Rare Earth Elements in Transportation

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Arnold Magnetic Technologies Corporation
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Let’s start with a brief introduction into our company.

Arnold was established in northern Illinois in 1895, becoming a chartered manufacturer in 1905 in Marengo, Illinois.

We serve over 2000 customers spread across 10 market segments.
Arnold Focus

• Magnet Production
  – SmCo RECOMA® - (Lupfig, Switzerland; Rochester, NY; Ganzhou, China)
  – Alnico, cast and sintered - (Marengo, IL)
  – Ferrite (Bonded) - (Marietta, OH; Norfolk, NE)
  – Injection Molded - (Shenzhen, China)
  – Electrical Steels - ARNON ® (Marengo, IL)
  – Electromagnets - (Ogallala, NE)

• Fabricated Magnets
  – Slice, grind, EDM

• Assemblies / Value Added Production
  – Precision machining centers for magnets and non-magnetic components
  – Precision assembly
    • Complex magnet and assembled shapes
    • Magnetized / un-magnetized assembly
    • High temperature and specialized adhesives
  – Encapsulation / sleeving
  – Rotor Balancing

• This is the business focus of Arnold today and is a summary of the manufacturing conducted at Arnold’s 10 factories.

• It includes vertically integrated manufacture of a number of magnetic materials with an emphasis on higher technology projects and precision machined components.
• Rare earth oxides, metals and alloys are contained in automotive equipment but are also used in the manufacturing process for components for the transportation industry.
• Due to time constraints, we will focus today on these three applications for rare earths: catalysts, batteries and drive motors.
Many of us might believe that electrically driven vehicles are rather new or that the auto industry has always been dependent upon gasoline.

However, some of the earliest vehicles were driven by steam.

Furthermore, electric cars were found in Europe and North America in the 1800s.

The discovery of oil in the USA in 1859 and subsequent development of the oil and gas industry “fueled” the North American industrial revolution and permitted growth of the internal combustion engine as a drive system of choice on cars and trucks.

“The 19th century was a period of great change and rapid industrialization. The iron and steel industry spawned new construction materials, the railroads connected the country and the discovery of oil provided a new source of fuel. The discovery of the Spindletop geyser in 1901 drove huge growth in the oil industry. Within a year, more than 1,500 oil companies had been chartered, and oil became the dominant fuel of the 20th century and an integral part of the American economy.” History.com

The energy content and convenience of liquid fuel caused the ICE (internal combustion engine) to substantially replace alternative drive systems, including steam and electric, examples of which are shown in these early photographs.
In this illustration of the Chevy Volt, GM shows us the diversity of rare earth content in vehicles and also many requirements for rare earths during processing of components.

We see, for example, that rare earths are used not only to polish glass but to modify the light transmission characteristics (neodymium) of glass.

Rare earths are used in the catalytic converter and also in refining the gasoline used to fuel the ICE (internal combustion engine).

There has been a transition from mechanical linkages to “drive-by-wire” technology. This requires sensors (many use rare earth magnets including SmCo magnets), wires to transmit the signals, a computer to analyze input and provide output, and motors and actuators to act on the signal from the computer.

Where a traction drive motor is utilized, a second, higher voltage battery is utilized. Hybrid vehicles have used NiMH batteries containing lanthanum and cerium (e.g., the Prius). There is a conversion to lithium-ion battery technology taking place but some vehicles still use the proven NiMH battery technology. Furthermore, end-of-battery-life replacement will require the same battery type. With over one million batteries in commercial use, the replacement market should be sizable.
This illustration from Hitachi provides applications and likely magnet type(s) with green representing ferrite and tan representing rare earth magnets, most of which are neodymium iron boron, though some SmCo magnets are used, especially in sensors.

When a motor is mentioned, most of us will immediately think of a device that drives a spinning shaft, but there are linear motors as well, such as door lock actuators and entertainment system speakers.

However, many of the vehicular systems still rely on ferrite magnets as they are less expensive and naturally corrosion resistant, for example to road salt.

Newer grades of ferrite magnets include minor amounts of lanthanum and cobalt to improve magnet performance by about 25%.
The USGS published figures on use of rare earths in various market segments.

