Accelerating Energy Innovations

Critical Materials Institute

AN ENERGY INNOVATION HUB

Focus Area #3 Improving Reuse and Recycling

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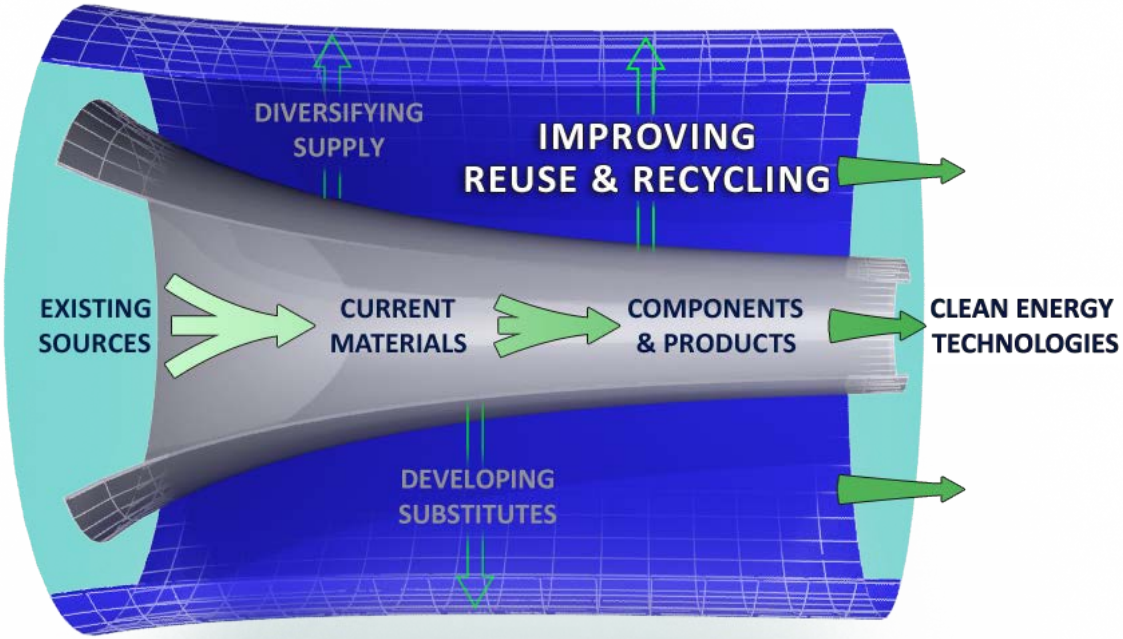
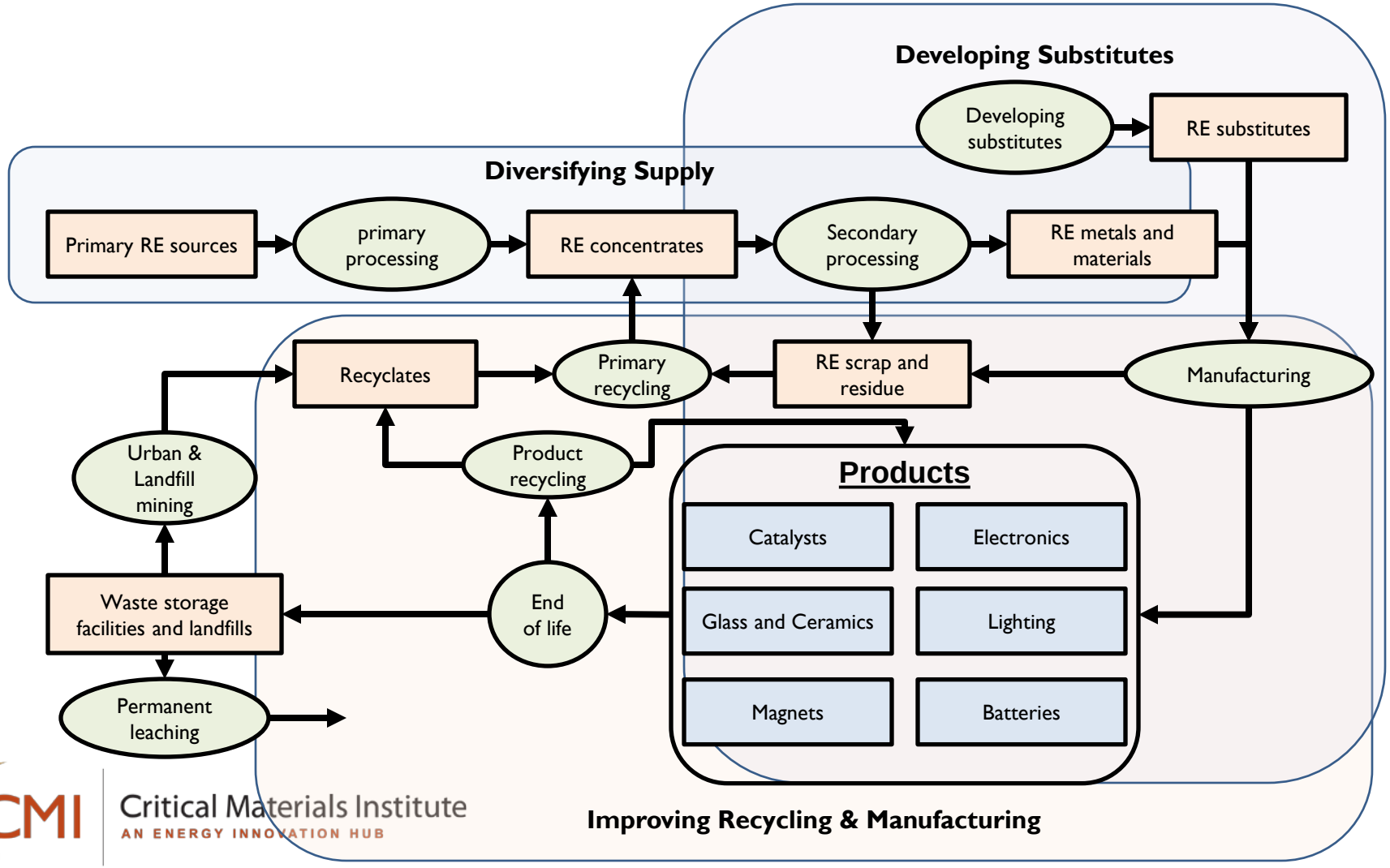
Improving Reuse and Recycling Focus Area

