ARNOLD® MAGNETIC TECHNOLOGIES

The Elements of Magnetics

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

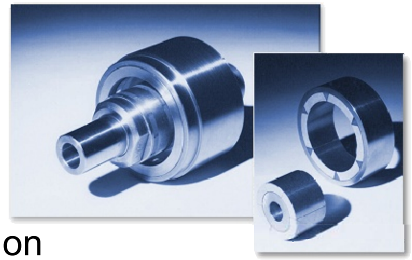
Case Western Reserve University EST. 1826
think beyond the possible®

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

ARNOLD MAGNETIC TECHNOLOGIES

Arnold – What We Manufacture

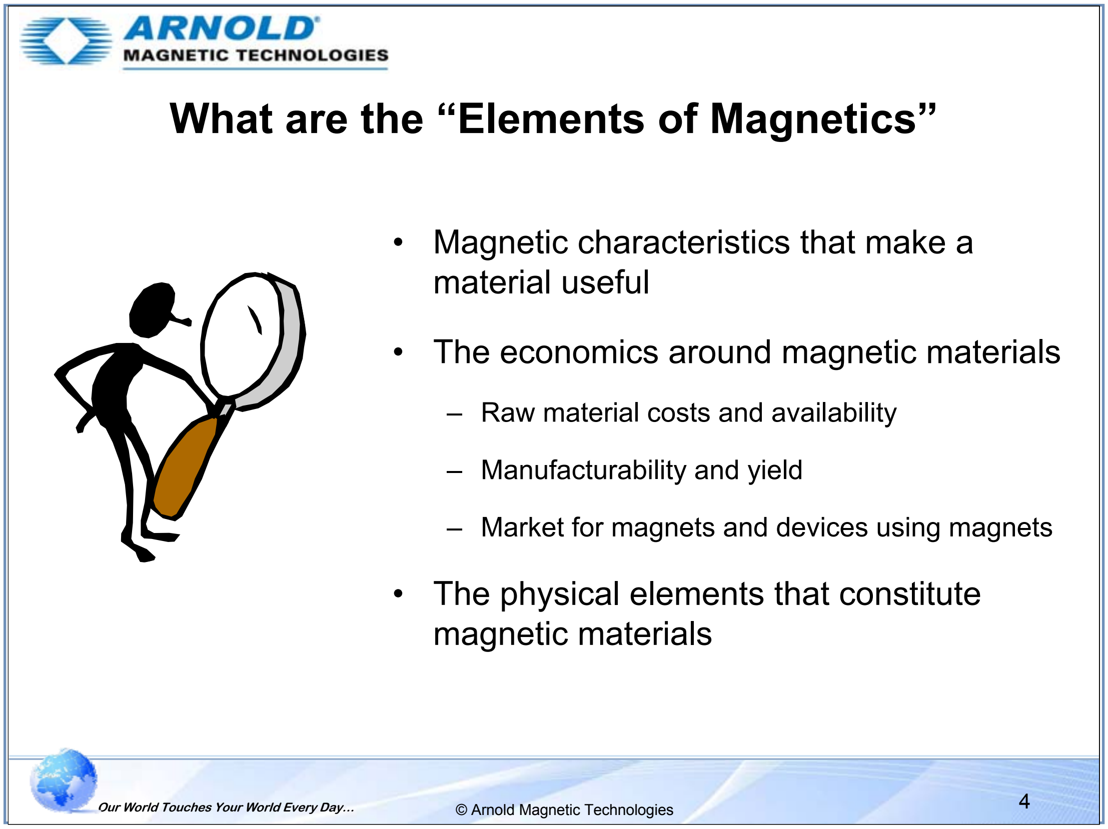
- Magnet Production
  - SmCo RECOMA® - (Lupfig, Switzerland; Rochester, NY; Ganzhou, China)
  - Alnico - (Marengo, IL)
  - Ferrite (Bonded) - (Marietta, OH; Norfolk, NE)
  - Injection Molded (Bonded) - (Shenzhen, China)
  - Electrical Steels - ARNON ® (Marengo, IL)
  - Electromagnets - (Ogallala, NE)



- 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

Our World Touches Your World Every Day...

- Arnold manufactures magnetic materials and produces sophisticated assemblies utilizing 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.

ARNOLD MAGNETIC TECHNOLOGIES

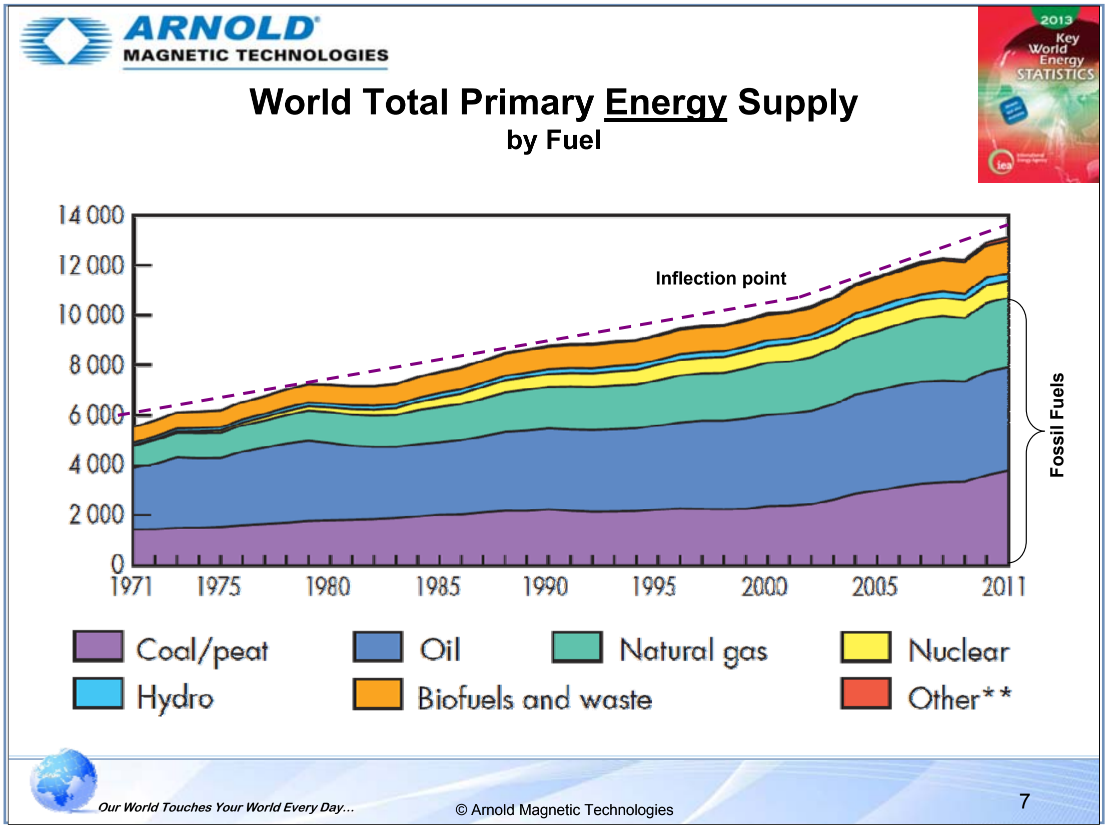
Agenda

- 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)

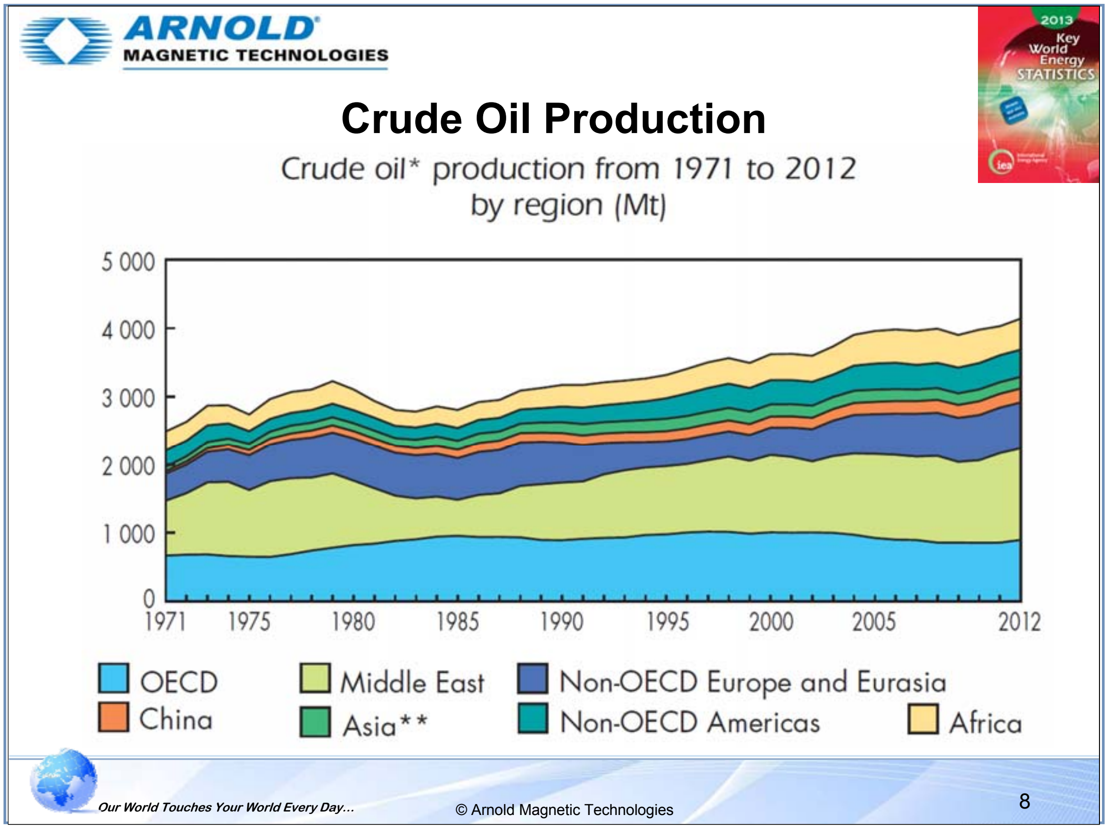
Our World Touches Your World Every Day...

- 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.

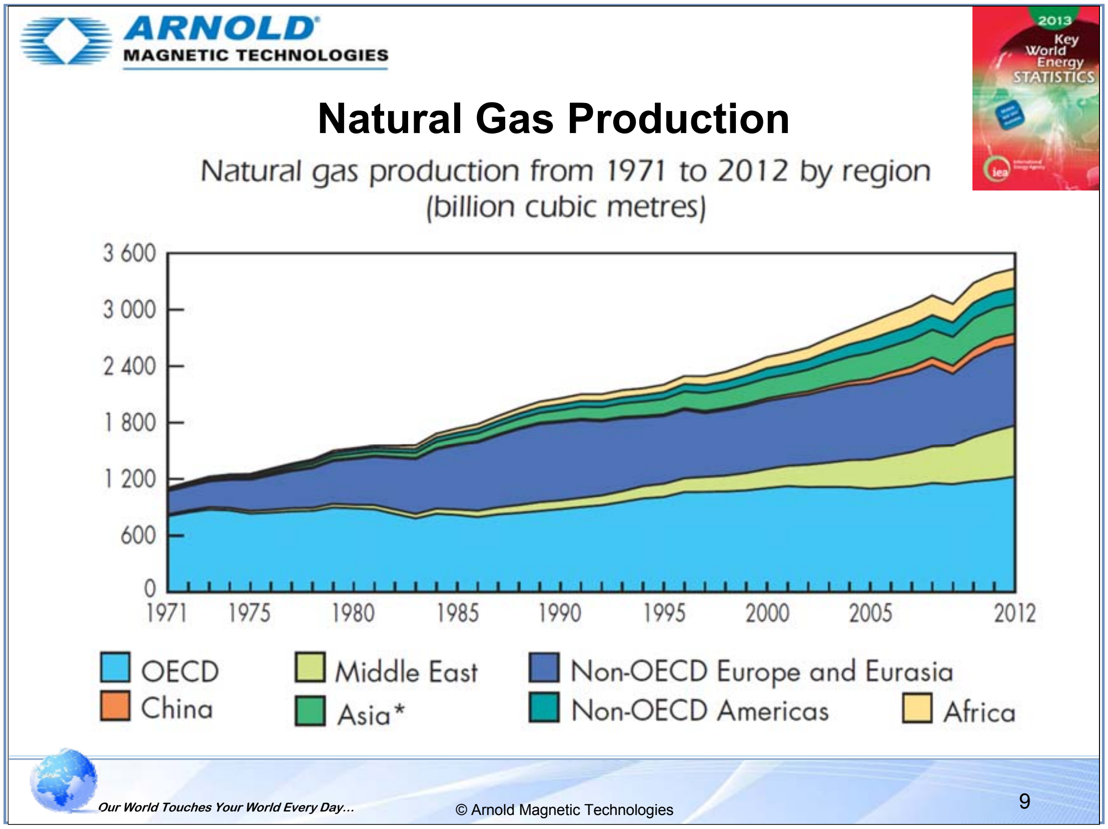
- In the global community, the IEA provides production and consumption statistics.
- The OECD is comprised of the countries listed to the right on this slide – shown in alphabetic order.



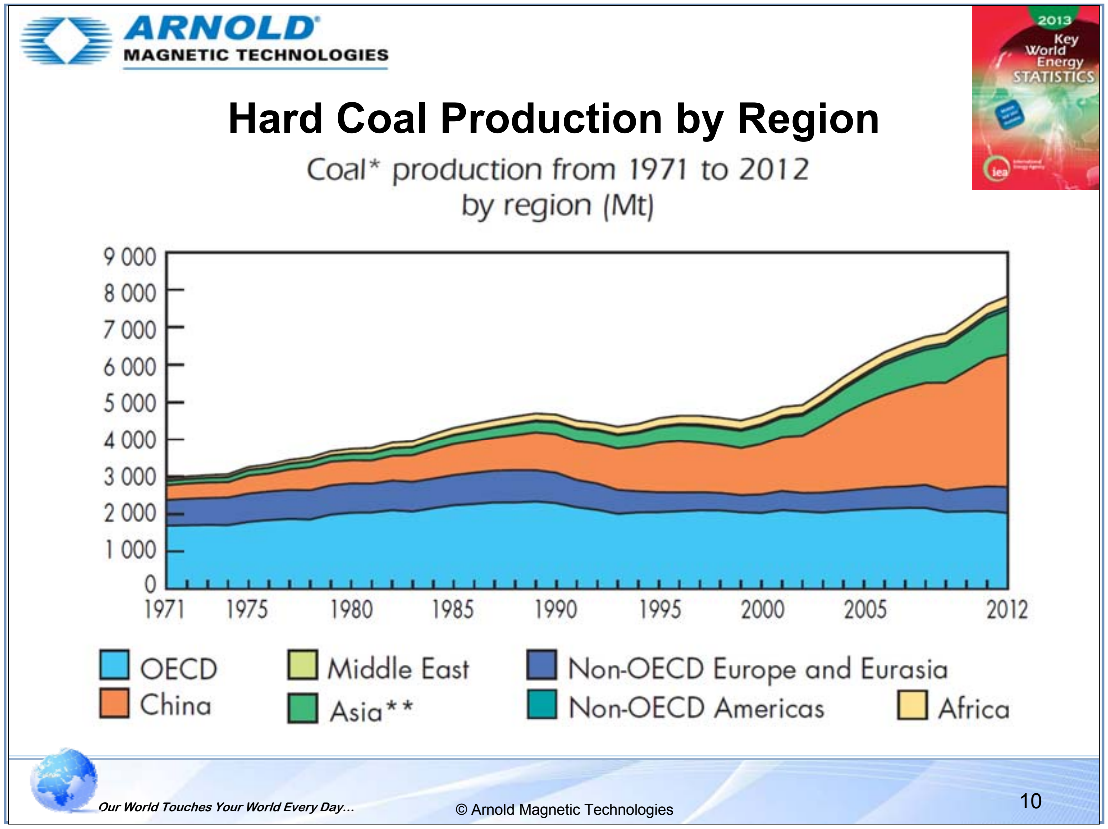
- Each year, an update is published showing energy production and consumption statistics.
- This slide shows total energy supply by fuel.
- An inflection point is evident at approximately year 2003.
- It is clear that fossil fuels represent the greatest fraction of energy sourcing.



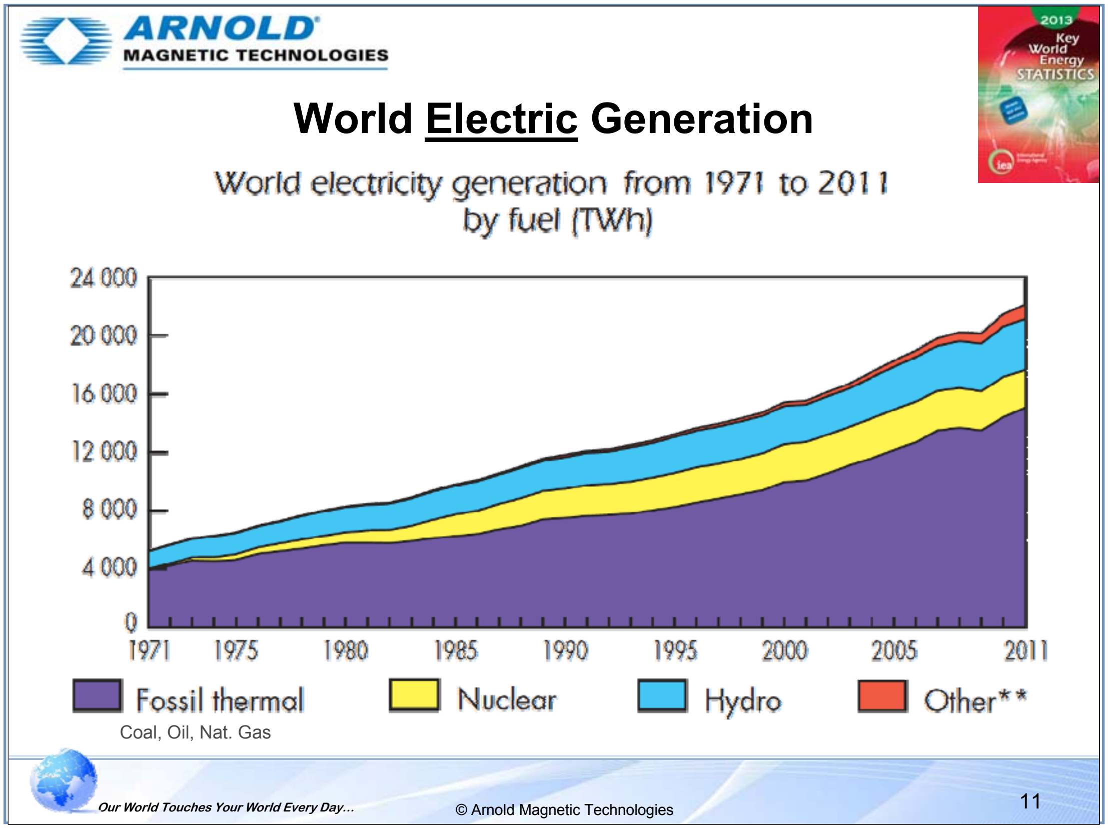
- Although overall energy production is increasing, crude oil output is growing very slowly, predominantly in the Middle East.



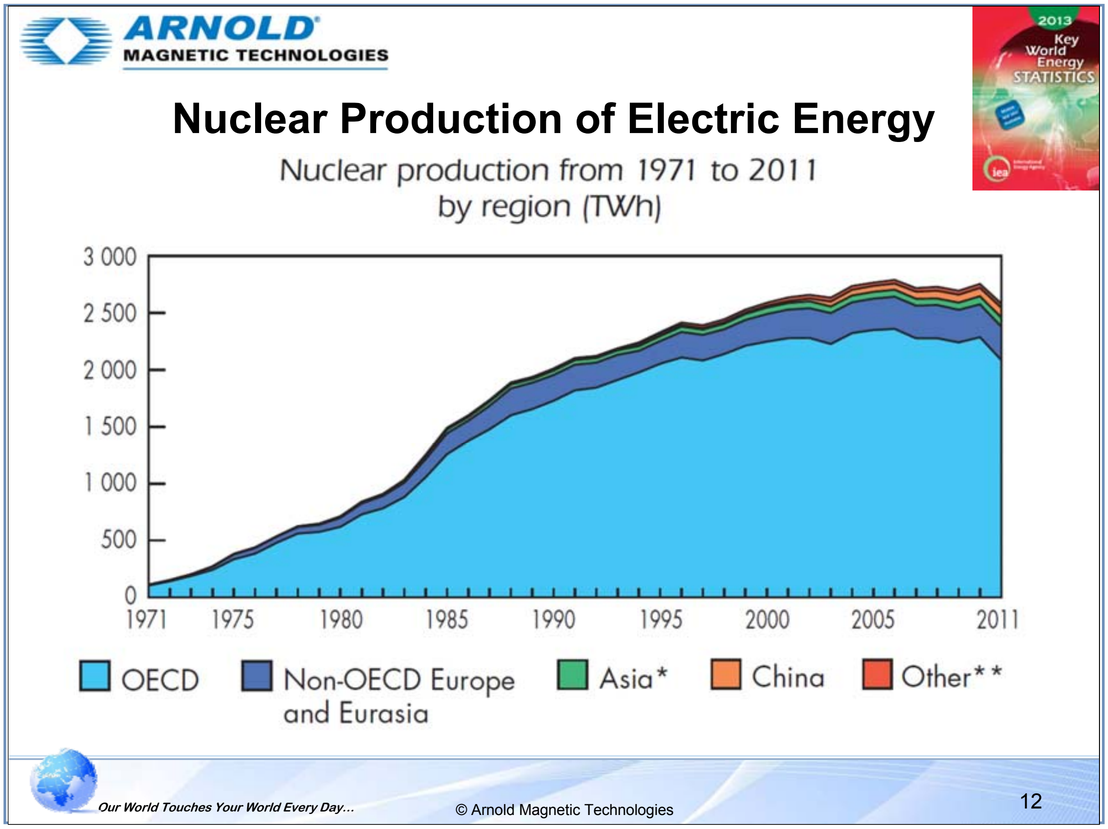
- Natural gas output is surging primarily due to "unconventional drilling" with increases in output occurring throughout the world.



