THE DEMAND FOR RARE EARTH MATERIALS IN PERMANENT MAGNETS

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ABSTRACT

A major use for many of the rare earths is in permanent magnets. While alternate technologies exist or are being researched, rare earth magnets are unlikely to be supplanted as a major input to clean technologies and high efficiency consumer and industrial devices. We'll examine where and how the magnet rare earths are utilized and the size of the market. Global market growth forecasts will be presented. A brief explanation of materials research in the US completes this material.

KEYWORDS

Rare earths, magnets, dysprosium, rare earth market, wind power, electric vehicles

Revision Notes

This revision of November 2023 corrects an error, clarifies some of the information and improves upon the linking of references within the text to the list of references. The data remains fundamentally as presented in 2012. The sum and substance of the paper remains accurate to the present with a few exceptions. For example, grain boundary diffusion has provided for significant reduction in the demand for heavy rare earth elements. Also, Neo magnets are now routinely made with a natural mix of neodymium and praseodymium (NdPr also called didymium). Additional grades are now available that incorporate cerium and lanthanum substituting for a portion of the NdPr. Lynas is producing separated rare earth oxides from the Mt. Weld mine in Australia and MP Materials is producing concentrate from the Mtn. Pass mine in California for sale to China.

Readers of this paper are encouraged to seek updated information on the markets for EVs and wind power, the two fastest growing applications for Neo permanent magnets. There are also many changes underway regarding a magnet supply chain development within the USA. One source of extensive information is the study completed in mid-2021: *The Global Permanent Magnet Industry 2020 to 2030* (www.MagnetReport.com).

For more information on fundamentals of magnetism, its symbols and terminology I recommend obtaining item #1 from the reference list.

THE DEMAND FOR RARE EARTH MATERIALS IN PERMANENT MAGNETS

ABSTRACT

A major use for many of the rare earths is in permanent magnets. While alternate technologies exist or are being researched, rare earth magnets are unlikely to be supplanted as a major contributor to clean technologies and high efficiency consumer and industrial devices. We'll examine where and how the magnet rare earths are utilized and the size of the market. Global market growth forecasts will be presented. A brief explanation of materials research in the US completes this material.

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INTRODUCTION

Rare earth magnets, first commercialized c.1969, have become essential for a wide range of consumer, industrial and military devices. For example, they are used in the speakers and vibrator motors of cell phones. Rare earth magnets spin the discs within hard disk drives and rare earth magnet voice coil motors position the read/write head over the spinning platter. Rare earth magnets are the heart of motors and generators used on airplanes – they are smaller and lighter weight than alternative materials/devices. Now rare earth permanent magnets are increasingly used in electric vehicles and wind power generation.

Rare earth minerals are difficult to extract from the ores and to separate from one another. The increase in use of rare earth magnets has placed a severe strain on existing sources of supply. The establishment of new mines and processing facilities is costly and requires upwards of 15 years for them to become commercially productive. The combination of rapid rise in use of rare earth minerals coupled with supply shortages has caused price increases and threat to delivery of product. The result of this disruptive situation has been a profound response at several levels: corporate, industry-wide and governmental. Let's learn more about why rare earth magnets are so important to modern society.

WHAT MAKES A MAGNET "GOOD"?

What characteristics of a magnet are considered when deciding which one to use? Each application has requirements unique to itself so there is no "one right answer." All the following are considered when selecting a material. Do not be concerned if some of the terms are unfamiliar as we will explain them later. Because customers must gauge a magnet's performance using these criteria, persons conducting research and development should also evaluate success based on how well the magnets optimize each of these characteristics.

- Flux density – B_r
- Energy Product – $(BH)_{max}$
- Resistance to demagnetization – H_{cJ}
- Usable temperature range

- Magnetization change with temperature – Reversible Temperature Coefficients
- Demagnetization (2nd quadrant) curve shape
- Recoil permeability – very slightly greater than 1
- Corrosion resistance
- Physical strength – toughness, tensile strength, bending strength, chip resistance
- Electrical resistivity – minimizes eddy currents
- Magnetizing field requirement
- Available sizes, shapes, and manufacturability
- Raw material cost and availability

An introduction to the concepts of permanent magnetism includes an understanding of the magnetic hysteresis loop. Please refer to the left side of Figure 1. Magnetic materials respond to an externally applied magnetic field by developing an internal field – an induced field. As we apply a stronger field in the positive direction, then weaken it and apply it in the opposite (negative) direction, we cause the internal field to respond accordingly. If we plot the applied field versus the induced field, we have what is called the hysteresis loop of the magnetic material.[1,2]

As we cycle the magnet around the hysteresis loop, we see that the 1st and 3rd quadrant are similar, though of reverse sign, and that the 2nd and 4th quadrants are similar. The dashed lines display initial magnetization. When initially magnetizing the sample, the Type 1 and Type 2 shown in this chart refer to the coercivity mechanism where Type 1 coercivity is due to a "nucleation" mechanism and Type 2 is caused by domain pinning.

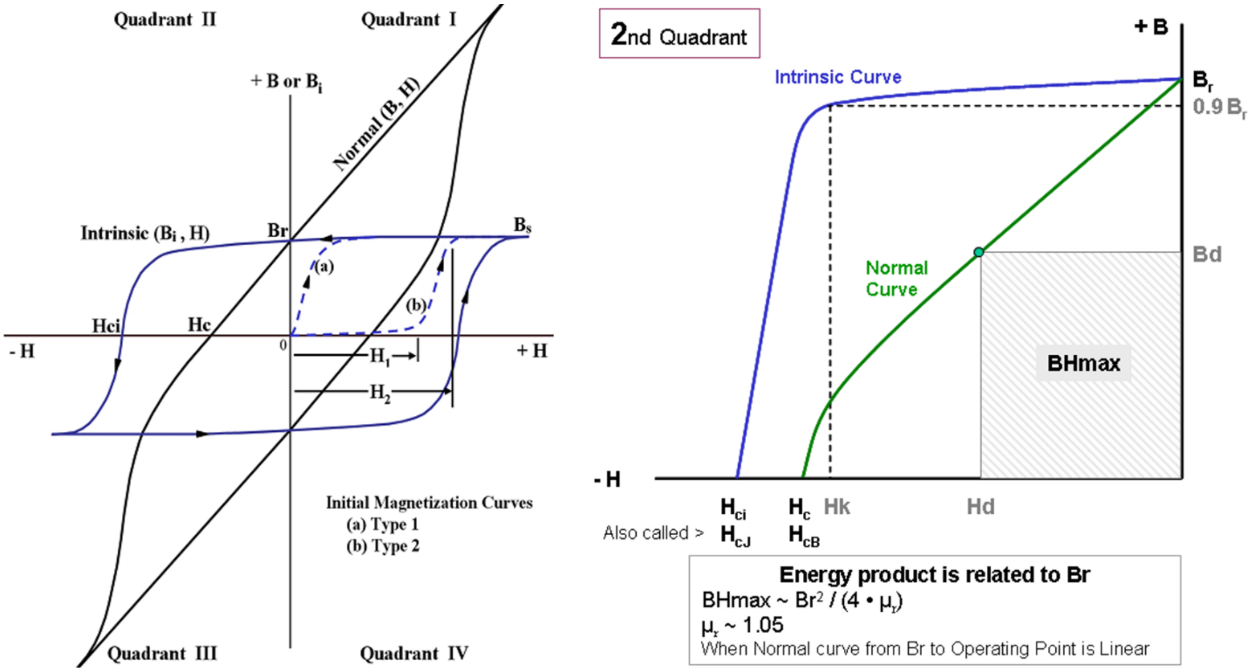


Figure 1. Left: Normal and Intrinsic hysteresis loops for a permanent magnet material.[2] Right: 2nd quadrant of the hysteresis loop with labels for key figures of merit[1]