- Enhance efficient reuse and recycling of a highly diverse set of materials
- Improve product design
- Understand recycling techno-economics



Identifying global stocks and flows

Rectangles represent storage of critical-material-relevant commodities. Ovals represent processes that use one commodity to create another. The task is to determine a technical and market design for the entire system that improves long-term value. The model will track prices and volumes in each rectangle, and costs vs. characteristics in each oval.



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Structure of FA #3

Focused on Recycling, Recovery Reuse of:

- Lamp phosphors (TRL 3 - 4)
- Permanent Magnets (TRL 4)
- Batteries
- Cadmium-Telluride photo-collectors (TRL 2)
- Electronics (TRL 4)
- Fluid Cracking Catalysts (future work)

Sources are both Consumer and Manufacturing reservoirs

Two Thrust Areas:

1) Source Preparation

2) Transformative Extraction and Materials Production

Focus Area #3
Thrust #1 Source Preparation

Development of approaches to source preparation and concentration for recycling – economically moving resource to recycling centers (FA 4) followed by resource recovery and concentration.

Deliverables:

Technology for pre-processing, extraction and processing of rare earth elements from lighting phosphors

Processes and software to enhance remanufacture, disassembly, and recovery of rare earth elements from generators and phosphors

Tools and processes for economic recycling of permanent magnets from disassembly to complete reprocessing

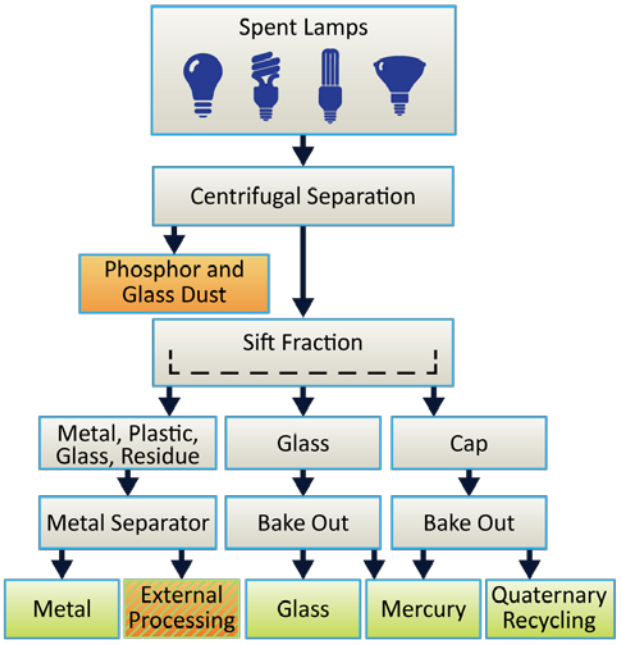
Demonstrate techniques for recovering high purity cadmium and tellurium from Cd/Te photovoltaics

Project 3.1.1 Almost ten million pounds of spent CFL not recycled in the US! (CSM, Advanced Recovery)

- **30 % of the used CFL fixtures are collected in the US. These contain valuable rare-earth oxides that must be recovered and recycled.**
  - La, Ce, Y, Tb and Eu oxides added as a part of color phosphors in CFL manufacturing present a valuable resource. At the current market value, one kg of phosphor dust contains $ 27 worth of RE oxides.
  - Challenges exist for collection, separation and cost-effective recycling of these scarce metals.

