



The Elements of Magnetics

Steve Constantinides, Director of Technology
Arnold Magnetic Technologies Corporation
November 19, 2013



About Arnold



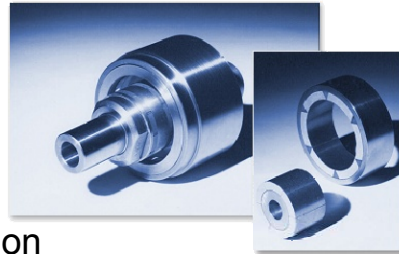
- Company founded in 1895
- 10 manufacturing facilities, globally
- Largest North American manufacturer of magnetic materials and systems
- One of only three North American rare earth magnet manufacturers
- 750 - 800 employees
- 2,000+ Customers



- Arnold Magnetic Technologies operates 10 factories: 2 in Europe, 6 in the USA and 2 in China.

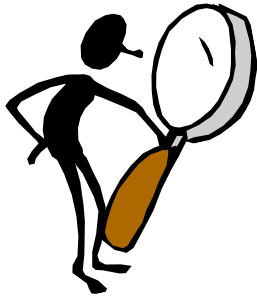
Arnold – What We Manufacture

- **Magnet Production**
 - SmCo RECOMA® - (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)
- **Fabricated 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 for Magnets and Components



- Arnold manufactures magnetic materials and produces sophisticated assemblies utilizing magnetic materials.

What are the “Elements of Magnetism”



- Magnetic characteristics that make a material useful
- The economics around magnetic materials
 - Raw material costs and availability
 - Manufacturability and yield
 - Market for magnets and devices using magnets
- The physical elements that constitute magnetic materials



- Due to time constraints we'll limit ourselves to these three “elements” of the magnetic materials industry.
- We'll identify those characteristics that make a material useful.
- We'll examine some of the more important economic issues that have occurred over the past few years.
- Finally, we'll attempt to identify from which elements the next great magnet will be made and the research projects on both existing materials and the hunt for new materials.

Agenda

- It's all about energy
- Soft magnetic materials
- Permanent magnet materials
- Materials market & pricing
- Permanent magnet applications
- Development of existing materials
- R & D (elemental discussion)



- The single largest driver affecting the magnetic materials market is production and use of energy.
- Energy to produce other material goods, food, perform services, for creature comfort, transportation and for entertainment.
- Our very survival is dependent upon adequate supply of affordable energy.

IEA - - The International Energy Agency

The International Energy Agency is a Paris-based autonomous intergovernmental organization established in the framework of the **Organization for Economic Co-operation and Development (OECD)** in 1974 in the wake of the 1973 oil crisis. The IEA was initially dedicated to responding to physical disruptions in the supply of oil, as well as serving as an information source on statistics about the international oil market and other energy sectors.

The IEA acts as a policy adviser to its member states, but also works with non-member countries, especially China, India and Russia. The Agency's mandate has broadened to focus on the "3Es" of sound energy policy: energy security, economic development, and environmental protection.[1] The latter has focused on mitigating climate change.[2] The IEA has a broad role in promoting alternate energy sources (including renewable energy), rational energy policies, and multinational energy technology co-operation.

 Australia	 South Korea
 Austria	 Luxembourg
 Belgium	 Netherlands
 Canada	 New Zealand
 Czech Republic	 Norway
 Denmark	 Poland
 Finland	 Portugal
 France	 Slovakia
 Germany	 Spain
 Greece	 Sweden
 Hungary	 Switzerland
 Ireland	 Turkey
 Italy	 United Kingdom
 Japan	 United States

www.iea.org

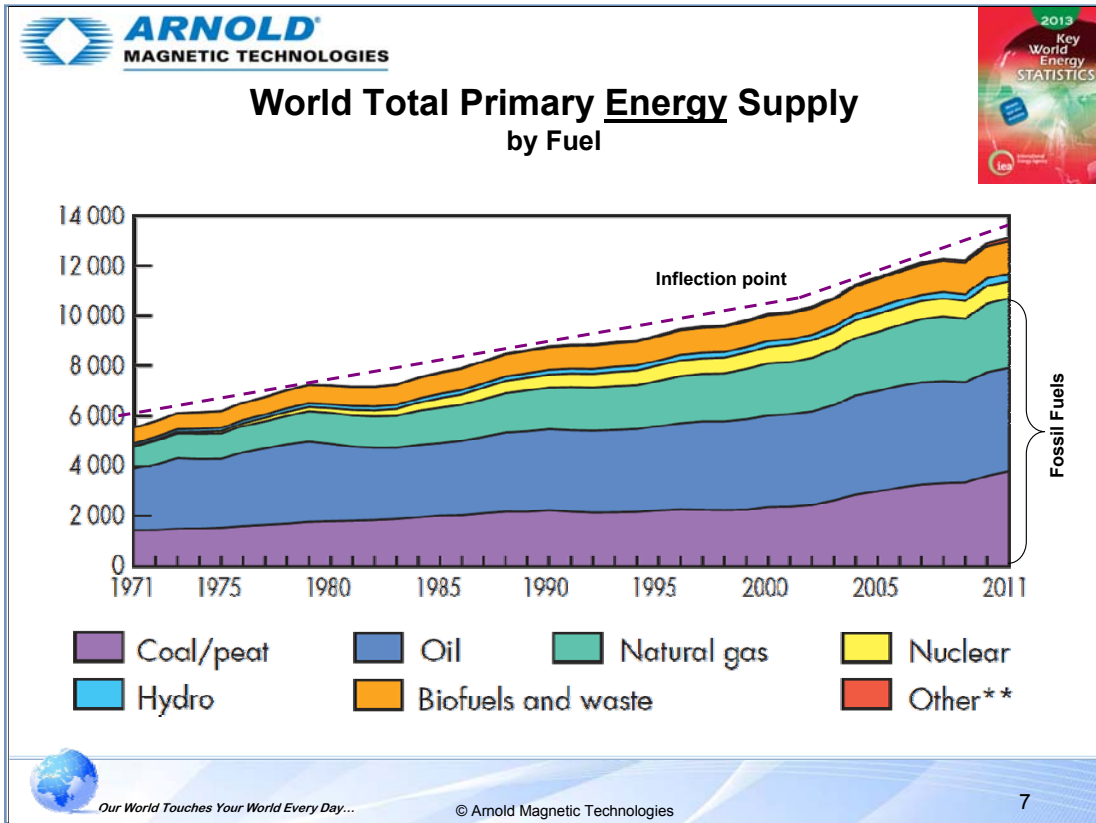


Our World Touches Your World Every Day...

© Arnold Magnetic Technologies

6

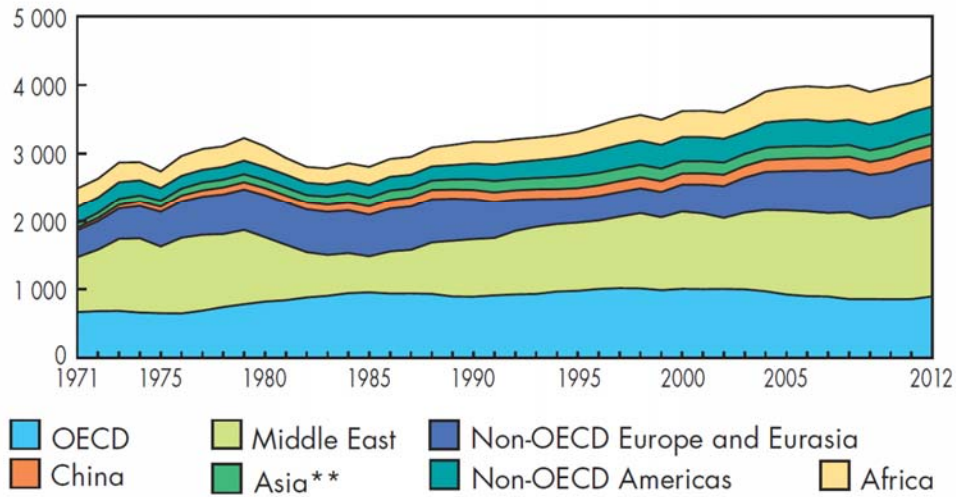
- In the global community, the IEA provides production and consumption statistics.
- The OECD is comprised of the countries listed to the right on this slide – shown in alphabetic order.



- Each year, an update is published showing energy production and consumption statistics.
- This slide shows total energy supply by fuel.
- An inflection point is evident at approximately year 2003.
- It is clear that fossil fuels represent the greatest fraction of energy sourcing.

Crude Oil Production

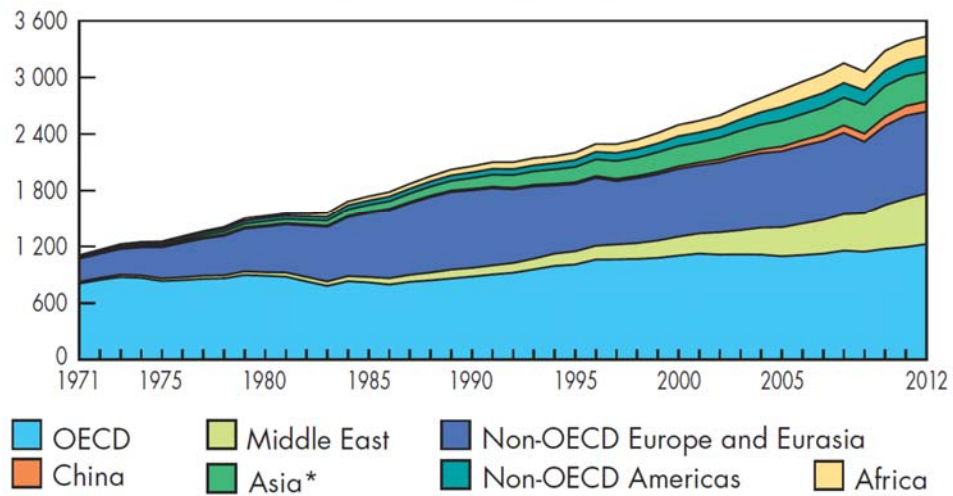
Crude oil* production from 1971 to 2012
by region (Mt)



- Although overall energy production is increasing, crude oil output is growing very slowly, predominantly in the Middle East.

Natural Gas Production

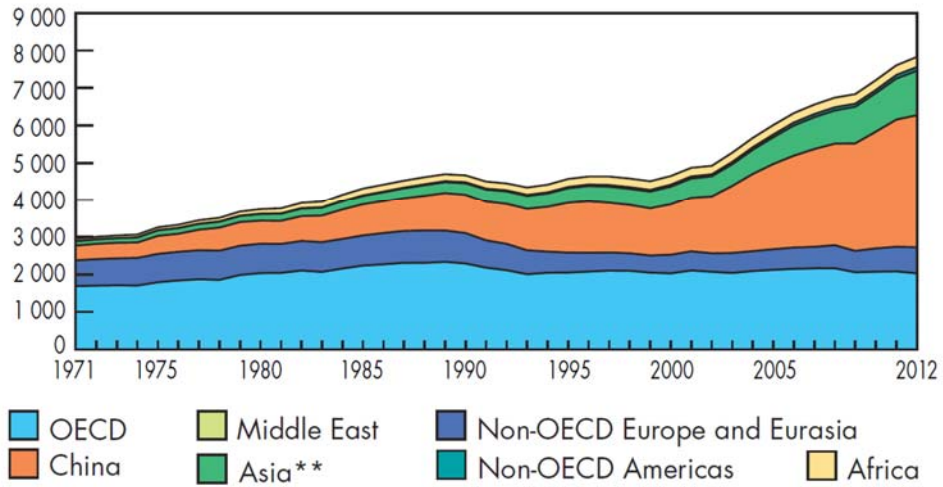
Natural gas production from 1971 to 2012 by region
(billion cubic metres)



- Natural gas output is surging primarily due to “unconventional drilling” with increases in output occurring throughout the world.

Hard Coal Production by Region

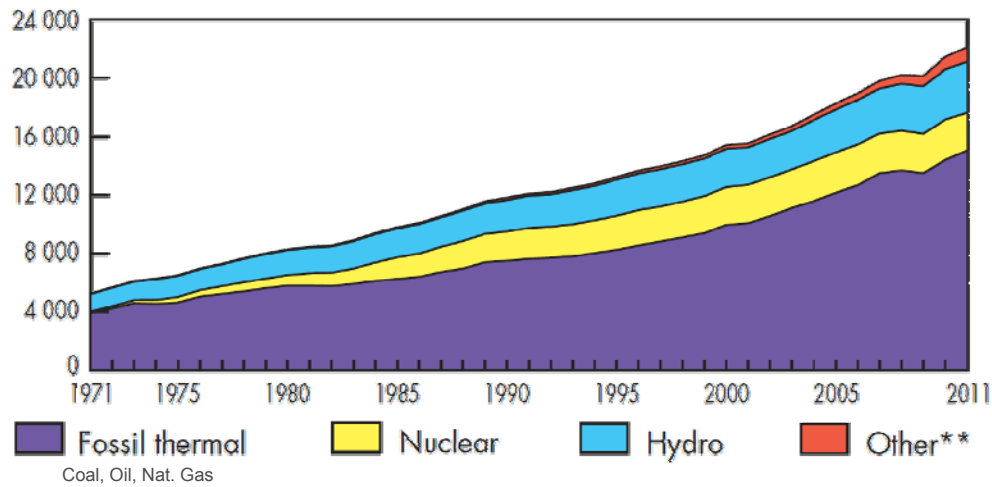
Coal* production from 1971 to 2012
by region (Mt)



- Coal production has most noticeable increased in China.

World Electric Generation

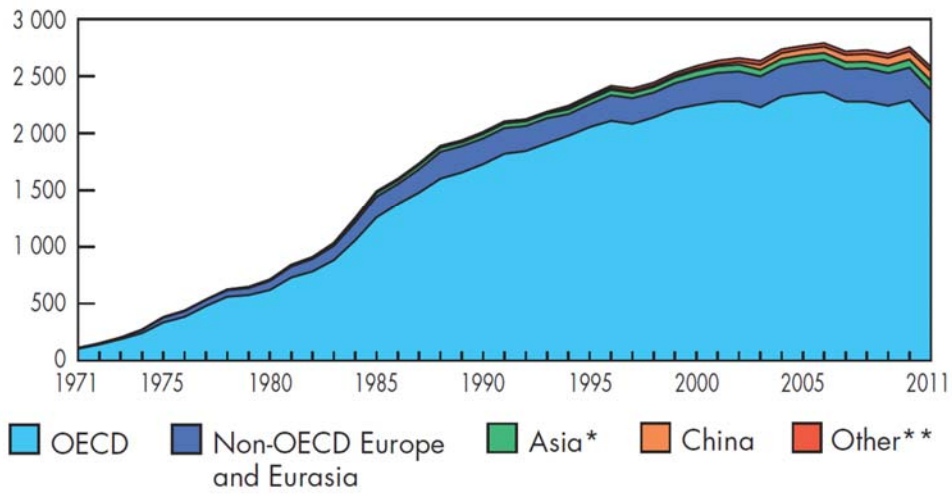
World electricity generation from 1971 to 2011
by fuel (TWh)



- Electric power generation is highly dependent upon fossil fuels, especially coal and natural gas.

Nuclear Production of Electric Energy

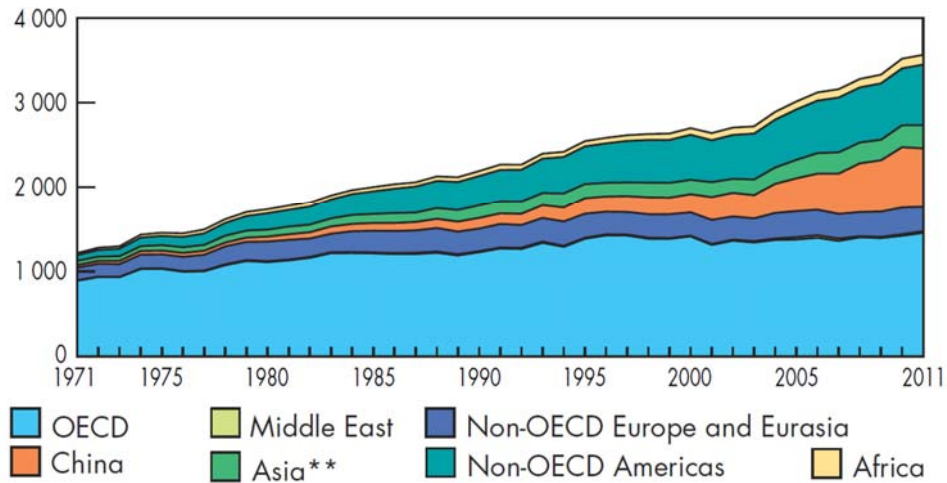
Nuclear production from 1971 to 2011
by region (TWh)



- Production of electric energy by nuclear generating systems has declined for several years, most noticeably in the OECD.

Hydro Production

Hydro* production from 1971 to 2011
by region (TWh)



- Hydro production, which has been stable in the OECD is growing in China and in Southeast Asia in general.

Fuel Used for Production of Electricity - 2011

Coal/peat	TWh	Natural gas	TWh	Oil	TWh
People's Rep. of China	3 723	United States	1 045	Japan	153
United States	1 875	Russian Federation	519	Saudi Arabia	142
India	715	Japan	374	Islamic Rep. of Iran	67
Japan	281	Islamic Rep. of Iran	160	Mexico	48
Germany	272	Mexico	156	Indonesia	42
South Africa	243	United Kingdom	147	United States	40
Korea	225	Italy	145	Kuwait	36
Australia	173	Egypt	117	Pakistan	34
Russian Federation	164	Korea	116	Russian Federation	27
Poland	141	India	109	Egypt	25
Rest of the world	1 332	Rest of the world	1 964	Rest of the world	444
World	9 144	World	4 852	World	1 058

We use the fuels which are available to us



- In these summary tables, we see that Coal produces more than three times the electric output of natural gas.
- Oil is not generally used to produce electricity as it is reserved for transportation where it is far more useful.
- Growth of natural gas output in the US from unconventional drilling has allowed increased use of this fuel for electric production.
- The lesson we learn here is that each country will use the fuel that represents the best combination of cost effectiveness.

Sources of Energy for Electricity Production

Non-renewable

- Coal / Peat
- Gas
- Nuclear
- Oil

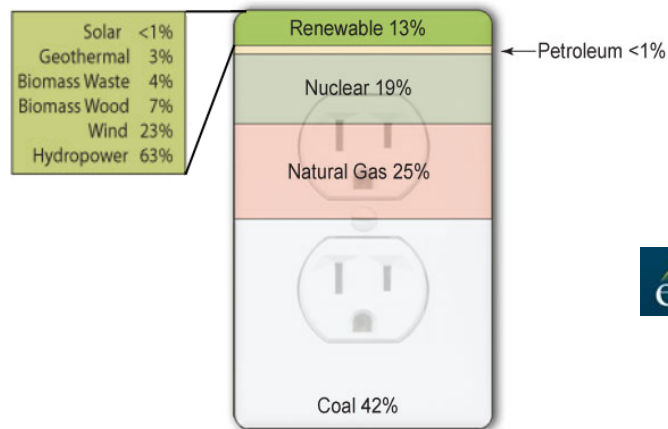
Renewable

- Hydro
- Wind
- Bio Fuels and Waste
- Solar
- Geothermal
- Tidal / Wave



- The DOE has divided fuel type into non-renewable and renewable.
- (The illustration was from the DOE site c.2011).

