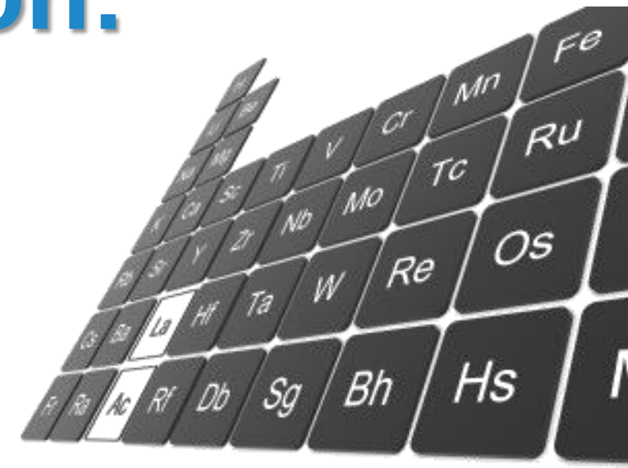
Partnering for Innovation: Critical Materials



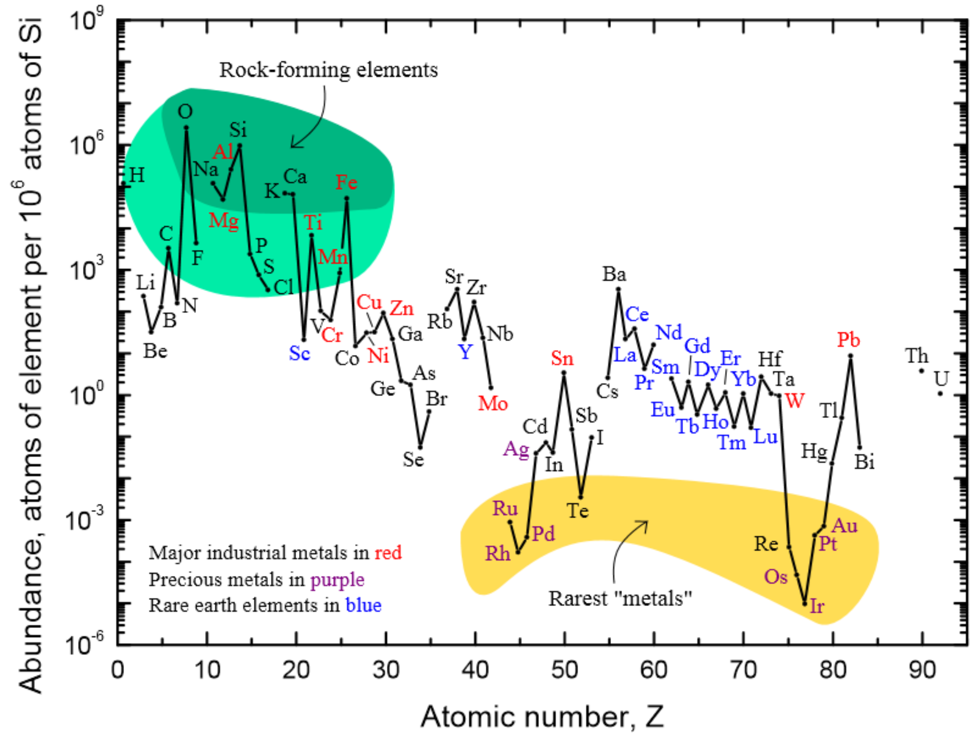
Roe-Hoan Yoon, Lead
Paul King, Business Development
Critical Materials Strategic Growth Area
NETL-Regional University Allience

2nd Energy & Innovation Conference
November 28-29, 2012

Critical Materials-Definition

- *Critical*:
  - Intrinsically rare, low grade, or currently unavailable in the United States.

- *Energy Critical Elements*:
  - Chemical elements that are essential for the deployment of transformative energy technologies.

