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The Demand for Rare Earth Materials in Permanent Magnets

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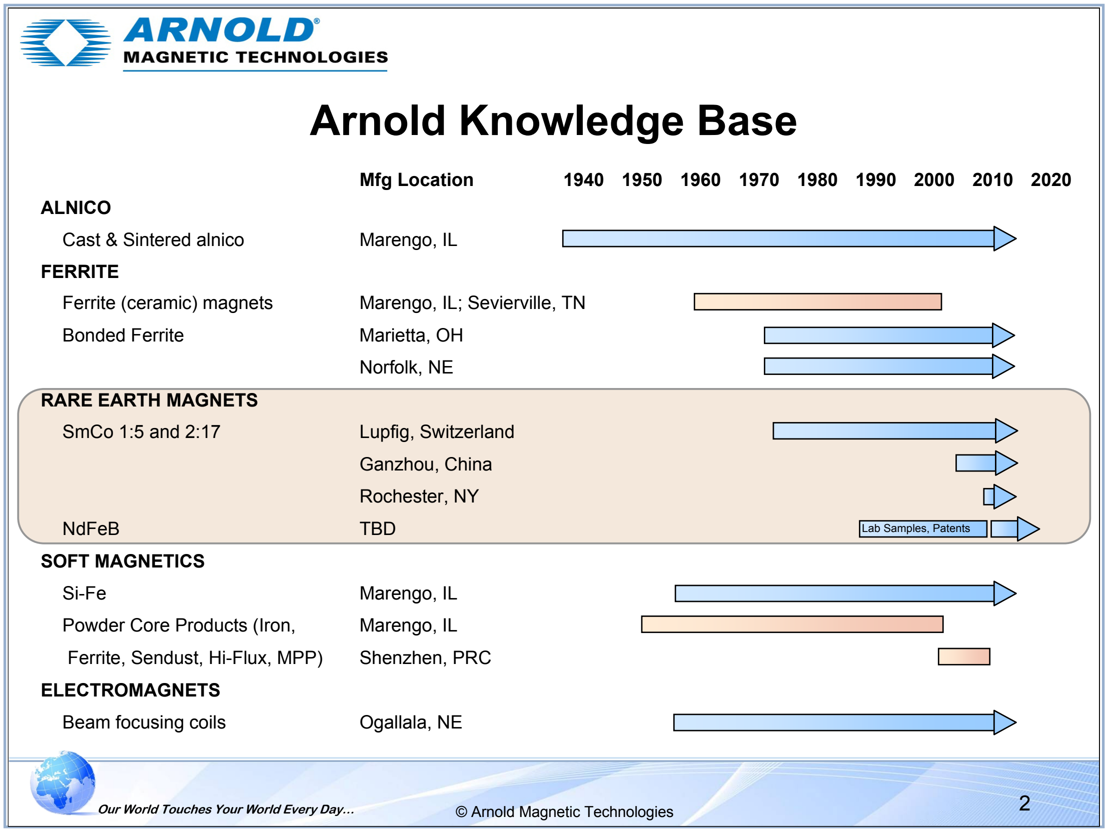
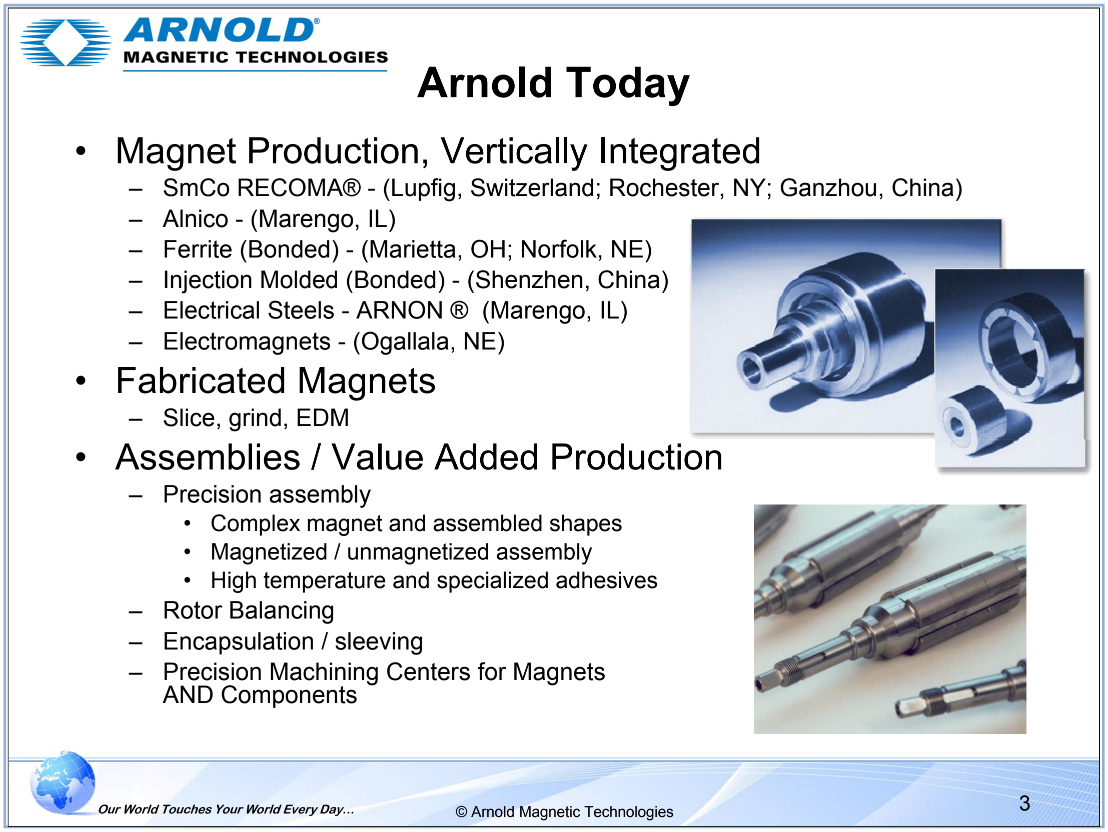
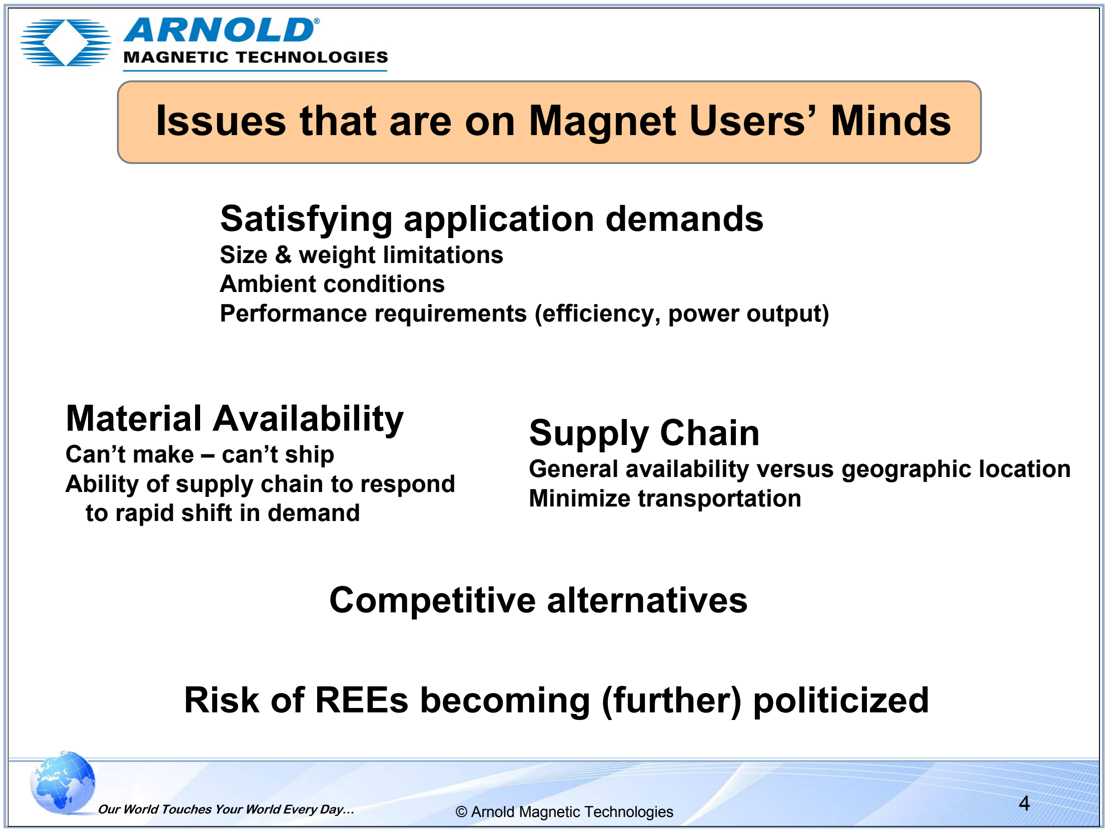


- A brief introduction to Arnold Magnetic Technologies for those who are unfamiliar with us.
- Arnold has been in business since 1895 and has manufactured magnetic products since 1939, starting with Alnico.
- We're one of the larger producers of SmCo with factories in Switzerland and China.
- We've made Neo magnets in the lab since 1985 with the most recent occasion being in September of 2012.



- This is a summary of the businesses conducted at Arnold’s 10 factories.
- It includes partial or full integration of manufacture of a number of magnetic materials, but excludes Neo due to no new licenses being issued.



- To understand the rare earth magnet market it is necessary to view it from the users' perspective.
- In particular, what have been the important issues of the last two+ years?

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Agenda

- What makes a good magnet?
- What are rare earth permanent magnets?
- Applications for rare earth magnets
- Rare earth magnet market
  - Sales and material supply
  - The dysprosium issue
- Raw material prices
- Magnet R&D

A lot of information…

…just a little time.

- These are the topics we'll cover today.
- Before we delve into the specific rare earth magnet applications, it will prove helpful to have a basic understanding as to what makes a magnet desirable to use.
- There is much to cover in very little time – so it will be a bit like "drinking water from a fire hose".
- A full copy of the presentation with notes is available by e-mailing the author.

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What makes a magnet *good*?

Requirements depend upon the application

- Flux density (Br)
- Energy Product (BHmax)
- Resistance to demagnetization (Hcj)
- Usable temperature range
- Magnetization change with temperature (RTC)
- Demagnetization (2^{nd} quadrant) curve shape
- Recoil permeability (minimal - close to one)
- Corrosion resistance
- Physical strength
- Electrical resistivity
- Magnetizing field requirement
- Available sizes, shapes, and manufacturability
- Raw material cost and availability

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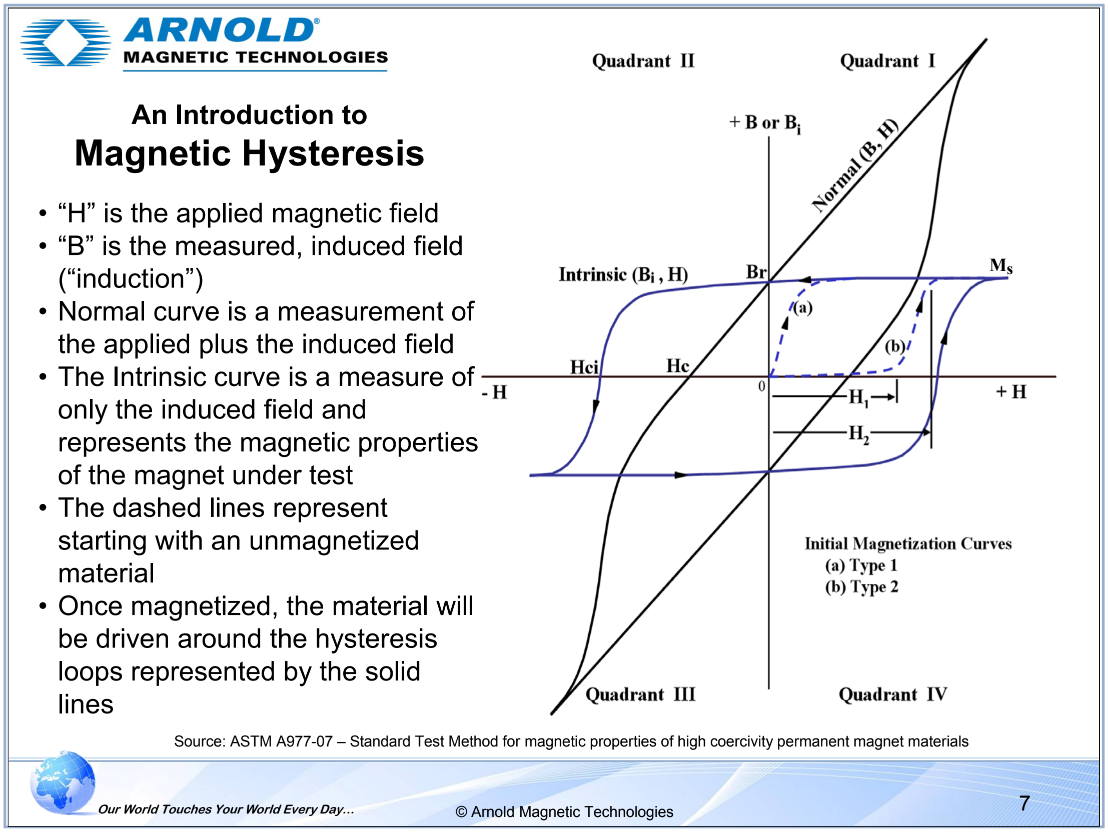
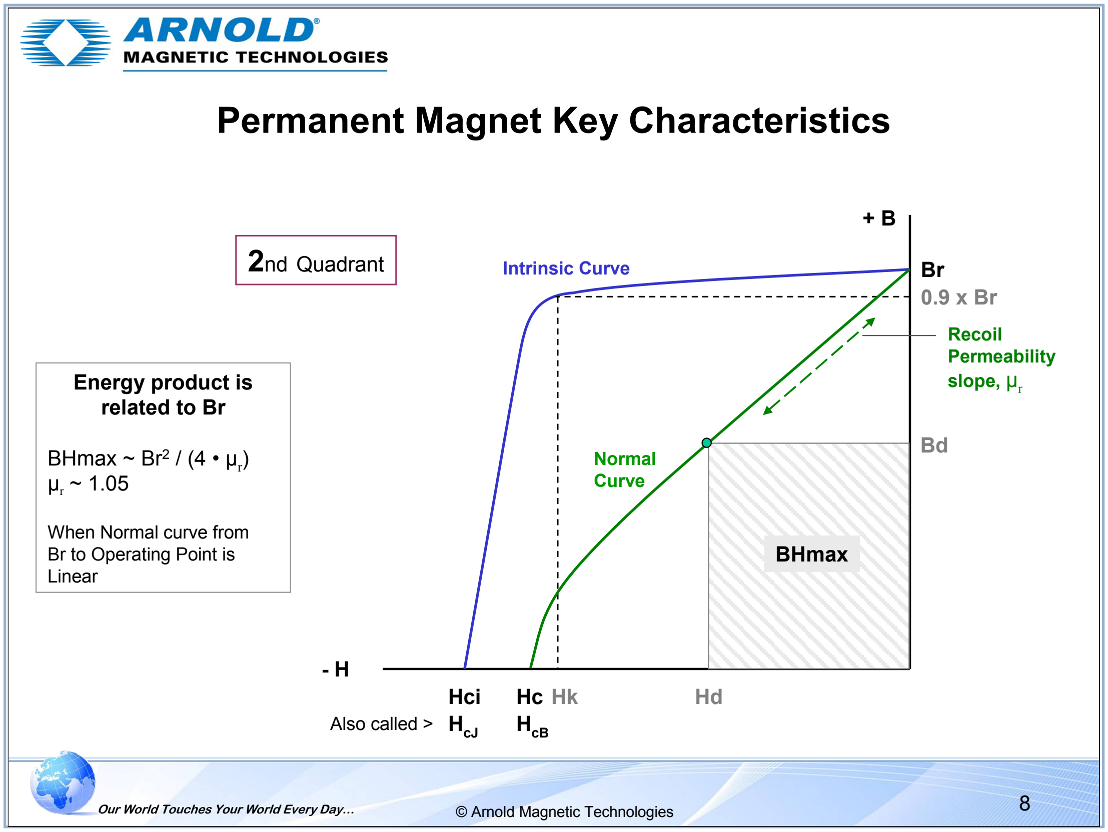
- For each application that uses a permanent magnet a subset of these characteristics will determine how well each type of magnet is suited to the application.
- Implicit in commerce is that the manufacturing cost (and selling price) of the magnet must also be economically practical.
- All of these characteristics (and probably some additional ones) should be considered when performing Product Development and R&D.



- Magnetic materials respond to an externally applied magnetic field by developing an internal field – an induced field.
- As we apply a stronger field in one direction (+H), weaken it and apply it in the opposite direction (-H) we cause the internal field to respond accordingly.
- If we plot the applied field (H) versus the induced field (B), we have what is called the hysteresis loop of the magnetic material.
- We measure the combination of applied and induced field and represent it with the "Normal Hysteresis Loop".
- When we subtract the magnitude of the applied field from the combined field, the result is the "Intrinsic Hysteresis Loop".
- As we cycle the magnet around the hysteresis loop, we see that the 1st and 3rd quadrant are identical, though of reverse sign just as the 2nd and 4th quadrants.
- The dashed lines display initial magnetization.
- When initially magnetizing the sample, the Type 1 and Type 2 shown in this chart refers to the coercivity mechanism where Type 1 coercivity is due to a "nucleation" mechanism and Type 2 is caused by domain pinning.



- For permanent magnets, we are primarily interested in the 2nd quadrant.
- This illustration is typical of the "demag" curves presented in product literature for ferrite, SmCo and Neo magnets.
- The key figures of merit for permanent magnet materials are indicated on this chart.
- The maximum energy product can be estimated from just the Br as shown in the equation – assuming an appropriate value for recoil permeability.
- Conversely, the Br can be estimated when the maximum energy product is known.
- As shown here, this material would be considered a straight line (Normal curve) or square loop (Intrinsic curve) material since the Normal curve is straight (at least to the maximum energy point).