U.S. Sources of Electricity Generation, 2011

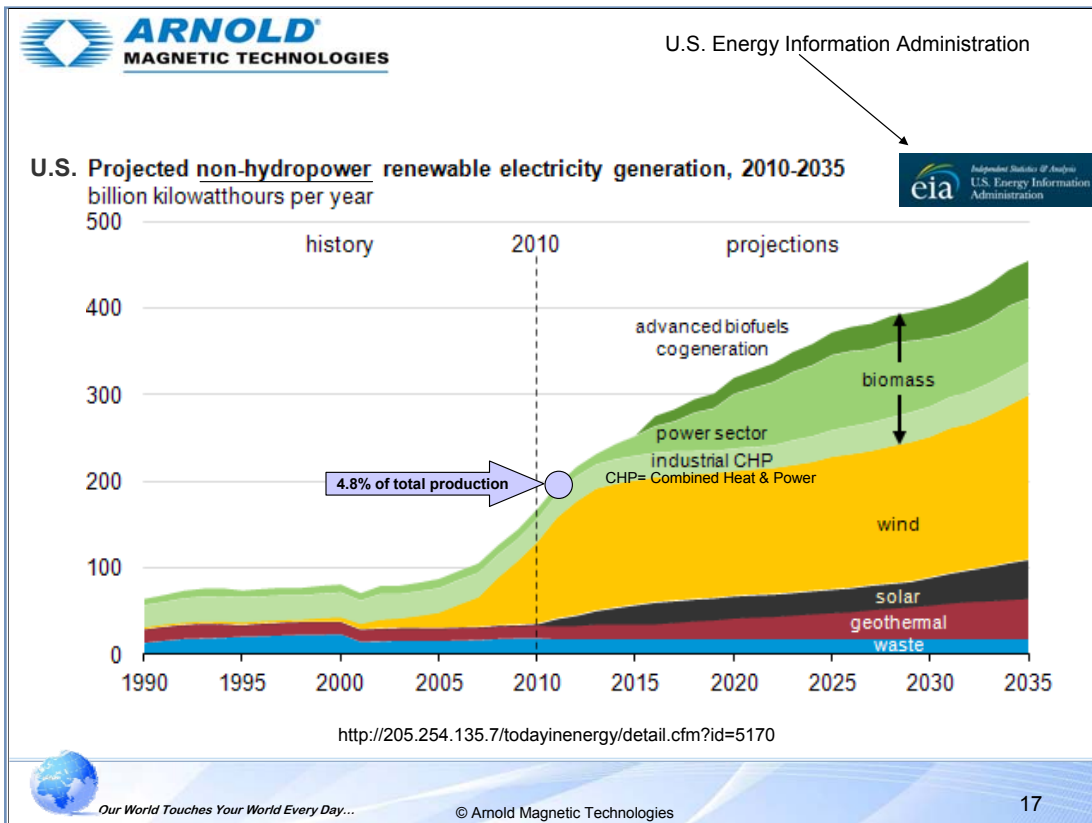


Note: Includes utility-scale generation only. Excludes most customer-sited generation, for example, residential and commercial rooftop solar installations

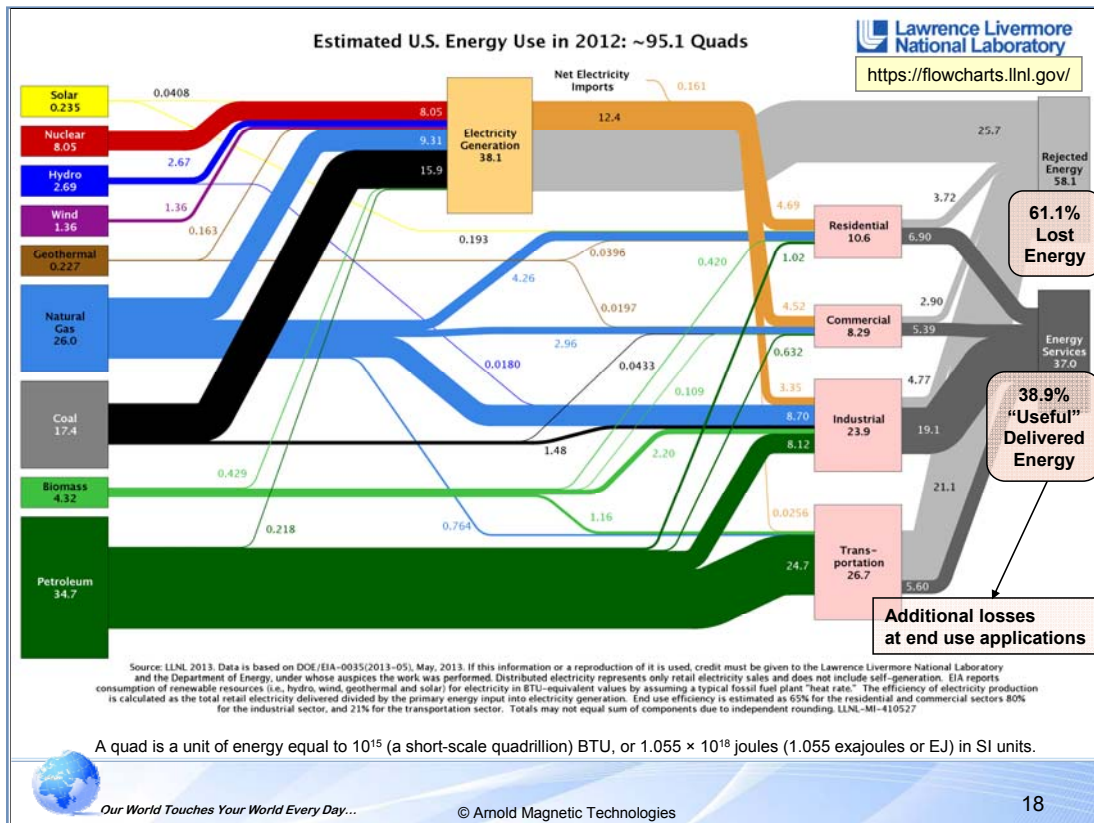
Source: U.S. Energy Information Administration, *Electric Power Monthly* (March 2012). Percentages based on Table 1.1, preliminary 2011 data.



- Renewable sources of electric generation were 13% of the total in 2011.
- As expected, oil (petroleum) was less than 1%.



- This is a powerful graphic!
- In 2011, output from non-hydro renewable energy sources was 4.8% of total.
- This forecast chart suggests that output will slightly more than double by 2035.
- If overall demand remains constant, renewables will account for about 11% of energy output.
- If overall electric energy demand increases at a CAGR of 1%, then non-hydro renewables will represent only 8.5% of the total.
- With hydro output remaining constant, total renewables (hydro plus non-hydro) will represent approximately 14.9% of electric production – which means that 85% will still be produced by fossil fuels.



- Lawrence Livermore National Labs produces Sankey diagrams for over one hundred countries of the world showing sources of energy and output.
- For the US, it is notable that more than half of the energy is lost in production and distribution.
- Electric production is shown in the top tan-colored box.

- Efficiency of fuel extraction & production
 - Net energy balance
 - Example: Ethanol production
- Use of toxic or hazardous materials during exploration and production
 - Environmental impact
 - Example: use of toxic or carcinogenic ingredients in high volume hydro-fracking
- End-use by-products (waste)
 - Storage and disposal
 - Example: Storage of radioactive waste from nuclear plants
- “Side effects”
 - Affect on cost of other essential products
 - Example: use of corn for bio-fuel increases price of food and animal stocks dependent upon corn for feed (hogs, beef, chickens)
- Byproducts of use
 - Example: carbon dioxide, ozone, aldehydes, nano-particulate carbon

There are no simple choices

- - only informed, intelligent decisions.

Series of articles submitted by Caterpillar to National Geographic Magazine – 1970's.



- Sources of energy will continue to be an issue with at least these considerations.

Energy, entropy and the “strive to thrive”

Efficient **Production**

Efficient **Transmission**

Efficient **Use**

...of electrical energy



- With the demand for electricity for commercial and personal use, it is apparent that we must strive for more efficiency in production, transmission and use.
- Magnetic materials play important roles in all three areas.

Agenda

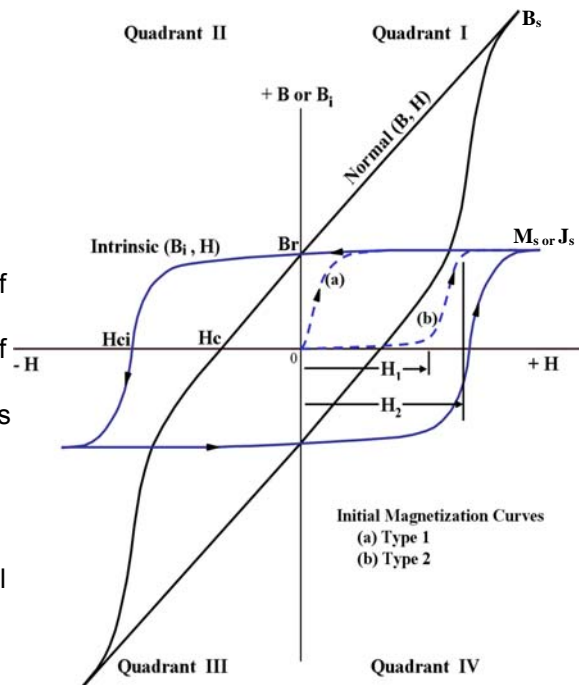
- It's all about energy
- Soft magnetic materials
- Permanent magnet materials
- Materials market & pricing
- Permanent magnet applications
- Development of existing materials
- R & D (elemental discussion)



- While motors and generators can operate without permanent magnets, soft magnetic materials to direct the “flow” of the magnetic field are highly beneficial.
- On a weight basis, far more soft magnetic material is produced each year than permanent magnets – greater than 20x more.

An Introduction to Magnetic Hysteresis

- “H” is the applied magnetic field
- “B” is the measured, induced field (“induction”)
- Normal curve is a measurement of the applied plus the induced field
- The Intrinsic curve is a measure of only the induced field and represents the magnetic properties of the magnet under test
- The dashed lines represent starting with an unmagnetized material
- Once magnetized, the material will be driven around the hysteresis loops represented by the solid lines

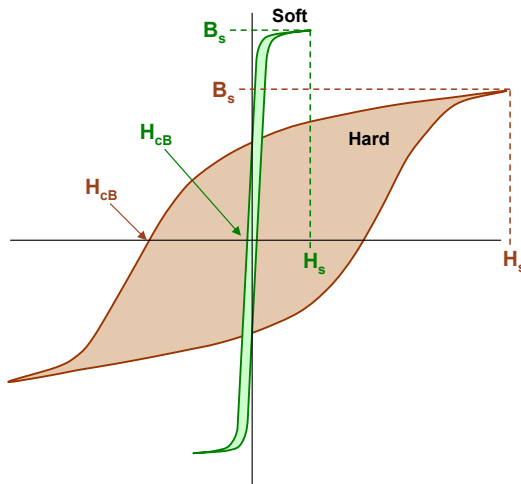


Source: ASTM A977-07 – Standard Test Method for magnetic properties of high coercivity permanent magnet materials



- I believe I am safe when saying that all magnetic materials are examined primarily for their hysteresis properties.
- In response to an externally applied field, magnetic materials generate an internal field – an induced field.
- As we apply a stronger field in a direction (+H), weaken it and then 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 as 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 (by changing the applied field), we see that the 1st and 3rd quadrant are identical, though of reverse sign just as the 2nd and 4th quadrants are the same.
- The dashed lines in this graphic display initial magnetization.
- When initially magnetizing the sample, the terms Type 1 and Type 2 shown in this chart refer to the coercivity mechanism where Type 1 coercivity is due to a “nucleation” mechanism and Type 2 is caused by domain pinning.

Hysteresis Energy



- A narrow hysteresis loop implies a small amount of dissipated energy. This is desirable to minimize energy loss in transformers and rotating machinery (motors).
- The energy expended in driving the material through its hysteresis loop is represented by the area within the loop (the shaded area).
- A broad loop with large hysteresis energy is typical of permanent magnetic materials.

These are "Normal" or "B" curves, not Intrinsic curves.



- The magnetic hysteresis loop provides a great deal of information about the material.
- First, it identifies the type of magnet: soft or permanent.
- A magnetically "soft" material has very small H_{cB} and the area within the loop is small, such as for the green curve and area shown here.
- On the other hand, a permanent magnet exhibits a much greater H_{cB} and a larger area within the loop as shown in the tan portion of the figure.
- Both curves, as shown here, are Normal curves. The green soft material is typical of silicon iron (Si-Fe) and the red curve is typical of alnico 8.
- The values of B_s represent the magnetic saturation and H_s is the applied field strength at which saturation occurs.
- The energy to force a magnet around the loop is proportional to the area within the loop.
- Therefore, transformers and laminations in motors benefit from being made of soft materials with very low H_{cB} and correspondingly small areas within the loop.

Definition and Examples

		H_{cB}	H_{cJ}	H at Bsat	Bsat. (~Msat.) ^A
Overview	Soft	< 25	< 25	< 700	X
	Semi-Hard	25 to ~700	25 to ~700	~700 to 2000	
	Permanent	> 700	> 700	> 2000	
Soft	Supermalloy	0.003		2	7,800
	Deltamax	0.08		10	16,000
	Si-Fe	0.6		100	19,500
Semi-Hard	FeCrCo ^B	50-300		700	9,000 - 12,000
	Remalloy	250		1,000	15,200
	Vicalloy	250		1,000	14,500
	Cunife	500		1,500	8,400
	Cunico	700		1,500	8,800
Permanent	Alnico 5-7	740	750	2,000	13,500
	Alnico 8	1,600	1,800	4,500	10,500
	Ferrite (Ceramic 8)	3,000	3,500	6,000	4,500
	SmCo 1:5 (R20)	8,700	30,000	30,000	10,000
	SmCo 2:17 (R26)	9,900	25,000	45,000	11,500
	NdFeB (N38SH)	12,000	20,000	35,000	14,000

^A Soft and Semi-Hard materials use Bsat.; PM materials use Msat.

^B FeCrCo can be heat treated to yield many combinations of Hc and Bsat.



- There is actually a continuum of materials from very soft to very hard.
- We can divide them into soft and hard magnetic materials or we can split them into three categories (as shown here) wherein each category has specific benefits.
- For convenience we have assigned arbitrary values to distinguish one category from the next, but there is no hard rule regarding the differentiation in category.
- Note that alnico is considered (for the most part) a permanent magnet material, yet the Normal curve is used to describe magnetic properties, not the Intrinsic curve. (Alnico was the first permanent magnet with appreciable coercivity).
- When Ferrite magnets were invented, suddenly we had a material with H_{cJ} much larger than H_{cB} and it became common practice to provide both the Normal and the Intrinsic curves.
- Some materials, such as FeCrCo, can have various levels of H_{cB} by adjusting the final heat treatment time, temperature and quench rate.

What Makes a Soft Magnetic Material *good*?

Key Characteristics of Soft Magnets

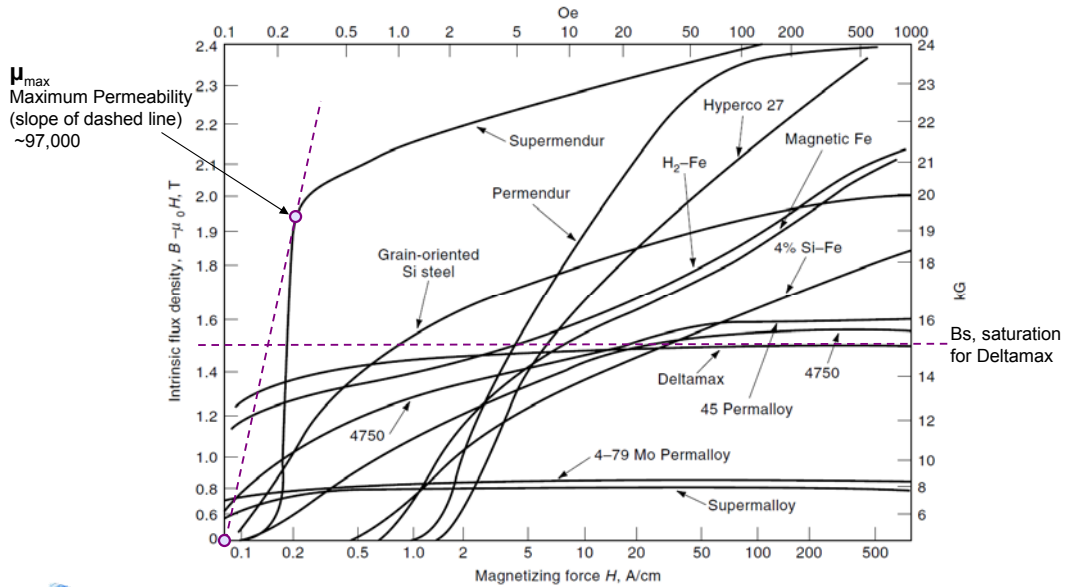
Related to eddy current
and hysteresis loss in
transformers and in
motors & generators

- Saturation magnetization (B_s or M_s)
- Coercivity (H_{cB}) (smaller is better)
- Ease of magnetization (maximum permeability is large)
- Electrical resistivity (higher is better)
- Usable temperature range
- Small magnetization change with temperature (RTC)
- Corrosion resistance
- Compromise of physical strength and malleability
 - Formability, for example to make laminations
- Manufacturability and formability
- Material availability and product cost



- The four most important characteristics of a soft magnetic material, determined by where the material is used, are shown at the top of this list.
- Electrical resistance affects eddy current and coercivity affects hysteresis loss of the material, both of which cause the material to absorb energy and heat up.
- It is the nature of the materials that most (but not all) magnetically soft materials are also physically “soft”. That is they are malleable – can be rolled to thinner strips or bent to shapes.
- If the material is deformed or mechanically worked, it may be desirable to thermally anneal it to re-establish low H_{cB} .

Soft Magnetic Alloys 1st Quadrant of the Hysteresis Loop



Source: Kirk-Othmer Encyclopedia of Chemical Technology; Magnetic Materials, Bulk; Jack Wernick, Bell Telephone Laboratories, Inc.



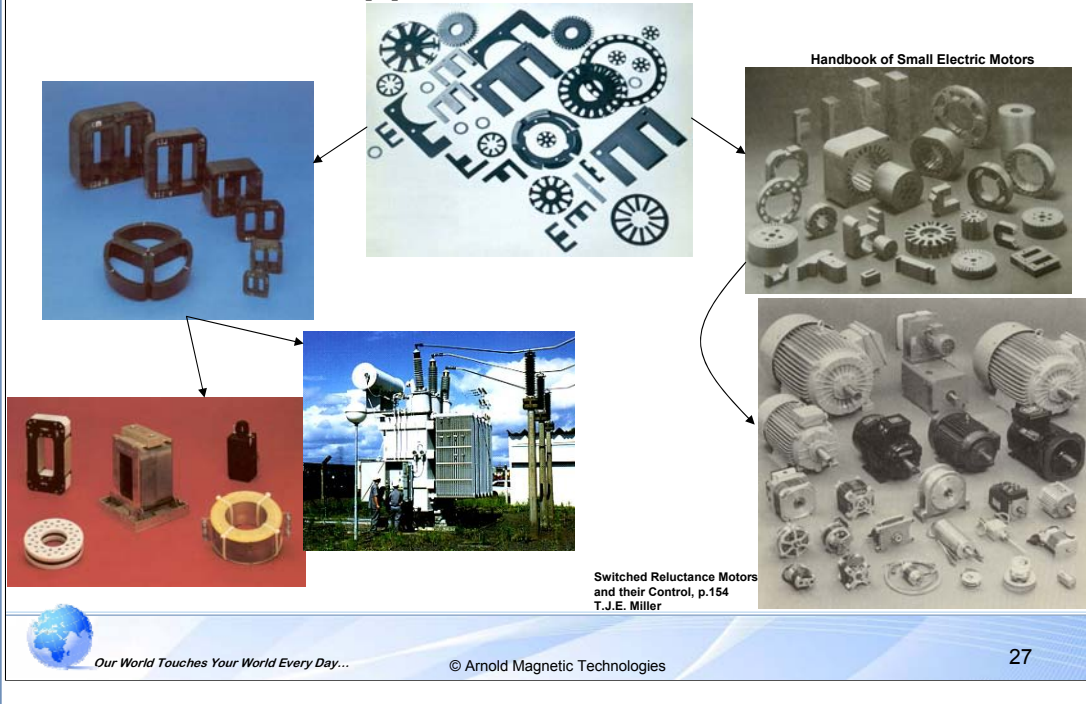
Our World Touches Your World Every Day...

© Arnold Magnetic Technologies

26

- The magnetic properties of interest for soft magnetic materials lie in the entire hysteresis loop or in the 1st quadrant.
- The two most interesting values in the 1st quadrant are the maximum permeability which is the slope of a line from the origin to the “knee” of the curve such as the dashed line in this chart hitting the Supermendur curve at the mark.
- The higher the slope, the easier the material is to magnetize.
- The second figure of interest is the saturation magnetization – on these curves, the value of B_s , and shown here for Deltamax with the near-horizontal dashed line.

Two Main Applications for Electrical Steel



- The most commonly used soft magnetic material is silicon-iron (Si-Fe, aka electrical steel) and as you may be aware, there are two major uses for it: Transformers/Inductors and Motors/Generators.
- Transformers are used not only for Electrical Power Distribution, but in virtually every power supply in every electrically powered electronic device in offices and homes.
- Motors have moved from industrial uses in the 1800's and early 1900's to home and automotive uses. In homes for example, we use motors in garage door openers, washing machines and dryers, furnaces for home heating, refrigerator compressor pumps, bathroom exhaust fans, garbage disposals, and electric powered shop tools.
- Motor usage in automobiles has expanded to include windshield wiper motors, seat adjusting motors, starters, cooling fans, passenger compartment fans, alternators, etc. Note however, many of these use low carbon steel cans for low cost and Si-Fe laminations are reserved for higher output, higher efficiency motors/generators.
- The newest example of lamination steel use in cars is the electric traction drive motor of hybrids or full electric vehicles.

Agenda

- It's all about energy
- Soft magnetic materials
- Permanent magnet materials
- Materials market & pricing
- Permanent magnet applications
- Development of existing materials
- R & D (elemental discussion)



- Now a look at permanent magnets.

What makes a permanent magnet *good*?

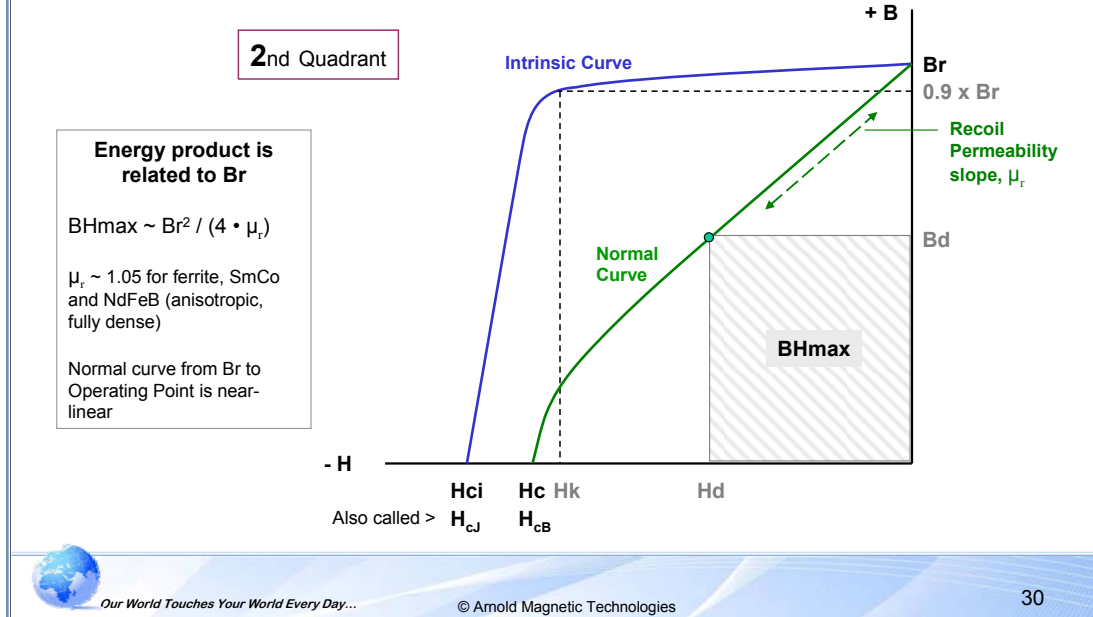
Key figures of merit

- Flux density (Br)
- (Maximum) Energy Product (BHmax)
- Resistance to demagnetization (H_{cJ})
- Usable temperature range
- Magnetization change with temperature (RTC)
- Demagnetization (2nd quadrant) curve shape
- Recoil permeability
- Corrosion resistance
- Physical strength
- Electrical resistivity
- Magnetizing field requirement
- Available sizes, shapes, and manufacturability
- Material availability and product cost



- Permanent magnets have a list of key characteristics that differs from soft magnetic materials.
- For each application a subset of these characteristics will determine how well a material is suited to the application.
- All of these should be considered when selecting a material and when performing R&D.
- The most discussed figure of merit is “maximum energy product”, abbreviated BHmax.
- A spring can be thought of as analogous to a magnet. We compress and release a spring to take advantage of its ability to store energy. Similarly, we magnetically “compress” the field from a magnet.
- The amount of energy we can temporarily store in a magnetic circuit is proportional to the magnet’s maximum energy product. Since these are supposed to be “permanent” magnets, we would not want them to demagnetize, so also important is the value of H_{cJ} which is a measure of resistance to demagnetization.
- Magnetic properties change with temperature, so it is important when selecting a material for an application to know what the properties are over the entire range of expected temperatures.