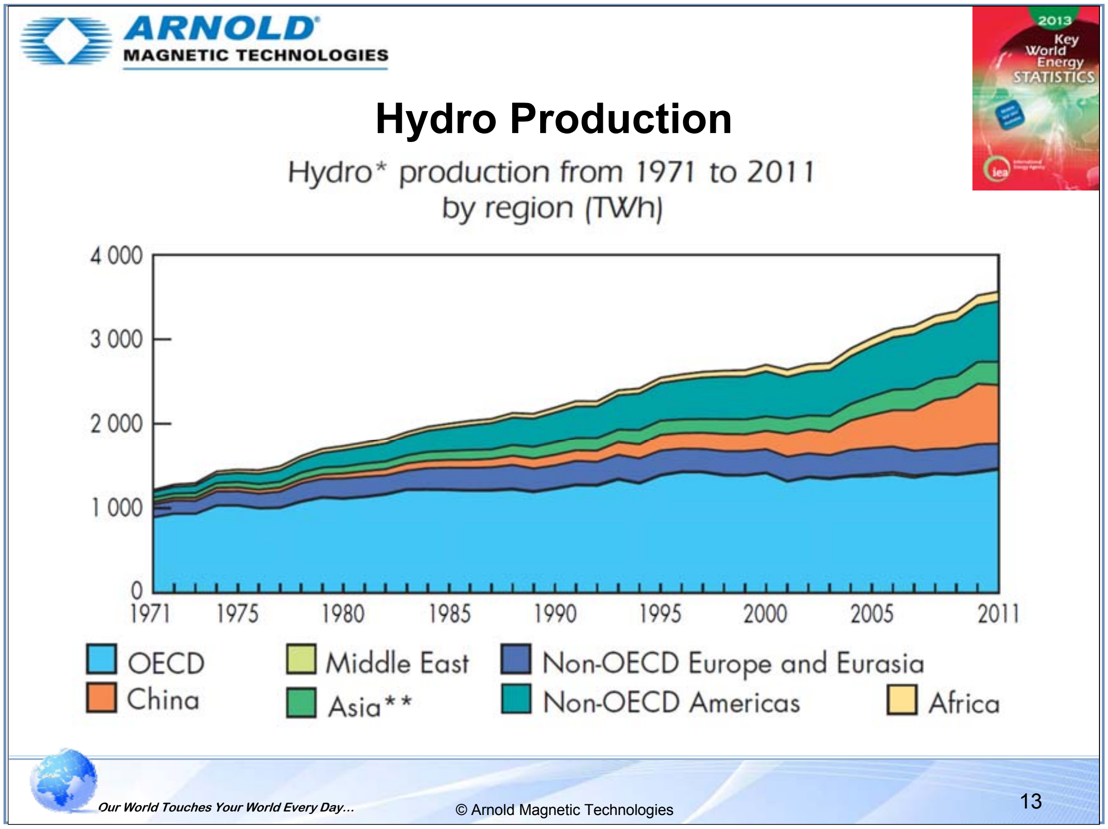
- Coal production has most noticeable increased in China.



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



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



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

ARNOLD® MAGNETIC TECHNOLOGIES

Fuel Used for Production of Electricity - 2011

Coal/peat	TWh
People's Rep. of China	3 723
United States	1 875
India	715
Japan	281
Germany	272
South Africa	243
Korea	225
Australia	173
Russian Federation	164
Poland	141
Rest of the world	1 332
World	**9 144**

Natural gas	TWh
United States	1 045
Russian Federation	519
Japan	374
Islamic Rep. of Iran	160
Mexico	156
United Kingdom	147
Italy	145
Egypt	117
Korea	116
India	109
Rest of the world	1 964
World	**4 852**

Oil	TWh
Japan	153
Saudi Arabia	142
Islamic Rep. of Iran	67
Mexico	48
Indonesia	42
United States	40
Kuwait	36
Pakistan	34
Russian Federation	27
Egypt	25
Rest of the world	444
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.

ARNOLD MAGNETIC TECHNOLOGIES

Sources of Energy for Electricity Production

Non-renewable

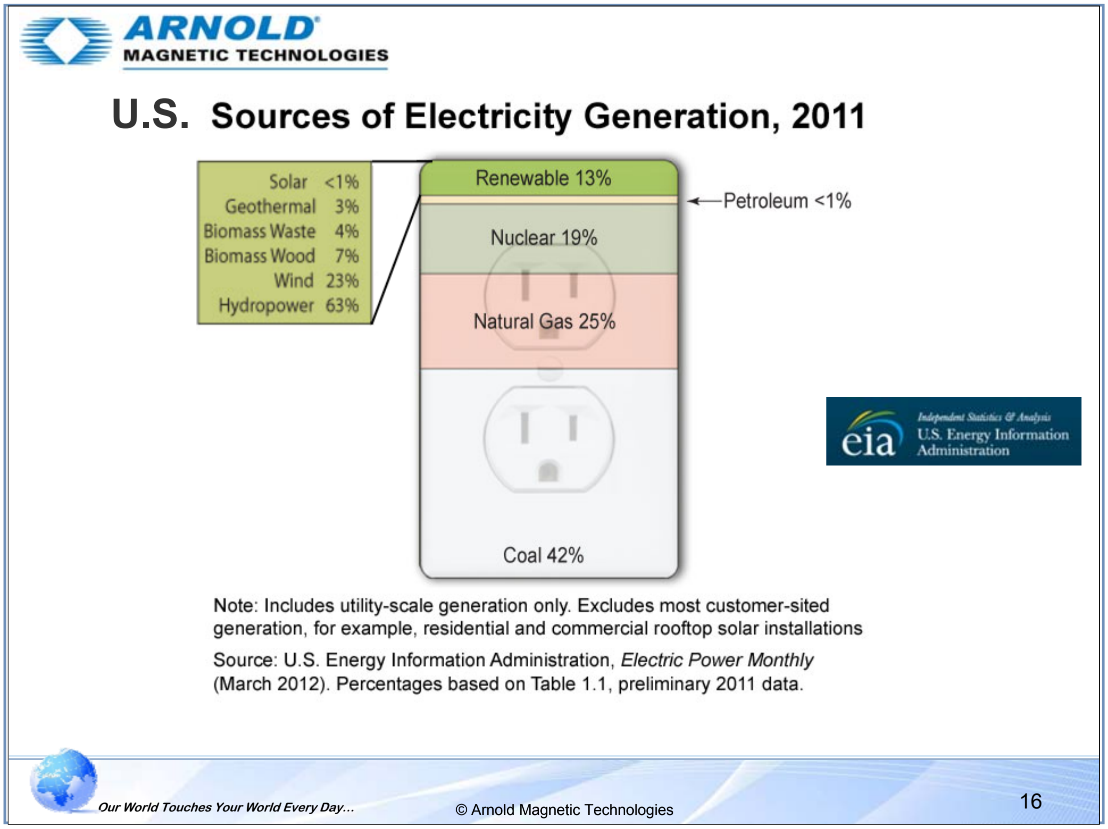
- Coal / Peat
- Gas
- Nuclear
- Oil

Renewable

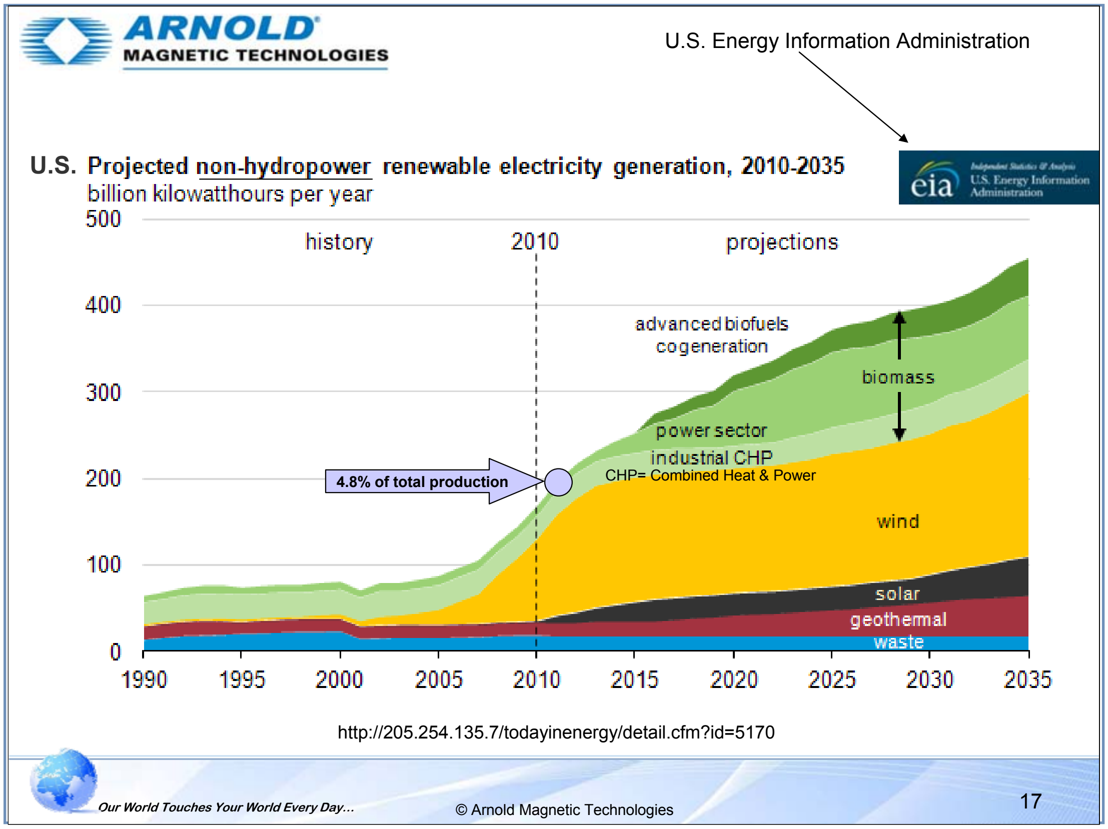
- Hydro
- Wind
- Bio Fuels and Waste
- Solar
- Geothermal
- Tidal / Wave

Our World Touches Your World Every Day...

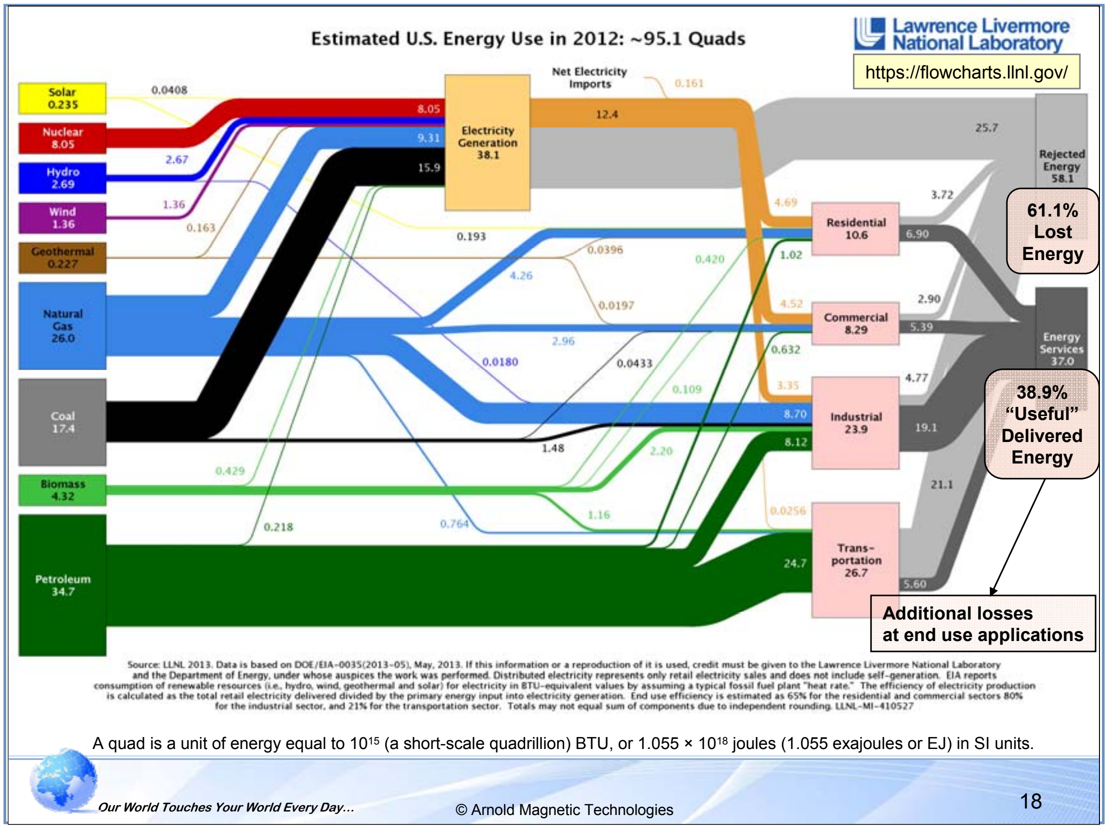
- The DOE has divided fuel type into non-renewable and renewable.
- (The illustration was from the DOE site c.2011).



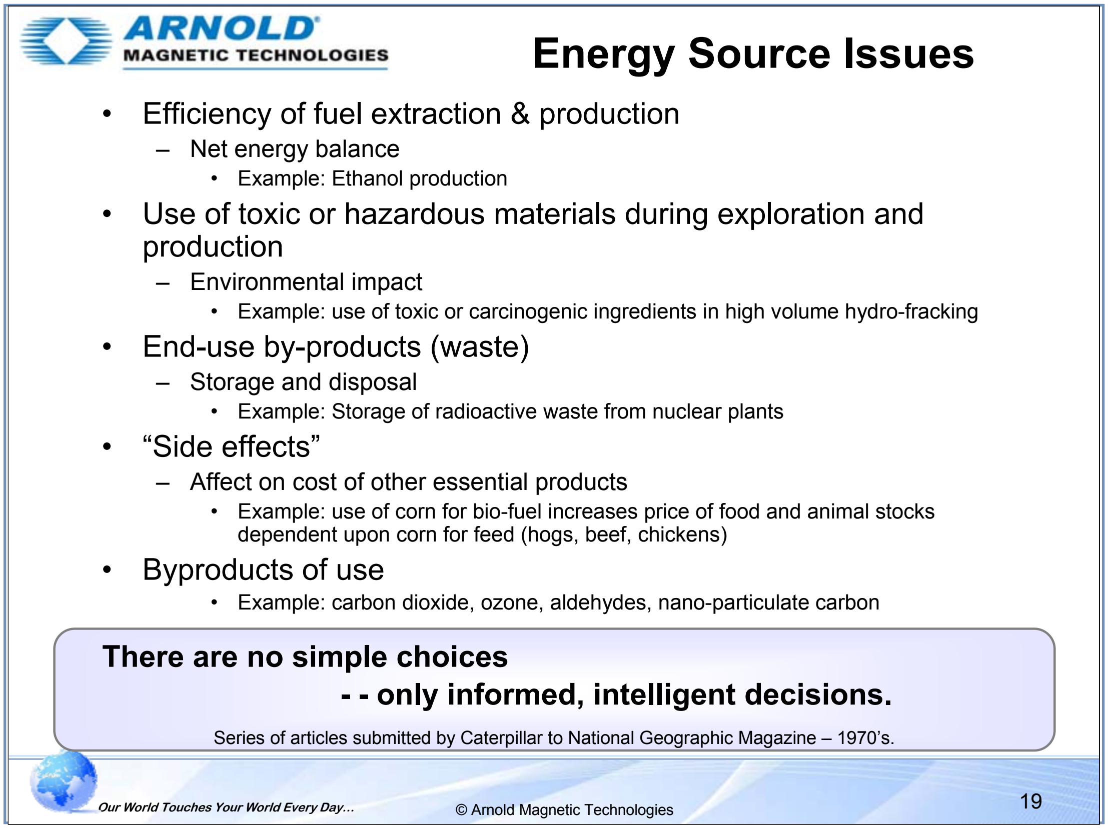
- Renewable sources of electric generation were 13% of the total in 2011.
- As expected, oil (petroleum) was less than 1%.



- 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.



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

ARNOLD MAGNETIC TECHNOLOGIES

Energy, entropy and the “strive to thrive”

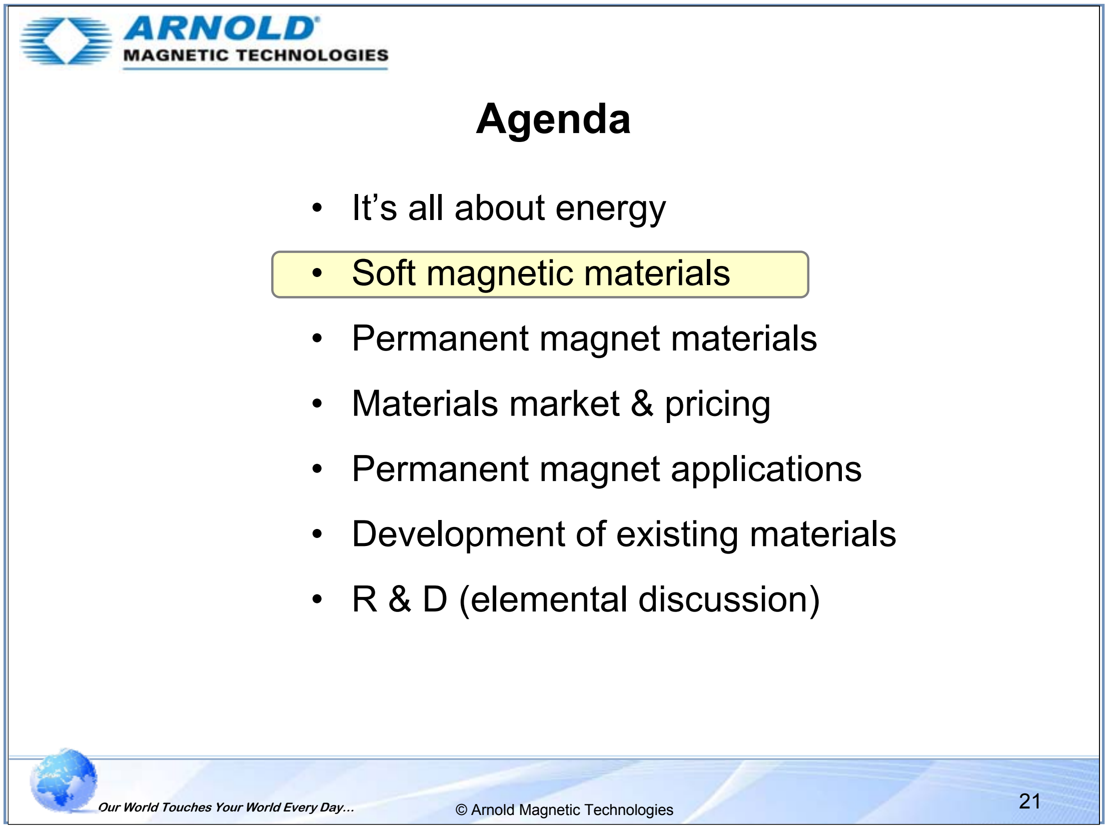
Efficient **Production**

Efficient **Transmission**

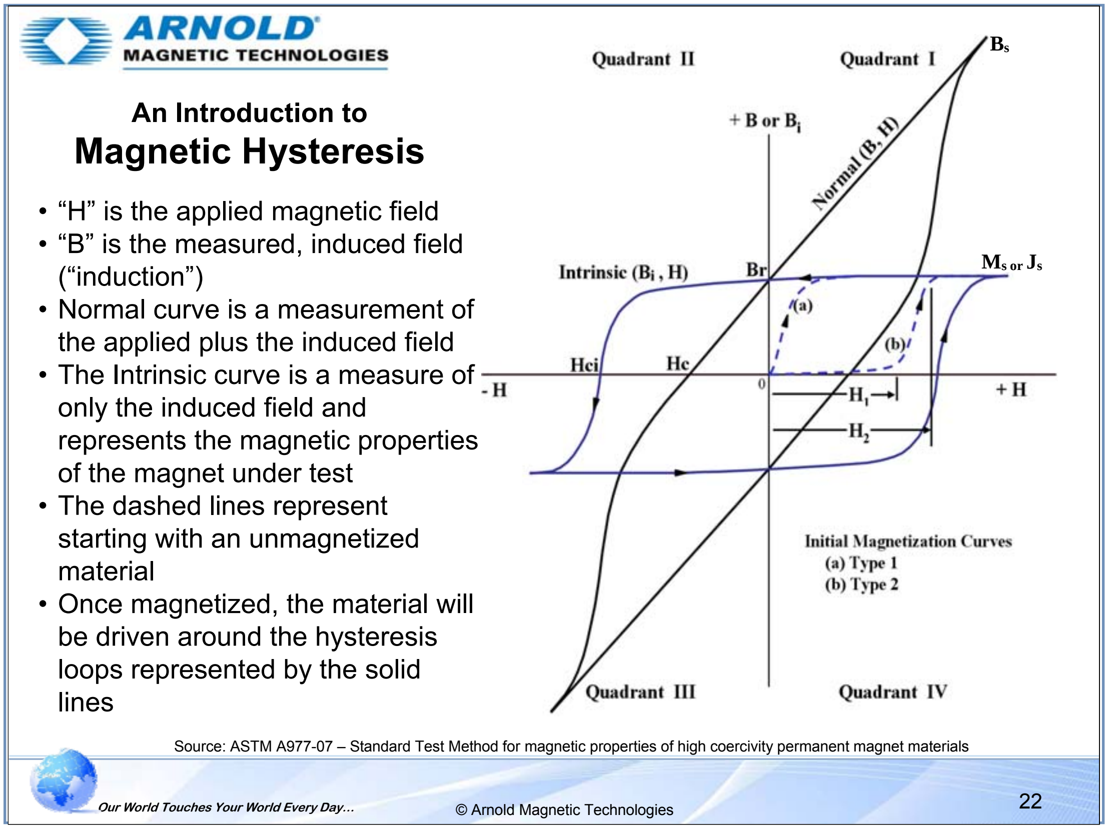
Efficient **Use**

...of electrical energy

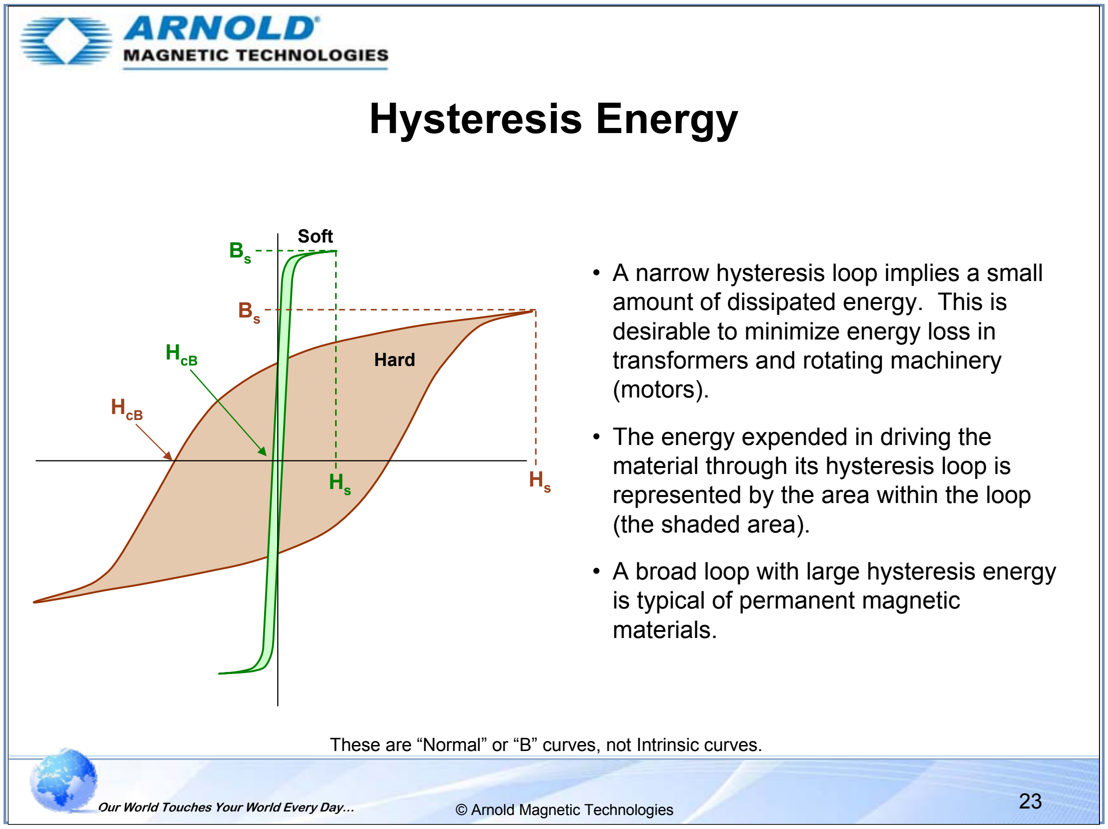
- With the demand for electricity for commercial and personal use, it is apparent that we must strive for more efficiency in production, transmission and use.
- Magnetic materials play important roles in all three areas.



