



Rare Earth Element Recovery from Coal-Based Materials

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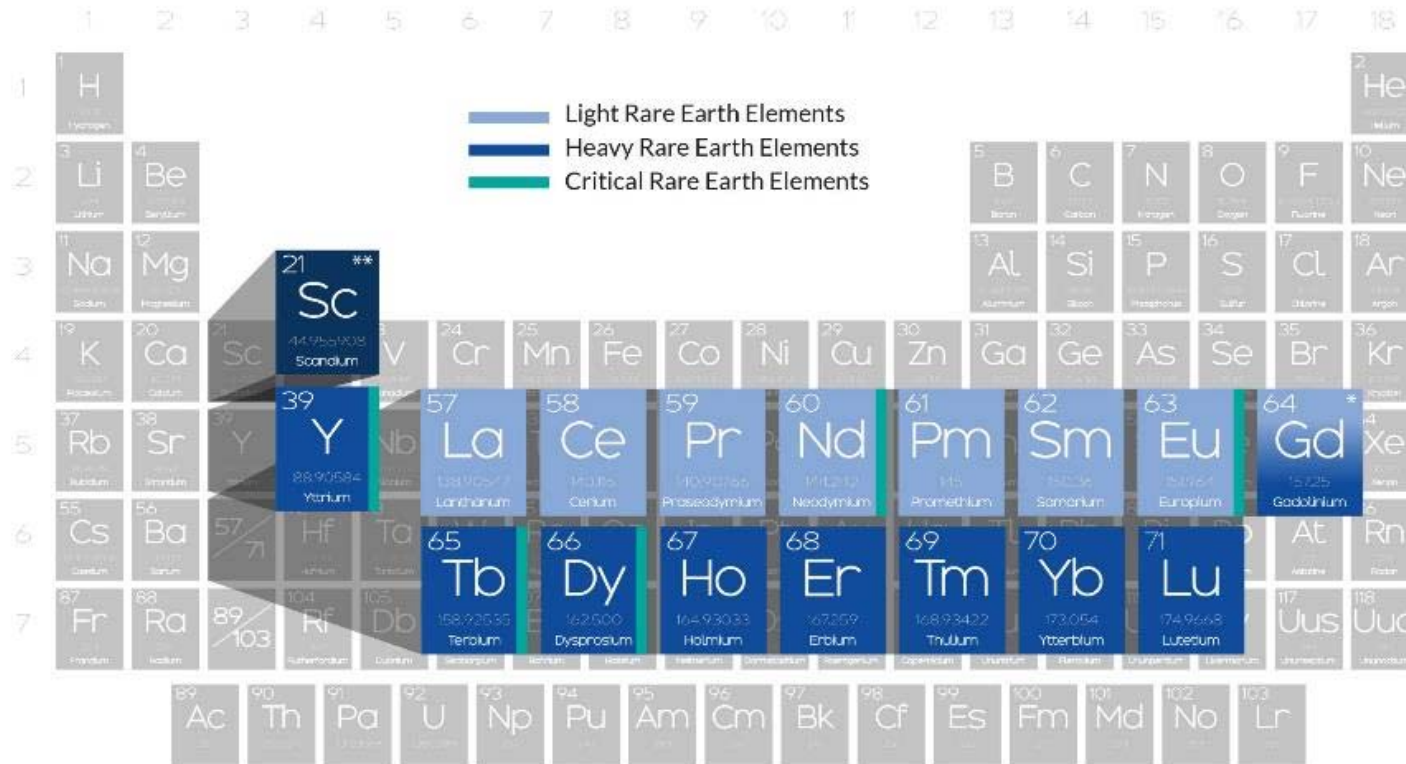
Mine Design, Operations & Closure Conference
– Nontraditional Commodities Session –

Fairmont Hot Springs, MT | May 8, 2019

Solutions for Today | Options for Tomorrow

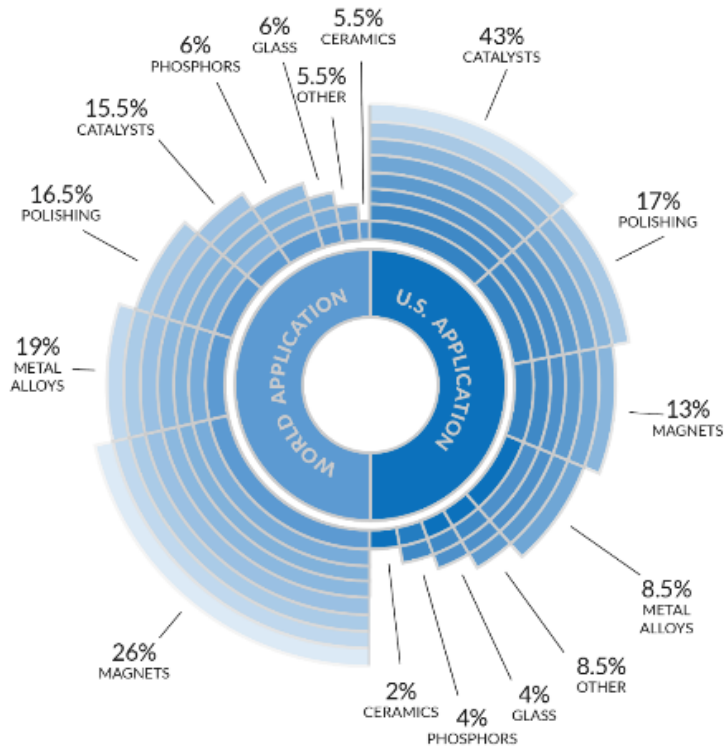


Rare Earth Elements (REEs)



