



Rare Earth Elements Extraction & Recovery: Research, Development, Demonstration and Deployment & Market Outlook

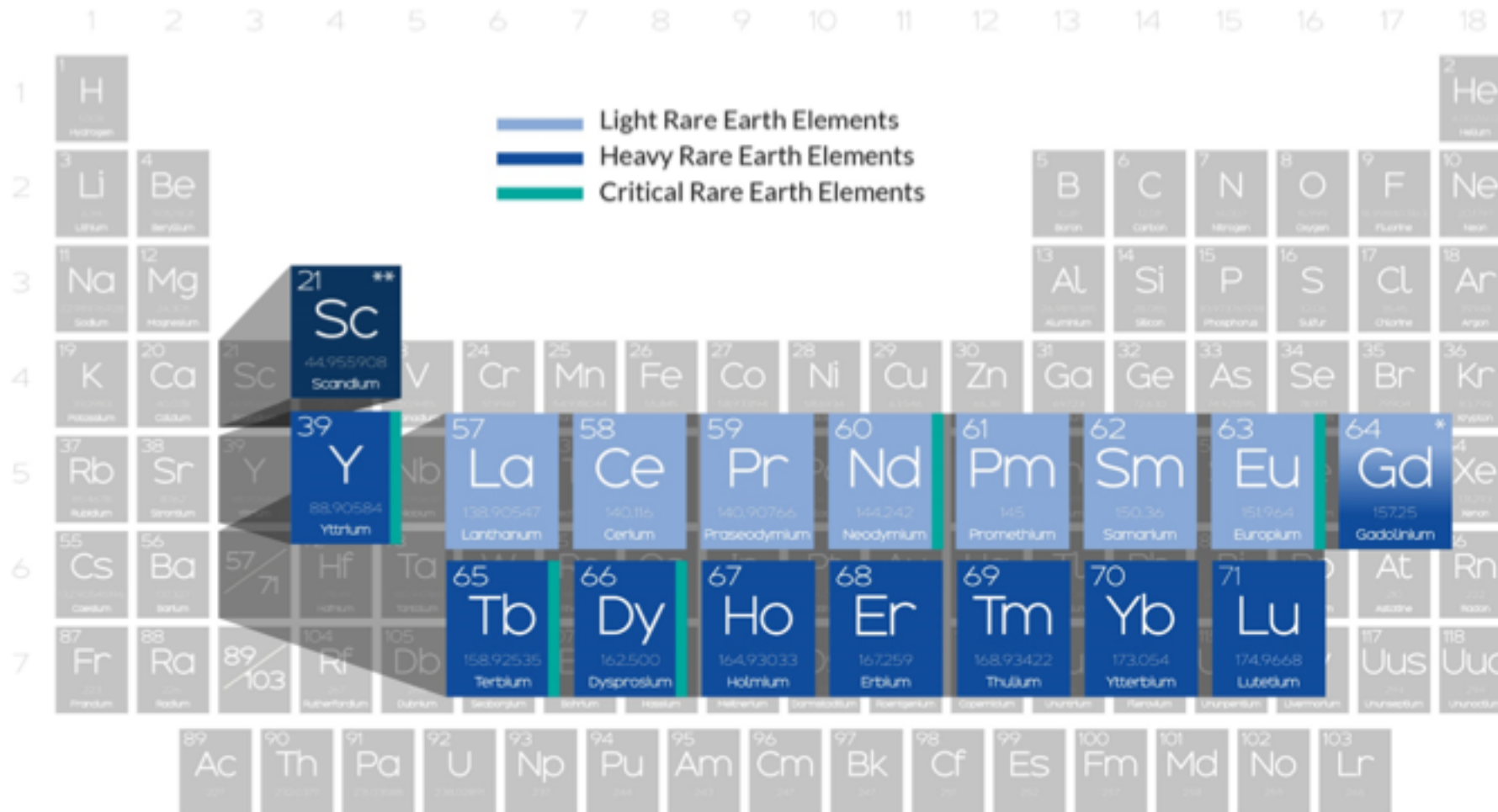
Mary Anne Alvin
NETL REE Technology Manager

National Association of State Energy
Officials (NASEO)

*Clean Coal and Carbon Capture and
Sequestration Workshop and Training*

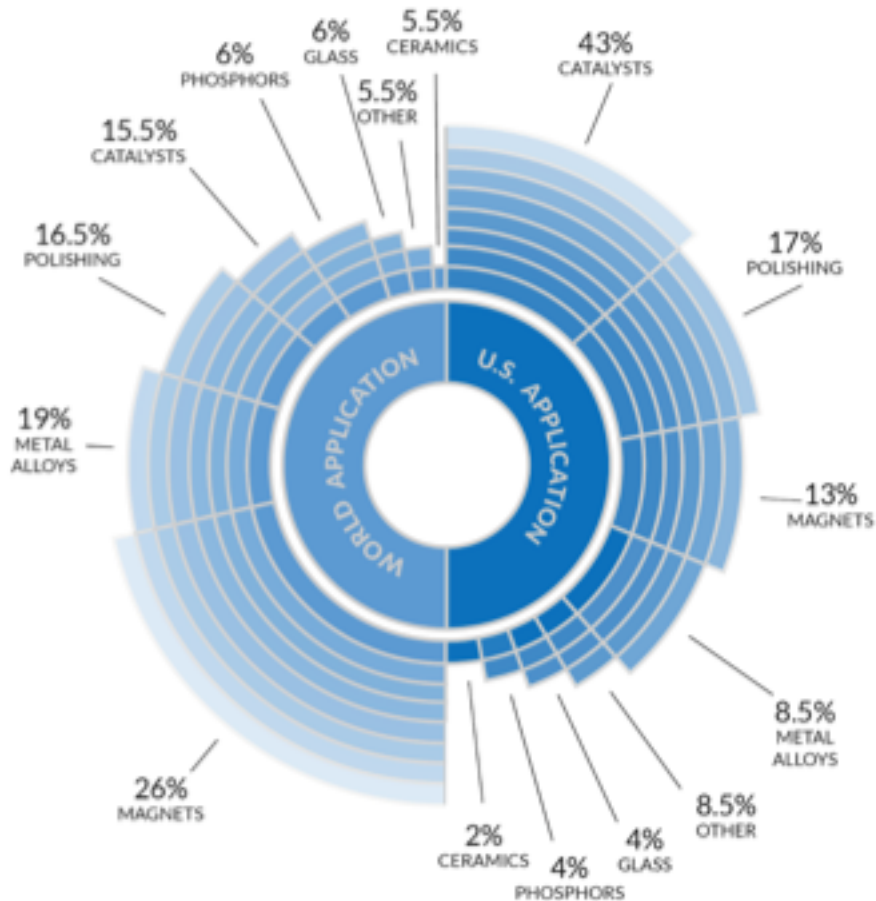
Houston, TX | June 14, 2018

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



METAL ALLOYS

NiMH Batteries
Fuel Cells
Steel
Super Alloys
Aluminum/Magnesium



DEFENSE

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



CATALYSTS

Petroleum Refining
Catalytic Converter
Fuel Additives
Chemical Processing
Air Pollution Controls