- 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.



- 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.



- 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 HcB 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 HcB 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 Bs represent the magnetic saturation and Hs 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 HcB and correspondingly small areas within the loop.

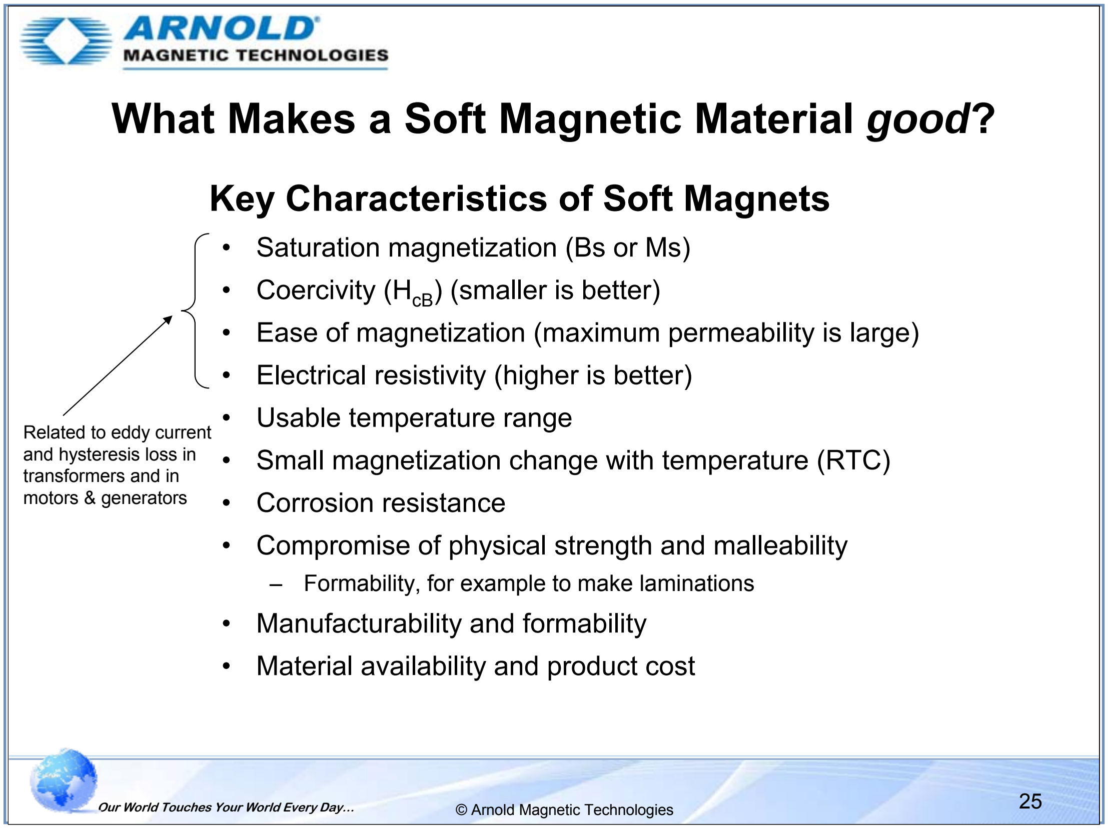
Definition and Examples

		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

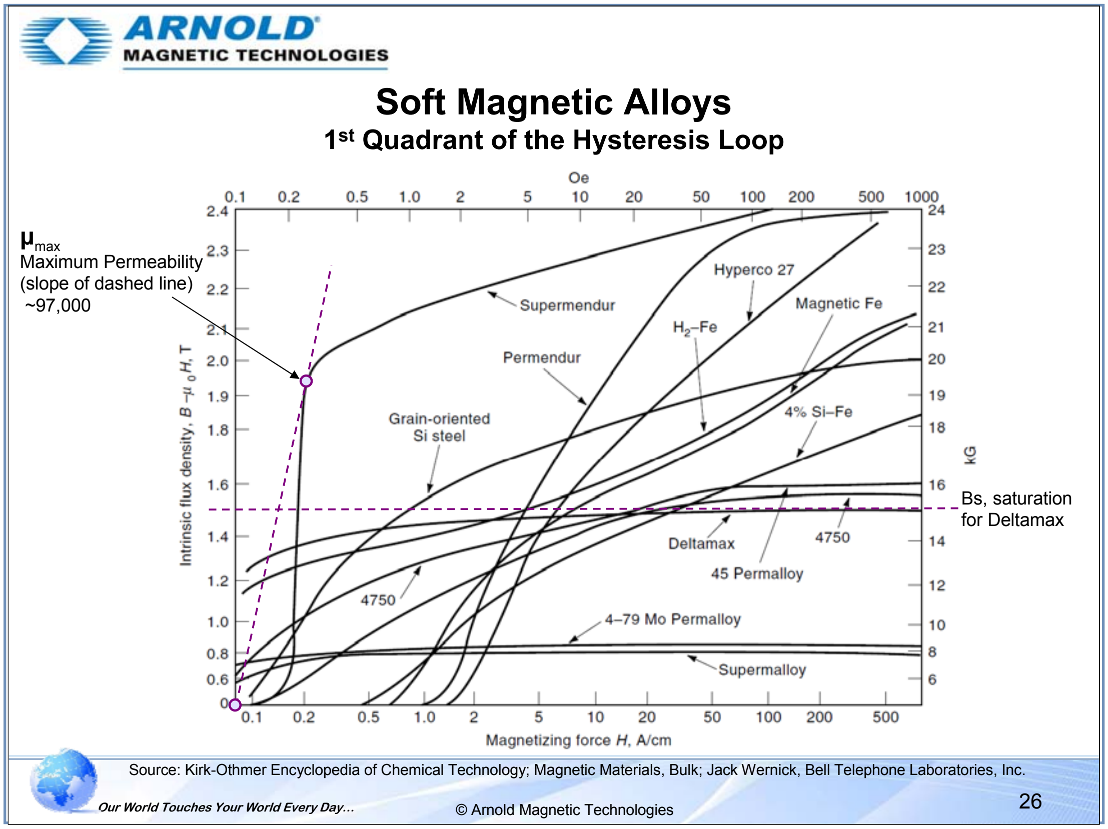
[A] Soft and Semi-Hard materials use Bsat.; PM materials use Msat.

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

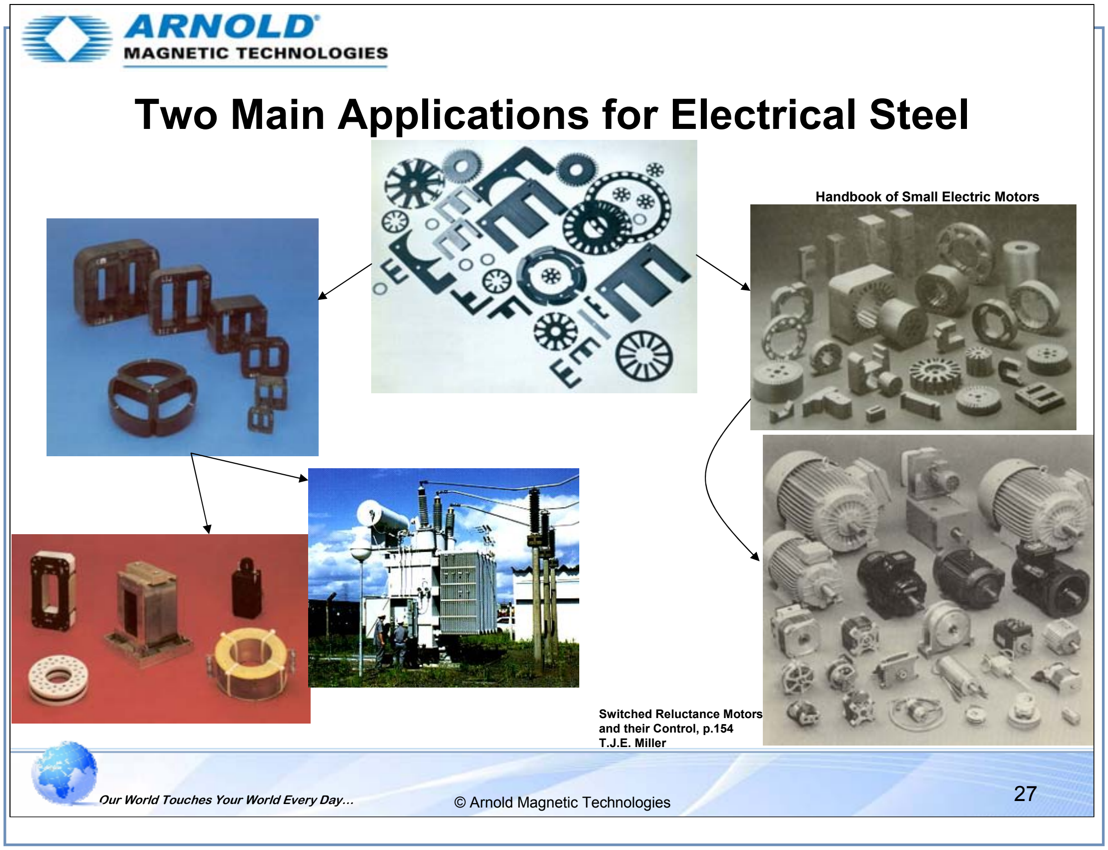
- There is actually a continuum of materials from very soft to very hard.
- We can divide them into soft and hard magnetic materials or we can split them into three categories (as shown here) wherein each category has specific benefits.
- For convenience we have assigned arbitrary values to distinguish 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 HcJ much larger than HcB and it became common practice to provide both the Normal and the Intrinsic curves.
- Some materials, such as FeCrCo, can have various levels of HcB by adjusting the final heat treatment time, temperature and quench rate.



- 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 HcB.



- 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 Bs, and shown here for Deltamax with the near-horizontal dashed line.

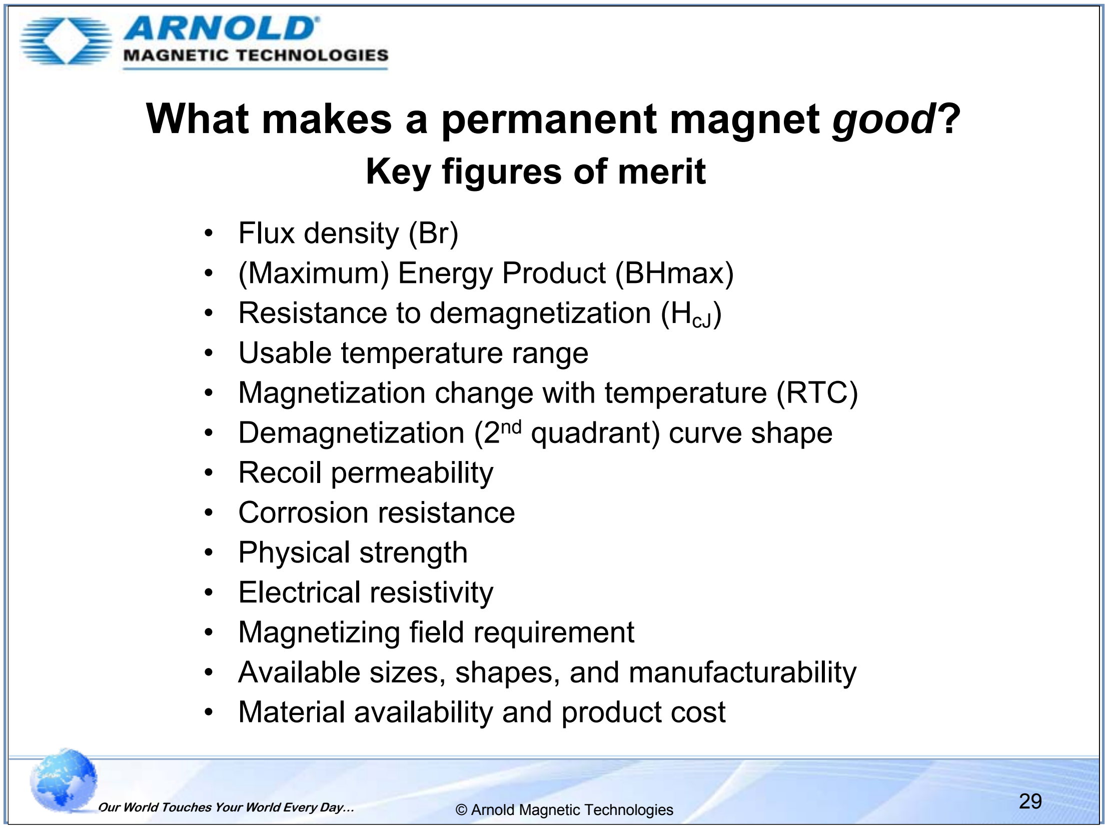


- The most commonly used soft magnetic material is silicon-iron (Si-Fe, aka electrical steel) and as you may be aware, there are two major uses for it: Transformers/Inductors and Motors/Generators.
- Transformers are used not only for Electrical Power Distribution, but in virtually every power supply 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.

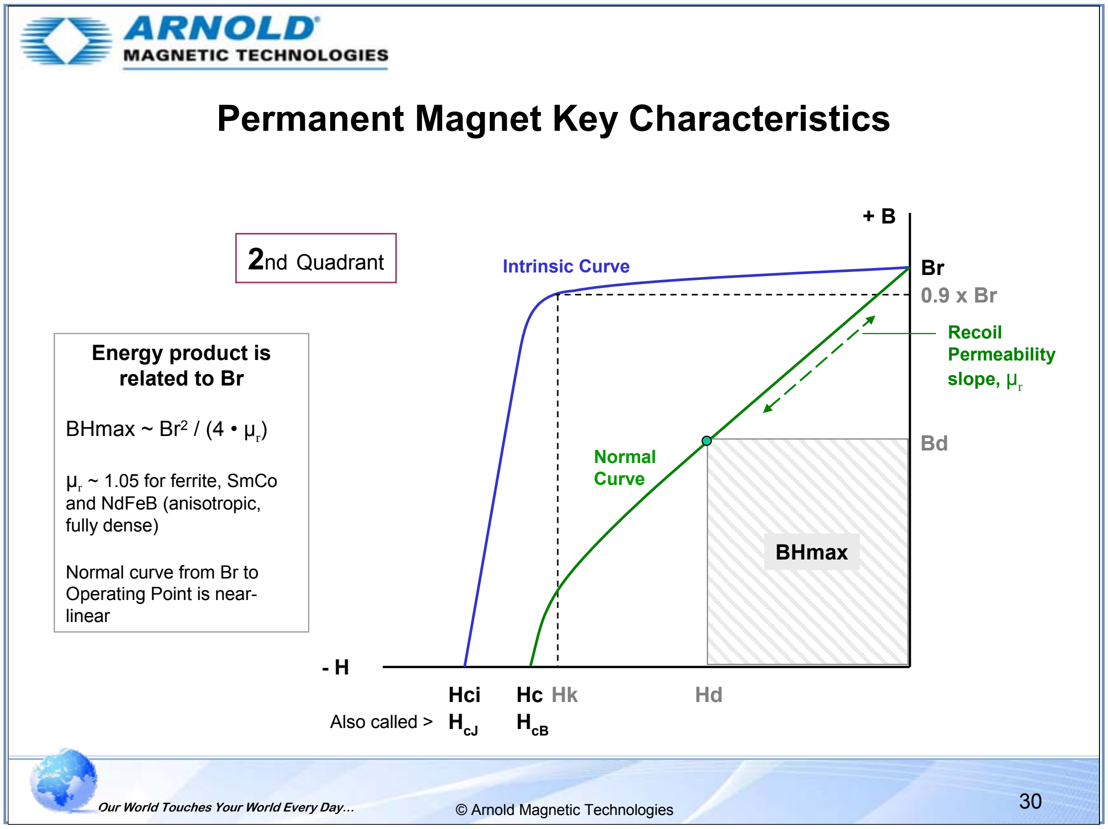
Agenda

- 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.



- 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 HcJ 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.



- 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).

ARNOLD
MAGNETIC TECHNOLOGIES

Permanent Magnet Development Timeline

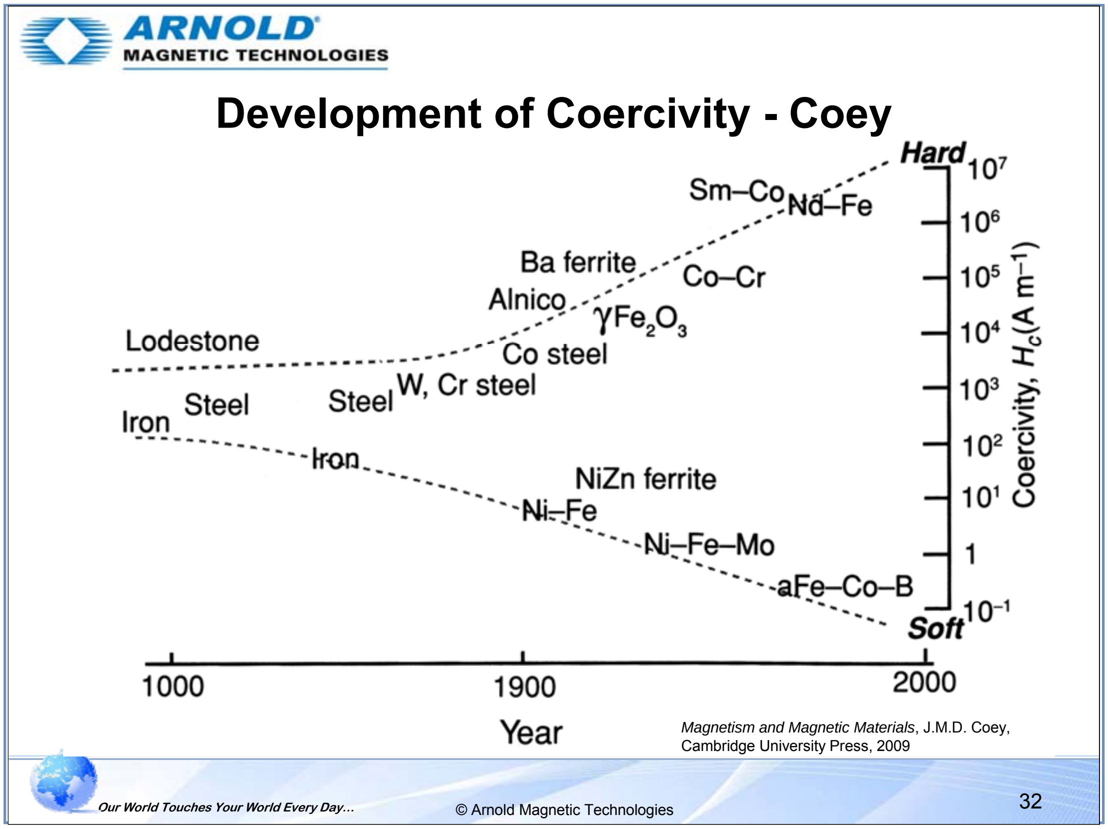
- Permanent Magnets have been developed to achieve
  - Higher Br and Energy Product (BHmax)
  - Greater resistance to demagnetization (Hci)
- Most are still in production
  - Exceptions
    - ***Lodex*** *was discontinued due to use of hazardous materials in production and in the product*
    - ***Cunife*** *has been replaced by FeCrCo*

