Opportunity DE-FE-0001627, and address questions relative to responding to the FOA.

- **102 Registered Participants**
  - Mineral Production, Mineral Processing, Universities, Soluble REE Production, REE Sales/Customers, Investors/Developers, Pyrometallurgy, Research & Consulting, State Agencies, NETL, FE-HQ, EERE HQ, National Labs

- **Success Outcomes**
  - Networking across the REE Value Chain – Open discussions
  - Workshops requested with government leaders
    - State-of-the-art technology discussions – Genesis of materials formation
    - Comparison of coal vs alternate feedstocks for REE production
    - Government – Private investment – Industry roles
  - Research needs for success
    - Feedstock dependency – Basic analyses of resources/Approach for predictive prospecting
    - Grinding kinetics for REE liberation & separation
  - Commercial aspects & risks
  - Schedule – Facility vs product definition & quantity produced; Production and market entry

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Rand Batchelder
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Matthew Fortner
Robert Thompson
William O'Connor
Fan Shi
Megan Macala
Duane Miller
Roger Lapeer
Jennie Stoffa
Brian Kail
Esmail Monazam
Hazen Research Inc
Steve Roe
Dennis Harkreader
Jeffrey Withum
Aaron Walsh
Scott Montross
Ronghong Lin
Walter Wilfong
Quiming Wang
Yungchieh Lai
Lu Liqiang

FOA-1202 Bench-Scale

University Wyoming
Rochester Institute of Technology, WVU
Kemal Williamson, Maohong Fan, Maciej Radosz, Hertanto Adidharma, Hanjing Tian, Eric Williams, Gabrielle Gaustad

Duke University
Yale University
Heileen Hsu-Kim, Mark Wiener, James Hower, Disiree Plata, Zachary Hendren

WVU RC
MepCo, Rosebud, WVDEP
Paul Ziemkiewicz, Ximbo Liu, Aaron Noble, Yontian Tom He, Tamara Vandivort

Battelle Memorial Institute
Ohio Coal Development Office, PA Bureau of Topographic and Geological Survey, WV Geological and Economic Survey
Annie Lane

University of North Dakota
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Steve Benson, Daniel Palo, Ed Murphy

FOA-1202 Pilot-Scale

University of Kentucky
Virginia Tech, WVU,
Eriez Mnufacturing
Blackhawk Mining
BRC Refining
Rick Honaker
Roe-Hoan Yoon
Aaron Noble, Jim Hower,

Physical Sciences Inc.
Equinix, University of Kentucky/CAER
Prakash Joshi
John Groppo
James Hower

Southern Research
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James Howe
Cortland Eble

West Virginia University, Water Resources Research Institute
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XLight Corporation
Robert Uhrin
David Uhrin

Tetra Tech Inc., Pennsylvania & Colorado
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Farley Woods
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AECOM
ORISE
KeyLogic
Deloitte
External

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http://www.netl.doe.gov/research/coal/rare-earth-elements/

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