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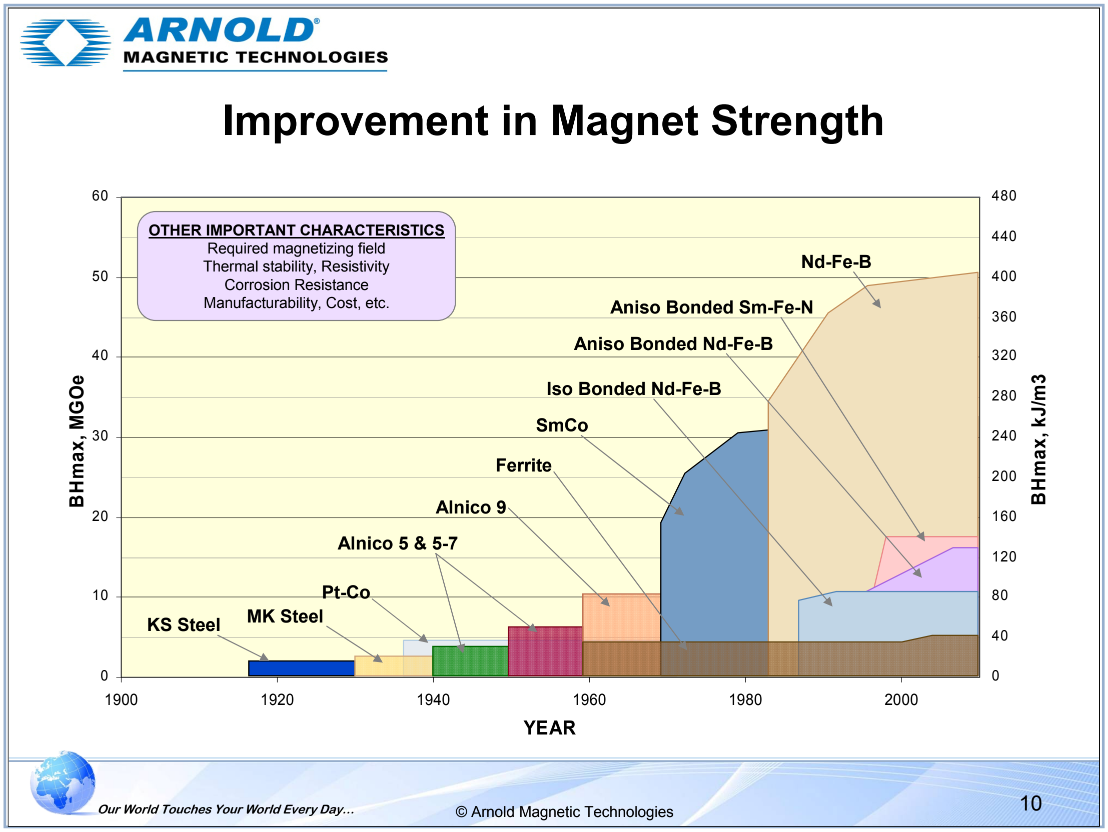
Permanent Magnet Development Timeline

- Permanent Magnets have been developed to achieve
  - Higher Br and Energy Product (BHmax)
  - Greater resistance to demagnetization (Hci)
- Most are still in production
  - Exceptions
    - ***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 it's high material cost*

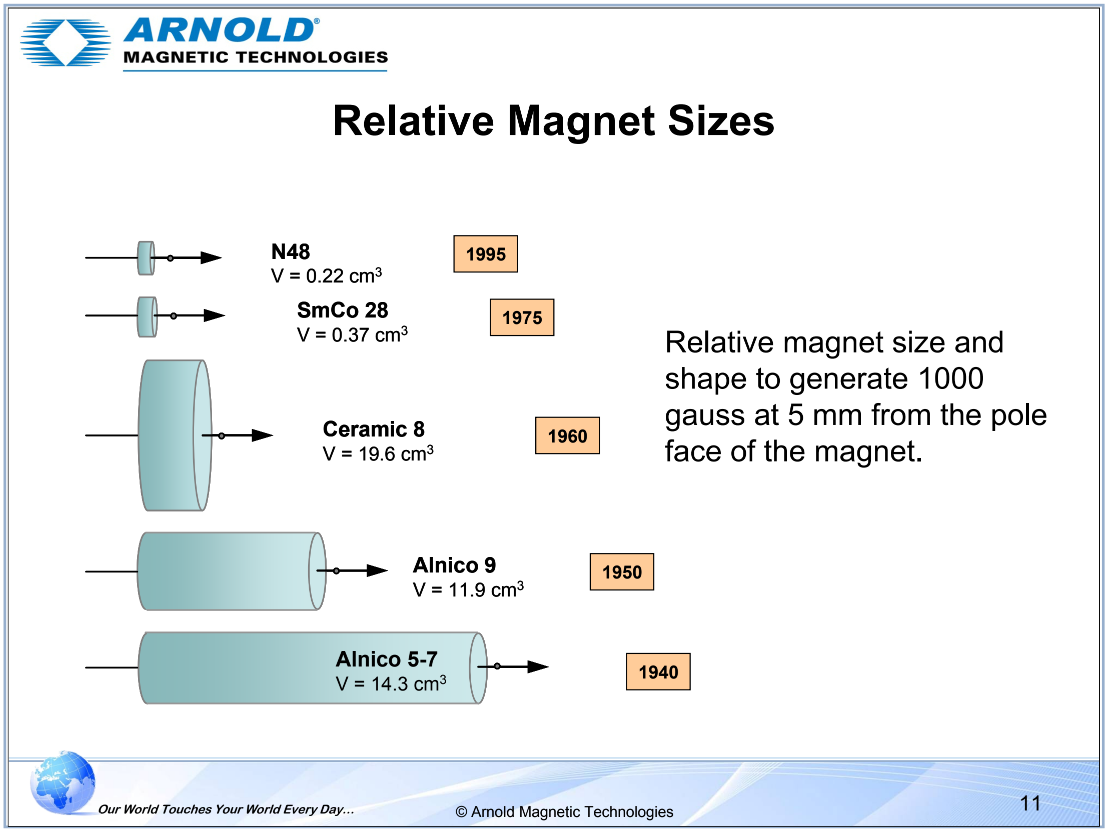
Material	First Reported	BH(max)	Hci
Remalloy	1931	1.1	230
Alnico	1931	1.4	490
PtCo	1936	7.5	4,300
Cunife	1937	1.8	590
Cunico	1938	1.0	450
Alnico, field treated	1938	5.5	640
Vicalloy	1940	3.0	450
Alnico, DG	1948	6.5	680
Ferrite, isotropic	1952	1.0	1,800
Ferrite, anisotropic	1954	3.6	2,200
Lodex®	1955	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

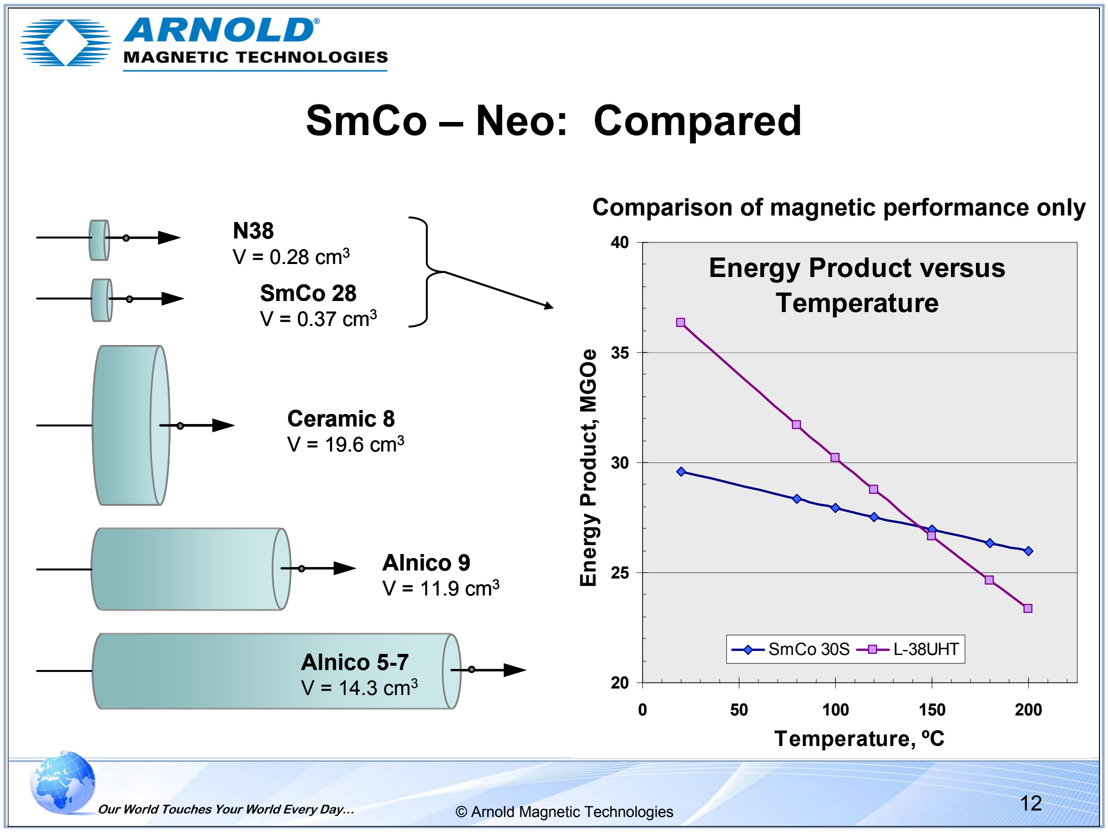
- What materials were used in motors prior to the discovery of the rare earth magnets?
- Prior to the discovery of Alnico and similar alloys in the 1930's, the materials used fell into a category called cobalt steels having high remanence (Br), but very low coercivity - values of 150 Oersteds being common.
- During the 1900's great strides were made in the development of improved permanent magnets as shown in this table.
- The first greatly enhanced and widely used commercial permanent magnet material was alnico starting in the late 1930's.
- This was followed by Ceramic (Hard Ferrite) magnets starting in 1954.
- Increased values of both maximum energy product (BHmax) and resistance to demagnetization (Hci), were made culminating with the rare earth magnets: SmCo and "Neo" magnets ($RE_2TM_{14}B$).



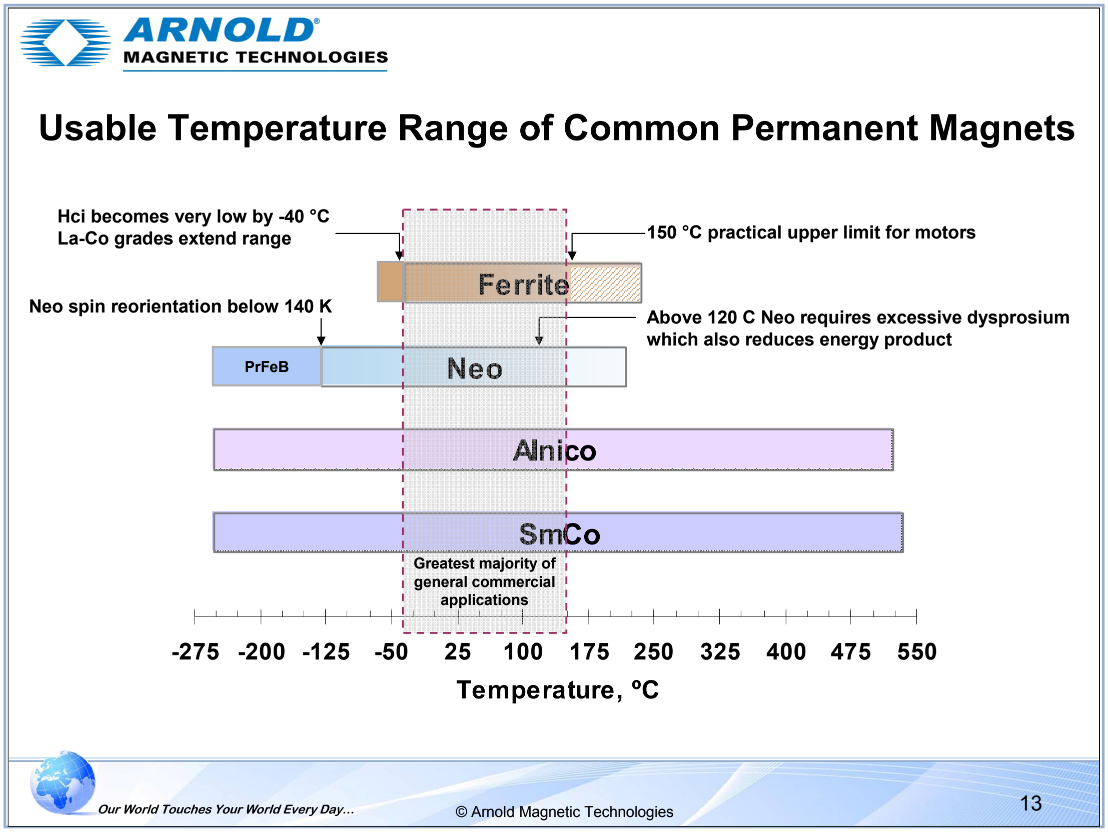
- We often present the improvement in energy product in charts such as this – it's visually more eye-catching.
- Please note that all the products shown are still used to some extent.
- Each material has a unique combination of properties that makes it well-suited to certain applications.
- This is suggested by the note in the upper left of the chart indicating that many other characteristics must be considered.
- Recall the earlier slide where we showed many characteristics that should be considered when deciding whether a permanent magnet is "good."
- Nevertheless, the huge gains in energy product have been an enabling technological breakthrough.



- The improvements in energy product that have facilitated modern applications can be pictorially demonstrated.
- The "V" under each product name is the magnet volume. For example, an N48 magnet with a V of 0.22 cubic centimeters provides the same magnetic field strength (magnetic field density) near the pole as a ceramic magnet that is 89 times larger.
- 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.



- Another consideration is temperature.
- The fields associated with magnets change as temperature changes
- Some materials change faster than others.
- Alnico is quite stable. Ferrite magnetic flux changes very quickly.
- SmCo is more stable than Neo. This is shown in the chart indicating that the very strong Neo magnet becomes weaker faster than the SmCo material and above a temperature of about 150 °C the SmCo material is stronger.



- There are limits to the maximum and the minimum temperatures that magnets can withstand.
- Thus, another key characteristic in selecting the best magnet is the expected temperature range of the application.
- We note here that both Neo and ferrite magnets have a more limited useful temperature range.
- 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.
- This is a very important point about which we'll speak further.
- Ferrite can be theoretically used to over 350 ºC. However, even by 150 ºC, it loses 25% of its flux output.
- And ferrite, unlike the others shown here, is ferrimagnetic (not ferromagnetic). Coercivity (resistance to demagnetization) decreases as temperature drops creating a practical minimum application temperature around -40 °C.

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- Now that we have an idea of what a permanent magnet is and how we measure their characteristics, let's focus on the rare earth magnets.

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What are the rare earth magnets?

- $SmCo_5$
  - Sintered (powder metallurgy)
- Sm_2Co_{17} – actually $Sm_2(CoFeCuZr)_{17}$
- Neo (neodymium iron boron)
  - Powder for bonded magnets: compression, extruded, injection molded
  - Sintered (powder metallurgy)
  - Hot rolled (no longer made): modified composition; Seiko-Epson
  - Die-upset / forged, fully dense: Magnequench MQ-3 process (original and modified); Daido Electronics
- SmFeN
  - Powder metallurgy process resulting in a fine powder suitable for bonded magnets
  - Unstable above ~450 °C – no known method for achieving a fully dense magnet