* Gd: IUPAC Light REE; USGS Heavy REE
 ** Included with rare earth elements

REE Applications



MAGNETICS

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

Nd Tb Dy Pr



METAL ALLOYS

NiMH Batteries
Fuel Cells
Steel
Super Alloys
Aluminum/Magnesium

Nd Y La Ce Pr



DEFENSE

Satellite Communications
Guidance Systems
Aircraft Structures
Fly-by-Wire
Smart Missiles

Nd Eu Tb Dy Y Lu Sm Pr La



CATALYSTS

Petroleum Refining
Catalytic Converter
Fuel Additives
Chemical Processing
Air Pollution Controls

Nd La Ce Pr



GLASS & POLISHING

Polishing Compounds
Pigments & Coatings
UV Resistant Glass
Photo-Optical Glass
X-Ray Imaging

Nd Gd Er Ho La Ce Pr



CERAMICS

Capacitors
Sensors
Colorants
Scintillators
Refractories

Nd Y Eu Dy Lu Gd La Ce Pr

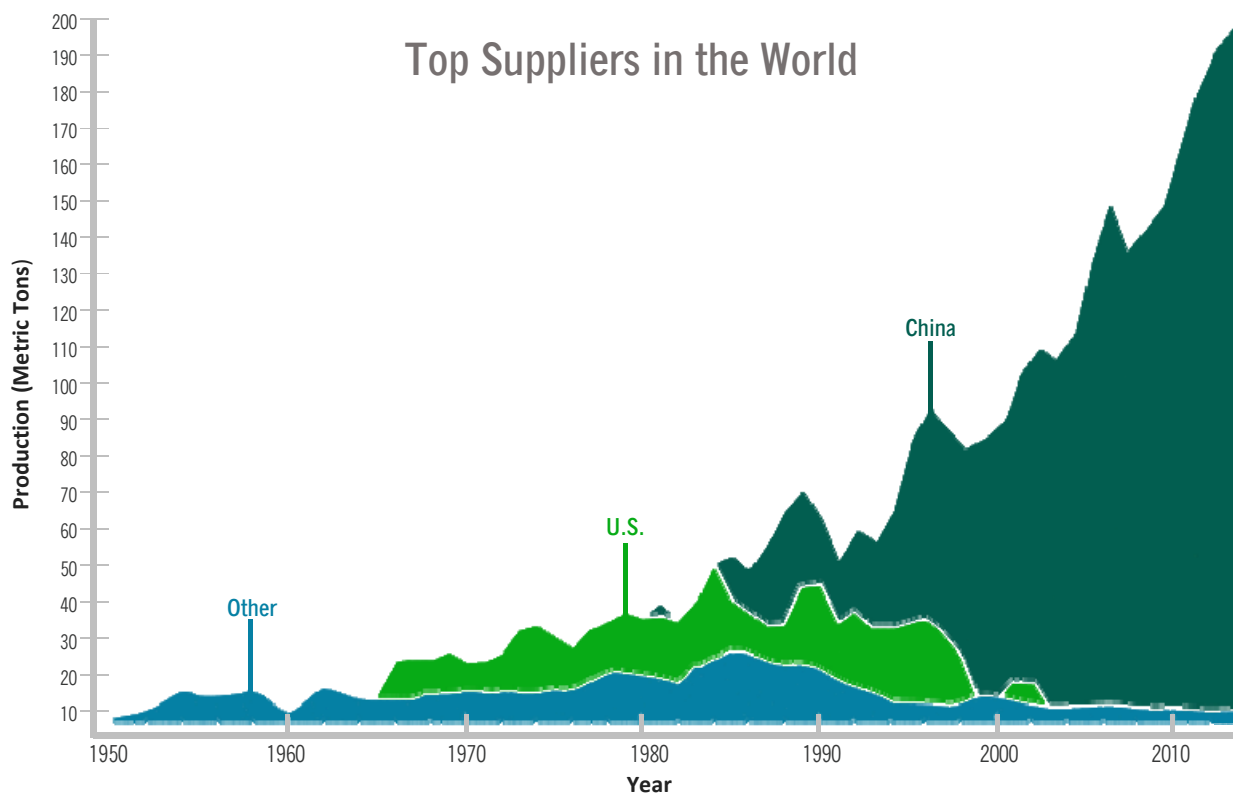


PHOSPHORS

Display phosphors-
CRT,LPD,LCD
Fluorescents
Medical Imaging
Lasers
Fiber Optics

Nd Eu Tb Y Er Gd Ce Pr

REE Suppliers



REE Market – REEs from Coal



Annual Global Rare Earth Market

- ~\$5B in 2015 (~149,000 tonnes/yr)