For permanent magnets, we are primarily interested in what happens in the 2nd quadrant. The right side of Figure 1 is an illustration typical of the "demag" curves presented in product literature. The key figures of merit for permanent magnet materials are indicated on this figure.

The maximum energy product, $(BH)_{max}$, can be estimated from just the B_r as shown in the equation (right side Figure 1) – assuming a value for recoil permeability. The recoil slope is approximately 1.05 for sintered (fully dense) rare earth magnets. Conversely, the B_r can be estimated when the maximum energy product is known. As shown here, this material would be considered a straight line material (referring to the Normal curve) or square loop material (Intrinsic curve) since the Normal curve is straight, at least to the maximum energy point at the intersection of the B_d and H_d lines.

A magnet in a motor or generator is used like a spring in a mechanical device. When the spring is compressed, we put energy into it. Then when it is released, energy is obtained back from it. Similarly, a magnet in a motor is affected by the external magnetic fields and energy put into it and obtained back out of it. Just as a spring has a spring constant, a magnet has a maximum energy product. Large wire diameter springs have large spring constants. Powerful magnets have large energy products. Rare earth magnets have the largest energy products.

Table 1. Permanent magnet development timeline based on Parker (1990)[11Wallace]

Material	First Reported	Reference	BH(max)	Hci
Carbon Steel	c.1600	Gilbert	0.2	50
Chrome Steels	c.1870	Hadfield	0.3	65
Cobalt Steel	1916	Honda et al	0.9	230
Remalloy	1931	Seljesater	1.1	230
Alnico	1931	Mishima	1.4	490
New KS	1934	Honda et al	2.0	790
PtCo	1936	Jellinghaus	7.5	4,300
Cunife	1937	Neumann et al	1.8	590
Cunico	1938	Dannöhl & Neumann	1.0	450
Alnico, field treated	1938	Oliver & Shedden	5.5	640
Vicalloy	1940	Nesbitt & Kelsall	3.0	450
Alnico, DG	1948	McCaig, Bemius, Ebeling	6.5	680
Ferrite, isotropic	1952	Went et al	1.0	1,800
Ferrite, anisotropic	1954	Stuijts eta al	3.6	2,200
Lodex®	1955	Luborsky et al	3.5	940
Alnico 8	1956	Koch et al	4.5	1,450
Alnico 9	1956	Koch et al	9.2	1,500
$RECo_5$	1966	Strnat et al	16.0	7,000
$RECo_5$	1970	Benz & Martin	19.0	8,000
$RE_2(Co,Fe,Cu,Zr)_{17}$	1972	Strnat et al	32.0	25,000
$RE_2TM_{14}B$	1984	Koon, Croat, Sagawa	26.0	**25,000**
		(range of properties)	**35.0**	11,000
$RE_2TM_{14}B$	2010	(numerous)	30.0	**35,000**
		(range of properties)	**52.0**	11,000

Prior to the discovery of Alnico in the 1930's, permanent magnet materials were mostly cobalt steels which had high saturation magnetization but very low coercivity – e.g., 150 Oersteds (12 kA/m). During the 1900's great strides were made in the development of improved permanent magnets as shown in Table 1. The first greatly enhanced and widely used commercial permanent magnet was alnico, discovered in Japan in 1931 and continuously improved through about 1974. Alnico was followed by Ceramic (Hard Ferrite) magnets starting in 1954 and became widely used by 1960. Prevalence of ferrite magnets followed by the discovery and use of SmCo magnets resulted in a halt of development of alnico. Increased values of both maximum energy product, $(BH)_{\max}$, and resistance to demagnetization, H_{cJ}, were achieved culminating with the rare earth magnets: SmCo and "Neo" ($RE_2TM_{14}B$).

Most of the products shown in Table 1 are still used to some extent as each material has a unique combination of properties that makes it well-suited to certain applications. The large gains in energy product have been an enabling technological breakthrough.

Motors and generators utilize a permanent magnet's energy product while sensors use the magnetic flux surrounding a magnet which is dependent upon the B_r. When we compare the magnetic output of commercial materials versus the size of magnet required to generate similar output, we obtain results shown in Figure 2.

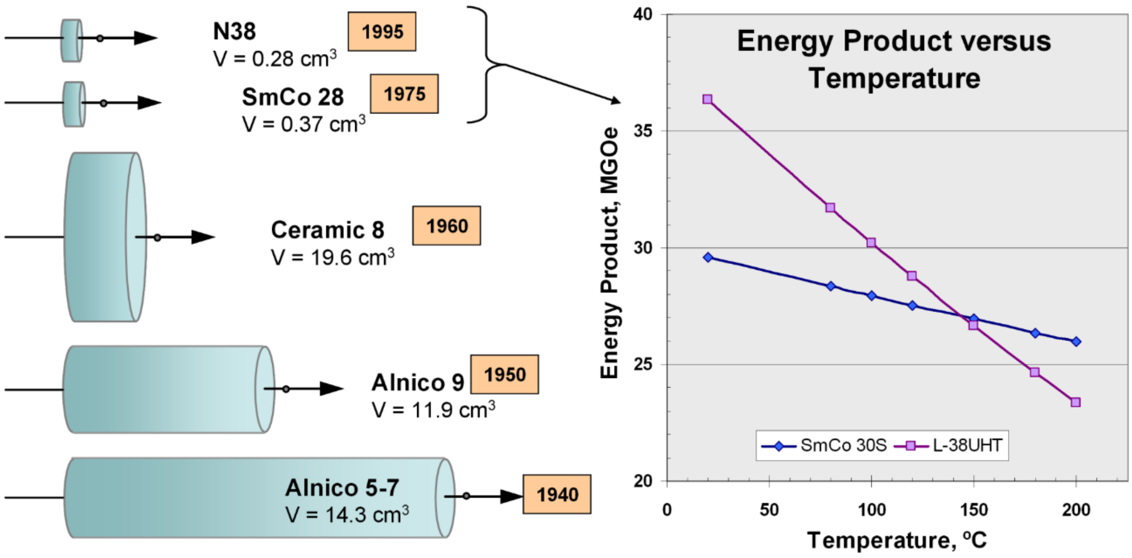


Figure 2. Relative magnet size to generate a 1,000 gauss field (0.1tesla) at 5 mm from the pole face of the magnet. The chart at the right compares energy products for Neo and SmCo magnets from 20 to 200 °C showing the superior temperature stability of SmCo.