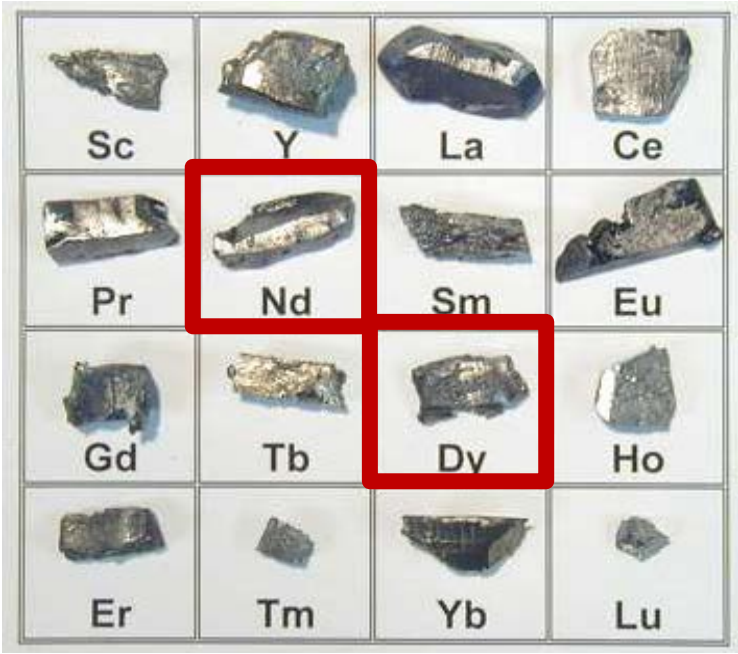
Solution: Develop technical pathways to recover and separate rare-earth metal oxides and other reusable products from phosphor dusts

- **Hydrometallurgical processes can be applied to recover up to 15 wt. pct. of Rare-earth oxides contained in phosphor dust:**
  - Sizing, calcination, acid digestion and precipitation allows the recovery of mixed rare-earth oxides that can be separated or returned to CFL manufacturing. Digestion allows the separation of about 80 wt. pct. of calcium phosphate and glass present in the dust.



Project 3.1.2 Demand for REEs is increasing and we are dependent on foreign supplies. No clear strategy for recovery and closing the loop on these critical materials (LLNL, ORNL, Purdue)

- **Rare Earth Elements (REEs):**
  - Wind turbines and electrical vehicles rely on REEs for the permanent magnets needed to make generators lighter and more efficient. Currently, small quantities of REEs are recovered from scrap. Recycling methods as well as more fully capitalizing on opportunities requires further research.



China controls 97% of the production of rare earth metals (e.g. dysprosium, neodymium) used in the manufacture of magnets for wind turbines, hard drives, and electrical motors.

Solution: Recover REEs value from generators and permanent magnets available in wind turbines and electric vehicles

1. Recovery and reuse of REEs from used products

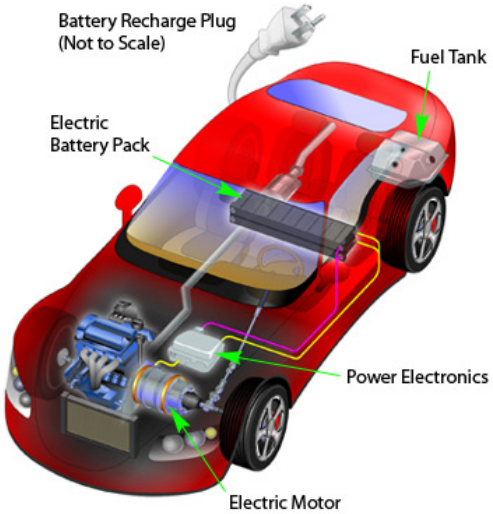
Using Design for Disassembly, maximize REE reuse, remanufacturing, and recycling opportunities.

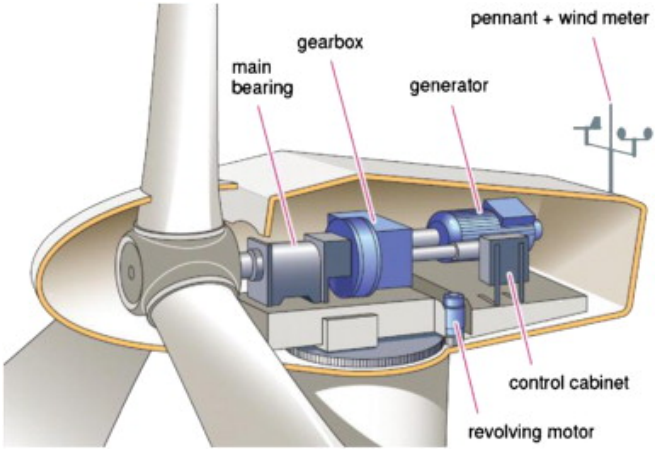
2. Characterize REEs material flows with EOL products in the US

Develop a material flow model and identify economic, and environmental costs and benefits for several scenarios.

3. Identify key supply chain partners.

Surveying key partners, identify supply chain challenges/ barriers for the recovery and reintroduction of REEs



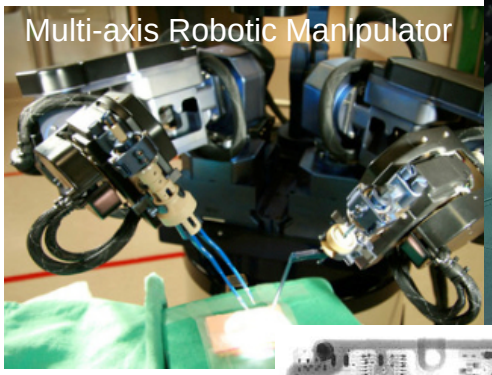


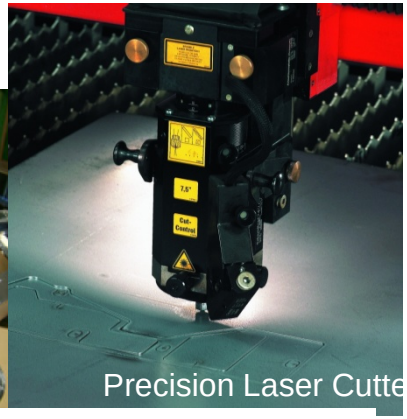
Project 3.1.3 Rare earth magnets are widely used in consumer goods, but rarely recycled (AMES, LLNL, CSM)