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

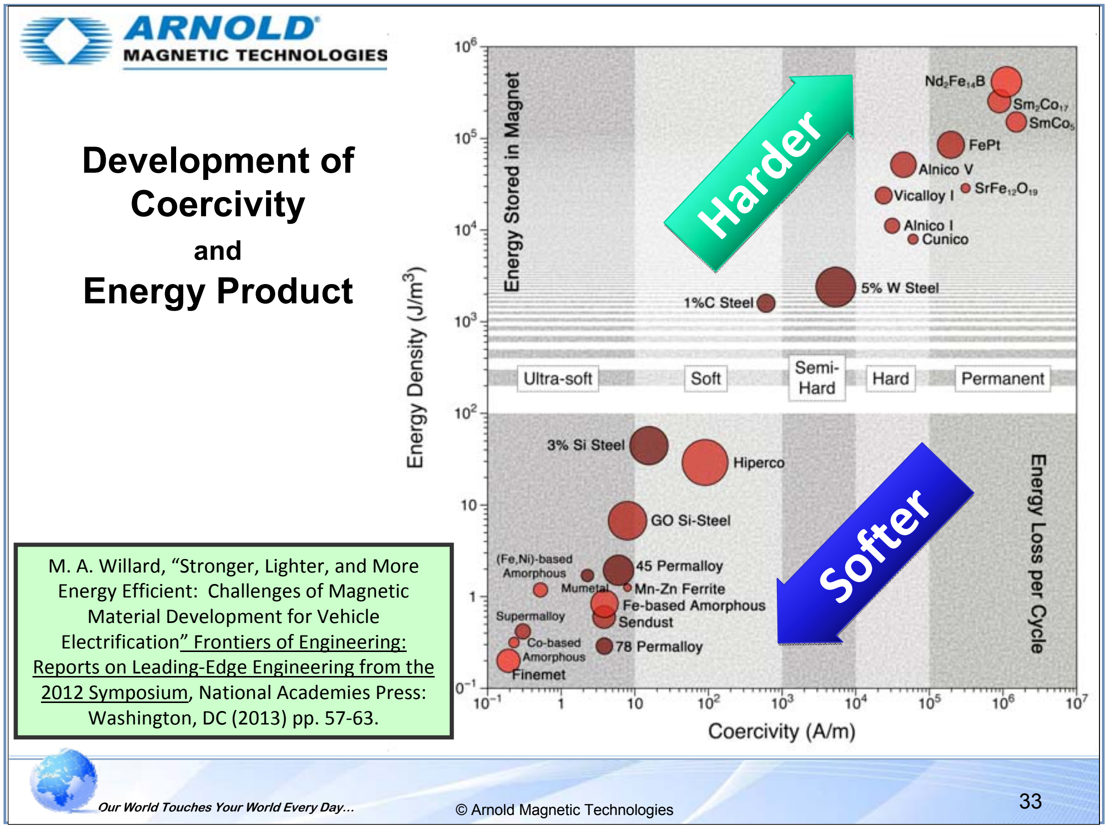
Table based on information in *Advances in Permanent Magnetism* by Rollin J. Parker, p.331-332

Our World Touches Your World Every Day…

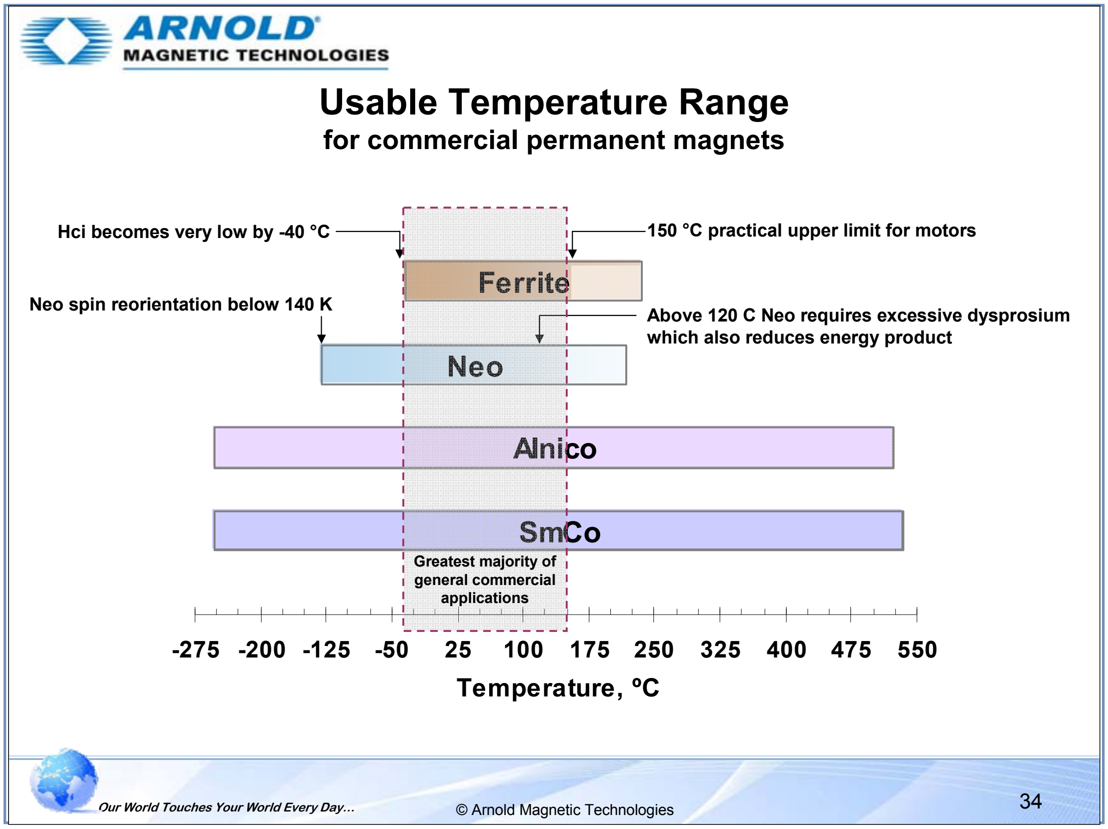
- What materials were used in motors prior to the discovery of the rare earth magnets?
- Prior to the discovery of Alnico and similar alloys in the 1930's, the materials used fell into a category called cobalt steels having high remanence (Br), but very low coercivity - values of 150 Oersteds being typical.
- 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 ($RE_2TM_{14}B$).



- Michael Coey graphically expresses the improvements to magnetic materials with soft materials achieving ever lower Hc and permanent magnetic materials exhibiting higher Hci.



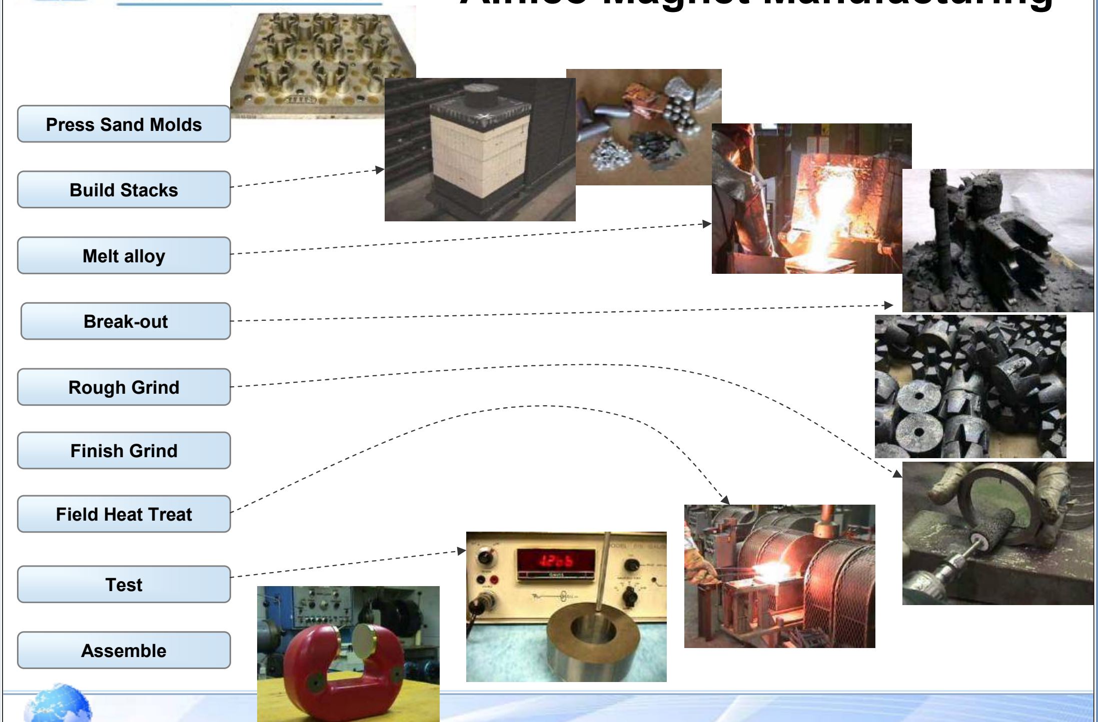
- Focusing on Coercivity and Energy Density (Maximum Energy Product), Matthew Willard provides this chart.
- Permanent magnets get better toward the upper right while soft magnetic materials improve toward the bottom left.



- 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 ºC. However, even by 150 ºC, it loses 25% of its flux output and so that is a practical limit for motor applications.

ARNOLD MAGNETIC TECHNOLOGIES

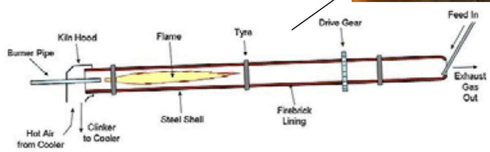
Alnico Magnet Manufacturing

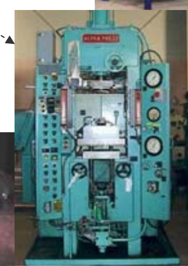


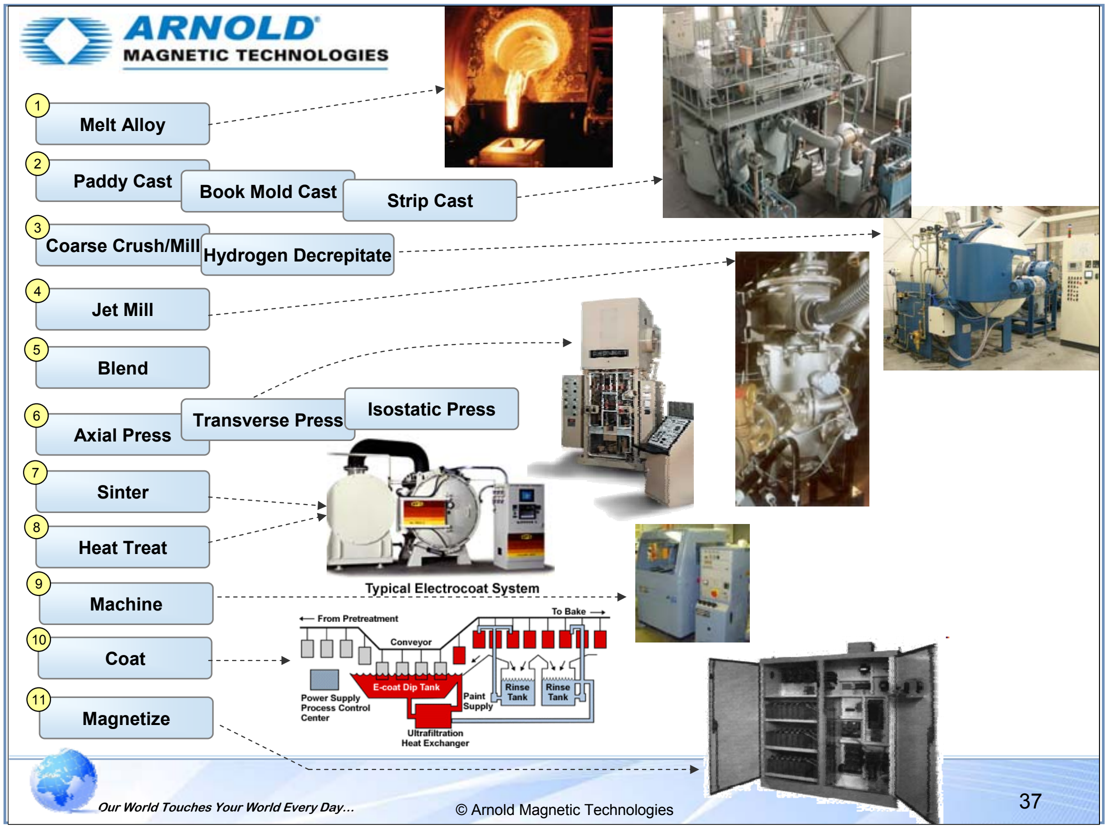
ARNOLD MAGNETIC TECHNOLOGIES

Ferrite Magnet Manufacturing

- Blend Powder Slurry
- Calcine
- Mill
- Storage: Dry or Slurry
- Press
- Sinter
- Grind / Slice
- Test






ARNOLD
MAGNETIC TECHNOLOGIES
1 Melt Alloy
2 Paddy Cast
Book Mold Cast
Strip Cast
3 Coarse Crush/Mill
Hydrogen Decrepitate
4 Jet Mill
5 Blend
6 Axial Press
Transverse Press
Isostatic Press
7 Sinter
8 Heat Treat
9 Machine
10 Coat
11 Magnetize
Typical Electrocoat System
From Pretreatment
To Bake
Conveyor
E-coat Dip Tank
Paint Supply
Rinse Tank
Rinse Tank
Power Supply Process Control Center
Ultrafiltration Heat Exchanger
Our World Touches Your World Every Day…
© Arnold Magnetic Technologies
37

ARNOLD MAGNETIC TECHNOLOGIES

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

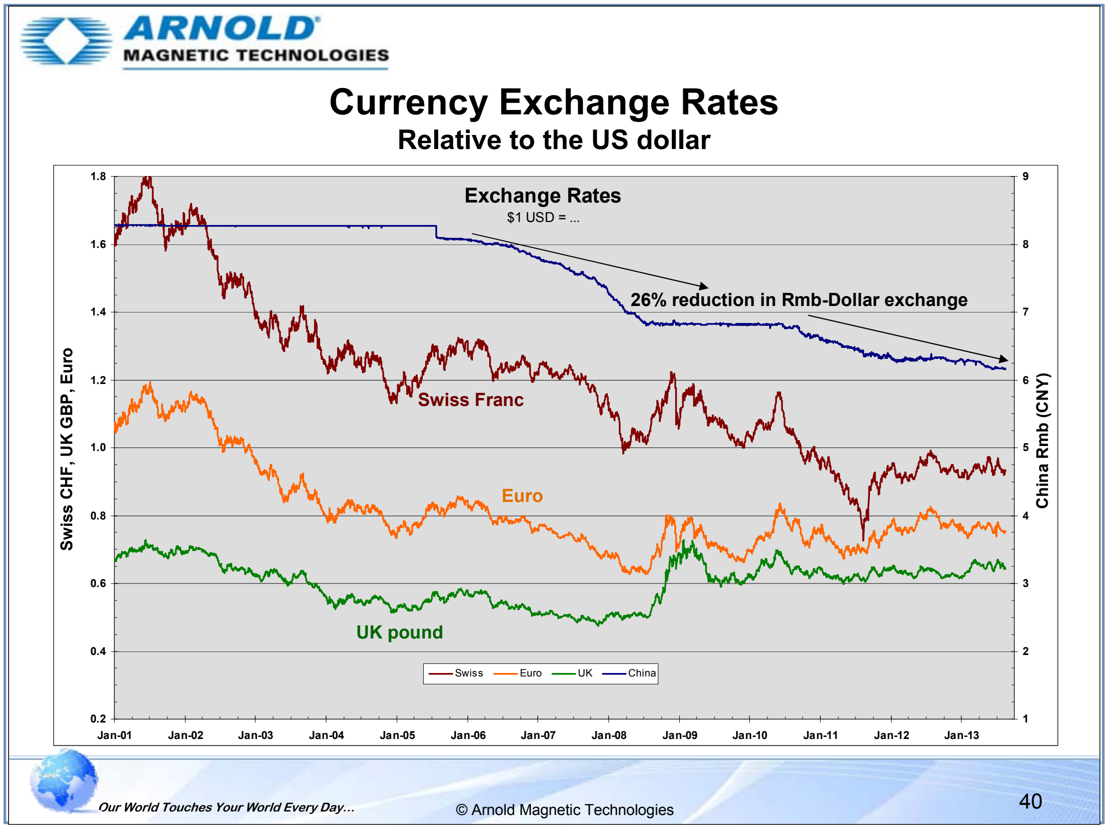
Our World Touches Your World Every Day...

- 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.

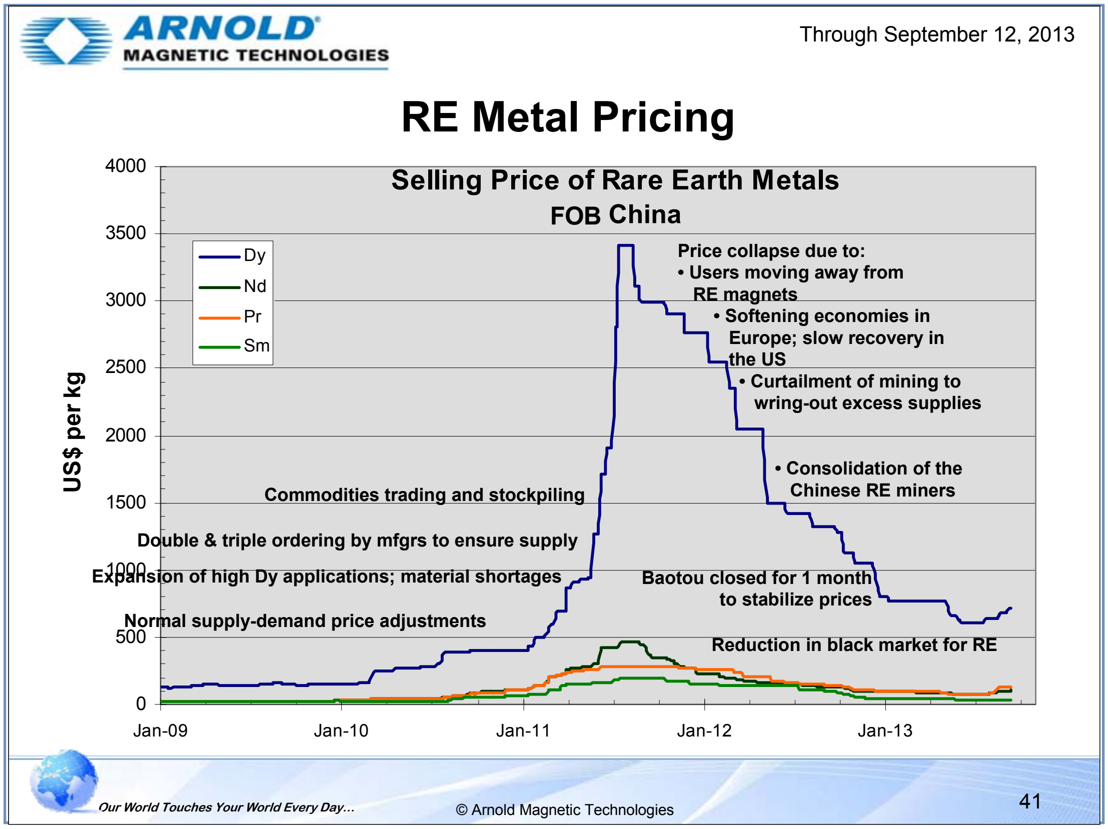
ARNOLD MAGNETIC TECHNOLOGIES

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)



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



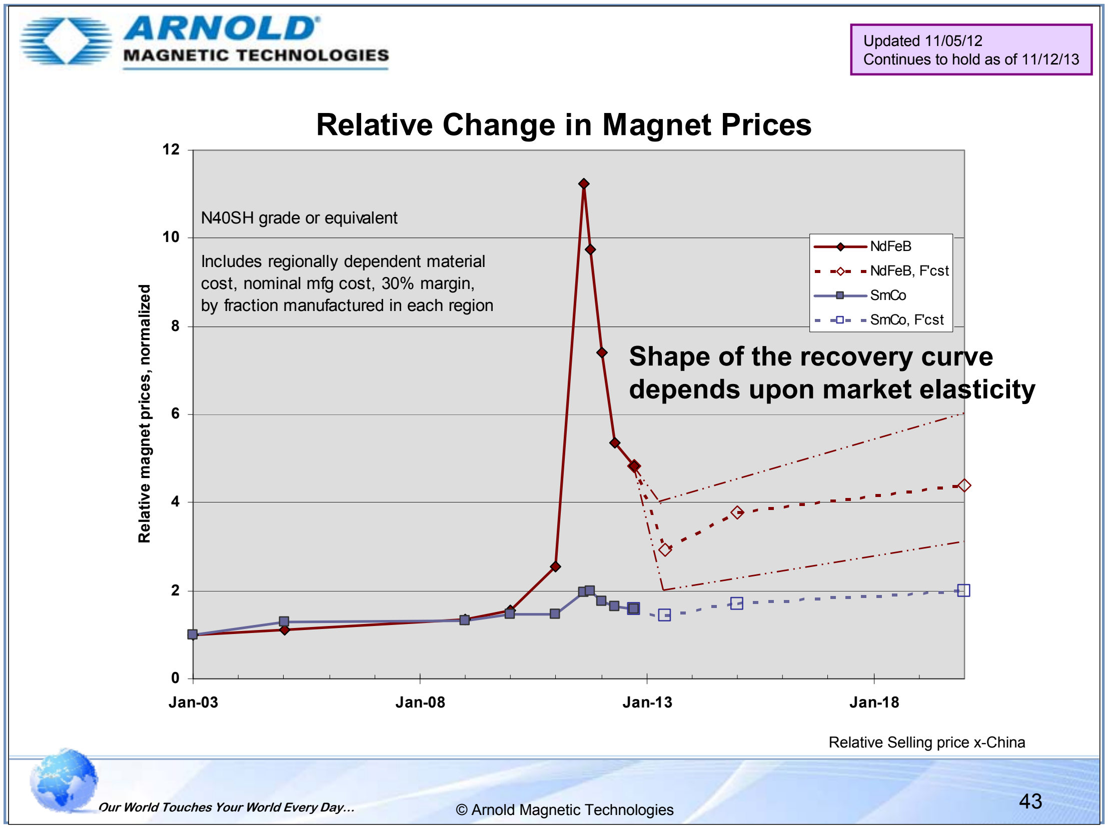
- Rare earth materials have experienced price inflation and market disruption.
- FOB China pricing is shown here.
- Notes on the chart indicate the main price drivers.
- It is educational to note that when prices became too high, users of rare earth magnets designed away from them and are now slow to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

ARNOLD MAGNETIC TECHNOLOGIES

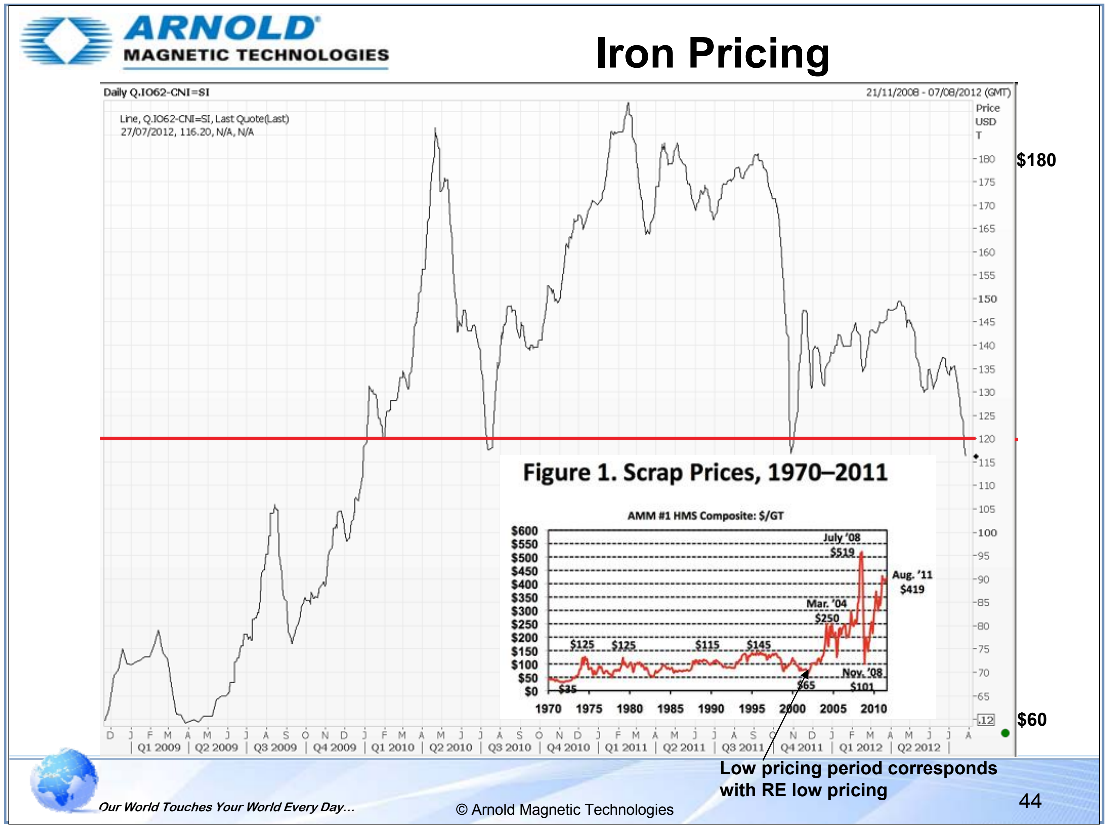
Australian Resources:
addressing the rare earth balance issue

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.

