Permanent Magnet Materials and Current Challenges

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Abstract

Magnets are ubiquitous. They are seldom seen, but critical to modern devices used to improve our quality of life. Powder Metallurgy is the most common technique used in manufacturing these important materials. These products include magnets for hard disk drives, motors, actuators, generators, and communication devices. More sophisticated applications include traveling wave tubes, magnetic bearings in flywheels, wind turbine electric generators, and high efficiency motors and generators for hybrid vehicles. With the rapidly increasing consumption of raw materials, especially those for rare earth magnets, it is important to understand and optimize the powder metallurgy manufacturing process in order to conserve our natural resources.

Introduction

Magnetic materials are essential for the quality of life enjoyed by the world's population. They make possible many of the devices we take for granted. The improvement in the standard of living for people around the globe is presenting raw material supply challenges and driving innovation in manufacturing. We'll provide a general understanding of magnetics materials and show how powder metallurgy plays an important role.

To understand the interest in magnets, it's helpful to review their development and define what makes one magnet superior to another. We'll take a quick look at the chain of events that led to the discovery of rare earth magnets, currently the most powerful available. Then we'll introduce a number of applications using magnets and show why they are so important to our economy, our standard of living and the very foundations of our technologies. Last, we'll look at the challenge of supplying enough of these powerful magnets and research into even better materials.

Development of Magnet Materials

Arnold Knowledge Base

Over the last 70 years, Arnold has developed an extensive knowledge base in a wide range of materials including, but not limited to those shown in Figure 1. The products with tan arrows to the left are based on powder metallurgical manufacturing. *(Watch for these arrows – we'll use them throughout the document.)* As products and markets have changed, Arnold's product line-up and manufacturing locations have adapted. This extensive knowledge base provides Arnold a uniquely broad understanding of and perspective on the magnetics industry.

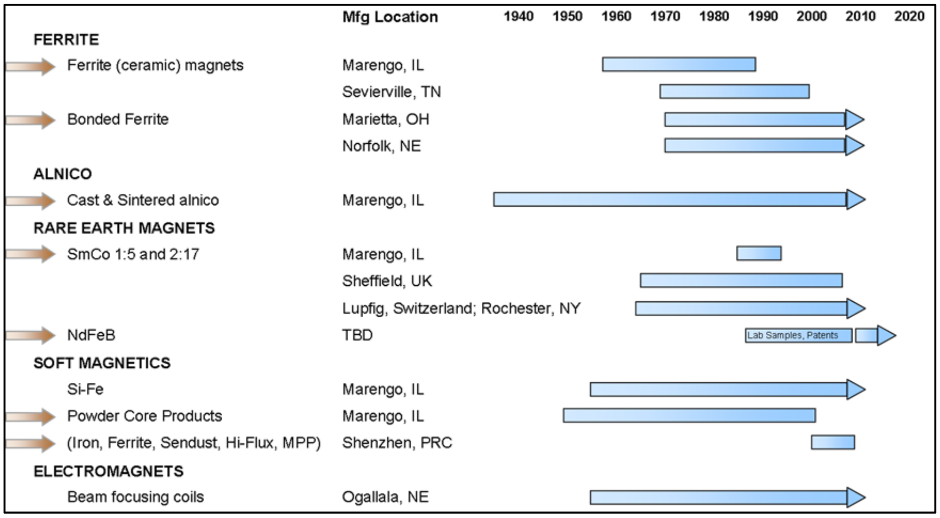


Figure 1: Arnold Knowledge Base

Arnold Today

Arnold is over 105 years old and is today involved in this diverse set of manufacturing technologies. Some of our valuable products and services include:

- Magnet Production, Vertically Integrated
  - SmCo (Lupfig, Switzerland; Rochester, NY; Ganzhou, China)
  - Alnico (Marengo, IL)
  - Ferrite (Bonded) (Marietta, OH; Norfolk, NE)
  - Injection Molded (Bonded) (Shenzhen, China)
  - Electrical Steels - ARNON® (Marengo, IL)
  - Electromagnets (Ogallala, NE)
- Fabricate Magnets
  - Slice, grind, EDM
- Assemblies / Value Added Production
  - Precision assembly
    - Complex magnet and assembled shapes
    - Magnetized / unmagnetized assembly
    - High temperature and specialized adhesives
  - Rotor Balancing
  - Encapsulation / sleeving
- Precision Machining Centers
  - Magnets and components

Permanent vs. Soft Magnetic Materials

Most of us have seen or played with permanent magnets and may even have been shown how a permanent magnet can lift paper clips or stick to the front of a refrigerator. Both soft and permanent magnets are crucial to devices we use. Soft magnetic steels make up the majority of weight in motors, generators, and transformers. But it is the permanent magnet that we must consider an enabling technology as we'll see when reviewing applications. Some of the more common terminology used in the magnetic industry includes:

Magnet: A material that produces a magnetic field.
Soft Magnetic Material: A material that in the presence of an externally applied magnetic field exhibits its own magnetism. When the external field is removed it no longer exhibits a magnetic field.
Permanent Magnet: A material that, once magnetized, continues to exhibit an external magnetic field in the absence of external stimulus.
Electromagnet: A magnetic field generated by the flow of electrons (a current) in a conductor.

Permanent Magnet Figures of Merit

Characteristics of particular importance for permanent magnets include the H_{ci}, Intrinsic Coercivity, which is a measure of a permanent magnets' resistance to demagnetization and the BH_{max} which is a measure of the strength of a magnet. These and others are as follows:

B_r, Residual Induction: Magnetic strength
H_{ci} (H_{cJ}), Intrinsic Coercivity: Resistance to Demagnetization
BH, Energy Product: A measure of the energy in the magnet in the magnetic circuit (alternate measure of "strength")

- BH_{max} is the maximum energy product and is very important for motors and generators

"**Straight Line**": Describes the shape of the Normal demagnetization curve in the second quadrant. This is also called "square loop" when the intrinsic curve is referenced. Neo, SmCo and Ferrite magnets are considered straight line materials
Temperature Coefficients: Define how a magnet's properties change with temperature

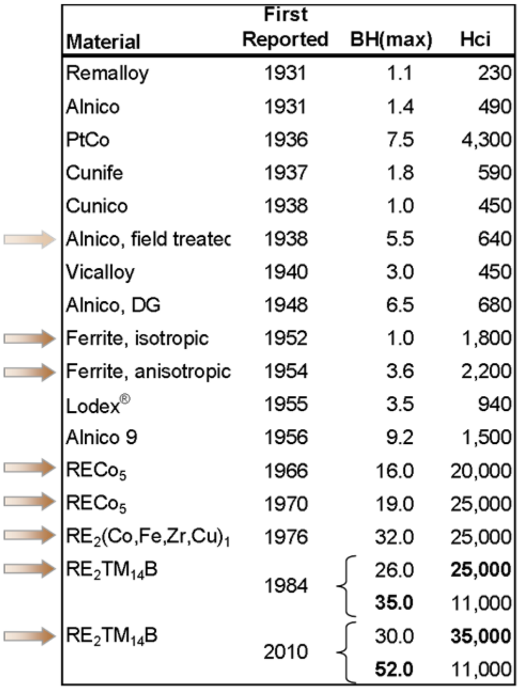
Permanent Magnet Development Timeline

During the 1900's great strides were made in the development of improved permanent magnets as shown in Table 1. Increased values of both maximum energy product and resistance to demagnetization were made culminating with neo magnets ($RE_2TM_{14}B$). Note too, the increasing use of powder metallurgy for manufacturing magnets.