Permanent Magnet Key Characteristics



- 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.
- These calculations can only be made with a “straight line” material. (This does not work for alnico).
- 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).

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

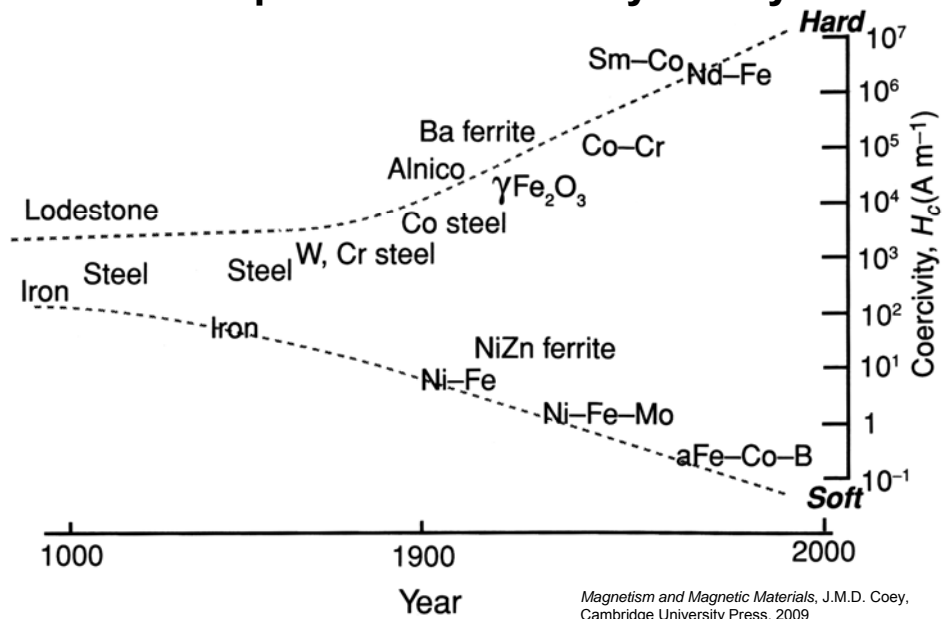
Table based on information in *Advances in Permanent Magnetism* by Rollin J. Parker, p.331-332

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 ₂ TM ₁₄ B	1984	26.0	25,000
		35.0	11,000
RE ₂ TM ₁₄ B	2010	30.0	35,000
		52.0	11,000



- 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 typical.
- 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 was alnico starting in the late 1930's.
- This was followed by Ceramic (Hard Ferrite) magnets starting in the mid 1950s.
- Increased values of both maximum energy product (BHmax) and Hci, resistance to demagnetization, were made culminating with the rare earth magnets: SmCo and "Neo" magnets (RE₂TM₁₄B).

Development of Coercivity - Coey



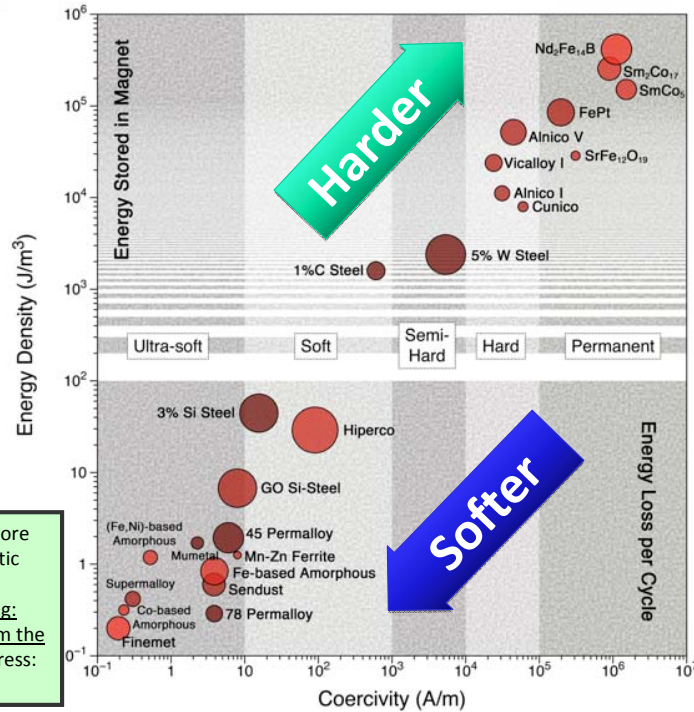
Magnetism and Magnetic Materials, J.M.D. Coey,
Cambridge University Press, 2009



- Michael Coey graphically expresses the improvements to magnetic materials with soft materials achieving ever lower H_c and permanent magnetic materials exhibiting higher H_{ci} .

Development of Coercivity and Energy Product

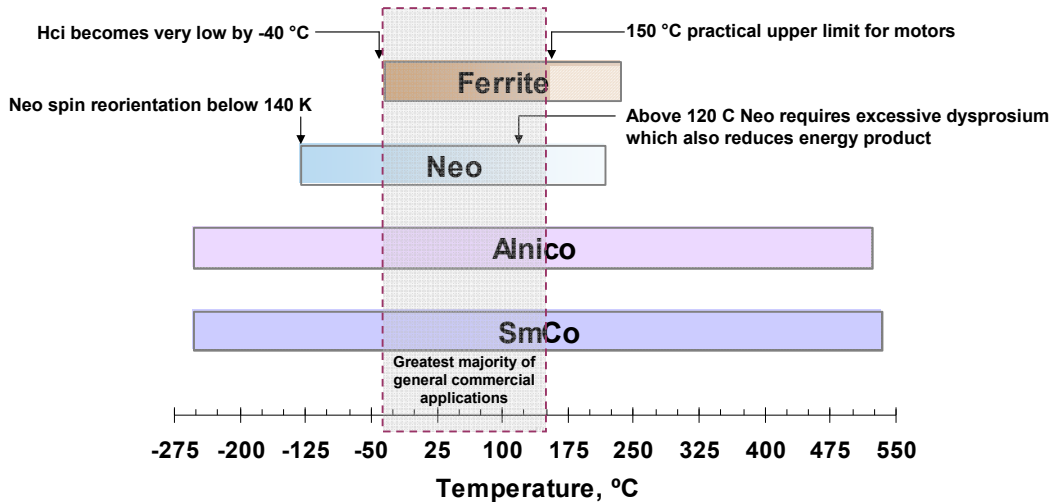
M. A. Willard, "Stronger, Lighter, and More Energy Efficient: Challenges of Magnetic Material Development for Vehicle Electrification" *Frontiers of Engineering: Reports on Leading-Edge Engineering from the 2012 Symposium*, National Academies Press: Washington, DC (2013) pp. 57-63.



- Focusing on Coercivity and Energy Density (Maximum Energy Product), Matthew Willard provides this chart.
- Permanent magnets get better toward the upper right while soft magnetic materials improve toward the bottom left.

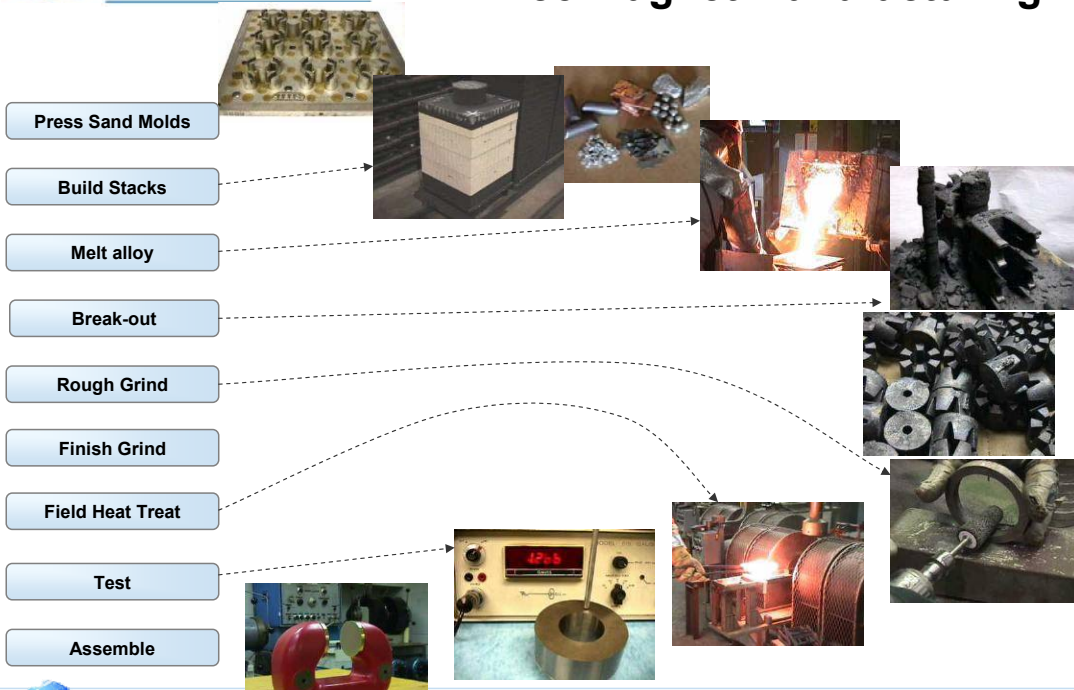


Usable Temperature Range for commercial permanent magnets



- A key characteristic in selecting the best magnet is the temperature range of the application.
- We note here that both Neo and ferrite magnets have a more limited useful temperature range than SmCo and alnico.
- 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.
- Ferrite can be theoretically used to over 350 °C. However, even by 150 °C, it loses 25% of its flux output and so that is a practical limit for motor applications.

Alnico Magnet Manufacturing



Our World Touches Your World Every Day...

© Arnold Magnetic Technologies

Ferrite Magnet Manufacturing

Blend Powder Slurry

Calcine

Mill

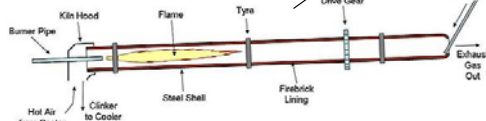
Storage: Dry or Slurry

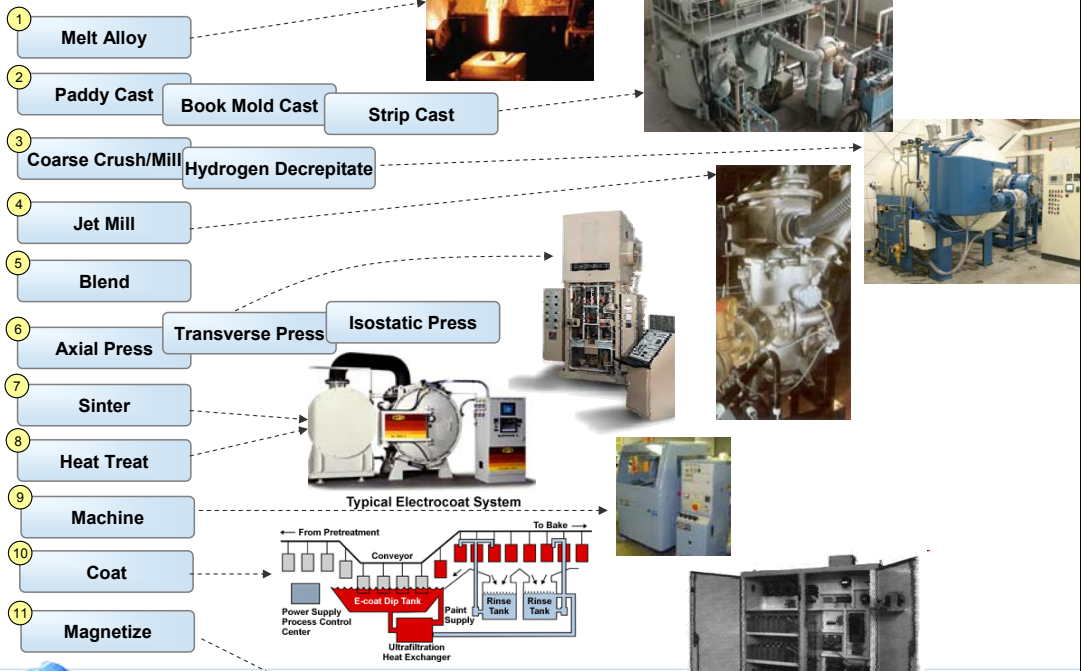
Press

Sinter

Grind / Slice

Test





Our World Touches Your World Every Day...



Magnet Producers

China totally dominates production of raw materials for and manufacture of permanent magnets. They are also, by far, the largest market for magnets.

	China	Japan & Korea	USA	Europe
ALNICO	Atlas Magtech Chengdu Amoeba China Hope Magnet HPMG Shanghai Dao Ye Many others	Pacific Metals	Arnold T&S PM Co.	SG Magnets Ltd Magnetfabrik Bonn Magneti Ljubljana
FERRITE	Anshang Dekang BGRIMM DMEGC Dongyang Gelin Jiangmen >50 more	Hitachi TDK	Hitachi TDK	Magnetfabrik Bonn Magnetfabrik Schramburg Ugimag
SmCo	Arnold Chengdu Mag Mat'l TianHe Tiannu Group Yunsheng >30 more	Hitachi Shin-Etsu TDK	Arnold EEC	Arnold Magnetfabrik Bonn Magnetfabrik Schramburg Vacuumschmelze
NdFeB*	Anhui Earth-Panda AT&M BGMT Ningbo Jinji San Huan Thinova Yantai Zhenghai Yunsheng >150 more	Daido Hitachi Shin-Etsu TDK	Hitachi	Magnetfabrik Bonn (not licensed) Magnetfabrik Schramburg Magneti Ljubljana (not licensed) Vacuumschmelze (Neorem)

*Licensed To sell into the USA



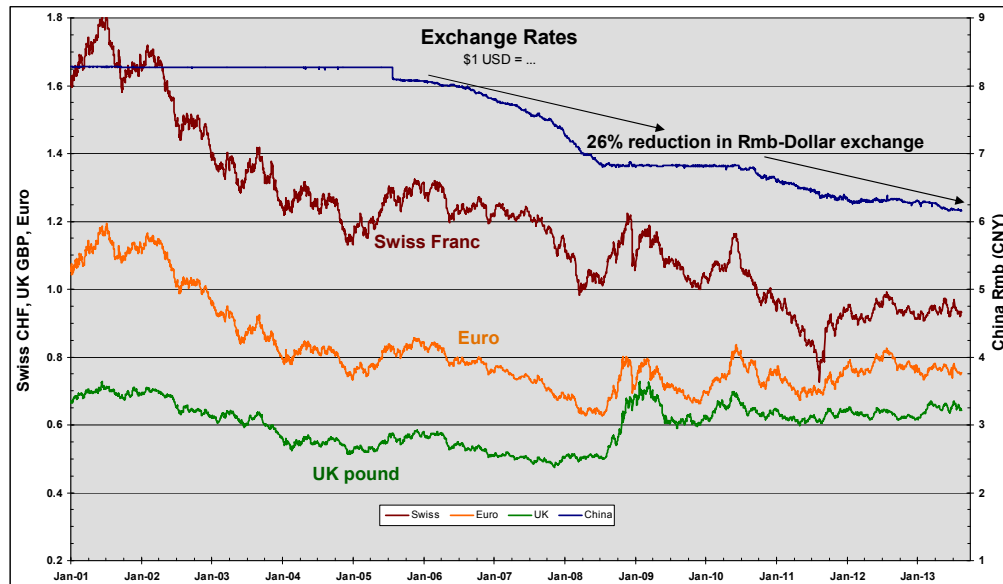
- China has for several years dominated in the production of permanent magnets.
- It has become increasingly obvious that they also consume the “lion’s share” of product.
- For example, they produce about 80% of the world’s rare earth magnets and export only 10% to the USA as magnets. Far more enter the US as magnets within products.
- If similar statistics apply to Europe, then China retains about 80% of the magnets they produce for re-sale domestically.

Agenda

- It's all about energy
- Soft magnetic materials
- Permanent magnet materials
- Materials market & pricing
- Permanent magnet applications
- Development of existing materials
- R & D (elemental discussion)

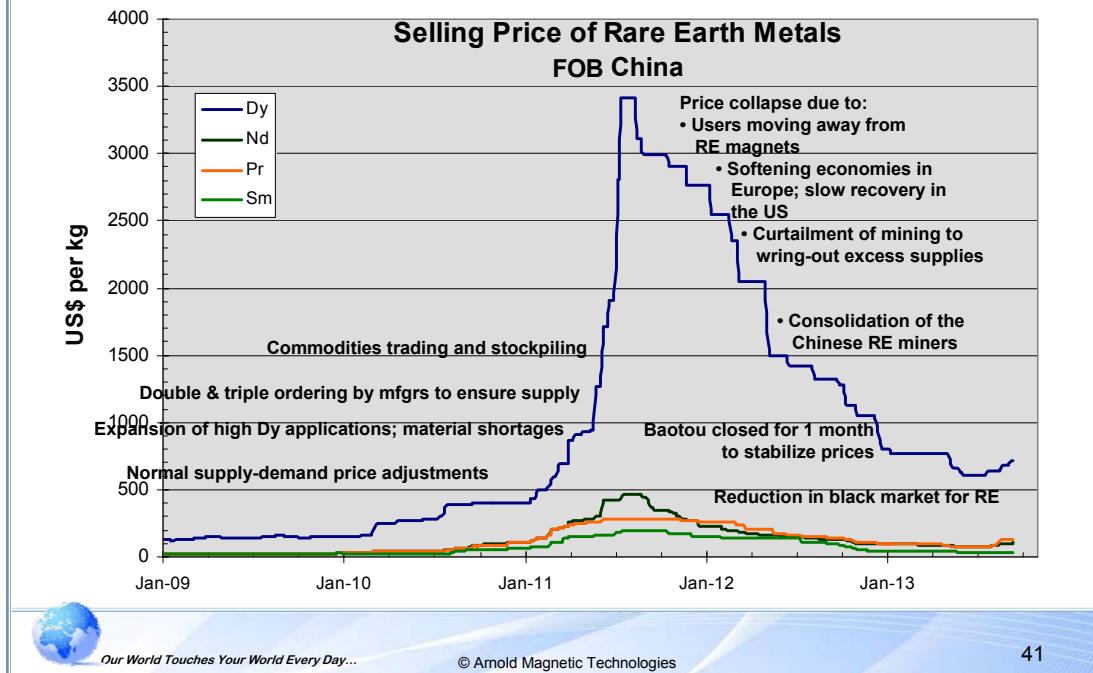


Currency Exchange Rates Relative to the US dollar



- In addition to quotas and tariffs (export and import), currency exchange rates also affect pricing of materials.

RE Metal Pricing



- Rare earth materials have experienced price inflation and market disruption.
- FOB China pricing is shown here.
- Notes on the chart indicate the main price drivers.
- It is educational to note that when prices became too high, users of rare earth magnets designed away from them and are now slow to return.

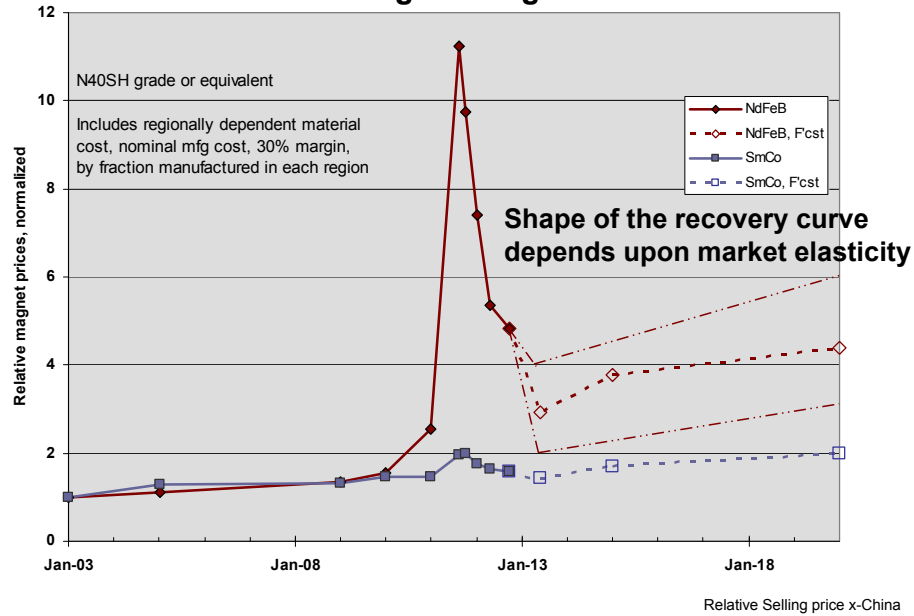
Australian Resources: addressing the rare earth balance issue

Current prices are not supportive of sustainable supply, let alone new production: Consolidation, and an increasing focus on the environmental impact of mining have seen operating costs in China increase. In response to falling prices China's largest mine announced production curtailments in December 2012. Western producers have also indicated there are likely to be delays to growth projects, and Lynas announced it would look to set a floor for prices. While we believe prices could continue to fall in the short-term, we expect light-rare earth basket prices to increase from US\$16/kg currently to US\$18/kg in 2014, US\$22/kg in 2015 and US\$27/kg in 2016.