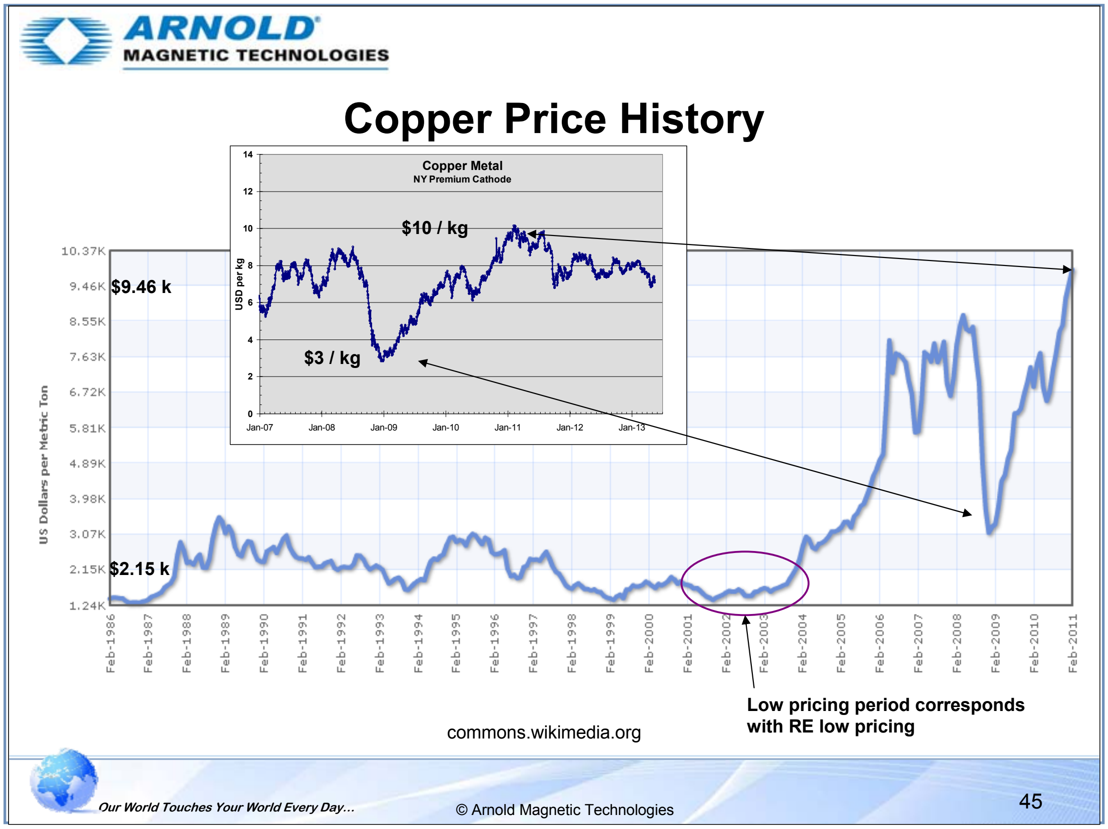
From document of same name, J.P. Morgan, Australia Equity Research, 11 July 2013



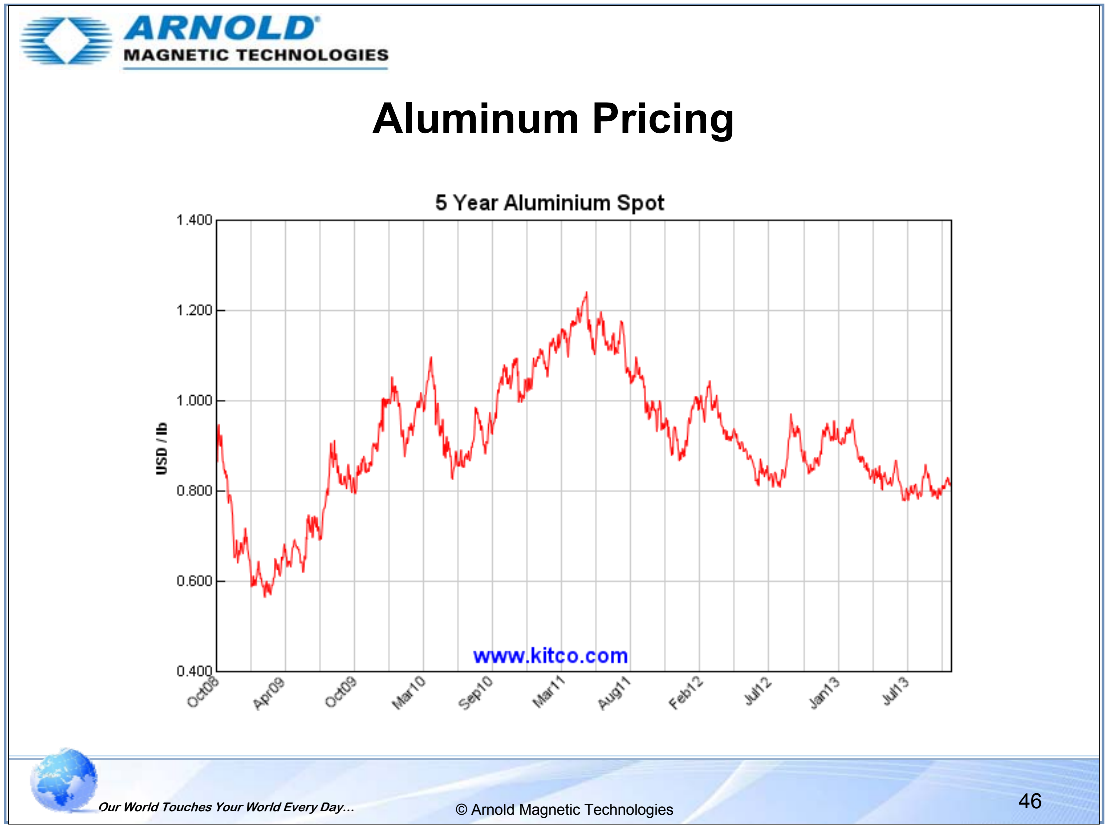
- This is my attempt to forecast relative magnet prices going forward based on costs over the past 9 years.
- It shows a slow continual uptick in SmCo magnet pricing.
- It also assumes that Neo magnet pricing will bottom out in early 2013 and rise slowly going forward and this appears to be happening.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



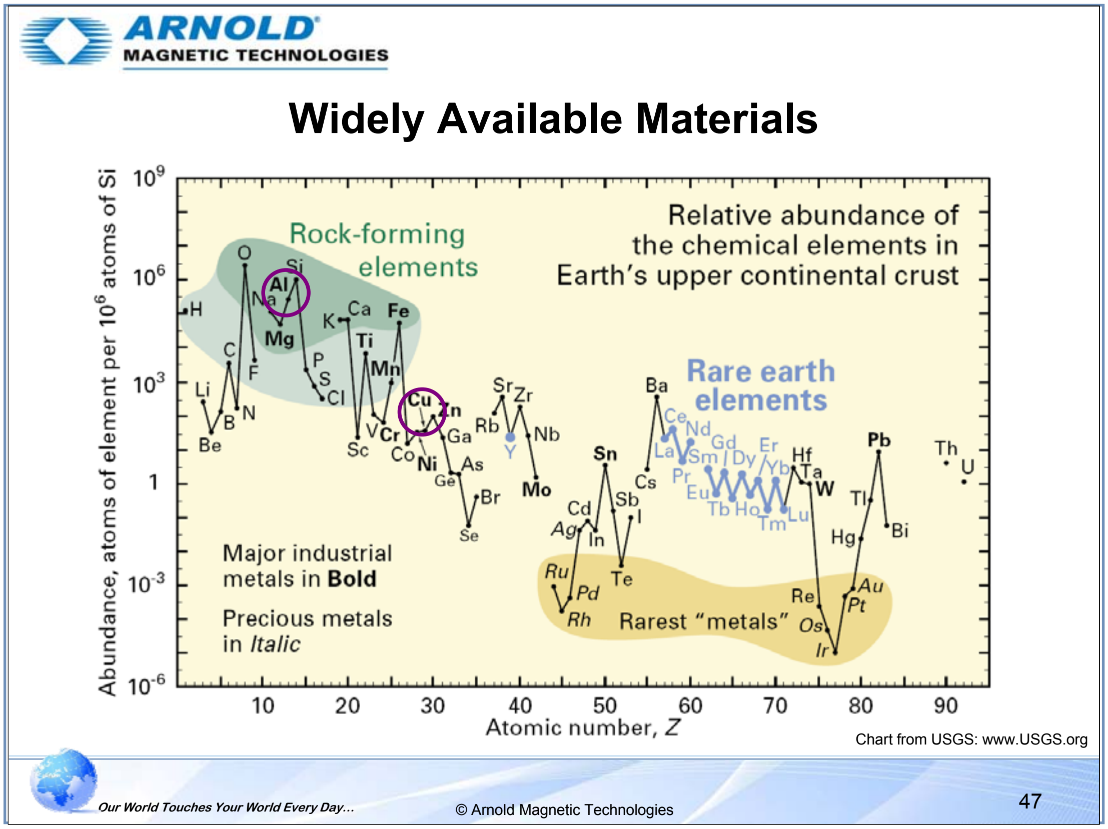
- Rare earths have not been the only materials to experience pricing cycles as we can see here with iron.
- Iron is a major constituent of electromagnetic devices on a weight basis so a doubling of cost can have a profound affect on product cost even though the cost per kilogram is not as great as for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



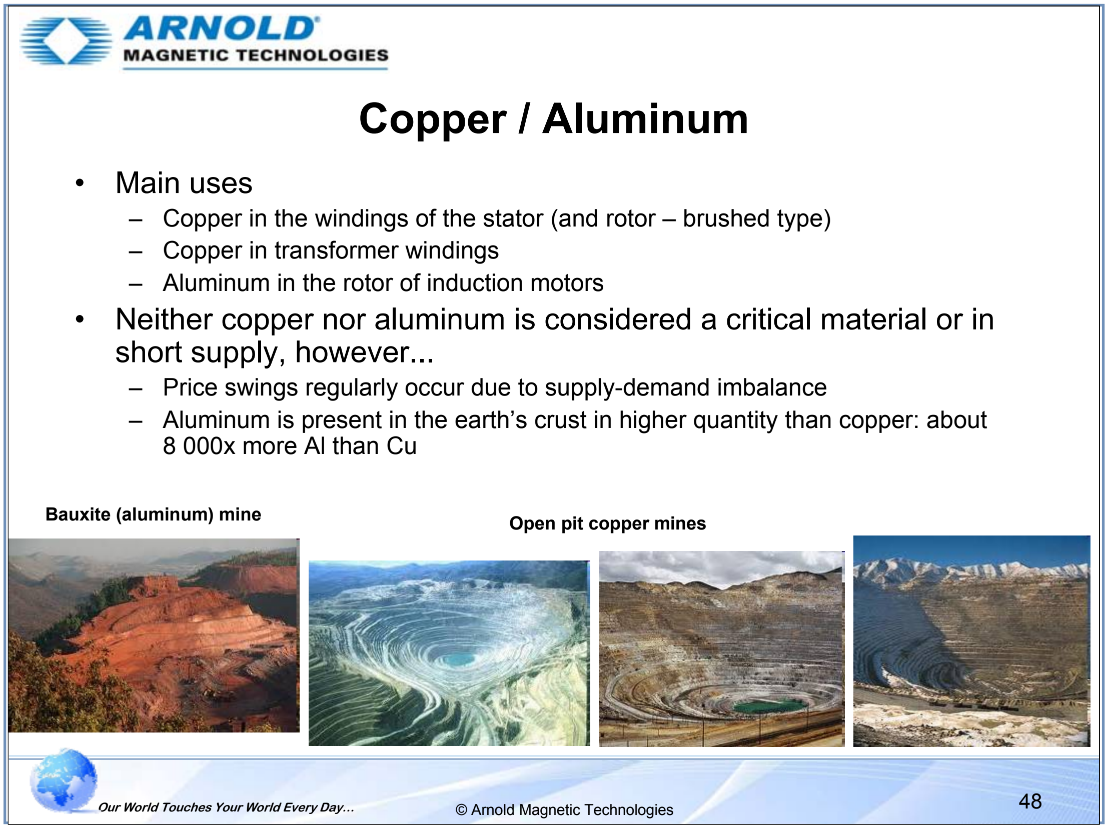
- And even induction and synchronous reluctance motors, which do not use permanent magnets, require field generation from coils of copper wire.
- These charts show copper price swings of 500%.



- Aluminum 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.



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



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

ARNOLD MAGNETIC TECHNOLOGIES

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)

ARNOLD MAGNETIC TECHNOLOGIES

Major PM Materials

	2010				2015			
	tons	%	$$$	%	tons	%	$$$	%
NdFeB	67,300	10.5%	5,700	65.1%	80,015	8.2%	9,305	62.6%
SmCo	2,310	0.4%	270	3.1%	3,510	0.4%	540	3.6%
Ferrite	567,000	88.2%	2,600	29.7%	881,120	90.7%	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.

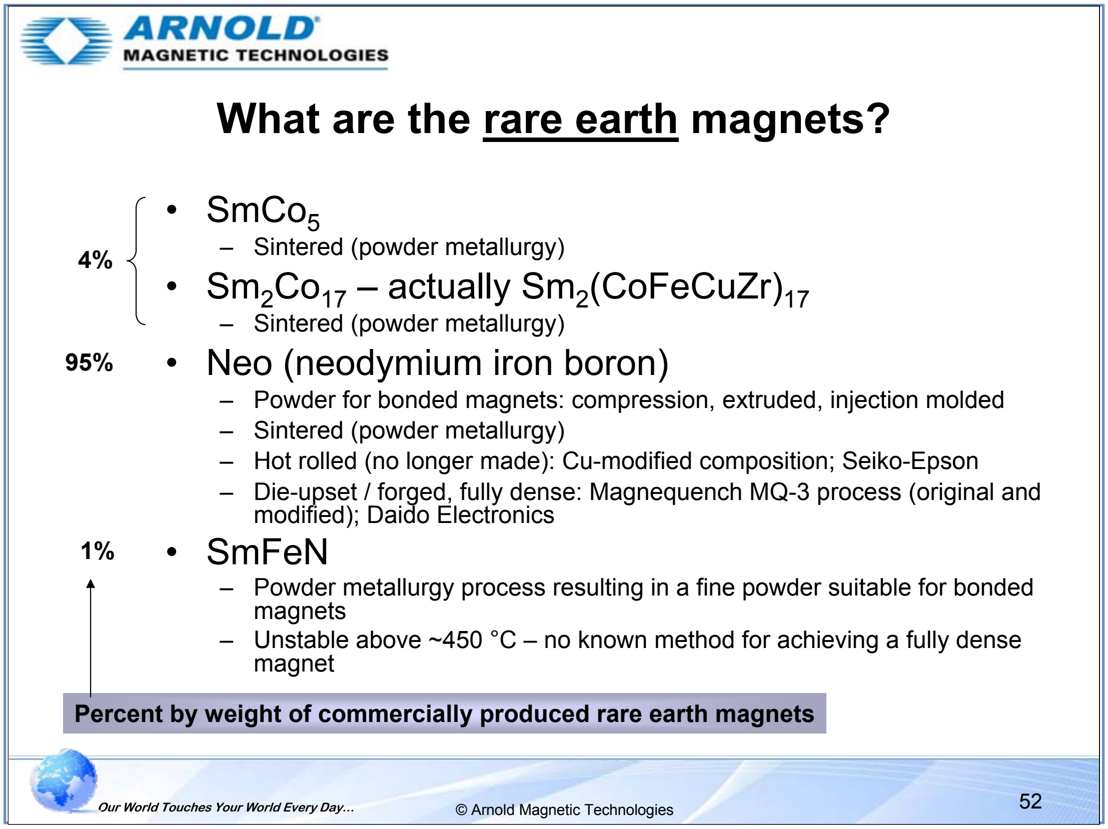
ARNOLD
MAGNETIC TECHNOLOGIES

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%	

Our World Touches Your World Every Day...

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



- 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.

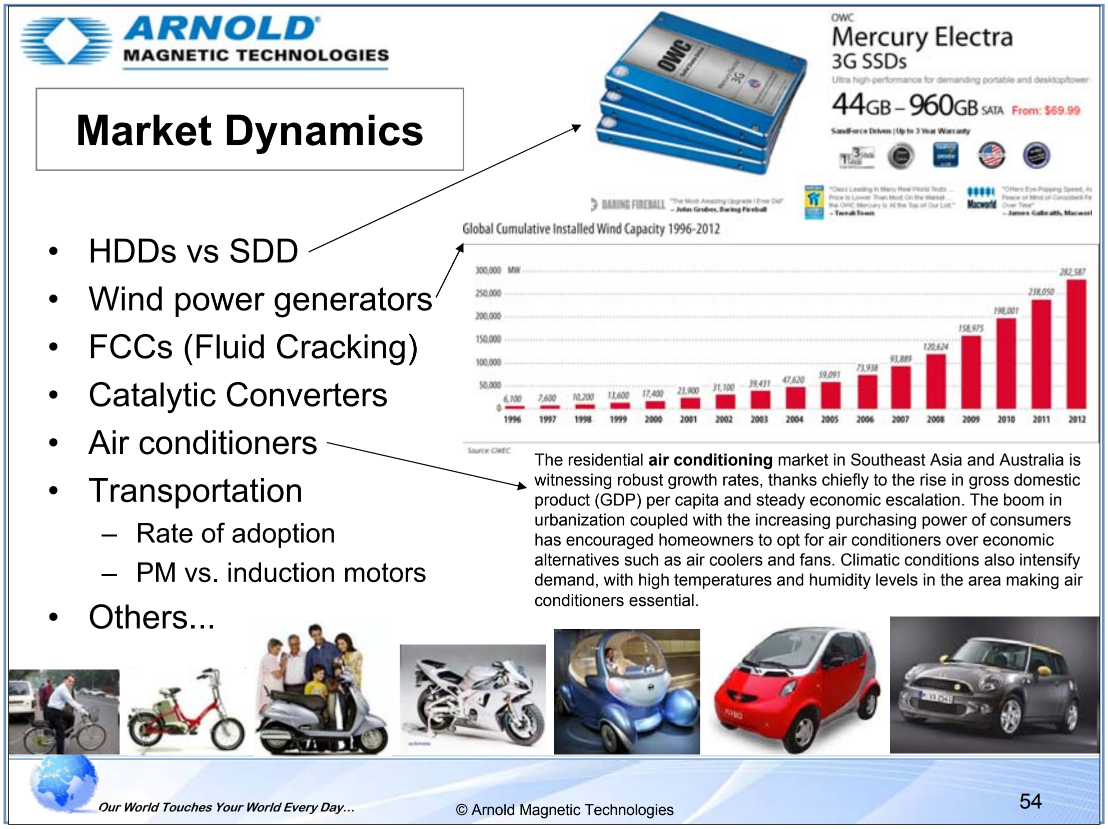
ARNOLD
MAGNETIC TECHNOLOGIES

Rare Earth Magnet Applications (2010)

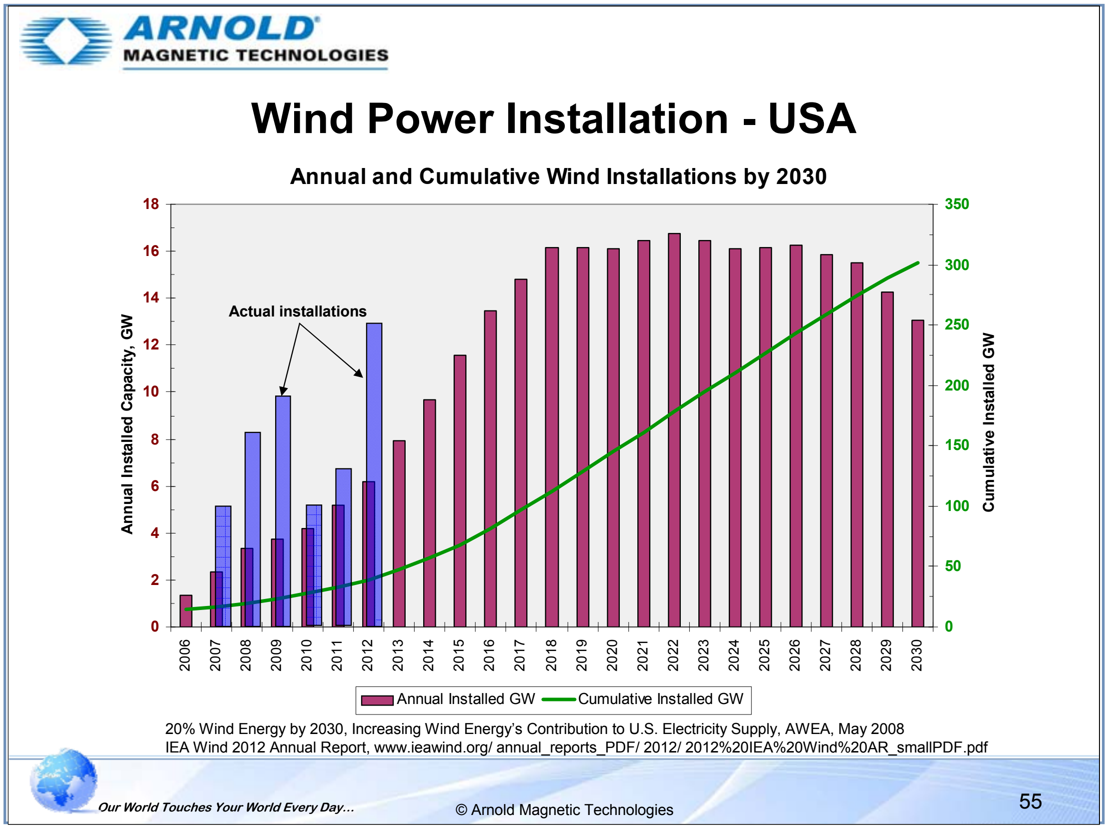
Motors, industrial, general auto, etc	24.0%
HDD, CD, DVD	16.3%
Electric Bicycles	8.4%
Transducers, Loudspeakers	8.1%
Magnetic Separation	4.6%
MRI	3.9%
Torque-coupled drives	3.3%
Sensors	3.1%
Generators	3.0%
Hysteresis Clutch	2.8%
Air conditioning compressors and fans	2.4%
Energy Storage Systems	2.3%
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%

Our World Touches Your World Every Day...