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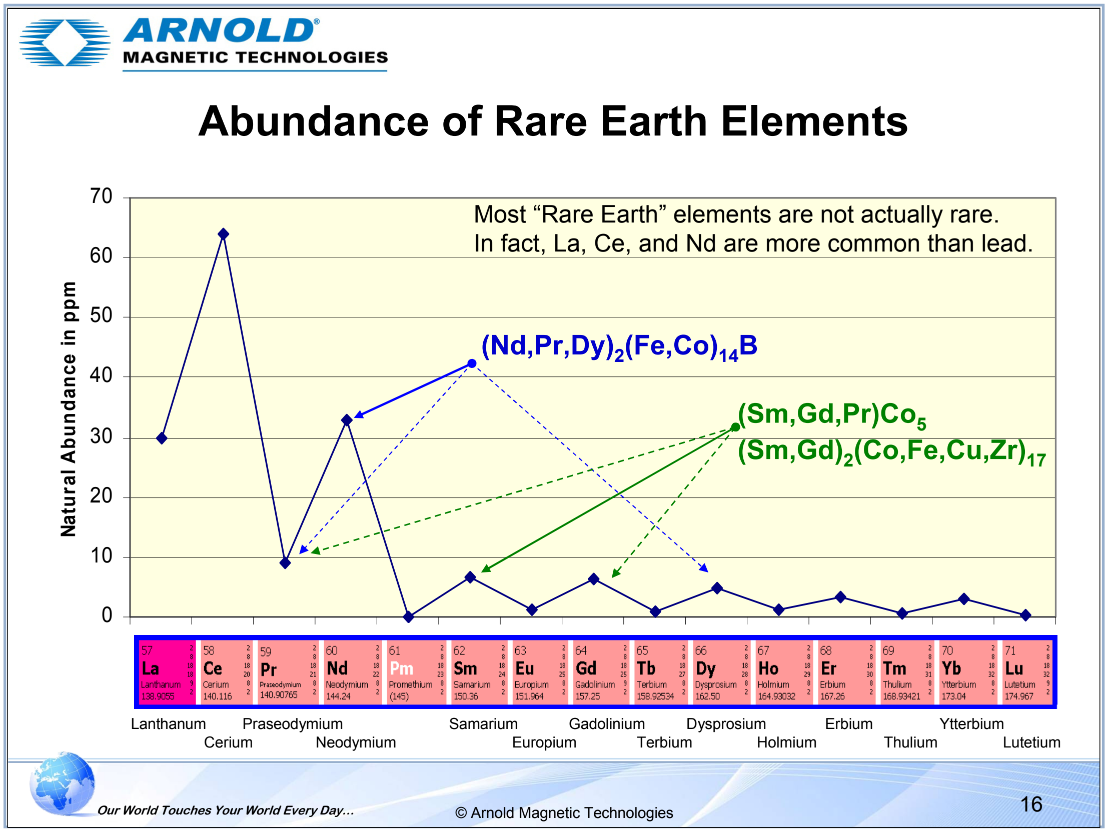
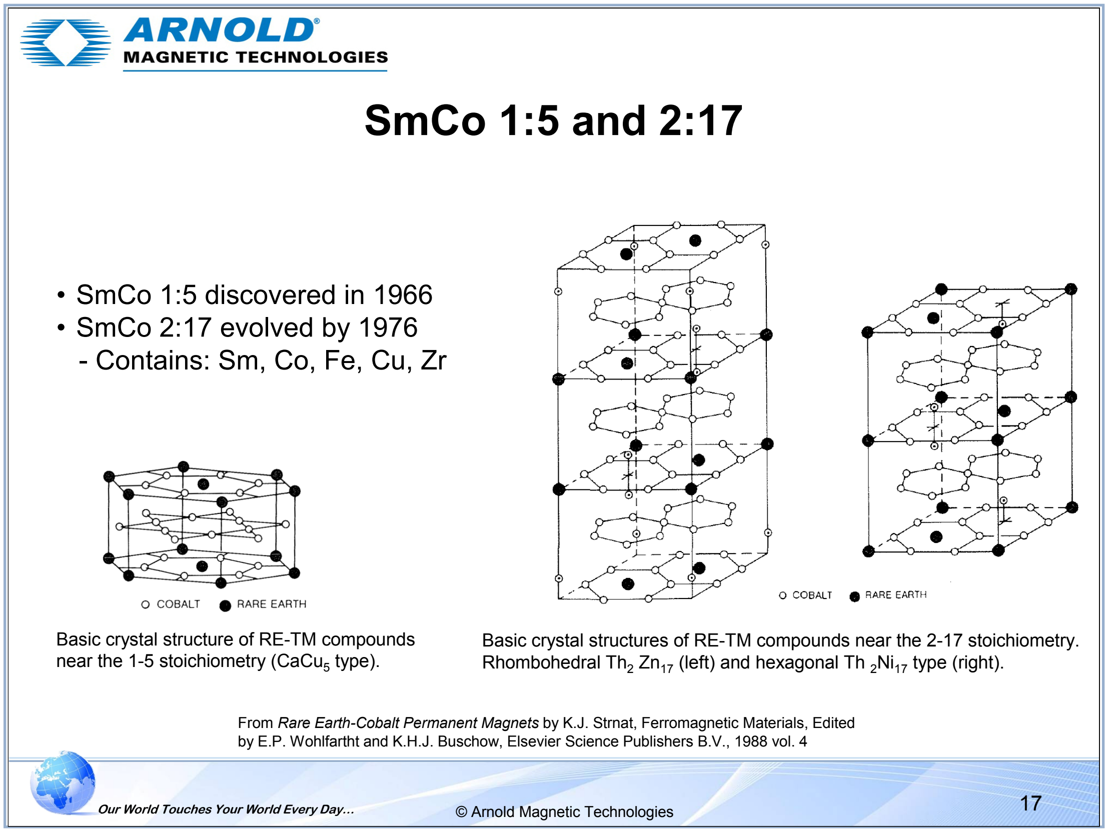
- Except for the powder made via rapid quenching and used in bonded magnets, these materials exhibit uniaxial crystalline anisotropy. That is, if the fine powders are oriented during manufacture so that the magnetic domains align, then the magnetic output is greatest.
- Rapidly quenched neo powder freezes-in random domain orientation resulting in an “isotropic” material structure.
- This structure 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 Br (Residual Induction) of about 64% of the fully oriented (anisotropic) material.
- Since energy product is proportional to the square of Br, it is, at most, about 0.64 x 0.64 = 41% of the anisotropic, oriented alternative materials.
- Anisotropic powder for bonded magnets is available as made via HDDR, a process utilizing hydrogen to decompose the Neo material and reconstitute it in anisotropic form.
- In the 1980’s Seiko-Epson developed a modified composition and process for hot rolling Neo. This was suitable for watch magnets.
- Magnequench developed a process for densifying Neo via hot-pressing. This generated what they called MQ-2 and MQ-3 magnets. The technology was licensed to other companies with Daido being the one remaining company to produce this type of product.
- The great majority of Neo has been and still manufactured by powder metallurgy.
- About 1990, researchers at the University of Dublin, Trinity College, converted SmFe with planar structure into a crystalline form with anisotropy by treating the material with nitrogen gas – the nitrogen being interstitial, not chemically reacted with the alloy.
- This resulted in a material with excellent magnetic properties. However, as lattice vibration increases with rising temperature, there is a point at which the nitrogen atoms can escape from the lattice allowing reversion to the planar isotropy.
- Numerous other rare earth-based alloys have been formulated for the purpose of making permanent magnets, but these are the only ones to have measurable commercial presence.



- The main constituents of rare earth magnets are shown in the formulae (only the Lanthanides are displayed) with arrows pointing to the chart data points indicating the elements' natural abundance.
- We see from the chart that Dy is only about 11% of the abundance of Nd+Pr.



- The crystal structure of SmCo magnets is fairly complex.
- During the 1950's and 1960's research was conducted on rare earths in combination with various transition metals such as iron, nickel, cobalt, and manganese.
- Widespread interest in RCo compounds seems to date from 1966, when Hoffer and Strnat of the Air Force Materials Laboratory reported that YCo_5 had a high anisotropy constant. (B.D. Cullity)
- Attempts to increase the Br and energy product through the addition of iron were only marginally successful until additional elements, copper and a heavy transition metal such as zirconium, were added.
- Neither of these compositions (1:5 and 2:17) would have been considered exceptional if it were not for the optimized thermal treatment for sintering, solution treatment and post-sintering heat treatment (temper or anneal).
- In SmCo 2:17, for example, Strnat teaches us that the final aging treatment from 850 to 400 ºC develops the intrinsic coercivity and "loop squareness". Cooling must take place slowly and optimal coercivity depend on duration of the hold at 400 °C.

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$Nd_2Fe_{14}B$

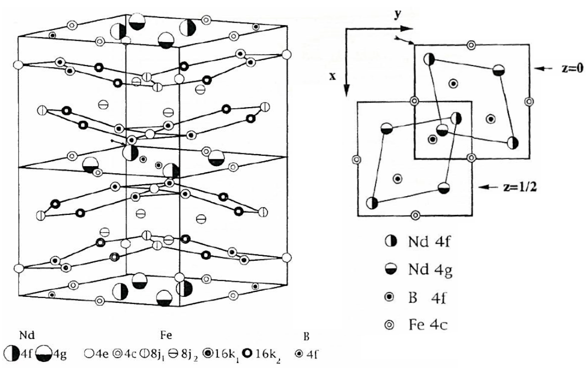


Figure 5.24. The crystal structure of $Nd_2Fe_{14}B$. A view looking down the tetragonal axis is shown on the right.

Permanent Magnetism, R. Skomski and J.M.D. Coey, IoP Publishing, 1999

Numerous labs were working on combinations of rare earths and iron (or cobalt), but it was Norman Koon at NRL who first added boron and obtained permanent magnet properties. The Navy filed for and received the first three patents on Neo.

This alloy might better be called RE•TM•B due to the large degree of substitution possible.

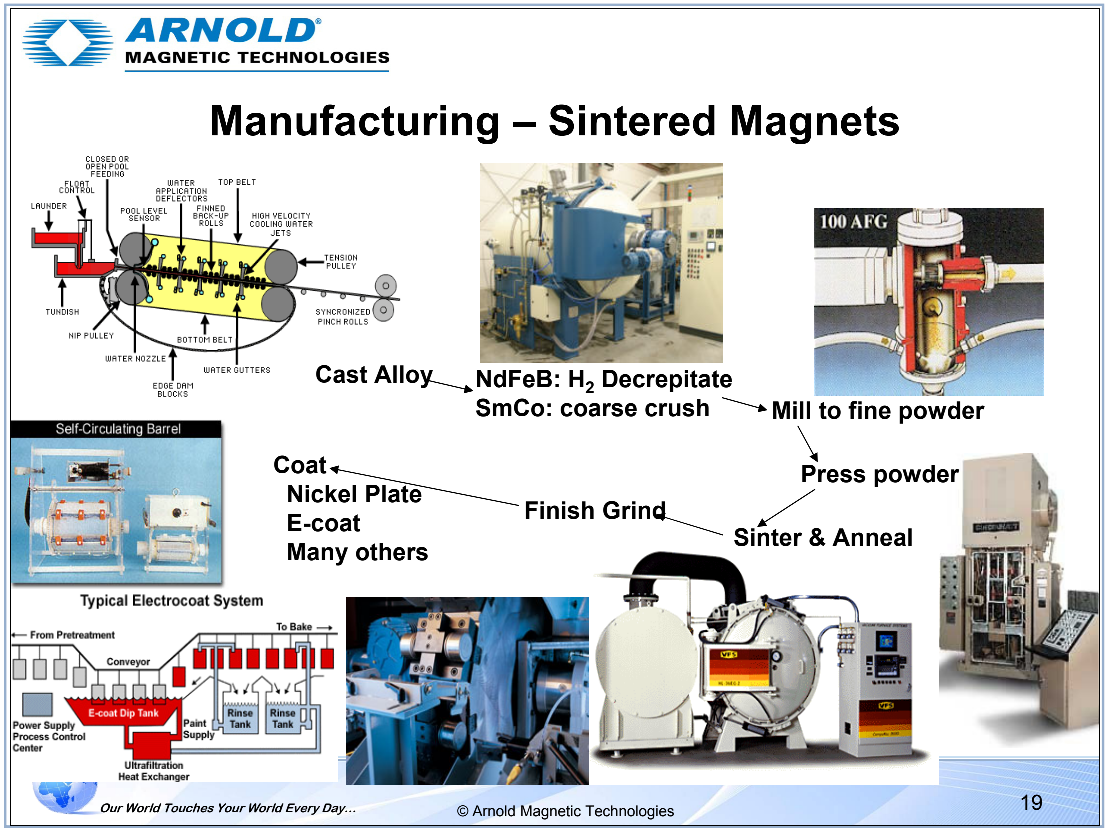
RE: Nd, Pr, Dy, Tb, Gd

TM: Fe, Co, V, Ti, Mo, Zr

Boron is not normally substituted for by other elements, though a carbon compound can be formed with substantially lower Hcj.

A grain boundary phase can also contain: Al, Ga, Cu.

- Although likely to be discovered through Edisonian methods (many trials and much hard labor), Neo was actually the result of a fortuitous accident.
- The story was related to me by Norm Koon in 1993 and later corroborated by Vince Harris of Northeastern University who also worked at the Naval Research Laboratories starting shortly after the discovery.
- Norm was seeking a “better” soft magnetic material by combining rare earth elements and transition metals, predominantly iron.
- Thinking that an amorphous structure might be beneficial, Norm added a small amount of boron, a well recognized “glass-former” and melt-spun the alloy.
- Melt spinning is a process which quenches the material – cooling it at a rate of about one million degrees per second.
- When measured, the alloy powder had remarkable hard magnetic properties – even without composition or heat treatment optimization.
- Optimization and commercialization was left to industry.
- The two companies to rapidly commercialize the material were Sumitomo Special Metals Corp (Musato Sagawa, Japan) and General Motors (John Croat, US).
- Eventually these two companies would cross-license the compositions and technologies and license other companies to make Neo magnets.
- In each of these examples, SmCo and Neo, it is hard to imagine starting with individual atoms and constructing the crystals in such a way as to produce such beneficial properties.



- The powder metallurgy process for making Neo and SmCo magnets is the same with only minor differences. Recall that while this is the predominant method used, other methods are also used, namely bonded magnets and die-upset.

The powder metallurgy manufacturing process consists of:

- Casting the alloy (paddy cast, book mold or strip cast as shown here)
- Hydrogen decrepitation (HD) for Neo to make milling easier and faster – SmCo is sufficiently frangible that HD is not necessary
- Fine particle milling (~3 microns in diameter for Neo and 4-5 microns for SmCo, FSSS equivalent spherical diameter).
- Compaction via hydraulic, mechanical or isostatic pressing, or a combination. Powder is magnetically aligned prior to or during compaction.
- Sintering, solutionizing and annealing (aka tempering)
- Grinding (poles and sometimes the perimeter of magnets), slicing, hole drilling, EDM machining, etc to achieve final shape and dimensional control.
- Coating (plating, e-coat, epoxy, etc.) to improve corrosion resistance and chip resistance.

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- Where are the rare earth magnets used?
- Why are they so important?
- Why is there such a fuss over supply of the raw materials?

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Rare Earth Magnet Applications
and RE 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**	4,117	79	14.4%	**14,040**	7,101	136
Electric Bicycles	9.1%	**5,680**	2,549	379	8.2%	**7,955**	3,570	531
Transducers, Loudspeakers	8.5%	5,290	2,609	118	6.5%	6,322	3,118	141
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**	29,046	3,039	100.0%	**97,296**	44,761	5,392

Nd: 54% increase
Dy: 77% increase

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

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- A break down of applications with approximate percentages of rare earth magnets going into each is shown here.
- 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. Product roll-outs have been delayed, new designs are being re-evaluated to use alternate magnet materials and alternate technologies without permanent magnets are being investigated and utilized.
- You can imagine that this makes forecasting very difficult.
- Note too that the change in magnet usage 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% - assuming adequate material is available.
- To understand the market dynamics better, let's look at a few specific applications – those in bold face in the table.

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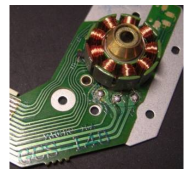
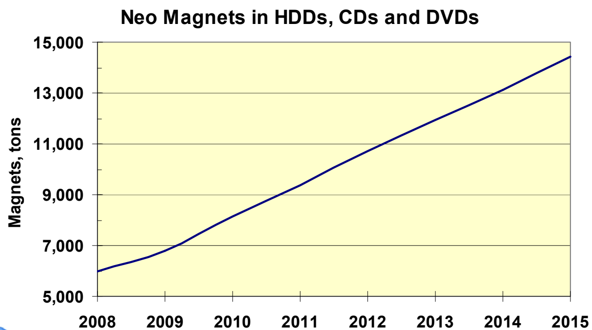
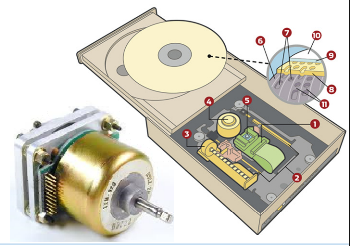
Hard Disk Drives (HDD's), CD's, DVD's

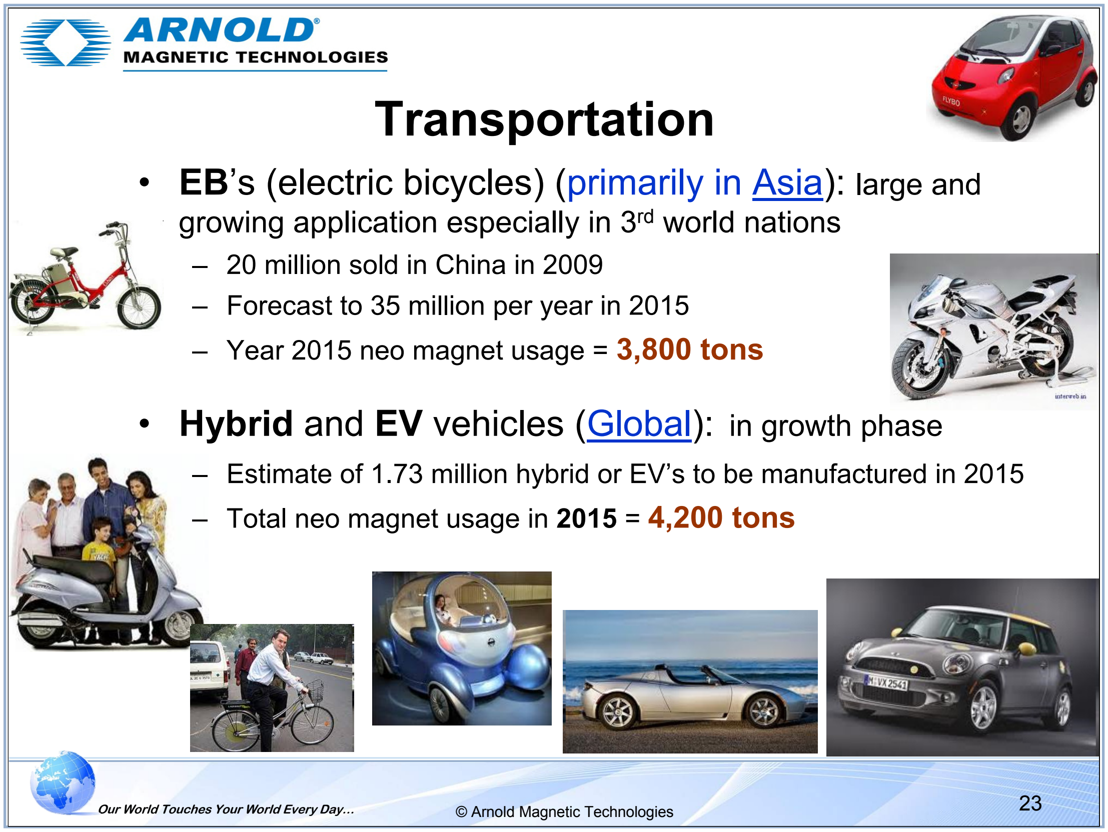
- Drives (Global): existing and growing market
  - Overall drive shipments for 2008 would total 593.2 million units, up 14.9% compared to… 2007 (iSuppliCorp: www.isuppli.com)
  - Shipments of HDDs alone in the first half of 2011 were 327.6 million, on track for 660 million by year's end



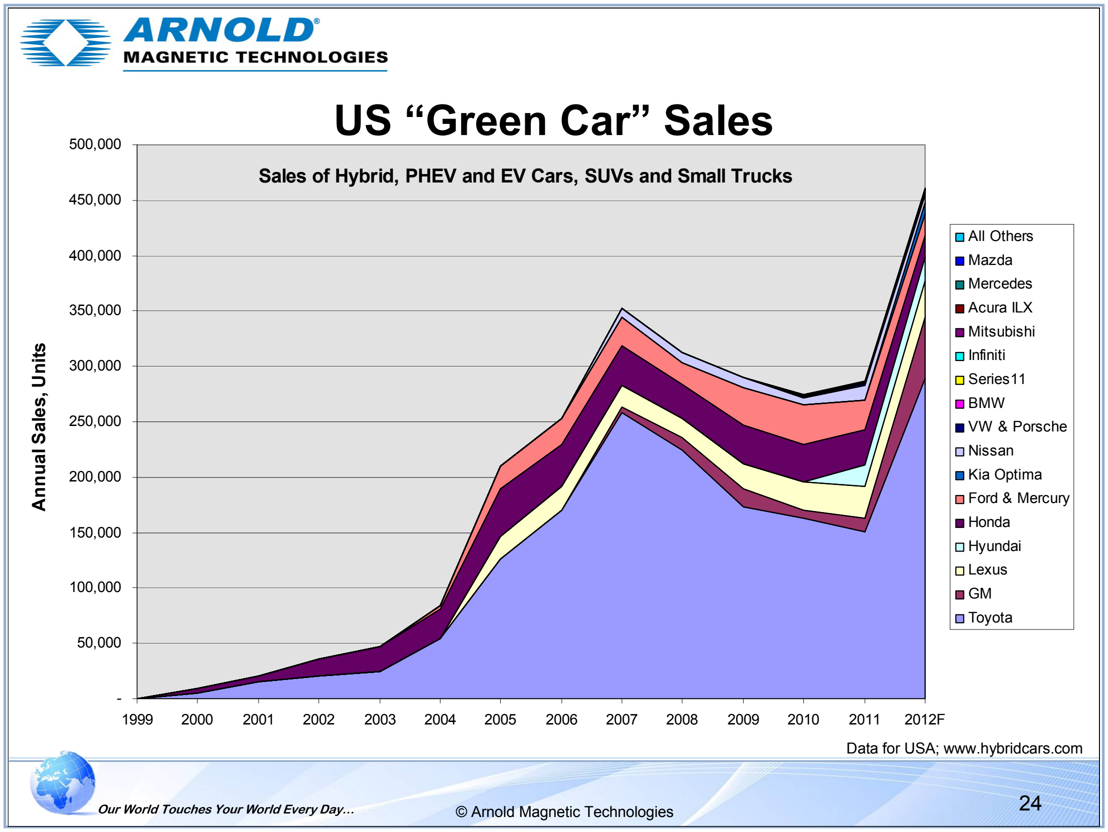




- One of the main uses for rare earth magnets, predominately neo, is in electronic devices such as hard disk drives, CDs and DVDs where the magnet is used for driving the spindle motor, for positioning the read/write head, and providing a clamping force (in some CDs and DVDs).
- Even though the amount used per drive is small, the huge quantity of devices requires large amounts of rare earth magnets.
- Importantly, these devices use no or very low dysprosium.