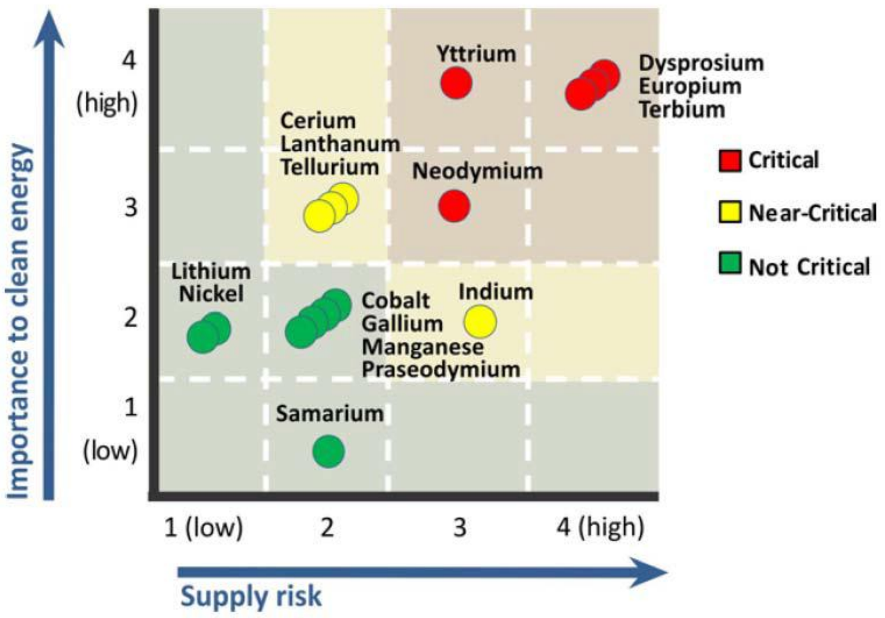


Application of Critical Materials

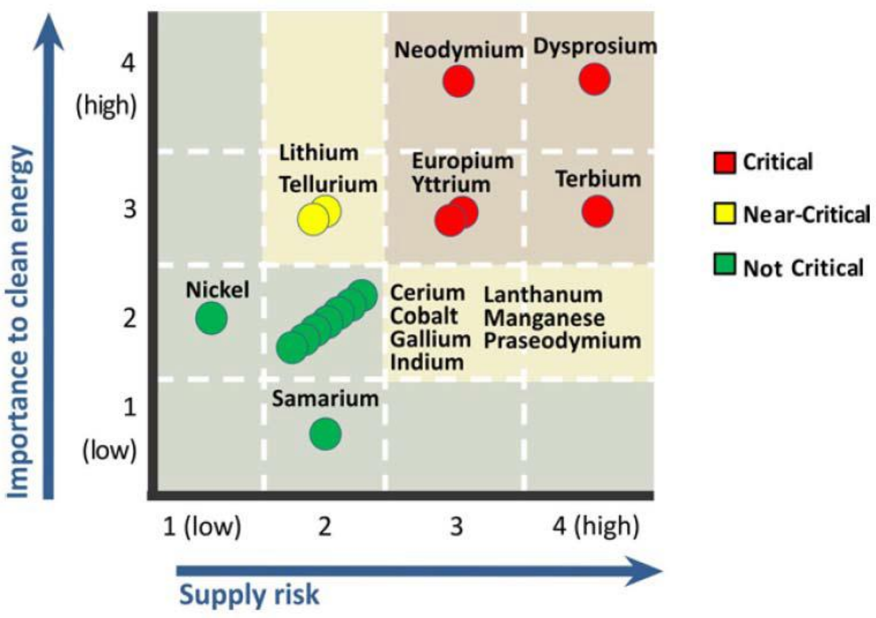
	Photovoltaic Films	Wind Turbines	Vehicles		Lighting
MATERIAL	*Coatings*	*Magnets*	*Magnets*	*Batteries*	*Phosphors*
Indium	●				
Gallium	●				
Tellurium	●				
Dysprosium		●	●		
Praesodymium		●	●	●	
Neodymium		●	●	●	
Lanthanum				●	●
Cobalt				●	
Manganese				●	
Nickel				●	
Lithium				●	
Cerium				●	●
Terbium					●
Europium					●
Yttrium					●

Criticality Matrix

- Short Term (present t - 2015)

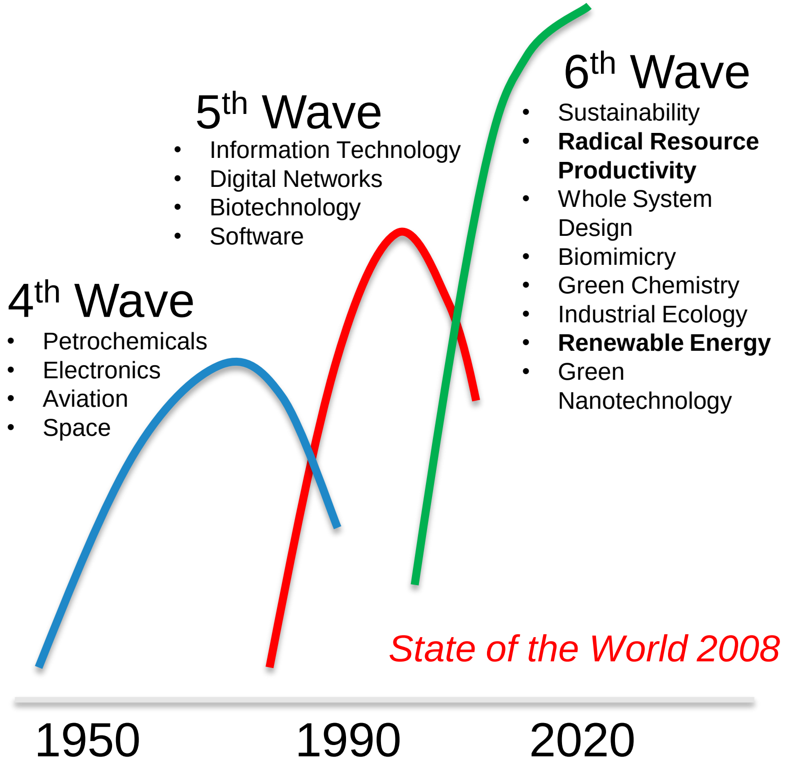


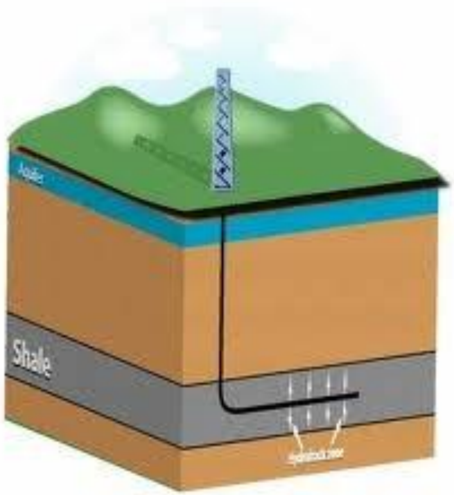
- Mid Term (2015 - 2025)

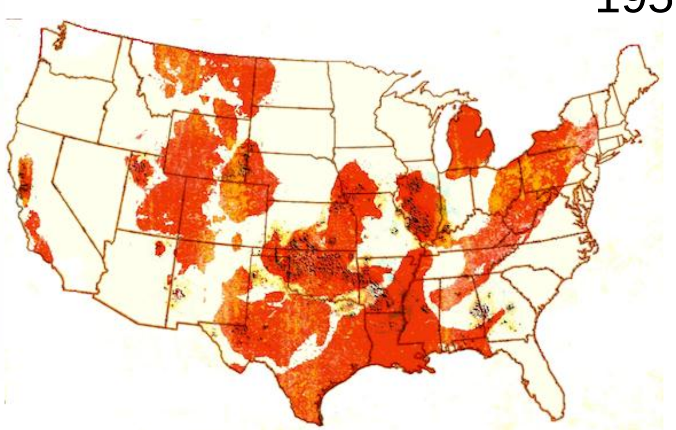


Why Critical Materials?