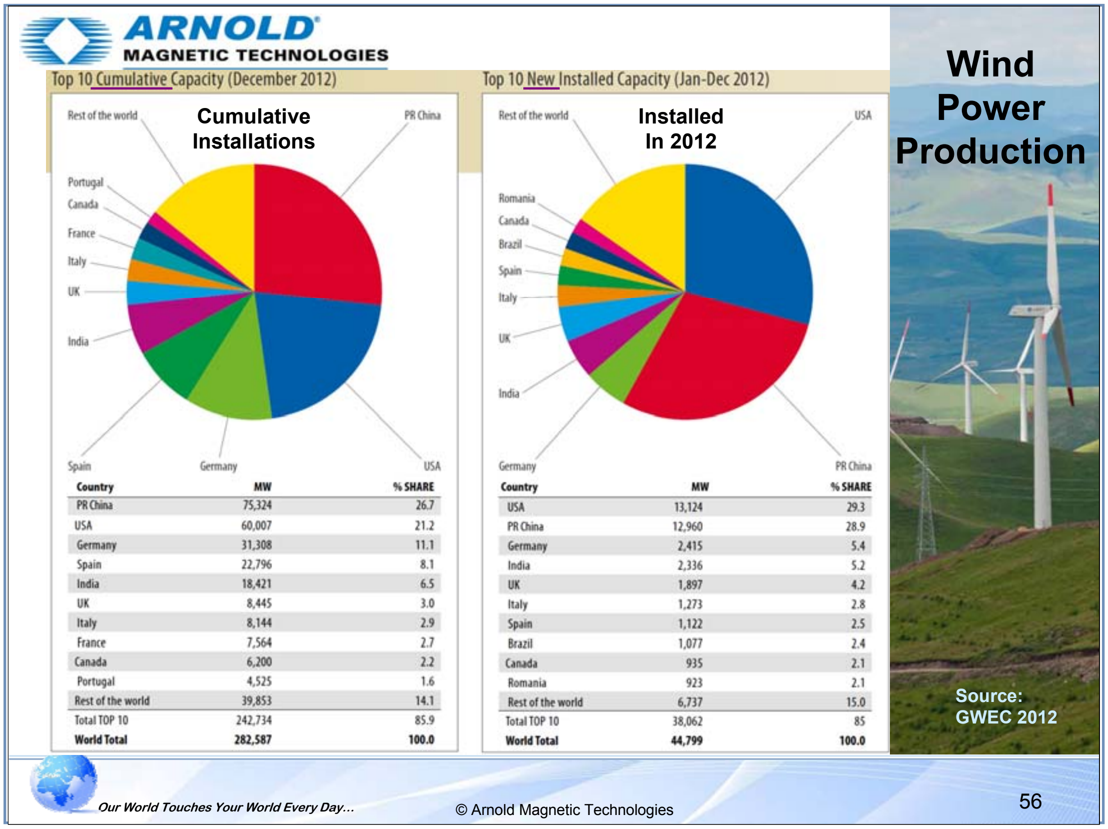
- Motors, generators, loudspeakers, represent about 67% of rare earth magnet usage.



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



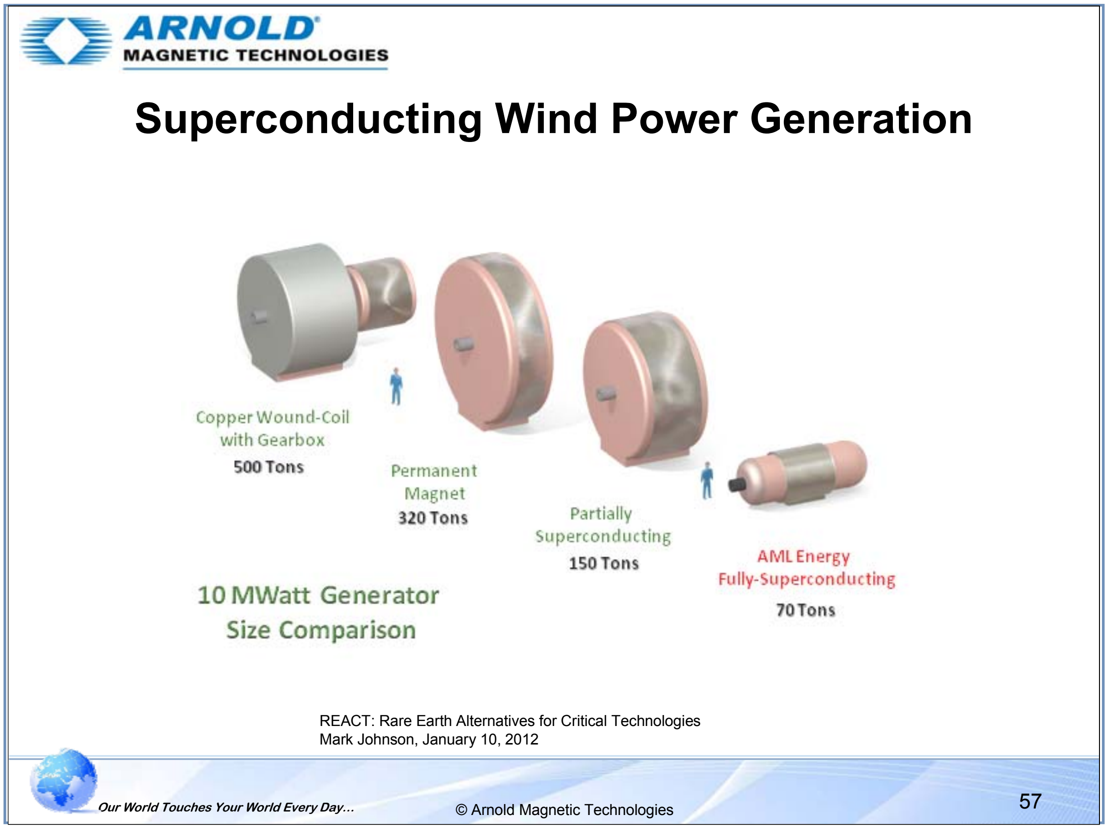
- A market for permanent magnets is wind power – generation of commercial electricity by large, tower-mounted generators.
- In 2008, the American Wind Energy Association (AWEA) forecast installations of wind per the plum-colored bars on this chart.
- I have plotted blue bars to show actual installations 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.



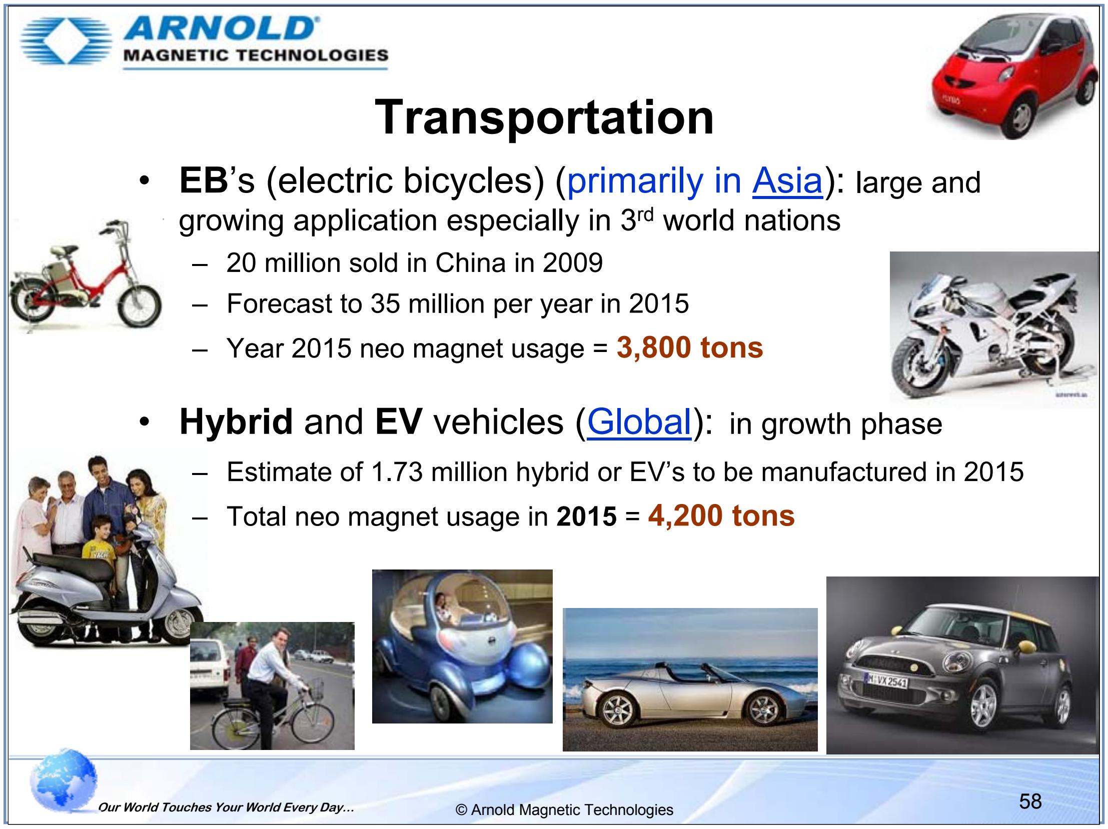
Country	MW	% SHARE
PR China	75,324	26.7
USA	60,007	21.2
Germany	31,308	11.1
Spain	22,796	8.1
India	18,421	6.5
UK	8,445	3.0
Italy	8,144	2.9
France	7,564	2.7
Canada	6,200	2.2
Portugal	4,525	1.6
Rest of the world	39,853	14.1
Total TOP 10	242,734	85.9
World Total	**282,587**	**100.0**

Country	MW	% SHARE
USA	13,124	29.3
PR China	12,960	28.9
Germany	2,415	5.4
India	2,336	5.2
UK	1,897	4.2
Italy	1,273	2.8
Spain	1,122	2.5
Brazil	1,077	2.4
Canada	935	2.1
Romania	923	2.1
Rest of the world	6,737	15.0
Total TOP 10	38,062	85
World Total	**44,799**	**100.0**

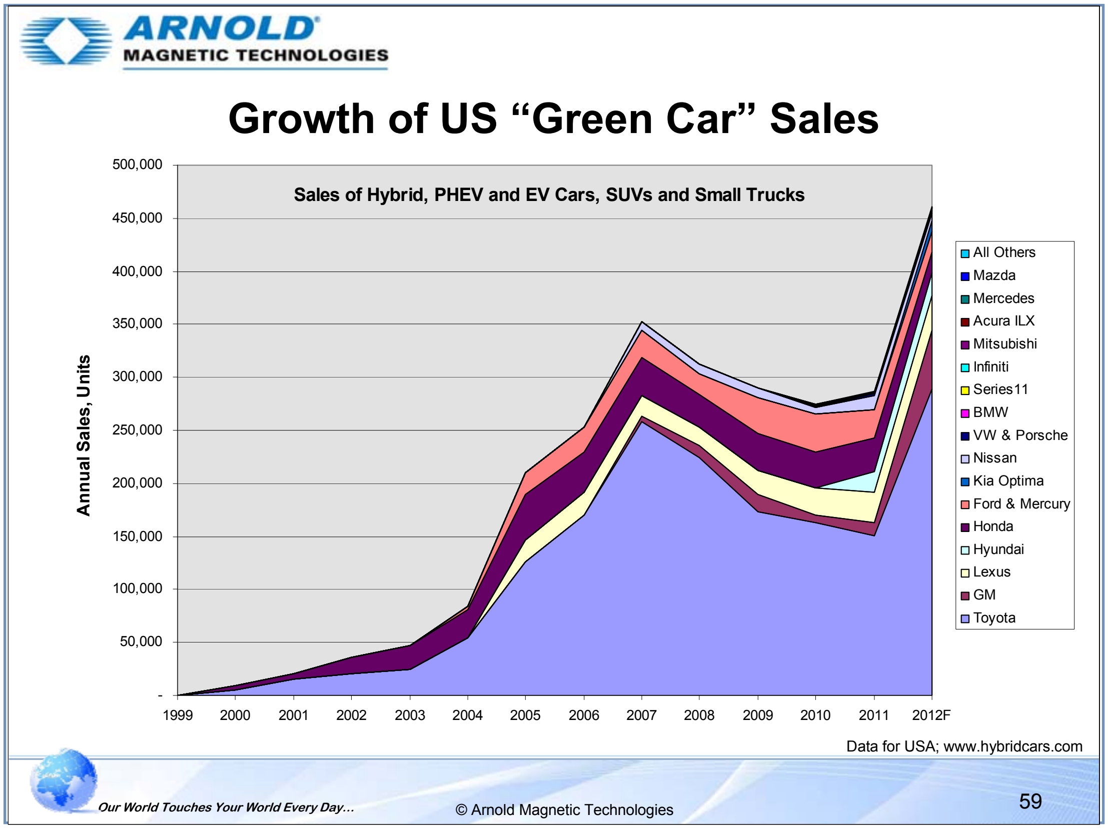
- Prior to 2005, China's wind power industry was close to non-existent.
- Since then it has grown rapidly and now cumulatively China has more wind power generation installed than any other country at 26.7% of global generation.
- In 2011 alone, China produced 43% of all installations world-wide with 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.



- 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.



- 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-boosted 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.



- 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.

ARNOLD MAGNETIC TECHNOLOGIES

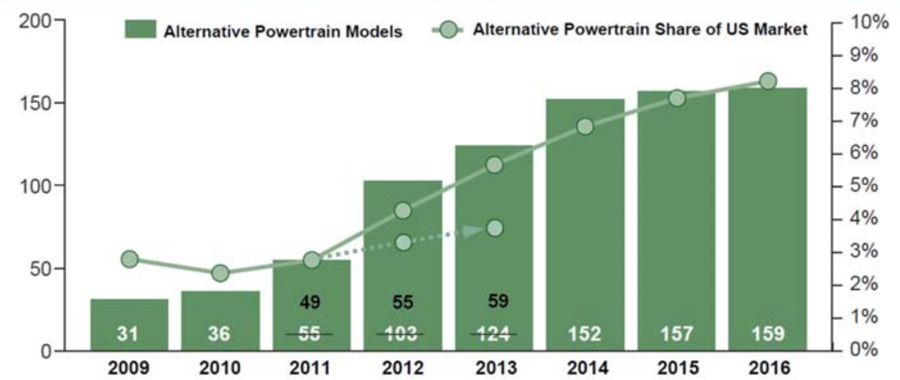
Hybrid and PEVs

Sales in USA of Cars, SUVs, Small Trucks

Data for USA; www.hybridcars.com

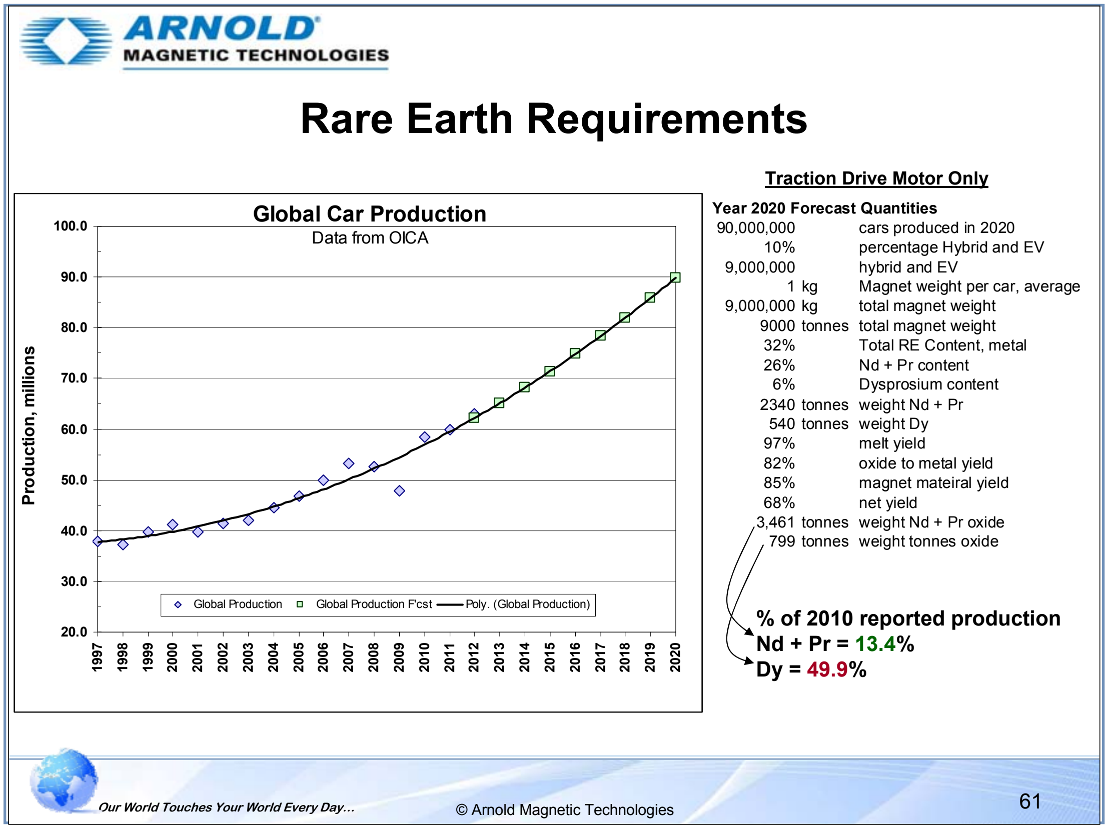
	2011		2012 (YTD August)		2012 Year-end F'cst	
	Units	%	Units	%	Units	%
Total Sales (units)	12,734,356		9,678,702		14,518,053	
Hybrid	268,807	2.11%	278,680	2.88%	418,020	2.88%
PEV	17,813	0.14%	25,290	0.26%	37,935	0.26%
Totals		2.25%		3.14%		3.14%

Alternative Powertrain Models and Market Share

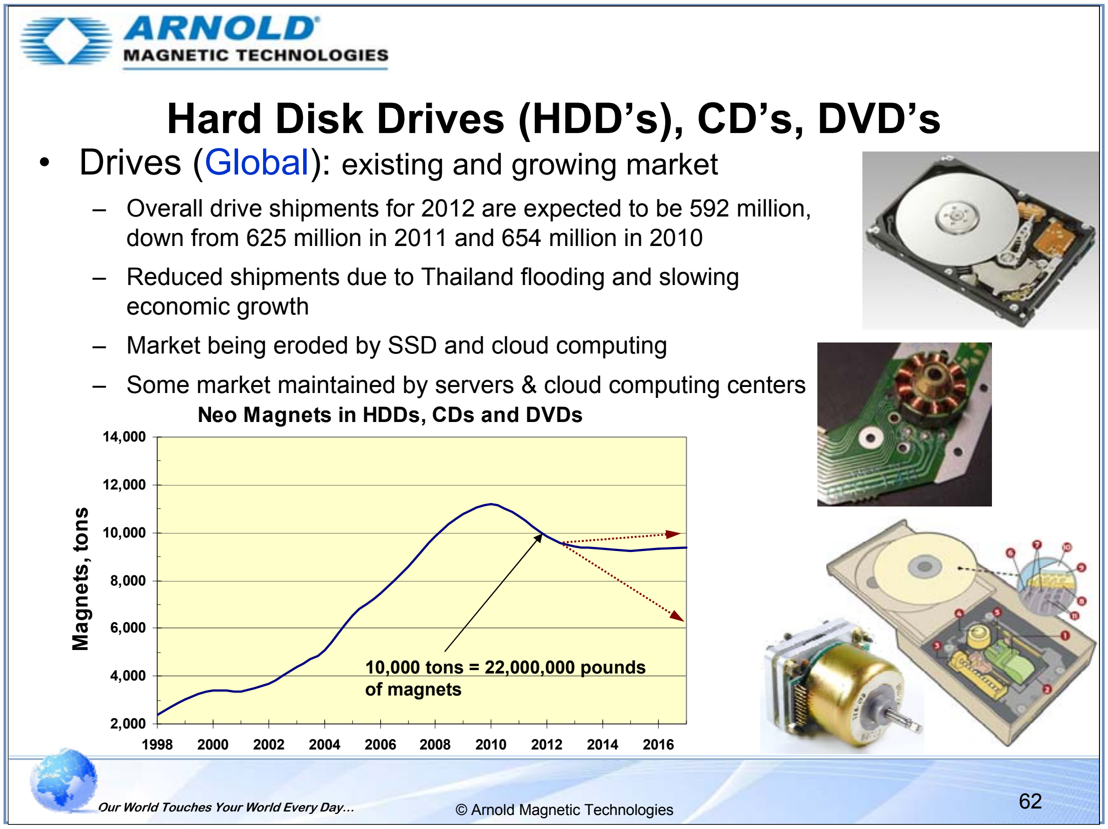


Source: J.D. Power and Associates 2011 US Green Automotive Study℠

- 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.