U.S. Consumes

- 11% (\$550M) or ~16,000 tonnes/yr in 2015



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

REE Active Mines



Base from U.S. Geological Survey Global 30 arc second elevation data (1996) and from Natural Earth (2014), Robinson projection; World Geodetic System 1984 datum

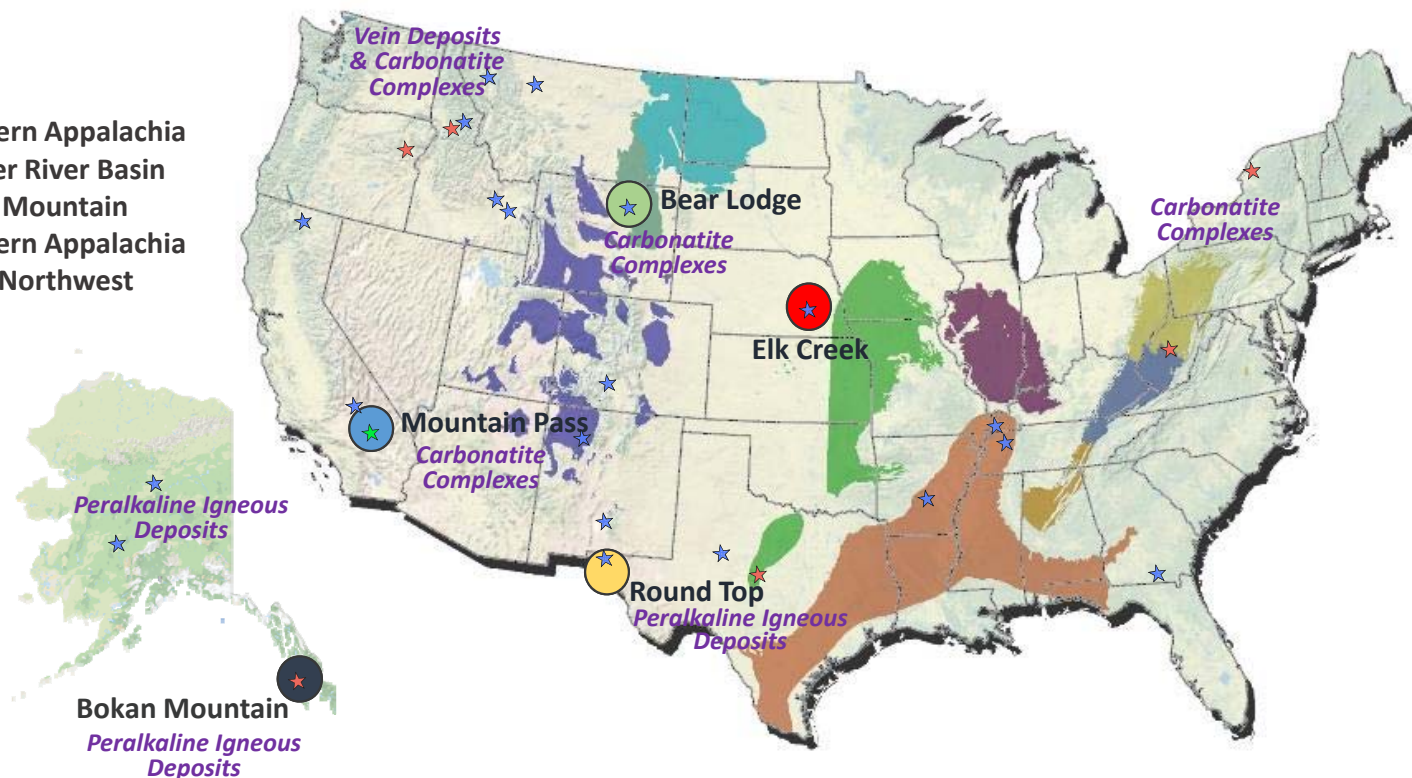
Rare Earth Elements – Coal Basins, REE Deposits, Mines



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



"Location of Deposits." *The Future of Strategic Natural Resources*, Massachusetts Institute of Technology, 2016, web.mit.edu/12.000/www/m2016/finalwebsite/solutions/deposits.html.
 David Lentz, University of New Brunswick. Ventyx Energy, Velocity 2012. National Geographic Society, i-cubed. USGS 30 arc-second elevation 1996, Natural Earth 2014, Robinson Projection, World Geodetic System 1984 datum.