- Hybrid and full electric vehicles are becoming increasingly more common in the US and Europe and there is also a strong push for them in China.
- However, 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 and India.
- Although the amount of magnet material per unit is small, the quantities of bicycles are large.
- And because the market is so diverse, it is difficult to assign an accurate average magnet weight per vehicle (80 grams is used here though estimates range from 60 for motor-boosted bicycles to over 350 grams for high power scooters).
- Intermediate dysprosium levels (~4-5%) are required in the motors for electric bikes.
- High dysprosium (~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 estimates in the US, but other geographic regions are adopting faster. China, for example is mandating rapid EV adoption to reduce urban pollution.



- Forecast sales for 2012 based on sales through August are 461,250 units.
- 2011 and 2012 represent watershed years in that EV and PHEV sales have just started.
- Changes in consumer preferences are due in large part to price of gasoline and overall economic prosperity.

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Hybrid and PEVs

Sales in USA of Cars, SUVs, Small Trucks

	2011		2012 (YTD August)	
	Units	%	Units	%
Total Sales (units)	12,734,356		9,678,702	
Hybrid	268,807	2.11%	278,680	2.88%
PEV	17,813	0.14%	25,290	0.26%

Data for USA; www.hybridcars.com

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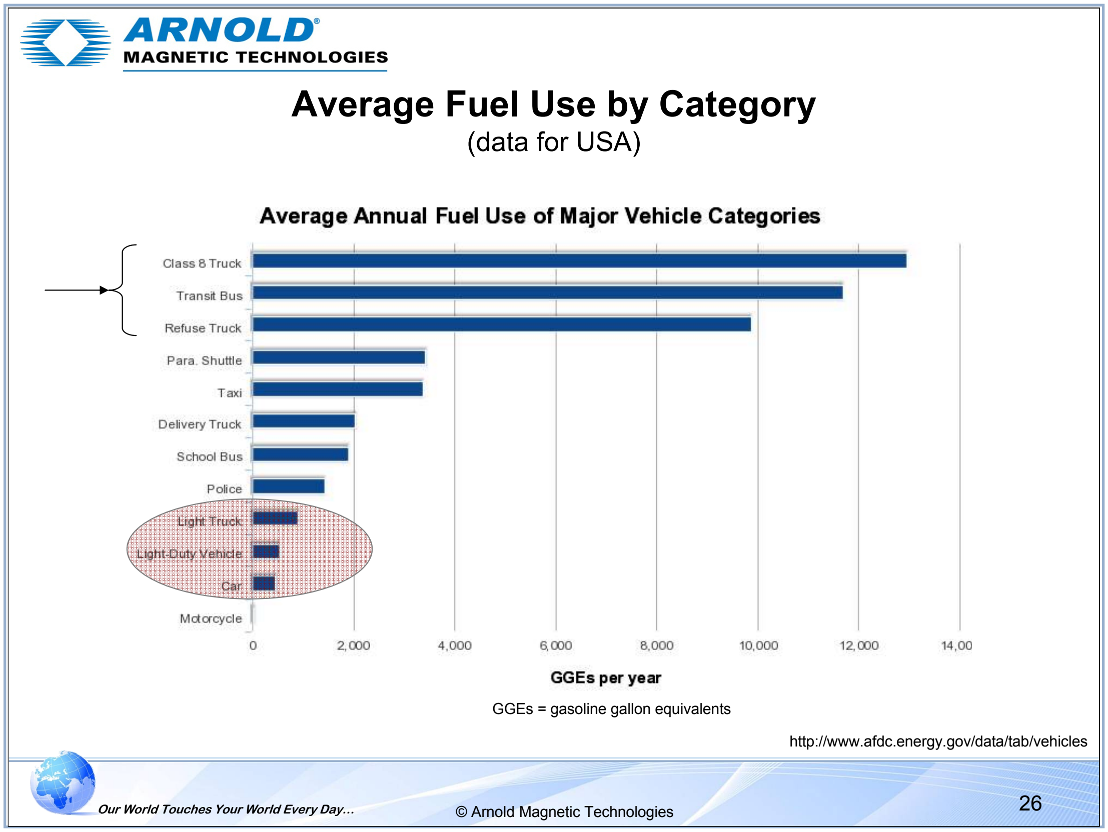
- EV sales as a percentage of overall sales in the USA is increasing.
- 2012 may end with EVs being over 3% of sales!



- However, we should note that additional market opportunities exist for EVs, especially in the stop-and-go performance of buses and garbage haulers.

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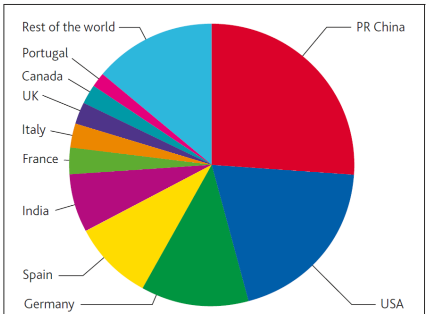
Wind Power Production

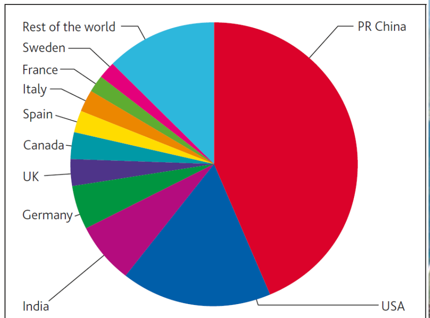
Top 10 cumulative capacity Dec 2011



Country	MW	% SHARE
PR China	62,364	26.2
USA	46,919	19.7
Germany	29,060	12.2
Spain	21,674	9.1
India	16,084	6.8
France**	6,800	2.9
Italy	6,737	2.8
UK	6,540	2.7
Canada	5,265	2.2
Portugal	4,083	1.7
Rest of the world	32,143	13.5
Total TOP 10	205,526	86.5
World Total	**237,669**	**100.0**

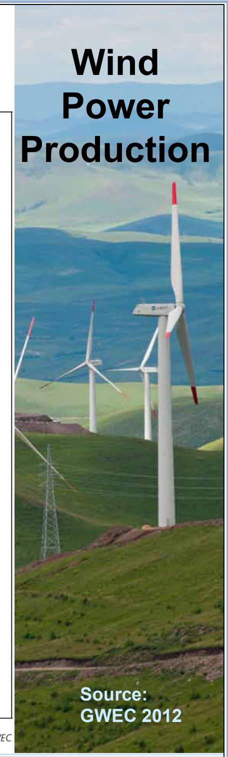
*** Provisional Figure* — *Source: GWEC*

Top 10 new installed capacity Jan-Dec 2011



Country	MW	% SHARE
PR China	17,631	43
USA	6,810	17
India	3,019	7
Germany	2,086	5
UK	1,293	3.2
Canada	1,267	3.1
Spain	1,050	2.6
Italy	950	2.3
France**	830	2.0
Sweden	763	1.9
Rest of the world	4,865	12.0
Total TOP 10	35,699	88
World Total	**40,564**	**100.0**

*** Provisional Figure* — *Source: GWEC*



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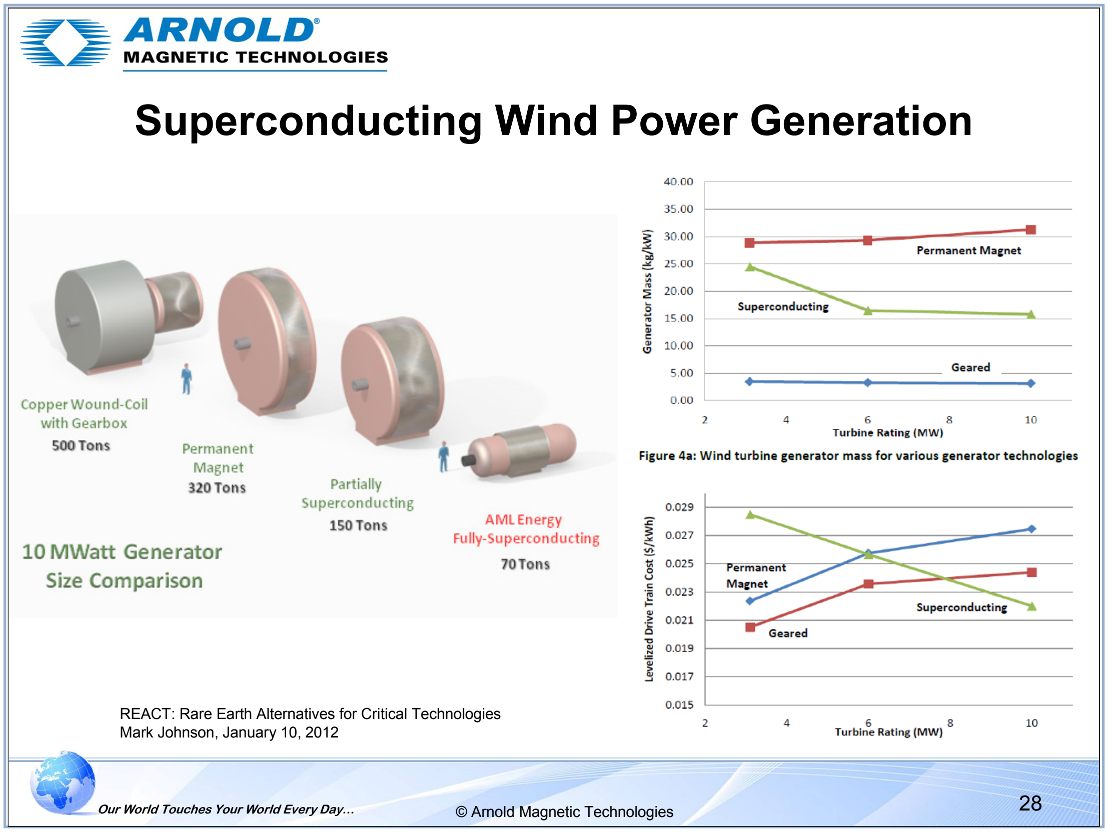
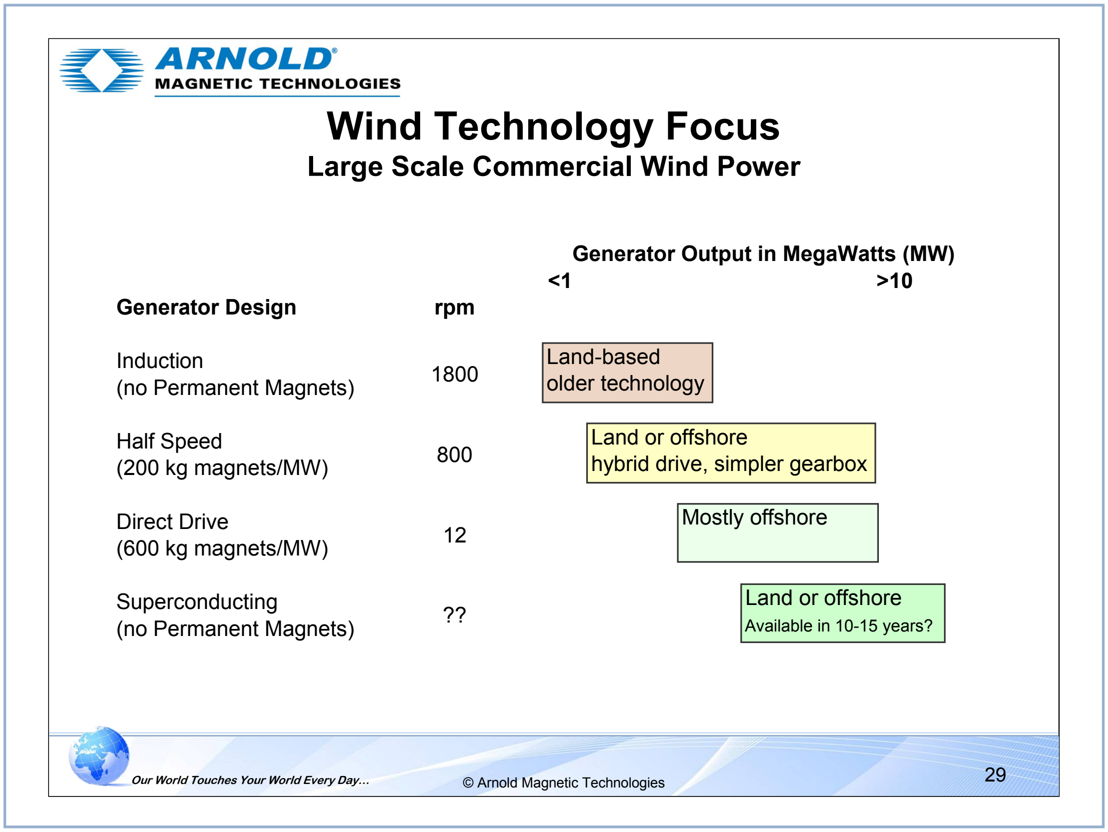
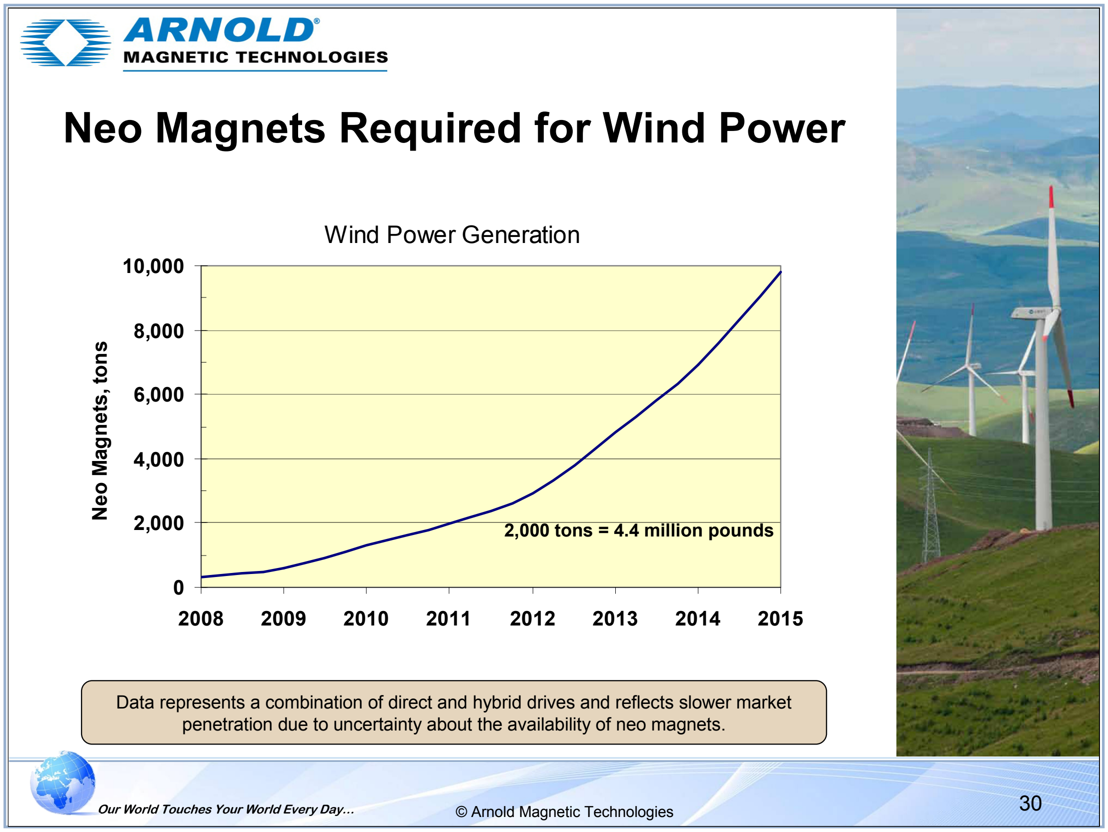
- This information about wind power was published in "2011: China Wind Power Outlook" by the Chinese Renewable Energy Industries Association (CREIA).
- Prior to 2005, China's wind power industry was close to non-existent.
- Since then it has grown rapidly and now cumulatively China has more wind power generation installed than any other country at 26.2% of global generation.
- In 2011 alone, China produced 43% of all installations world-wide with a substantial portion being Gen-4, permanent magnet generator type.
- Estimates of fraction PM type generators range from 25 to 95% with a consensus building at ~45%.
- Production and installation of wind generation in 2011 dropped noticeably from 2010 for a number of reasons.
- In China, conventional power production did not keep up with wind installations and the grid was not able to accept all new installations. It has also been reported that some of the installations are having operating problems – quality may have been compromised. As in the US, Chinese government subsidies/mandates have been reduced or dropped.
- 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 small fraction of overall generating capacity.
- In other words, the market is going through a shake out that will likely last through 2012.