CERAMICS

Capacitors
Sensors
Colorants
Scintillators
Refractories



GLASS & POLISHING

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

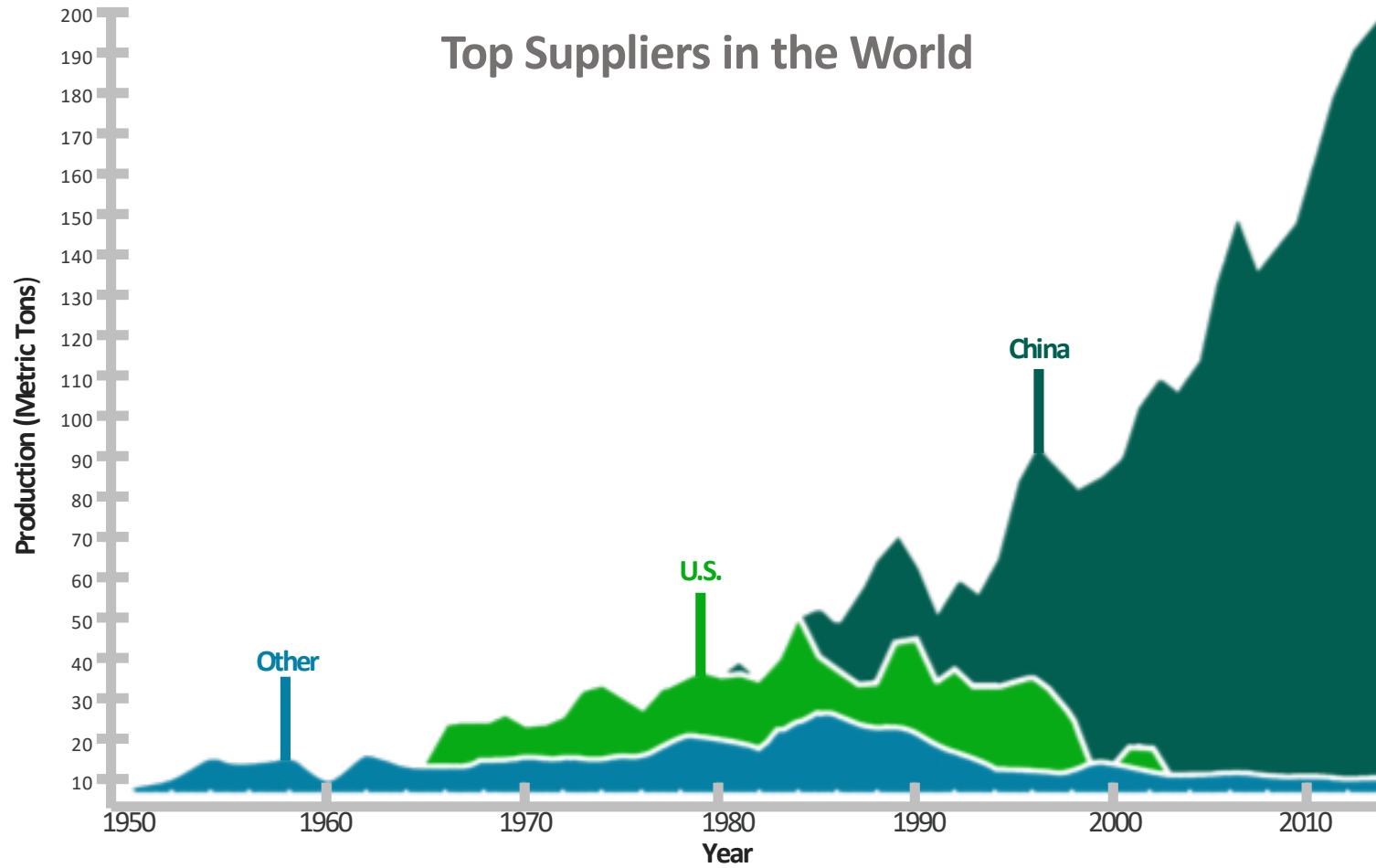


PHOSPHORS

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



REE Suppliers

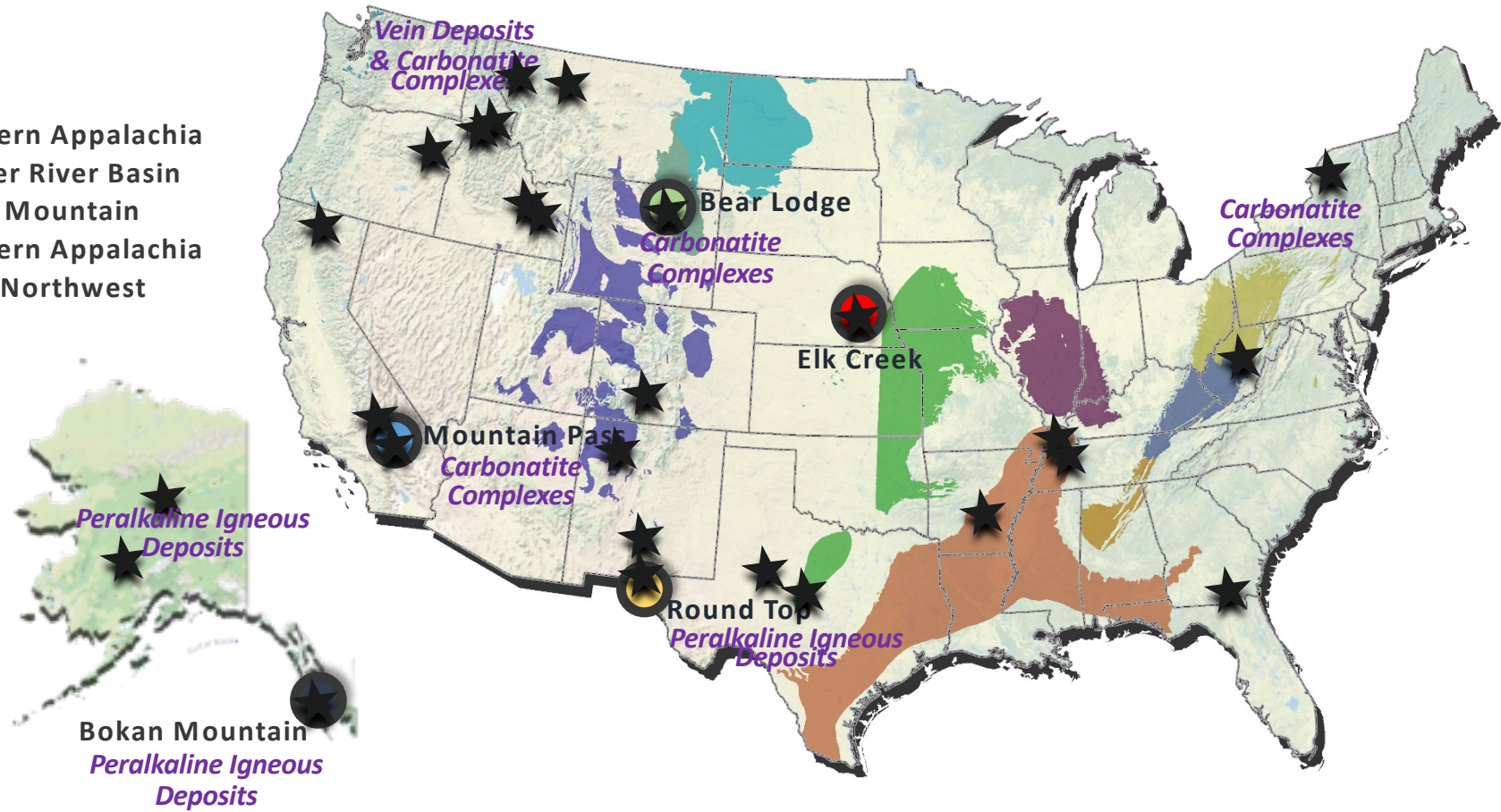


Rare Earth Elements – Coal Basins, REE Deposits, Mines

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

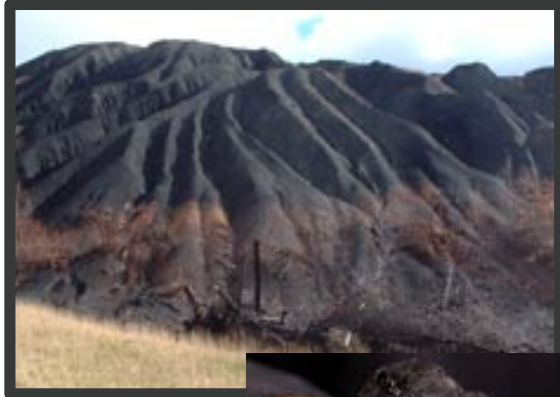


REE Program Feedstock Materials



Feedstock Materials

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



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

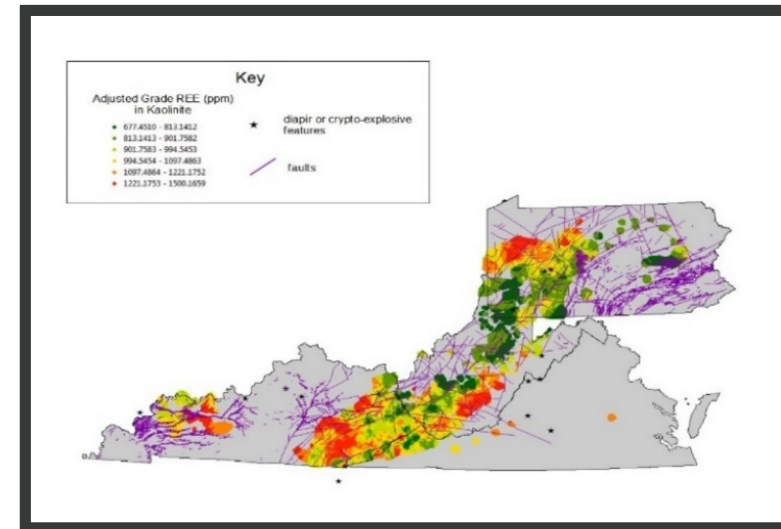
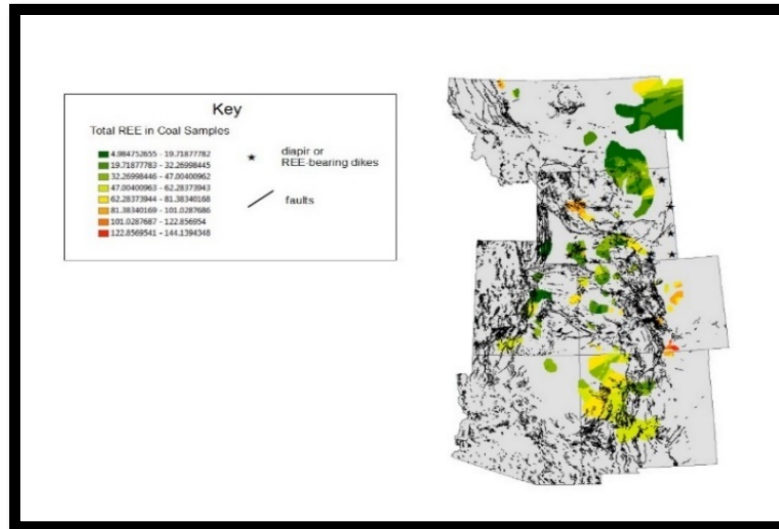
- ~75M tons of coal ash generated
 - Average concentration of ~470 ppm REE+Y, yields ~35,250 tons (~31,980 tonnes) of REE+Y annually
- If completely extracted, potential for generation of REEs from coal exceeds U.S. demand