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

REE Program



Feedstock Materials

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

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

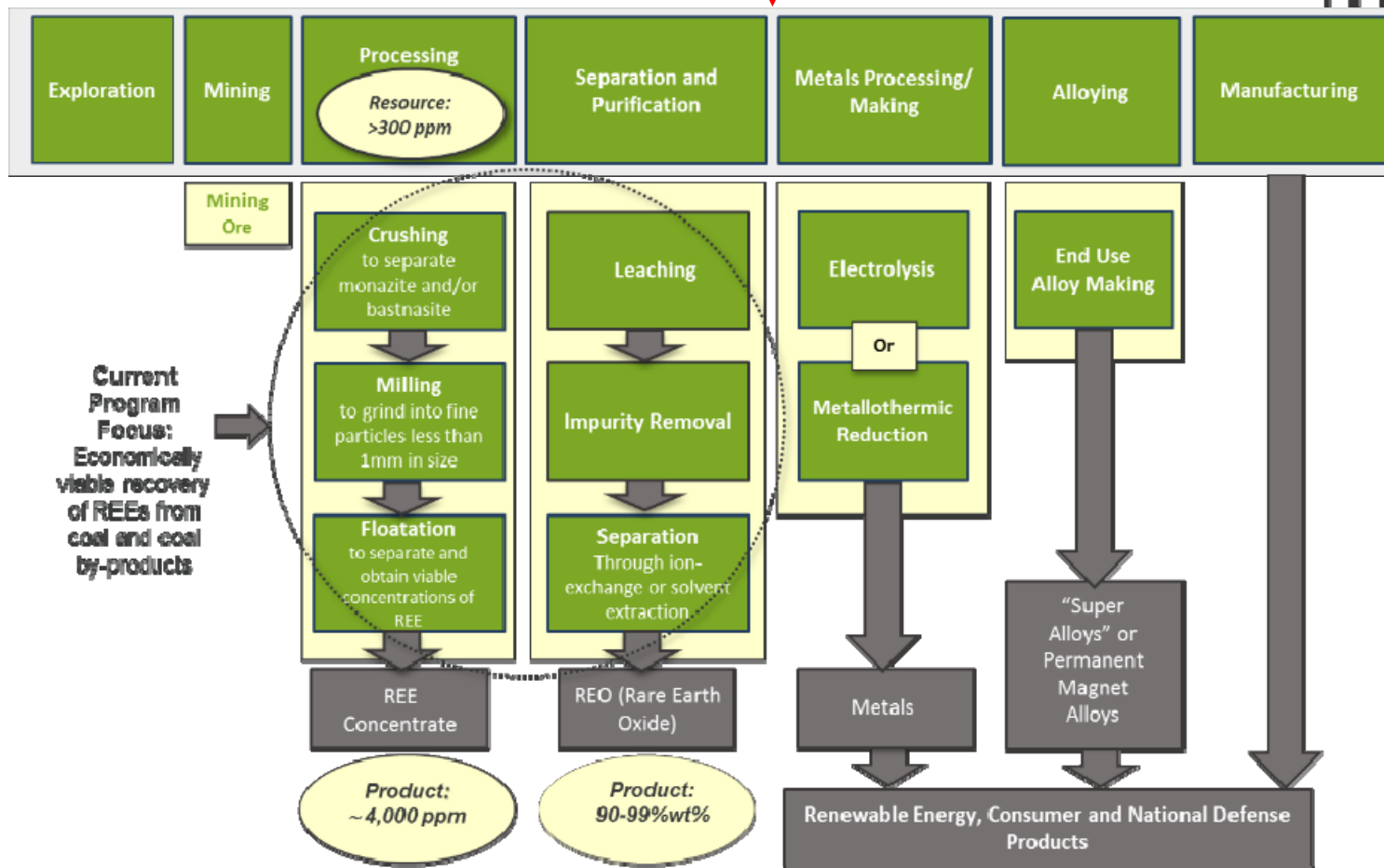
Objectives

- 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

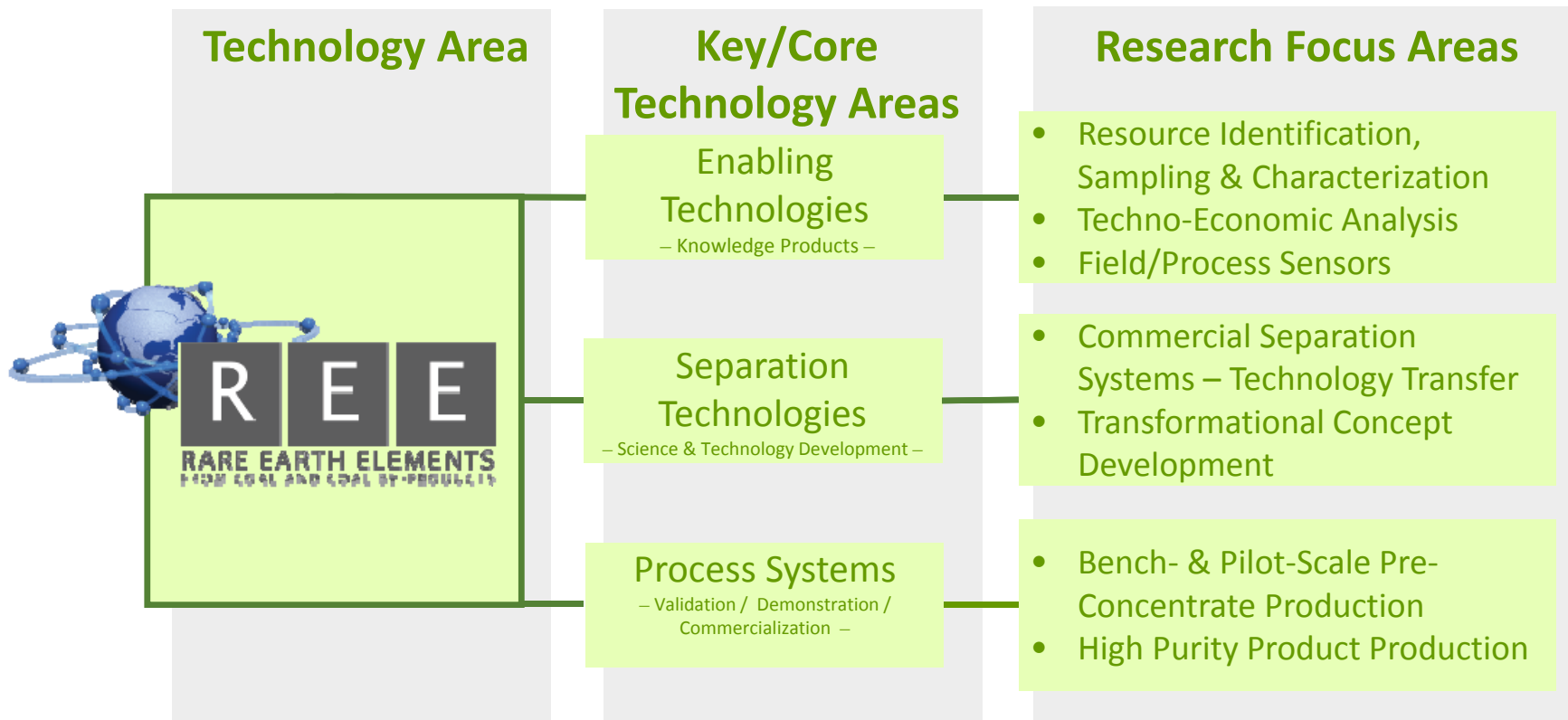
Goals

- 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*



REE Program – Structure



REE Program – Metrics



	2014-2018	2020 Target	2025 Target
REE Pre-Concentrates	>2wt% Laboratory/Bench-Scale Production	90-99wt%	90-99wt%
Economic Targets for Domestic REE Production	Off-Shore Markets/Pricing	Near Commercial Market Pricing	Competitive or Surpass Market Pricing
Environmental impact	Hazardous Off-Shore Production	Non-Hazardous	Non-Hazardous
Developmental Scale	Laboratory-Scale Concepts; Transitioning of Conventional Separation Technologies (TRL 2-3)	Validate Technical & Economic Feasibility of Prototype Salable High Purity REE Systems (TRL 5-7)	Integration of Transformational Technologies in Pilot-Scale Systems (TRL 7-9)