Temperature stability of permanent magnets is less important in inexpensive, general use products. However, it is a very important issue in sophisticated devices or where the ambient conditions may be extreme such as in aircraft or outer space applications. Each magnetic material has a useful temperature range. Grades of alnico and SmCo can be used from 4 K to 550 °C. The practical temperature range for ferrite magnets is -40 °C to 150 °C. For ferrite, the upper temperature is limited by the large loss in flux output with rising temperature. Newer ferrites with La-Co additions may be used to temperatures from -60 °C to over 200 °C, but flux loss remains large at elevated temprratures.

Standard Neo magnets are limited to use above 140 K. Below that temperature Neo experiences a spin reorientation to a "cone of anisotropy" – simply, it becomes considerably weaker. (This can be avoided by substituting praseodymium for 80% or more of the neodymium.) The maximum use temperature is limited by: 1) the magnet's approach to Curie temperature which, depending on grade of sintered magnet, is between 310 °C and 350 °C and 2) excessive loss of H_{cJ} (Intrinsic coercivity) resulting in potential demagnetization. Neo grades exist for use up to ~230 °C, but high temperature results in a significant loss of magnetic flux.

WHAT ARE RARE EARTH PERMANENT MAGNETS?

There are four general compositions of commercially available rare earth magnets.

- **$SmCo_5$:** Usually produced as sintered magnets which are manufactured by powder metallurgy. This material was developed and commercialized between 1966 and 1969. It is anisotropic and benefits from orienting during processing. Energy products of grades today range from 18 to 25 MGOe. The 25 MGOe grade is achieved by substituting praseodymium for almost half of the samarium. The praseodymium addition raises the magnetic strength of the magnet but also increases corrodibility. Temperature stabilized grades of $SmCo_5$, where gadolinium is substituted for part of the samarium, provide almost no change in flux output from -40 °C to 150 °C but magnetic flux is lower than for samarium-only materials. Maximum use temperature of $SmCo_5$ is generally advertised as 250 °C.
- **Sm_2Co_{17}** (more accurately $Sm_2(CoFeCuZr)_{17}$): Usually produced as sintered magnets manufactured by powder metallurgy. A small amount of compression bonded and injection molded Sm_2Co_{17} is found in the marketplace. This material was developed between 1969 and 1974. Energy products range from 24 to 34 MGOe. Temperature stabilized grades, where gadolinium is substituted for part of the samarium, provide almost no change in flux output from -40 to 150 °C. Maximum use temperature is generally advertised as 350 °C but higher temperature grades have also been made for use to over 500 °C. This is achieved by increasing the cobalt content with a corresponding reduction of iron.
- **$Nd_2Fe_{14}B$** ("Neo", neodymium iron boron): Neo magnets first appeared in the marketplace in November of 1984. Production expanded rapidly and was concurrent with growth of the personal computer market. In 1990, it was reputed that 75% of all neo magnets was used in hard disk drives (bonded spindle drive magnets and sintered voice coil actuator magnets). The majority of Neo is produced via powder metallurgy and the anisotropic powder benefits from orientation during manufacture. Rapidly quenched powder for bonded magnets is magnetically isotropic and does not benefit from attempts to orient it. Manufacturing improvements and composition enhancements have led to higher energy product and reduced corrosion. Maximum use temperature is dependent upon heavy rare earth (HRE) content – usually dysprosium or sometimes terbium. 11% dysprosium content grades can be used up to 230 °C. Newer technology for grain boundary diffusion of the HRE or modified grain boundary alloys are providing enhanced performance with lower fractions of HRE.
- **SmFeN:** Manufactured as a powder often via ball milling. The fine powder is suitable for bonded magnets but not for sintered product as the interstitial nitrogen will "come out" of the lattice when heated above ~450 °C. It does have excellent temperature stability. It is an anisotropic powder, so benefits from aligning during the bonded magnet production process. It has produced higher energy product than anisotropic neo powder in bonded magnets. However, the materials and process are costly and it is considered a niche product. (Coey & Sun, 1990; Wallace & Huang, 1992).[4,14]

Additional comments on available magnet materials follow. Except for the powder made via rapid quenching and used in bonded magnets, these materials exhibit uniaxial crystalline anisotropy. That is, if the fine powders are oriented during manufacture so that the magnetic domains align, then the magnetic output is greatest. Rapidly quenched neo powder freezes-in random domain orientation resulting in an "isotropic" material structure which does not benefit from aligning and the finished magnet can be magnetized in any combination of poles and in any direction relative to the magnet. However, the random orientation results in a maximum B_r (Residual Induction) of about 64% of the fully oriented (anisotropic) material. Since energy product is proportional to the square of B_r, it is, at most, about 0.64 x 0.64 = 41% of the anisotropic, oriented alternative materials. Anisotropic powder for bonded magnets is available and made via HDDR, a process utilizing hydrogen to decompose the Neo material and reconstitute it in anisotropic powder form. Bonded magnets also suffer from a dilution of magnetic output by the non-magnetic binder. Magnetic flux density, B_r, is a function of volumetric loading of the magnetic phase. Molded Neo is about 65 volume percent magnetic material; compression and extruded products are 75 to 80 volume percent magnetic material.

In the 1980's Seiko-Epson developed a modified composition (copper addition) and process for hot rolling Neo. This was suitable for watch magnets, replacing the expensive platinum-cobalt type magnet.

Magnequench developed a process for densifying Neo powder via hot-pressing. This generated what they called MQ-2 (isotropic) and MQ-3 (anisotropic) magnets. The technology was licensed to other companies with Daido Electronics being one company to produce this type of product. Daido has learned how to make magnets not just by hot compaction, but also by re-flow (thin wall cylindrical magnets with radial magnetic orientation) and extrusion technologies (arcs, rectangles and other shapes). However, the great majority of Neo has been and still is manufactured by powder metallurgy.

About 1990, researchers associated with Trinity College, Dublin, Ireland, and Daido Steel, Nagoya, Japan, independently modified the crystal structure of SmFe by the interstitial introduction of nitrogen gas to form the $Sm_2Fe_{14}N_3$ structure converting SmFe with planar isotropy into a crystalline form with uniaxial anisotropy – the nitrogen being interstitial, not chemically reacted with the alloy (Coey & Sun, 1990; Wallace & Huang, 1992).[4] This resulted in a material with excellent magnetic properties. However, as lattice vibration increases with rising temperature, there is a point at which nitrogen atoms can escape from within the lattice allowing reversion to the planar isotropy. This temperature is ~450 °C – too low to allow sintering or other thermal densification processes but high enough to permit manufacture of molded and compression bonded magnets.