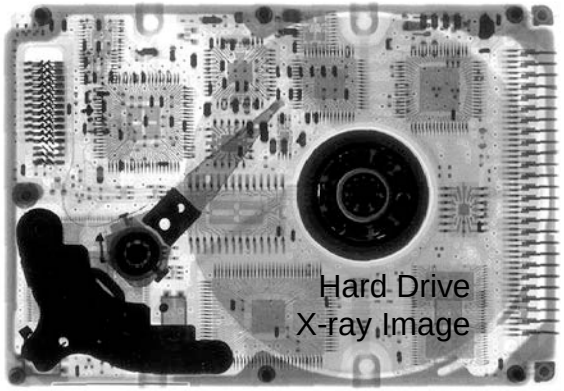
- U.S. demand for rare earth (RE) magnets will increase 4-fold over the next decade (CRS report R41347, 2011).
- The wide variety of magnet sizes, shapes, placement, and protective or structural materials makes it difficult to recover and directly reuse magnets.
- Motors, generators, and computer hard drives use RE magnets to improve performance and efficiency.
- Supplies of critical RE raw materials are being limited.

Solution: Develop Automated Magnet Identification and Extraction System

- **Integrated Pilot Scale System for Magnet Recycle at ORNL**
  - Develop magnet detection sensor
  - Integrate sensor front-end with computer vision system for precise identification and location
  - Develop high throughput cutting tool
  - Design automated robotic manipulator to position items (computer hard drives, motors etc.) within the location and removal work zone
- **2-Stage Recycling Process for Magnet SWARF at Ames and Colorado School of Mines**
  - Quantify and characterize the potential waste streams containing RE magnets
  - Develop cost effective means to remove unwanted contaminates from waste streams
  - Demonstrate thermal processing methods to reduce transition metal content and concentrate high value RE materials (i.e. Dy)
  - Demonstrate plant-scale integrated process







Various forms of swarf including a block of compressed swarf.

Project 3.1.4 Beneficiation of Photovoltaic (and other) Functional Coatings (initiates in FY 13) (CSM)

- **Recycling of used PV and Plasma Display Panels can lead to increased domestic supply of tellurium from PV panels and indium and rare earths from plasma display panels.**

Plasma Display Panel Cut Away

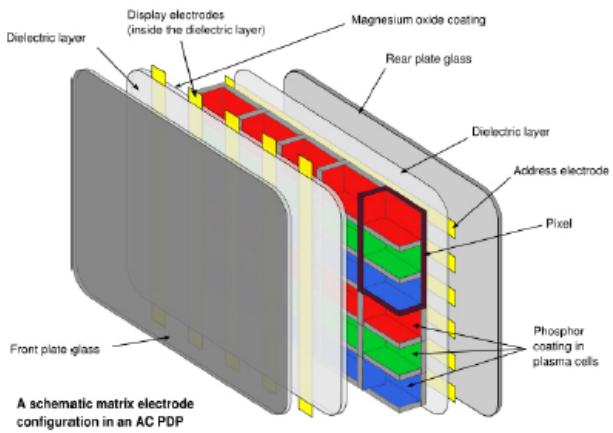
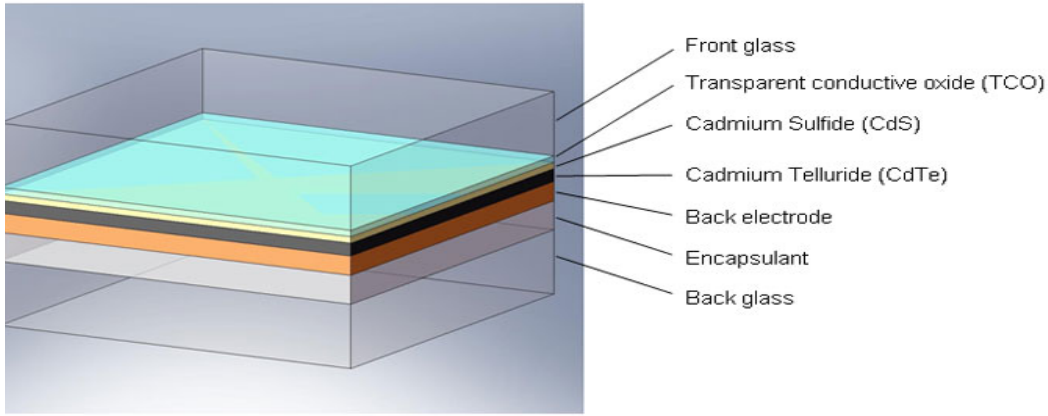