REE Program – Project Portfolio

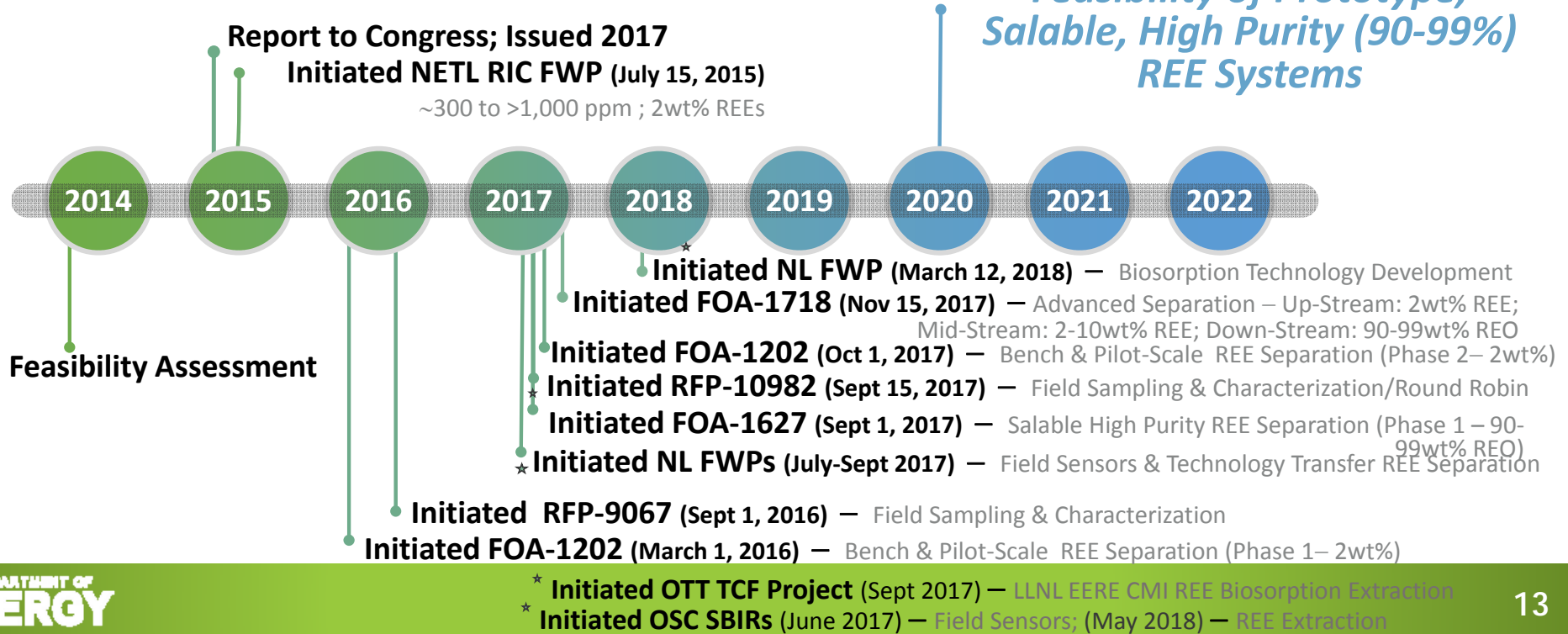


Key Drivers

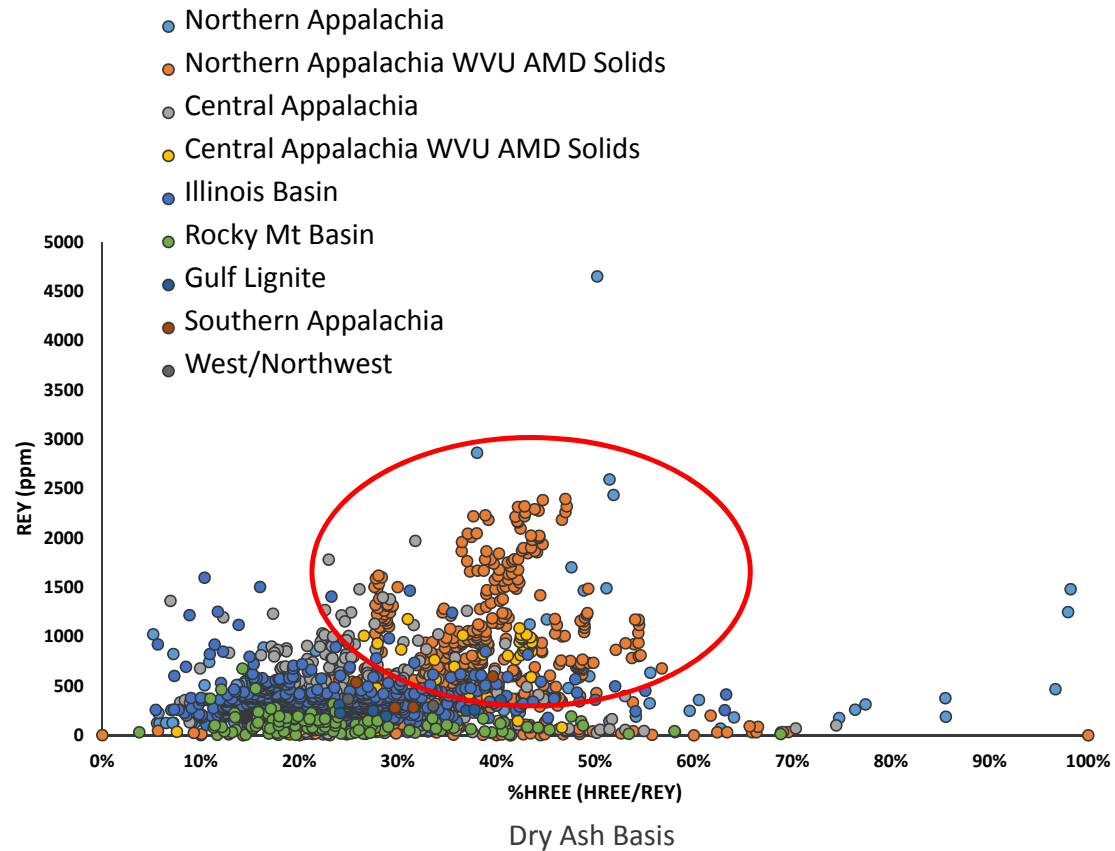
- National Security & Economy
- Environmental Impact
- Economic Targets
- Build U.S. Domestic Infrastructure for On-Shore Production

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

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



REE Program – Prospecting



REE Program – Processing



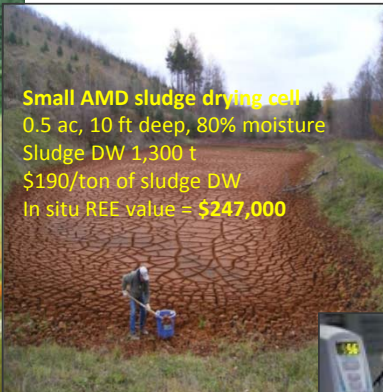
FOA DE-FE-0002012 – Opportunities to Develop High Performance, Economically Viable, and Environmentally Benign Technologies to Recover Rare Earth Elements (REEs) from Domestic Coal