Numerous other rare earth-based alloys have been formulated for the purpose of making permanent magnets, but the ones listed here are the only ones to have measurable commercial presence.

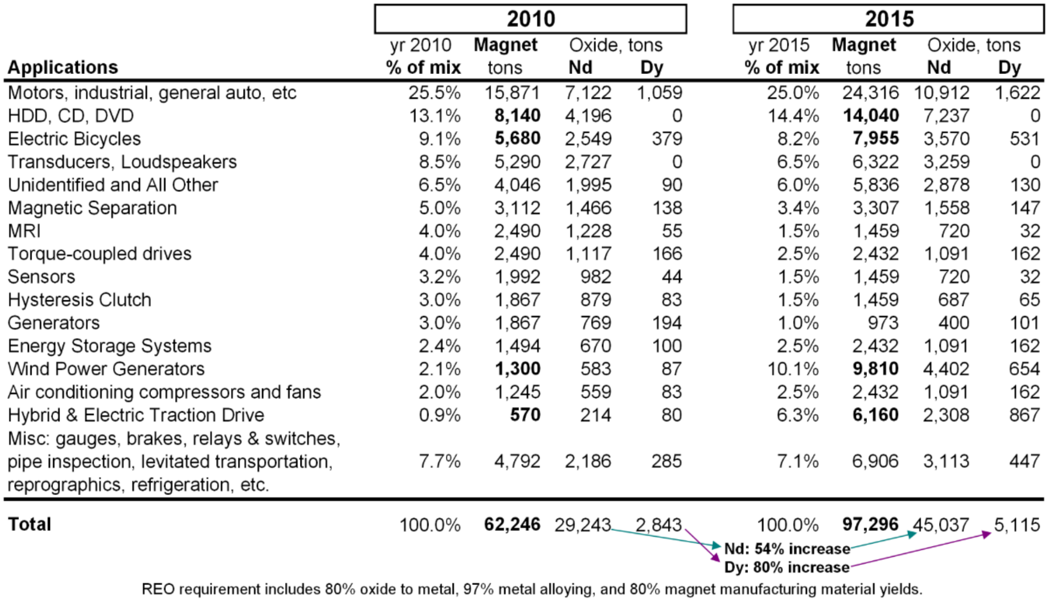
APPLICATIONS FOR RARE EARTH MAGNETS

A break down of applications with approximate percentages of rare earth magnets going into each is shown in this section for rare earth magnets (excluding SmFeN). This is an overview of the entire market, but there are significant geographic differences in mix depending on where the downstream products are made and what market segment is being serviced.

China now manufactures about 80% of all rare earth magnets, Japan makes about 17%, and about 3% are made in Europe. Because of raw material supply price variability and questions about availability, numerous manufacturers have changed plans: new product roll-outs have been delayed, new designs are being re-evaluated to use alternate magnet materials and alternate technologies that do not use permanent magnets.

The change in magnet usage indicated in Table 2 predicts a required increase in dysprosium content of 80% between 2010 and 2015 while the requirement for neodymium will increase far less at about 54%. To understand the market dynamics better, let's discuss a few specific applications – those in bold face in the table.

Table 2. Rare earth magnet applications and oxide requirements



	2010				2015			
	yr 2010	**Magnet**	Oxide, tons		yr 2015	**Magnet**	Oxide, tons	
Applications	**% of mix**	tons	**Nd**	**Dy**	**% of mix**	tons	**Nd**	**Dy**
Motors, industrial, general auto, etc	25.5%	15,871	7,122	1,059	25.0%	24,316	10,912	1,622
HDD, CD, DVD	13.1%	**8,140**	4,196	0	14.4%	**14,040**	7,237	0
Electric Bicycles	9.1%	**5,680**	2,549	379	8.2%	**7,955**	3,570	531
Transducers, Loudspeakers	8.5%	5,290	2,727	0	6.5%	6,322	3,259	0
Unidentified and All Other	6.5%	4,046	1,995	90	6.0%	5,836	2,878	130
Magnetic Separation	5.0%	3,112	1,466	138	3.4%	3,307	1,558	147
MRI	4.0%	2,490	1,228	55	1.5%	1,459	720	32
Torque-coupled drives	4.0%	2,490	1,117	166	2.5%	2,432	1,091	162
Sensors	3.2%	1,992	982	44	1.5%	1,459	720	32
Hysteresis Clutch	3.0%	1,867	879	83	1.5%	1,459	687	65
Generators	3.0%	1,867	769	194	1.0%	973	400	101
Energy Storage Systems	2.4%	1,494	670	100	2.5%	2,432	1,091	162
Wind Power Generators	2.1%	**1,300**	583	87	10.1%	**9,810**	4,402	654
Air conditioning compressors and fans	2.0%	1,245	559	83	2.5%	2,432	1,091	162
Hybrid & Electric Traction Drive	0.9%	**570**	214	80	6.3%	**6,160**	2,308	867
Misc: gauges, brakes, relays & switches, pipe inspection, levitated transportation, reprographics, refrigeration, etc.	7.7%	4,792	2,186	285	7.1%	6,906	3,113	447
Total	100.0%	**62,246**	29,243	2,843	100.0%	**97,296**	45,037	5,115

REO requirement includes 80% oxide to metal, 97% metal alloying, and 80% magnet manufacturing material yields.

Hard Disk Drives

Hard disk, CD and DVD drives all use motors to spin the discs and for positioning the read/write head (GMR or laser). In all cases, the spindle drive motors are made using compression bonded ring magnets. These magnets average approximately 6 grams each and the magnet material is the melt-spun Magnequench powder which does not use dysprosium.

The hard disk drives require a very fast positioning mechanism and these have for several decades been made using neo magnets. A flat form coil sits in the opening of the magnet holding fixture. An interaction between the coil and the magnets causes the read/write head to move back and forth across the disc. Average access times are on the order of 9 milliseconds: moving to the approximate target sector, reading actual location, moving to the precise sector, allowing the read/write head vibration to settle and reading the information. The number of turns for the coil is limited by the thin gap in the magnetic structure, so the strongest possible magnets are desired. The drives operate at relatively low temperatures (35 to 45 °C) in a high permeance circuit so grades of neo with little dysprosium are used.

Although the quantity of magnet material per drive is low, the number of drives is very high. Forecasts for year-end 2011 were that 660 million hard disk drives were to have been made and sold. (iSuppli.com industry statistics; Maleval, 2010[10]; Zhang, 2011)[15]

Transportation

Hybrid and electric vehicles are in the news - and in the forefront in our thoughts every time gasoline reaches $4.00 per US gallon ($1.57/liter). There are many other types of transport vehicles that do or potentially could use an electric drive system. Starting from the small end of the spectrum we have motor assisted bicycles, mopeds, small enclosed vehicles, cars, small trucks, SUVs and larger trucks, busses, off-road vehicles, construction vehicles, and finally, large mining and earth-moving equipment. To-date, the three main commercial products using electric drives either alone or with an ICE (internal combustion engine) are electric bicycles, hybrid (HEVs), plug-in hybrid (PHEVs) and full electric (battery electric vehicles, BEVs).