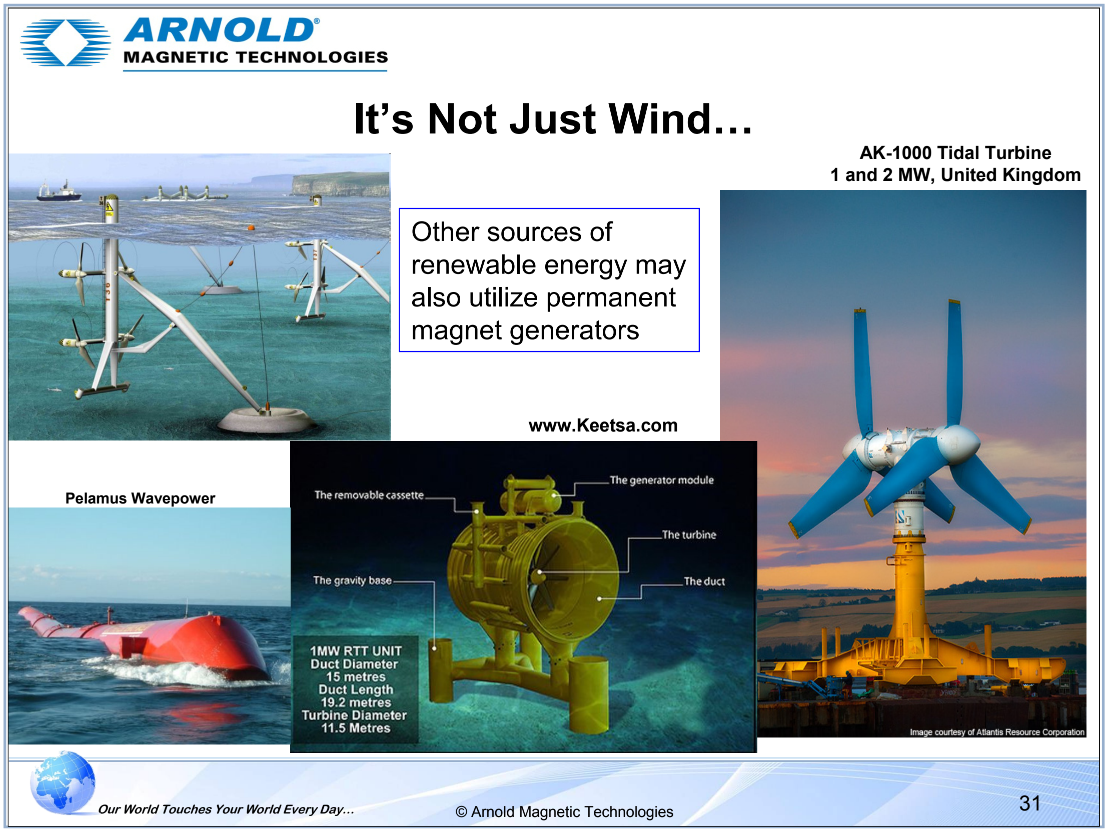
- Wind power generator type selection is a function of factors such as installed cost, operating maintenance costs, ease of maintenance, efficiency of power output, low speed cut-in and high speed cut-out, reliability, on-land versus off-shore, etc.
- Size and weight of the nacelle become an increasingly important factor as the output increases above 5 MW. By 10 MW, the only recognized feasible technology is superconducting generation.
- One questions is: as superconducting technology improves, where will the actual cross-over be?



- The cost and availability (or lack thereof) of neo magnets will likely determine the rate of conversion to Generation 4, PM generators.
- However, they are more likely to be adopted rapidly for use at sea and in larger MW towers even on land and hybrid (half-speed) systems may predominate over direct drive due to the lower magnet usage.
- This chart is an attempt to show where each design is more likely to be applied.

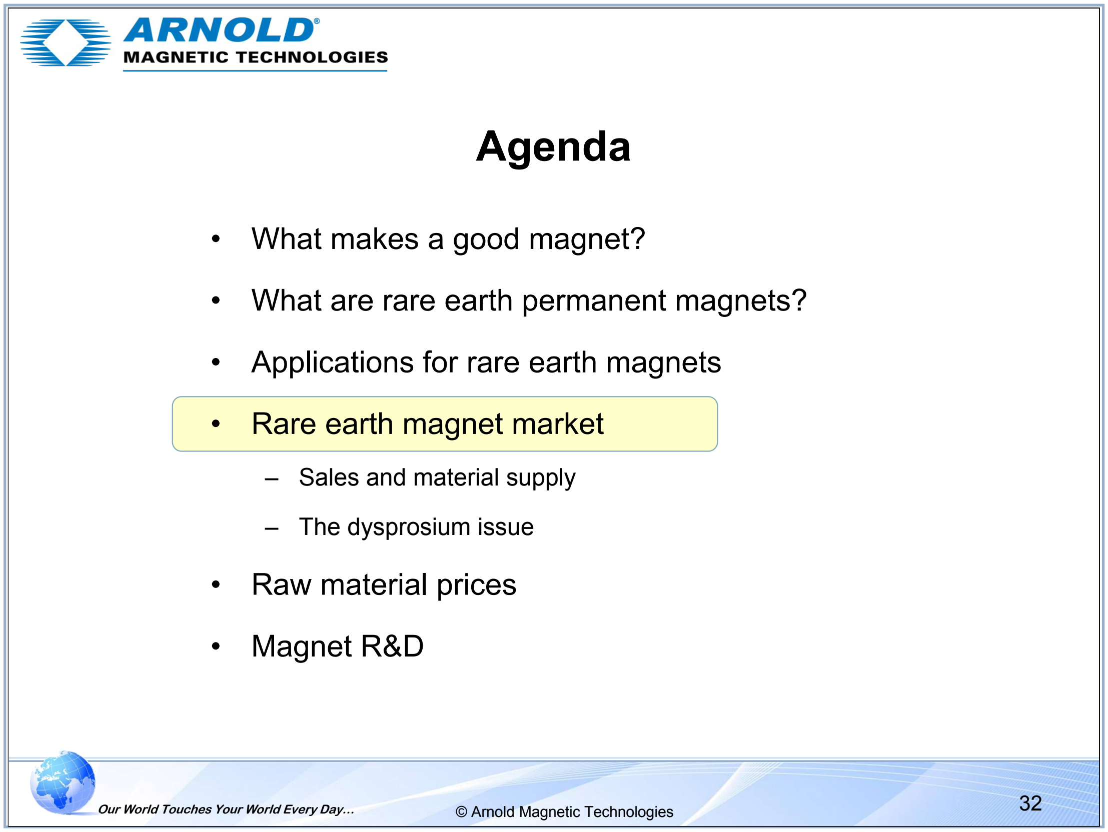


- Calculations for this forecast include percentage permanent magnet generators by geographic region, percentage land based and percentage off shore, weight of magnets per megawatt output, and percentage hybrid drives versus direct drives.
- These are strictly estimates and are likely to change as the market situation develops and as new technologies are introduced.
- Although the curve is continuous, year-to-year the installations are likely to be up and down with an overall upward trend through 2020.

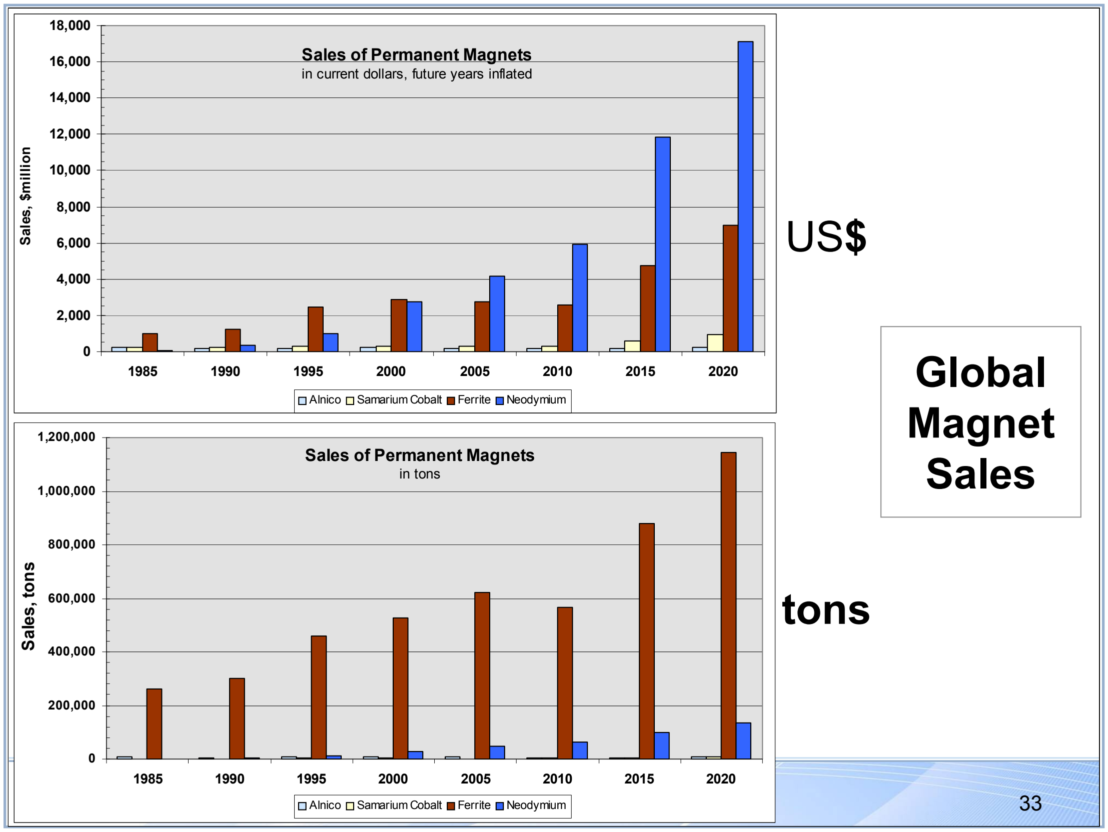


- And it's not just wind – other renewable energy sources are being pursued such as Tidal Turbines, some using PM generators.

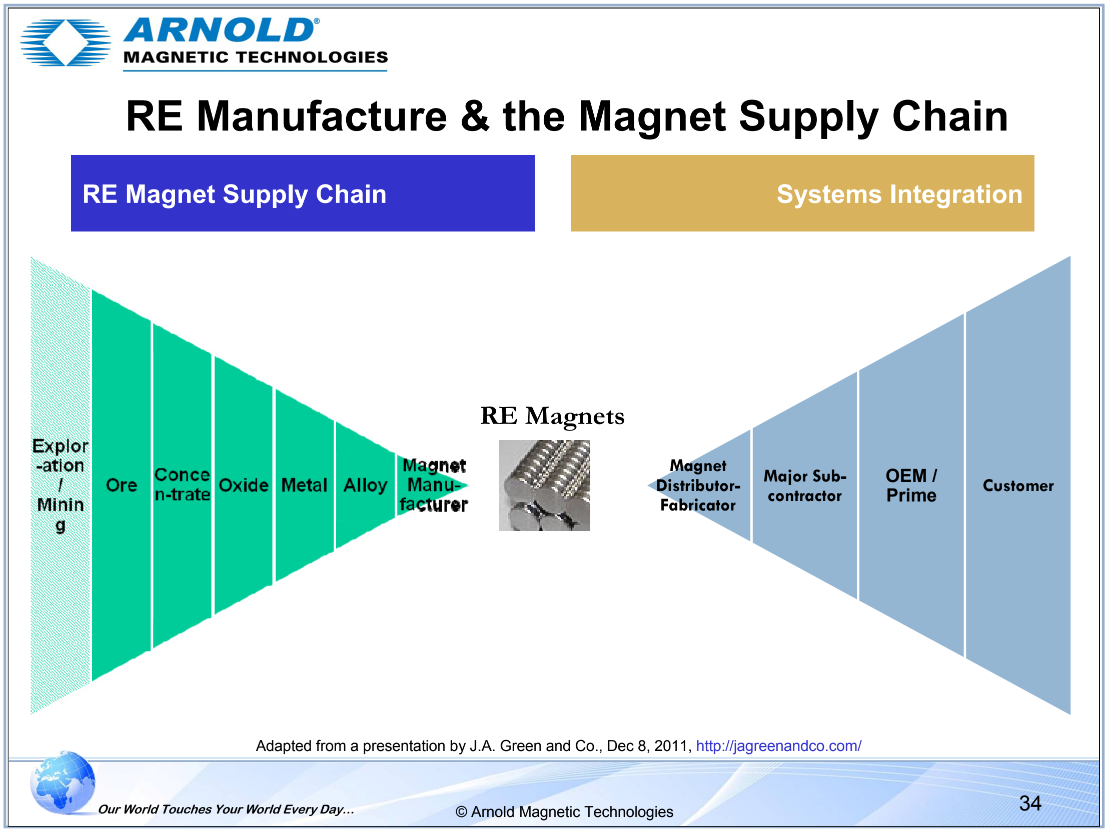
- We might say that the 1900's was the century of technological innovation leading to increased consumption among the world's more powerful countries.
- This century may well be known as the century of materials criticality with intermittent shortages leading to competition for resources and implementation of alternate and multiple competing technologies. This applies to many materials, not just rare earths.
- The challenge is to produce more energy using "greener" technology while conserving resources and avoiding harming the environment.



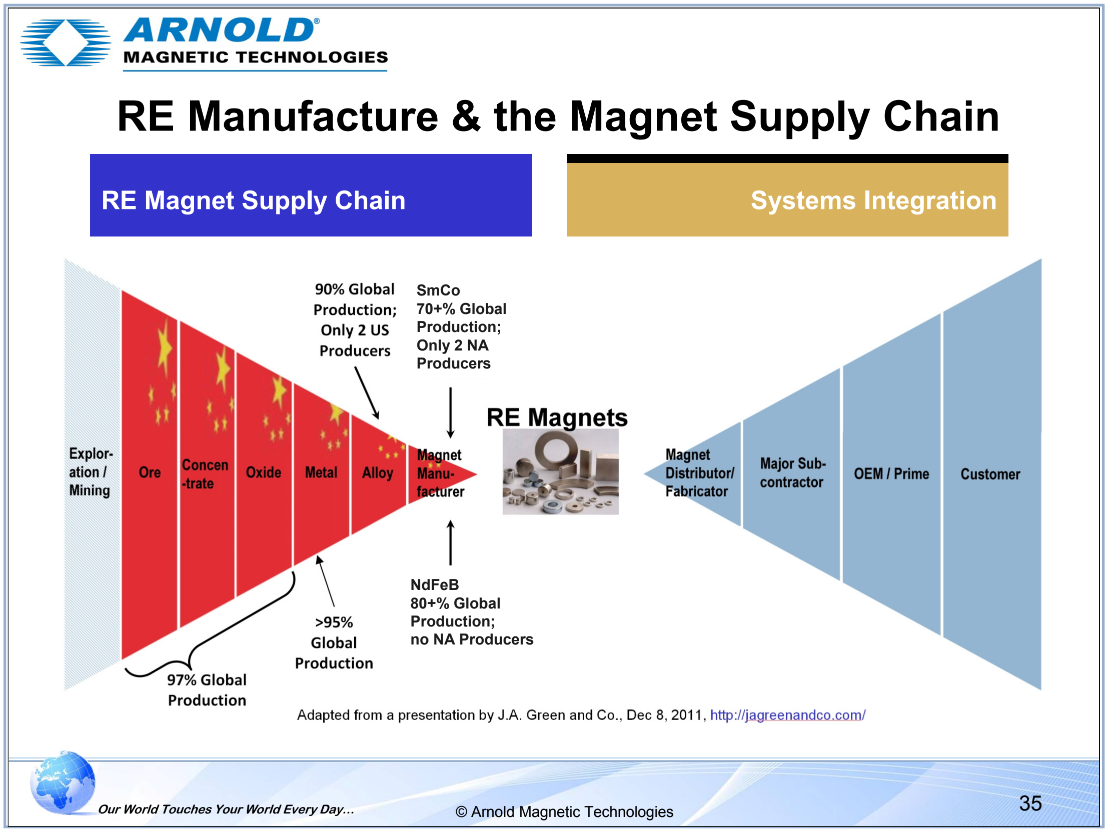
- We see that a large market exists for permanent magnets.
- Let’s dig into some of the sales and material supply details.