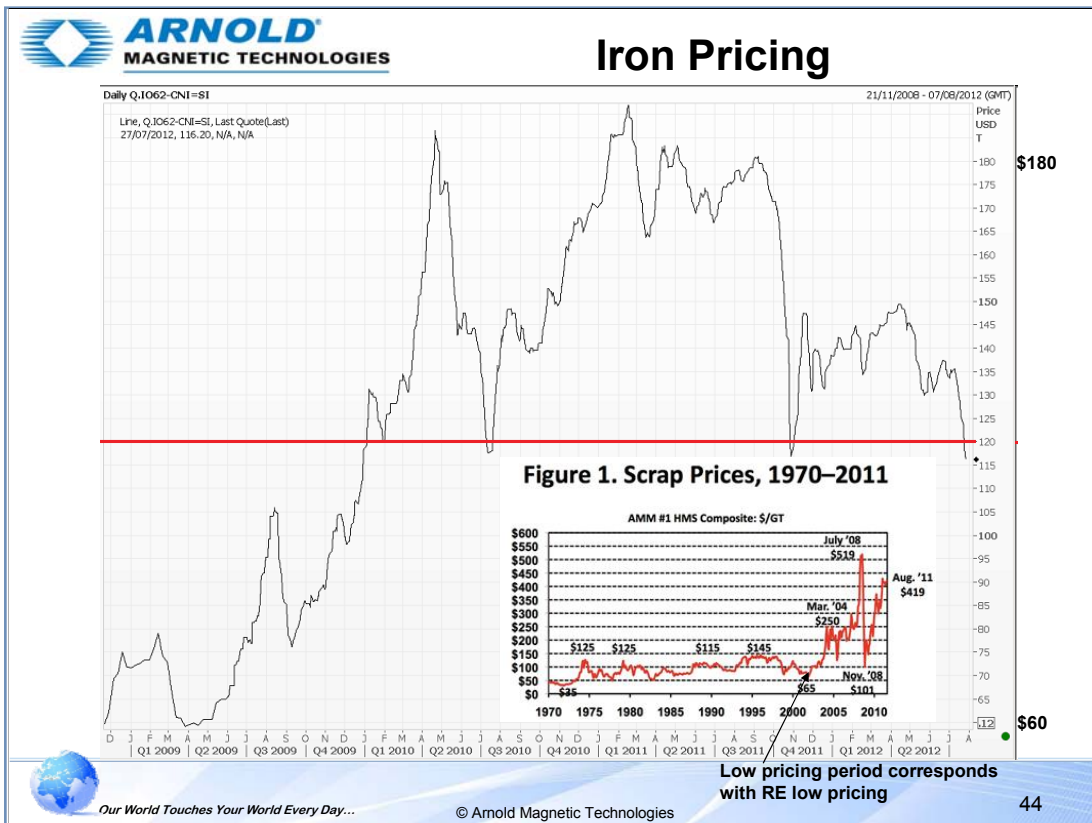
From document of same name, J.P. Morgan, Australia Equity Research, 11 July 2013



Relative Change in Magnet Prices

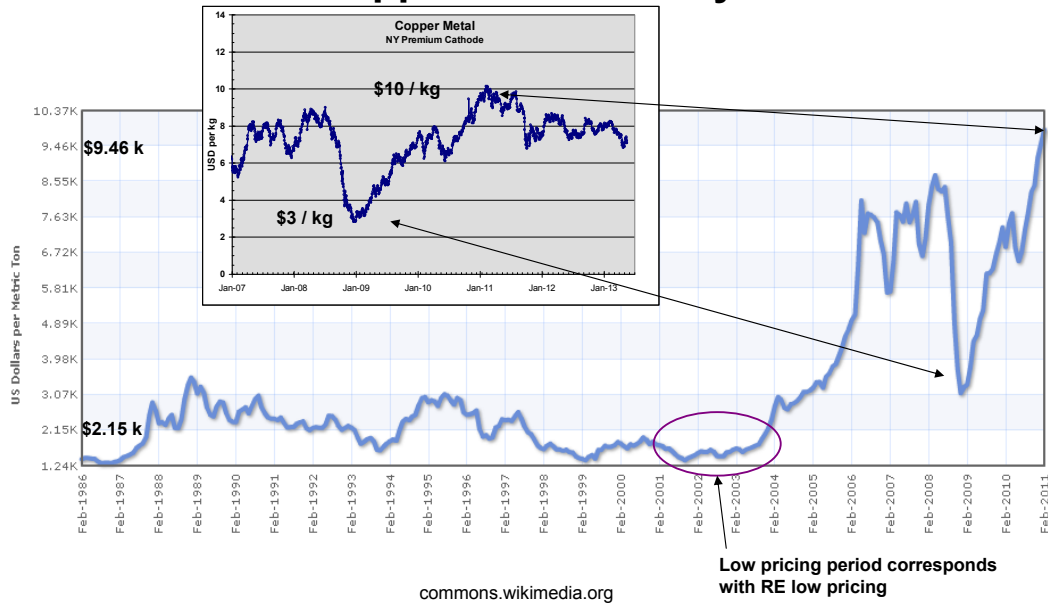


- This is my attempt to forecast relative magnet prices going forward based on costs over the past 9 years.
- It shows a slow continual uptick in SmCo magnet pricing.
- It also assumes that Neo magnet pricing will bottom out in early 2013 and rise slowly going forward and this appears to be happening.
- Dashed lines provide pessimistic and optimistic pricing as well as a likely middle value.



- Rare earths have not been the only materials to experience pricing cycles as we can see here with iron.
- Iron is a major constituent of electromagnetic devices on a weight basis so a doubling of cost can have a profound affect on product cost even though the cost per kilogram is not as great as for NdFeB magnets.

Copper Price History



commons.wikimedia.org

Low pricing period corresponds
with RE low pricing

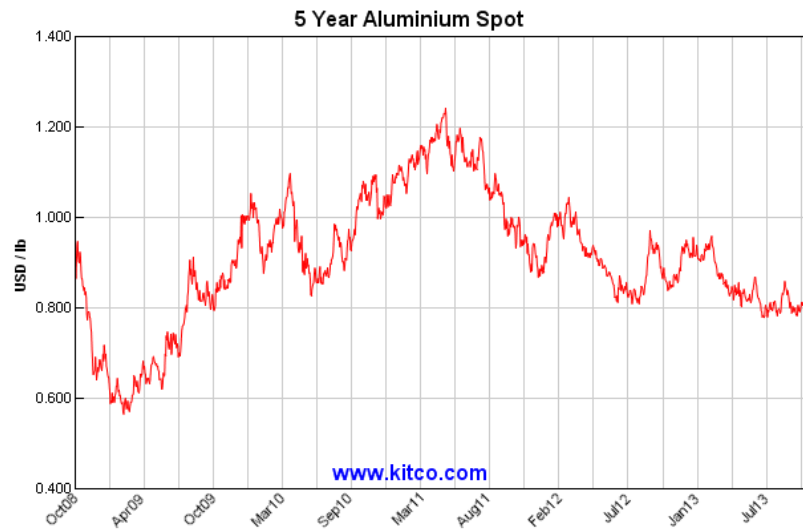


Our World Touches Your World Every Day...

© Arnold Magnetic Technologies

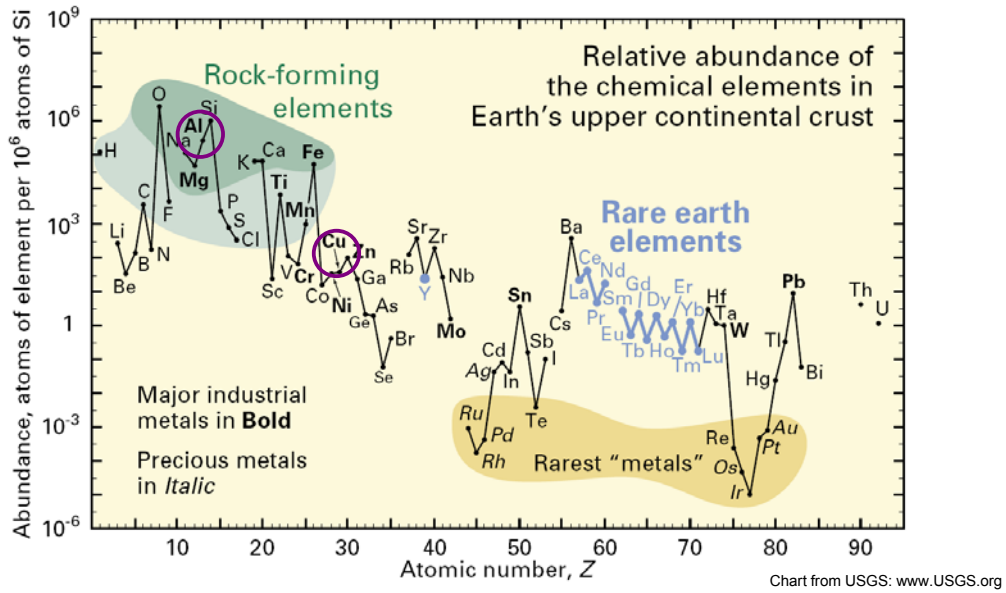
- And even induction and synchronous reluctance motors, which do not use permanent magnets, require field generation from coils of copper wire.
- These charts show copper price swings of 500%.

Aluminum Pricing



- Aluminum is the third most prevalent material in the crust of the earth.
- Yet it too experiences wide price swings as supply and demand get out of synch.
- It is difficult for the mining-processing industry to respond to rapid swings in market demand.

Widely Available Materials



- Copper is only slightly more prevalent in the earth's crust than neodymium.

Copper / Aluminum

- Main uses
 - Copper in the windings of the stator (and rotor – brushed type)
 - Copper in transformer windings
 - Aluminum in the rotor of induction motors
- Neither copper nor aluminum is considered a critical material or in short supply, however...
 - Price swings regularly occur due to supply-demand imbalance
 - Aluminum is present in the earth's crust in higher quantity than copper: about 8 000x more Al than Cu

Bauxite (aluminum) mine



Open pit copper mines



- Both copper and aluminum are obtained from very large mines.

Agenda

- It's all about energy
- Soft magnetic materials
- Permanent magnet materials
- Materials market & pricing
- Permanent magnet applications
- Development of existing materials
- R & D (elemental discussion)



Major PM Materials

	2010				2015			
	<u>tons</u>	<u>%</u>	<u>\$\$\$</u>	<u>%</u>	<u>tons</u>	<u>%</u>	<u>\$\$\$</u>	<u>%</u>
NdFeB	67,300	10.5%	5,700	<u>65.1%</u>	80,015	8.2%	9,305	<u>62.6%</u>
SmCo	2,310	0.4%	270	3.1%	3,510	0.4%	540	3.6%
Ferrite	567,000	<u>88.2%</u>	2,600	29.7%	881,120	<u>90.7%</u>	4,760	32.0%
Alnico	5,555	0.9%	125	1.4%	6,440	0.7%	185	1.2%
Other	540	0.1%	65	0.7%	580	0.1%	75	0.5%
Totals	642,705	100.0%	8,760	100.0%	971,665	100.0%	14,865	100.0%

Sales \$\$ are in millions



- These are the most common permanent magnet materials.
- While neo magnets now represent between 62 and 65% of magnet sales on a dollar basis, ferrite dominates on a weight basis at over 88%.
- With the improved grades of ferrite both weight and dollar percentages are expected to rise.
- Ferrite magnets are considerably lower cost than rare earth magnets and the raw materials are widely available.

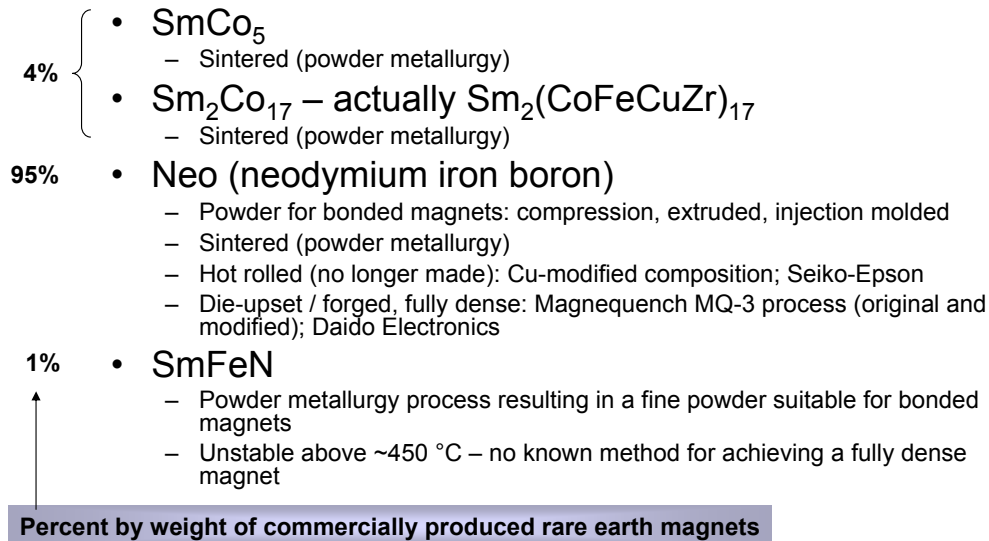
Ferrite Magnet Applications (2010)

Motors - Automotive	18%	} 70%
Motors - Appliances	13%	
Motors - HVAC	13%	
Motors - Industrial & Commercial	12%	
Motors - All Other	5%	
Loudspeakers	9%	
Separation Equipment	5%	
Advertising & Promotional Products	5%	
Holding & Lifting	5%	
MRI	3%	
Relays & Switches	1%	
All Other - Miscellaneous	11%	



- The majority of ferrite applications are motors.
- (Loudspeakers are linear motors).

What are the rare earth magnets?




- Switching to rare earth magnets...
- Since 2010, major topics of interest have been pricing and availability of rare earths and rare earth magnets.
- The materials shown here comprise the family of Rare Earth magnets.
- Although SmCo magnets are superior for elevated temperature applications, the combination of greater material availability and historically lower cost has propelled Neo magnets into a dominant position.
- However, for Neo to perform successfully at elevated temperature requires substituting dysprosium for some of the neodymium.
- Of late, the supply of dysprosium has not been adequate resulting in high material prices and a continuing long-term shortage is likely.
- SmFeN is an excellent material except that 1) it decomposes at a fairly low temperature preventing consolidation to full density and 2) because it must be used as a bonded magnet, maximum energy product is limited by the dilution with a non-magnetic binder.


Rare Earth Magnet Applications (2010)

Motors, industrial, general auto, etc	24.0%
HDD, CD, DVD	16.3%
Electric Bicycles	8.4%
Transducers, Loudspeakers	8.1%
Magnetic Separation	4.6%
MRI	3.9%
Torque-coupled drives	3.3%
Sensors	3.1%
Generators	3.0%
Hysteresis Clutch	2.8%
Air conditioning compressors and fans	2.4%
Energy Storage Systems	2.3%
Wind Power Generators	1.9%
Gauges	1.5%
Magnetic Braking	1.5%
Relays and Switches	1.3%
Pipe Inspection Systems	0.9%
Hybrid & Electric Traction Drive	0.8%
Reprographics	0.6%
Wave Guides: TWT, Undulators, Wigglers	0.3%
Unidentified and All Other	6.6%



- Motors, generators, loudspeakers, represent about 67% of rare earth magnet usage.



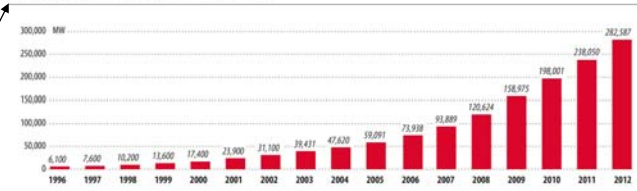


OWC Mercury Electra
3G SSDs
Ultra high-performance for demanding portable and desktop power.
44GB - 960GB SATA From: \$69.99
Sawhorse Edition (Up to 3 Year Warranty)

Market Dynamics

- HDDs vs SDD
- Wind power generators
- FCCs (Fluid Cracking)
- Catalytic Converters
- Air conditioners
- Transportation
 - Rate of adoption
 - PM vs. induction motors
- Others...








Global Cumulative Installed Wind Capacity 1996-2012




Year	Capacity (MW)
1996	4,100
1997	7,600
1998	10,200
1999	13,600
2000	17,400
2001	21,900
2002	27,100
2003	33,411
2004	47,620
2005	59,091
2006	73,930
2007	93,889
2008	120,624
2009	158,975
2010	198,001
2011	238,850
2012	282,587

Source: GWEC

The residential **air conditioning** market in Southeast Asia and Australia is witnessing robust growth rates, thanks chiefly to the rise in gross domestic product (GDP) per capita and steady economic escalation. The boom in urbanization coupled with the increasing purchasing power of consumers has encouraged homeowners to opt for air conditioners over economic alternatives such as air coolers and fans. Climatic conditions also intensify demand, with high temperatures and humidity levels in the area making air conditioners essential.

 Our World Touches Your World Every Day...

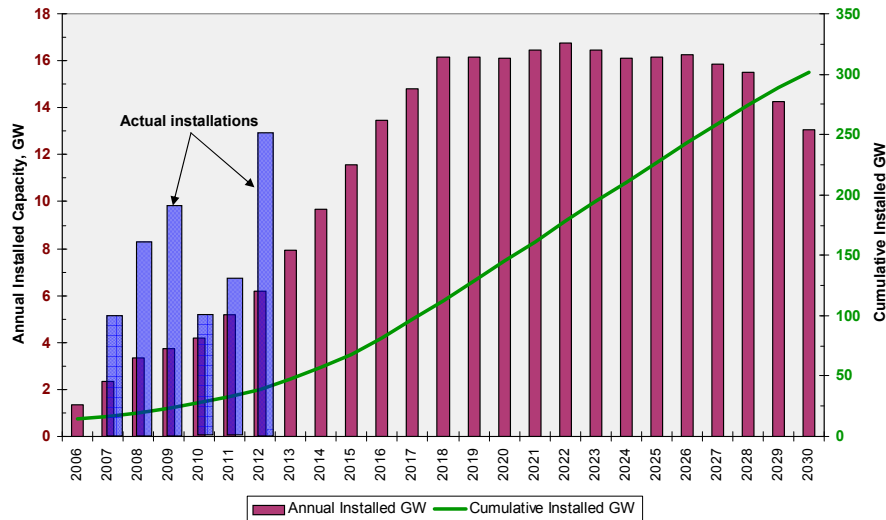
© Arnold Magnetic Technologies

54

- The market for rare earth magnets is experiencing dramatic shifts with a few examples shown here.

Wind Power Installation - USA

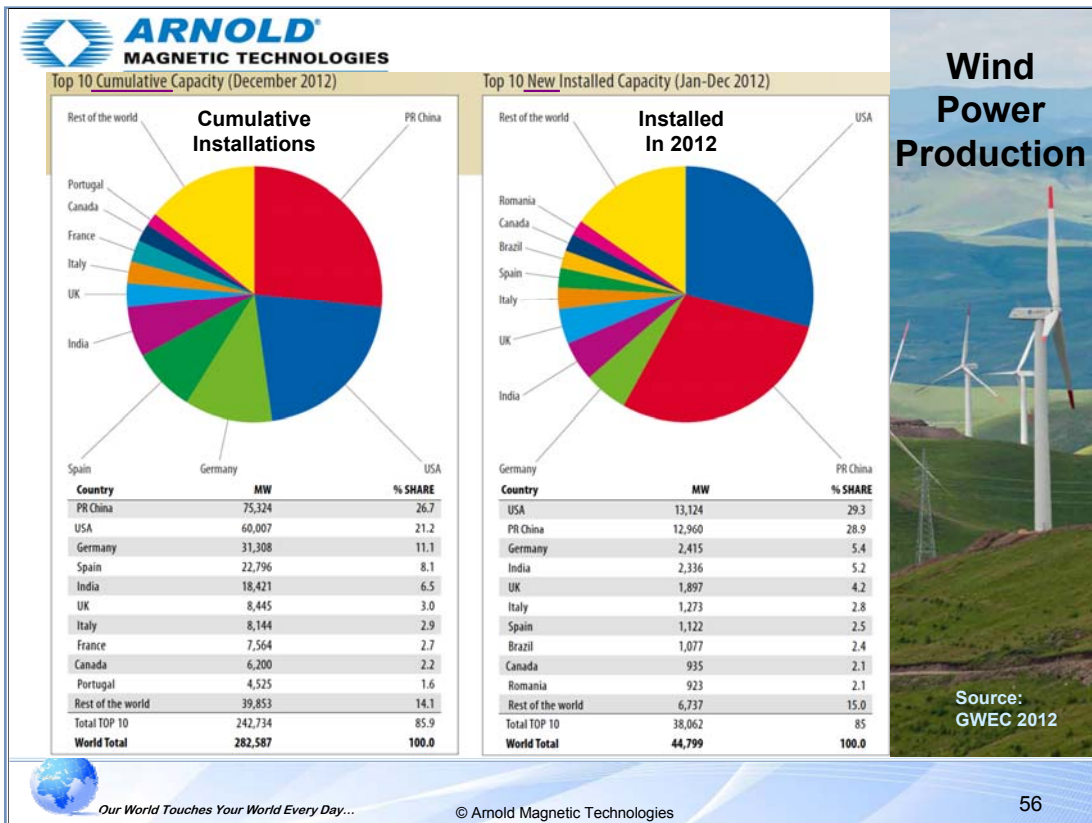
Annual and Cumulative Wind Installations by 2030



20% Wind Energy by 2030, Increasing Wind Energy's Contribution to U.S. Electricity Supply, AWEA, May 2008
IEA Wind 2012 Annual Report, www.ieawind.org/annual_reports_PDF/2012/2012%20IEA%20Wind%20AR_smallPDF.pdf

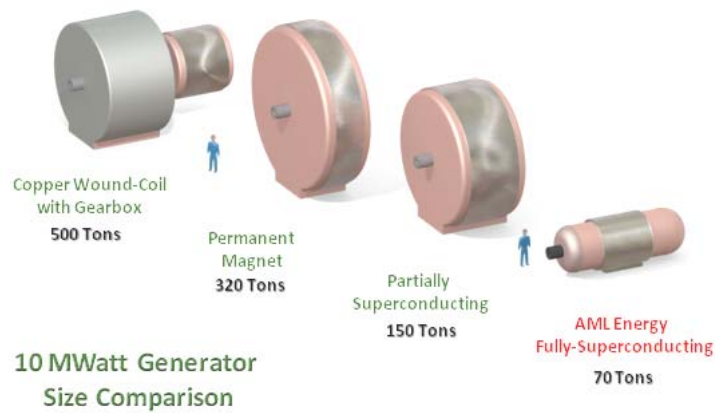


- A market for permanent magnets is wind power – generation of commercial electricity by large, tower-mounted generators.
- In 2008, the American Wind Energy Association (AWEA) forecast installations of wind per the plum-colored bars on this chart.
- I have plotted blue bars to show actual installations each year through 2012.
- Actual installations have exceeded forecast largely due to government incentives.
- In addition to the potential to use permanent magnet generators, there are two other large motors in the tower: 1) the blade pitch motor and 2) the nacelle rotation motor.