The economy of much of the world is such that cars are financially out-of-reach for the majority of the population. The less expensive electric bike is providing a path of upward mobility (if you'll pardon the pun) throughout southeast Asia, India and China. Although the amount of magnet material per unit is small, the quantities of bicycles are large. It was reported that 20 million were sold in China alone in 2009. And because the market is so diverse, it is difficult to assign an accurate average magnet weight per vehicle (estimates range from 60 grams for motor-assisted bicycles to over 350 grams for high power scooters). Intermediate dysprosium levels (~4-5%) are required in the motors for electric bikes.

On the other hand, high dysprosium content (~8-10%) is required for EV's due primarily to the higher temperature of the application coupled with localized high demagnetization fields. Rate of hybrid or EV adoption is in-part driven (bad pun again) by the cost of gasoline, incentives such as rebates on car purchases, fees on non-hybrid vehicles, express lane commuting advantages, government mandates, etc.

The rate of EV adoption has failed to keep up with forecasts in the US, but other geographic regions are adopting faster. China, for example is mandating rapid EV adoption to reduce urban pollution.

Wind Power

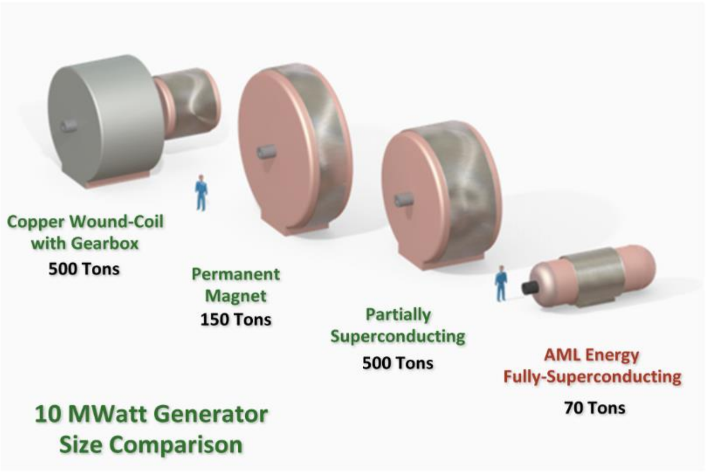
Electric energy production via wind power has been an industry for close to three decades. However, the increasing sensitivity to polluting gases from conventional power generating facilities, fear of catastrophic failure of nuclear power plants, depletion of oil and gas reserves, and the concern that combustion may be contributing to global weather changes – all have resulted in an emphasis on alternative and renewable sources of energy. Wind power is not without controversy, but has been increasingly implemented as part of national energy strategies. (Global Wind Energy Council publications of 2010 and 2011; Petersen & Larsen, 2011)[5,6,7,12]

Large wind power generator manufacturers of Europe and North America include Vestas, GE, Suzlon, Siemens/Gamesa, and several others. Chinese companies have also become frequent suppliers into the global market, with five companies claiming to be larger than Vestas, the largest manufacturer outside China.

Prior to 2005, China's wind power industry was close to non-existent. Since then it has grown rapidly and now cumulatively China has more wind power generation installed than any other country at 22.7% of global generation. In 2010 alone, China produced half of all installations world-wide with a substantial portion being Gen-4, permanent magnet generator type. Estimates of the fraction of new generators which are PM-type in China range widely from 25% to 95% with a consensus building at ~45%. PM generators outside of China are a much lower 5 to 10% of new installations.

Production and installation of wind power generation dropped noticeably in 2011 from 2010 for several reasons. In China, alternate power production did not keep up with wind installations and the grid was not able to accept all new installations – up to 30% were not grid connected as of September 2011. News reports also indicate the likelihood that some of the installations are having operating problems – that is, quality may have been compromised in a rush to install.

Installations have slowed dramatically in some countries. For example, in 2010, installations in the US were just over half of forecast. As in the US, Chinese government subsidies/mandates have been reduced or dropped. On the other hand, Germany has announced that they will shutter nuclear power plants and depend more on renewable resources. But wind is an unpredictable power source and can only be a fraction (~30%) of overall generating capacity. In other words, the market is going through a shake out that will likely last through 2012.



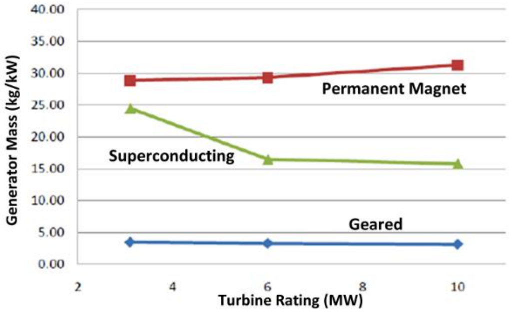
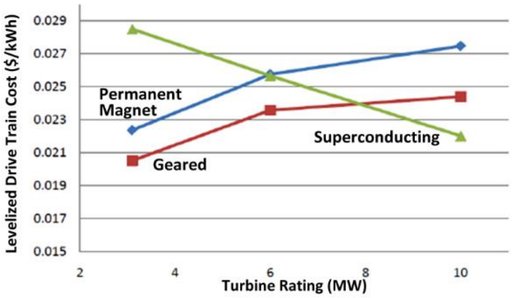


Figure 4a: Wind turbine generator mass for various generator technologies



REACT: Rare Earth Alternatives for Critical Technologies
Mark Johnson, January 10, 2012

Figure 3. Superconducting wind power generation as an alternate technology for large wind turbines (Johnson, 2012)[9]

A complicating factor for companies producing the generators is the rapid change in price of magnets or threat of unavailability of magnets. Companies have slowed the introduction of Gen-4 PM machines and accelerated development of superconducting generators. As generator output exceeds 5 MW per tower, the nacelle size and weight become increasingly large. Over 10 MW output, it is estimated that neither induction nor permanent magnet designs will be practical. Figure 3 shows this graphically.

Selection of wind power generator type is a function of factors such as installed cost, operating & maintenance costs, ease of maintenance, efficiency of power output, low speed cut-in and high speed cut-out, reliability, on-land versus off-shore, etc. As superconducting technology improves, where will the actual cross-over be? When will superconducting technology be developed and proven for roll-out?

Consumption of neo magnets could reach 10,000 tons per year in 2015, assuming:

- There is adequate neodymium, praseodymium, dysprosium, and terbium raw material
- Magnet pricing is stable and adequately low to be competitive with induction generators
- The fraction of installations which use permanent magnet generators becomes prevalent
- Accuracy of global forecasts for installation of wind power on land and off-shore – offshore towers tend to be higher MW, 8 to 14 MW, versus 1.5 to 8 MW for land-based towers.