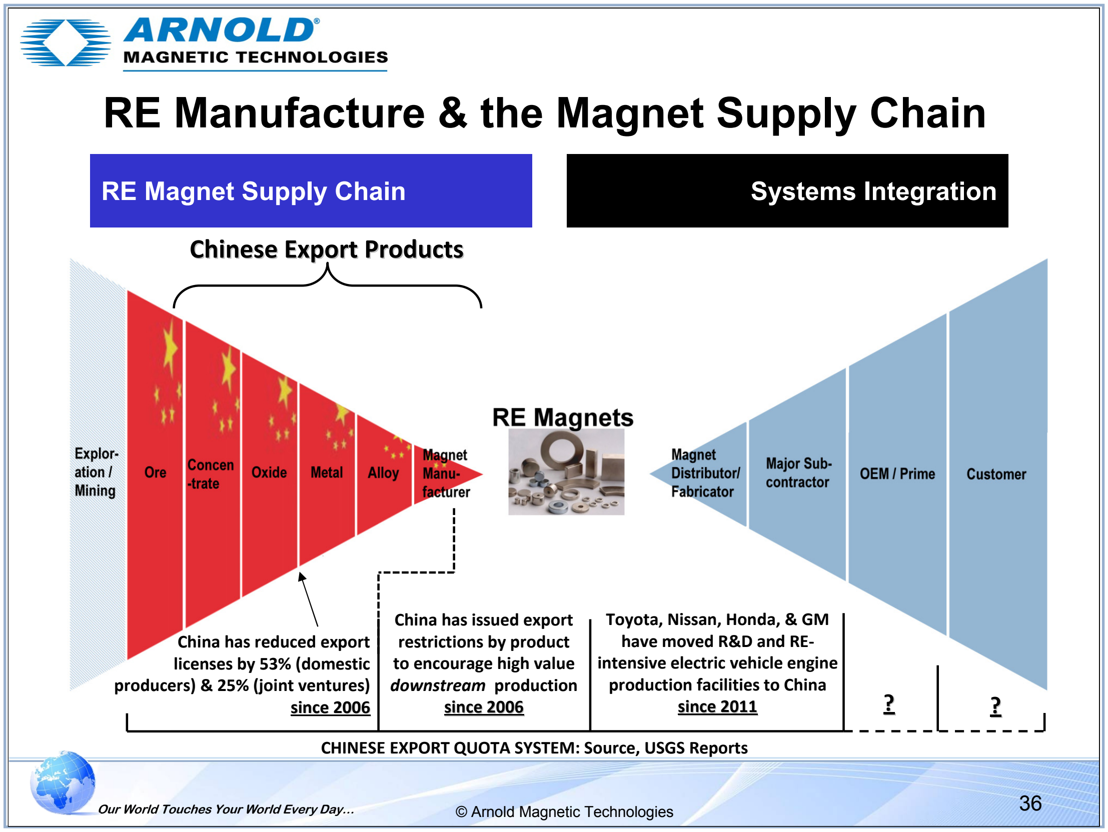
- Market information for magnetic materials consists of both data that is readily available (transparent market) and that which is difficult to obtain or not credible (opaque market).
- The information presented here is based on transparent market data, that is excluding Russia, much of India and a portion of the Chinese market activity.
- We see 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 price inflation estimates of 5% per year, are based on 2010 raw materials pricing and are predicated on adequate supplies of not only the light rare earths (Nd and Pr) but also on enough dysprosium 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.
- According to the forecast, ferrite continues to be very widely used, primarily due to its low cost and general availability. Also because development efforts have improved ferrite properties enough to expand its opportunities for use.



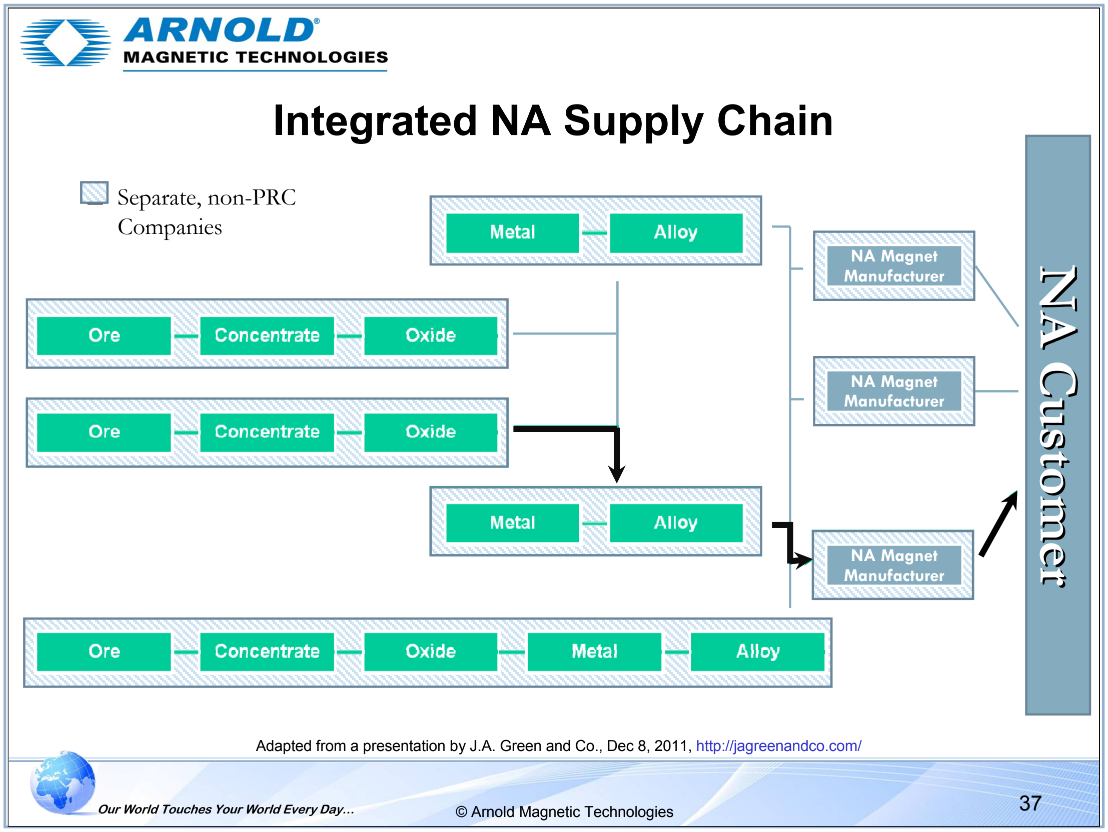
- Jeff Green's staff put this illustration together and I've simplified it a little to focus on the elements of the supply chain for rare earth magnets.



- Here we begin to look at the geographic issues associated with supply.
- China controls almost all the raw materials and a majority of magnet production.
- They still enjoy a lower cost of doing business and the selling price of products from China is lower than we can match in Japan, Germany or North America.



- Furthermore China has "managed" the market for their domestic commercial success.
- It is important to recognize that they have the need to improve the standard of living for the Chinese people and that is coming at the expense of manufacturing jobs in the rest of the world (ROW).
- As China seeks to move up the supply chain (to the right on this chart) there will be further erosion of our 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.



- Manufacture of magnets outside China will require a coordinated supply chain for raw materials – also outside of China.
- It is likely that at least some of the raw materials produced outside China will be transported to China to satisfy their internal demand. This is especially likely until consumption of the raw materials increases outside of China.
- This is true today with several other commodities such as cobalt and strontium carbonate.

ARNOLD MAGNETIC TECHNOLOGIES

Rare Earth China Export Quotas

Year		RARE EARTH OXIDE EXPORT QUOTAS							
		1st Allocation		2nd Allocation		Total		Grand Total	% Change
		Domestic Companies	Foreign Companies	Domestic Companies	Foreign Companies	Domestic Companies	Foreign Companies		
2005		n/a	n/a	n/a	n/a	48,040	17,569	65,609	
2006		n/a	n/a	n/a	n/a	45,752	16,069	61,821	-5.8%
2007		19,600	8,211	23,974	8,289	43,574	16,500	60,074	-2.8%
2008		22,780	8,211	11,376	5,082	34,156	13,293	47,449	
		Adjusted for 12-month basis				40,987	15,834	56,939	-6.6%
2009		15,043	6,685	18,257	10,160	33,300	16,845	50,145	-11.9%
2010		16,304	5,978	6,208	1,768	22,512	7,746	30,258	-39.7%
2011		10,762	3,746	12,221	3,517	14,508	15,738	30,246	0.0%
2012	LRE	9,095	12,605	2,274	3,151	11,369	15,756	27,125	
	HRE	1,451	1,753	363	438	1,814	2,191	4,005	
	Total	10,546	14,358	2,637	3,590	13,183	17,948	31,130	2.9%

- **Separating rare earth export quotas into LREs and HREs suggests that China understands they need to be separately managed**

2012 quotas are divided into LRE and HRE; 1st half quotas are published; second half quotas are inferred to be 20% of annual total resulting in a 2.9% increase year over year.

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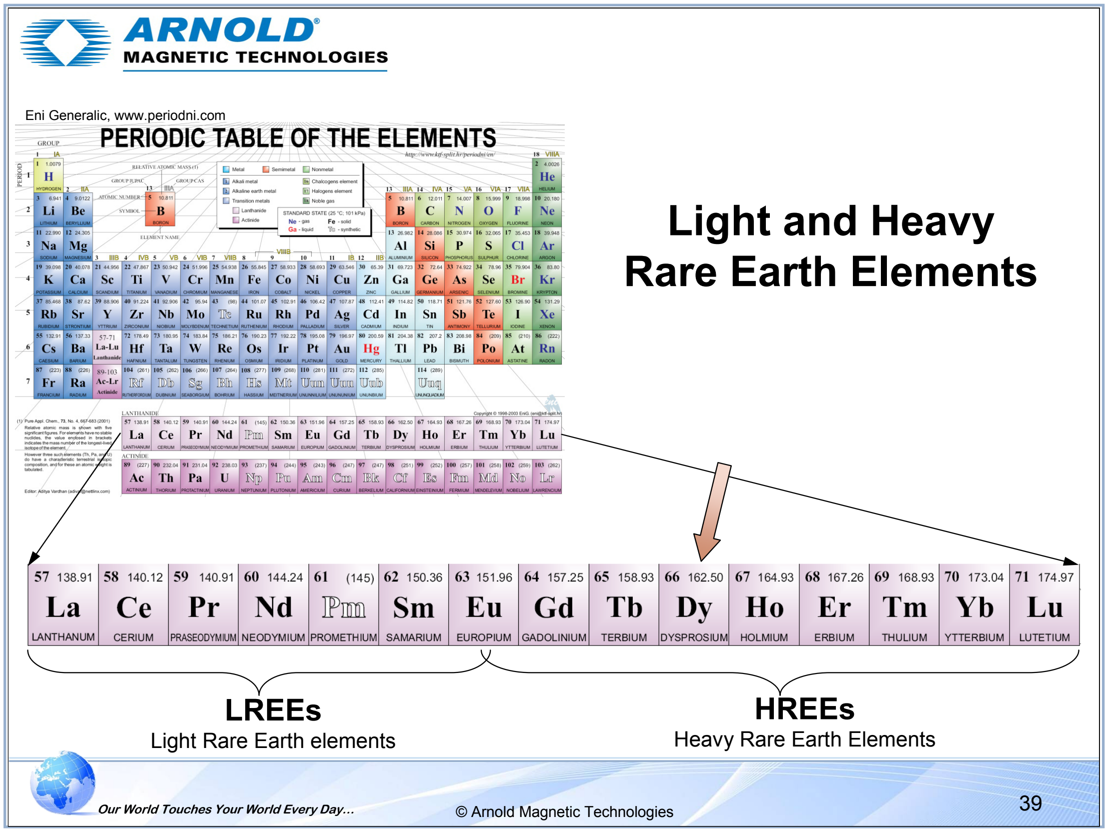
- The Chinese government imposes quotas on the mining and production of rare earths.
- They also have quotas on the export of rare earth chemical, metals, and alloys.
- Furthermore, they charge an export tax on rare earths, putting the ROW at a cost disadvantage.
- That the light and heavy rare earths are, starting in 2012, to be treated separately for quota purposes, is an explicit recognition of the relative importance of the heavies.
- The quotas for the second half of 2012 have recently bee issued are very close to the numbers in this not-yet updated table.



- Let's define which are light (LREEs) and which are heavy (HREEs).
- As we see here, elements from Lanthanum to Samarium are LREEs.
- Europium is also generally , though not universally, considered a LREE.
- However, from Gadolinium through Lutetium we find the HREEs.
- Among these is the important, at least for magnets, element Dysprosium.
- Dysprosium is required to raise the maximum use temperature of Neo magnets.

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Dysprosium is a Short & Long Term Issue

	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

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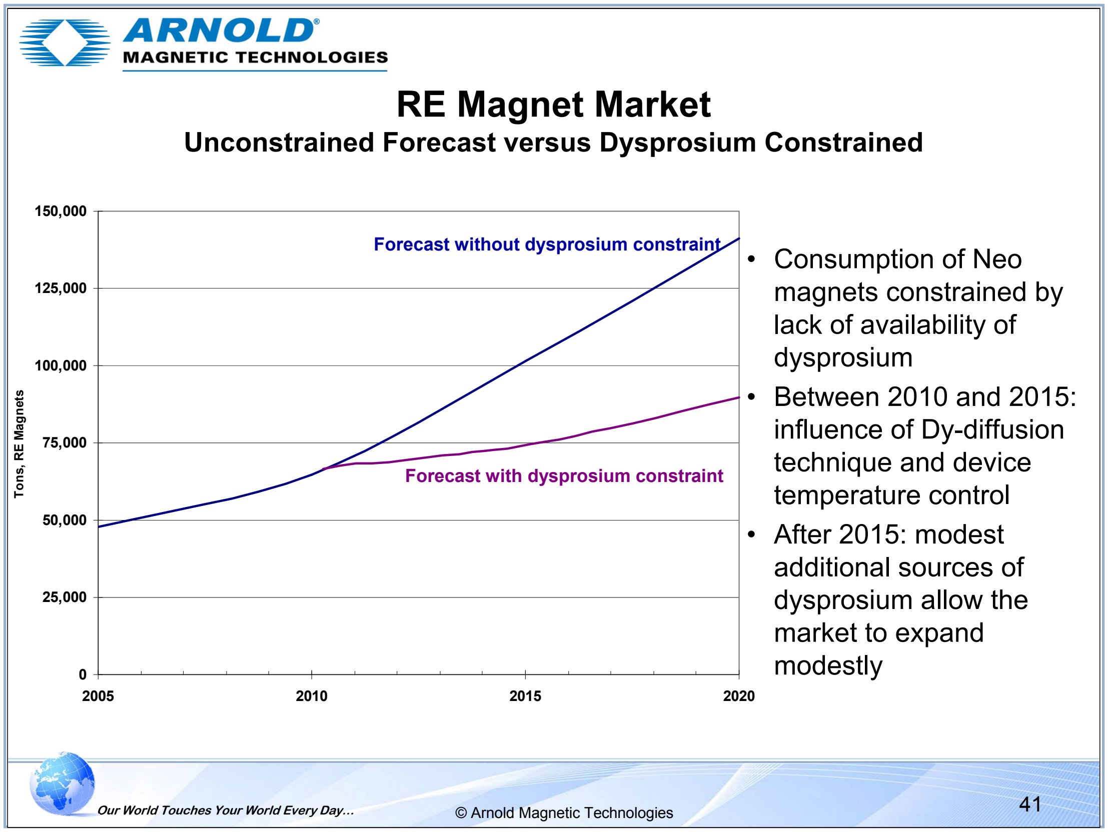
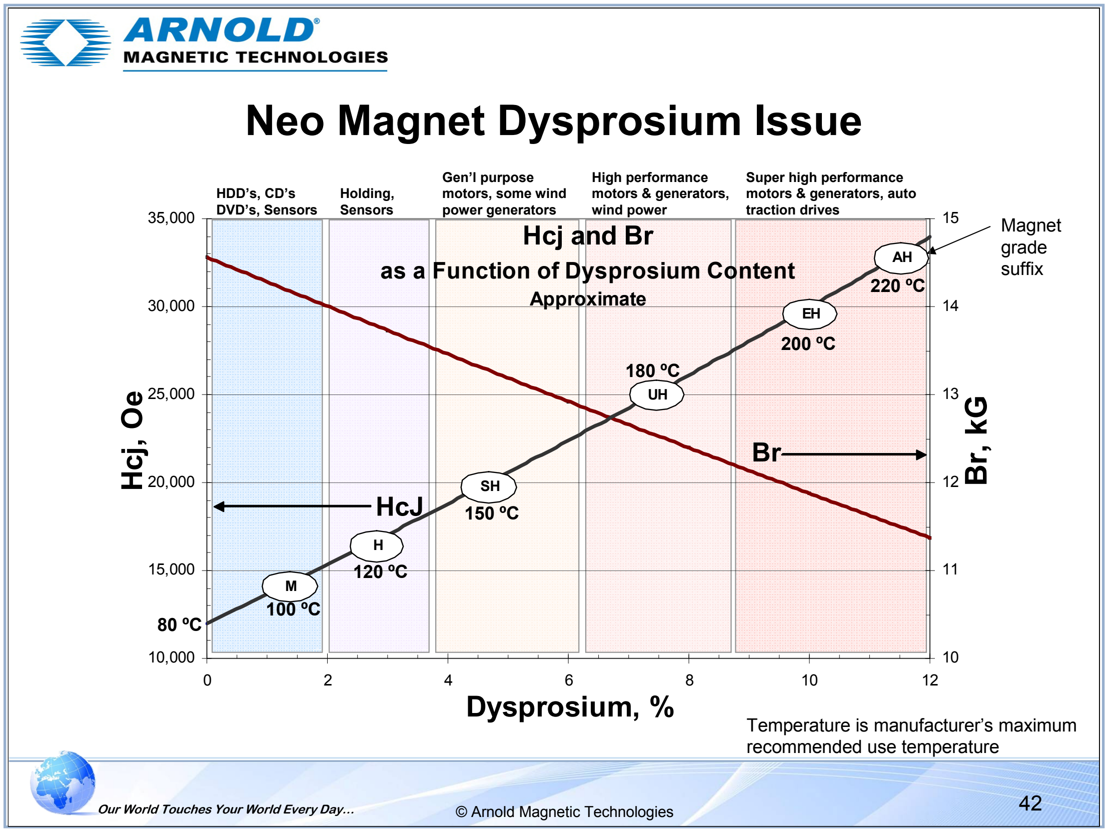
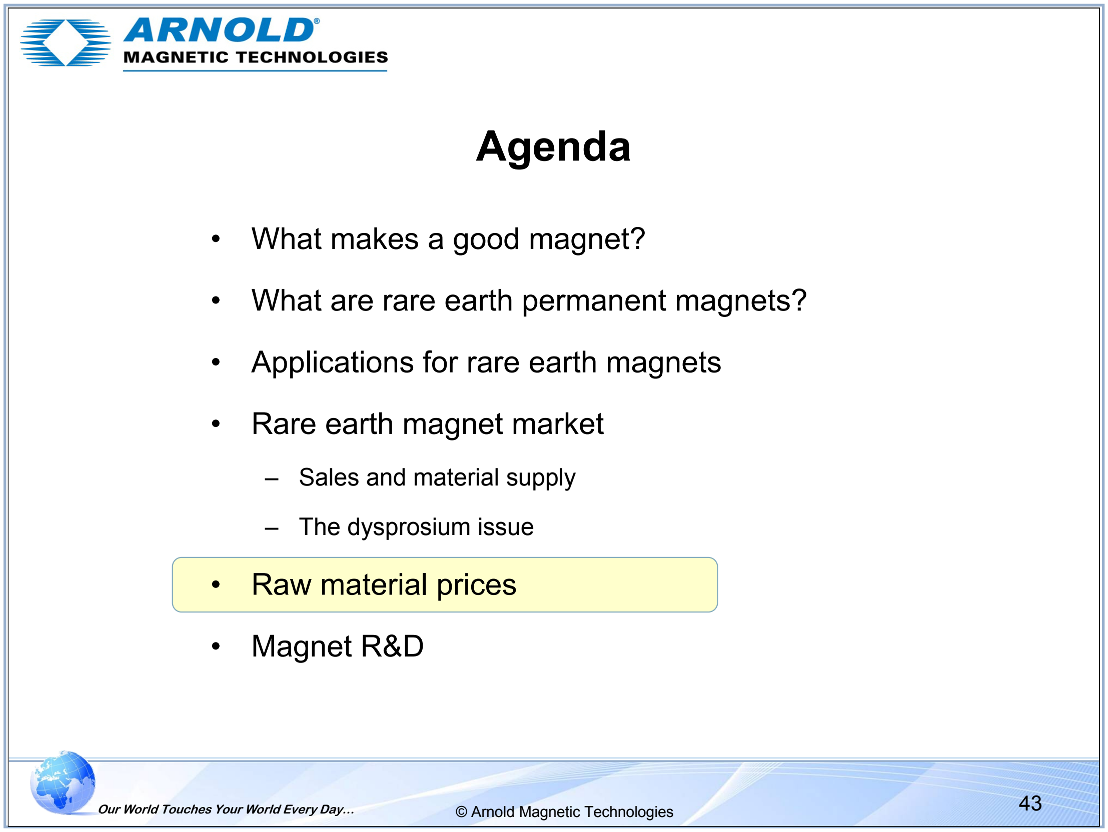
- Rare earth minerals are recognized as crucial to the success of clean energy initiatives.
- For that reason, the United States Department of Energy (DOE) produced a document in December, 2010 called the Critical Materials Strategy.
- It was a thorough document and covered almost every element in the periodic table – more than just rare earths.
- The study continued during 2011 and a second, updated report was issued in late December 2011.
- Be sure to obtain the final version: DOE_CMS2011_FINAL_Full.pdf
- This table is from the report. It shows supply of the light magnet rare earths growing by 43% (samarium) and 65% (neodymium) between 2010 and 2015.
- However, dysprosium is shown increasing just 6%.
- Note that this table is for rare earth oxides, not metals.