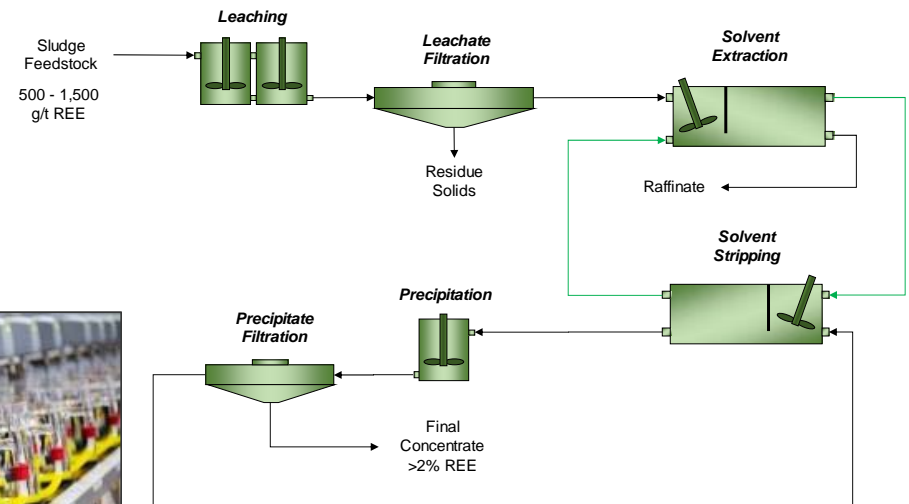
REE Program – Bench-Scale Processing



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

REE Program – Pilot-Scale Modular Processing



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

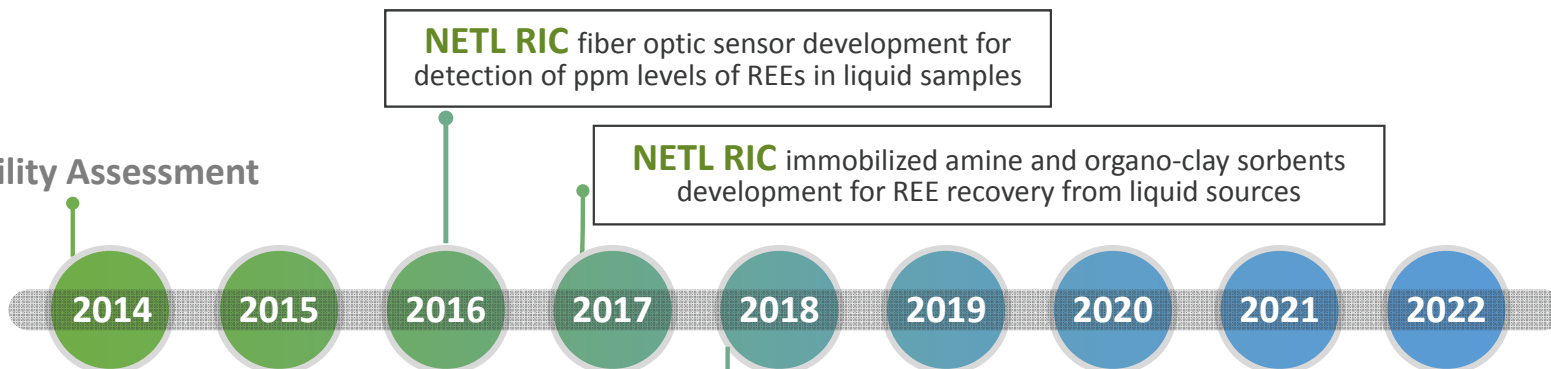
AOI-2 – Pilot-Scale Facilities University of Kentucky