Challenges & Opportunities
Material Reserves
Environmental & Economic Impact

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 750 million 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

Congressional Language

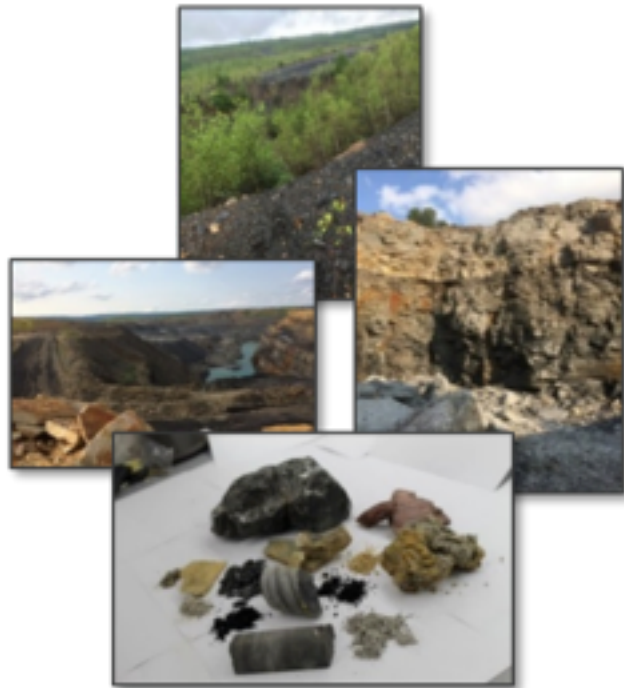
– Feasibility of Recovering Rare Earth Elements (REEs) –

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 APPROPRIATIONS ACT, 2018 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 byproduct sources** having the highest potential for success.



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/sandstone 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.

Challenges

- Currently U.S. does not produce REEs: Off-shore supply dependence
 - Potential international market volatility
 - Risk to the U.S. economy and defense
- Coal as an alternate REE resource
 - Low REE concentrations
 - Heterogeneous feedstocks
- Technology transfer
 - Conventional separations applied to coal-based resources
 - International visibility; Technology utilization

Drivers

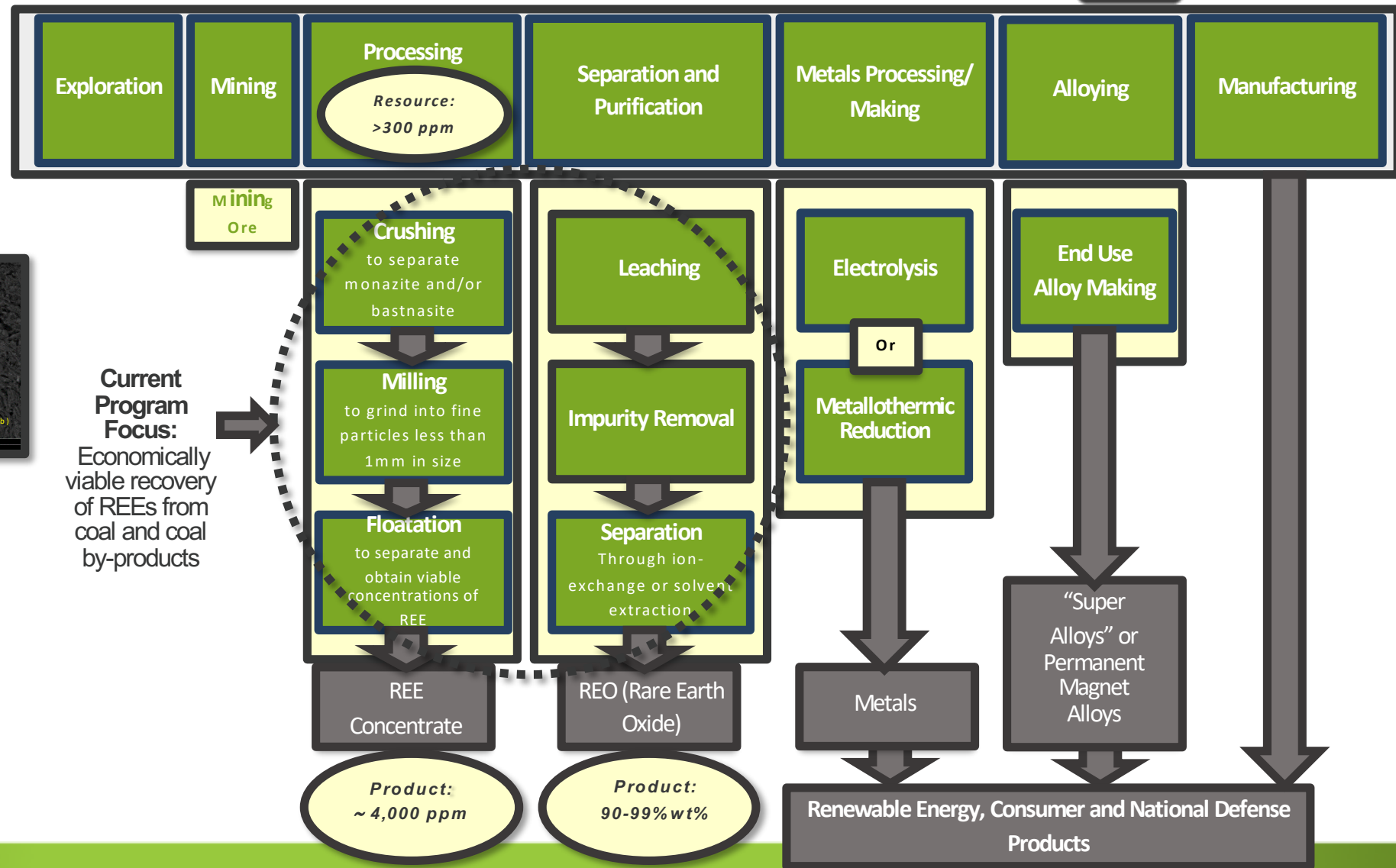
- Potential international market volatility
- National security/economy
- Environmental impact
- Economic targets competitiveness
- Heavy REE concentration in coal-based materials
- Development of U.S. domestic infrastructure for on-shore production of
 - REEs
 - Critical minerals/materials
 - Intermediate and end products