- 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.



- 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

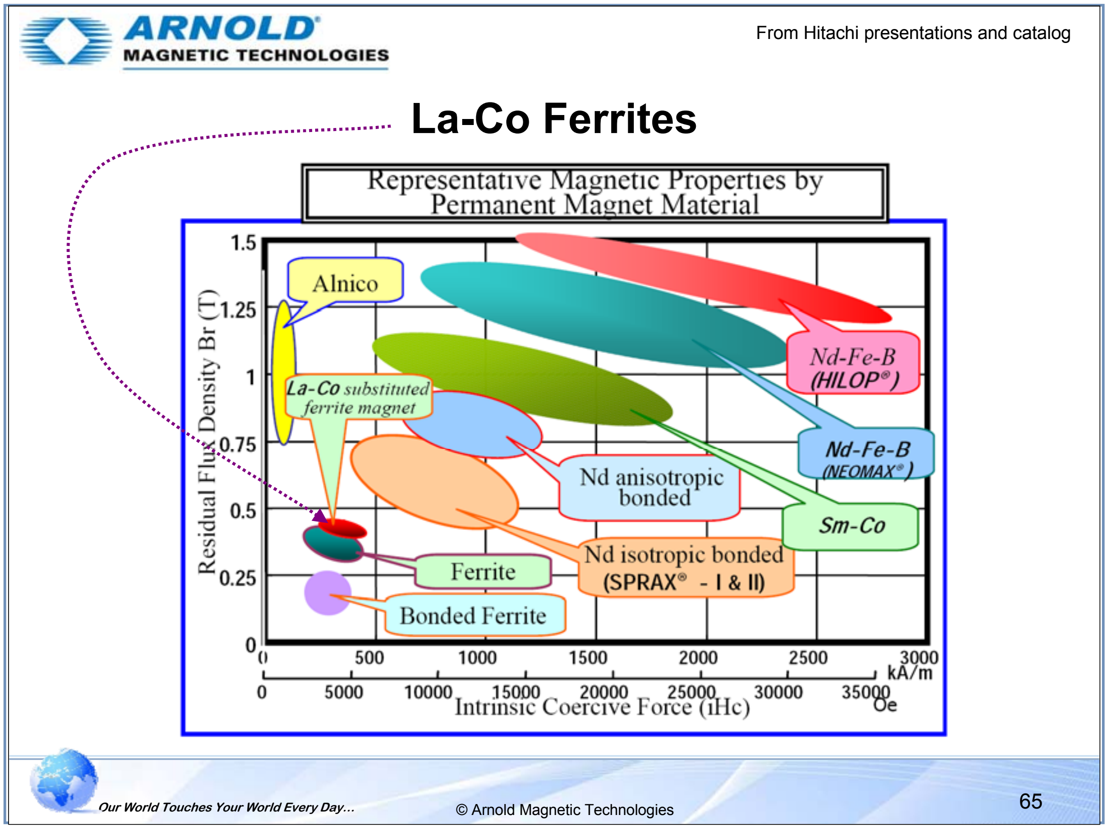
- It's all about energy
- Soft magnetic materials
- Permanent magnet materials
- Materials market & pricing
- Permanent magnet applications
- Development of existing materials
- R & D (elemental discussion)

ARNOLD MAGNETIC TECHNOLOGIES

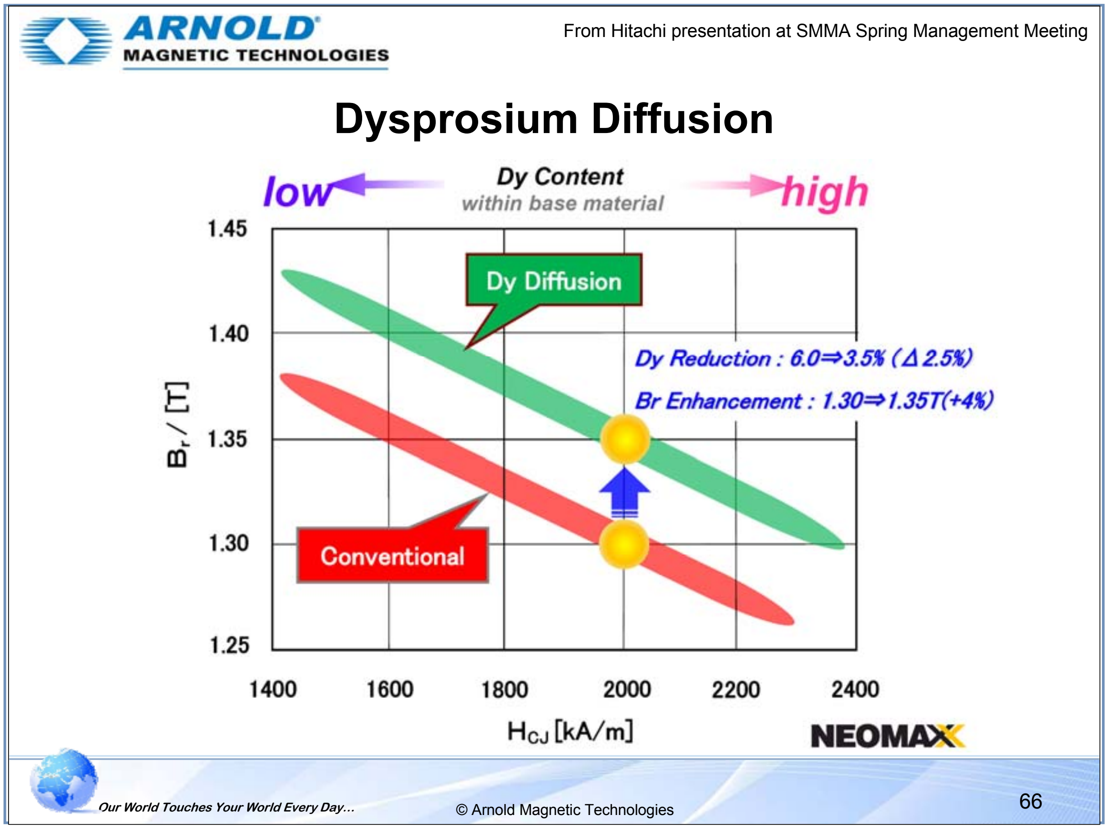
Development of Existing Materials

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

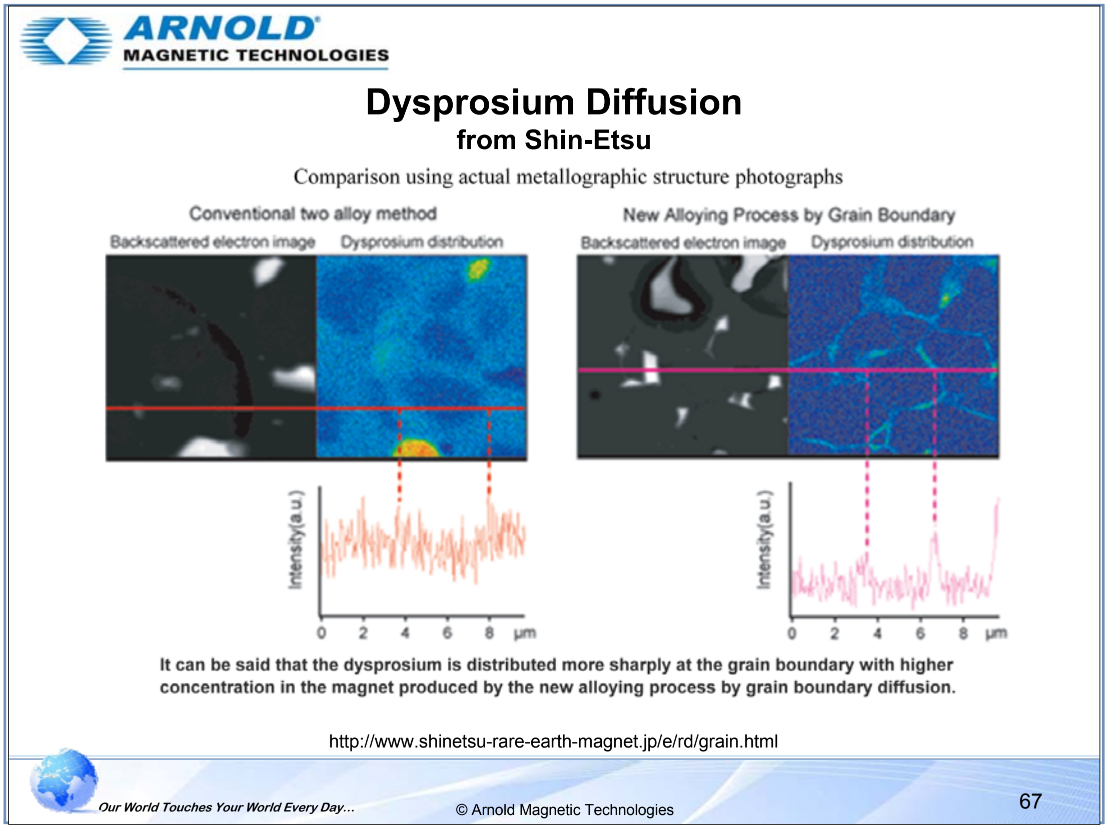
- Common, commercially available permanent magnetic materials.



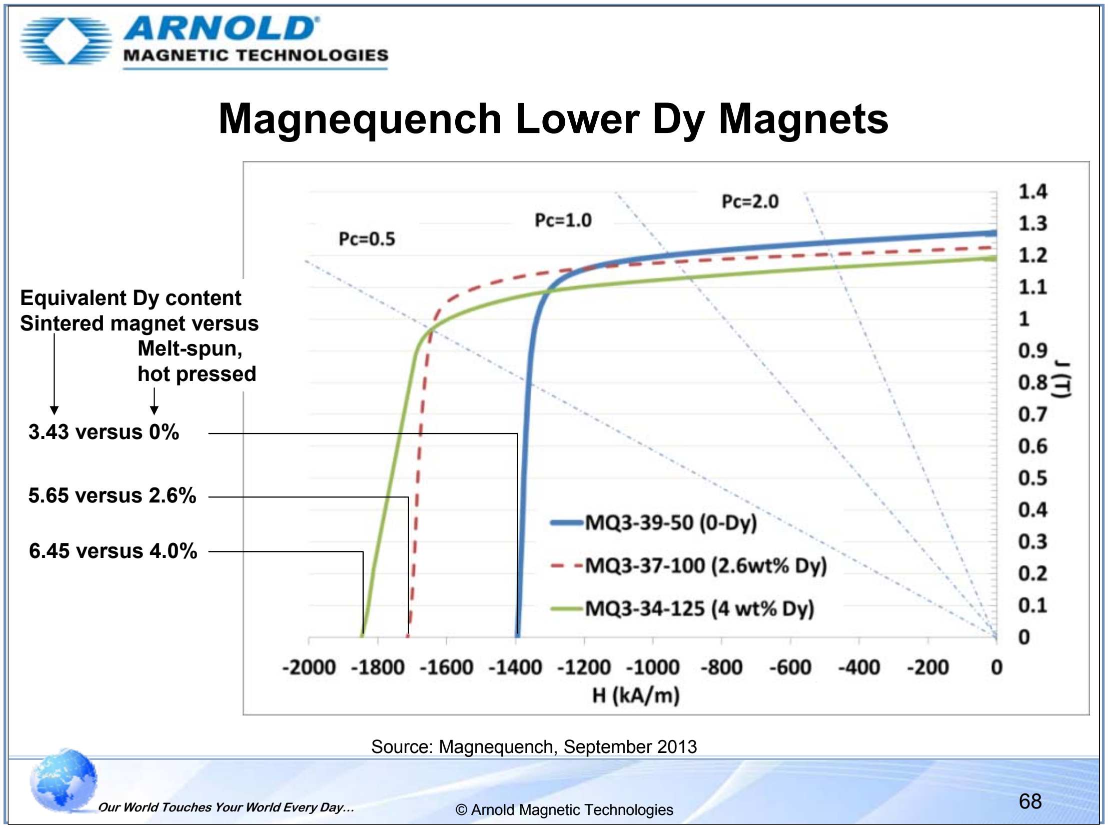
- La-Co additions to strontium-ferrite permanent magnets has resulted in a 20%+ increase in energy product and high coercivity.
- Considering the relatively low cost of ferrite, enhanced performance suggests an even greater market share going forward.



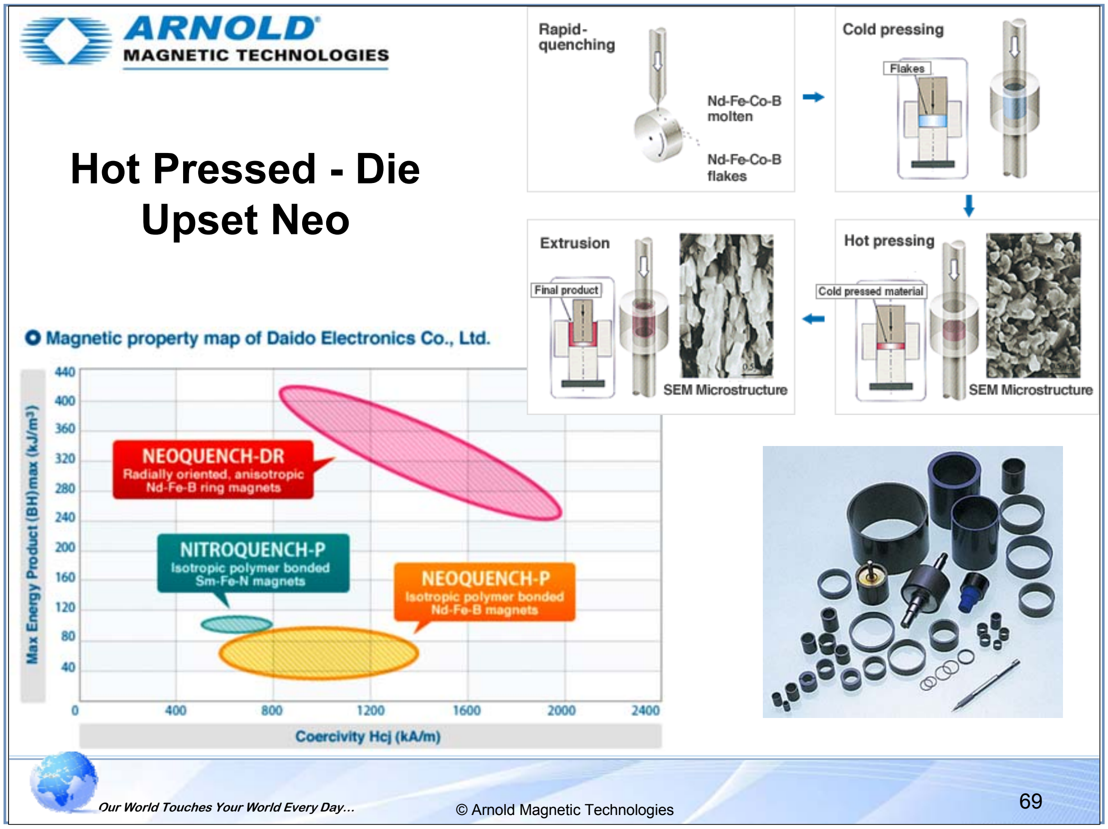
- The dysprosium diffusion process provides more efficient use of dysprosium.
- Users may chose to 1) keep dysprosium as existing levels and benefit from the higher coercivity or 2) reduce the dysprosium to meet minimum acceptable coercivity and benefit from higher energy product.



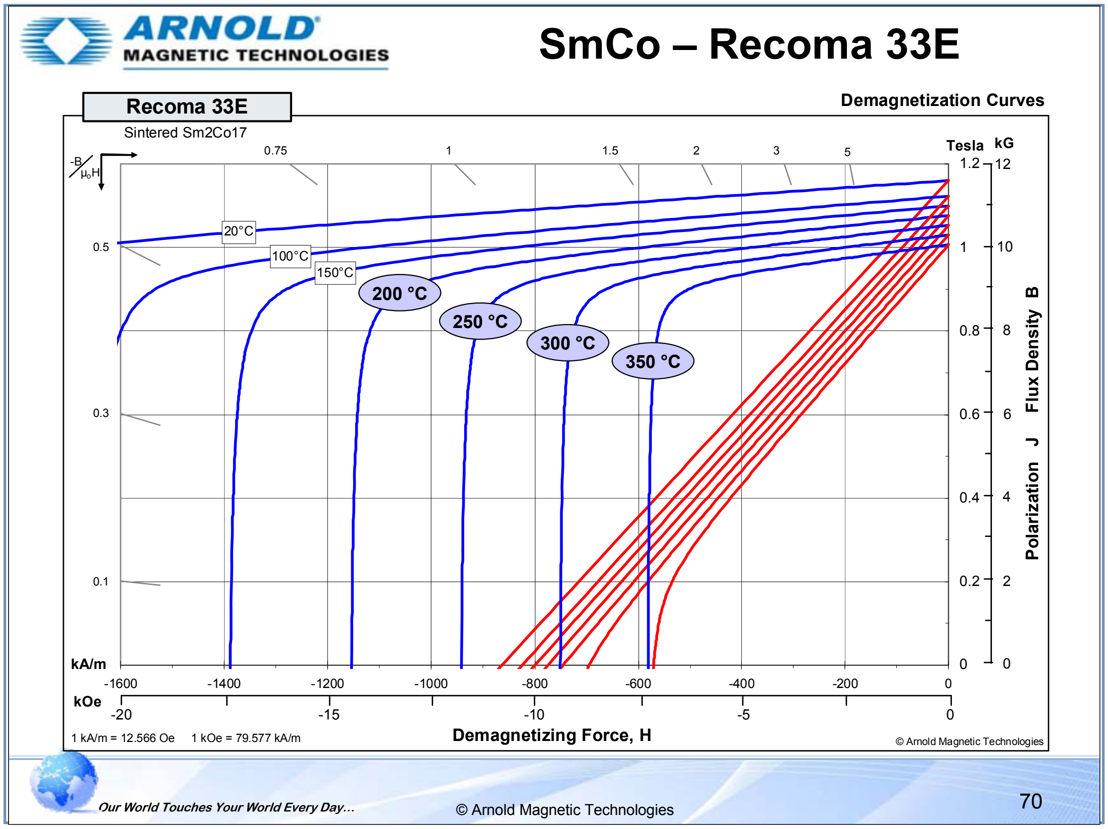
- While not a new technique, it was practiced starting in the mid 1980s, the current method optimizes the effect of dysprosium diffusion.



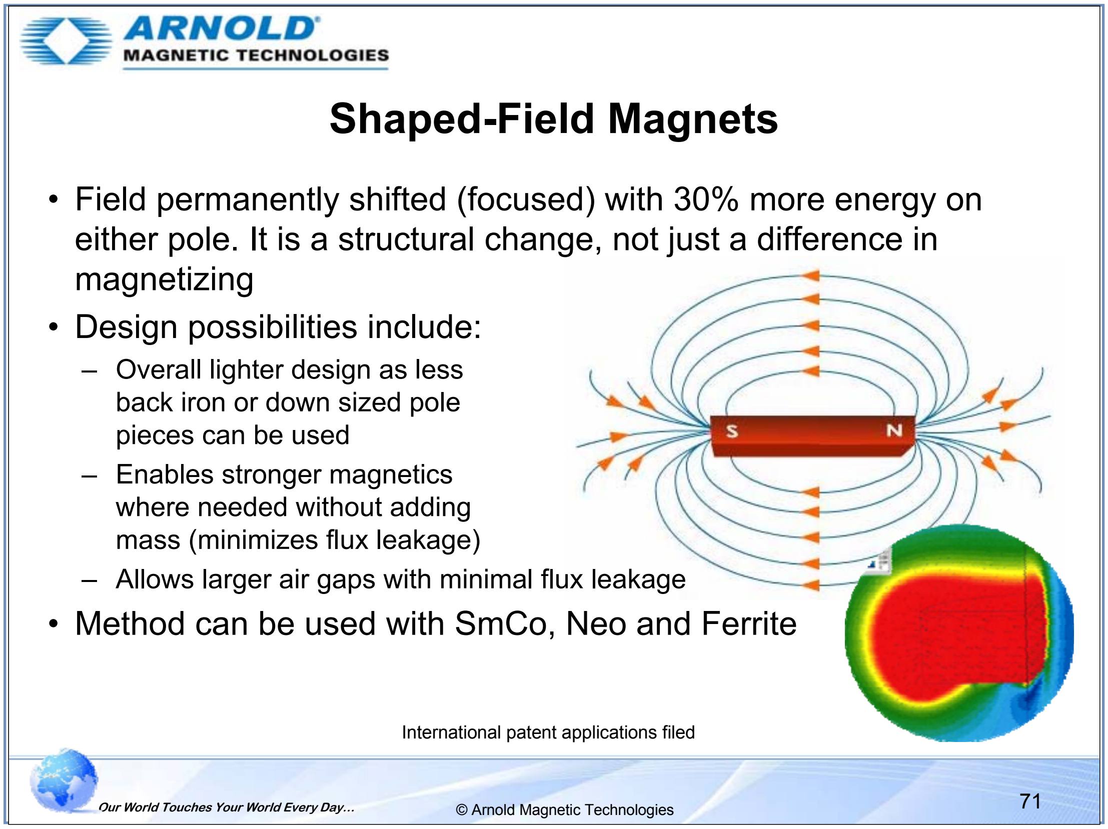
- Magnequench has presented about the use of minor dysprosium additions to melt spun (jet cast) neo powders for use in hot-pressed and die-upset magnets.
- This slide shows a comparison of the coercivity of magnets made via conventional powder metallurgy and those made by jet-casting and die-upsetting.