Figure 2-2. Simple Composition of the Alternating Current Plasma Display Panel with Matrix Electrode Design.
Source: Jari Laamanen March 2007
http://commons.wikimedia.org/wiki/Image:Plasma-display-composition.svg

CdTe Photovoltaic panel cut away view



Solution: Beneficiation of Photovoltaic (and other) Functional Coatings

- Develop methods to disassemble and recover both Cadmium and Tellurium from CdTe photovoltaic panels.
- Cadmium is problematic in disposal and tellurium is a critical metal.
- Develop methods to dissemble and recover rare earths and indium from plasma display panels.
- Rare Earths and Indium are critical metals

Focus Area #3
Thrust #2 Transformative Extraction and Materials Production

Efficient recycling of rare earths requires development of recycling processes that are flexible, environmentally-friendly, fully-integrated, and commercially sound.

Deliverables:

Flexible supercritical fluid-based rare earth extraction processes that allow direct dissolution separation of dissolved components and refinement of separated elements.

Demonstration of dispersion free supported liquid membrane solvent extraction for separation, concentration and recovery of rare earths from dilute streams

Demonstration of electro-recycling cell technology for recovery of selected critical materials from consumer products

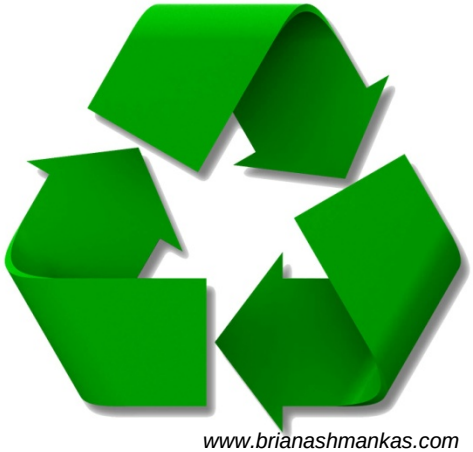
Demonstration of energy efficient pyroprocessing technologies that limit oxidation of scrap materials and provide methods of upgrading oxidized materials

Development and demonstration of a slurry bioleaching process to economically recover critical rare earth elements from selected recycling streams.

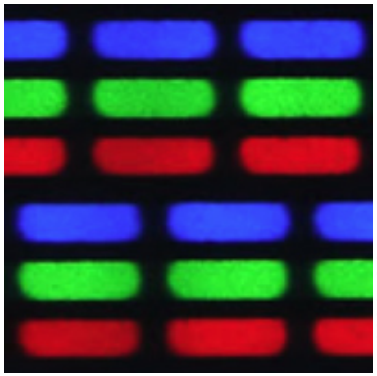
Project 3.2.1 Supercritical Fluid Beneficiation of Waste Streams (INL, Univ. of Idaho)

Need efficient rare earths recycling methods that are flexible, environmentally-friendly, fully-integrated, and commercially sound.

www.howstuffworks.com



www.brianashmankas.com



www.cis.rit.edu

www.tradeindia.com

Solution: Develop a liquid/SCF CO2 SX process that employs many of the advantages of a conventional SX approach (e.g., many of the same ligands):

-An integrated process - dissolution, extraction, and separation in the same process

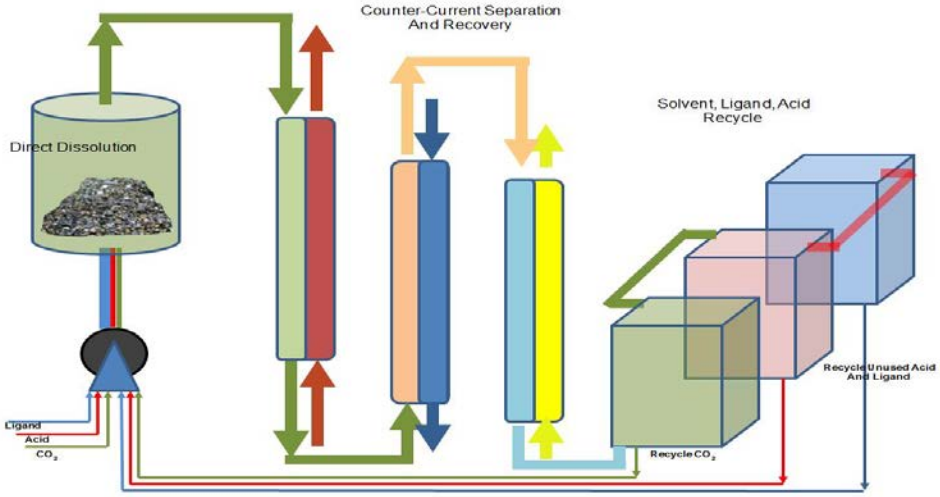
-Environmentally-friendly safe, inert, fully-recyclable solvent.

-Flexible, direct-dissolution chemistry that can handle diverse, constantly changing e-waste streams – recovery >90% REO targeted

-Intra-series separations of lanthanides due to chemical power of the ligand and tunable density (solubility) of the solvent. Target purity is >98%.

-Industrially scalable, high throughput, cost-effective, promotes recovery and recycle and reuse of ligands and other organics used in the process.

-Low energy consumption, minimal secondary waste.