THE RARE EARTH MAGNET MARKET

Market information for magnetic materials consists of data that is readily available (transparent market) and that which is difficult to obtain or not credible (opaque market). The information presented here is based on transparent market data, that is excluding Russia, much of India and a portion of the Chinese domestic market activity.

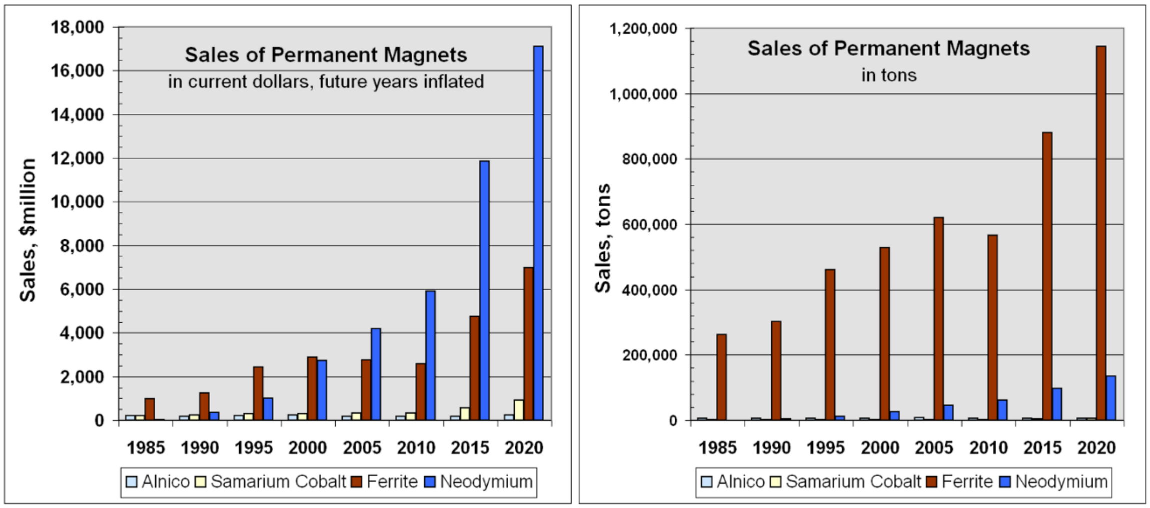


Figure 4. Permanent magnet sales by US Dollars and by metric tons for the four largest commercially available materials. Data for 2015 and 2020 are forecasts.[3]

We see in Figure 4 (Benecki, et al, 2010)[3] that sales in current dollars are increasing exponentially, with the fastest growth for neodymium-iron-boron (Neo) magnets – the light blue bar in the charts. Sales estimates for 2015 and 2020 include inflation estimates of 5% per year and are based on 2010 raw material pricing (before the upward spike of 2011) and are predicated on adequate supplies of not only the light rare earths (Nd and Pr) but also on enough dysprosium and terbium to permit Neo to be used in EV and wind power applications. In 2005, sales of all permanent magnets were only $8 billion. By 2020, Neo alone could account for sales over $17 billion – that is, if there are adequate supplies of the raw materials.

According to the forecast shown in the charts, ferrite continues to be very widely used, primarily due to its low cost and general availability. Development efforts have improved ferrite magnet properties enough to expand its use opportunities.

The rare earth magnet supply chain has increasingly developed along geographic lines. China controls almost all the raw materials and most of the magnet production (>80%). China still enjoys a lower cost of doing business and the selling price of products from China is lower than the West can match, whether, Japan, Germany, or North America.

Furthermore, China has “managed” the market for their domestic commercial success. For example, they have reduced export licenses by 53% (domestic producers) and 25% (joint ventures) since 2006. China has issued export restrictions by product to encourage high value downstream production in China since 2006. Toyota, Nissan, Honda and GM have established R&D and rare earth intensive electric vehicle traction drive motor production in Chinese facilities since 2011.

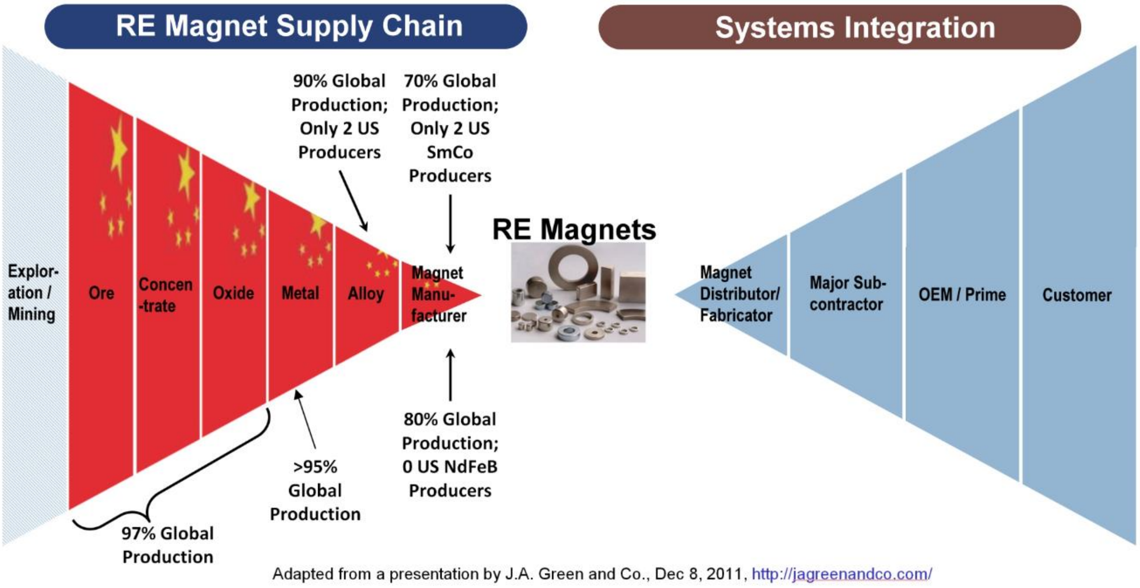


Figure 5. Rare earth magnet supply chain. Adapted from a presentation by Jeff Green of J.A. Green and Co., (Green & Zolnowski, 2011)[8]

It is important to recognize that China has the legitimate need to improve the standard of living for its people and to do this it is being funded by the rest of the world. As China seeks to move up the supply chain (to the right side of Figure 5) there will be further erosion of the West's manufacturing base. What we ALL require is a balance in supply at all stages of the supply chain so that China can continue to develop and ROW countries can re-establish and maintain domestic manufacturing capability of rare earth raw materials and products containing them.