Highlighted here are the three segments we’ll be exploring further today and their approximate share of the total rare earth materials market.

Together they represent approximately one half of the market.

### Distribution of Rare Earth Oxide consumption by market in 2008

<table>
<thead>
<tr>
<th>Rare Earth Oxide</th>
<th>Catalysts</th>
<th>Catalytic Converters (auto)</th>
<th>Ceramics</th>
<th>Glass industry</th>
<th>Metallurgy except batteries</th>
<th>Neodymium magnets</th>
<th>Battery alloys</th>
<th>Phosphors</th>
<th>Other</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cerium</td>
<td>1,980</td>
<td>6,840</td>
<td>840</td>
<td>18,620</td>
<td>5,980</td>
<td>-</td>
<td>4,040</td>
<td>990</td>
<td>2,930</td>
<td>42,220</td>
</tr>
<tr>
<td>Dysprosium</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1,310</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1,310</td>
<td>-</td>
</tr>
<tr>
<td>Europium</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>441</td>
<td>-</td>
<td>441</td>
</tr>
<tr>
<td>Gadolinium</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>525</td>
<td>-</td>
<td>162</td>
<td>75</td>
</tr>
<tr>
<td>Lanthanum</td>
<td>17,800</td>
<td>380</td>
<td>1,190</td>
<td>8,050</td>
<td>2,990</td>
<td>-</td>
<td>6,050</td>
<td>765</td>
<td>1,430</td>
<td>38,700</td>
</tr>
<tr>
<td>Neodymium</td>
<td>-</td>
<td>228</td>
<td>840</td>
<td>360</td>
<td>1,900</td>
<td>18,200</td>
<td>1,210</td>
<td>-</td>
<td>1,130</td>
<td>23,900</td>
</tr>
<tr>
<td>Praseodymium</td>
<td>-</td>
<td>152</td>
<td>420</td>
<td>694</td>
<td>633</td>
<td>6,140</td>
<td>399</td>
<td>-</td>
<td>300</td>
<td>8,740</td>
</tr>
<tr>
<td>Samarium</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>399</td>
<td>-</td>
<td>150</td>
<td>549</td>
</tr>
<tr>
<td>Terbium</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>53</td>
<td>-</td>
<td>414</td>
<td>-</td>
<td>467</td>
<td>-</td>
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<tr>
<td>Yttrium</td>
<td>-</td>
<td>3,710</td>
<td>240</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6,230</td>
<td>1,430</td>
<td>11,600</td>
<td></td>
</tr>
<tr>
<td>Other oxides</td>
<td>-</td>
<td>-</td>
<td>480</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>75</td>
<td>555</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>19,800</td>
<td>7,600</td>
<td>7,000</td>
<td>28,400</td>
<td>11,500</td>
<td>26,300</td>
<td>12,100</td>
<td>9,000</td>
<td>7,500</td>
<td>129,000</td>
</tr>
</tbody>
</table>

Values are rounded.

21% 20% 9%

Rare Earths Elements - End Use and Recyclability - USGS, Table 2, Page 5, USGS
• So, as time is critical, we’d better “get cracking”.
• There are two main catalyst applications for transportation: 1) fluid cracking catalysts (FCCs) for producing fuels from crude oil and 2) catalysts used in catalytic converters (CATCONs) to reduce exhaust pollution.

• Each application has traditionally used three precious metals: platinum, palladium and rhodium.

• Due to these materials’ costs (and rarity), rare earths were introduced into the formulations.

References:
http://apps-stage.catalysts.basf.com/Main/precious_base_metal_services/refining.be
Each of the precious metals has experienced both overall increase in cost and noticeable rapid, sizable changes in pricing.

The combination of cost increases and volatility drove the substitution of rare earths into the catalyst formulations.
Now that we have also experienced a dramatic short term swing in rare earth material pricing, a re-examination has taken place regarding rare earth use in catalysts.