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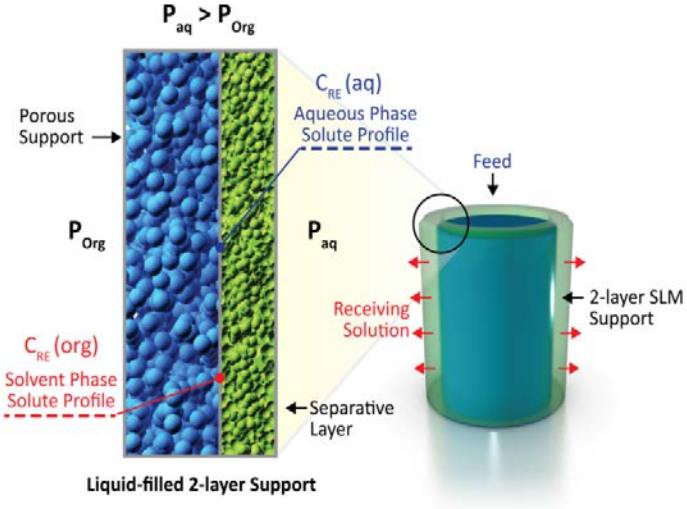
Project 3.2.2 Need More Efficient Solvent Extraction Methods for RE Recycle and Reuse – Dilute Feeds (ORNL, INL)

- **Solvent extraction (SX) is inefficient to cost-effectively recover rare earth elements such as Y, Eu, Nd and Tb from dilute feed streams.**
- **Extraction and stripping is carried out in two separate stages which adds to cost and complexity, and reduces throughput.**
- **High energy consumption using centrifugal extractor and mixer settler for dilute systems.**
- **There is a significant cost related to loss of solvent and extractant due to carryover and entrainment.**

Solution: Membrane Solvent Extraction

- A novel approach for multistage extraction performance in a single stage.
- Cost-effective recovery and recycle of dilute rare earth elements such as Y, Eu, Nd and Tb.
- Dispersion-free MSX eliminates phase separation.
- Provides superior process stability-lower phase ratios.
- Compact membranes require low energy to operate and provide high throughput.
- Wide range of separations with functionalized surfaces.
- Robust membranes with long life can lower operating cost by >25%.

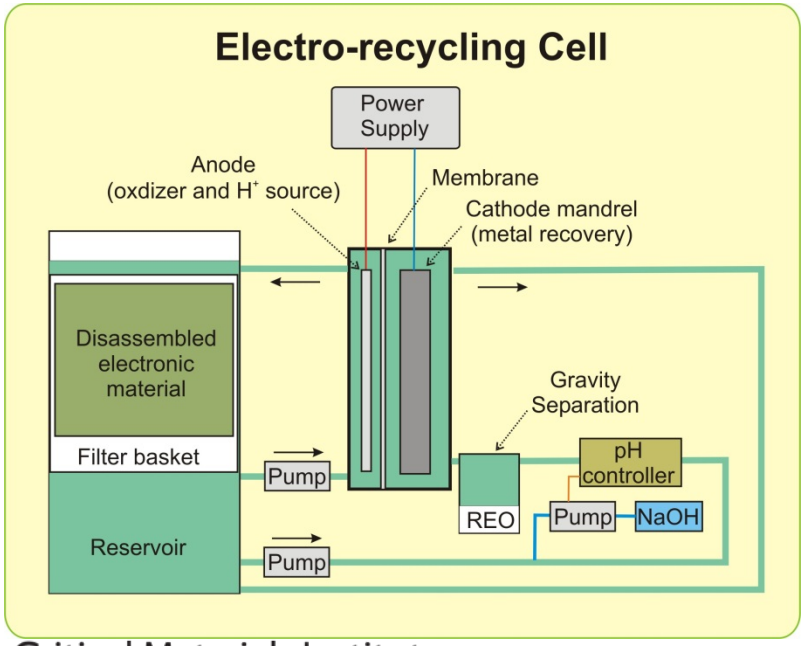


Project 3.2.3 Critical Material Recycling is Limited By Dilution Within Product Matrices (INL, Advanced Recovery)

- **Technology devices such as smart phones and tablets employ critical materials:**
  - Displays
  - Batteries
  - Other isolated components
- **Current chemical paths offer no cost advantage over ore extraction**
  - Acid dissolution
  - Precipitation or solvent extraction
  - Burning

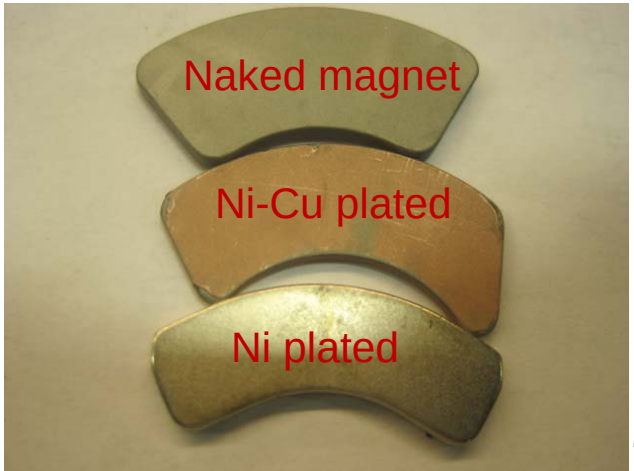
Solution: Incorporate a Holistic Approach to Recycling Metals in Electronic Waste