Permanent magnets have been developed to achieve higher Br and energy product (BH_{max}) along with greater resistance to demagnetization (H_{ci}). Most are still in production with the exception of the following:

- ***Lodex***$^{®}$ *was discontinued due to use of hazardous materials in production and in the product*
- ***Cunife*** *has been replaced by FeCrCo*
- ***PtCo*** *is a specialty item made in very limited quantities due to its high material cost*

Table 1: Permanent Magnet Development Timeline



	Material	First Reported	BH(max)	Hci
	Remalloy	1931	1.1	230
	Alnico	1931	1.4	490
	PtCo	1936	7.5	4,300
	Cunife	1937	1.8	590
	Cunico	1938	1.0	450
➡	Alnico, field treatec	1938	5.5	640
	Vicalloy	1940	3.0	450
	Alnico, DG	1948	6.5	680
➡	Ferrite, isotropic	1952	1.0	1,800
➡	Ferrite, anisotropic	1954	3.6	2,200
	Lodex$^{®}$	1955	3.5	940
	Alnico 9	1956	9.2	1,500
➡	$RECo_5$	1966	16.0	20,000
➡	$RECo_5$	1970	19.0	25,000
➡	$RE_2(Co,Fe,Zr,Cu)_1$	1976	32.0	25,000
➡	$RE_2TM_{14}B$	1984	26.0	**25,000**
			35.0	11,000
➡	$RE_2TM_{14}B$	2010	30.0	**35,000**
			52.0	11,000

Table based on information in *Advances in Permanent Magnetism* by Rollin J. Parker, p.331-332

Improvement in Magnet Strength

The graphic presentation of the energy product shown in Figure 2 emphasizes improvement in magnetic strength over the years.

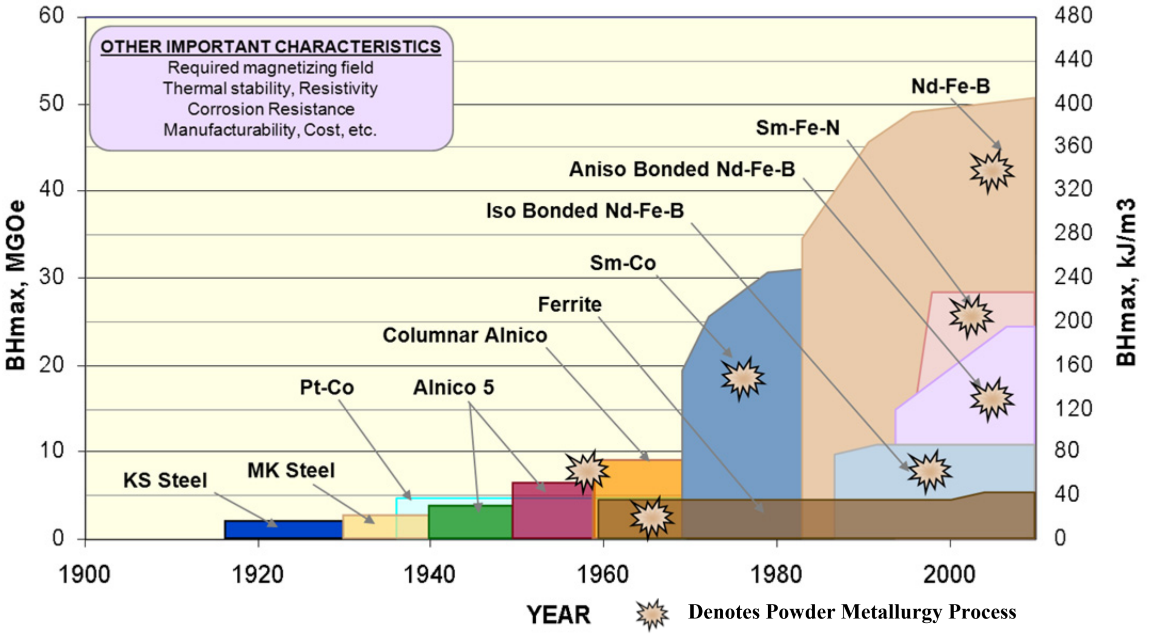


Figure 2: Improvement of Magnet Strength

All the materials presented here are still used in selected applications where their combination of price and performance is superior to the others.

For example, even though ferrite magnets are far weaker than the rare earths, they continue to dominate in sales on a weight basis representing over 85% of permanent magnets sold in the free world. However, the focus on device low weight and small size has driven usage of rare earth magnets so that neo magnets now represent over half of all magnet sales on a dollar basis. And on a dollar basis, powder metallurgy manufactured magnets represent more than 98% of all magnets whether on a weight or sales dollar basis.

Relative Magnet Sizes

To further emphasize the magnitude of the strength improvement, we can pictorially show it, as seen in Figure 3. These are the relative magnet sizes and shapes needed to generate 1000 gauss at 5 mm from the pole face of the magnet for each type of material. The volume (V) is also shown for each of the magnets with the alnico 9 magnet needing to be 54 times larger than the N48 (neo) magnet. So wherever small size and low weight are preferred, rare earth magnets are necessary.

System size depends also on the steel flux path. A larger, weaker magnet requires a larger structure which requires more steel.

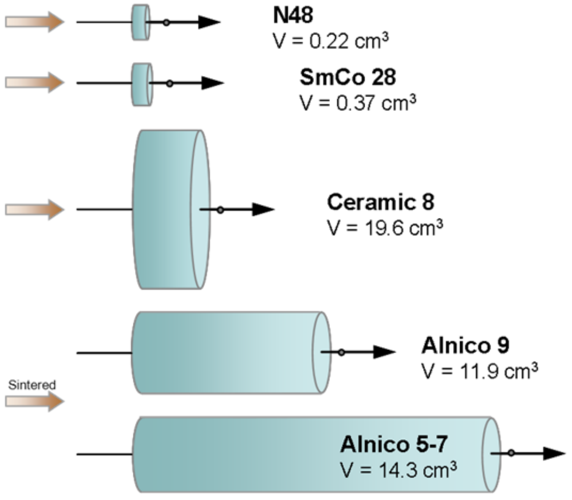


Figure 3: Relative Magnet Sizes

Magnets via Powder Technology

Basically magnets are made from powder alloys, but there are many different powder metallurgy processes involved. Samarium-cobalt and neodymium-iron-boron hard magnets are made using a milling, pressing, and sintering process. Bonded magnets are manufactured using an extrusion process, an injection process, a calendaring process, or a compression bonding process. They all are needed to provide the unique magnetic properties of the final magnet.

Process for Making NdFeB and SmCo Magnets

In Figure 4 we show a typical manufacturing process for either a neo or samarium cobalt (rare earth) magnet.