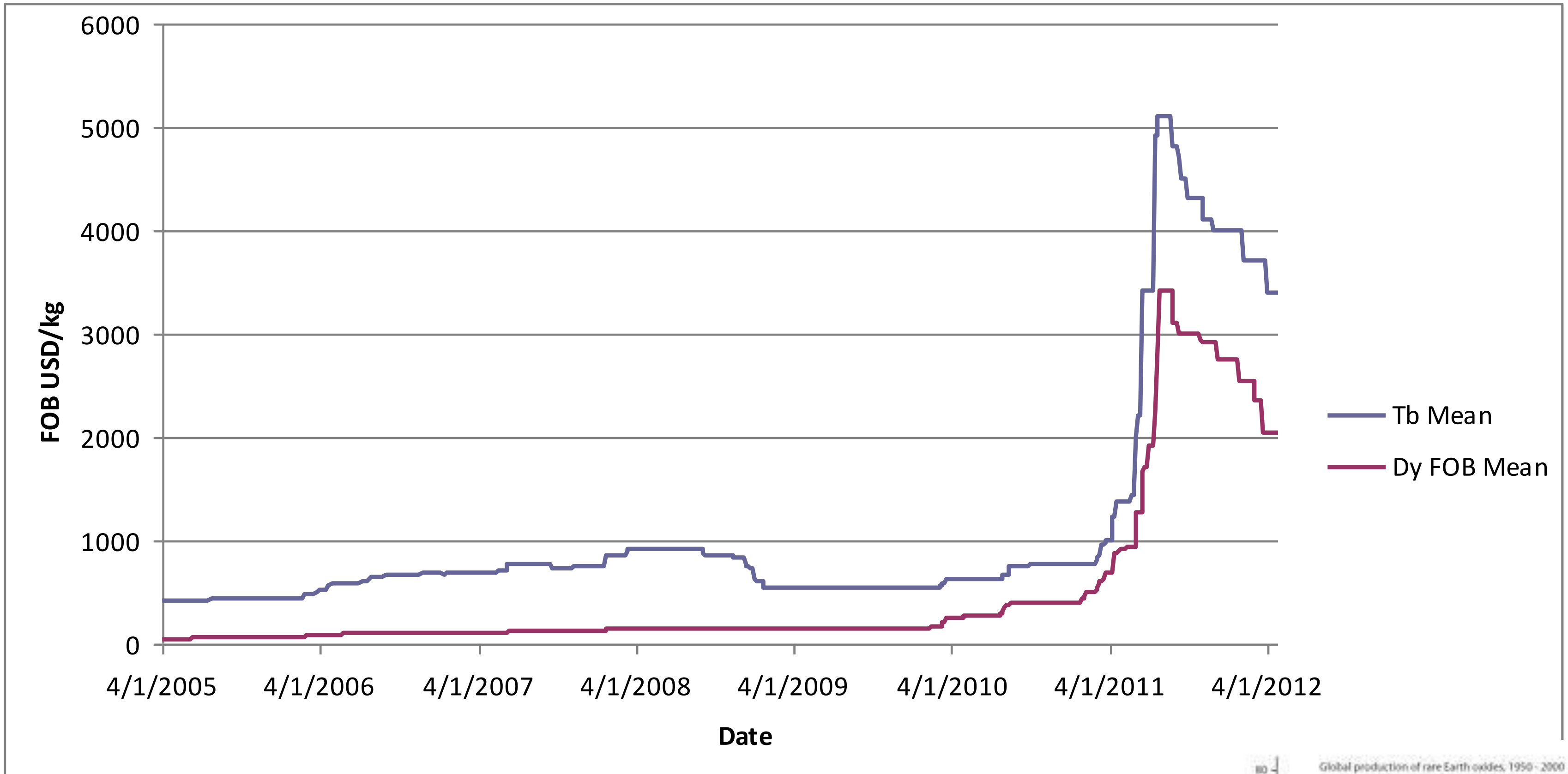
- ❑ Essential for the U.S. leading the 6th wave of technology innovation
  - Renewable energy development
  - High-tech industry
  - Sustainability
  - Radical resource productivity



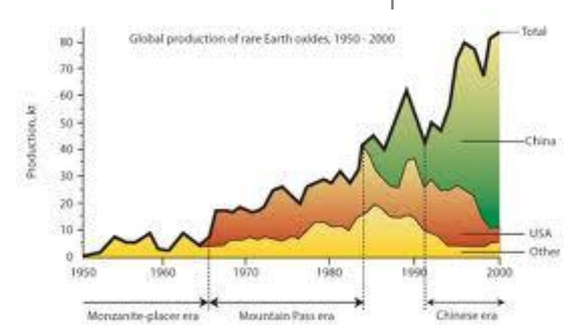




Heavy Rare Earth Prices



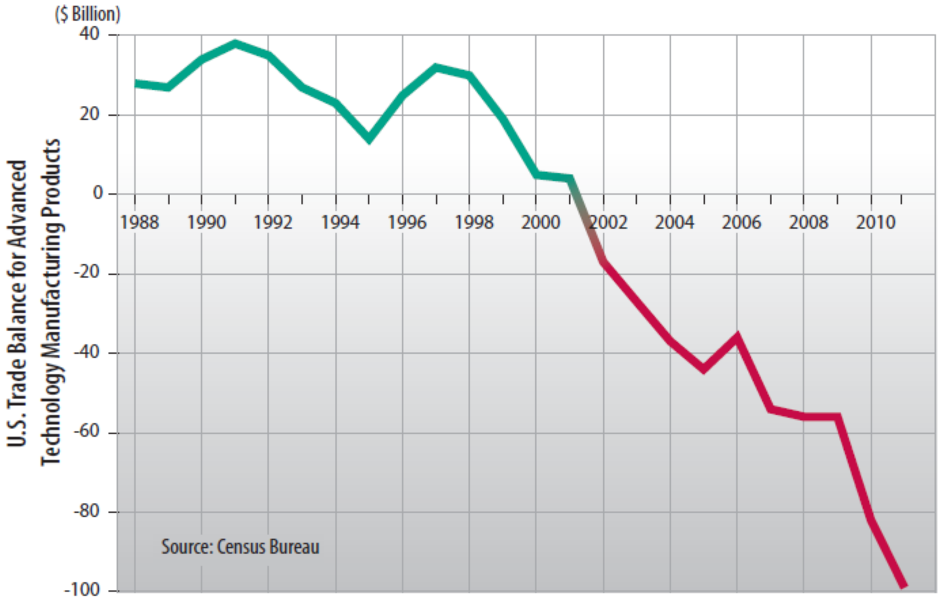
Source: Metal-pages.com



Advanced Manufacturing Initiative (AMI)