- **Recovery of all value metals within the matrix using an electrochemical approach**
  - Generation of dissolving environment (acid and oxidizing agents) at anode
  - Recovery of common metals (Cu, Ni etc) at cathode
  - pH driven ppt of REE



Project 3.2.4 NdFeB Magnets: Recovery, reuse, and Remanufacturing (INL)

- Individual components melted into an ingot, the ingot is pulverized to fine powders and the magnet is fabricated through a powder metallurgical route.
- Highly energy intensive, generates ~ 20-30% wastes during the final manufacturing stages.
- No effective substitution for Nd has yet been found.
- No processing of scraps to recover the valuable component (Nd) is currently in practice.
- Right reprocessing schemes can prove to be extremely valuable tools to recover Nd and/or transform the discarded magnets, recovered from significant amounts of e-scraps/sources, to useful products.



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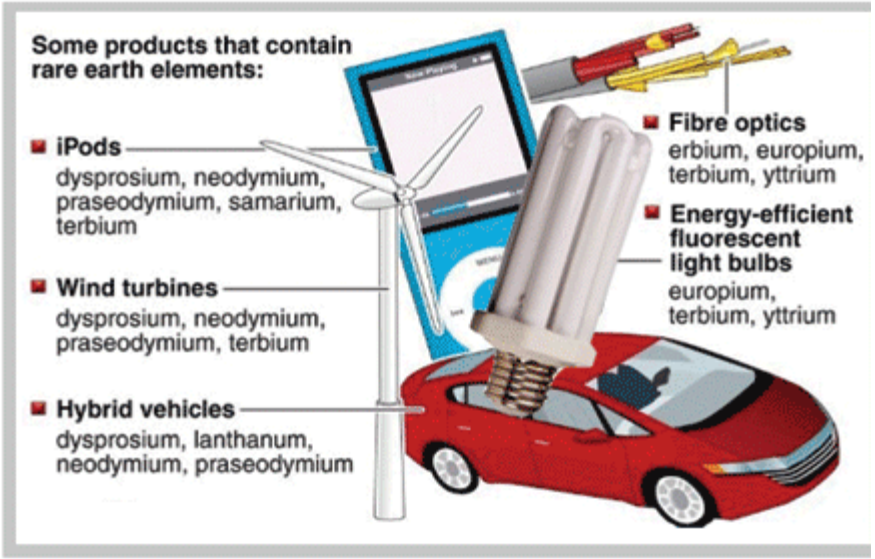
Solution: Develop Energy Efficient and Low Waste Generation Pyrometallurgical Processes to Recycle Magnets recovered from Consumer Products

- Hydriding-Dehydriding (HDD) Process
  - Develop and optimize experimental parameters to prepare fine alloy powders.
  - Examine the suitability of the re-fabrication of the magnet from the de-hydrided powder by adjustment of the composition(s).
  - Evaluate of the magnetic properties of the re-fabricated magnets vis-à-vis the unprocessed magnets.
  - Examine the suitability of the de-hydrided powder for the recovery of Nd content by the use of a suitable electrostatic/magnetic separator.
- Molten Salt Electrochemical Process
  - Examine the suitability of an alkali/alkaline earth based molten salt system to selectively recover Nd from the magnet scraps.
  - Preparation of the Nd-Fe master alloy for the fabrication of the magnet.
  - Removal of oxygen from heavily oxidized magnet scraps to assess their re-fabrication to useful magnet components.

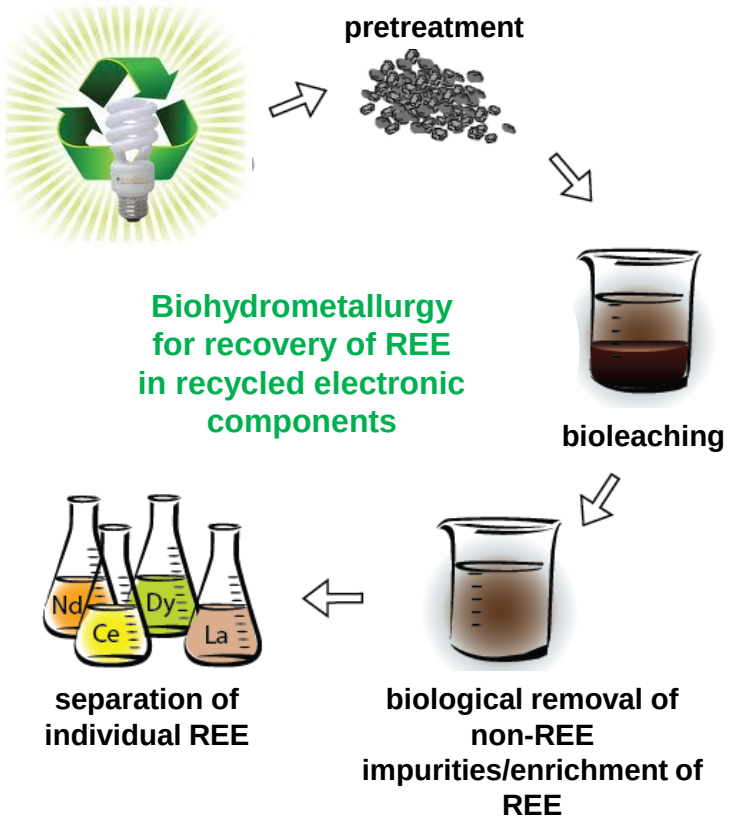
Project 3.2.5 Recovery of rare earth elements from electronics by bioleaching is in infancy (INL)