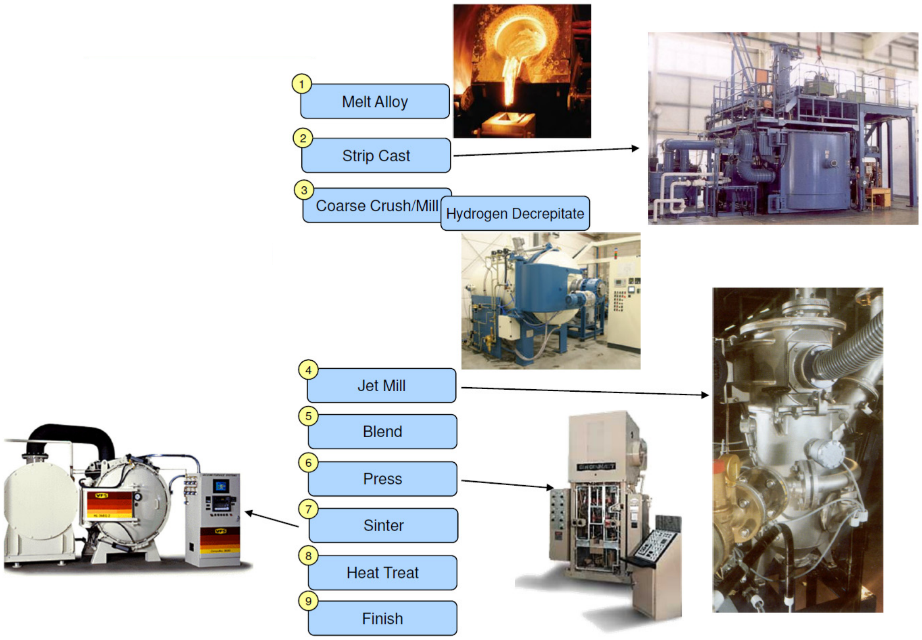


Figure 4: SmCo & NdFeB Magnet Manufacturing Process

Magnet alloys are melted, strip cast, and then crushed into large particles. Next they are finely milled to a powder particle size between 3 and 8 microns. The milled powder is then blended to make the proper composition and pressed. Once pressed, the "green body" is sintered and heat-treated in a furnace. Due to the reactivity of the alloys, sintering and heat treating are done in a vacuum, or inert gas. Finish operations include slicing, grinding, and coating. The process for making ferrite magnets is similar except that, as an oxide, processing is performed in an air atmosphere.

Bonded Magnets via Extrusion

Instead of sintering magnet powder into a dense body, it is possible to use these powders with a non-magnetic matrix to form a bonded magnet. In the example shown in Figure 5 a continuous extrusion of a highly loaded elastomeric or thermoplastic compound is used to produce continuous profiles of strip or sheet in a very efficient process. The material is continuously extruded from a die and is flexible if a thermoplastic binder is used.

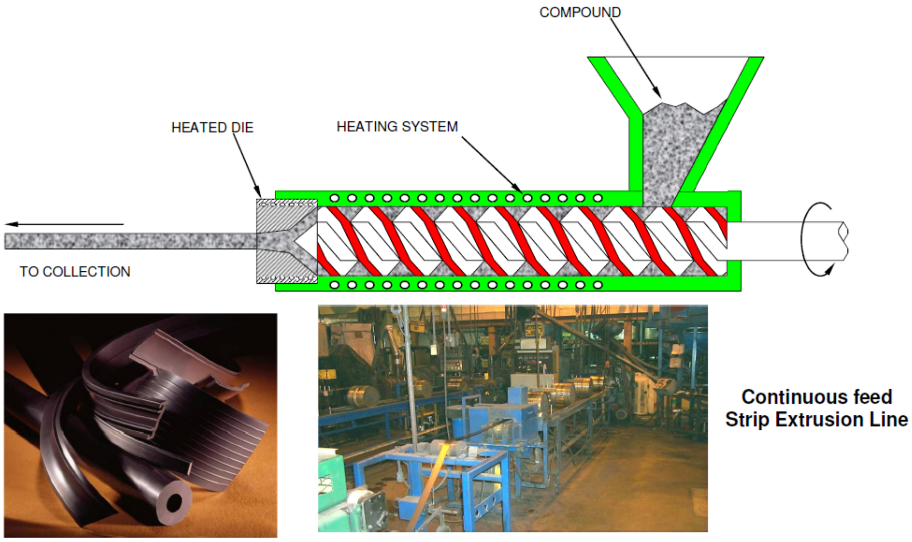


Figure 5: Extrusion Process for Bonded Magnets

Bonded Magnets via Injection Molding

In a similar process using an injection molding system, as shown in Figure 6, the material is forced into a mold cavity. The binder system is typically a thermoplastic such as nylon or PPS (polyphenylene sulfide). The example shown here is a vertically oriented rotary injection molder.

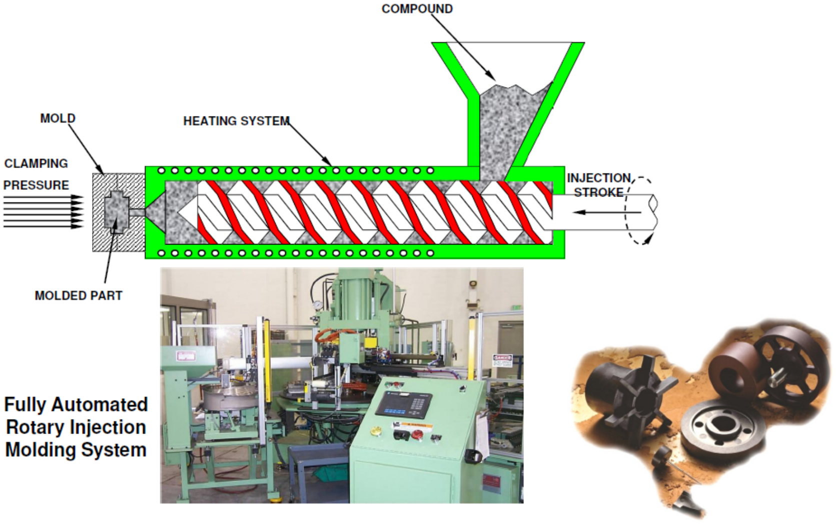
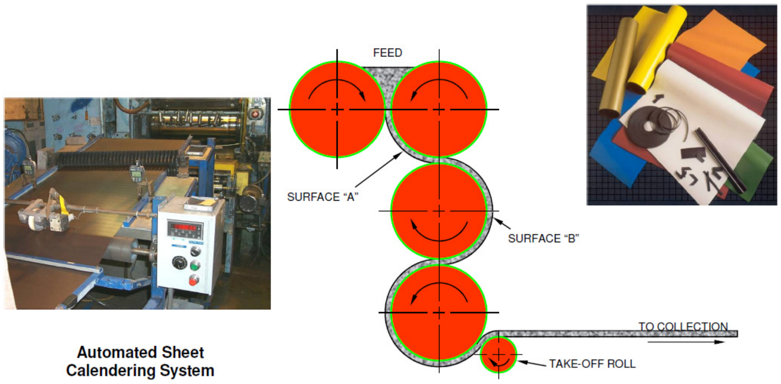


Figure 6: Injection Molded Process for Bonded Magnets

Mold tooling can contain magnetic circuit(s) using either permanent magnets or electromagnets to provide an orienting field. The process can produce very precise and complex-featured components. It is highly capable with the ability to generate complex magnetic orientation patterns. Magnetization (during processing), insert and over mold assemblies are all possible and additional finishing steps are seldom required.

Bonded Magnets via Calendering

A calendering process, as seen in Figure 7, utilizes highly loaded elastomeric compound, most often rubber, to produce wide sheet. The compound is rolled and pressed between rolls until it is in a thin sheet form. These sheets can then have thin layers of vinyl or metalized film adhered to their surfaces for printing and decorative purposes.



