Rare Earth Magnet Recycling

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Outline

- Overview of Rare Earth Magnets and supply chain
- REPM Current Recycling Practices
- REPM Recycling Opportunities
Rare Earths Magnets - Modern Technology's Backbone

- The strength of permanent magnets (PMs) is the single factor affecting the power density and energy efficiency of countless devices.

Wind turbines with PM generators are very efficient at low wind speeds.

Hybrid electric vehicles are particularly demanding for power density of their PM motors.

PM hydroelectric turbine generators eliminate need for gearboxes.

In this generator buoy, the floater moves coils relative to the PM to induce voltages.

Missiles, tanks, warplanes & submarines
The Rare Earth Value Chain

- RE Magnets
- RE Magnet Alloys
- Pure RE Metals
- Individual RE Separation (oxides, carbonates, etc.)
- Mixed Concentrates
- Mining - Rare Earth Ore Production (all RE’s)
Manufacturing Process for Sintered Rare Earth Magnets

Raw Materials
Sm, Gd, Co, Fe, Cu, Zr (Sm-Co2:17)
Nd, Pr, Dy, Tb, Fe, B, Co (NdFeB)

Induction Melting
Crushing
~ 200 - 500 μm

Machining by Grinding, lapping, honing, Or wire EDM
Sintering, Solution and Heat treatment

Pressing

Ball milling or Jet milling
To ~ 2-5 μm
DoE- Critical Materials Strategy

**Figure ES-1. Short-term criticality matrix**

**Figure ES-2. Medium-term criticality matrix**

Source: DOE Critical Materials Strategy, December 2010
### Global Metal Production 2008 - Record Year

<table>
<thead>
<tr>
<th>Item</th>
<th>2008 Mine Prod. (Metric Tons)</th>
<th>Item</th>
<th>2008 Mine Prod. (Metric Tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Steel</td>
<td>1,360,000,000</td>
<td>Uranium (2007)</td>
<td>41,279</td>
</tr>
<tr>
<td>Pig Iron</td>
<td>958,000,000</td>
<td>Lithium</td>
<td>27,400</td>
</tr>
<tr>
<td>Aluminum</td>
<td>39,700,000</td>
<td>Silver</td>
<td>20,900</td>
</tr>
<tr>
<td>Copper</td>
<td>15,700,000</td>
<td>Cadmium</td>
<td>20,800</td>
</tr>
<tr>
<td>Manganese</td>
<td>14,000,000</td>
<td>Bismuth</td>
<td>5,800</td>
</tr>
<tr>
<td>Zinc</td>
<td>11,300,000</td>
<td>Boron</td>
<td>4,100</td>
</tr>
<tr>
<td>Lead</td>
<td>3,800,000</td>
<td>Gold</td>
<td>2,330</td>
</tr>
<tr>
<td>Nickel</td>
<td>1,610,000</td>
<td>Selenium</td>
<td>1,590</td>
</tr>
<tr>
<td>Magnesium</td>
<td>808,000</td>
<td>Zirconium</td>
<td>1,360</td>
</tr>
<tr>
<td>Strontium Materials</td>
<td>512,000</td>
<td>Tantalum</td>
<td>815</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>212,000</td>
<td>Yttrium (2001)</td>
<td>600</td>
</tr>
<tr>
<td>Antimony</td>
<td>165,000</td>
<td>Indium</td>
<td>568</td>
</tr>
<tr>
<td>Rare Earths (mixed, oxides)</td>
<td>124,000</td>
<td>Palladium</td>
<td>206</td>
</tr>
<tr>
<td>Cobalt</td>
<td>71,800</td>
<td>Platinum</td>
<td>200</td>
</tr>
<tr>
<td>Vanadium</td>
<td>60,000</td>
<td>Rhenium</td>
<td>45</td>
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<tr>
<td>Niobium (Columbium)</td>
<td>60,000</td>
<td>Rhodium</td>
<td>30</td>
</tr>
<tr>
<td>Tungsten</td>
<td>54,000</td>
<td>Hafnium</td>
<td>25</td>
</tr>
</tbody>
</table>