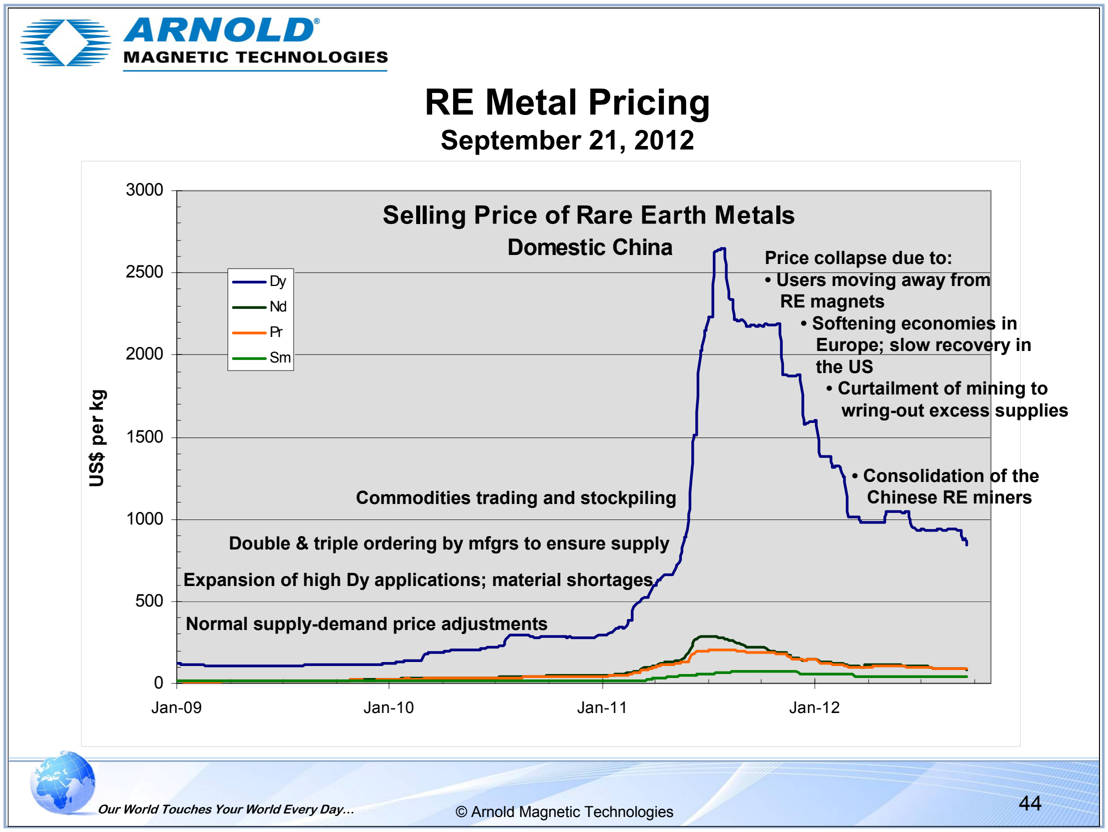
- While the market demand for Neo magnets could be strong, high prices and erratic availability have discouraged use.
- Furthermore, chronic insufficient supply of dysprosium will constrain Neo use going forward – unless applications are modified to reduce in-use temperatures so that less dysprosium is required.



- As we examine applications for neo magnets more closely, we become aware of the important issue of the forecast "shortage" of dysprosium.
- Hcj is a measure of a magnet's "resistance to demagnetization." Br is a measure of a magnet's field strength. In both cases, generally the larger the number, the better.
- In terms of relative abundance in the crust of the earth, dysprosium is less than 1% of all rare earths and where it is present in higher percentages it is most often accompanied by either thorium or uranium, both of which are radioactive. While the radioactivity can be managed, it does raise the cost of production.
- The only known occurrence of dysprosium-rich ore without significant radioactive by-products is the ion adsorption clays of southern China. The actual dysprosium content is low, but it is easily separated.
- Those deposits are estimated to have a 15 to 25 year life at current rates of consumption.
- Dysprosium is required to allow Neo magnets to be used at elevated temperatures, that is above 80 ºC, especially in the presence of demagnetizing stress such as in motors and generators.
- We see in this chart that wind power uses Neo with over 4% dysprosium and that traction drives use 8-12% - both represent usage that is considerably higher than the natural abundance.



- The rapidly rising demand for Neo magnets coupled with the long lead times to develop mining and processing facilities has resulted in material shortages, stockpiling, and commodities trading.
- The result was material prices that rose faster and further than justified by a normal supply / demand situation.
- It had the effect of placing magnet manufacturers in financial peril. Prices for replacement inventory rose faster than the price increases that could be passed to the market thus creating a liquidity crunch.



- The rare earth market is currently controlled by China: they mine over 90% of all rare earths and process over 95% of all REO.
- Supply contracts are private between the supplier and purchaser. Therefore, there is poor transparency of the market.
- Prices that are reported (Asian Metals and Metal Pages) are crude estimates of the market based on spotty information and are generally agreed to be well off mark. Nevertheless they do offer directional guidance.
- A large part of the difference between domestic China and x-China pricing is the export tariff.
- The general consensus is that material prices will stabilize near the present values and then begin a slow rise.
- All of this is dependent upon consistent behavior in managing the industry by the Chinese government and general economic conditions around the globe.

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MAGNETIC TECHNOLOGIES

Magnet RE Raw Material Costs

FOB China Raw Material Pricing, USD

Element	SmCo 26HE	SmCo 30S	N30AH	N35EH	N40UH	N45SH
Nd	-	-	26.9	29.5	32.2	35.1
Dy	-	-	145.8	115.3	84.8	54.3
Sm	26.7	26.7	-	-	-	-
All Rare Earth	26.7	26.7	172.6	144.8	117.0	89.4

Domestic China Raw Material Pricing, USD

Element	SmCo 26HE	SmCo 30S	N30AH	N35EH	N40UH	N45SH
Nd	-	-	17.9	19.8	21.7	23.7
Dy	-	-	92.4	73.1	53.7	34.4
Sm	10.1	10.1	-	-	-	-
All Rare Earth	10.1	10.1	110.3	92.9	75.5	58.1

- **While neodymium has become expensive it is the very expensive dysprosium that dominates Neo magnet material costs.**
  - Based on 1 kg block magnet
  - Material prices of September 21, 2012 as published by Metal-Pages

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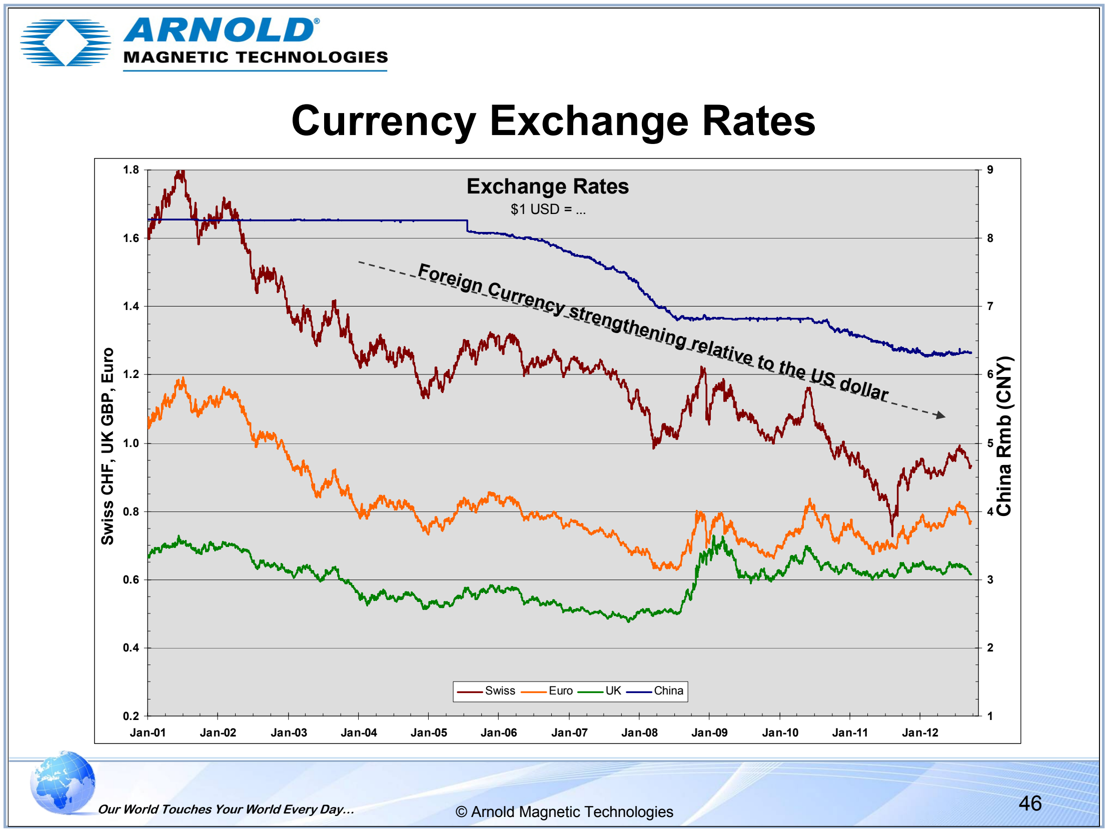
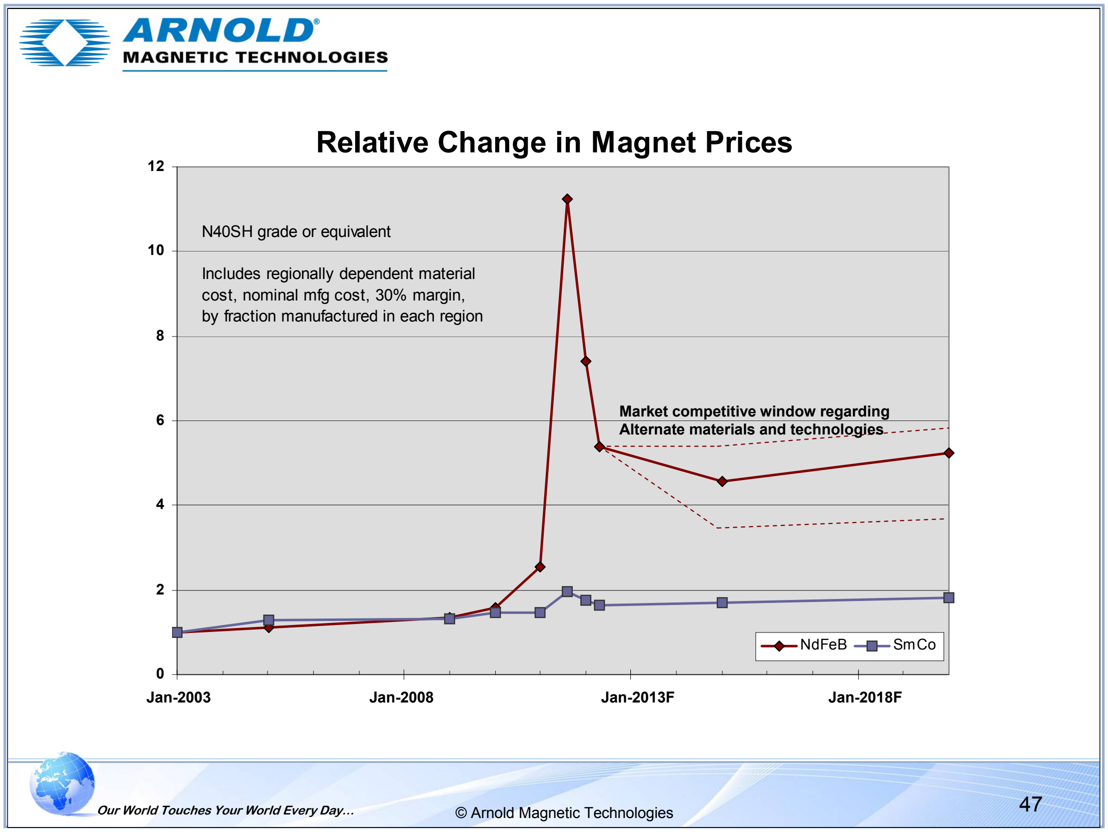
- Prices for rare earth magnets have reflected the high raw material costs.
- As shown here, the raw material accounts for up to 95% of the finished magnet cost of manufacture, primarily driven by dysprosium.
- Thus magnet prices are hugely affected by the rare earth pricing.



- Many of the material are sold across national boundaries.
- The changing exchange rate affects prices and must be considered.



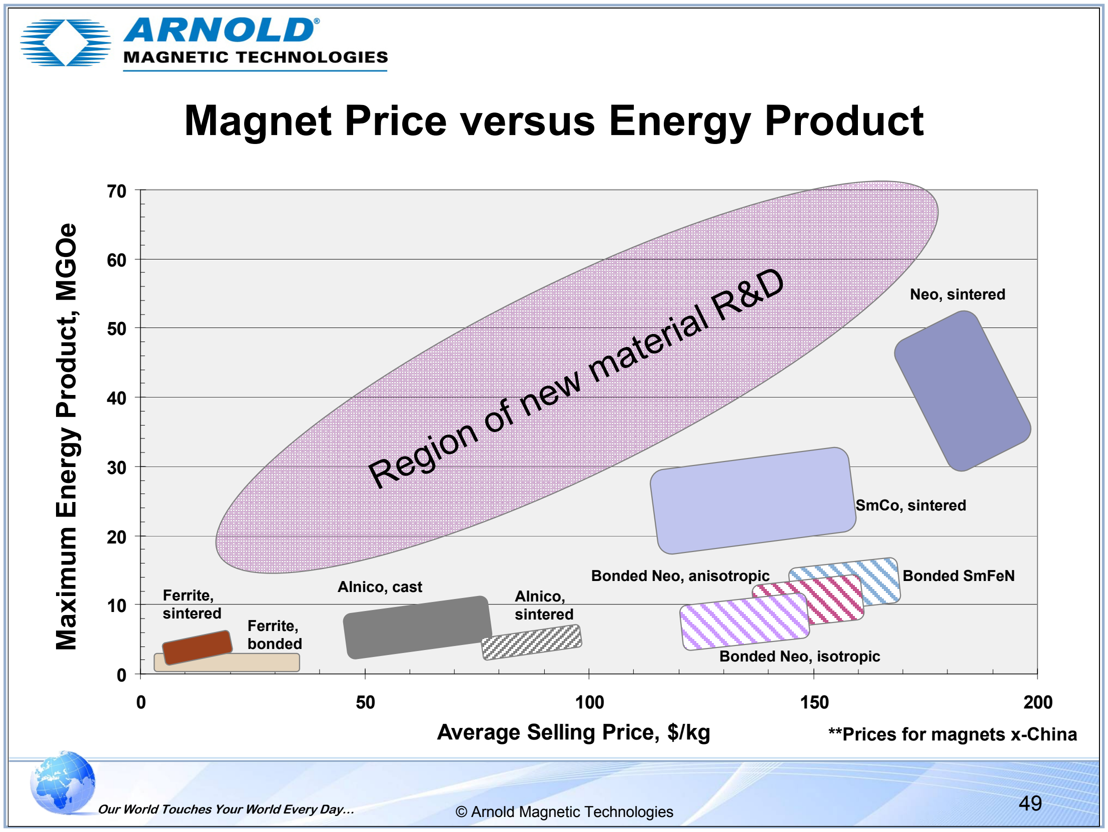
- The forecast pricing of Neo and SmCo magnet is expected to follow trends are shown here.