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 Value Chain



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

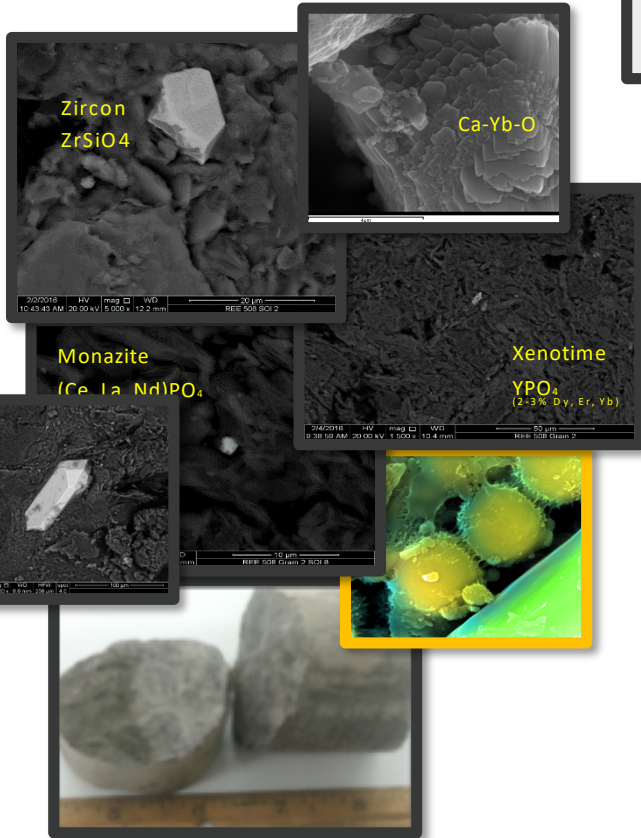
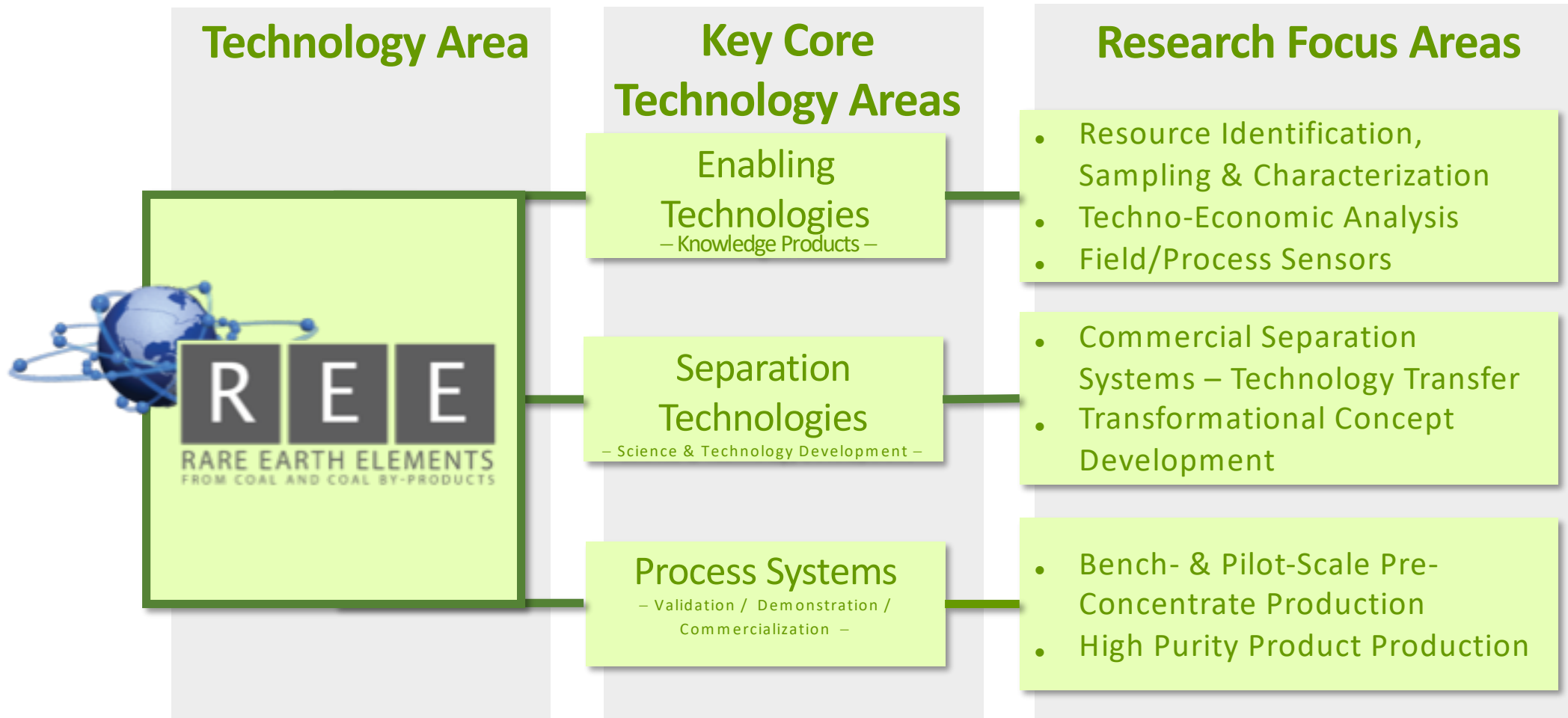


Photo & Micrographs Courtesy of NETL RIC



REE Program

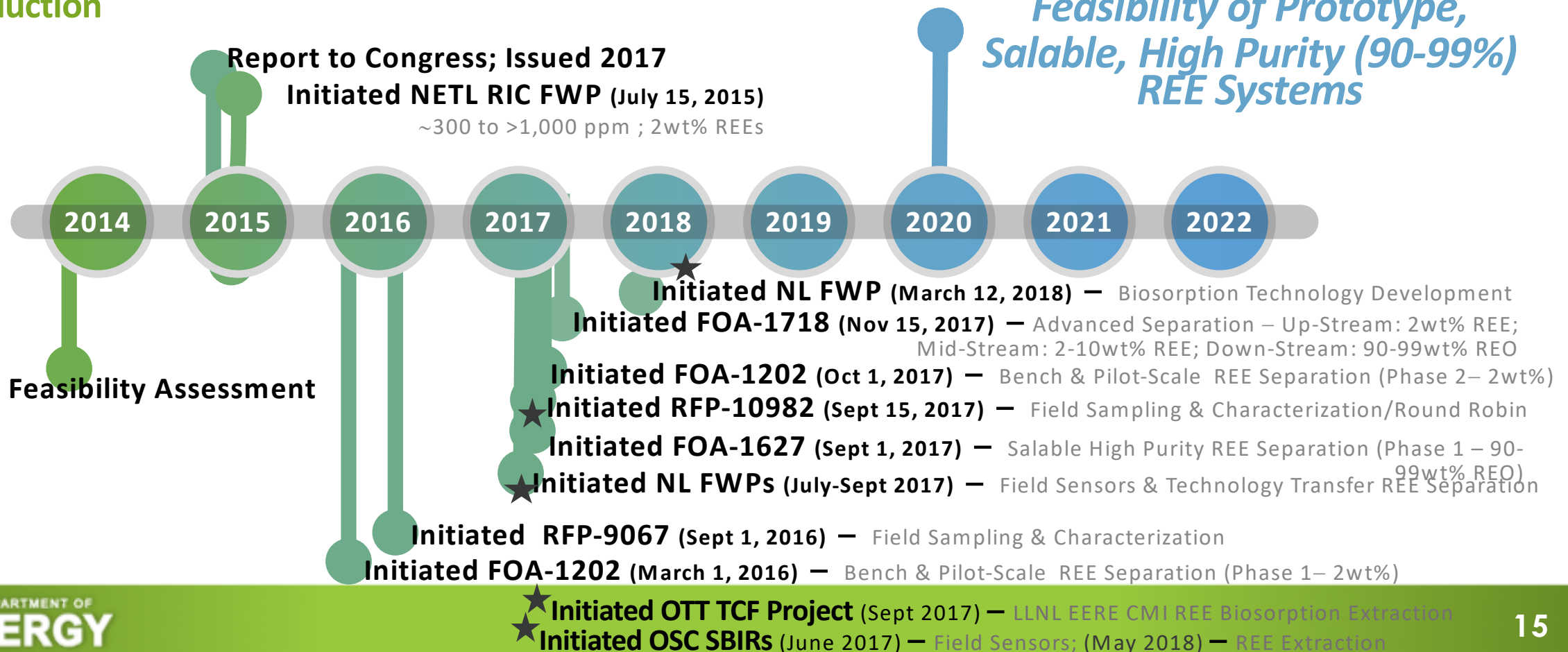


Key Drivers

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

FY17: 15 Active Projects
 FY18: >30 Active Projects
 Budget: \$15M/FY

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



REE Program Portfolio – Technology Crosswalk



| REE | National Lab FWP | | | | RFP (9067) (10982) | FOA | | SBIR | Other | | |
|--------------------------|------------------|-----|------|------|--------------------------|--------------------------------------|------------------------------------|-------|-------|-----|---------------|
| | NETL RIC | INL | LANL | LLNL | | Conventional (1202, 1627) PNNL | Transformational (1718) PNNL | | UCFER | TCF | LTI (FY14) |
| Prospecting | ● | | | | ● (5) | ● (6) | ● (9) | | ● | | ● |
| Processing | ● | | ● | ● | | ● (6) | ● (9) | | | ● | |
| Production | | | | | | ● (6) | | | | | |
| Sensor Development | ● | ● | ● | | | | | ● (4) | | | |
| Techno-Economic Analysis | ● | | | | | ● (6) | | | | | |
| CFD Modeling | ● | | | | | | | | | | |
| Geospatial Modeling | ● | | | | | | | | | | |

NETL: National Energy Technology Lab
 INL: Idaho National Lab
 LANL: Los Alamos National Lab
 LLNL: Lawrence Livermore National Lab
 PNNL: Pacific Northwest National Lab
 RIC: Research & Innovation Center

FY17: 15 Active Projects
FY18: >30 Active Projects

FWP: Field Work Proposal
 RFP: Request for Proposal
 FOA: Funding Opportunity Announcement
 SBIR: Small Business Innovative Research
 UCFER: University Coalition Research
 TCF: Technology Commercialization Funding
 LTI: Leonardo Technologies Inc.