Bottom line is that while catalysts can function without rare earths, they offer performance enhancement that will make their elimination difficult.
Rare earth elements (REEs) play an important role in petroleum refining. Lanthanum and cerium are used as additives for fluid catalytic cracking (FCC), a key process in gasoline production. These REEs increase gasoline yield and reduce air emissions from the oil refining process. A modest reduction of rare earth supply would not likely have a large impact on gasoline supplies or prices. The unprecedented increases in rare earth oxide (REO) costs during the past year have likely added less than a penny to the price of gasoline. However, current high REO prices are providing incentives for catalyst manufacturers to develop catalysts with low or near-zero rare earth content. Under more extreme conditions, with a sudden loss of significant rare earth supply, gasoline production per barrel of oil would decline, but with weak gasoline demand in the Atlantic Basin expected for several years, overall refinery capacity should still be adequate to meet demand.

Higher rare earth cost has little effect on gas prices and alternatives do exist should there be a total curtailment


• And, as Diana Bauer of the US DOE points out, the higher rare earth cost has had negligible affect on fuel pricing.
• What exactly is the function of the CATCON?

• As shown in this graphic, the variable valence state of cerium facilitates completion of the reaction of partially combusted output gases.

• Other CATCON structures are used, but the honeycomb structure is most common.

• Corning, Inc, a manufacturer of CATCON substrates has announced the construction of a new factory for the production of CATCONs targeted at the diesel engine market for North America.
“Rare Metal” usage in catalytic converters

“There is simply not enough platinum and rhodium going round on this planet to satisfy the collective demand of automotive emission-control systems and all of these other areas.”

Johannes Schwank, 2007, a chemical engineer at the University of Michigan in Ann Arbor

• However, as we produce more and more cars and trucks, it is becoming evident that… (see quote).
• Therefore, rare earths will play an increasingly important role in catalysis.
Recycling of CATCONs is necessary to re-capture precious metals and rare earths. This is accomplished by crushing the CATCON, separating the precious and rare earth metal content (to the extent economically and technically possible) adding additional fresh catalyst content and applying the mix to new CATCONs. The chart shows the chemical analysis of crushed CATCONs for recycling and includes at least some of the matrix material. What we see is the large percentage of rare earth use relative to the precious metals.
• In Don Bleiwas’ report (reference is at bottom of slide), he calculates the potential for recycled cerium oxide for 1) all vehicles in-use, 2) for only 2010 vehicles and 3) from scrapped equipment.

• Note that these figures apply only to the USA and represent total available “Ce-oxide equivalent” rare earth.

• Annual recycling will be a fraction of the total vehicles in use.

• Amount potentially recoverable derives from a 70% recycle rate and 70% recycle yield.

### Table 1. Estimated amount of cerium oxide contained in catalytic converters in the United States in 2010 and potentially recoverable cerium oxide equivalents.

<table>
<thead>
<tr>
<th>Source category</th>
<th>Number of vehicles(^1) (millions)</th>
<th>Amount of cerium oxide per converter(^2) (grams)</th>
<th>Total amount of contained cerium oxide (metric tons)</th>
<th>Amount of potentially recoverable cerium oxide equivalents(^3) (metric tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicles in use in 2010(^4)</td>
<td>7.904</td>
<td>80</td>
<td>19,000</td>
<td>5.000</td>
</tr>
<tr>
<td>Heavy-duty trucks</td>
<td>11.62</td>
<td>180</td>
<td>2,000</td>
<td>500</td>
</tr>
<tr>
<td>Light-duty trucks</td>
<td>8.212</td>
<td>23</td>
<td>190</td>
<td>90</td>
</tr>
<tr>
<td>Total</td>
<td>25.22</td>
<td></td>
<td>21,800</td>
<td>5,500</td>
</tr>
<tr>
<td>New vehicles and CATCONs sold in 2010</td>
<td>11.90</td>
<td>80</td>
<td>990</td>
<td>50</td>
</tr>
<tr>
<td>New cars and light-duty trucks(^5)</td>
<td>0.379</td>
<td>100</td>
<td>90</td>
<td>20</td>
</tr>
<tr>
<td>New heavy-duty trucks(^6)</td>
<td>0.367</td>
<td>23</td>
<td>8</td>
<td>3.5</td>
</tr>
<tr>
<td>New off-highway motorcycles(^7)</td>
<td>2.5</td>
<td>80</td>
<td>20</td>
<td>9.8</td>
</tr>
<tr>
<td>Total</td>
<td>15.85</td>
<td></td>
<td>1,080</td>
<td>400</td>
</tr>
<tr>
<td>From scrap and other sources in 2010(^8)</td>
<td>10.63</td>
<td>80</td>
<td>850</td>
<td>420</td>
</tr>
<tr>
<td>CATCONs from replacement and other sources(^9)</td>
<td>2.5</td>
<td>80</td>
<td>200</td>
<td>90</td>
</tr>
<tr>
<td>Total</td>
<td>13.13</td>
<td></td>
<td>1,150</td>
<td>510</td>
</tr>
</tbody>
</table>