- 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 26.7% 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. New installations dropped to 26.9% of global installations in 2012.
- In the USA only 233 permanent magnet generators have been installed out of more than 33,000. In China the number is higher, but no more than 25% of those installed in 2010-2011.

Superconducting Wind Power Generation



REACT: Rare Earth Alternatives for Critical Technologies
Mark Johnson, January 10, 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 installation, etc.
- Size and weight of the nacelle become an increasingly important factor as the output increases above 5 MW. By 10 MW, the only currently feasible technology is suggested to be superconducting generation.

Transportation



- **EB's** (electric bicycles) ([primarily in Asia](#)): large and growing application especially in 3rd world nations



- 20 million sold in China in 2009
- Forecast to 35 million per year in 2015
- Year 2015 neo magnet usage = **3,800 tons**



- **Hybrid and EV vehicles** ([Global](#)): in growth phase

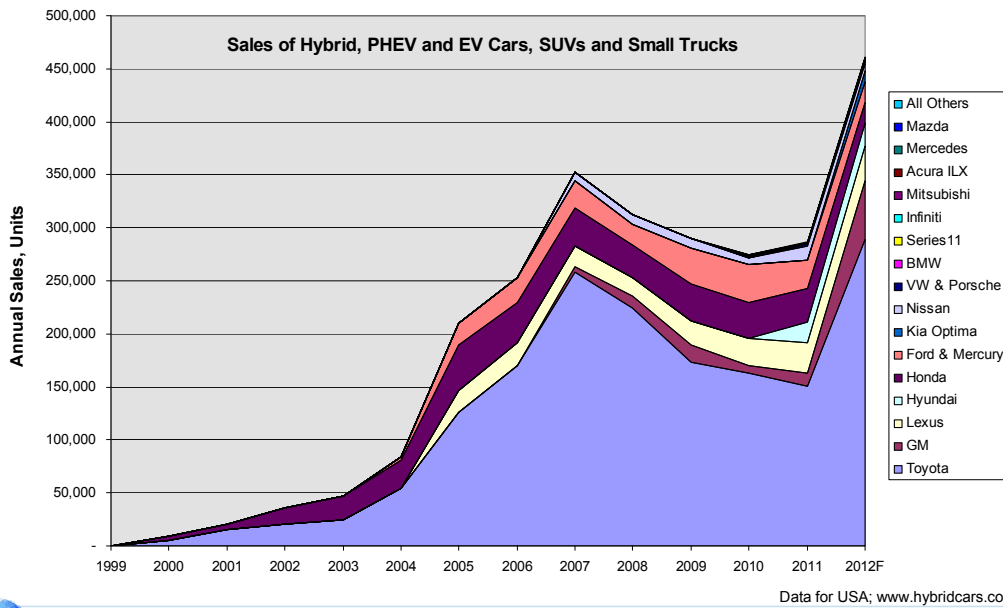


- Estimate of 1.73 million hybrid or EV's to be manufactured in 2015
- Total neo magnet usage in **2015 = 4,200 tons**



- Hybrid automobiles and full electric vehicles are becoming increasingly more common in the US and Europe
- 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-boasted bicycles to over 350 grams for high power scooters).
- Intermediate dysprosium levels (~4-6.5%) 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.

Growth of US "Green Car" Sales



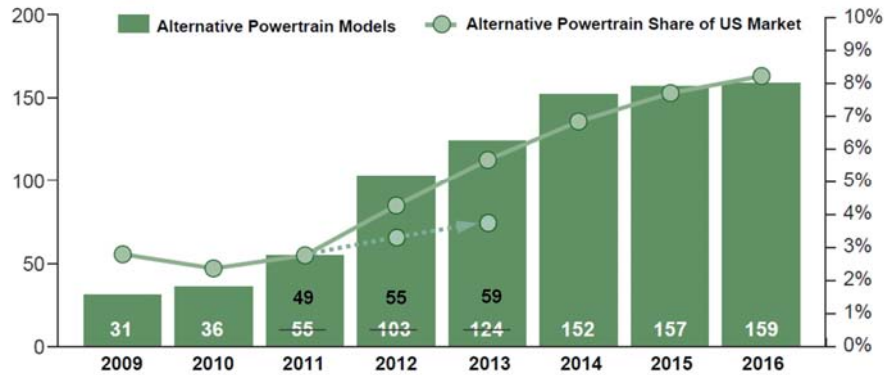
- Sales for 2012 were approximately 461,250 units.
- 2011 and 2012 represent watershed years in that EV and PHEV sales have just started.
- Change in consumer preferences are due in large part to price of gasoline and overall economic prosperity.

Hybrid and PEVs

Sales in USA of Cars, SUVs, Small Trucks
Data for USA: www.hybridcars.com

	2011		2012 (YTD August)		2012 Year-end F'cst	
	Units	%	Units	%	Units	%
Total Sales (units)	12,734,356		9,678,702		14,518,053	
Hybrid	268,807	2.11%	278,680	2.88%	418,020	2.88%
PEV	17,813	0.14%	25,290	0.26%	37,935	0.26%
Totals		2.25%		3.14%		3.14%

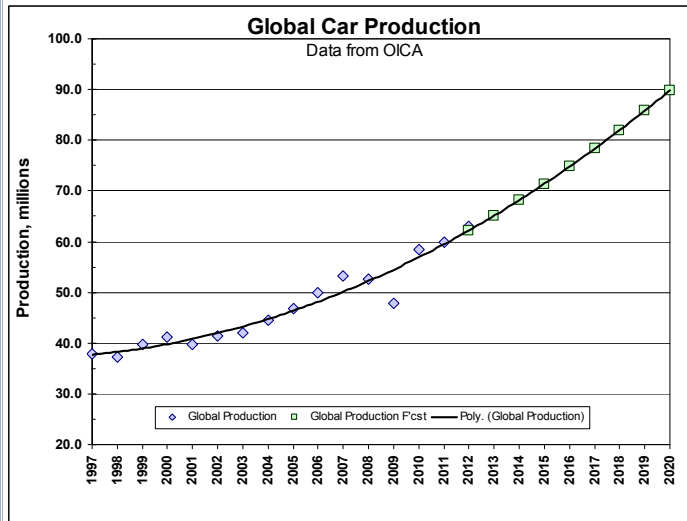
Alternative Powertrain Models and Market Share



Source: J.D. Power and Associates 2011 US Green Automotive StudySM

- EV sales as a percentage of overall sales in the USA is increasing.
- 2012 ended with EVs being over 3% of sales!
- Despite the smaller number of models available in 2013 (59) versus JD Power's 124 there is no doubt that we are at a turning point regarding use of hybrid and electric vehicles.

Rare Earth Requirements



Traction Drive Motor Only

Year 2020 Forecast Quantities

90,000,000	cars produced in 2020
10%	percentage Hybrid and EV
9,000,000	hybrid and EV
1 kg	Magnet weight per car, average
9,000,000 kg	total magnet weight
9000 tonnes	total magnet weight
32%	Total RE Content, metal
26%	Nd + Pr content
6%	Dysprosium content
2340 tonnes	weight Nd + Pr
540 tonnes	weight Dy
97%	melt yield
82%	oxide to metal yield
85%	magnet material yield
68%	net yield
3,461 tonnes	weight Nd + Pr oxide
799 tonnes	weight tonnes oxide

% of 2010 reported production

Nd + Pr = 13.4%

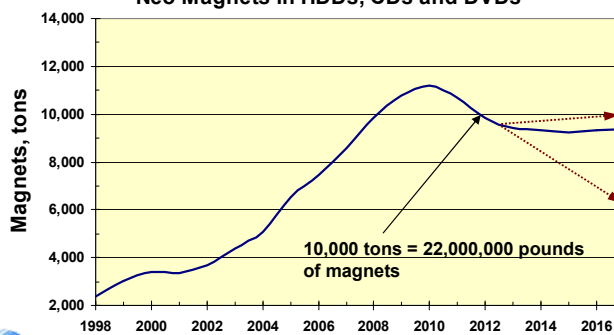
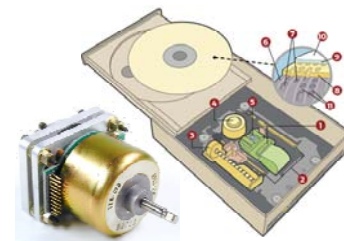
Dy = 49.9%



- Global car production has been tracked by OICA and is charted here from 1997 through 2012.
- A second order regression fit allows us to extrapolate to year 2020 when it's possible that 90 million automobiles might be manufactured and sold.
- If 10% of those are to be hybrid vehicles they might use 3,461 metric tons of neodymium and praseodymium oxide which represents ~13.4% of 2010 reported global supply.
- However, dysprosium usage would require just under half of global supply.

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

- Drives (**Global**): existing and growing market
 - Overall drive shipments for 2012 are expected to be 592 million, down from 625 million in 2011 and 654 million in 2010
 - Reduced shipments due to Thailand flooding and slowing economic growth
 - Market being eroded by SSD and cloud computing
 - Some market maintained by servers & cloud computing centers



- 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 very low or even no dysprosium.
- This market is being eroded by expansion of SSD drives especially in portable devices which has resulted in double digit drops in desktop computers for two years in a row.
- Continuing markets for HDDs are for servers and high end desktop systems.

Agenda

- It's all about energy
- Soft magnetic materials
- Permanent magnet materials
- Materials market & pricing
- Permanent magnet applications
- Development of existing materials
- R & D (elemental discussion)



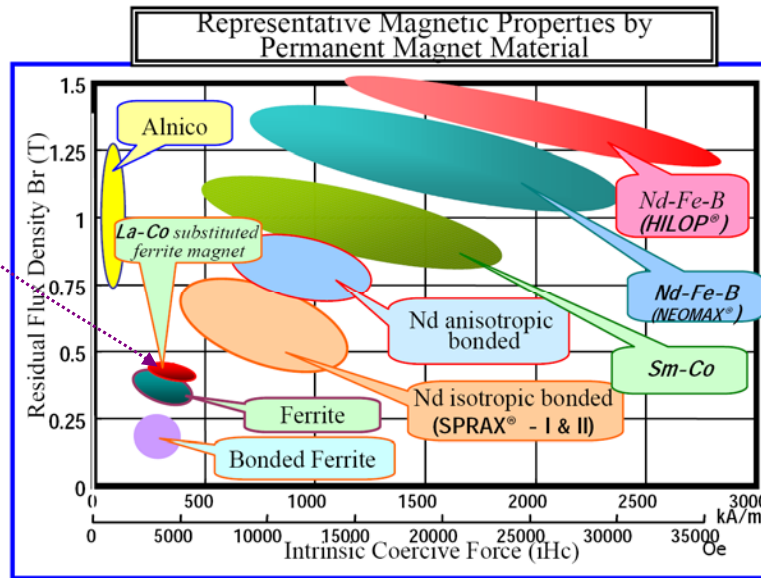
Development of Existing Materials

- Ferrite (Ceramic) magnets
- Neo magnets, especially regarding dysprosium
- SmCo
- SmFeN
- Alnico



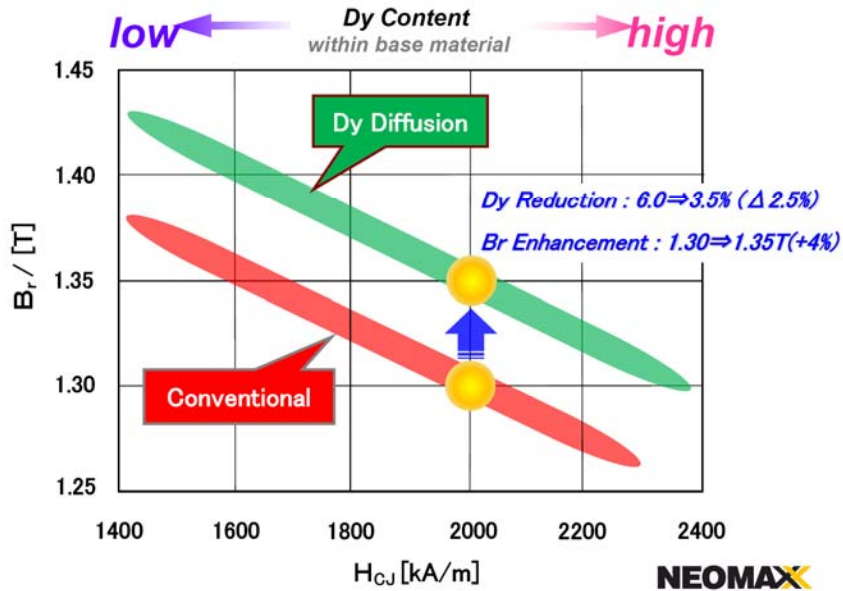
- Common, commercially available permanent magnetic materials.

La-Co Ferrites



- La-Co additions to strontium-ferrite permanent magnets has resulted in a 20%+ increase in energy product and high coercivity.
- Considering the relatively low cost of ferrite, enhanced performance suggests an even greater market share going forward.

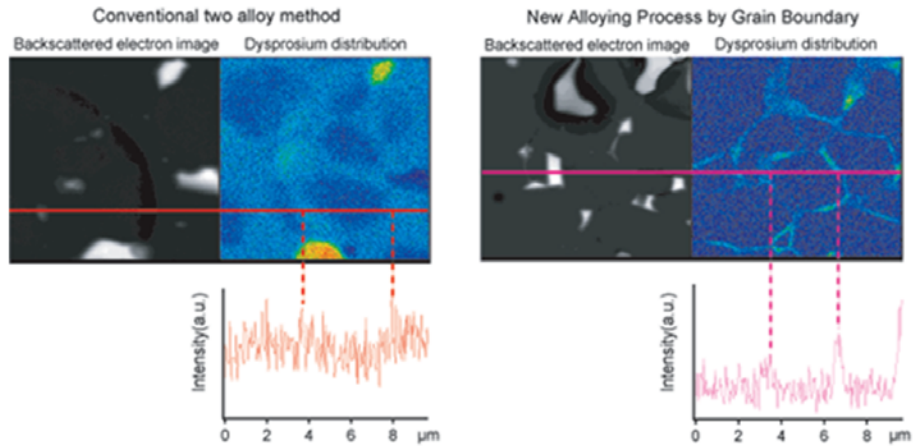
Dysprosium Diffusion



- The dysprosium diffusion process provides more efficient use of dysprosium.
- Users may choose to 1) keep dysprosium at existing levels and benefit from the higher coercivity or 2) reduce the dysprosium to meet minimum acceptable coercivity and benefit from higher energy product.

Dysprosium Diffusion from Shin-Etsu

Comparison using actual metallographic structure photographs



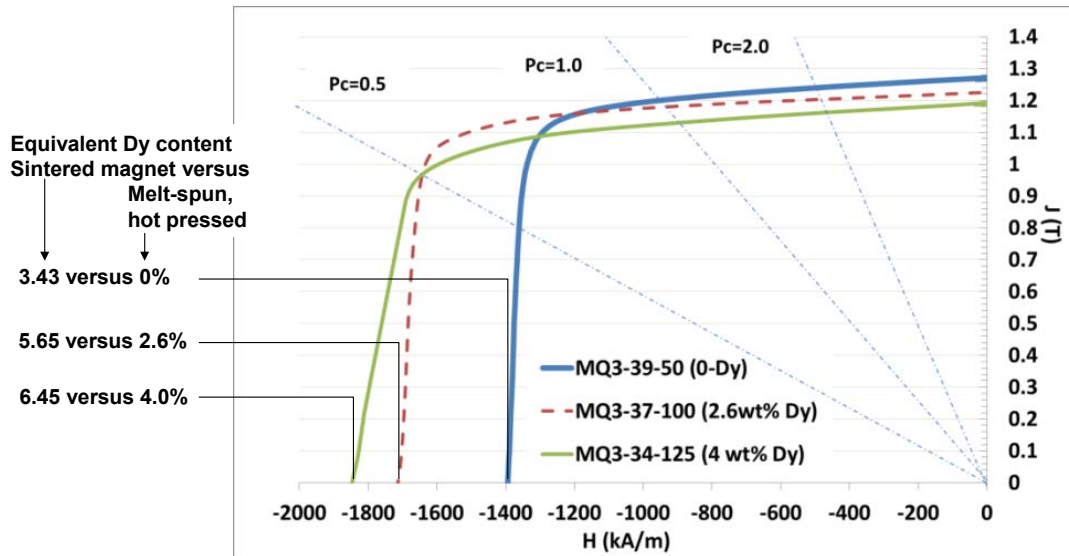
It can be said that the dysprosium is distributed more sharply at the grain boundary with higher concentration in the magnet produced by the new alloying process by grain boundary diffusion.

<http://www.shinetsu-rare-earth-magnet.jp/e/rd/grain.html>



- While not a new technique, it was practiced starting in the mid 1980s, the current method optimizes the effect of dysprosium diffusion.

Magnequench Lower Dy Magnets



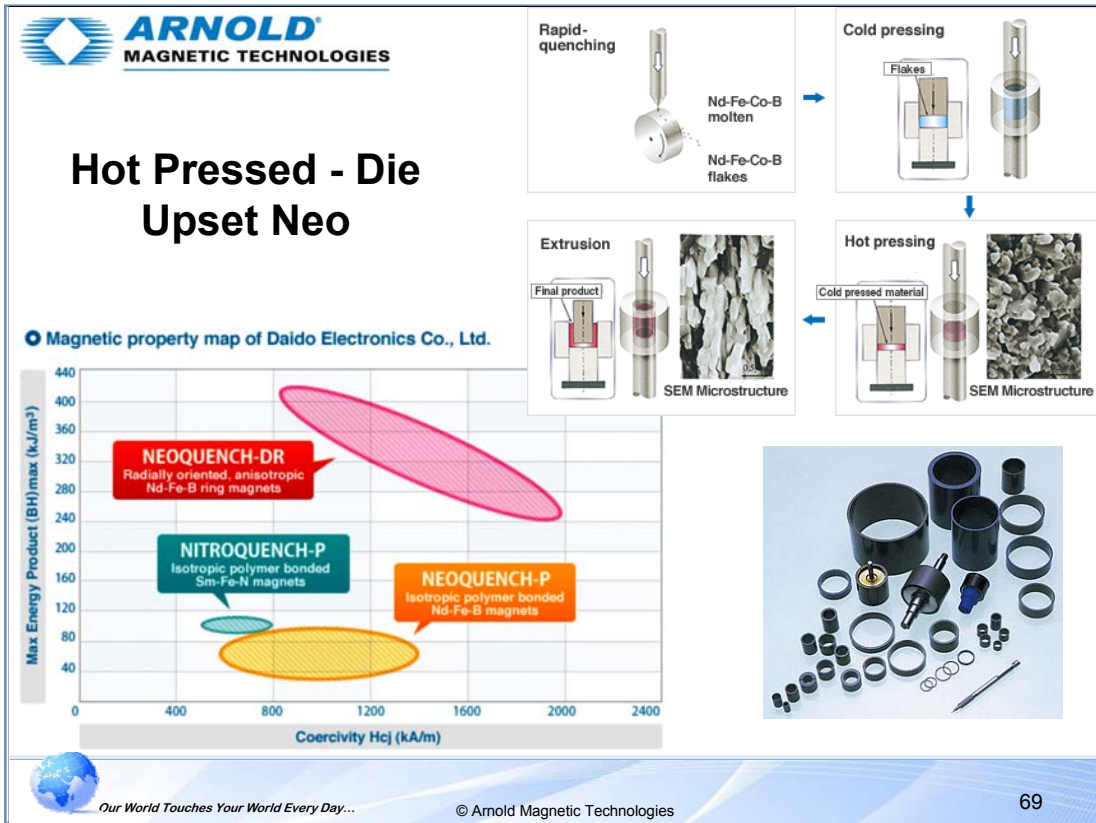
Source: Magnequench, September 2013



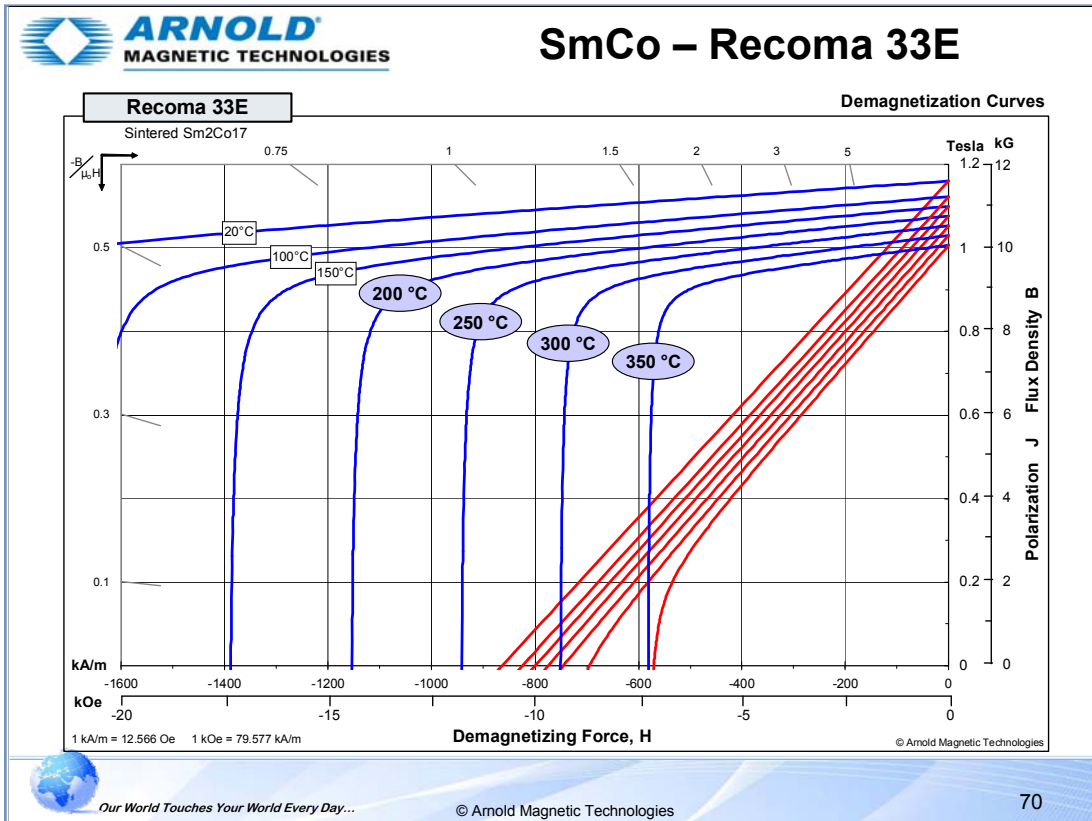
Our World Touches Your World Every Day...