- Initiated by the Executive Office of the President, June 2011
  - $500 million to $1 billion over four years
    - Part of the funding comes from existing programs
  - Energy Innovation Hub on Critical Materials

- Jobs that came back (USA Today, July 16, 2012)
  - Service
    - 114.8 million jobs
    - 71%
  - Goods-producing
    - 18.3 million
    - 15%

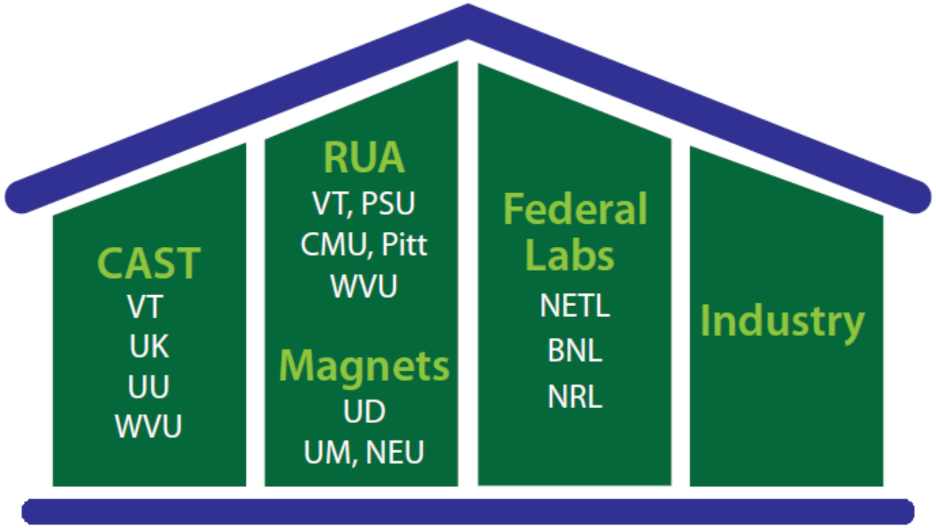


- Secretary Steven Chu:
  - “most of the material scientists haven't really been focused on mining, extraction, purification, recycling, which might seem mundane, but it will become increasingly important. We do have finite resources, and we are going to have to deal with that. And nothing focuses a mind more than $150 a kilogram, or higher.”

- Assistant Secretary David Sandalow:
  - Three pillars of research:
    - Supply chain diversification
    - Substitute materials
    - Recycling

NETL-RUA Team

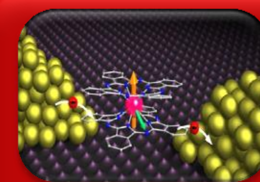
- Team consists of university consortia, federal labs and industry with **long history of working together**
- Implements under-one-roof principle:
  - Virginia Tech provides 15,000 ft^2 central office space
    - 4,742 ft^2 nano-scale characterization lab below
  - 20,000 ft^2 pilot plant at Virginia
  - 5,994 ft^2 pilot plant at Utah
  - Use a virtual presence technology
  - DOE user facilities



Proposed Hub Activities

- ❑ Three Research Pillars are cross-linked and leverage diverse expertise *via*
  - Life Cycle Analysis
  - Tech Transfer & Outreach
- ❑ Integrated Interdisciplinary Project Teams (IIPT)
  - PI driven
  - Crosscutting
  - Grass root

Supply Chain Diversification
- Feedstock Recovery
- Separation & Processing
- Process Design & Testing
- Environmental Control



Substitute Materials & Alternate Technologies
- Materials Discovery
- Magnets
- Phosphors
- Advanced Manufacturing

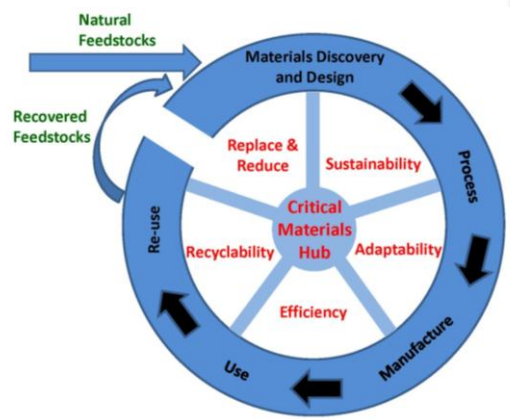
Recycling & Reuse
- Recyclability Improvement
- Separation & Recovery
- Post-Industrial Byproducts

Lifecycle Analysis
- Criticality of Materials
- Economics & Market Assessment
- Environmental Impact
- Criticality Assessment

Tech Transfer & Outreach
- Training & Workforce Development
- Commercialization Alliance
- Policy Development

Supply Chain Diversification

- The U.S. can produce critical materials at low cost
  - Rare earth elements (REEs) can be produced as **byproducts** from
    - Phosphate industry
      - Florida has 7 operating plants, which could produce 30,000 Mt REO per year
    - Heavy sand industry
      - Virginia, Carolinas, Georgia
    - Iron ore industry
  - Need to develop
    - advanced separation and processing technologies
    - adaptive technologies