\(^1\) Estimated on an average catalytic converter per vehicle. Calculated estimates for cerium oxide and cerium oxide equivalents are rounded to two significant figures. CATCON, catalytic converter.

\(^2\) Assuming a 70% recycle rate and 70% recycle yield.

\(^3\) Assumes a 70% recycle rate and 70% recycle yield.

\(^4\) Includes both domestic and imported vehicles.

\(^5\) Includes new cars and light-duty trucks.

\(^6\) Includes new heavy-duty trucks.

\(^7\) Includes new off-highway motorcycles.

\(^8\) Includes CATCONs from replacement and other sources.

\(^9\) Includes CATCONs from replacement and other sources.
Notes for Table 1

1 Rounded to the nearest thousand, except for new aftermarket CATCONs, which was rounded to two significant figures.
2 Estimate based on 70 percent capture of CATCONs recovered from vehicles classified as scrapage and 70 percent metallurgical recovery. Scraped vehicles were defined by the National Automobile Dealers Association as those vehicles no longer registered from a previous year. Vehicles may be re-registered at a later time, exported, or delivered to parts and scrap dealers.
3 Source: U.S. Department of Transportation, Research and Innovative Technology Administration, 2011.
5 Source: Davis, Diesel, and Boundy, 2011.
7 National statistics on the aftermarket sales and recycling of CATCONs were not available; however, it was reported that 880,000 new aftermarket CATCONs were sold in California during 2007 (Ozone Transport Commission, 2011). Based on the sales data in California, it can be grossly estimated that 2.5 million new aftermarket CATCONs containing 80 grams of cerium oxide in each converter were installed in vehicles in 2010 and that an equal number became potentially available for recycling.
8 Scrapage is defined as the number of registered vehicles with major damage—from an accident or flood, for example—and vehicles that have not been registered within 1 year. If a vehicle is re-registered, it is added back to the approximation of the number of vehicles in use (National Automobile Dealers Association, 2011). Some of these vehicles, and the CATCONs installed in them, may not be immediately available for recycling if they are exported out of the country, remain idle, or are placed back into service. The estimate does not represent the actual number of vehicles that enter the recycling stream by being dismantled for parts or shredded, that information was not available. Statistical data related to scrapage of heavy-duty vehicles and motorcycles were also not available.
Catalyst Summary

- Rare earth additions to FCCs and CATCONs reduce the demand for precious metals
- In addition to substituting for precious metals, RE additions in FCCs improve cracking and separation for obtaining select output materials
- Recycling is currently done for the precious metals, not for the relatively abundant Cerium and Lanthanum
Agenda

- Introduction
- Catalysts
  - Batteries
- Traction Drive Motors
• Hybrid drive systems are complex with dual voltage systems, charging circuits, and battery management.

• High voltage systems (100 to 350 volts or more) present safety problems and repair worker training requirements.

• Vehicle accident and rescue personnel require training in driver extraction from damaged vehicles to avoid electrocution.

For comparison…

• Home electric power usage is 3 to 10 kW versus traction drive motors of 20 to over 100 kW.
• The Ragone chart, named after David Ragone, is a chart used for performance comparison of various energy storing devices.

• On such a chart the values of energy density (in Wh/kg) are plotted versus power density (in W/kg).

• One or both axes are logarithmic, which allows comparing performance of very different devices (for example extremely high, and extremely low power).

• Battery requirements for three electric vehicle types are indicated on this plot by dark colored rectangles.

• Full electric (battery electric) vehicles are dependent upon the higher energy storage of Li-ion batteries while PHEV and HEV vehicles can use NiMH batteries.
This table showing several vehicles from many manufacturers and over seven years presents the dominance of NiMH batteries through 2010.