Prospecting → Processing → Production

FY16 RFP DE-SOL-0009067 – Domestic

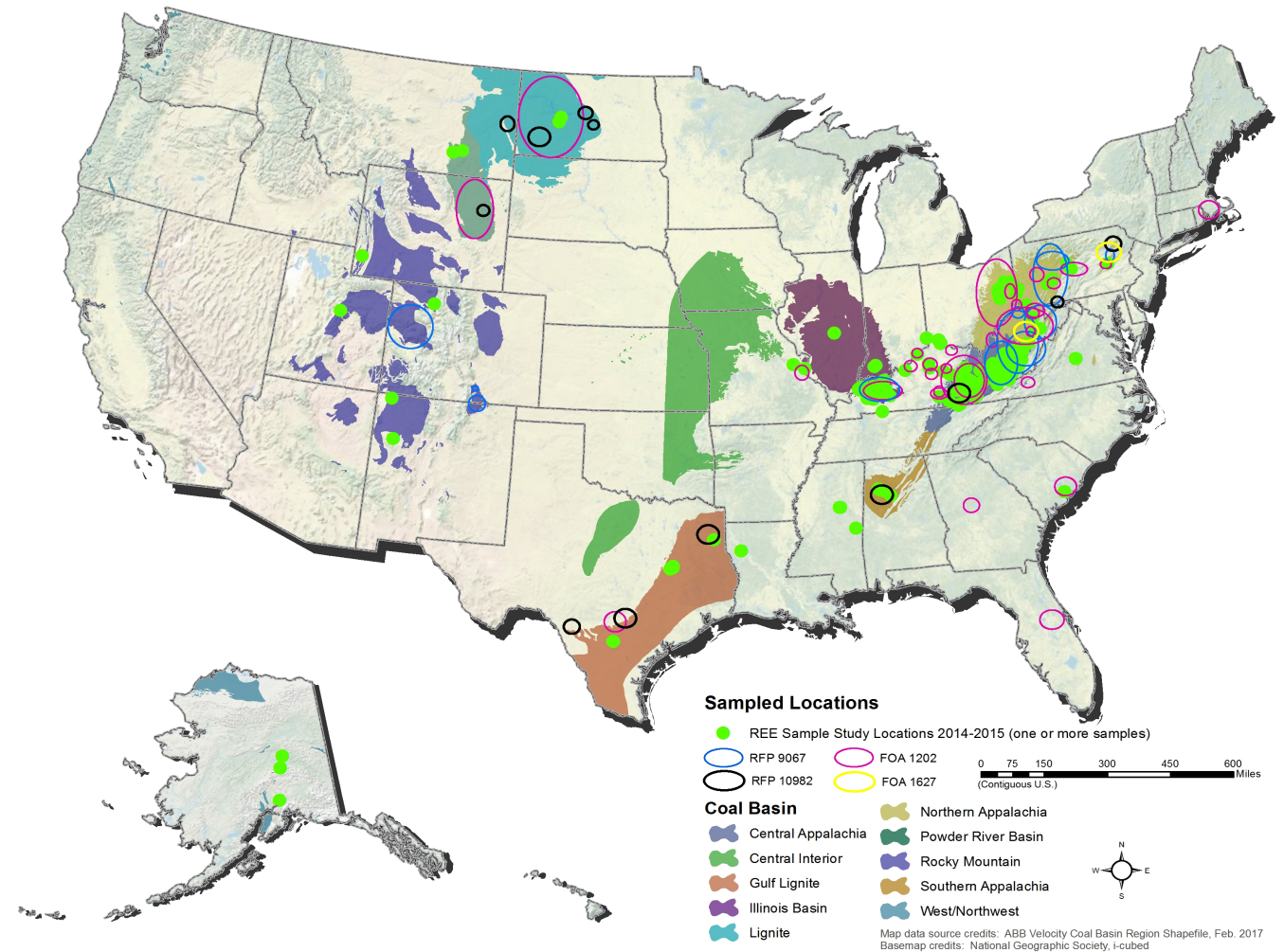
Field Sampling & Characterization

- **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
- **XLight Corporation:** Coals in the Eastern Pennsylvania Anthracite Region

FY17 RFP DE-SOL-0010982 – Domestic

Field Sampling & Characterization; Round Robin Analyses

- **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



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 (2wt% Pre-Concentrates)

- West Virginia University– AOI-1 Bench-Scale
- University of North Dakota – AOI-1 Bench-Scale

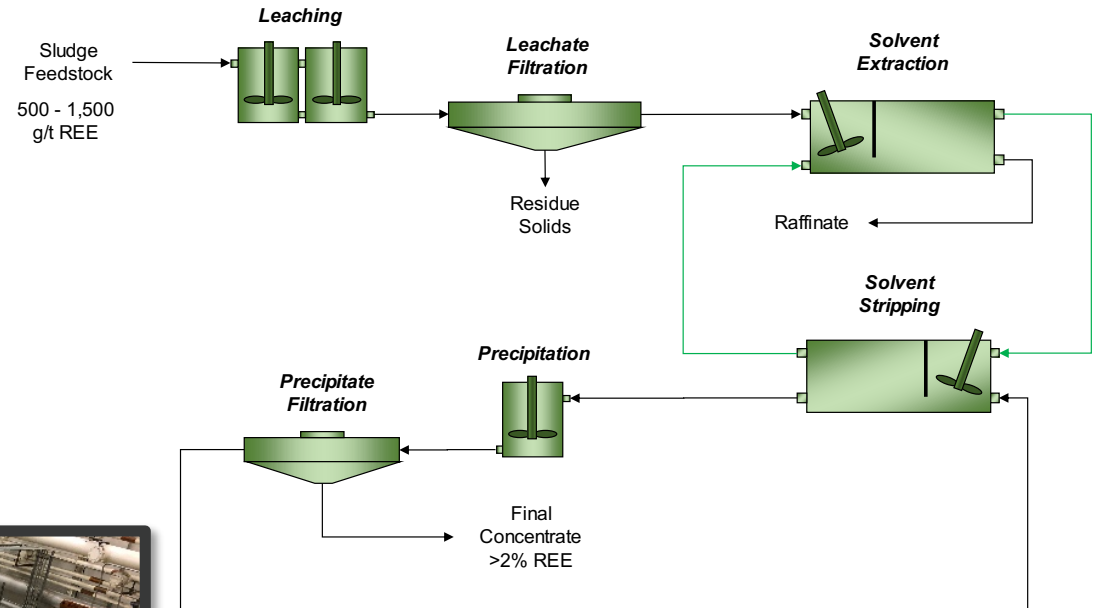
- University of Kentucky – AOI-2 Pilot-Scale
- Physical Sciences Inc. – AOI-2 Pilot-Scale

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 2,712 t
 \$135/kg REE
 Estimated Contained REE Value = **\$365,963**

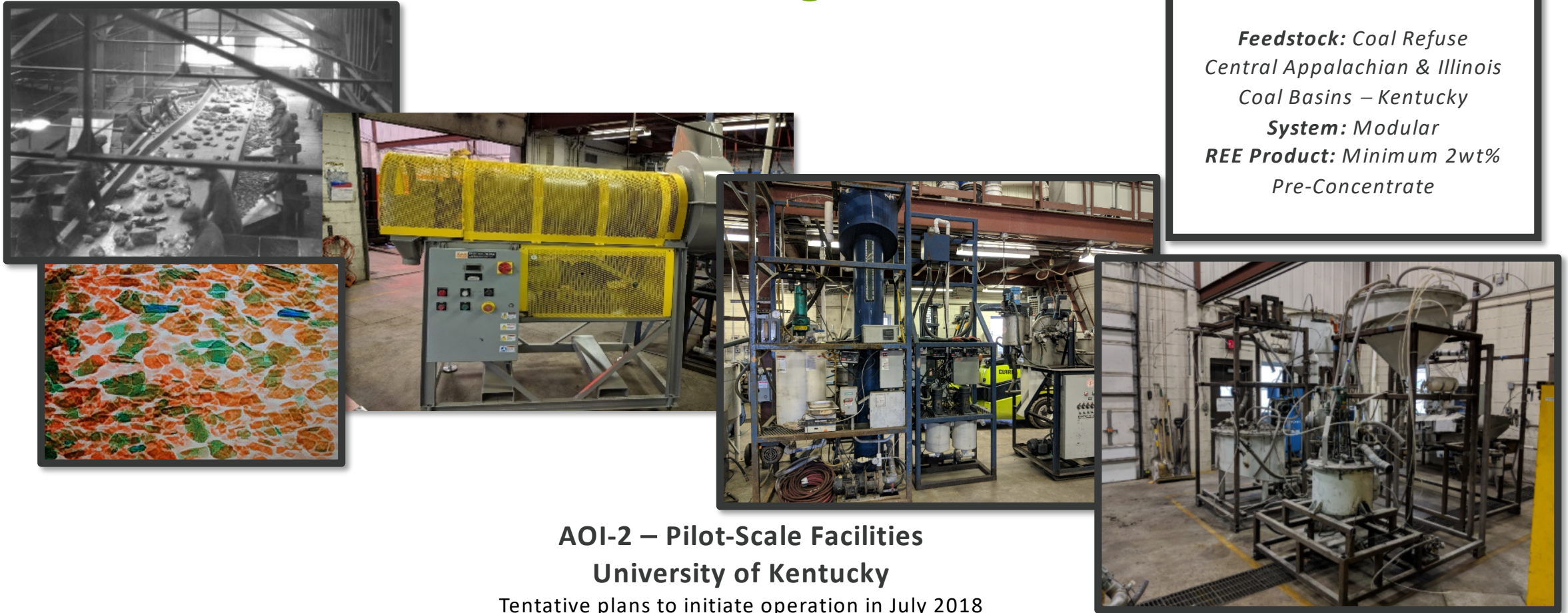
Courtesy of Paul Ziemkiewicz, WVU



AOI-1 Bench-Scale Facilities West Virginia University

Schematic of an acid mine drainage (AMD) treatment system
 Tentative plans to initiate operation in June 2018