- **Harsh chemical methods proposed for leaching:**
  - Application of high concentrations of mineral acids and elevated temperatures are necessary for leaching of rare earth elements from electronic components found in batteries, computer parts, lamp phosphors, etc.



Solution: Recovery of REE from recycled electronic components can be accomplished in environmentally friendly manner using biohydrometallurgy techniques

- **Bioleaching using microbially produced acids**
  - Organic and/or mineral acids produced by microbes as well as direct activity of microbes used for leaching REE from processed recyclates
- **Separation and recovery of REE using bioprocessing**
  - Selective precipitation of REE using microbially produced products
  - Separation of individual REE using selective biosorptive processes



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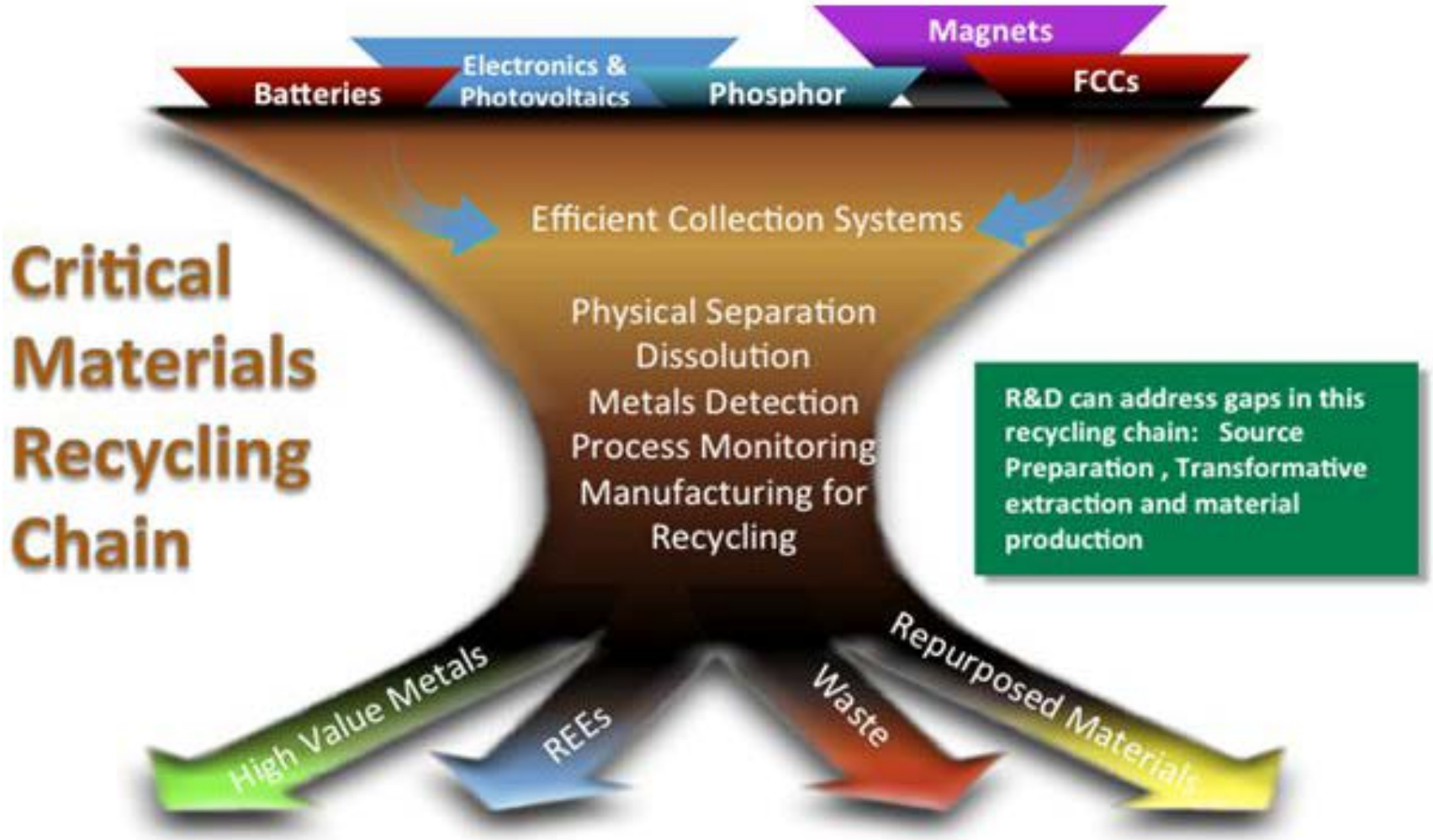
Summary: Improving Reuse and Recycling Focus Area