© Arnold Magnetic Technologies

- Magnequench has presented about the use of minor dysprosium additions to melt spun (jet cast) neo powders for use in hot-pressed and die-upset magnets.
- This slide shows a comparison of the coercivity of magnets made via conventional powder metallurgy and those made by jet-casting and die-upsetting.



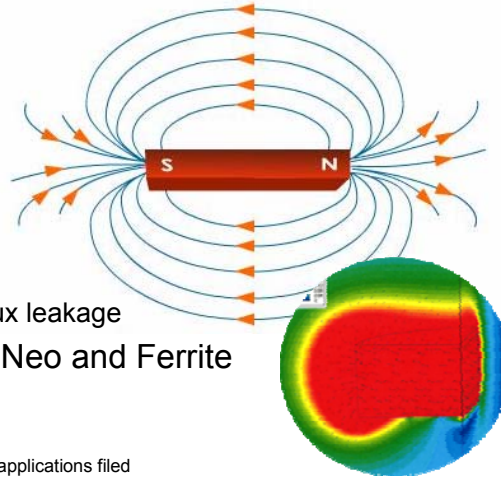
- Daido has been a long practitioner of the die upset magnet manufacturing process, primarily for the production of hollow, radially oriented cylinders.
- Presumably the addition of dysprosium will enhance their product properties accordingly.



- Arnold has improved the composition and processing of SmCo to produce a grade of 2:17 SmCo with exceptional properties and with high production yield.
- For application temperatures above 180 °C, this material is superior from both a cost and performance standpoint.

Shaped-Field Magnets

- Field permanently shifted (focused) with 30% more energy on either pole. It is a structural change, not just a difference in magnetizing
- Design possibilities include:
 - Overall lighter design as less back iron or down sized pole pieces can be used
 - Enables stronger magnetics where needed without adding mass (minimizes flux leakage)
 - Allows larger air gaps with minimal flux leakage
- Method can be used with SmCo, Neo and Ferrite



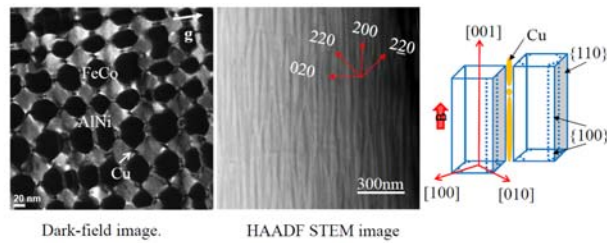
International patent applications filed



- Arnold has also introduced magnets with complex magnetic orientation built-in.
- The resulting field patterns have reduced flux leakage and enhanced coupling in torque-coupled assemblies by over 30%.
- The patent applied for process is also applicable to ferrite and neo magnets.

Alnico Coercivity Enhancement

- BREM Project at Ames
 - Funded by EERE as part of the VTP
 - Management by DOE through ORNL



Dark-field image.

HAADF STEM image

- FeCo phase has faceted bcc grains inside $L2_1$ ordered AlNi-rich phase with Cu at the corner of two {110} facets.
- Coherent FeCo/AlNi interface, semicoherent Cu/AlNi interface.
- Very long FeCo-rich rod with aspect ratio >10 .



- Alnico exhibits values of B_r comparable with neo magnets.
- The problem with alnico lies in low coercivity.
- Projects are underway to develop higher coercivity alnico while minimizing loss of B_r .

Summary: Current Magnet Options

- Alnico, especially grades 5-7, 8 and 9
- Ferrite (Ceramic)
- Ferrite with La-Co enhancement
- Neodymium Iron Boron (conventional, sintered)
- Neodymium Iron Boron (with diffused dysprosium)
- Neodymium Iron Boron (bonded, iso- and anisotropic)
- SmCo 1:5
- SmCo 2:17
- SmFeN (bonded)

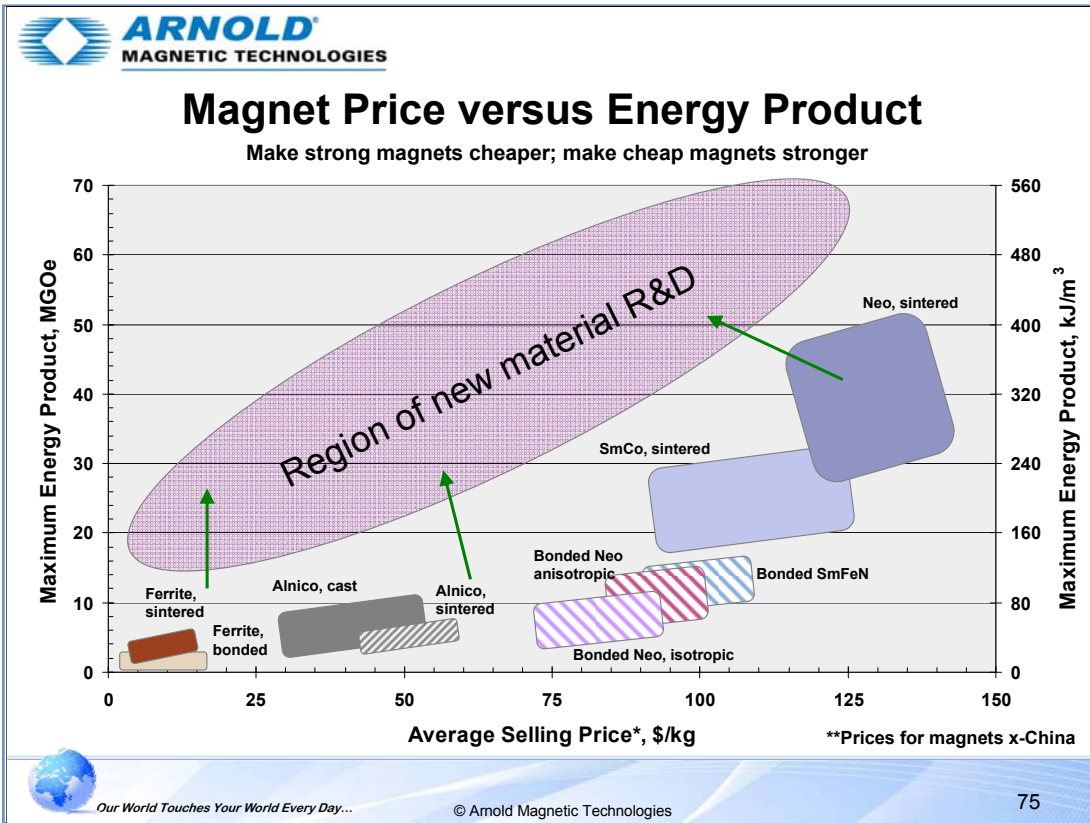
In Alphabetical order



Agenda

- It's all about energy
- Soft magnetic materials
- Permanent magnet materials
- Materials market & pricing
- Permanent magnet applications
- Development of existing materials
- R & D (elemental discussion)





- Looking at the price chart for magnetic materials, the highlighted region shows target price and energy for new materials development.
- 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.

Magnetic Domains versus Particles

DOMAINS

"A domain is a small volume of a substance that is spontaneously magnetized in one direction. In bulk a piece of magnetic material contains many domains magnetized in different directions. The material is demagnetized if these directions are completely random for the material as a whole, so that its net magnetization is zero."

M. McCaig, Permanent Magnets in Theory and Practice, p.25

Recall that a magnetic field is a vector having both magnitude and direction.

SOME FEATURES OF FERROMAGNETIC MATERIALS

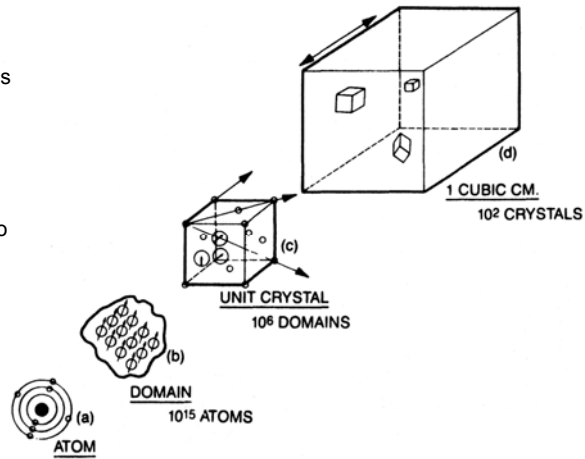


Figure 3.2 Exploded assembly of ferromagnetic volume.

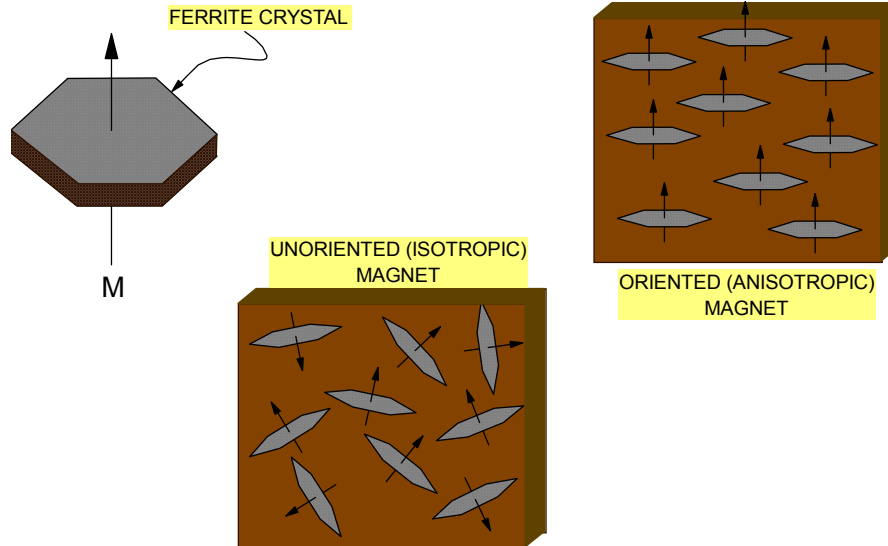
R.J. Parker, Advances in Permanent Magnetism, p.47



- A key consideration of new materials development is maximum performance which is dependent upon co-parallel orientation of magnetic domains.
- This illustrations helps one to differentiate among crystals, domains, and particles.

Defining Oriented and Anisotropic

CRYSTALLINE (POWDER) vs. MAGNET



- There is considerable confusion regarding these terms.
- Let us define what is meant by anisotropic versus isotropic and oriented versus unoriented.
- Most grains of magnetic material have an “easy axis of magnetization”. This means that the crystalline material magnetizes in one orientation only. An example is the ferrite crystal shown above. In technical jargon, this is referred to as “uniaxial crystalline anisotropy”.
- If the grains of magnetic material are not oriented during the manufacture of the magnet, when the magnetic material is subsequently “charged” (magnetized), it will be weaker than it could potentially be. However, it may be magnetized in any direction.
- If the grains are oriented during manufacture, then the magnet will have a net magnetic field in only that orientation.
- For any material, if the anisotropic magnetic powder is well-aligned during manufacturing it will have the greatest possible magnetic output for that material type.
- Typical % of perfect orientation is about 96-97%.

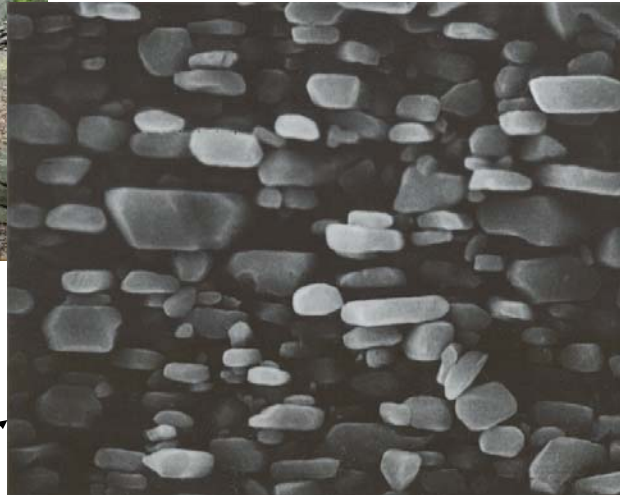
Ferrite Oriented Flakes



Similar to a shale stone wall

Somewhat irregular shapes well-layered

Ferrite magnet fracture surface



- This SEM photomicrograph of bonded ferrite shows the particle morphology and alignment.
- Although the particles are not perfect hexagonal platelets, they are generally flat and aligned well, much like this New England shale stone wall.

Origin of the Field - 2

- Filling of the 3d shell doesn't proceed until the 4s shell is filled
- Incomplete filling of the 3d shell is key to para- and ferromagnetism

Atomic number	Element	Shell Sub-shell	K (1)		L (2)			M (3)			N (4)			Number of unpaired spins (circles)
			1s	2s	2p	3s	3p	3d	4s	4p	4d	4f		
21	Scandium		↑ ↓	↑ ↓	↑↑↑ ↑↑↑	↑ ↓	↑↑↑ ↑↑↑	↑ ↓	↑ ↓	↑ ↓	↑ ↓	↑ ↓	1	
22	Titanium		↑ ↓	↑ ↓	↑↑↑ ↑↑↑	↑ ↓	↑↑↑ ↑↑↑	↑↑ ↑↓	↑ ↓	↑ ↓	↑ ↓	↑ ↓	2	
23	Vanadium		↑ ↓	↑ ↓	↑↑↑ ↑↑↑	↑ ↓	↑↑↑ ↑↑↑	↑↑↑ ↑↓↑	↑ ↓	↑ ↓	↑ ↓	↑ ↓	3	
24	Chromium		↑ ↓	↑ ↓	↑↑↑ ↑↑↑	↑ ↓	↑↑↑ ↑↑↑	↑↑↑↑↑ ↑↓↑↑↑	↑ ↓	↑ ↓	↑ ↓	↑ ↓	5-1	
25	Manganese		↑ ↓	↑ ↓	↑↑↑ ↑↑↑	↑ ↓	↑↑↑ ↑↑↑	↑↑↑↑↑ ↑↓↑↑↑	↑ ↓	↑ ↓	↑ ↓	↑ ↓	5	
26	Iron		↑ ↓	↑ ↓	↑↑↑ ↑↑↑	↑ ↓	↑↑↑ ↑↑↑	↑↑↑↑↑ ↑↓↑↑↑	↑ ↓	↑ ↓	↑ ↓	↑ ↓	4	
27	Cobalt		↑ ↓	↑ ↓	↑↑↑ ↑↑↑	↑ ↓	↑↑↑ ↑↑↑	↑↑↑↑↑ ↑↓↑↑↑	↑ ↓	↑ ↓	↑ ↓	↑ ↓	3	
28	Nickel		↑ ↓	↑ ↓	↑↑↑ ↑↑↑	↑ ↓	↑↑↑ ↑↑↑	↑↑↑↑↑ ↑↓↑↑↑	↑ ↓	↑ ↓	↑ ↓	↑ ↓	2	
29	Copper		↑ ↓	↑ ↓	↑↑↑ ↑↑↑	↑ ↓	↑↑↑ ↑↑↑	↑↑↑↑↑ ↑↓↑↑↑	↑ ↓	↑ ↓	↑ ↓	↑ ↓	1	
30	Zinc		↑ ↓	↑ ↓	↑↑↑ ↑↑↑	↑ ↓	↑↑↑ ↑↑↑	↑↑↑↑↑ ↑↓↑↑↑	↑ ↓	↑ ↓	↑ ↓	↑ ↓	0	

**Pairing of electron spins
in selected transition metal elements**



- What is the origin of (electro-) magnetism?
- If we represent the electron spins, within an atom, by arrows in a tabular form, we can look at several elements at once, as in this table of elements 21 through 30.
- As electrons are added, along with protons, neutrons, etc to form higher atomic number elements, the natural order would be to fill the electron shells in sequence. However, the energy level of the 4s shell is lower than the 3d shell and after the element Argon (atomic number 18), electrons fill the 4s shell for potassium and calcium before starting to fill the 3d shell.
- Electron spin pair imbalance is presented in the last column.
- Electron spin imbalance alone is insufficient to cause strong ferromagnetism.
- Additionally, the dipole-dipole interaction in the crystallized material is too weak to be the source of ferromagnetism.

Origin of the Field - 3

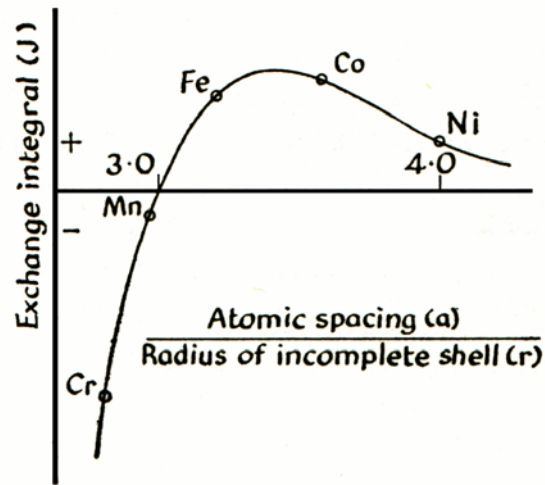
- Heisenberg: quantum theory explanation for ferromagnetism

Keywords:

Exchange Interaction

In physics, the exchange interaction is a quantum mechanical effect which increases or decreases the expectation value of the energy or distance between two or more identical particles when their wave functions overlap.

Heavy Math - - Use with Caution

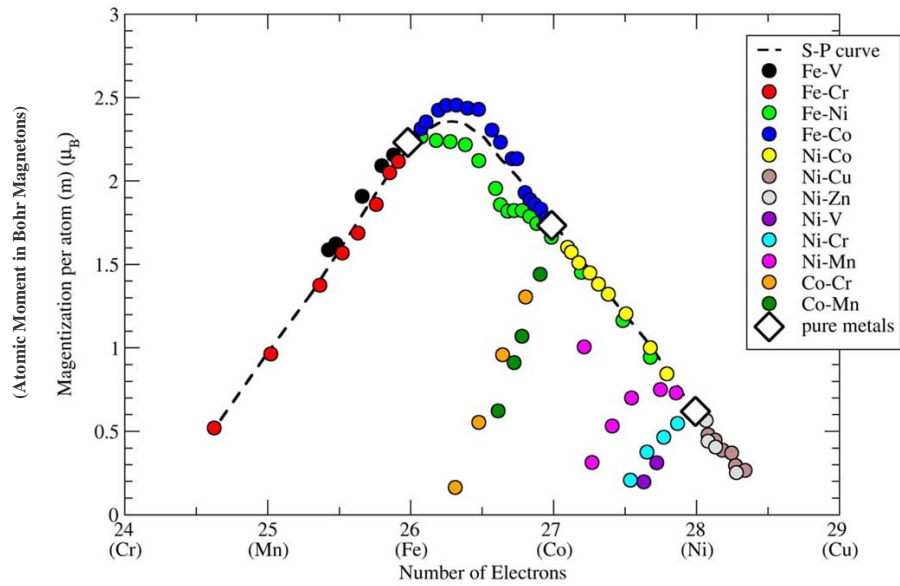


The exchange integral



- Heisenberg, using the quantum theory, in 1928 explained that as atoms with partially filled electronic shells at large distances from each other move closer to one another their shells begin to overlap and quantum mechanical exchange forces arise between the incomplete shells. The corresponding energy appears in the mathematical formulation as an “exchange integral”.
- When the exchange energy is positive, as it is for Fe, Co and Ni, ferromagnetic properties are exhibited. This occurs when the atomic spacing (a) is about 3-4 times the radius of the incomplete shell (r).
- Additionally, some combinations of otherwise weak magnetic materials have strong magnetic characteristics. An example is MnAlC and MnBi. Alloying increases the exchange interaction for manganese, moving it from a negative value to positive.