FOA-1202 Phase 2: REE Extraction System – Conventional Technologies (Minimum 2wt%)



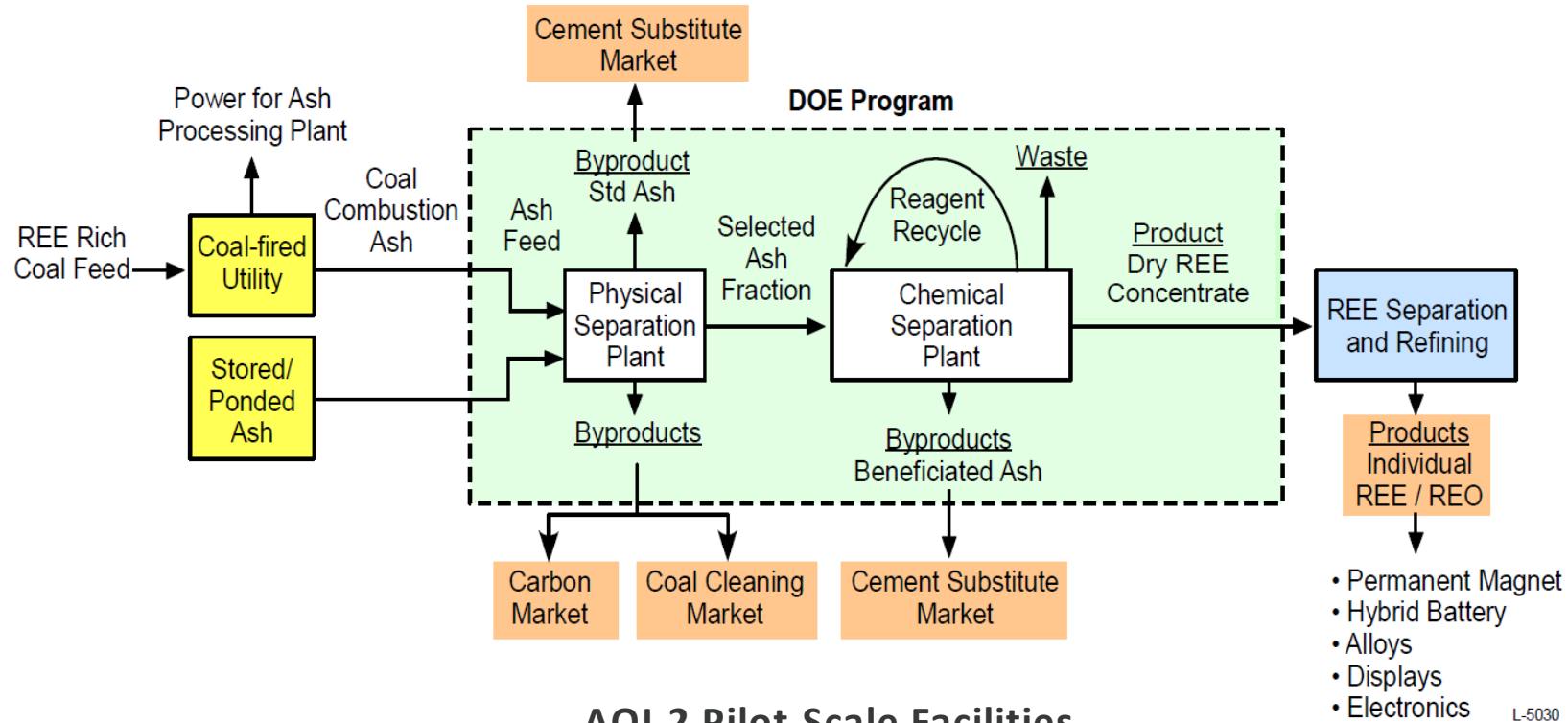
Feedstock: Coal Refuse
Central Appalachian & Illinois
Coal Basins – Kentucky
System: Modular
REE Product: Minimum 2wt%
Pre-Concentrate

AOI-2 – Pilot-Scale Facilities University of Kentucky

Tentative plans to initiate operation in July 2018
Production of REEs in December 2018

*Courtesy of Rick Honaker, Univ Kentucky,
Roe-Hoan Yoon, Virginia Tech*

FOA-1202 Phase 2: REE Extraction System – Conventional Technologies (Minimum 2wt%)



AOI-2 Pilot-Scale Facilities
Physical Sciences, Inc.

Schematic of fly ash REE extraction system

L-5030

FY17-FY18 FOA DE-FE-0001718 – Advanced Transformational REE Separations Development (3 AOIs)

2wt% REE Pre-Concentrates (AOI-1)

- **University of Kentucky, Virginia Tech, Blackhawk Mining, and Alliance Coal** – Low Temperature Plasma Treatment for Enhanced Recovery of Highly Valued Critical REEs from Coal
- **Virginia Tech** – Development of a Cost-Effective Extraction Process for the Recovery of Heavy and Critical Rare Earth Elements from the Clays and Shales Associated with Coal
- **RTI, Cerahelix, Veolia Water Technologies** – Low Cost REE Recovery from Acid Mine Drainage Sludge
- **University of North Dakota, Pacific Northwest National Laboratory** – Economic Extraction and Recovery of REEs and Production of Clean Value-Added Products from Low-Rank Coal Fly Ash
- **The Ohio State University** – Concentrating Rare Earth Elements in Acid Mine Drainage Using Coal Combustion By-Products Through Abandoned Mine Land Reclamation

2-10wt% REE Pre-Concentrates (AOI-2)

- **University of Utah, Virginia Tech** – Economic Extraction, Recovery, and Upgrading of Rare Earth Elements from Coal-Based Resources
- **Wayne State University, LLNL, UCLA** – Coupled Hydrothermal Extraction and Ligand-Associated Organosilica Media Recovery of REEs from Coal Fly As

90-99wt% High Purity REE (AOI-3)

- **Battelle Memorial Institute, Rare Earth Salts** – Recovery of High Purity Rare Earth Elements (REEs) from Coal Ash via a Novel Electrowinning Process
- **West Virginia University, Virginia Tech** – At-source Recovery of Rare Earth Elements from Coal Mine Drainage

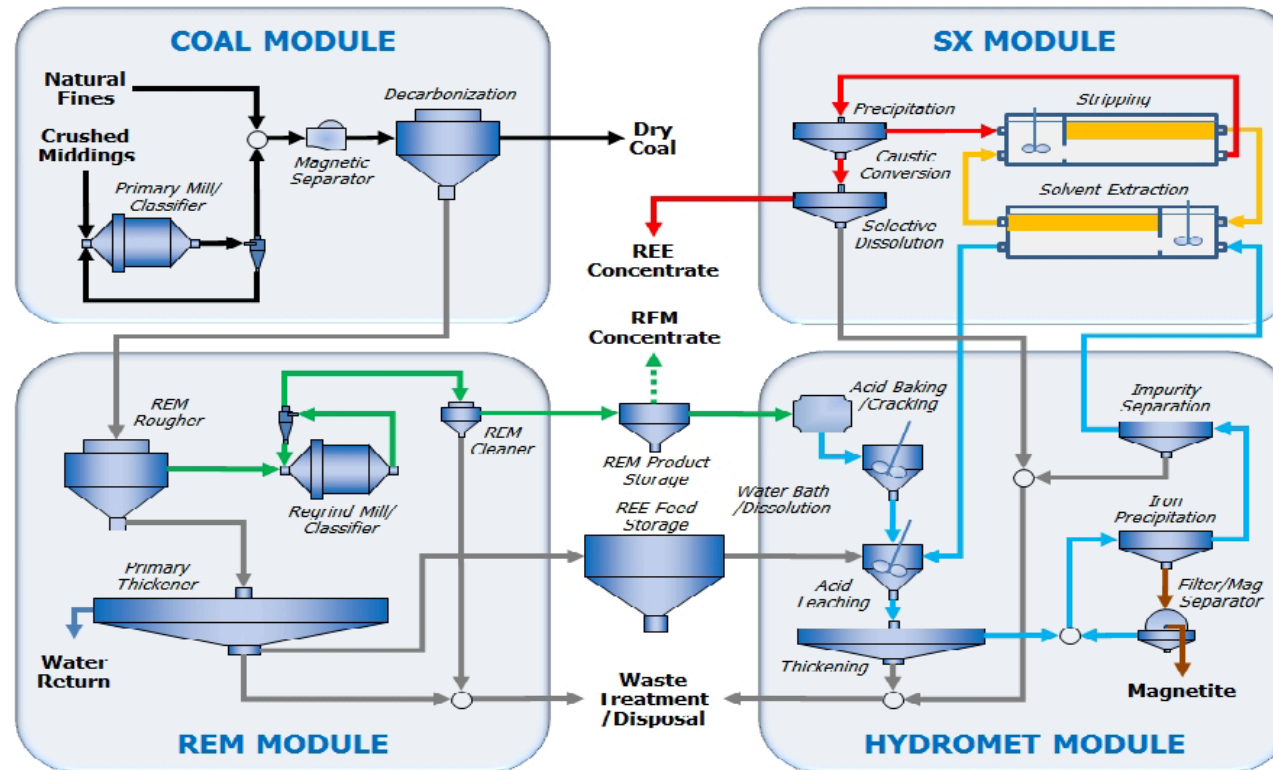
FY16-FY17 FOA DE-FE-0001627 Phase 1 – Production of Salable Rare Earth Elements from Domestic U.S. Coal and Coal By-Products

- 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

REE Program Goal

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.