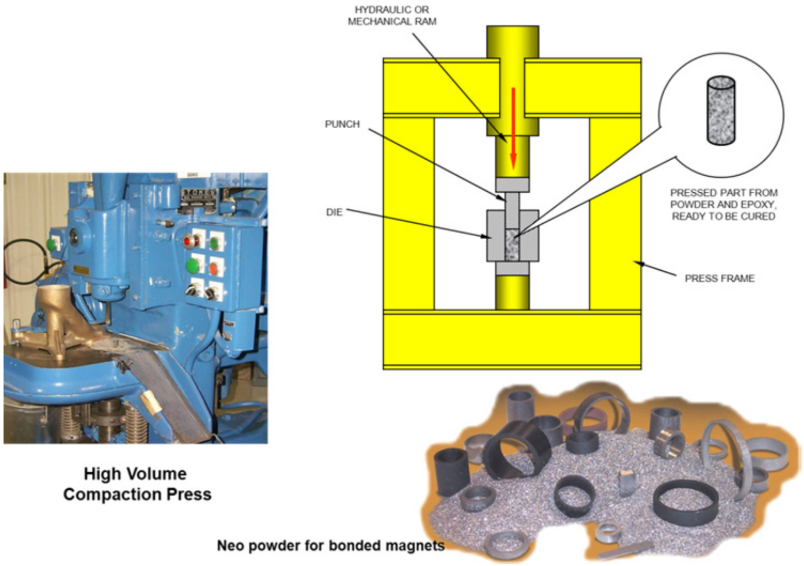
Automated Sheet Calendering System

Figure 7: Calendering Process for Bonded Magnets

Predominantly ferrite powders are used with the ferrite powder being oriented mechanically during the calendering to produce anisotropic properties.

Bonded Magnets via Compression Molding

Compression bonded magnet manufacturing is shown in Figure 8.



High Volume Compaction Press

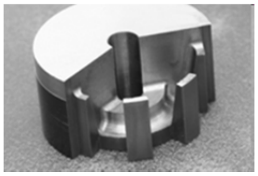
Neo powder for bonded magnets

Figure 8: Compression Molding Process for Bonded Magnets

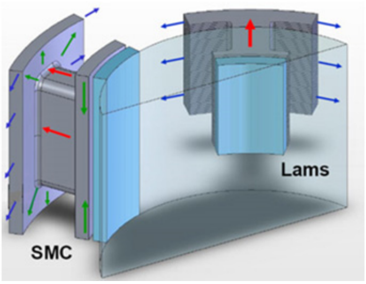
A uniaxial pressing process is used to manufacture compression bonded magnets. The binder is usually a thermosetting epoxy. The magnetic material in this example is neodymium-iron-boron. Compression bonded magnets have higher loading than injection or calendered magnets, 78 versus 65 volume percent, resulting in higher BH_{max}. It is possible to extrude magnets with loading comparable to compression bonded magnets, but the process is difficult and the output product is stiff (not flexible).

SMC's (Soft Magnetic Composites)

When a soft magnetic powder is used in a compression bonding process, a soft magnetic compact (SMC) is formed. These are gaining in use due to the unique magnetic properties. The presence of an insulating film on



the surface of each particle increases the resistivity of the compact. This reduces eddy currents generated in motors and generators thus reducing energy loss – raising device efficiency.



For many decades, common commercial motors have operated between 1800 and 3600 rpm and are constructed with between two and eight poles creating switching frequencies of between 60 and 480 Hz. Motors for electric vehicles are to run up to 14,000 rpm and have eight or more poles creating a switching frequency over 1800 Hz. At these frequencies, eddy current losses can be large. High eddy current losses are normally addressed by use of thin laminations. SMC's offer lower saturation magnetization, but improved high frequency performance.

Applications for Magnets

Magnets are used in many applications that are not readily known or easily seen. The following are a few of the more predominant ones, focusing mostly on permanent magnets.

Automotive

The current estimate by industry experts is that between 70 and 150 magnets are used per vehicle. For example, each instrument gauge in the dash of a car (speedometer, odometer, gas, oil pressure, etc) uses a stepper motor and each of these contains a small permanent magnet.

Antilock brake systems function by using magnets and sensors to detect how fast each wheel is turning. When a wheel spins at a greatly different speed, the computer assumes there is a problem. If the wheel is turning too slowly and the car is being braked, it is assumed that the wheel has locked up to slippery conditions. If the wheel is spinning much more rapidly than the others during acceleration, the assumption is that the wheel is slipping. In either case, the computer controls the application of the brakes to all wheels attempting to prevent wheel lock or to warn the driver of slippery conditions.

Home & Office

Magnets are also widely used in homes and offices.

For example, a cordless power tool (drill, saw, etc.) uses both permanent and soft magnetic materials. Office equipment uses motors for cooling (internal fans) and, in printers, for pushing paper through. Except for the refrigerator door, most of these magnets are "out of sight and out of mind."

Hard Disk Drives (HDD)

One of the main uses for rare earth magnets, predominately NdFeB, is in electronic devices such as hard disk drives, CD's and DVD's where the magnet is used both for driving the spindle motor and for positioning the read/write head. Even though the amount used per drive is small, the huge quantity of devices requires large amounts of rare earth magnets.

The existing HDD (Global) market is strong and continues to grow. Overall HDD shipments for 2008 were 593.2 million units, up 14.9% as compared to 2007 (iSuppliCorp). IDC, a technology research group based in Framingham, Massachusetts forecasts a 13.4% growth in worldwide shipments in 2009 and a 12% in 2010. Conservatively estimating a 10% growth in 2011 and 2012 the magnet total weight (neo magnets) in 2012 is estimated to equal **14,200 tonnes.**

Electric Bicycles

While hybrid automobiles and full electric vehicles are becoming increasingly more common in the US, Japan, and Europe, 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 EB's (electric bicycles), primarily in Asia, are a large and growing application especially in 3rd world nations with 300-350 grams of neo magnets per EB. Over 20 million were sold in China in 2009 with forecasts up to 30 million in 2012 which leads to an estimated annual neo magnet usage equal to **9,700 tonnes.**

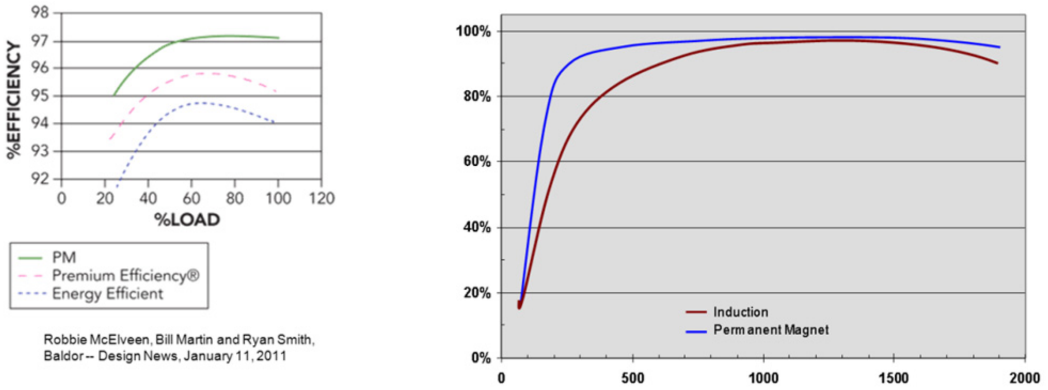
Electric Cars

Along with the rare earths in hybrid and electric cars, vehicles using NiMH batteries also use about 15 to 25kg of lanthanum. Conversion to lithium-ion batteries is expected, but the replacement battery market will exist for the approximately 2 million sets of NiMH batteries already in use. The conversion is also expected to take more than a decade. In addition to cars, buses and commercial vehicles are being designed for hybrid or full electric traction drive systems.

The hybrid vehicles global market is in a rapid growth phase with estimates of between 6 and 10 million hybrids to be manufactured in 2012. Each hybrid drive utilizes an average of 1.25 kg of neo magnets. Total neo magnet usage in 2012 for 6 million vehicles is equal to **7,500 tonnes.**

Permanent Magnet Motors

Why use permanent magnets in these drive systems? The current state-of-the-art motors show that permanent magnet designs offer higher efficiencies than induction motors as seen in Figure 9. Research into alternative induction motor designs is taking place and may allow them to compete with PM drives in the future.