Slater-Pauling Curve



R.M. Bozorth, Ferromagnetism, IEEE, 1993, p.438-441

Color-edited by Dr. Bill McCallum, Ames Lab





Periodic Table of the Elements - Complete

Based on table from Vertex42.com

Group	1	2	Phase at STP										13	14	15	16	17	18	
IA	IIA	Gas										IIIA	IVA	VIA	VIA	VIA	VIA	VIIIA	
Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
1	H Hydrogen [1] 1.00794 +1												B Boron [5] 10.811 +3	C Carbon [6] 12.011 +2, +4	N Nitrogen [7] 14.00644 +3, +5, +2, -1, -2, -3	O Oxygen [8] 15.999 -2	F Fluorine [9] 18.9984032 -1	Ne Neon [10] 20.1797 0	
2	Li Lithium [3] 6.941 +1	Be Beryllium [4] 9.01224 +2											Al Aluminum [13] 26.9815385 +3	Si Silicon [14] 28.0855 +4	P Phosphorus [15] 30.973762 +3, +5	S Sulfur [16] 32.06 -2, +4, +6	Cl Chlorine [17] 35.453 -1, +1, +3, +5, +7	Ar Argon [18] 39.948 0	
3	Na Sodium [11] 22.98976928 +1	Mg Magnesium [12] 24.304 +2											Ga Gallium [31] 70.023171 +3	Ge Germanium [32] 72.64 +4	As Arsenic [33] 74.9216 +3, +5	Se Selenium [34] 78.9718 -2, +4, +6	Br Bromine [35] 79.904 -1	Kr Krypton [36] 83.798 0	
4	K Potassium [19] 39.0983 +1	Ca Calcium [20] 40.078 +2	Sc Scandium [21] 44.9559122 +3	Ti Titanium [22] 47.8827 +4	V Vanadium [23] 50.9415 +3, +4, +5	Cr Chromium [24] 51.9961 +2, +3, +4, +6	Mn Manganese [25] 54.938044 +2, +3, +4, +6, +7	Fe Iron [26] 55.845 +2, +3	Co Cobalt [27] 58.933194 +2, +3	Ni Nickel [28] 58.6934 +2	Cu Copper [29] 63.546 +1, +2	Zn Zinc [30] 65.38 +2							
5	Rb Rubidium [37] 85.4678 +1	Sr Strontium [38] 87.62 +2	Y Yttrium [39] 88.905848 +3	Zr Zirconium [40] 91.224 +4	Nb Niobium [41] 92.90638 +3, +4, +5	Mo Molybdenum [42] 95.94 +4, +5, +6	Tc Technetium [43] 98 +4, +5, +6, +7	Ru Ruthenium [44] 101.07 +4, +5, +6, +7, +8	Rh Rhodium [45] 101.07 +3, +4, +5, +6, +7, +8	Pd Palladium [46] 106.367 +2, +4, +6	Ag Silver [47] 107.8682 +1	Cd Cadmium [48] 112.411 +2	In Indium [49] 114.818 +3	Sn Tin [50] 118.710 +2, +4	Sb Antimony [51] 121.757 +3, +5	Te Tellurium [52] 127.6 -2, +4, +6	I Iodine [53] 126.905 -1	Xe Xenon [54] 131.29 0	
6	Cs Cesium [55] 132.905 +1	Ba Barium [56] 137.327 +2	Lanthanide Series		Hf Hafnium [72] 178.49 +4	Ta Tantalum [73] 180.948 +3, +4, +5	W Tungsten [74] 183.84 +4, +5, +6	Re Rhenium [75] 186.207 +4, +5, +6, +7	Os Osmium [76] 190.23 +4, +5, +6, +7, +8	Ir Iridium [77] 192.222 +3, +4, +5, +6, +7, +8	Pt Platinum [78] 195.084 +2, +4, +6	Au Gold [79] 196.966569 +1, +3	Hg Mercury [80] 200.59 +2	Tl Thallium [81] 204.384 +1, +3	Pb Lead [82] 207.2 +2, +4	Bi Bismuth [83] 208.9804 +3, +5	Po Polonium [84] 209 -2, +4	At Astatine [85] 210 -1	Rn Radon [86] 222 0
7	Fr Francium [87] 223 +1	Ra Radium [88] 226 +2	Actinide Series		Rf Rutherfordium [104] 261 +4	Db Dubnium [105] 262 +5	Sg Seaborgium [106] 263 +6	Bh Bohrium [107] 264 +7	Hs Hassium [108] 265 +8	Mt Meitnerium [109] 266 +9	Ds Darmstadtium [110] 267 +10	Rg Roentgenium [111] 268 +11	Cn Copernicium [112] 269 +12	Uut Ununtrium [113] 270 +3	Uuq Ununquadium [114] 271 +4	Uup Ununpentium [115] 272 +5	Uuh Ununhexium [116] 273 +6	Uus Ununseptium [117] 274 +7	Uuo Ununoctium [118] 276 0
Lanthanides			La Lanthanum [57] 138.905 +3	Ce Cerium [58] 140.12 +3, +4	Pr Praseodymium [59] 140.90765 +3	Nd Neodymium [60] 144.242 +3	Pm Promethium [61] 144.9127 +3	Sm Samarium [62] 150.36 +2, +3	Eu Europium [63] 151.964 +2, +3	Gd Gadolinium [64] 157.25 +2, +3	Tb Terbium [65] 158.92535 +3	Dy Dysprosium [66] 162.5 +2, +3	Ho Holmium [67] 164.93033 +3	Er Erbium [68] 167.259 +2, +3	Tm Thulium [69] 168.93032 +3	Yb Ytterbium [70] 173.054 +2, +3	Lu Lutetium [71] 174.967 +3		
Actinides			Ac Actinium [89] 227 +3	Th Thorium [90] 232.0377 +4	Pa Protactinium [91] 231.036889 +3, +4	U Uranium [92] 238.02891 +3, +4	Np Neptunium [93] 237 +3, +4	Pu Plutonium [94] 244 +3, +4	Am Americium [95] 243 +3, +4	Cm Curium [96] 247 +2, +3	Bk Berkelium [97] 247 +3	Cf Californium [98] 251 +2, +3	Es Einsteinium [99] 252 +2, +3	Fm Fermium [100] 257 +2, +3	Md Mendelevium [101] 258 +2, +3	No Nobelium [102] 259 +2, +3	Lr Lawrencium [103] 260 +3		

Our World Touches Your World Every Day... © Arnold Magnetic Technologies 82

- Let's work with the periodic table to see what elements are likely candidates for use in magnetic materials.
- I will use a method similar to that of Bill McCallum of Ames Laboratory who kindly shared his notes with me a year or two ago.
- And I should point out that this table was obtained from Vertex in Excel format. It has been modified to simplify the information in each cell. Go to www.vertex42.com for this and other useful spreadsheets and documents.
- This first table lists all of the elements... so let's start thinning the list.


Periodic Table of the Elements

No synthetic elements

Group	1	2	Phase at STP										13	14	15	16	17	18												
IA	IIA											IIIA	IVA	VIA	VIA	VIA	VIA	VIIIA												
1	H Hydrogen [1] 1.00794 +1, -1												B Boron [5] 10.811 +3	C Carbon [6] 12.011 +2, +4, -4	N Nitrogen [7] 14.00644 +3, +5, -3, -2, -1	O Oxygen [8] 15.999 -2	F Fluorine [9] 18.9984 -1	Ne Neon [10] 20.1797 0												
2	Li Lithium [3] 6.941 +1	Be Beryllium [4] 9.01224 +2											Al Aluminum [13] 26.9815385 +3	Si Silicon [14] 28.0855 +4, -4	P Phosphorus [15] 30.973762 +3, +5, -3	S Sulfur [16] 32.065 +6, +4, -2	Cl Chlorine [17] 35.453 -1, +1, +3, +5, +7	Ar Argon [18] 39.948 0												
3	Na Sodium [11] 22.98976928 +1	Mg Magnesium [12] 24.304 +2											K Potassium [19] 39.0983 +1	Ca Calcium [20] 40.078 +2	Sc Scandium [21] 44.9559122 +3	Ti Titanium [22] 47.88 +4	V Vanadium [23] 50.9415 +5, +4, +3, +2, -1	Cr Chromium [24] 51.9961 +6, +3, +2, -1	Mn Manganese [25] 54.938044 +7, +4, +3, +2, -1	Fe Iron [26] 55.845 +2, +3	Co Cobalt [27] 58.933195 +2, +3	Ni Nickel [28] 58.6934 +2, +3	Cu Copper [29] 63.546 +1, +2	Zn Zinc [30] 65.38 +2	Ga Gallium [31] 69.723 +3	Ge Germanium [32] 72.64 +4	As Arsenic [33] 74.9216 +3, +5, -3	Se Selenium [34] 78.96 +6, +4, -2	Br Bromine [35] 79.904 -1, +1, +3, +5	Kr Krypton [36] 83.798 0
4	Rb Rubidium [37] 85.4678 +1	Sr Strontium [38] 87.62 +2	Y Yttrium [39] 88.905848 +3	Zr Zirconium [40] 91.224 +4	Nb Niobium [41] 92.90638 +5	Mo Molybdenum [42] 95.94 +6, +5, +4, +3, +2, -1	Tc Technetium [43] 98.90625 +7, +6, +4, +3, +2, -1	Ru Ruthenium [44] 101.07 +8, +6, +4, +3, +2, -1	Rh Rhodium [45] 102.9055 +9, +8, +6, +4, +3, +2, -1	Pd Palladium [46] 106.3678 +4, +2, -1	Ag Silver [47] 107.8682 +1	Cd Cadmium [48] 112.411 +2	In Indium [49] 114.818 +3	Sn Tin [50] 118.710 +4, +2	Sb Antimony [51] 121.757 +3, +5, -3	Te Tellurium [52] 127.603 +6, +4, -2	I Iodine [53] 126.905 -1, +1, +3, +5, +7	Xe Xenon [54] 131.29 0												
5	Cs Cesium [55] 132.905 +1	Ba Barium [56] 137.327 +2	Lanthanide Series		Hf Hafnium [72] 178.49 +4	Ta Tantalum [73] 180.94788 +5	W Tungsten [74] 183.84 +6, +5, +4, +3, +2, -1	Re Rhenium [75] 186.207 +7, +6, +5, +4, +3, +2, -1	Os Osmium [76] 190.23 +8, +6, +4, +3, +2, -1	Ir Iridium [77] 192.222 +9, +8, +6, +4, +3, +2, -1	Pt Platinum [78] 195.084 +2, +4, +6	Au Gold [79] 196.966569 +1, +3	Hg Mercury [80] 200.59 +2, +1	Tl Thallium [81] 204.3833 +3, +1	Pb Lead [82] 207.2 +4, +2	Bi Bismuth [83] 208.9804 +3, +5, -3	Po Polonium [84] 209 -2, +4	At Astatine [85] 210 -1, +1, +3, +5, +7	Rn Radon [86] 222 0											
6	Fr Francium [87] 223 +1	Ra Radium [88] 226 +2	Actinide Series		Rf Rutherfordium [104] 261 +4	Db Dubnium [105] 262 +5	Sg Seaborgium [106] 263 +6	Bh Bohrium [107] 264 +7	Hs Hassium [108] 265 +8	Mt Meitnerium [109] 266 +9	Ds Darmstadtium [110] 267 +10	Rg Roentgenium [111] 268 +11	Cn Copernicium [112] 269 +12	Uut Ununtrium [113] 270 +3	Uuq Ununquadium [114] 271 +4	Uup Ununpentium [115] 272 +5	Uuh Ununhexium [116] 273 +6	Uus Ununseptium [117] 274 +7	Uuo Ununoctium [118] 276 0											
			Lanthanides		La Lanthanum [57] 138.90547 +3	Ce Cerium [58] 140.12 +3, +4	Pr Praseodymium [59] 140.90766 +3, +4	Nd Neodymium [60] 144.242 +3, +4	Pm Promethium [61] 144.9126 +3, +4	Sm Samarium [62] 150.36 +2, +3	Eu Europium [63] 151.964 +2, +3	Gd Gadolinium [64] 157.25 +2, +3	Tb Terbium [65] 158.92535 +3	Dy Dysprosium [66] 162.5 +3	Ho Holmium [67] 164.93033 +3	Er Erbium [68] 167.259 +3	Tm Thulium [69] 168.934 +3	Yb Ytterbium [70] 173.0547 +2, +3	Lu Lutetium [71] 174.967 +3											
			Actinides		Ac Actinium [89] 227 +3	Th Thorium [90] 232.0377 +4	Pa Protactinium [91] 231.036888 +3, +4	U Uranium [92] 238.02891 +3, +4	Np Neptunium [93] 237 +3, +4	Pu Plutonium [94] 244 +3, +4	Am Americium [95] 243 +3, +4	Cm Curium [96] 247 +3, +4	Bk Berkelium [97] 247 +3, +4	Cf Californium [98] 251 +3, +4	Es Einsteinium [99] 252 +3, +4	Fm Fermium [100] 257 +3, +4	Md Mendelevium [101] 258 +3, +4	No Nobelium [102] 259 +3, +4	Lr Lawrencium [103] 260 +3, +4											



- This chart has eliminated the synthetic elements – those that are man-made and do not survive more than a very short time.



Periodic Table of the Elements

No synthetic and no radioactive elements

Group 1												18																																				
IA												IIIA		IVA		VA		VIA		VIIA		VIIIA																										
1	H Hydrogen [1] 1.00794 +1											5	B Boron [5] 10.811 +3	6	C Carbon [6] 12.011 +2, +4	7	N Nitrogen [7] 14.00644 +3, +5	8	O Oxygen [8] 15.999 -2	9	F Fluorine [9] 18.9984 -1	10	Ne Neon [10] 20.1797 0																									
2	Li Lithium [3] 6.941 +1	Be Beryllium [4] 9.0122 +2											13	Al Aluminum [13] 26.9815 +3	14	Si Silicon [14] 28.0855 +4	15	P Phosphorus [15] 30.9738 +3, +5	16	S Sulfur [16] 32.06 -2	17	Cl Chlorine [17] 35.453 -1	18	Ar Argon [18] 39.948 0																								
3	Na Sodium [11] 22.98977 +1	Mg Magnesium [12] 24.304 +2											19	K Potassium [19] 39.0983 +1	20	Ca Calcium [20] 40.078 +2	21	Sc Scandium [21] 44.9559 +3	22	Ti Titanium [22] 47.88 +2, +3, +4	23	V Vanadium [23] 50.9415 +3, +4, +5	24	Cr Chromium [24] 51.9961 +2, +3, +6	25	Mn Manganese [25] 54.938 +2, +3, +4, +6, +7	26	Fe Iron [26] 55.845 +2, +3	27	Co Cobalt [27] 58.9332 +2, +3	28	Ni Nickel [28] 58.6934 +2	29	Cu Copper [29] 63.546 +1, +2	30	Zn Zinc [30] 65.38 +2	31	Ga Gallium [31] 69.723 +3	32	Ge Germanium [32] 72.64 +2, +4	33	As Arsenic [33] 74.9216 +3, +5	34	Se Selenium [34] 78.96 -2	35	Br Bromine [35] 79.904 -1	36	Kr Krypton [36] 83.796 0
4	Rb Rubidium [37] 85.4678 +1	Sr Strontium [38] 87.62 +2	Y Yttrium [39] 88.9058 +3	Zr Zirconium [40] 91.224 +4	Nb Niobium [41] 92.90638 +3, +5	Mo Molybdenum [42] 95.94 +2, +3, +4, +5, +6	Tc Technetium [43] 98 +4, +5, +6, +7	44	Ru Ruthenium [44] 101.07 +2, +3, +4, +6	45	Rh Rhodium [45] 102.9055 +3	46	Pd Palladium [46] 106.3676 +2, +4	47	Ag Silver [47] 107.8682 +1	48	Cd Cadmium [48] 112.411 +2	49	In Indium [49] 114.818 +3	50	Sn Tin [50] 118.710 +2, +4	51	Sb Antimony [51] 121.757 +3, +5	52	Te Tellurium [52] 127.6 -2	53	I Iodine [53] 126.905 -1	54	Xe Xenon [54] 131.29 0																			
5	Cs Cesium [55] 132.90545 +1	Ba Barium [56] 137.327 +2	Lanthanide Series		Hf Hafnium [72] 178.49 +4	Ta Tantalum [73] 180.94788 +3, +5	W Tungsten [74] 183.84 +2, +3, +4, +5, +6	Re Rhenium [75] 186.207 +2, +3, +4, +5, +6, +7	Os Osmium [76] 190.23 +2, +3, +4, +6	Ir Iridium [77] 192.222 +3, +4	Pt Platinum [78] 195.084 +2, +4	Au Gold [79] 196.96657 +1, +3	Hg Mercury [80] 200.59 +2	Tl Thallium [81] 204.3833 +1, +3	Pb Lead [82] 207.2 +2, +4	Bi Bismuth [83] 208.9804 +3, +5	Po Polonium [84] 209 -2	At Astatine [85] 210 -1	Rn Radon [86] 222 0																													
6	Fr Francium [87] 223 +1	Ra Radium [88] 226 +2	Actinide Series		Rf Rutherfordium [104] 261 +4	Db Dubnium [105] 262 +5	Sg Seaborgium [106] 263 +4, +6	Bh Bohrium [107] 264 +3, +5	Hs Hassium [108] 265 +4, +6	Mt Meitnerium [109] 266 +5, +7	Ds Darmstadtium [110] 267 +4, +6	Rg Roentgenium [111] 268 +3, +5	Cn Copernicium [112] 269 +2, +4	Uu1 Ununbium [113] 270 +3	Uuq Ununquadium [114] 271 +4	Uup Ununpentium [115] 272 +3	Uuh Ununhexium [116] 273 +2	Uus Ununseptium [117] 274 +1	Uuo Ununoctium [118] 276 0																													
7			Lanthanides		La Lanthanum [57] 138.90547 +3	Ce Cerium [58] 140.12 +3, +4	Pr Praseodymium [59] 140.90766 +3	Nd Neodymium [60] 144.24 +3	Pm Promethium [61] 145 +3	Sm Samarium [62] 150.36 +2, +3	Eu Europium [63] 151.964 +2, +3	Gd Gadolinium [64] 157.25 +2, +3	Tb Terbium [65] 158.92535 +3	Dy Dysprosium [66] 162.5 +2, +3	Ho Holmium [67] 164.93033 +3	Er Erbium [68] 167.259 +2, +3	Tm Thulium [69] 168.934 +2, +3	Yb Ytterbium [70] 173.0547 +2, +3	Lu Lutetium [71] 174.967 +3																													
		Actinides		Ac Actinium [89] 227 +3	Th Thorium [90] 232 +2, +3, +4	Pa Protactinium [91] 231 +3, +4	U Uranium [92] 238 +3, +4, +5, +6	Np Neptunium [93] 237 +3, +4, +5, +6	Pu Plutonium [94] 244 +3, +4, +5, +6	Am Americium [95] 243 +3, +4, +5, +6	Cm Curium [96] 247 +2, +3, +4, +5, +6	Bk Berkelium [97] 247 +3, +4, +5, +6	Cf Californium [98] 251 +2, +3, +4, +5, +6	Es Einsteinium [99] 252 +2, +3, +4, +5, +6	Fm Fermium [100] 257 +2, +3, +4, +5, +6	Md Mendelevium [101] 258 +2, +3, +4, +5, +6	No Nobelium [102] 259 +2, +3, +4, +5, +6	Lr Lawrencium [103] 260 +3																														

- And let's eliminate the radioactive elements – we won't want to put them in commercial magnets!
- As a side note Arnold has patents on Actinide magnets using uranium, iron and boron. They have interesting properties. But every known salt of uranium is either toxic or carcinogenic.

Periodic Table of the Elements

No synthetic, no radioactive, no inert elements

Group 1																		18																				
IA												IIIA	IVA	VA	VIA	VIIA	VIIIA																					
1	2											13	14	15	16	17	18																					
1	2											5	6	7	8	9	10																					
1	2											B	C	N	O	F	Ne																					
2	3											11	12	13	14	15	16	17																				
2	3											Li	Be											Na	Mg	Al	Si	P	S	Cl	Ar							
3	4											19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36									
3	4											K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr									
4	5											37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54									
4	5											Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe									
5	6											55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72									
5	6											Cs	Ba	Lanthanide Series										Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
6	7											87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106							
6	7											Fr	Ra	Actinide Series										Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Uuq	Uup	Uuh	Uus	Uuo
7	8											119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138							
7	8											Lanthanides										La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu		
7	8											Actinides										Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr		



Our World Touches Your World Every Day...

© Arnold Magnetic Technologies

- Let's also eliminate the noble gases – the inert elements. No magnetics available here.

Periodic Table of the Elements

No synthetic, no radioactive, no inert, no toxic elements

																		Phase at STP Gas Liquid Solid Synthetic																			
																		Categories																			
																		Alkali Metals Alkaline Earth Metals Transition Metals Rare Earth Metals Four Metals										Halogens Noble Gases Non-metals Metalloids									
																		Alkali Metals										Halogens									
																		Alkaline Earth Metals										Noble Gases									
																		Transition Metals										Non-metals									
																		Rare Earth Metals										Metalloids									
																		Four Metals										Metalloids									

Group 1 IA																																						Group 18 VIIIA																																																																																																																																																					
1 H Hydrogen [1] 1.008 +1																																						2 He Helium [2] 4.003 0																																																																																																																																																					
2 3 Li Lithium [3] 6.941 +1																		4 Be Beryllium [4] 9.012 +2																				5 B Boron [5] 10.811 +3										6 C Carbon [6] 12.011 +2, +4										7 N Nitrogen [7] 14.007 +3, +5										8 O Oxygen [8] 15.999 -2										9 F Fluorine [9] 18.998 -1										10 Ne Neon [10] 20.180 0																																																																																																			
3 11 Na Sodium [11] 22.990 +1																		12 Mg Magnesium [12] 24.305 +2																				13 Al Aluminum [13] 26.982 +3										14 Si Silicon [14] 28.086 +4										15 P Phosphorus [15] 30.974 +3, +5										16 S Sulfur [16] 32.06 -2										17 Cl Chlorine [17] 35.453 -1										18 Ar Argon [18] 39.948 0																																																																																																			
4 19 K Potassium [19] 39.098 +1																		20 Ca Calcium [20] 40.078 +2										21 Sc Scandium [21] 44.956 +3										22 Ti Titanium [22] 47.88 +2, +3, +4										23 V Vanadium [23] 50.942 +2, +3, +4, +5										24 Cr Chromium [24] 51.996 +2, +3, +6										25 Mn Manganese [25] 54.938 +2, +3, +4, +6, +7										26 Fe Iron [26] 55.845 +2, +3										27 Co Cobalt [27] 58.933 +2, +3										28 Ni Nickel [28] 58.693 +2										29 Cu Copper [29] 63.546 +1, +2										30 Zn Zinc [30] 65.38 +2										31 Ga Gallium [31] 69.723 +3										32 Ge Germanium [32] 72.64 +2, +4										33 As Arsenic [33] 74.922 +3, +5										34 Se Selenium [34] 78.96 -2										35 Br Bromine [35] 79.904 -1										36 Kr Krypton [36] 83.8 0									
5 37 Rb Rubidium [37] 85.468 +1																		38 Sr Strontium [38] 87.62 +2										39 Y Yttrium [39] 88.906 +3										40 Zr Zirconium [40] 91.224 +2, +3, +4										41 Nb Niobium [41] 92.906 +3, +5										42 Mo Molybdenum [42] 95.94 +2, +3, +4, +5, +6										43 Tc Technetium [43] 98 +7										44 Ru Ruthenium [44] 101.07 +2, +3, +4, +6										45 Rh Rhodium [45] 101.07 +3										46 Pd Palladium [46] 106.36 +2, +4										47 Ag Silver [47] 107.868 +1										48 Cd Cadmium [48] 112.411 +2										49 In Indium [49] 114.818 +3										50 Sn Tin [50] 118.710 +2, +4										51 Sb Antimony [51] 121.757 +3, +5										52 Te Tellurium [52] 127.6 +4										53 I Iodine [53] 126.905 -1										54 Xe Xenon [54] 131.29 0									
6 55 Cs Cesium [55] 132.905 +1																		56 Ba Barium [56] 137.327 +2										Lanthanide Series										58 Ce Cerium [58] 140.12 +3										59 Pr Praseodymium [59] 140.908 +3										60 Nd Neodymium [60] 144.24 +3										61 Pm Promethium [61] 145 +3										62 Sm Samarium [62] 150.36 +2, +3										63 Eu Europium [63] 151.964 +2, +3										64 Gd Gadolinium [64] 157.25 +2, +3										65 Tb Terbium [65] 158.925 +3										66 Dy Dysprosium [66] 162.5 +2, +3										67 Ho Holmium [67] 164.93 +3										68 Er Erbium [68] 167.259 +2, +3										69 Tm Thulium [69] 168.934 +3										70 Yb Ytterbium [70] 173.054 +2, +3										71 Lu Lutetium [71] 174.967 +3																			
7 87 Fr Francium [87] 223 +1																		88 Ra Radium [88] 226 +2										Actinide Series										89 Ac Actinium [89] 227 +3										90 Th Thorium [90] 232 +2, +3, +4										91 Pa Protactinium [91] 231 +3, +4										92 U Uranium [92] 238 +3, +4										93 Np Neptunium [93] 237 +3, +4										94 Pu Plutonium [94] 244 +3, +4										95 Am Americium [95] 243 +3										96 Cm Curium [96] 247 +2, +3										97 Bk Berkelium [97] 247 +3										98 Cf Californium [98] 251 +2, +3										99 Es Einsteinium [99] 252 +2, +3										100 Fm Fermium [100] 257 +2, +3										101 Md Mendelevium [101] 258 +2, +3										102 No Nobelium [102] 259 +2, +3										103 Lr Lawrencium [103] 262 +3									



- Here we have eliminated radioactive elements.
- It's fair to say "no" to toxic materials – so they are gone from this list.