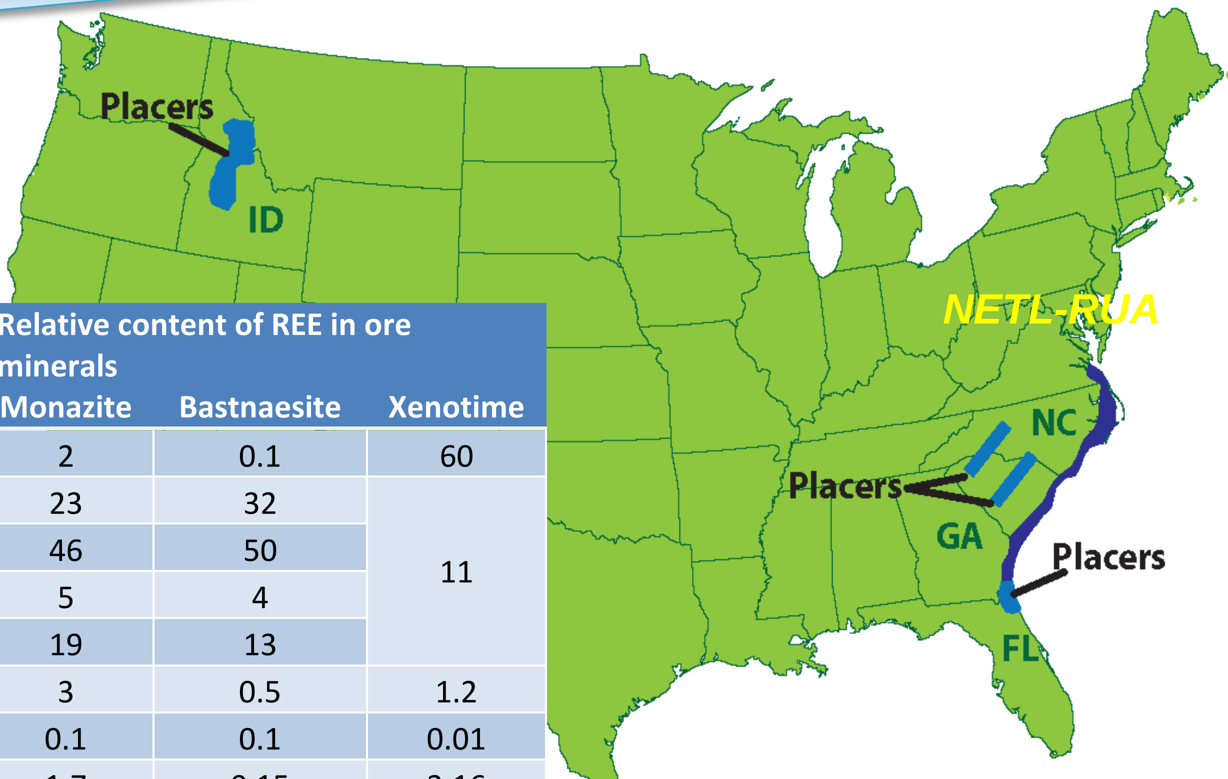
Supply Chain Diversification
- Feedstock Recovery
- Separation & Processing
- Process Design & Testing
- Environmental Control

Phosphate Separation Plant

Mineral (%)	+106 µm	106x75 µm	75x53 µm	-53 µm	Total (%)
Apatite	0.7	0.5	0.5	0.1	1.8
Chlorite	0.3	1.0	0.3	0.0	1.6
Epidote	0.2	0.8	0.3	0.1	1.4
Fe-Oxides	0.0	0.7	2.6	1.2	4.5
Grossular	0.6	1.6	0.5	0.1	2.8
Ilmenite	1.3	9.6	7.4	1.4	19.7
Micas/Clays	0.0	0.2	0.2	0.1	0.5
Monazite	0.1	1.9	3.5	0.7	6.2
Other Silicates	0.0	0.1	0.0	0.0	0.1
Pyrite	0.1	0.5	1.3	1.2	3.1
Quartz/Feldspar	0.1	0.0	0.1	0.0	0.2
Rutile	1.1	5.6	3.8	0.9	11.4
Sphene	0.0	0.3	0.3	0.1	0.7
Xenotime	0.0	0.1	0.2	0.0	0.3
Zircon	6.2	21.9	14.1	3.4	45.6
Total	10.7	44.8	35.1	9.3	100.0

from Mosaic

Monazite and Xenotime Byproducts



From USGS

REE oxide of:	Relative content of REE in ore minerals Monazite	Bastnaesite	Xenotime
Y	2	0.1	60
La	23	32	11
Ce	46	50	
Pr	5	4	
Nd	19	13	
Sm	3	0.5	1.2
Eu	0.1	0.1	0.01
Gd	1.7	0.15	3.16
Tb	0.16	0	1
Dy	0.5	0	7.5
Ho	0.09	0	2
Er	0.13	0	6.2
Tm	0.01	0	1.27
Yb	0.06	0	6
Lu	0.006	0	0.63