Robbie McElveen, Bill Martin and Ryan Smith, Baldor-- Design News, January 11, 2011

Figure 9: Comparison between Induction and Permanent Magnet Motor Performance

Wind Power

Another application for permanent magnet devices is in the generators of wind towers. The first three design generations utilized induction generators. Induction generators must spin at high speeds, typically at or greater than 1800 rpm. The props that spin the generator of large, commercial towers turn at 10-12 rpm. Thus approximately a 170:1 gearbox is required to increase the shaft rotational speed. This gearbox has been the Achilles' heel of wind power. It is expensive, heavy, noisy, and requires frequent rebuild. Dismantling and exchanging gearboxes is an expensive proposition, especially for those towers on top of mountains or out at sea.

The global wind turbine market is expanding rapidly and designs are currently in their fourth generation which use permanent magnet generators. Between 250 and 600 kg of neo magnets are needed per MW output. The replacement of a 1 GW coal-fired power plant would require 400 tonnes of neo magnets. Approximately 220 GW of wind power is to be installed in the US by 2030 with a peak annual magnet usage in the period of 2018 through 2025 estimated to be at 6,400 tonnes / year. The peak global usage is estimated at 2.5 times this which equates to **16,000 tonnes** per year.

In permanent magnet, Generation 4, designs the generator spins at lower rpm's. Wind power is now one of the newest and largest drivers for increased neo magnet usage, specifically 1) the increase in wind tower installations and 2) the conversion from wound field to permanent magnet generators. Figure 10 clearly indicates why PM generator designs are attractive to wind power companies.

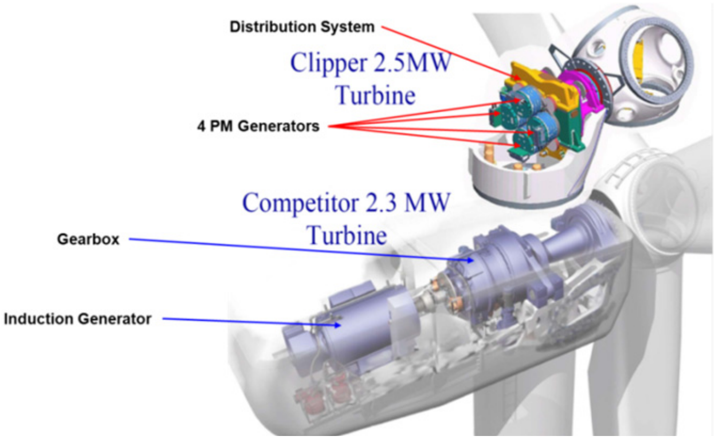


Figure 10: Generation 4 Wind Turbine

Since the PM generator spins at low rpm it requires a large number of magnetic “poles” to be efficient since power output is related to polarity switching as a function of time. This is aided by using a larger diameter generator. Rpm (and size) of the propellers is limited by structural strength of the propellers. The propeller size and rpm are a complex compromise to provide maximum output at maximum possible speed over the widest possible range of wind speed.

The cost and availability, or lack thereof, of neo magnets will likely determine the rate of conversion to Generation 4, PM generators. They are more likely to be adopted rapidly for use at sea and in larger MW towers. Figure 11 shows where each design is more likely to reside in terms of the type of generator and it points out the amount of magnet usage by design.

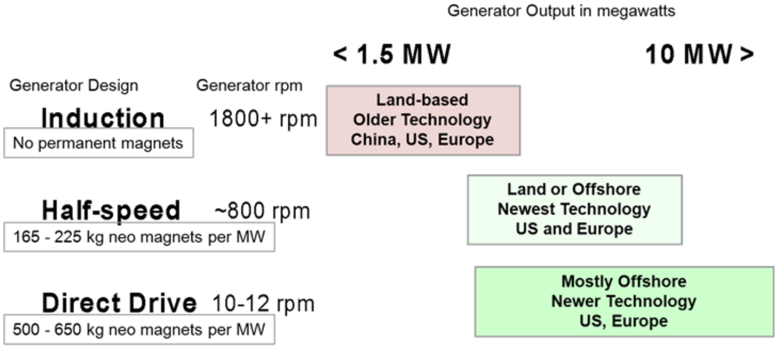


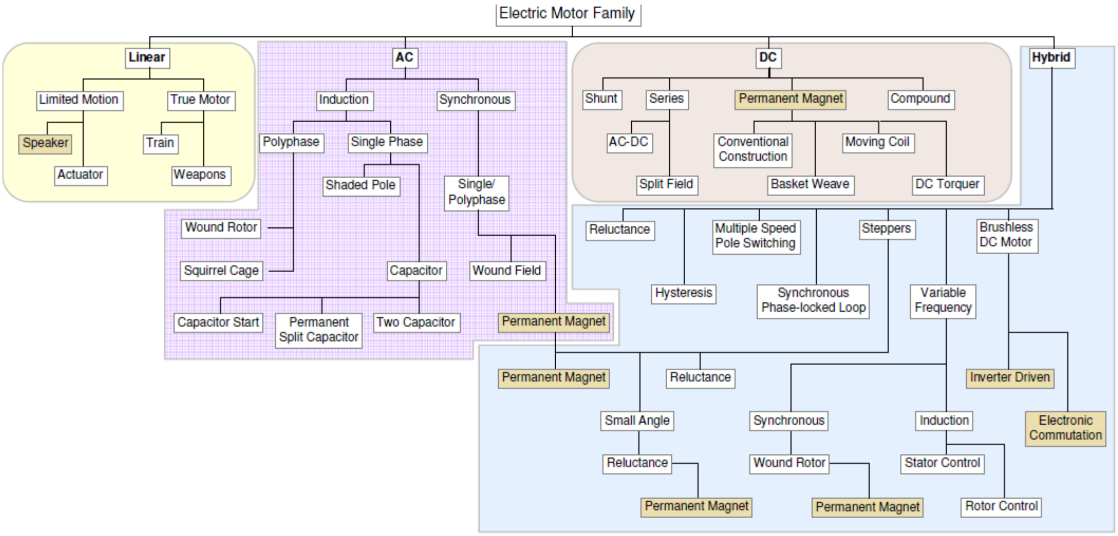
Figure 11: Wind Technology Focus for Large Scale Commercial Wind Power

In addition to wind power, other environmentally friendly generators are being designed and installed such as tidal turbines and wave action generators some using permanent magnet generators as seen in Figure 12.

Figure 12: Various Tidal Turbines

Motors and Generators

The single largest use for permanent magnets is in motors. Only a fraction of all motor types use permanent magnets as seen in Figure 13.



Based on: Rollin J. Parker, Advances in Permanent Magnetism, Figure 7.26, Motor family tree

Figure 13: The Electric Motor Family Tree

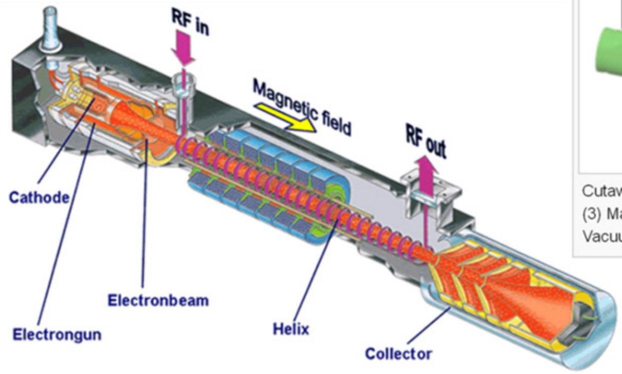
PM motors are becoming more common due in part to government efficiency regulations - they are more efficient than induction motors, wound field and similar types. Improvements in electronics and the reduced cost of electrical controls are allowing permanent magnet BLDC and ECM drives to penetrate the market to an extent not possible 20 years ago.