Periodic Table of the Elements

No synthetic, no radioactive, no inert, no toxic and no rare elements

Group 1 IA	2 IIA	Phase at STP Gas Liquid Solid Synthetic										13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA									
1 H Hydrogen [1] 1.00794 +1																	2 He Helium [2] 4.002602 0									
3 Li Lithium [3] 6.941 +1	4 Be Beryllium [4] 9.0122 +2											5 B Boron [5] 10.811 +3	6 C Carbon [6] 12.011 +2, 4	7 N Nitrogen [7] 14.0064 +3, 5, 4, 2, 2, 3	8 O Oxygen [8] 15.999 -2	9 F Fluorine [9] 18.998 -1	10 Ne Neon [10] 20.179 0									
11 Na Sodium [11] 22.990 +1	12 Mg Magnesium [12] 24.305 +2											13 Al Aluminum [13] 26.9815 +3	14 Si Silicon [14] 28.0855 +4	15 P Phosphorus [15] 30.9738 +3, 5, 3	16 S Sulfur [16] 32.065 -2, 4	17 Cl Chlorine [17] 35.453 -1	18 Ar Argon [18] 39.948 0									
19 K Potassium [19] 39.0983 +1	20 Ca Calcium [20] 40.078 +2	21 Sc Scandium [21] 44.9559 +3	22 Ti Titanium [22] 47.88 +2, 3, 4	23 V Vanadium [23] 50.9415 +3, 4, 5	24 Cr Chromium [24] 51.9961 +2, 3, 6	25 Mn Manganese [25] 54.938 +2, 3, 4, 7	26 Fe Iron [26] 55.845 +2, 3	27 Co Cobalt [27] 58.933 +2, 3	28 Ni Nickel [28] 58.693 +2, 3	29 Cu Copper [29] 63.546 +1, 2	30 Zn Zinc [30] 65.38 +2	31 Ga Gallium [31] 69.723 +3	32 Ge Germanium [32] 72.64 +4	33 As Arsenic [33] 74.9216 +3, 5, 3, 4, 5	34 Se Selenium [34] 78.96 -2, 4	35 Br Bromine [35] 79.904 -1	36 Kr Krypton [36] 83.798 0									
37 Rb Rubidium [37] 85.4678 +1	38 Sr Strontium [38] 87.62 +2	39 Y Yttrium [39] 88.9058 +3	40 Zr Zirconium [40] 91.224 +3, 4	41 Nb Niobium [41] 92.9064 +3, 5	42 Mo Molybdenum [42] 95.94 +2, 3, 4, 5, 6	43 Tc Technetium [43] 98 +4, 5, 6, 7	44 Ru Ruthenium [44] 101.07 +2, 3, 4, 5, 6, 7, 8	45 Rh Rhodium [45] 102.905 +3, 4, 5, 6, 7, 8	46 Pd Palladium [46] 106.367 +2, 3, 4, 5, 6, 7, 8	47 Ag Silver [47] 107.868 +1	48 Cd Cadmium [48] 112.411 +2	49 In Indium [49] 114.818 +3	50 Sn Tin [50] 118.710 +2, 4	51 Sb Antimony [51] 121.757 +3, 5	52 Te Tellurium [52] 127.6 +4, 6	53 I Iodine [53] 126.905 -1	54 Xe Xenon [54] 131.29 0									
55 Cs Cesium [55] 132.905 +1	56 Ba Barium [56] 137.327 +2	Lanthanide Series										57 La Lanthanum [57] 138.905 +3	58 Ce Cerium [58] 140.12 +3, 4	59 Pr Praseodymium [59] 140.907 +3	60 Nd Neodymium [60] 144.24 +3	61 Pm Promethium [61] 144.9128 +3, 4, 5	62 Sm Samarium [62] 150.36 +2, 3	63 Eu Europium [63] 151.964 +2, 3	64 Gd Gadolinium [64] 157.25 +2, 3	65 Tb Terbium [65] 158.925 +3	66 Dy Dysprosium [66] 162.5 +2, 3	67 Ho Holmium [67] 164.930 +3	68 Er Erbium [68] 167.259 +3	69 Tm Thulium [69] 168.930 +3	70 Yb Ytterbium [70] 173.054 +2, 3	71 Lu Lutetium [71] 174.967 +3
71 Fr Francium [71] 223 +1	72 Ra Radium [72] 226 +2	Actinide Series										87 Ac Actinium [87] 227 +3	88 Th Thorium [88] 232 +2, 3, 4	89 Pa Protactinium [89] 231 +3, 4, 5	90 U Uranium [90] 238 +3, 4, 5, 6	91 Np Neptunium [91] 237 +3, 4, 5, 6, 7	92 Pu Plutonium [92] 244 +3, 4, 5, 6, 7	93 Am Americium [93] 243 +3, 4, 5, 6, 7	94 Cm Curium [94] 247 +2, 3, 4, 5, 6, 7	95 Bk Berkelium [95] 247 +3, 4, 5, 6, 7	96 Cf Californium [96] 251 +2, 3, 4, 5, 6, 7	97 Es Einsteinium [97] 252 +2, 3, 4, 5, 6, 7	98 Fm Fermium [98] 257 +2, 3, 4, 5, 6, 7	99 Md Mendelevium [99] 258 +2, 3, 4, 5, 6, 7	100 No Nobelium [100] 259 +2, 3, 4, 5, 6, 7	101 Lr Lawrencium [101] 260 +3



- And let's get rid of the elements that are truly rare such as platinum, palladium, gold, silver, etc.

Periodic Table of the Elements - Net

No synthetic, no radioactive, no inert, no toxic, no rare, no salt-forming elements, no hydrogen


Group	1	2											13	14	15	16	17	18	
IA	IIA											IIIA	IVA	VA	VIA	VIIA	VIIIA		
1	H	He											B	C	N	O	F	Ne	
2	Li	Be											Boron	Carbon	Nitrogen	Oxygen	Fluorine	Neon	
3	Na	Mg											Al	Si	P	S	Cl	Ar	
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe	
6	Cs	Ba	Lanthanide Series		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	Ra	Actinide Series		Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Uuq	Uup	Uuh	Uus	Uuo

Lanthanides

57	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
	Lanthanum	Cerium	Praseodymium	Neodymium	Promethium	Samarium	Europium	Gadolinium	Terbium	Dysprosium	Holmium	Erbium	Thulium	Ytterbium	Lutetium

Actinides

89	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
	Actinium	Thorium	Protactinium	Uranium	Neptunium	Plutonium	Americium	Curium	Berkelium	Californium	Einsteinium	Fermium	Mendelevium	Nobelium	Lawrencium



Our World Touches Your World Every Day...

© Arnold Magnetic Technologies

88

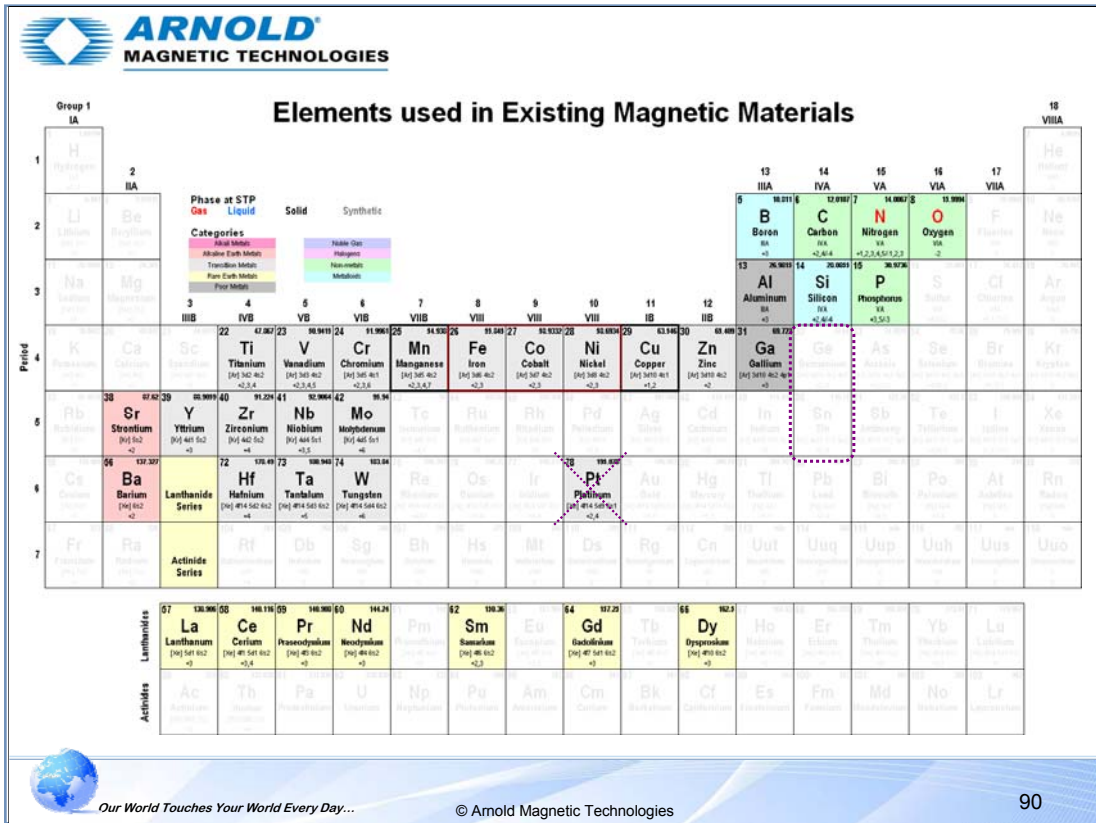
- Oh and hydrogen and the rock-forming elements won't do us any good either – at least that's our tentative belief.
- So we're down from 90 naturally occurring elements to 36 – still a lot to work with.
- Let's ask a question: what elements have been used over the last 150 years to make magnetic materials?

Elements in Existing Magnetic Materials

	Major constituents				Minor constituents			Comments		
Soft Magnetic Materials										
Iron	Fe							Low carbon mild steel		
Silicon Steel	Fe				Si			Si at 2.5 to 6%		
Nickel-Iron	Fe	Ni						Ni at 35 to 85%		
Moly Permalloy	Ni	Fe			Mo			Ni at 79%, Mo at 4%, bal. Fe		
Iron-Cobalt	Fe	Co			V			23 to 52% Co		
Soft Ferrite	Fe	Mn	Ni	Zn	O					
Metallic Glasses	Fe	Co	Ni		B	Si	P	Amorphous and nanocrystalline		
Permanent Magnets										
Co-Steels	Fe	Co								
Alnico	Fe	Ni	Co	Al	Cu	Ti	Si			
Platinum Cobalt	Pt	Co								
Hard Ferrites	Fe	Sr						Oxygen dilutes; Ba no longer used		
SmCo	Co	Sm	(Gd)	Fe	Cu	Zr				
Neodymium-iron-boron	Fe	Nd	Dy	(Y)	B	Co	Cu	Ga	Al	Nb
Cerium-iron-boron	Fe	Nd	Ce	B						Limited use in bonded magnets
SmFeN	Fe	Sm	N							Nitrogen is interstitial; stability issue
MnBi	Mn	Bi								Never commercialized
MnAl(C)	Mn	Al				C				Not successfully commercialized



- This list contains most (though not all) common magnetic materials and the elements used to make them.
- Take a good look and then move to the next slide showing them on the periodic table.



- These elements are, with three exceptions, the same elements we selected by paring down the periodic table.
- The exceptions:
 - 1) platinum-cobalt was the first high performance magnet. It was used to make watch drive motor magnets whose very small size compensated for the high material cost.
 - 2) Germanium and Tin have not been used except as very minor additives, at least to my knowledge, in commercial magnets, but like aluminum and gallium might make suitable modifying constituents to assist sintering or phase formation.

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, MnAl(C)
- Heusler alloys
- Alnico – modified to enhance coercivity
- Carbides: FeC, CoC, Co,TM-C
- Modified Ferrites (chemical or structural modifications):
La-Co Ferrites, Core-Shell structure ferrites
- Ce-Co,Fe and Ce-Fe,Co-B,C



- Existing research projects is split here into two categories.
- The first could be called “Variation on a Theme” as it represents an extension of research on materials that have been previously examined and it is shown in the list on this slide.
- However, there are several differences between what took place “then” and what is being pursued “now”.
- One difference 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 with a focus on the structure.

“Greenfield” Magnets

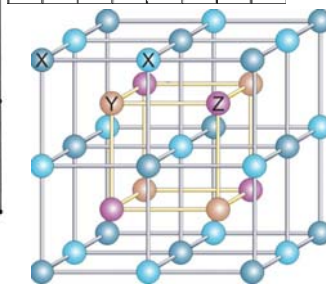
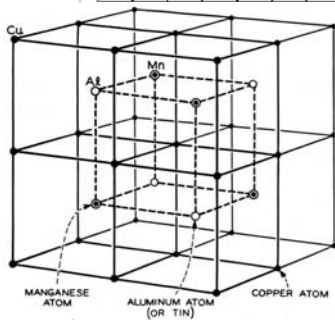
- Computer calculations to arrive at alloy structure with net magnetic moment
- Promising alloys are then formed in the lab and evaluated
- 2 and 3-component alloys are practical
 - 4+ component alloys represent significant computational difficulty
- Finished magnet must be...
 - Fully dense to take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



- We started with 90 naturally occurring elements and ended with 36 promising ones.
- The “bottoms-up” approach is to take the 36 remaining elements from our experiment with the periodic table and to combine them using computer algorithms to forecast the potential for generating a magnetic moment.
- Then the list of most promising alloys must be produced in the lab 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 crystal shape anisotropy (e.g. alnico) or magneto-crystalline anisotropy (e.g. ferrite, SmCo and Neo).
- In either case, during manufacture the magnetic domains must be mutually aligned “co-parallel” to obtain maximum properties.
- Simultaneous densification and alignment of nano-particulates has been a difficult problem awaiting solution.

Heusler Alloys – interesting structures

"A Heusler alloy is a ferromagnetic metal alloy based on a Heusler phase. Heusler phases are intermetallics with particular composition and face-centered cubic crystal structure. They are ferromagnetic—even though the constituting elements are not—as a result of the double-exchange mechanism between neighboring magnetic ions. The latter are usually manganese ions, which sit at the body centers of the cubic structure and carry most of the magnetic moment of the alloy."



Sources: Ferromagnetism, Richard M. Bozorth, IEEE Press, p.328; Wikipedia

Magnetism and Magnetic Materials, J.M.D. Coey, p.394

Table 11.9. Heusler and half-Heusler alloys

	a_0 (pm)	T_c (K)	σ_0 (A m ² kg ⁻¹)	m (μ_B)
Cu ₂ MnIn	621	500	75	4.0
Co ₂ MnGa	577	694	93	4.1
Co ₂ MnSi ^a	565	985	141	5.0
Co ₂ MnGe ^a	574	905	116	5.1
Co ₂ MnSn	600	829	97	5.1
Ni ₂ MnGa	583	380	96	4.2
Ni ₂ MnSn	605	360	81	4.2
Pd ₂ MnSb	642	247	63	4.4
NiMnSb ^a	592	730	93	4.0
PtMnSb ^a	620	572	60	4.0
Mn ₂ VAl ^a	760	730	59	2.0

^a Half-metal



- Heusler alloys have interesting crystalline structures.
- They were first identified as a family of materials in 1905 and have found recent revival in spintronics.

A Heusler alloy is a ferromagnetic metal alloy based on a Heusler phase. Heusler phases are intermetallics with particular composition and face-centered cubic crystal structure. They are ferromagnetic—even though the constituting elements are not—as a result of the double-exchange mechanism between neighboring magnetic ions. The latter are usually manganese ions, which sit at the body centers of the cubic structure and carry most of the magnetic moment of the alloy.

(Wikipedia)

Sensitivity to Thermal Treatment

Affect of Thermal Treatment on SmCo 2:17 Magnetic Properties

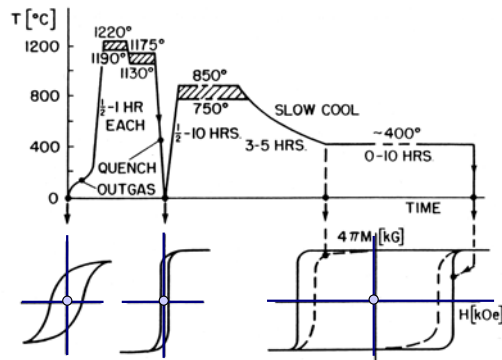


Fig. 32. Typical temperature profile for the sintering and heat-treating of "2-17"-type Sm(Co, Fe, Cu, Zr)_{7.2-8.5} magnets.

Source: Rare earth-Cobalt Permanent Magnets, K.J. Strnat, 1988

Affect of Thermal Treatment in an aligning magnetic field on magnetic Properties of alnico 5

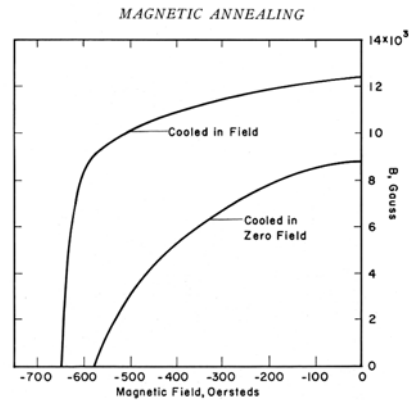


Fig. 8—Effect of Magnetic Annealing of Alnico 5 (142).

Source: Magnetic Properties of Metals and Alloys, published by the American Society for Metals, 1958, Chapter 13, C.D. Graham, Jr., p.307



- In current research, in addition to the importance of structure is the importance of thermal processing in the development of optimal microstructure – “phase equilibrium 101”.
- With the exception of ceramic (hard ferrite) magnets, magnetic alloys are just that – alloys.
- Therefore, thermal treatments to form the stable and desirable phase structure is not only preferable but also very common.
- In the chart at the left, Strnat shows the development of the hysteresis loop of SmCo 2:17 during its thermal treatment.
- In the chart to the right, we see the improvement of magnet properties of alnico due to thermal processing in the presence of an aligning magnetic field.

Alnico Thermal Treatment

Three treatments

- Solution treatment above 1200 °C
- Isothermal treatment for spinodal decomposition and magnetic alignment
- Draw (precipitation hardening) cycle

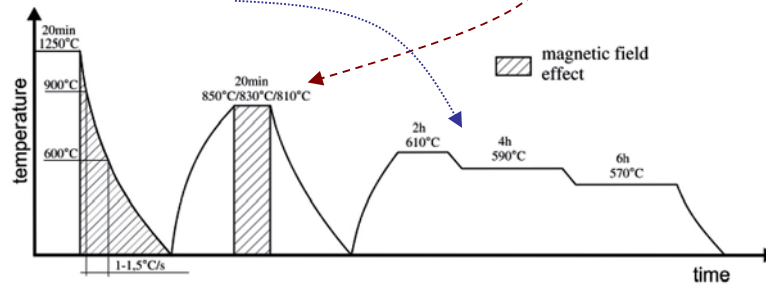


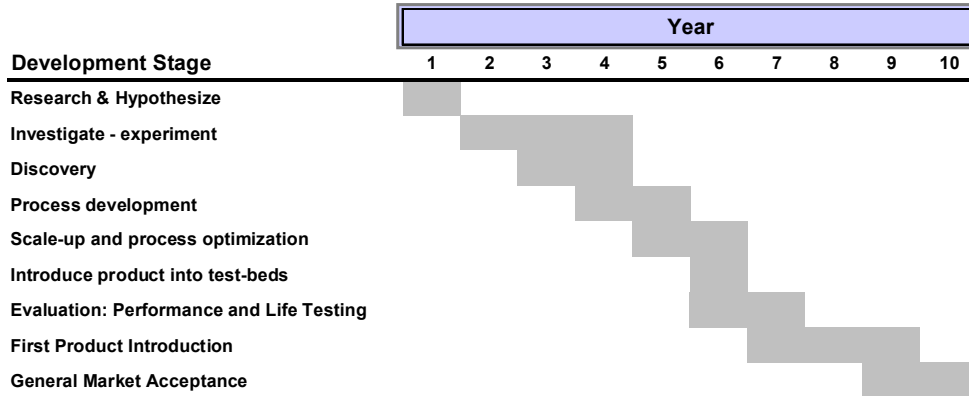
Fig. 3. Scheme of thermo-magnetic treatment of Alnico 8 alloy

Source: Investigations of Thermo-Magnetic Treatment of Alnico 8 Alloy, Stanek et al, Archives of Metallurgy and Materials, Vol 55, 2010 Issue 2



- In another example, alnico is solution treated at high temperature (about 1230 °C) followed by a conditioning treatment effected by controlled cooling from the solution treatment temperature or by isothermal treatment of the magnets – anisotropic magnets are treated in a field during spinodal decomposition at ~820 °C.
- The third and final treatment is called a “draw” or “coercive aging treatment” to obtain maximum coercivity and optimal loop shape.
- We might say that the right composition provides the opportunity and the right thermal treatment creates the right phase structure.

Time to New Products



We cannot legislate invention but the inventive effort can be managed.



- Problems with pricing and supply of permanent magnets include both logistic and technical issues.
- Technical issues are resolved by R&D for new, improved materials which strategy is suitable as a long-term plan but is highly unlikely to have any short-term influence.



<http://www.theodoregray.com/PeriodicTable/Posters/Poster3.2000.JPG>

THE ELEMENTS

© Arnold Magnetic Technologies