Byproducts are of low cost and rich in heavy rare earths

Supply Chain Diversification

- Feedstock Recovery
- Separation & Processing
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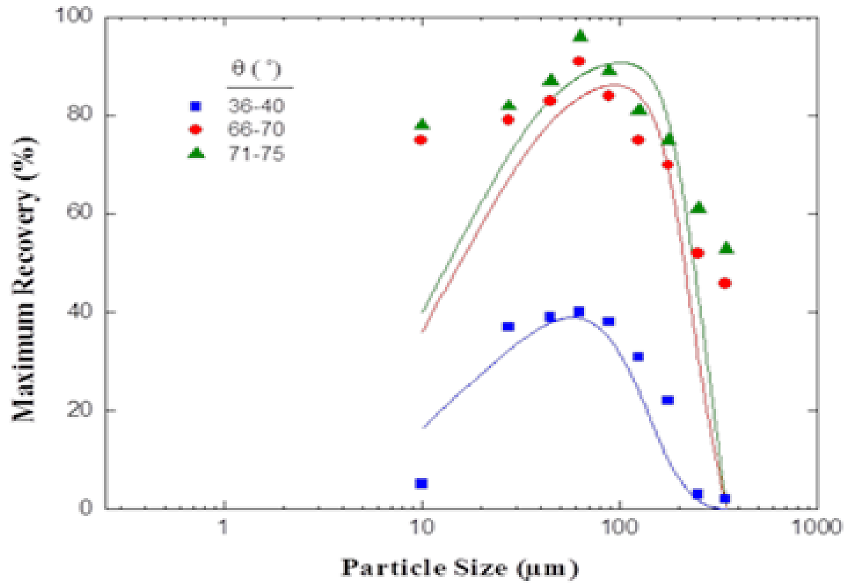
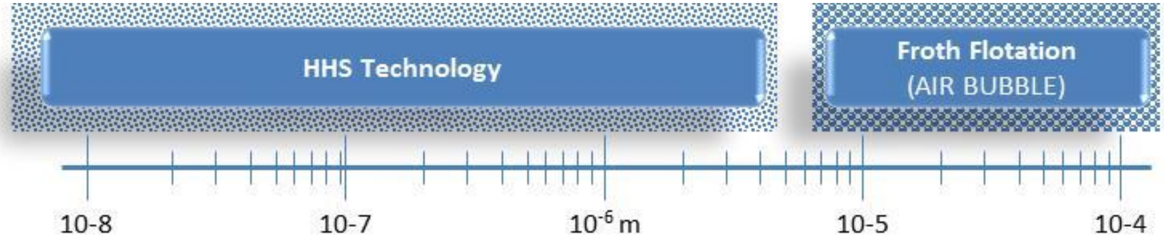
- Environmental Control

Feedstocks Recovery

- First principle flotation model



- Improving recovery by developing novel separation method
  - Hydrophobic-Hydrophilic Separation (HHS)



Supply Chain Diversification
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POC-Scale Testing

- Mineral Refining Company has licensed the HHS process
  - Proof-of-Concept (POC) unit is being built at Virginia Tech
  - $500,000 as industry cost share for an ongoing NETL-sponsored project.
  - >80% complete
  - Board meeting scheduled
    - December 12, 2012
    - Commercialization plan

Supply Chain Diversification

- Feedstock Recovery
- Separation & Processing
- Process Design & Testing
- Environmental Control

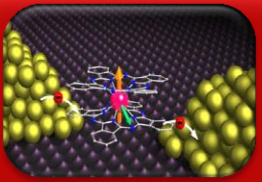
Thrusts of the Materials Pillar

- ❑ High throughput materials discovery
- ❑ Focus on key applications
  - Magnets
  - Phosphors

	Global REE Reductions (Mt)			%Savings Projected
	Magnets	Phosphors	Total	
Dy	1120	-	1120	66
Eu	-	359	359	65
Nd	13600	-	13600	50
Tb	64	159	223	66
Y	-	10345	10345	95

MRS Bulletin, 37, p.325, 2012

- ❑ Develop materials processes for advanced manufacturing



Substitute Materials & Alternate Technologies

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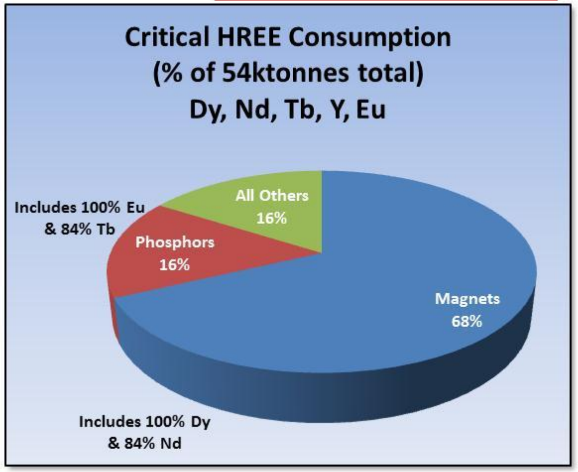
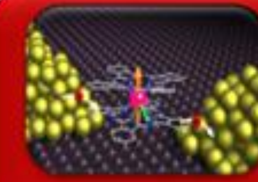
- Phosphors
- Advanced Manufacturing