FOA-1627 Phase 1: REE Extraction & Separation System – Conventional Technologies (90-99wt%)



Phase 1: Design, TEA, Supplemental Testing
Feedstock: Coal Refuse
WV Coal Prep Plant
System: Stationary
REE Product: Salable, High Purity, 90-99% REOs

Marshall Miller & Associates Small Pilot-Scale Validation

Marshall Miller & Associates, Inc. process block diagram for the proposed REE recovery facility

National Laboratories – Field Work Proposals (FWP)

- National Energy Technology Laboratory (NETL) Research & Innovation Center (RIC)
- Los Alamos National Laboratory (LANL)
- Idaho National Laboratory (INL)
- Lawrence Livermore National Laboratory (LLNL)
- Pacific Northwest National Laboratory

Field Resource Assessment

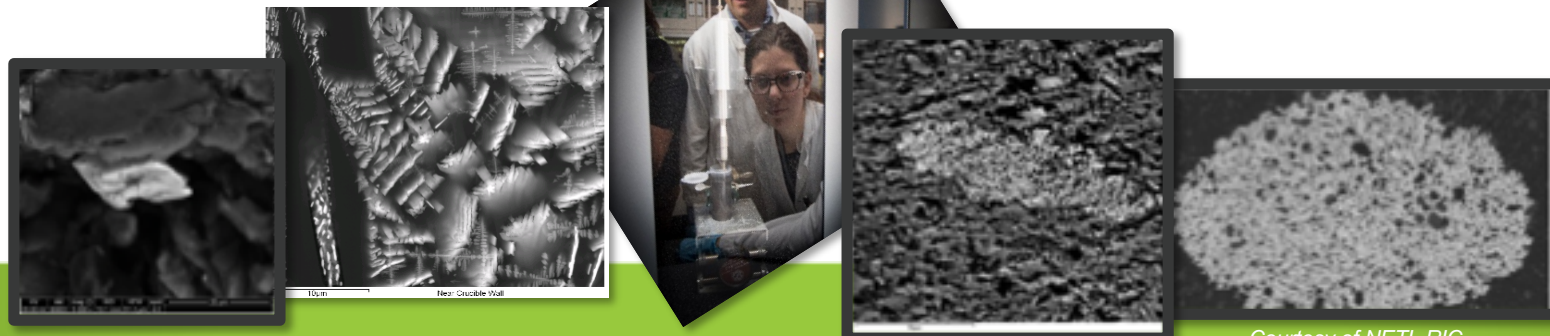
- 768 field samples from PA & WV were collected in collaboration with FE-HQ and analyzed
 - Thorium spectral gamma-ray indicated the presence of REE-rich zones
 - L-REE correlation with thorium
 - H-REE association with zirconium, yttrium, hafnium
 - Samples with high REE concentrations appear to contain physically weathered monazite grains
 - Titanium/aluminum ratio correlates strongly with REE and indicates REEs were concentrated during periods of high erosion
- **Partnerships/Collaborations**
 - EPRI, USGS, Consol
- **Patent Applications**
 - Fiber optic probe: Detection of REEs at ppm level in liquid samples

Separation & Extraction Technologies

- **Patent Applications**
 - Regenerable immobilized amine sorbents for REE and heavy metals recovery from liquid sources
 - Organo-clays for recovery of rare earth elements
 - Recovery of REEs from thermal slag processing
- **REE Separation & Extraction**
 - Achieved ~ 4,000 - 6,000 ppm REE pre-concentrate from 300-500 ppm REE coal-based material
- **Development of multiphase CFD tools**
 - Simulation and optimization of REE ammonium sulfate separation processes

Techno-Economic Analyses

- **Model Development**
 - Performance and economics assessment of REE separation & extraction processes



Courtesy of NETL RIC

FY17-FY18 National Labs

- **FY15-FY17 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
- **FY18 LLNL/Duke Univ/Purdue Univ FWP** – Application of Biosorption for REE Recovery from Coal Byproducts

FY17 Technology Commercialization Fund (TCF)

- **FY17 LLNL** – Rare Earth Metal Extraction for Clean Technologies

Office of Science (OSc) – Small Business Innovative Research Initiatives (SBIRs)

FY17 Small Business (SBIR) Projects

- **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

- **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

REE Program – Major Accomplishments



Key Drivers

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

2020 GOAL

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

Feasibility Assessment



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

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

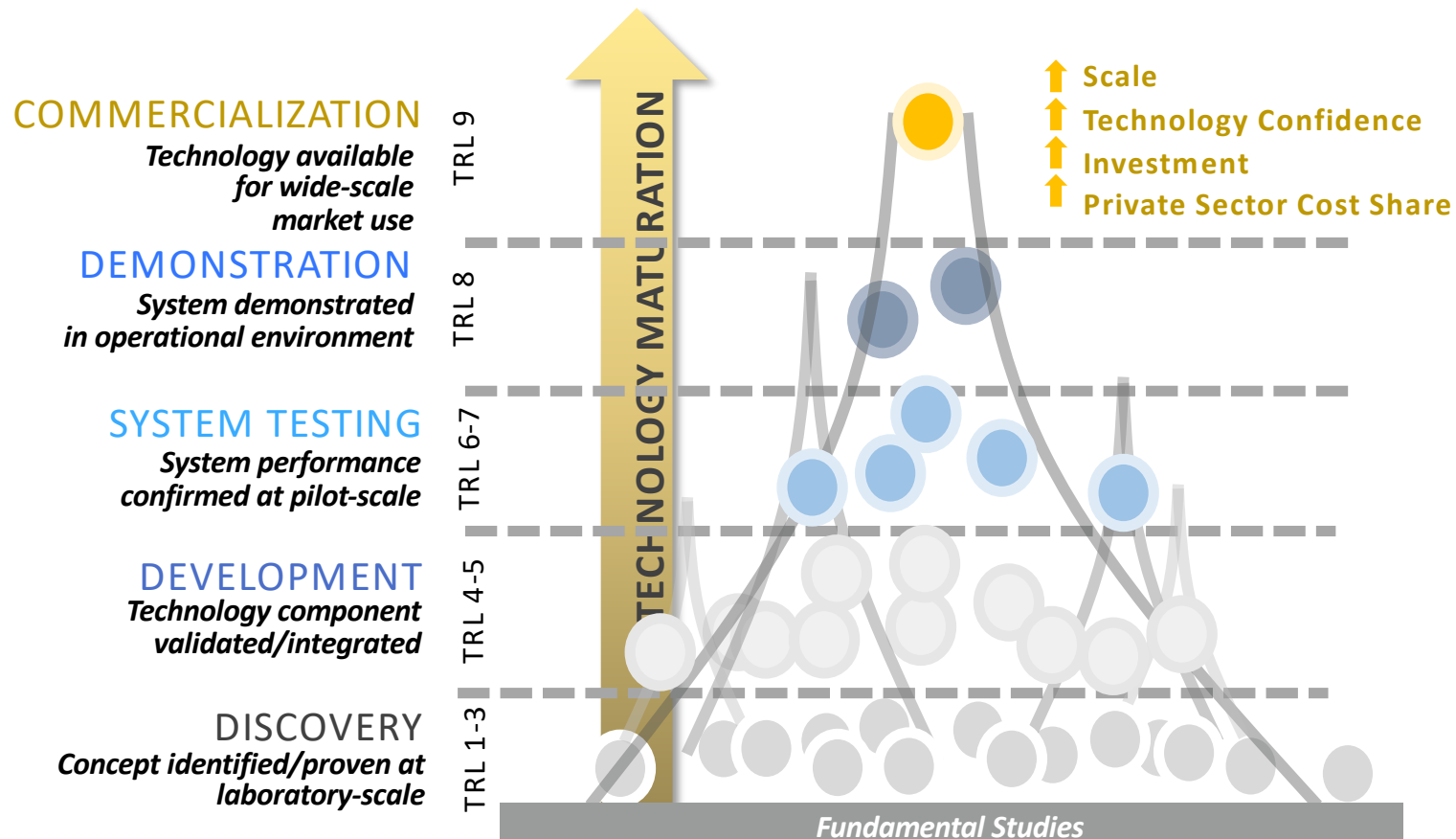
West Virginia University achieved recovery of nearly 100 percent REEs from coal acid mine drainage (AMD) sludge