ARNOLD MAGNETIC TECHNOLOGIES

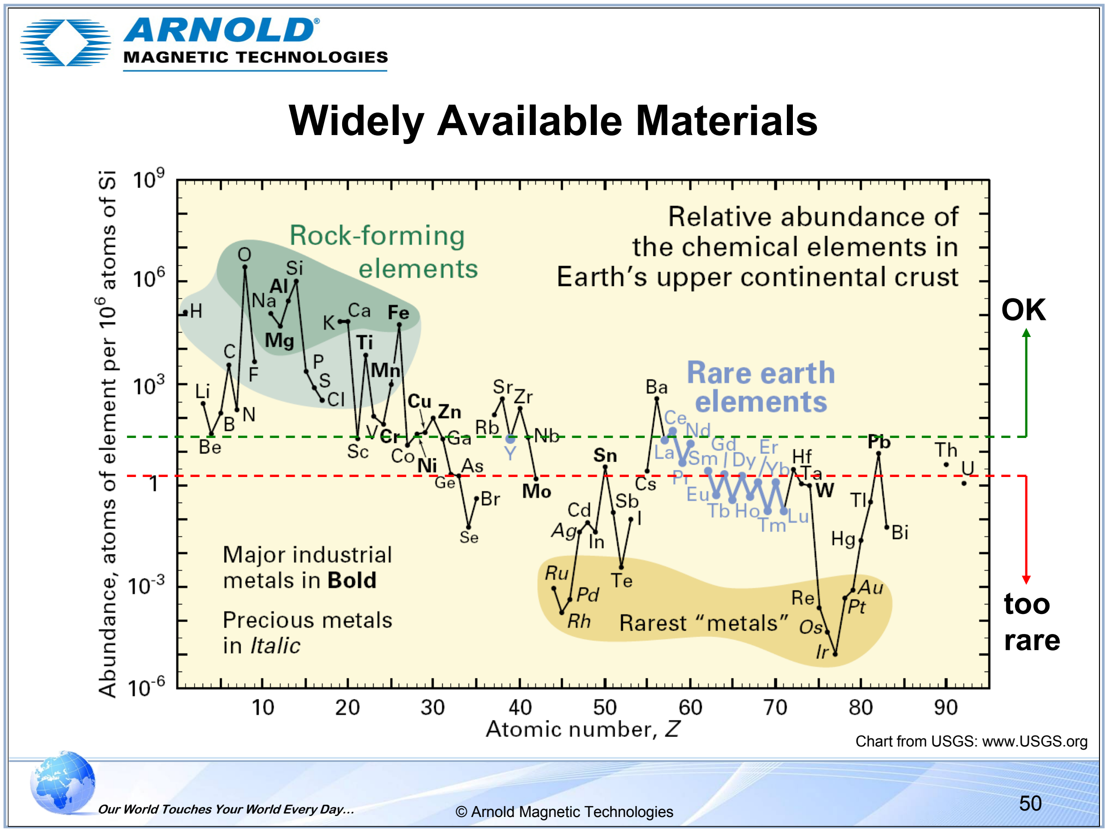
Agenda

- What makes a good magnet?
- What are rare earth permanent magnets?
- Applications for rare earth magnets
- Rare earth magnet market
  - Sales and material supply
  - The dysprosium issue
- Raw material prices
- Magnet R&D

- 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 product selling price of each of the major commercial permanent magnets highlights the high cost of rare earth magnets.
- Bear in mind that many factors such as shape, complexity and size contribute to a magnet's selling price.
- The values shown here are fair estimates for simple shapes and intermediate sizes.
- Selling price shown here is that observed in the USA and Europe and provides comparative values.
- 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's highly recommended to select more common materials such as those above the green dashed line.
- Minor ingredients may be from between the green and red lines.
- But elements from below the dashed red line should be avoided except in the very smallest additions.
- Notice where the rare earths fall.

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MAGNETIC TECHNOLOGIES

R&D Activities (U.S.)

Some Major Current Projects (DOE Sponsored)

- 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

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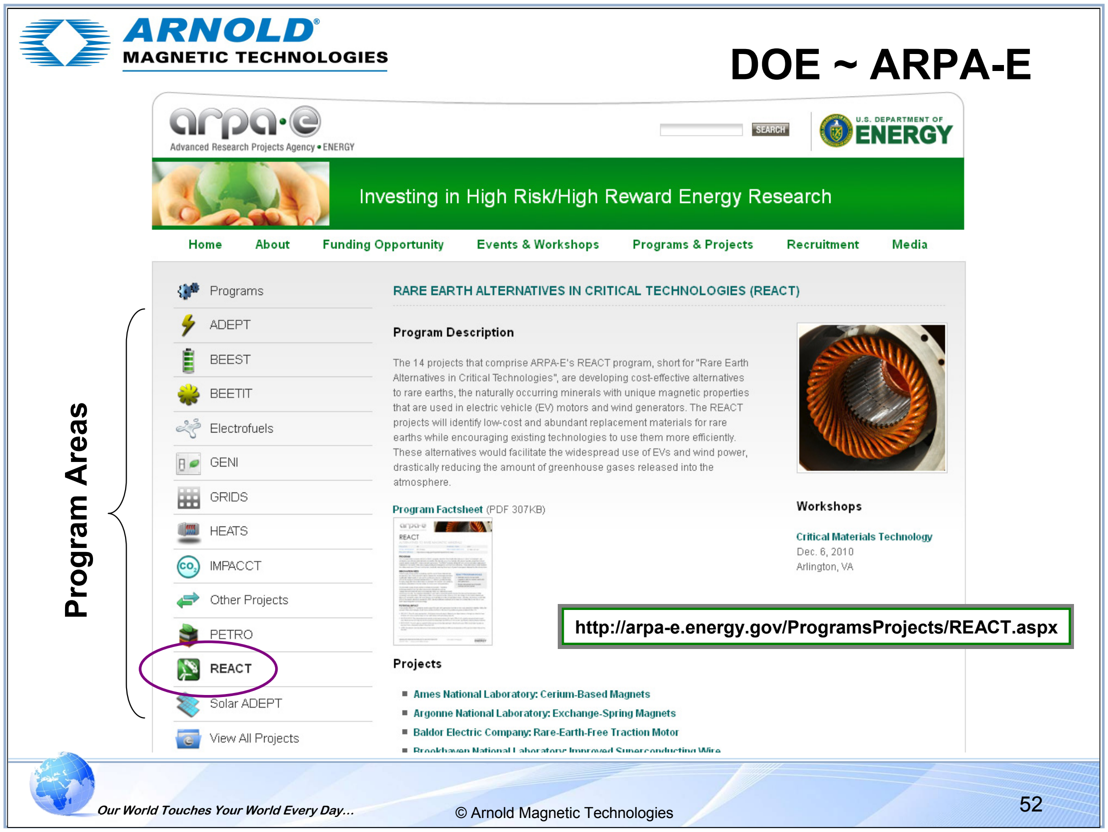
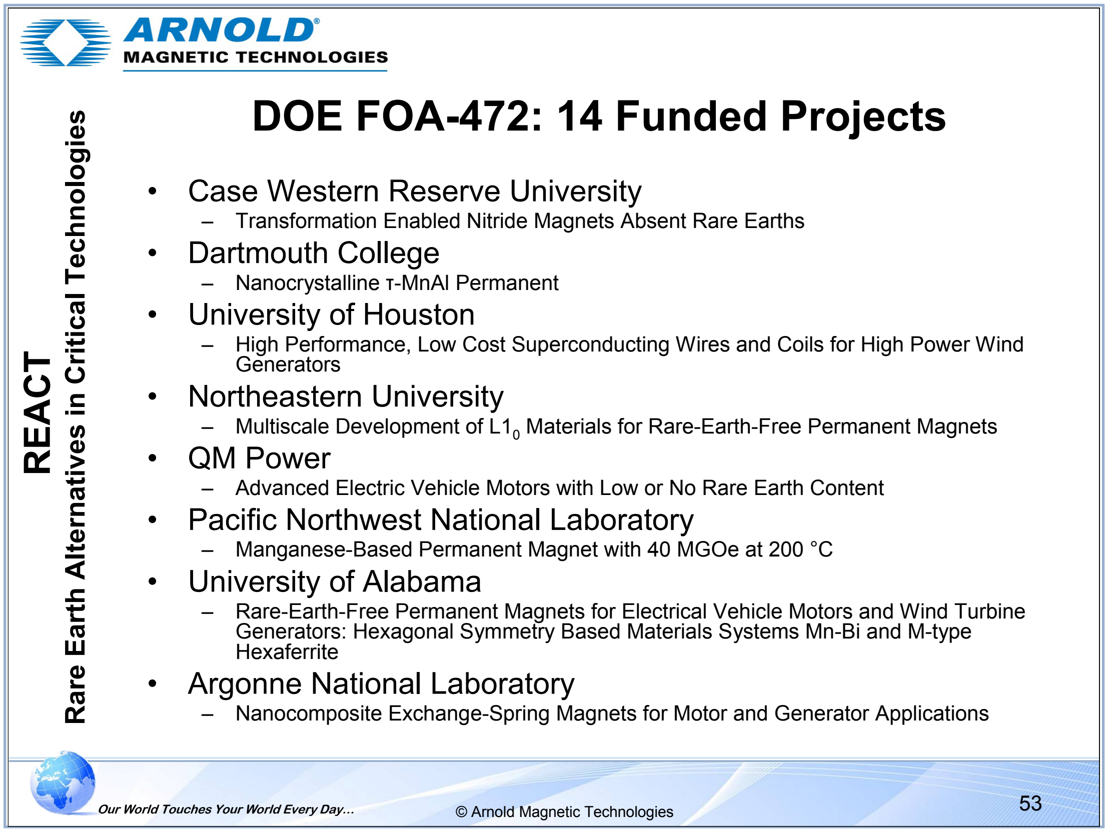
- Research activities into the next great magnetic material involve multiple approaches.

Some thoughts related to a good magnetic material:

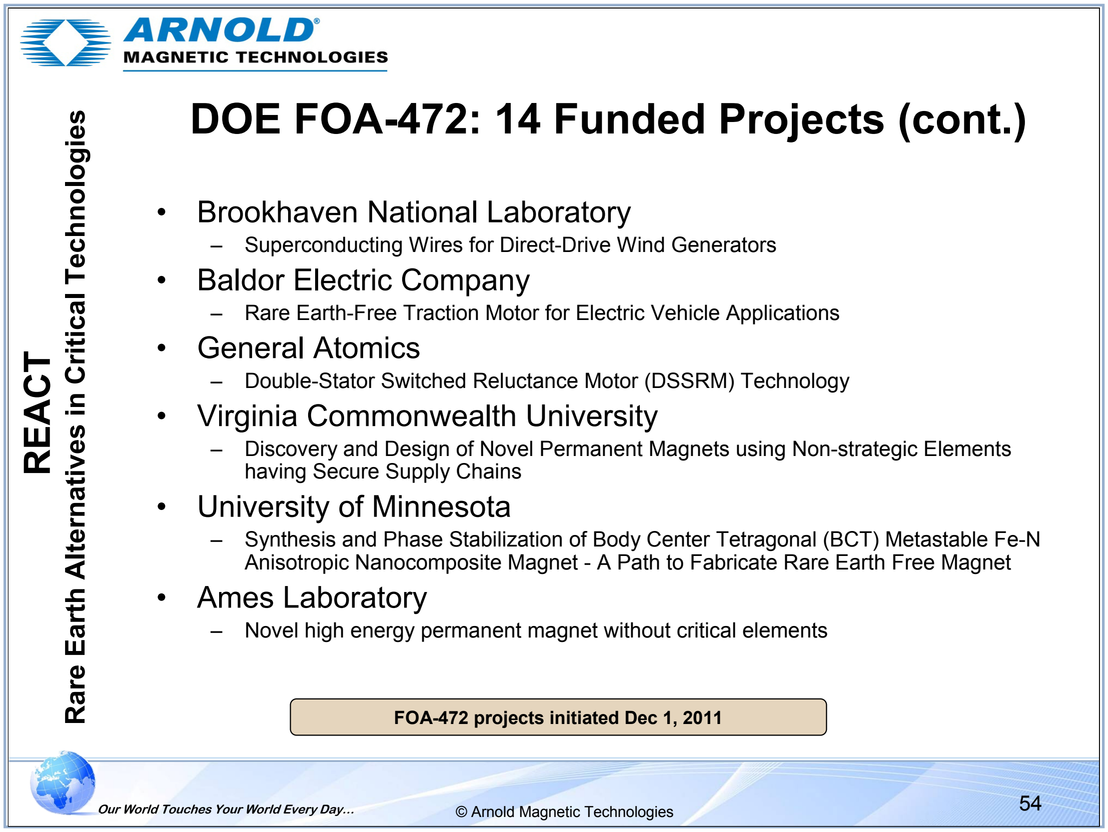
- To obtain full benefit from the magnetic material, it should be fully dense (no dilution of the magnetic phase), it should have uniaxial crystalline anisotropy (for maximizing magnetic saturation), and magnetic domains should be oriented within the bulk structure.
- Raw materials need to be widely available and at reasonable cost.
- Raw materials and the finished composition must not be toxic or environmentally hazardous.
- The material should be easily and safely manufacturable.
- The magnets should be recyclable.



- We have an intersection of needs: saving US manufacturing and creating am energy secure future.
- DOE through its operating division ARPA-E is supporting high risk research into alternate materials and technologies in the areas of energy production, transmission and use.



- The following 14 projects were awarded by ARPA-E at the end of 2011 for research into a low-to-no rare earth magnet materials or for devices that can avoid using rare earth magnets.



- The financial backing provided by DOE is bootstrapping a domestic magnetics industry which has been financially stressed and disinclined to fund adequate levels of research, especially high risk research.

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MAGNETIC TECHNOLOGIES

Variations on a Theme

Revisiting & modifying prior materials

- SmCo plus exchange-coupled soft phase
- NdFeB plus exchange-coupled soft phase
- 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

Our World Touches Your World Every Day…

- I've split the indicated research into two categories. The first could be called "Variations on a Theme" as it represents an extension of research on materials that have been previously examined.
- However, there are several differences between "then" and "now".
- One is that current analytic capabilities are superior to what existed even two or three decades ago.
- Secondly, we now have techniques to 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.

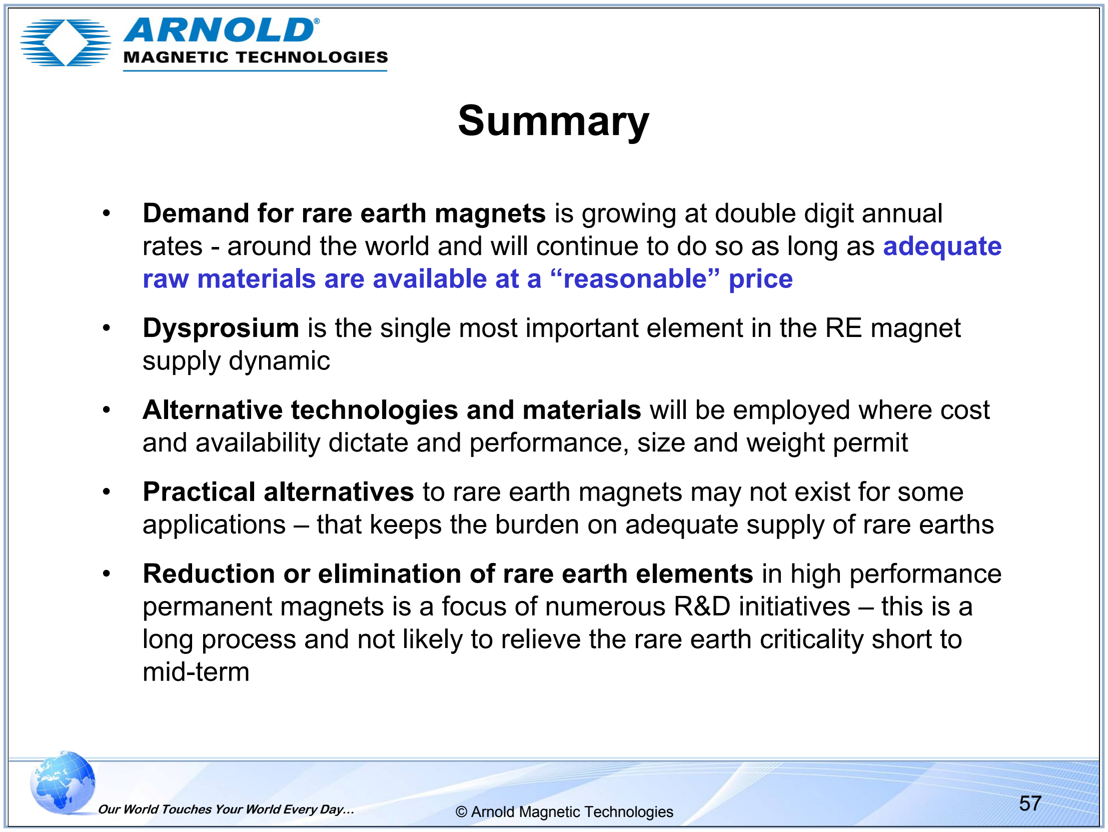
ARNOLD®
MAGNETIC TECHNOLOGIES

"Greenfield" Magnets

- Computer calculations to arrive at alloy structure with net magnetic moment
- Promising alloys are then formed in the lab and evaluated
- 2 and 3-component alloys are practical
  - 4+ component alloys represent significant computational difficulty
- Finished magnet must be...
  - Fully dense to take advantage of undiluted properties
  - Domains benefit from orientation so that the magnetic field is in one preferred direction

Our World Touches Your World Every Day...

- We start with about 100 elements occurring in nature.
- Dr. Bill 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 this 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 magneto-crystalline (shape) anisotropy (e.g. alnico) 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 properties.
- Simultaneous densification and alignment has been a difficult problem to solve for nanostructured materials.



- Recall our question: is there anything such as a long-term shortage?
- The premises are that supplies will rise to meet demand or that industry and the consuming market will find or develop alternatives.
- These alternatives can be materials, alternate devices or technologies, or changed life-style.
- In many circumstances, industry may be reluctant to commit resources to an uncertain future. In those situations, it may be necessary for governments to encourage R&D or even offer market legislation to clarify industrial policy.
- One example of such a policy initiative is CAFÉ standards.
- Thank you for your attention.

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