Motors range in size from fractional horsepower to more than 1000 HP. Even the graphite “brush” in some motors is an example of a powder metallurgy product.

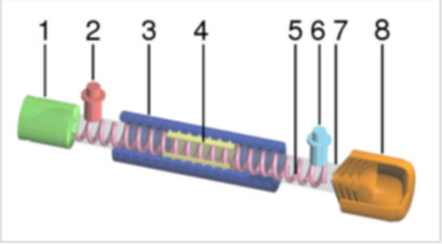
Traveling Wave Tubes

Another use for permanent magnets is in radio wave amplification. A traveling-wave tube (TWT) is an electronic device used to amplify radio frequency signals to high power, usually in an electronic assembly known as a traveling-wave tube amplifier (TWTA). TWT’s use predominately SmCo magnets due to the temperature of the application and the demagnetizing stress experienced. Figure 14 shows two examples of TWT’s.

Thales Electron Devices GmbH



Wikipedia



Cutaway view of a TWT. (1) Electron gun; (2) RF input; (3) Magnets; (4) Attenuator; (5) Helix coil; (6) RF output; (7) Vacuum tube; (8) Collector.

Figure 14: Traveling Wave Tube Examples

The importance of these devices outweighs their size and quantity with key uses being for radar and telecommunications.

Magnetically Coupled Devices

Magnetically coupled devices fall into three categories. As we discuss these, remember that the permanent magnet might also be an electromagnet though the PM offers better size efficiency and lower cost. The first is torque coupled devices which use sets of magnets interacting with each other. The second is eddy current devices which utilize magnets interacting with a conductor (most often a copper disc or preform). The final is Hysteresis coupled devices which use a permanent magnet to interact with a weaker magnetic material otherwise known as a "hysteresis material". Figure 15 shows an example of each of these.

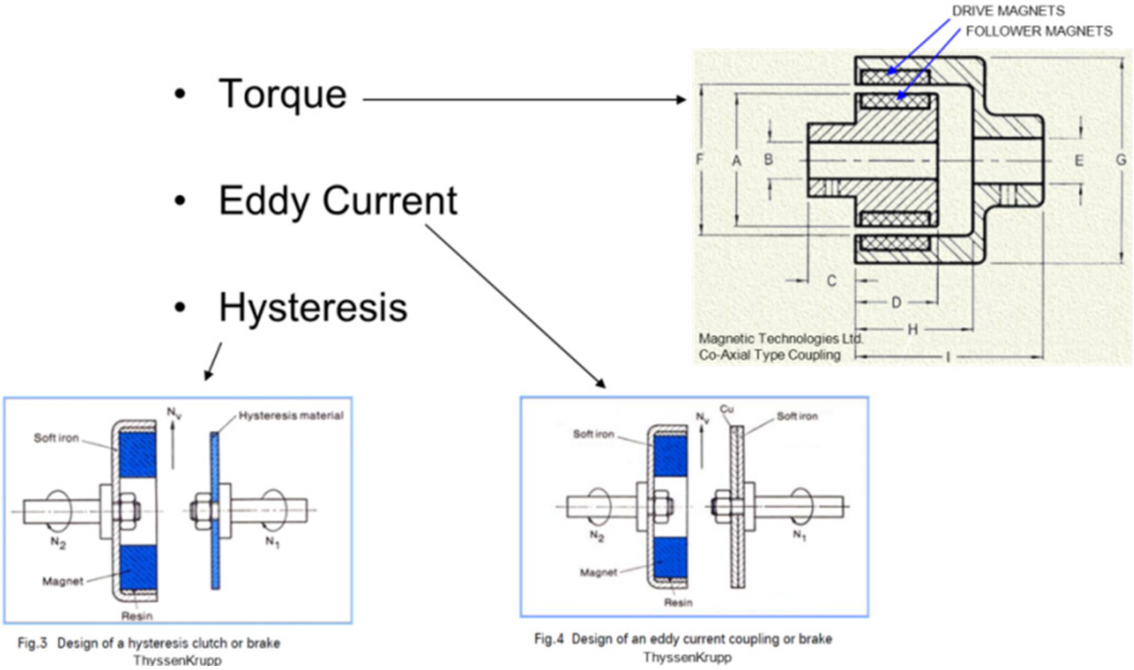


Fig.3 Design of a hysteresis clutch or brake
ThyssenKrupp

Fig.4 Design of an eddy current coupling or brake
ThyssenKrupp

Figure 15: Magnetically Coupled Device Examples

The Magnet Challenge

Even though the magnet industry has been around for decades and is fairly well established, there are many challenges today in terms of supply and demand of the materials used to create high performance magnets.

Magnet Sales

Total magnet sales are increasing exponentially, but the fastest growth is for neodymium-iron-boron (Neo) magnets as seen in Figure 16. In 2005, the total sale of all permanent magnets was only $8 billion. By 2020, Neo alone could account for sales over $17 billion. Neo is growing the fastest because it represents the best combination of performance, price and availability.

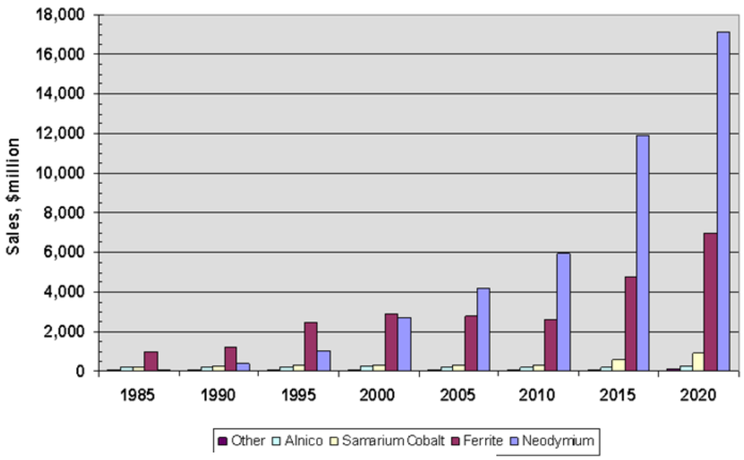


Figure 16: Magnet Sales

Rare Earth Metal Requirements

Table 2 shows the Rare Earth magnet applications sorted by neodymium requirements in 2008. Other than motors, the four applications highlighted in blue represent either current or forecasted largest usages of neodymium along with other rare earths used in magnets. The growth in the wind power industry is the most dramatic, ramping from 92 to 2428 tons per year, which is a 73% annual growth rate.