Several vehicle models are now using Li-ion batteries and new vehicles are expected to depend increasingly on Li-ion.

Each battery “pack” is comprised of numerous modules.
Battery Summary

• Li-ion is starting to replace NiMH on new applications
• Large number of existing NiMH batteries provides a sizable replacement market
• Additional battery development is required for wide acceptance of BEV technology
  – Reduced battery cost/unit of power output
  – Larger battery for extended range capability
  – Elimination of “range anxiety”
• Drive motors in transportation range from pedal-assist motors on bicycles to high performance motors in dragsters.
• Electric vehicle size ranges from under 100 pounds to over several tons.
Although other motor topologies are used, permanent magnet motors offer the optimal combination of performance (efficiency) versus cost.
• Motors are the single largest application for both ferrite and rare earth permanent magnets.

• This chart presents the more commonly used permanent magnets for each application with vehicular transportation highlighted.
• A key characteristic in selecting the best magnet is the temperature range of the application.

• We note here that both Neo and ferrite magnets have a more limited useful temperature range than SmCo and alnico.

• Ferrite can be theoretically used to over 250 °C. However, even by 150 °C, it loses 25% of its flux output and that is the practical upper temperature limit for ferrite magnet applications.

• Neo is not naturally a high temperature magnet material - we try to make it work at high temperatures by substituting dysprosium for some of the neodymium.
• In order to get a Neo magnet to resist demagnetization, it has been necessary to add HREs, heavy rare earths (dysprosium and/or terbium), to the composition.

• Dysprosium is preferred as it is more available and lower cost than terbium.

• While permitting use of Neo magnets at higher temperatures, use of HREs results in a reduction in Br and maximum energy product (BHmax).

• Some typical applications are shown for each range of material grades.
Global car production has been tracked by OICA and is charted here from 1997 through 2012.

A second order regression fit allows us to extrapolate to year 2020 when it’s possible that 90 million automobiles might be manufactured and sold.

If 10% of those are to be hybrid vehicles they might use 3,461 metric tons of neodymium and praseodymium oxide which represents ~13.4% of forecast global supply.

However, dysprosium usage would require approximately half of global supply.

The calculations include a reduction in dysprosium content by 25% permitted by the dysprosium diffusion technology. As the diffusion technology develops still lower dysprosium content may be possible.
• In 2005, gasoline and diesel represent 99% of fuel input.
• This declines to 83% in 2015 with the greatest alternative drive system growth being hybrid drive systems.
• An important issue with this slide is the recognition that even with the growth in use of alternative power sources, that conventional fuel vehicles will continue to increase in number.
• Forecasts for implementation of alternative drives and fuels have been consistently over-optimistic.

• For example, in this JD Power’s forecast from 2011, we see the number of vehicle models is about half the previously forecast number and market penetration is about 2/3 of forecast.

• Nevertheless, the number of hybrid and electric vehicles is increasing significantly. (See data below for year 2011 and 2012).

<table>
<thead>
<tr>
<th></th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Units</td>
<td>%</td>
</tr>
<tr>
<td>Total Sales (units)</td>
<td>12,734,356</td>
<td>2.11%</td>
</tr>
<tr>
<td>Hybrid</td>
<td>268,807</td>
<td>2.11%</td>
</tr>
<tr>
<td>PEV</td>
<td>17,813</td>
<td>0.14%</td>
</tr>
<tr>
<td>Total Hybrid, EV, PEV</td>
<td>286,620</td>
<td>2.25%</td>
</tr>
</tbody>
</table>
Final wrap up…
Traction Drive Motor Summary

- Adoption of HEV and BEV is lagging earlier forecasts but likely to continue growing
  - Dependent on alternate fuel cost
  - Development of battery technology
  - Competitive cost of the technology
- Permanent magnet drive motors are dependent upon
  - Availability of dysprosium
  - Other device demand for Neo magnets
- Permanent magnet drives offer best efficiency
- All motors are dependent upon price stability of copper and steel, not just on magnet materials
Mercedes-Benz SLS AMG Electric Drive:
740-hp super-sports car with one electric motor per wheel