- Large users volume have mature recycling infrastructure
- RE Recycling market not yet developed
- Rare metals have high price
- Recycling economics
- High recovery cost
- Questionable economic model

2011 Nd = $400-450/kg
2012 Nd = $200/kg

Courtesy: Jack Lifton
China Dominates Growing Magnet Materials Market

WW Total Market Size $7B
2010, $15B by 2020

NdFeB magnets 75%

Rare Earth Oxide Ore production 95%

Rare Earth pure Metals nearly 100%

Approx ½ WW Alnico & SmCo production

Hard ferrites 65+ %

Japan, US, European producers close plants, move production
The RE Demand by Application- US and World-2010

Source: Congressional Research Service 7-5700, R41347, 2011
The RE Demand by Application- US and World-2015

Source: Congressional Research Service 7-5700, R41347, 2011
Where will prices fall over the long term? Big impact on economics of recovering REE’s.
The RE supply Chain

<table>
<thead>
<tr>
<th>Year</th>
<th>Production (t/yr)</th>
<th>Demand (t/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>125,000</td>
<td>134,000</td>
</tr>
<tr>
<td>2014</td>
<td></td>
<td>182,000</td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td>200,000</td>
</tr>
</tbody>
</table>

Projected 5 year REE tons/year. (IMCOA projections)

Demand projected to increase by 8 to 10% per year – by 2015 need 4 new 20,000 tpa TREO operations
Cost of Sm

Sm Metal Price History
(source: metal-pages.com)

USD / Kg

Date (mm/dd/year)

Sm Metal 99% min FOB Chin (CN)

$/kg

Nov Dec Jan Feb Mar Apr
Cost of Co

Cobalt Metal Price History
99.4% Purity
(source: metal-pages.com)
Cost of Nd

Nd Metal Price History
(source: metal-pages.com)

USD / Kg

Date (mm/dd/year)


Nd Metal 99% min FOB Chin (CN)
Dy Metal Price History
(source: metal-pages.com)

USD / Kg

Date (mm/dd/year)

Dy Metal 99% min FOB Chin (CN)
REPM Current Recycling Practices

Nd-Fe-B
– some scrap is remelted into virgin alloy
– reduces properties and limits amounts
– Many grades with many chemistries

Sm-Co
– most scrap is recycled for Cobalt only
– Predominantly chipped and broken magnets
– Organics from machining contaminants preclude swarf and machining scrap opportunities
REPM recycling issues

• Brittle magnets assembled on assemblies with epoxies – very difficult to physically remove.
• Powders are very reactive, oxidize readily
• Nickel coating for corrosion protection – has magnetic properties, detrimental to magnetic structure
• Unknown compositions of the scrap magnets
• Complete removal of plating from the scrap magnets is not easy
Possible solutions

• Labeling of magnets in consumer products?
• Hard drives, air conditioner, HEV, wind turbine, TWT magnets
• Industrial scrap magnets are easy to identify the composition than consumer product used magnets
REPM Recycling Opportunities

• In a typical neodymium-iron-boron (Nd-Fe-B) magnet manufacturing facility, about 20–30% of the magnets were wasted as scraps in order to machine them to desired shapes, which is estimated to be about 1500–2500 tons/year.

• In the case of Sm-Co magnets, about 15-30% of the raw materials were wasted as scraps in a typical Sm-Co manufacturing sites.

• Rare earth element recovery is on the verge of being the next big thing

GOAL: Tuning magnetic scrap into possible alloy
REPM Recycling Opportunities

• From alloy to magnets roughly 50% of feed metals becomes finished magnets
• Limited number of REPM producers outside China – under 12
• Market could double by end of decade
• Non-Chinese production sintered REPM 2009 production
  – SmCo 2000 T/year => 580 T/yr Sm recovery potential
  – NdFeB 12000 T/year => 4080 T/yr Nd, Dy, Pr, Tb recovery potential

REPM Recycling Opportunities

- To date, only very small quantities of rare earth elements (estimated to be around 1%) have been recycled from pre-consumer scrap, mainly permanent magnet scrap, despite the fact that typical magnet manufacturing processes could generate around 25% of scrap material.