Table 2: Application Usage of Rare Earth Materials

	2008				2014			
Applications	**% of mix**	**Alloy*** tons	**Nd Req'd*** metal tons	**Dy Req'd*** metal tons	**% of mix**	**Alloy*** tons	**Nd Req'd*** metal tons	**Dy Req'd*** metal tons
Motors, industrial, general auto, etc	26.0%	15,860	4,418	657	23.0%	20,786	5,791	861
HDD, CD, DVD	14.8%	**9,017**	2,822	63	18.0%	**16,312**	5,106	114
Electric Bicycles	9.2%	**5,600**	1,560	232	11.4%	**10,286**	2,866	426
Transducers, Loudspeakers	9.0%	5,490	1,681	76	6.0%	5,422	1,660	75
All Other	7.2%	4,392	1,345	61	6.0%	5,422	1,660	75
Magnetic Separation	5.0%	3,050	892	84	3.5%	3,163	925	87
MRI	4.0%	2,440	747	34	1.5%	1,356	415	19
Torque-coupled drives	3.0%	1,830	510	76	2.5%	2,259	629	94
Sensors	3.0%	1,830	560	25	1.5%	1,356	415	19
Hybrid & Electric Traction Drive	3.0%	**1,800**	419	157	6.1%	**5,510**	1,282	482
Wind Power Generators	0.5%	**329**	92	14	9.6%	**8,714**	2,428	361
Misc.: Generators, clutches, brakes, relays, switches, wave guides, reprographics, etc	15.3%	9,333	2,592	394	10.8%	9,760	2,719	405
Total	100.0%	60,971	**17,638**	**1,872**	100.0%	90,347	**25,895**	**3,016**
Average Dy Content				**3.07%**				**3.34%**

NdFeB Magnet Dysprosium Issue

An even more important issue than availability of neodymium is the current "shortage" of dysprosium. In terms of relative abundance in the crust of the earth, dysprosium is less than 1% of all rare earths. In order for Neo magnets to perform at elevated temperatures, they require dysprosium at up to 12 weight percent as shown in Figure 17.

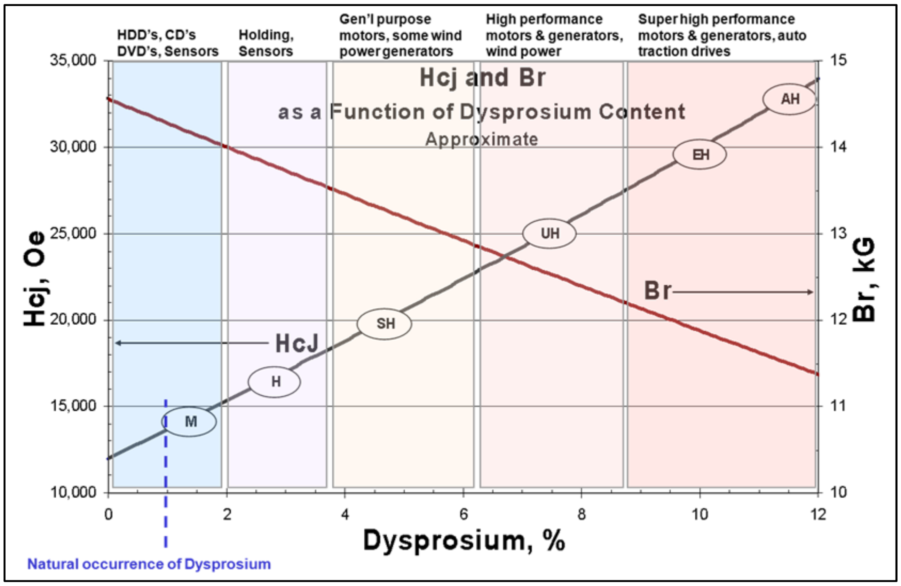


Figure 17: Dysprosium Requirements

Rare Earth Supply and Demand by the Numbers

Focusing on the five largest uses for rare earth magnets we see a disproportionately large increase in demand for dysprosium. Other than HDD & CD's, the high growth applications use a large fraction of dysprosium to perform at elevated temperatures. This can be seen in Table 3.

Table 3: Metal Requirements for Major Applications

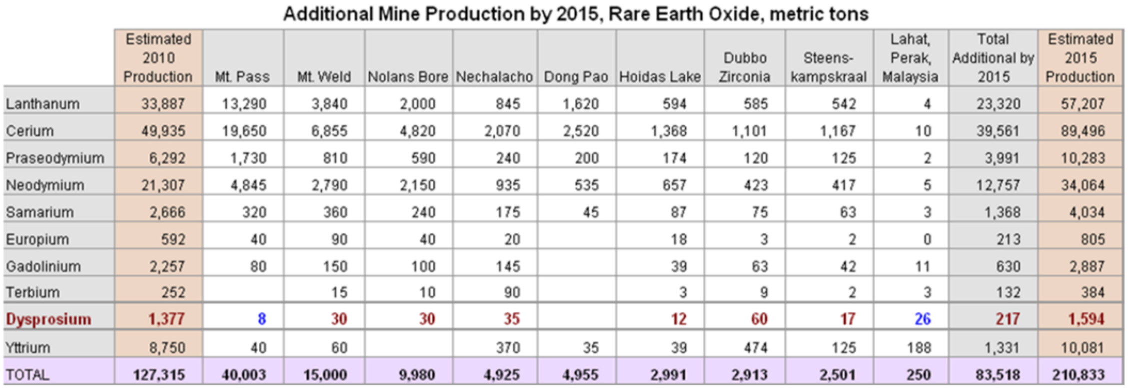
Metal Requirements, tons

	Neodymium		Dysprosium	
	2008	2014	2008	2014
Motors: industrial, general auto, etc	4,420	5,790	660	860
HDD, CD, DVD	2,885	5,220	~0	~0
Electric Bicycles	1,560	2,865	230	425
Hybrid & Electric Traction Drive	420	1,280	155	480
Wind Power Generators	92	2,430	14	360
	87% increase		>100% increase	

Dysprosium is a Short and Long Term Issue

According to published figures, as seen in Table 4 and Table 5, for the production of dysprosium, there is currently a shortage of supply and that shortage is expected to grow despite bringing the identified mines into production. This is one reason we are seeing high prices for the rare earths in general and dysprosium in particular exceeding $800 per kg in March 2011 – about half the price of platinum!

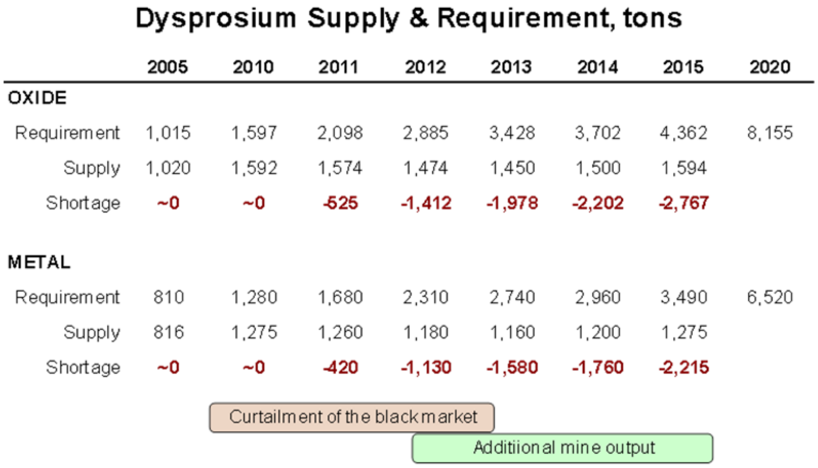
Table 4: Estimated Mining Production



Additional Mine Production by 2015, Rare Earth Oxide, metric tons

	Estimated 2010 Production	Mt. Pass	Mt. Weld	Nolans Bore	Nechalacho	Dong Pao	Hoidas Lake	Dubbo Zirconia	Steens-kampskraal	Lahat, Perak, Malaysia	Total Additional by 2015	Estimated 2015 Production
Lanthanum	33,887	13,290	3,840	2,000	845	1,620	594	585	542	4	23,320	57,207
Cerium	49,935	19,650	6,855	4,820	2,070	2,520	1,368	1,101	1,167	10	39,561	89,496
Praseodymium	6,292	1,730	810	590	240	200	174	120	125	2	3,991	10,283
Neodymium	21,307	4,845	2,790	2,150	935	535	657	423	417	5	12,757	34,064
Samarium	2,666	320	360	240	175	45	87	75	63	3	1,368	4,034
Europium	592	40	90	40	20		18	3	2	0	213	805
Gadolinium	2,257	80	150	100	145		39	63	42	11	630	2,887
Terbium	252		15	10	90		3	9	2	3	132	384
Dysprosium	**1,377**	**8**	**30**	**30**	**35**		**12**	**60**	**17**	**26**	**217**	**1,594**
Yttrium	8,750	40	60		370	35	39	474	125	188	1,331	10,081
TOTAL	**127,315**	**40,003**	**15,000**	**9,980**	**4,925**	**4,955**	**2,991**	**2,913**	**2,501**	**250**	**83,518**	**210,833**