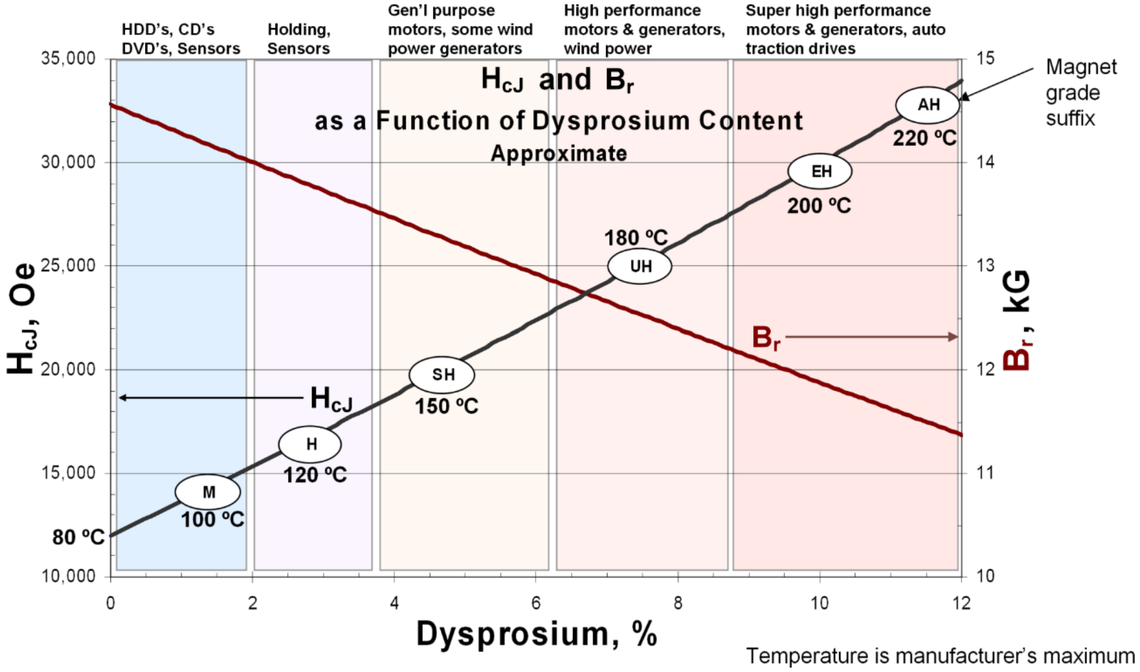
THE DYSPROSIUM ISSUE

No discussion of rare earth magnets would be complete without expanding on the need for and shortage of dysprosium. Neodymium, praseodymium and samarium, the main rare earth constituents of rare earth magnets, are part of a group called the light rare earth elements (LREEs) which include elements from lanthanum (atomic number 57) through europium (atomic number 63). Elements from atomic number 64 (gadolinium) through 71 (lutetium) are called the heavy rare earth elements (HREEs). The heavy rare earths dysprosium and terbium are useful in neo magnets to raise the intrinsic coercivity (resistance to demagnetization). Terbium is more effective than dysprosium, but it is also less abundant, so dysprosium has been the key element for providing neo magnets the ability to perform at elevated temperatures, that is, above 80 °C. Along with raising the intrinsic coercivity, dysprosium also reduces the rate at which coercivity decreases with increasing temperature.

A very rough estimate of relative abundance of the magnet rare earths as a fraction of production from operating mines, the data for which are based on a combination of bastnasite ore and ionic clays, is 15:5:3:1 as follows, in round numbers.

- Neodymium: 15% of all rare earths produced
- Praseodymium: 5%
- Samarium: 3%
- Dysprosium: 1%

The total rare earth content of a neo magnet is about 31 weight percent. Therefore, the grand average weight percent dysprosium in a neo magnet can be about 1.5% and be in balance with existing supplies.



Temperature is manufacturer's maximum recommended use temperature

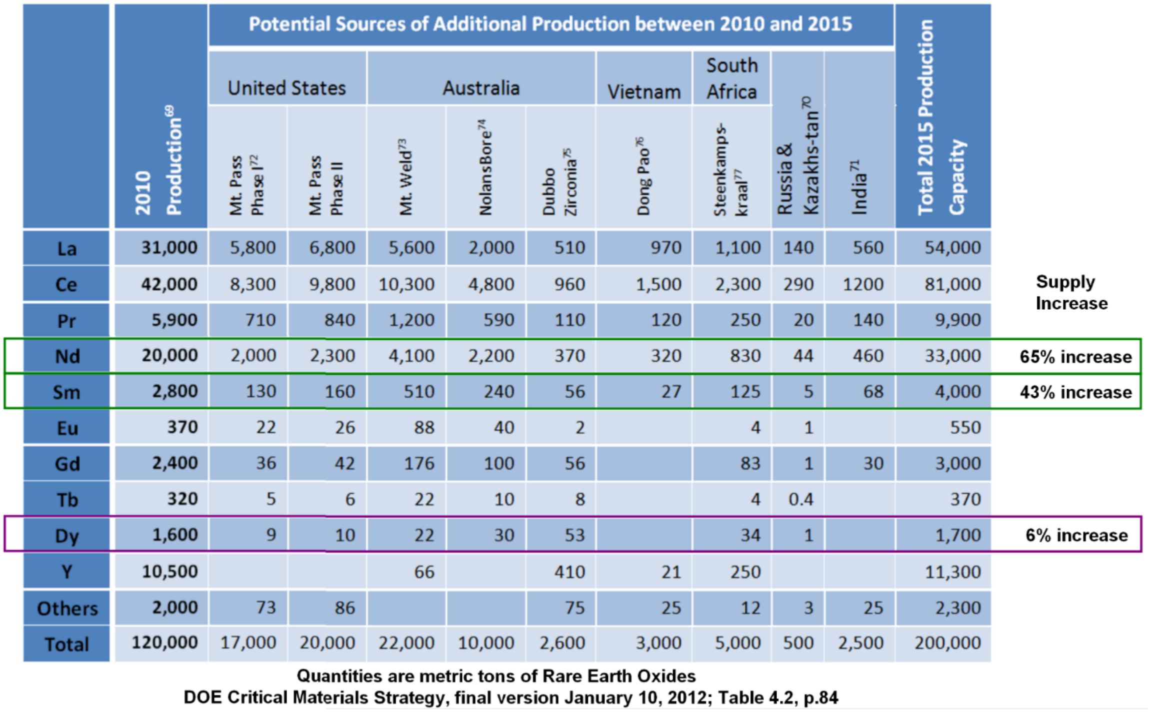
Figure 6. Dysprosium usage in Neo magnets; affect of dysprosium on intrinsic coercivity and residual induction; typical uses for each level of dysprosium.

We see from Figure 6 that most of the applications lie above this 1.5 weight percent point, including wind power and electric vehicles of all types. Even general industrial motors use over 4% dysprosium.

The US DOE (Department of Energy) in its Critical Materials Strategy of December 2010 and updated in December 2011 (http://energy.gov/pi/office-policy-and-international-affairs/downloads/2011-critical-materials-strategy) identify dysprosium as a material with high supply risk and high importance to clean energy both in the near and the mid-term. In Figure 7, DOE presents its finding for the current availability of each of the rare earth elements. New sources are identified showing the additional quantity of each element that will come from each of the new sources. The information is based on new sources as of 2015.