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

REE Program – Major Accomplishments: 2016-2017



Feasibility Assessment

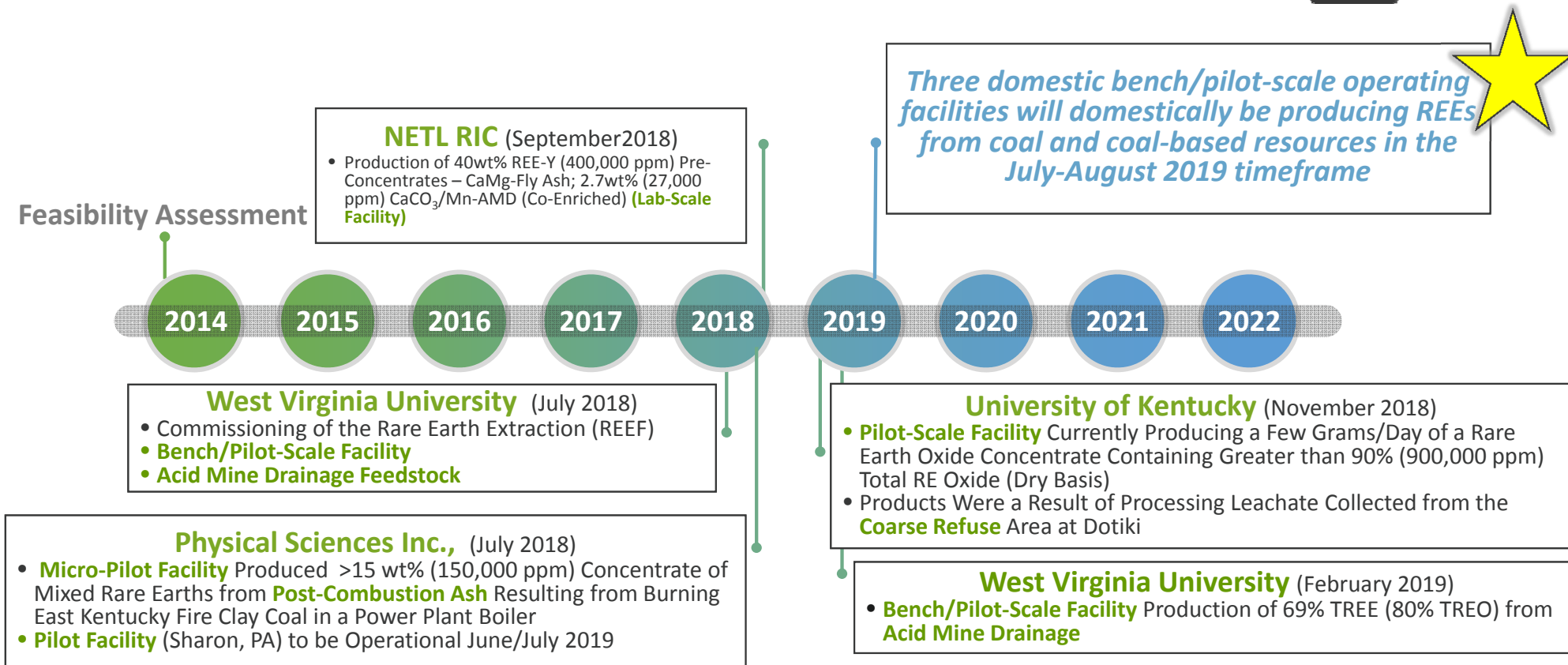


Physical Sciences Inc. (PSI), University of Kentucky, University of Wyoming, and others achieved **>30 wt% (300,000 ppm)** mixed REE pre-concentrates from coal-based materials

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

REE Program – Major Accomplishments: 2018-2019



REE Program – Summary



✓ *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

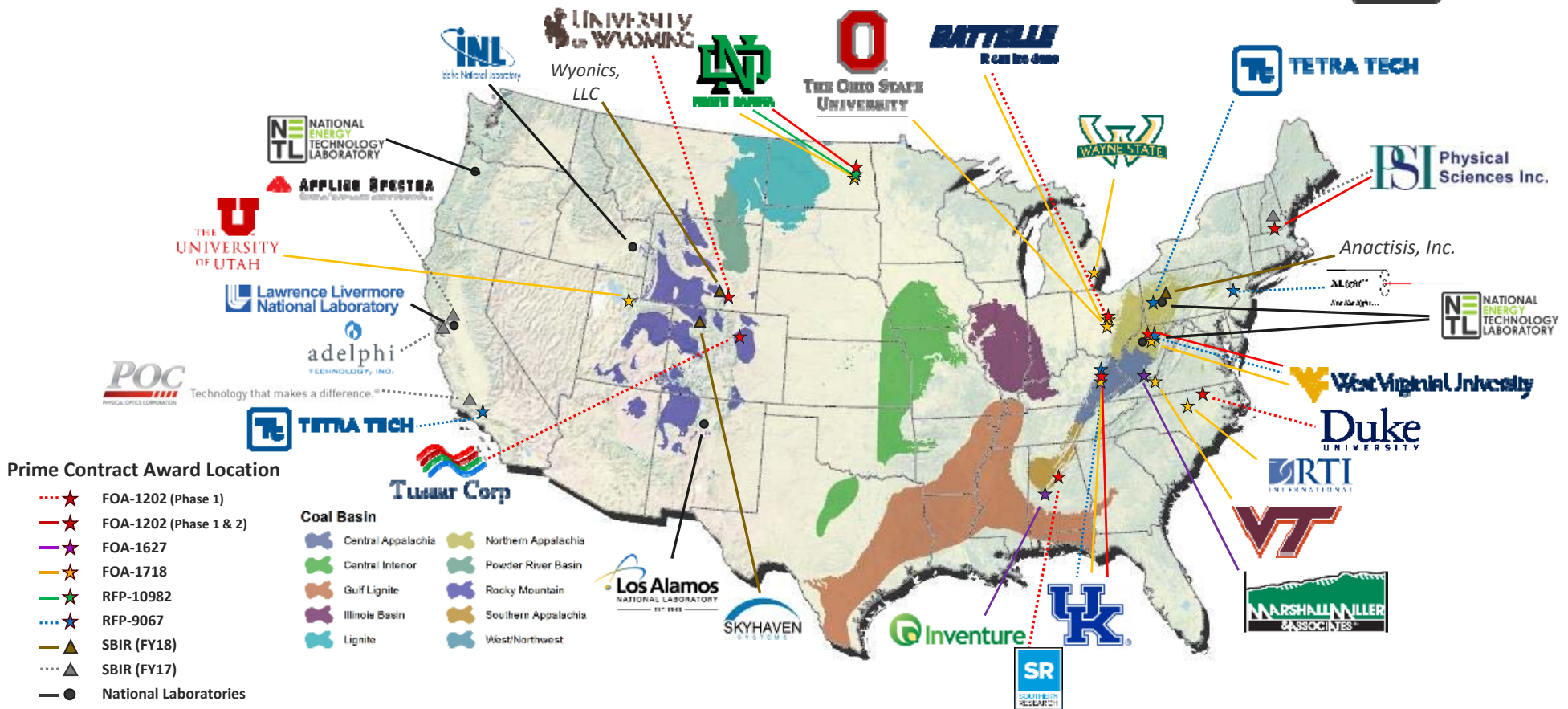
What Is Needed for Tomorrow

- ✓ **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 Re-Cycling*

REE Program – Acknowledgments



REE Program – Contact Information



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

<https://edx.netl.doe.gov/ree/>

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