Advanced Manufacturing



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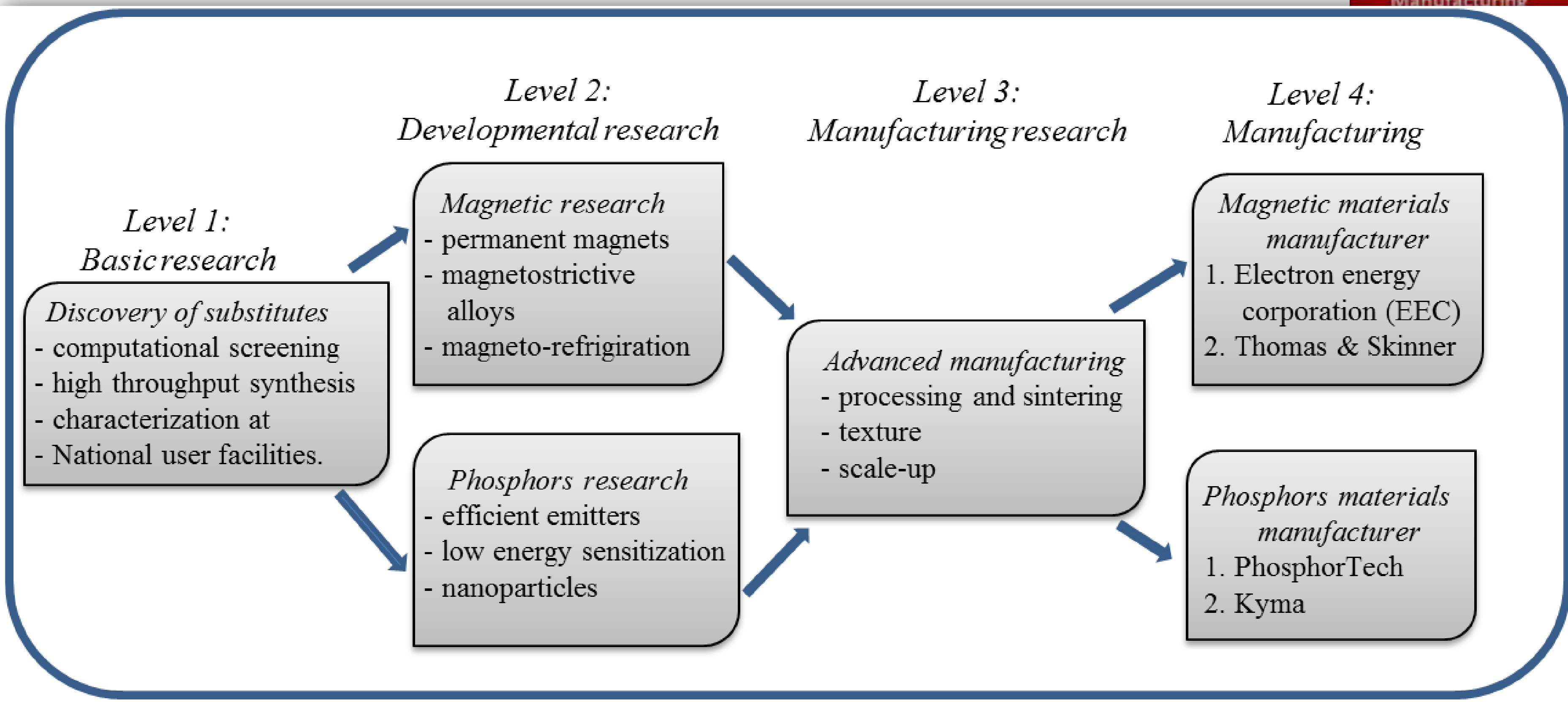
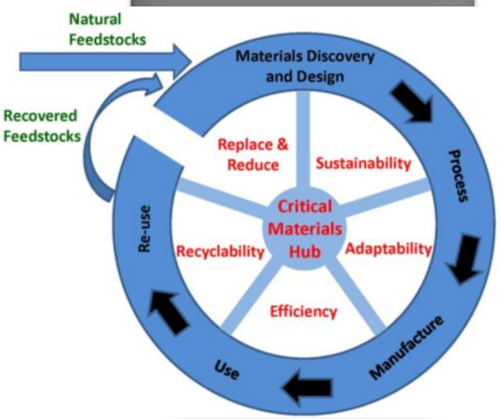


Post-consumer Products

- Permanent magnets and batteries
  - Molten salt electrolysis process
    - Use Mg to reduce the melting points of heavy rare earths
    - Potential: 6,000 Mt/yr of rare earth
- Li-ion batteries
    - Shredding, solid-solid separation, leaching, precipitation as carbonate
- Phosphor powders
  - Liquid-liquid separation and ion exchange
  - >90% Eu
  - 84% Tb
  - >70% Y

Recycling & Reuse

- Recyclability Improvement
- Separation & Recovery
- Post-Industrial Byproducts



Research Plans

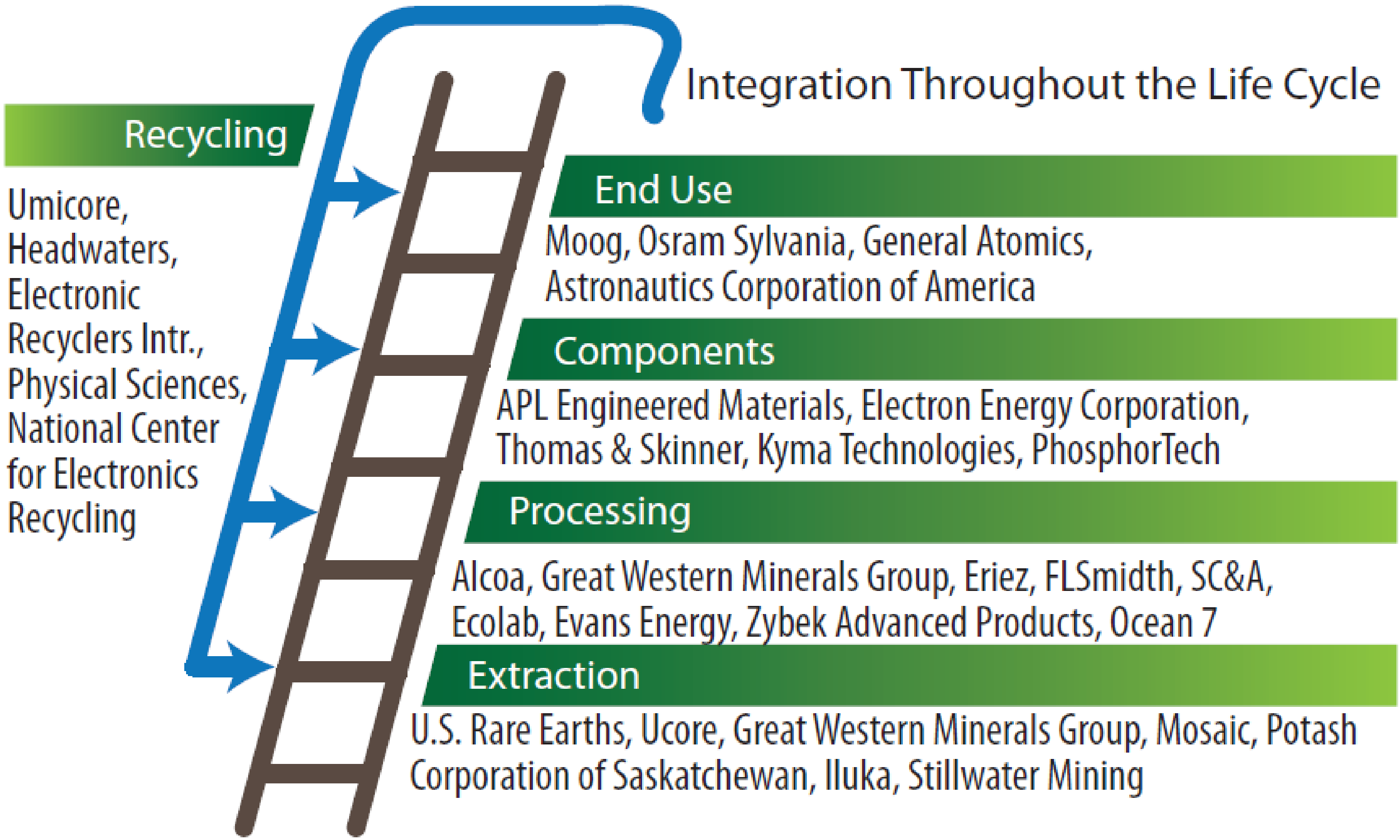
- ❑ Critical Materials Hub
  - Did our best and wait for the best
  - Focus on rare earth materials