What we note is that there are several additional sources of the light rare earths which will provide about a 50% increase over current supplies. However, dysprosium is expected to increase only 6%. Even that may be optimistic since in the short term, China is attempting to curb unlicensed producers, especially in the south of the country which is also the source of most of the HREEs.

China has also, for the first time, separated export quotas for 2012 into light and heavy rare earths. While speculative, it suggests that China is sensitive to the importance of the HREEs both domestically and in international trade. Export quotas for all of 2012 are expected to be similar to 2011. In 2011, exports were reported to be about half of the quota amount. Since the quotas had been reduced from previous years, this is an indication that the rare earth market outside China may not be as robust as believed but that we must, none-the-less, re-establish the domestic supply chain for magnets and other products which use rare earths.



	2010 Production[69]	Potential Sources of Additional Production between 2010 and 2015									Total 2015 Production Capacity	
		United States		Australia			Vietnam	South Africa				
		Mt. Pass Phase I[72]	Mt. Pass Phase II	Mt. Weld[73]	NolansBore[74]	Dubbo Zirconia[75]	Dong Pao[76]	Steenkamps-kraal[77]	Russia & Kazakhs-tan[70]	India[71]		Supply Increase
La	**31,000**	5,800	6,800	5,600	2,000	510	970	1,100	140	560	54,000	
Ce	**42,000**	8,300	9,800	10,300	4,800	960	1,500	2,300	290	1200	81,000	
Pr	**5,900**	710	840	1,200	590	110	120	250	20	140	9,900	
Nd	**20,000**	2,000	2,300	4,100	2,200	370	320	830	44	460	33,000	65% increase
Sm	**2,800**	130	160	510	240	56	27	125	5	68	4,000	43% increase
Eu	**370**	22	26	88	40	2		4	1		550	
Gd	**2,400**	36	42	176	100	56		83	1	30	3,000	
Tb	**320**	5	6	22	10	8		4	0.4		370	
Dy	**1,600**	9	10	22	30	53		34	1		1,700	6% increase
Y	**10,500**			66		410	21	250			11,300	
Others	**2,000**	73	86			75	25	12	3	25	2,300	
Total	**120,000**	17,000	20,000	22,000	10,000	2,600	3,000	5,000	500	2,500	200,000	

Quantities are metric tons of Rare Earth Oxides

DOE Critical Materials Strategy, final version January 10, 2012; Table 4.2, p.84

Figure 7. Potential sources of additional production of rare earths between 2010 and 2015; table 4.2 of the DOE Critical Materials Strategy (US Department of Energy, 2011)[13]

RESEARCH AND DEVELOPMENT OF PERMANENT MAGNETS

Largely as a result of the instability (price and availability) of the rare earth materials market, research into alternate materials and technologies has risen to crisis proportion. An examination of the selling price of each of the major commercial permanent magnet materials accentuates the high cost of rare earth magnets. Prices of raw materials increased four times or more in less than one year. And while prices have moderated considerably, they are still well above levels seen in 2009 and early 2010. Magnet prices rose so-fast-and-so-far that using companies switched away from rare earth permanent magnets.

Permanent magnet R&D is focused on one or two objectives: increasing magnetic output and/or reducing the product cost all while using readily available materials. As a primary ingredient, it is strongly recommended to select more common materials such as those with at least the availability of nickel. Minor ingredients may be from the less available elements, but only when they are used in very small percentages. Truly rare elements should be avoided.

Research activities into the next great magnetic material involve multiple approaches. Here are some thoughts related to a “good magnetic product.”

- To obtain full benefit from the magnetic material, it should:
  - ➢ Be fully dense (no dilution of the magnetic phase)
  - ➢ Have uniaxial crystalline anisotropy (for maximizing magnetic saturation and resistance to demagnetization)
  - ➢ Magnetic domains should be oriented within the bulk structure.
- Raw materials need to be widely available and at reasonable cost.

- Raw materials and the finished composition must not be toxic or environmentally hazardous.
- The magnets should be easy and safe to manufacture.
- The magnets should be easily recyclable at end of life (EOL).

Indicated research is divided into two categories. The first could be called "Variation on a Theme" as it represents an extension of research on materials that have been previously examined. However, there are several differences between when the earlier research was conducted and the present time. One is that current analytic capabilities are superior to what existed even two or three decades ago. Secondly, we now have techniques to controllably form these materials with a refined structure at micro- and nano-scales. Research is focused on materials that exhibit ferromagnetic properties either naturally or when combined with alloying elements.

We start with about 100 elements occurring in nature. Dr. William McCallum has shown in earlier presentations how much of the periodic table of the elements is unsuitable for examination due to being truly rare, highly toxic, radioactive, contributing no magnetic moment, being chemically inert, etc. The "bottoms-up" approach is to take the remaining elements and combine them using computer algorithms to forecast the potential for generating a magnetic moment. Then the list of promising alloys must be produced and evaluated. One of the more significant hurdles is to make a nano-structured material fully dense and to do so in a scalable, economic manner.

The beneficial properties of magnetic materials are due in part to either shape anisotropy (e.g., alnico and iron-chrome-cobalt) or uniaxial crystalline anisotropy (e.g., ferrite, SmCo and Neo). In either case, during manufacture the magnetic domains must be mutually aligned to obtain maximum magnetic properties. Simultaneous densification and alignment have often been a source of difficulties in production.

Some of the materials being investigated are:

- SmCo plus exchange-coupled soft phase
- NdFeB plus exchange-coupled soft phase
- NdFeB with Ce and/or La substitution for a portion of Nd
- Fe-N (variation of SmFeN), interstitial N
- Mn alloys: MnBi, MnAlC
- Heusler alloys
- Alnico – modified to enhance coercivity
- Carbides: FeC, CoC
- Modified Ferrites (chemical or structural modifications): La-Co Ferrites, Core-Shell structure ferrites
- Ce-Co,Fe and Ce-Fe,Co-B,C

The cycle time for research from start to conclusion is between 5 (very optimistic) and 20+ years. While it is important to perform research, that which is being conducted today will probably not provide a slip-in replacement for rare earth magnets nor provide a new powerful (non-rare earth) magnet for many years. It is essential, therefore, for the mining and producing community to step up (domestic) production of rare earths: oxides, metals and alloys.

SUMMARY

- Demand for rare earth magnets is growing at double digit annual rates around the world and will continue to do so for as long as adequate raw materials are available at an "acceptable" price
- HREEs (dysprosium and terbium) are the most critical elements in the RE magnet supply dynamic
- Alternative technologies and materials will be employed where cost and availability dictate and performance, size, and weight permit
- Practical alternatives to rare earth magnets may not exist for some applications – that keeps the burden on adequate supply of rare earths
- Reduction or elimination of rare earth elements in high performance permanent magnets is a focus of numerous R&D initiatives – this is a long process and not likely to relieve the rare earth criticality short to mid-term
- Considering all the above, it is imperative that applications maximize use of the available magnetic flux output through design optimization

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