- There is no information or evidence of any current activities in the post-consumer recycling of RE magnets on a large scale in the USA.
Current life cycle of rare earth element in permanent magnets

1. REE mining and separation
2. RE Magnet Manufacturing
3. Applications in motors, generators, electronic devices, etc.
4. Magnet ended up in Landfill together with other E-waste
Life Cycle with EEC Recycling Approach

REE mining and separation

RE Magnet Manufacturing

Applications in motors, generators, electronic devices, etc.

Scrap magnets removed and separated

Recycle to make RE alloys

Manufacturing waste
EEC recycling approach from E-wastes (Computer hard drive disk magnets)

Hard drive Nd-Fe-B scrap magnets with bracket assembly

EEC’s proprietary approach to make Ni/Cu coating free Nd-Fe-B magnets for reuse/recycle

EEC recycling approach

Nd-Fe-B scrap magnet (free of Ni surface plating)

- $B_r = 12.543 \, kG$
- $H_{ci} = 15.520 \, kOe$
- $H_c = 11.871 \, kOe$
- $H_k = 14.590 \, kOe$
- $BH_{max} = 37.002 \, MGOe$
EEC recycling approach

- Ni-free surface
- Oxygen is about 1-2%
- Less carbon content
- Dy content

<table>
<thead>
<tr>
<th>Component</th>
<th>Mole Conc.</th>
<th>Conc.</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gd</td>
<td>0.000</td>
<td>0.000</td>
<td>wt. %</td>
</tr>
<tr>
<td>Ni</td>
<td>0.000</td>
<td>0.000</td>
<td>wt. %</td>
</tr>
<tr>
<td>Co</td>
<td>1.960</td>
<td>1.847</td>
<td>wt. %</td>
</tr>
<tr>
<td>Fe</td>
<td>83.813</td>
<td>74.825</td>
<td>wt. %</td>
</tr>
<tr>
<td>O</td>
<td>5.011</td>
<td>1.282</td>
<td>wt. %</td>
</tr>
<tr>
<td>B</td>
<td>0.000</td>
<td>0.000</td>
<td>wt. %</td>
</tr>
<tr>
<td>Nd</td>
<td>6.489</td>
<td>14.963</td>
<td>wt. %</td>
</tr>
<tr>
<td>Dy</td>
<td>2.727</td>
<td>7.084</td>
<td>wt. %</td>
</tr>
<tr>
<td>Total</td>
<td>100.000</td>
<td>100.000</td>
<td>wt. %</td>
</tr>
</tbody>
</table>

SEM-EDX analysis
EEC recycling approach

- Ni/Cu free surface (using EEC’s Proprietary method)
- Oxygen is about 1-2 wt.%%
- Less carbon content
- Dy content from 5-8 wt.%%
- Large composition variation

Large quantity sample analysis is required to optimize the composition for recycling the E-waste magnets.

Possible solution: Labeling?
End of Life REPM Recycling

• High volume, larger magnets, limited number of compositions --- easier to recycle
• 100s of applications
• Many methods and tools to strip out components without RE content
• Small magnets ---- more costly to recover
• Return on Investment issues
• Long term pricing structure of REE?
Potential Environmental Benefits

➢ To save natural resources, and prevent environmental pollution.
  Example: Boron (B) that may be contained in acid dissolving sludge can pollute the underground water supply.

➢ Preventing the resource depletion of rare earth materials by recycling the magnets from consumer products and hence to prevent the waste electronic landfills and its environmental effects.

➢ Reduced impacts on the environment including water resources and biodiversity, reduced energy requirements and hence cuts in greenhouse gas emissions.

➢ The valuable rare earths should be returned to the industrial metabolism “Rare Earth Recycling”
Thanks you for your attention

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