Table 5: Dysprosium Shortage



Dysprosium Supply & Requirement, tons

	2005	2010	2011	2012	2013	2014	2015	2020
OXIDE								
Requirement	1,015	1,597	2,098	2,885	3,428	3,702	4,362	8,155
Supply	1,020	1,592	1,574	1,474	1,450	1,500	1,594	
Shortage	**~0**	**~0**	**-525**	**-1,412**	**-1,978**	**-2,202**	**-2,767**	
METAL								
Requirement	810	1,280	1,680	2,310	2,740	2,960	3,490	6,520
Supply	816	1,275	1,260	1,180	1,160	1,200	1,275	
Shortage	**~0**	**~0**	**-420**	**-1,130**	**-1,580**	**-1,760**	**-2,215**	

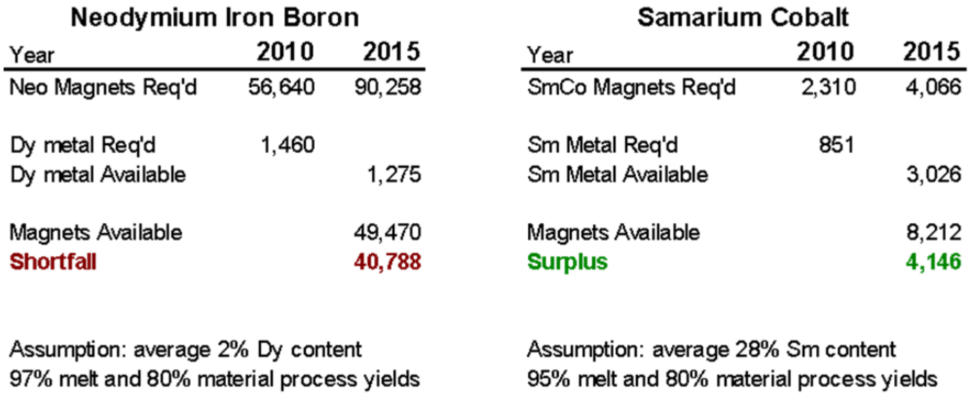
Curtailment of the black market

Addiitional mine output

What is the Rare Earth Shortage?

If dysprosium supply could keep up with total RE demand, in 2015, the market would use over 90,000 tons of neo magnets as noted in Table 6. The constrained dysprosium supply will, based on current and future known producers, allow approximately 50,000 tons to meet requirements. That is a shortfall of 41,000 tons of neo magnets.

Table 6: Rare Earth Shortage?



Neodymium Iron Boron

Year	2010	2015
Neo Magnets Req'd	56,640	90,258
Dy metal Req'd	1,460	
Dy metal Available		1,275
Magnets Available		49,470
Shortfall		**40,788**

Assumption: average 2% Dy content
97% melt and 80% material process yields

Samarium Cobalt

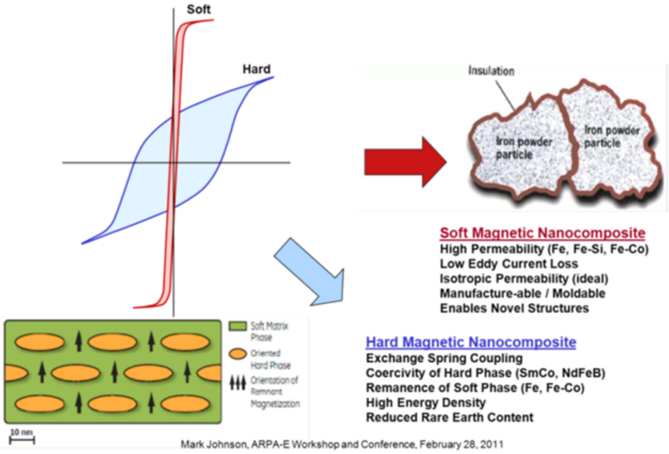
Year	2010	2015
SmCo Magnets Req'd	2,310	4,066
Sm Metal Req'd	851	
Sm Metal Available		3,026
Magnets Available		8,212
Surplus		**4,146**

Assumption: average 28% Sm content
95% melt and 80% material process yields

On the other hand, there is a surplus of samarium. With current and forecast mine output, more than double the current SmCo production could be supplied.

Nanotechnology

Mark Johnson of ARPA-E summarized R&D of magnetic materials by highlighting five areas under each magnetic material type as seen in Figure 18. DOE and other government agencies are stimulating, coordinating and funding research into improved materials.



Soft Magnetic Nanocomposite
High Permeability (Fe, Fe-Si, Fe-Co)
Low Eddy Current Loss
Isotropic Permeability (ideal)
Manufacture-able / Moldable
Enables Novel Structures

Hard Magnetic Nanocomposite
Exchange Spring Coupling
Coercivity of Hard Phase (SmCo, NdFeB)
Remanence of Soft Phase (Fe, Fe-Co)
High Energy Density
Reduced Rare Earth Content

Mark Johnson, ARPA-E Workshop and Conference, February 28, 2011

Figure 18: Nanotechnology Breakout

Research & Development

There are basically five approaches to the research and development of a resolution to the rare earth crisis. The first is enhance Alnico which involves improving the metallurgical processing of Alnico in order to improve its overall magnetic properties in a way that it is comparable to some of the lower grades of SmCo and NdFeB magnets. The second is to invent a New Magnetic Phase that uses less rare earth content but still maintains the desired magnetic properties of today's magnets. The third involves research into Nanotechnology which may be able to produce strong magnets by building them at the atomic level using less rare earth material. The fourth includes research into Diffusion Coating which may allow for a material to be coated and heat treated with a thin layer of high coercivity magnetic material. The fifth and final area involves the development of Layering Techniques which would use thin layers of magnetic material to achieve enhanced properties.

Active projects as of March 13, 2010 include:

> **Permanent Magnet Development for Automotive Traction Motors:** Ames Lab multiyear project funded by Vehicle Technologies Program at DOE; Collaborators are Magnequench, Arnold Magnetic Technologies, Baldor, UW-Madison, GM, GE, Synthesis Partners.
>
> **Beyond Rare Earth Magnets (BREM):** Ames Lab 5 year EERE project funded at $10 million; Project partners are Ames Lab, ORNL, U. Maryland, UNL, Brown Univ., Arnold Magnetic Technologies; Technology Advisors are Baldor, UW-Madison

High energy Permanent Magnets for Hybrid Vehicles and Alternative Energy: U. Delaware, 3 year DOE Vehicle Technologies Project funded at $4.4 million; Participants are U. Delaware, Ames Lab, UNL, NEU, VCU and EEC

Transformational Nanostructured Permanent Magnets: GE, $2.25 million funding from DOE

Summary

Powder Metallurgy has been and continues to be an essential manufacturing method for magnetic products. Rare Earth Magnets represent essential products for the commercial marketplace and for defense industries. Demand for rare earth magnets is growing at double digit annual rates both in the USA and around the world. For some applications there is no practical alternative. However, alternative technologies will be employed where cost and availability dictate and performance, size and weight permit them to be used. Sophisticated powder technology processing may hold the solution to the current shortfall in supply of critical magnetic materials