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

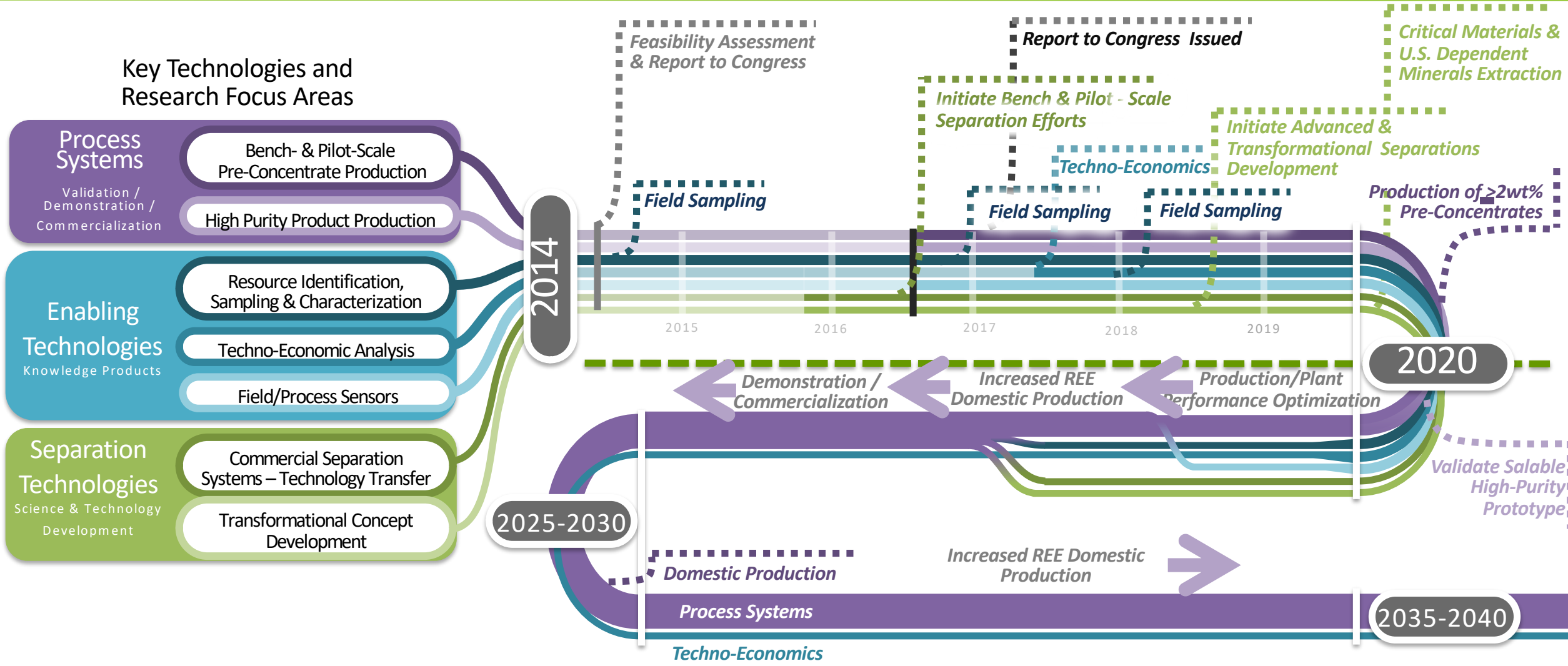
University of Kentucky produced small quantities of 80 percent (800,000 ppm) total REEs on a dry whole mass basis and more than 98 percent (980,000 ppm) REOs. Critical elements such as neodymium and yttrium — used in national defense technologies and the high-tech and renewable energy industries — represented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

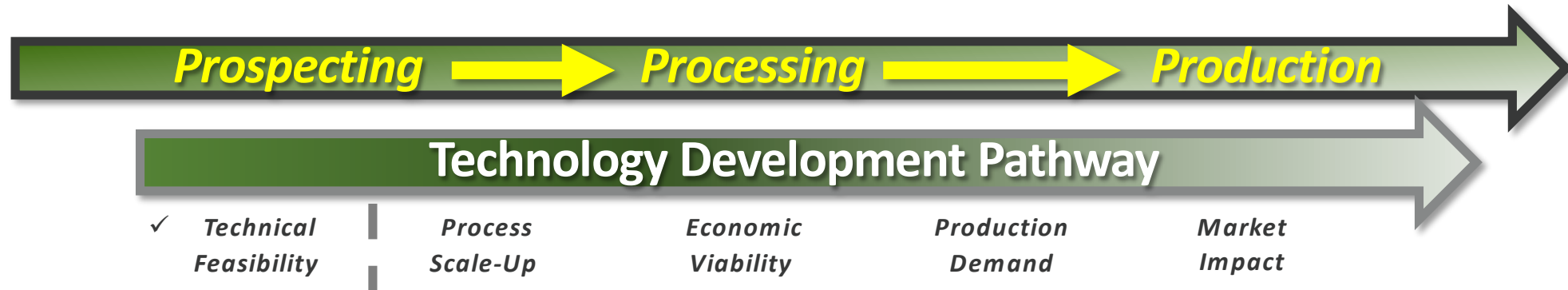
DOE-NETL Research Programs

– An Active Portfolio from Concept to Market Readiness –



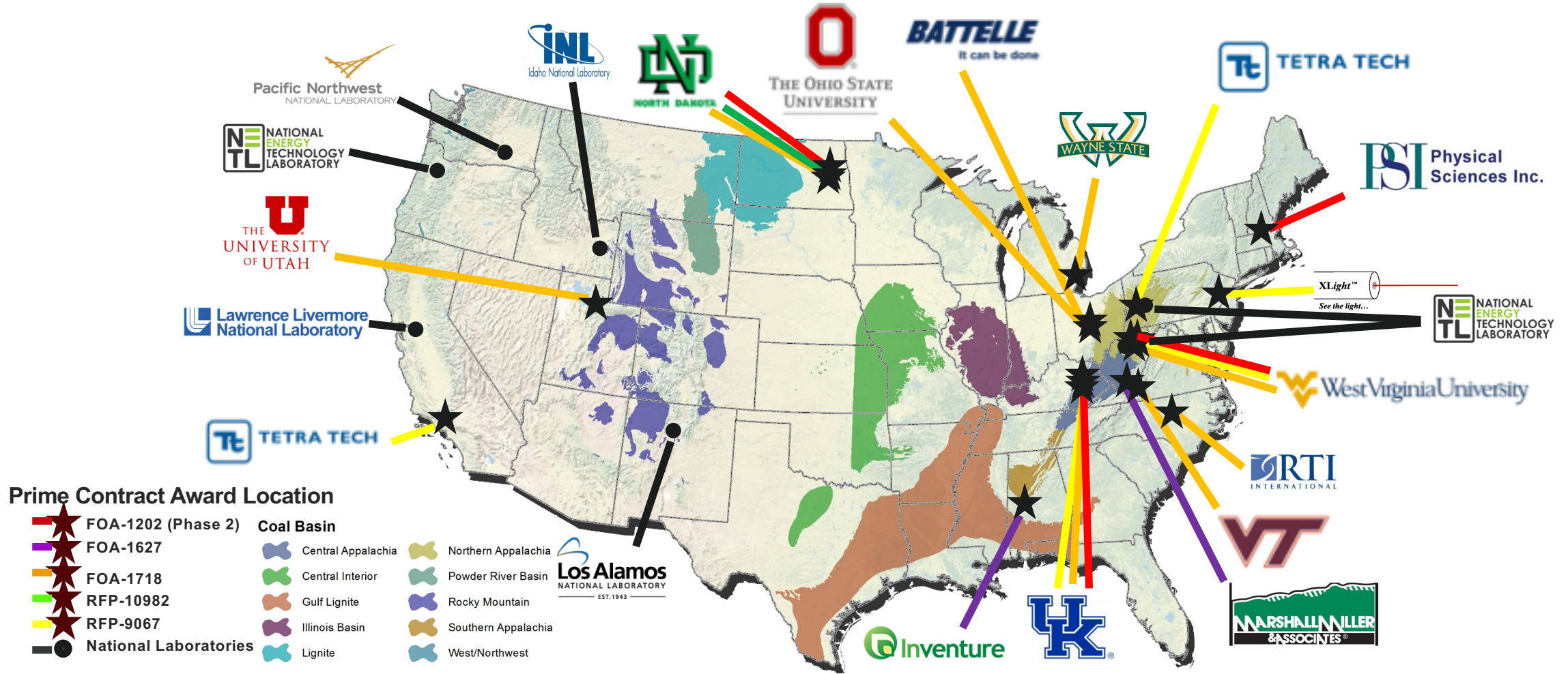
REE Technology Development Timeline





- ✓ Technical Feasibility of Extracting REE from Coal-Based Resources Demonstrated at Laboratory/Bench-Scale
- ✓ 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
- *Process Scale-Up and Economic Viability Need to Be Demonstrated*
- *Impact of REE Production on International Market Needs to Be Demonstrated*

REE Program – Acknowledgments



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

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