- ❑ Baseline R&D activities
  - Broad spectrum of critical materials
    - V, Mg, Mo, Co, PGM, Li, etc.
    - REEs
  - Materials development
    - Magnets, phosphors, catalysts, sensors, and other applications
    - Substitute elements and materials
    - Alternative technologies
    - White papers submitted
      - Dave Waldeck on phosphors to ONR
      - Andy Gellman on substitute materials ONR

- ❑ Seed money has been made available by NETL

Vertical Integration of Industry

Essential for Commercialization



Summary

Develop domestic critical materials resources

Develop viable recycling technologies

Develop low- and/or free-REE magnets and phosphors

REE-free phosphors and magnets

Develop models for supply, demand, and environmental impacts

Defense Applications

Excalibur Artillery Shell
(NdFeB magnets)

AIM-120 AMRAAM
(SmCo magnets)

Virginia Class
Submarine
(Terfenol-D)

Phalanx CIWS
(Alnico – SmCo –
NdFeB magnets)

F135 engine – F35 JSF
(Yttria-stabilized zirconia)

F/A-18 HUD
(Tb: Gd_2O_2S)

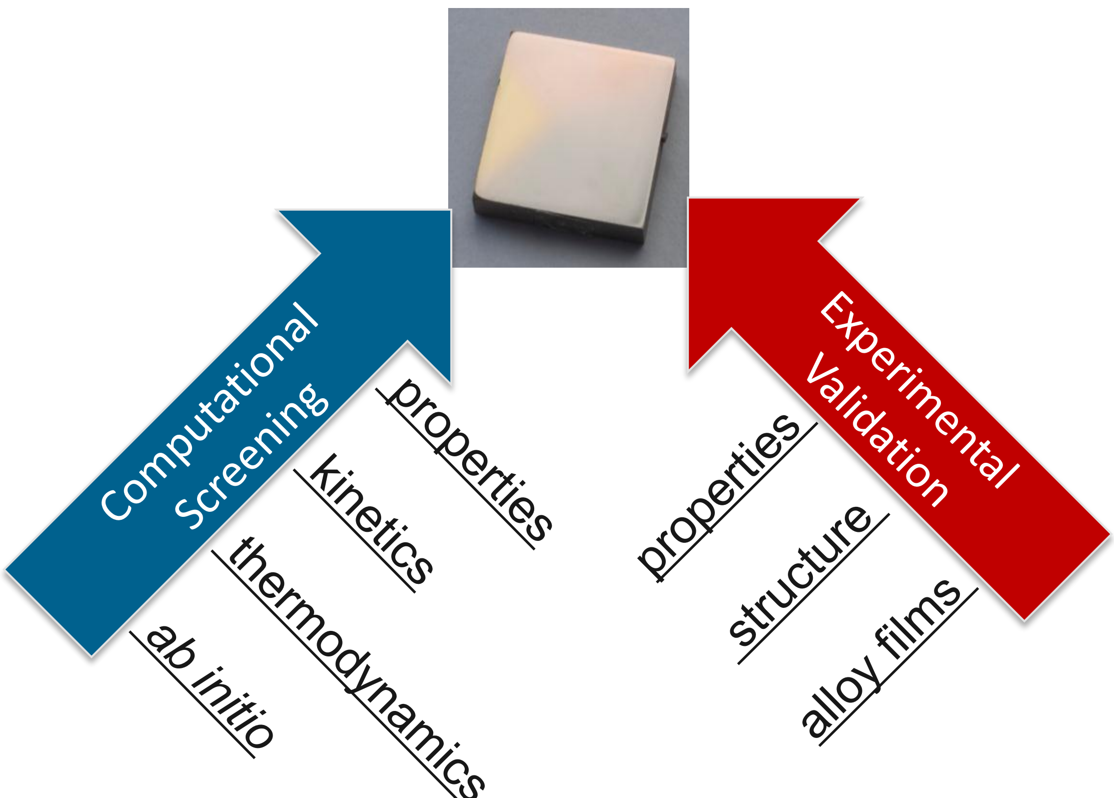
Blackhawk Helicopter
(Mg-Y alloys, NdFeB magnets,
Terfenol-D [stealth systems])

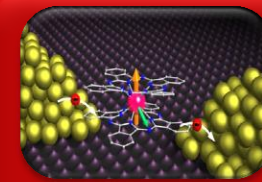
Ground Laser Target
Designator III
(Nd: YAG garnet)

Materials Discovery

- ❑ Computational screening
- ❑ Combinatorial synthesis and property screening
- ❑ Structure and functional property characterization

New Materials





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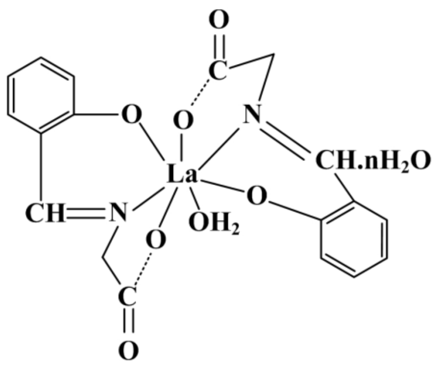
Designed Extractants and Solvents

- Highly selective separations
  - Molecular recognition
  - Volume-phase transition



- Electrodeposition and recovery of REEs from room temperature ionic liquids
  - Can replace molten salt electrolysis

Supply Chain Diversification

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