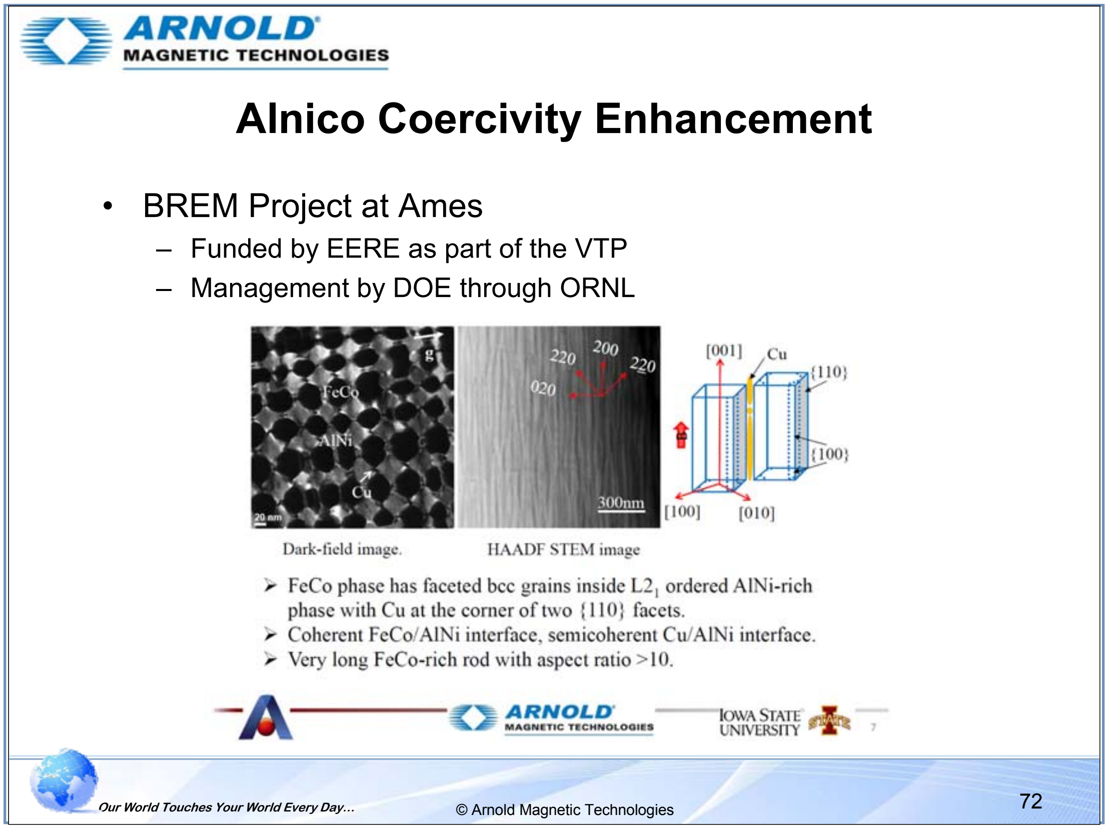
- Daido has been a long practitioner of the die upset magnet manufacturing process, primarily for the production of hollow, radially oriented cylinders.
- Presumably the addition of dysprosium will enhance their product properties accordingly.



- 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.



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

ARNOLD MAGNETIC TECHNOLOGIES

Summary: Current Magnet Options

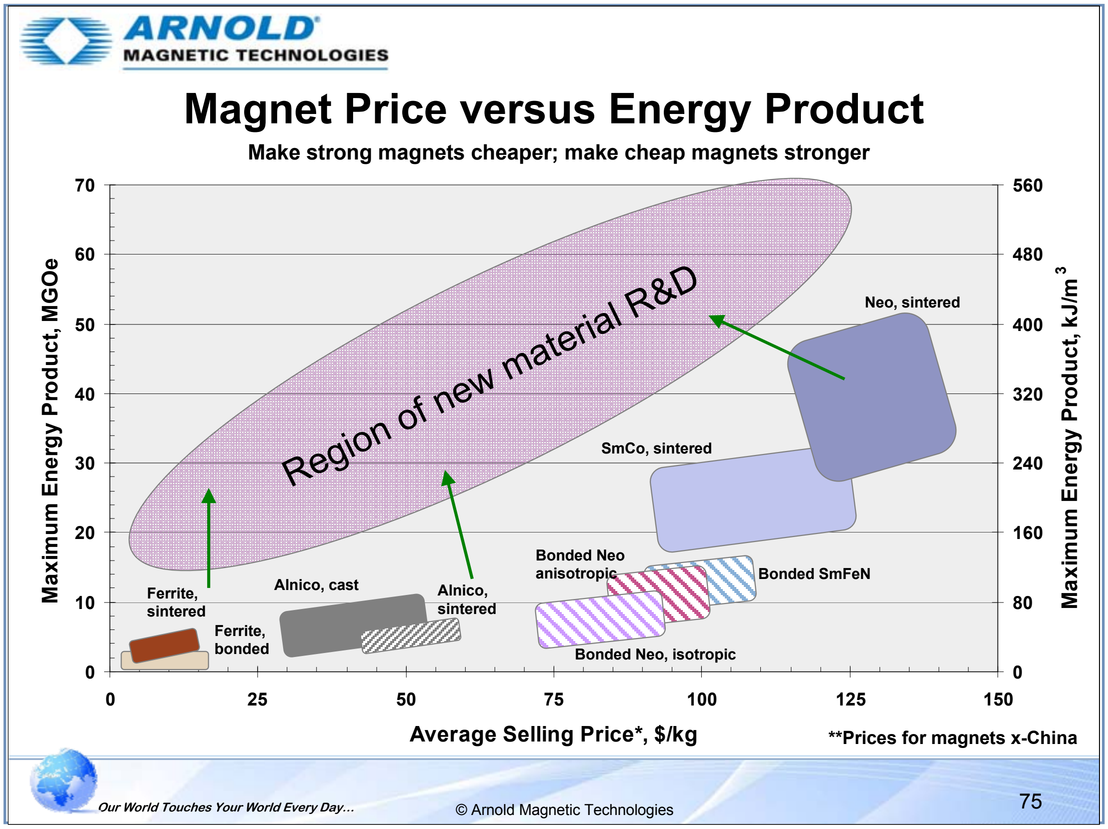
In Alphabetic order

- 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)

ARNOLD MAGNETIC TECHNOLOGIES

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.

ARNOLD MAGNETIC TECHNOLOGIES

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

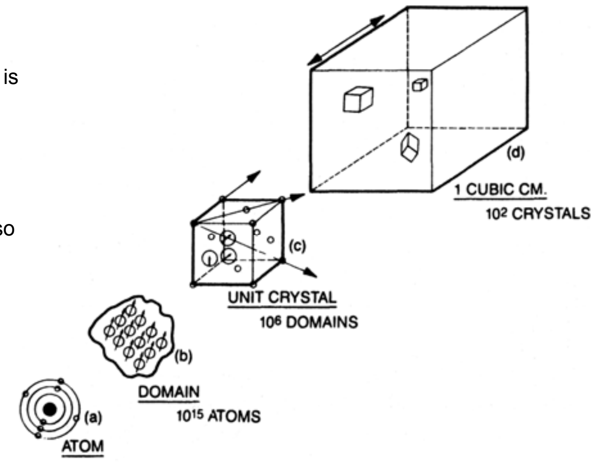
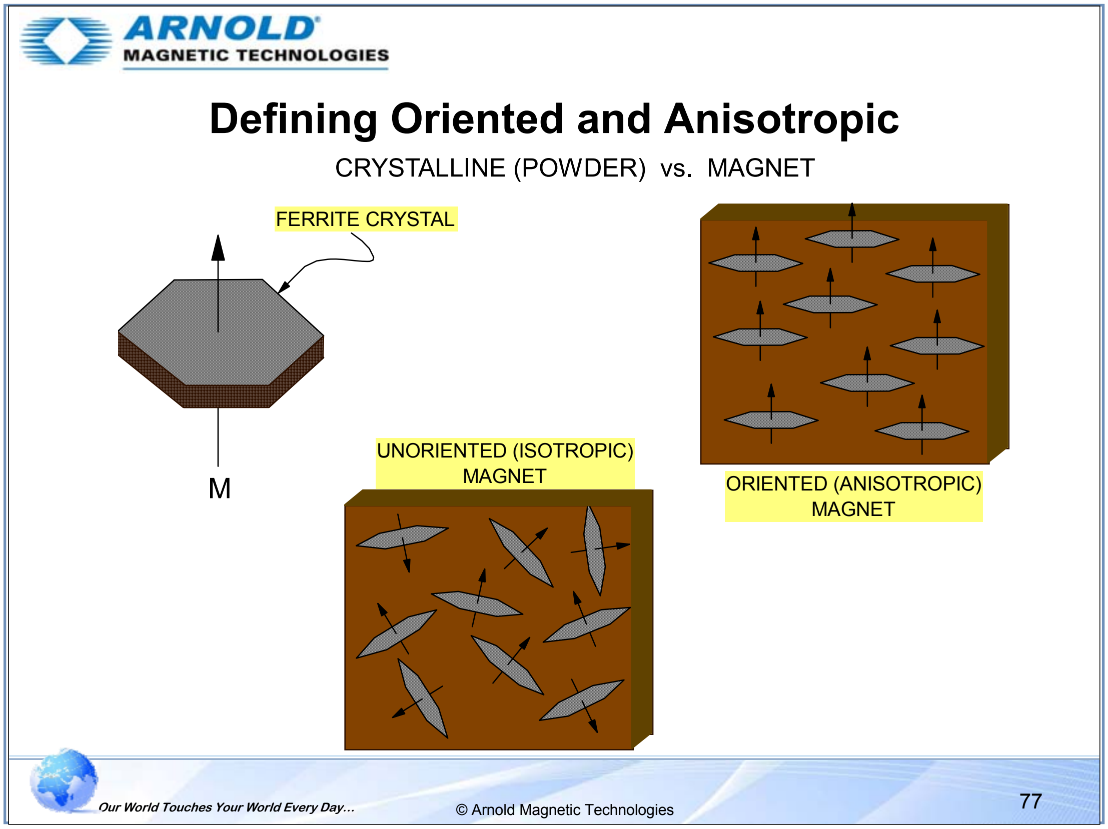


Figure 3.2 Exploded assembly of ferromagnetic volume.

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

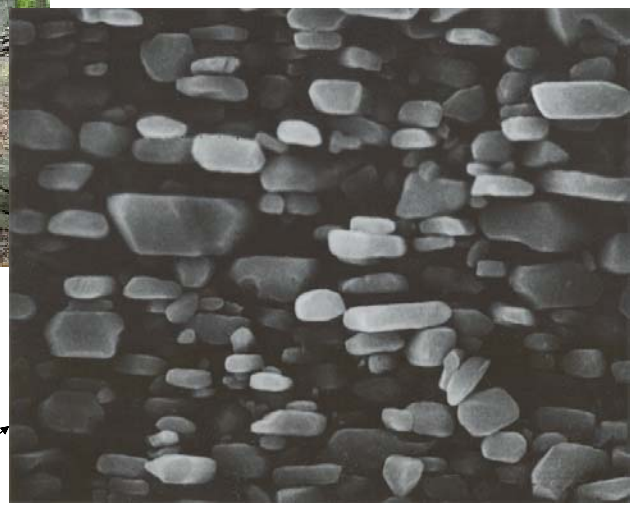
- A key consideration of new materials development is maximum performance which is dependent upon co-parallel orientation of magnetic domains.
- This illustrations helps one to differentiate among crystals, domains, and particles.



- 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%.

ARNOLD®
MAGNETIC TECHNOLOGIES

Ferrite Oriented Flakes

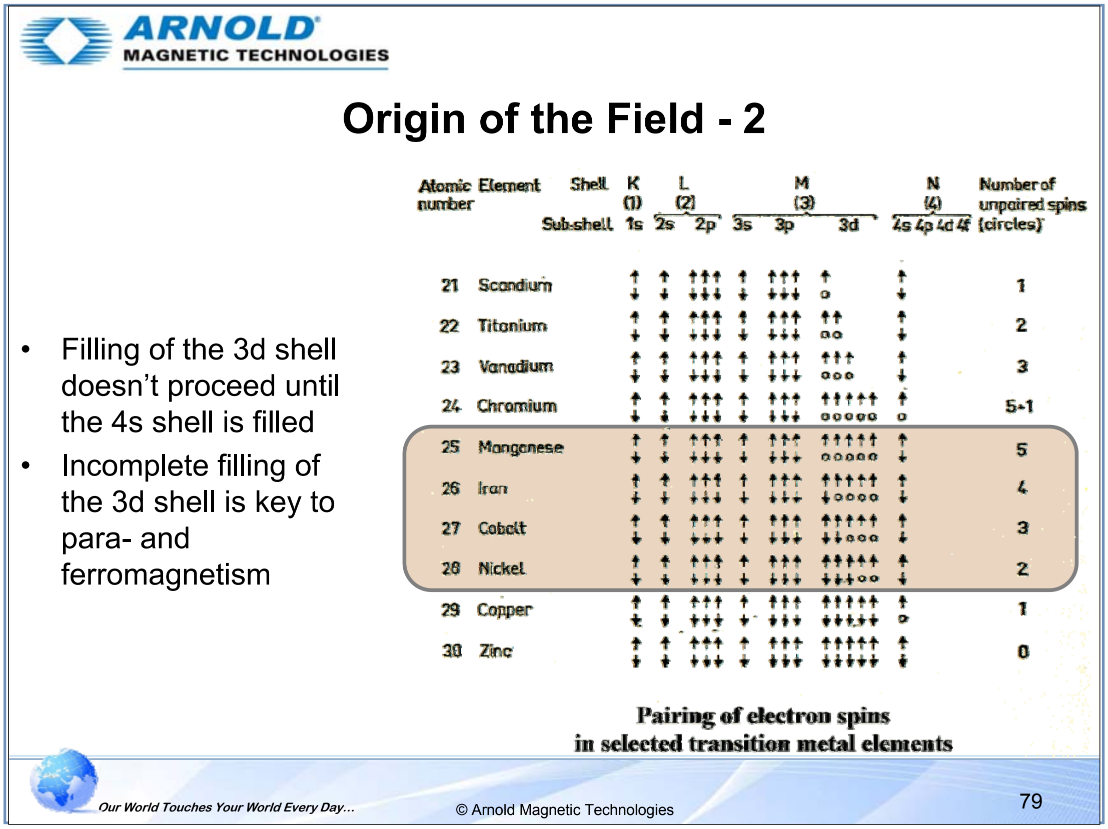


Similar to a shale stone wall

Somewhat irregular shapes well-layered

Ferrite magnet fracture surface

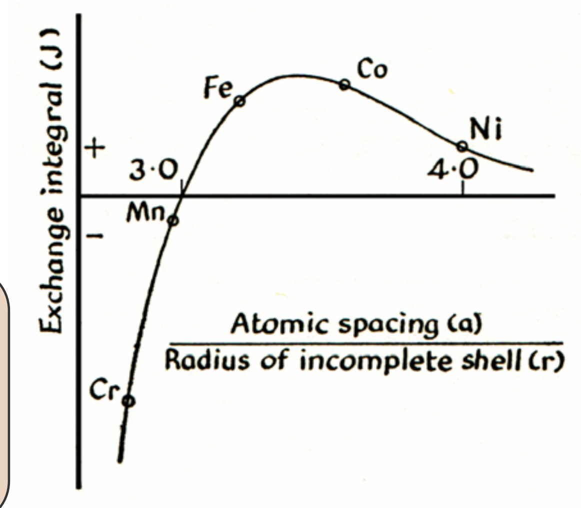
- This SEM photomicrograph of bonded ferrite shows the particle morphology and alignment.
- Although the particles are not perfect hexagonal platelets, they are generally flat and aligned well, much like this New England shale stone wall.



- 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



The exchange integral

Keywords:

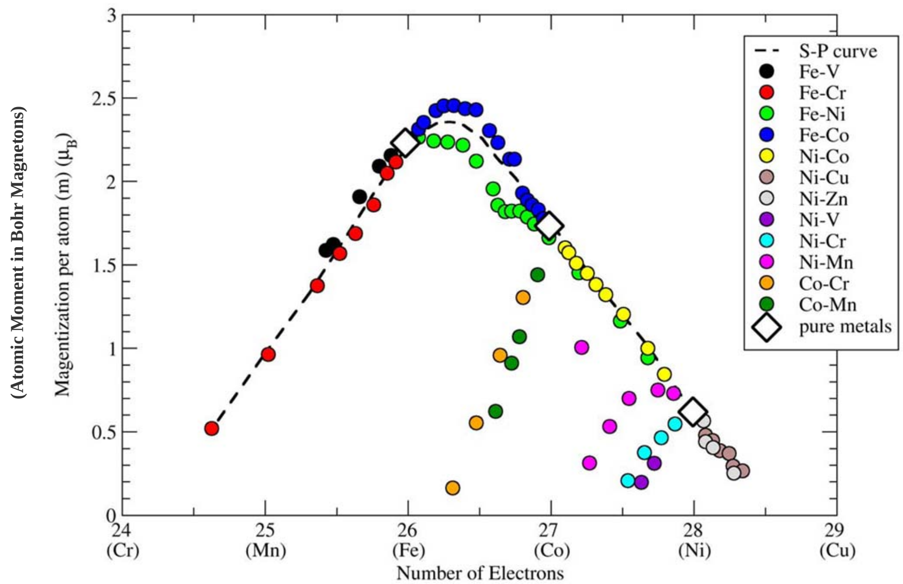
Exchange Interaction

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.

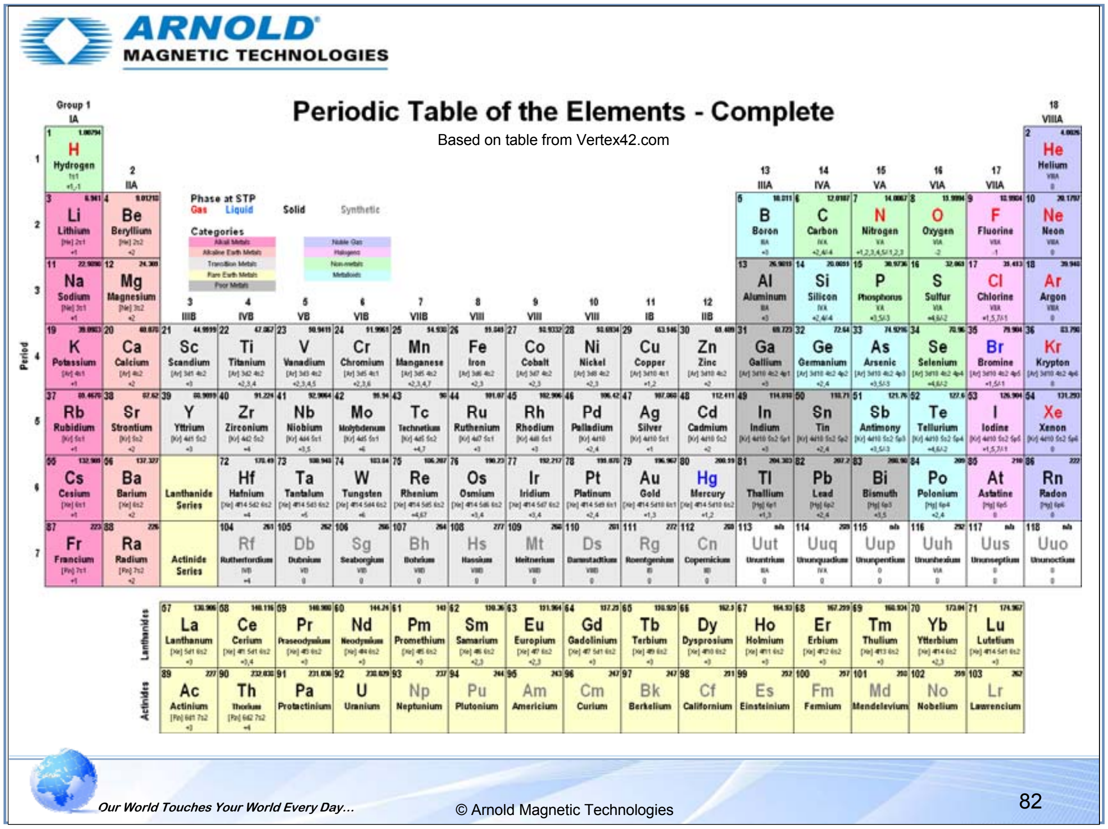
Heavy Math - - Use with Caution

- 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.

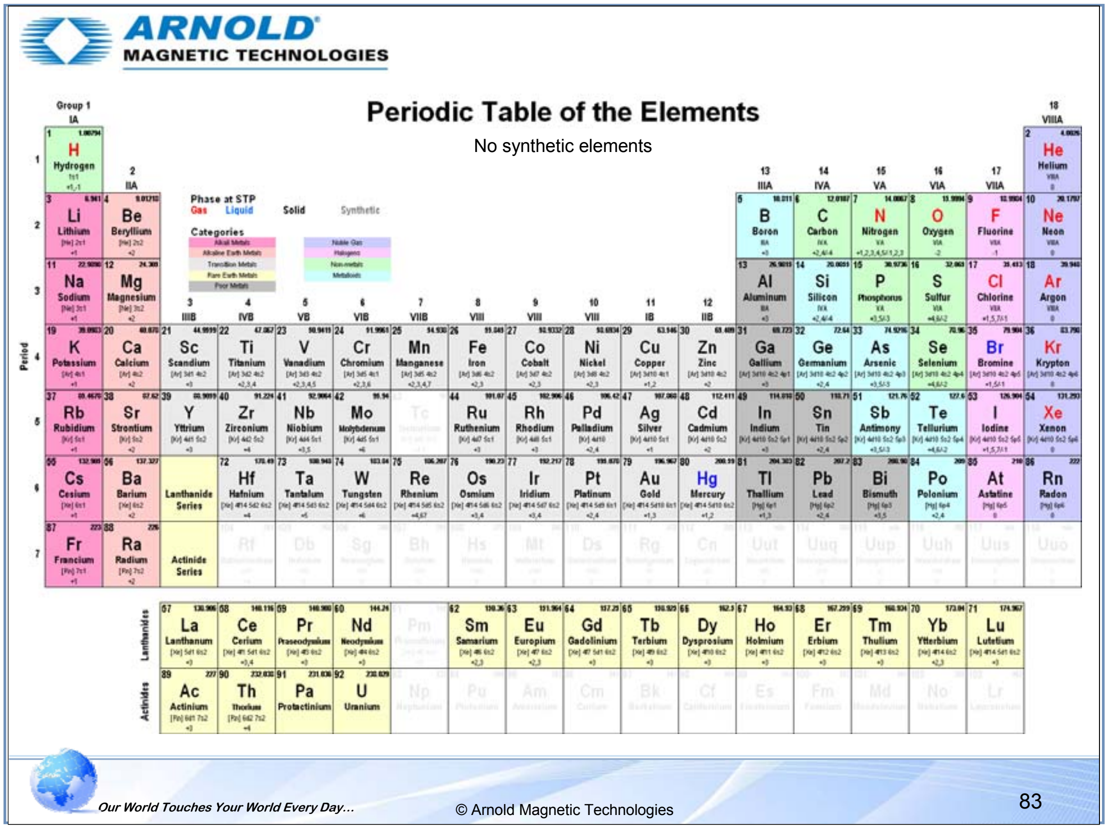
Slater-Pauling Curve



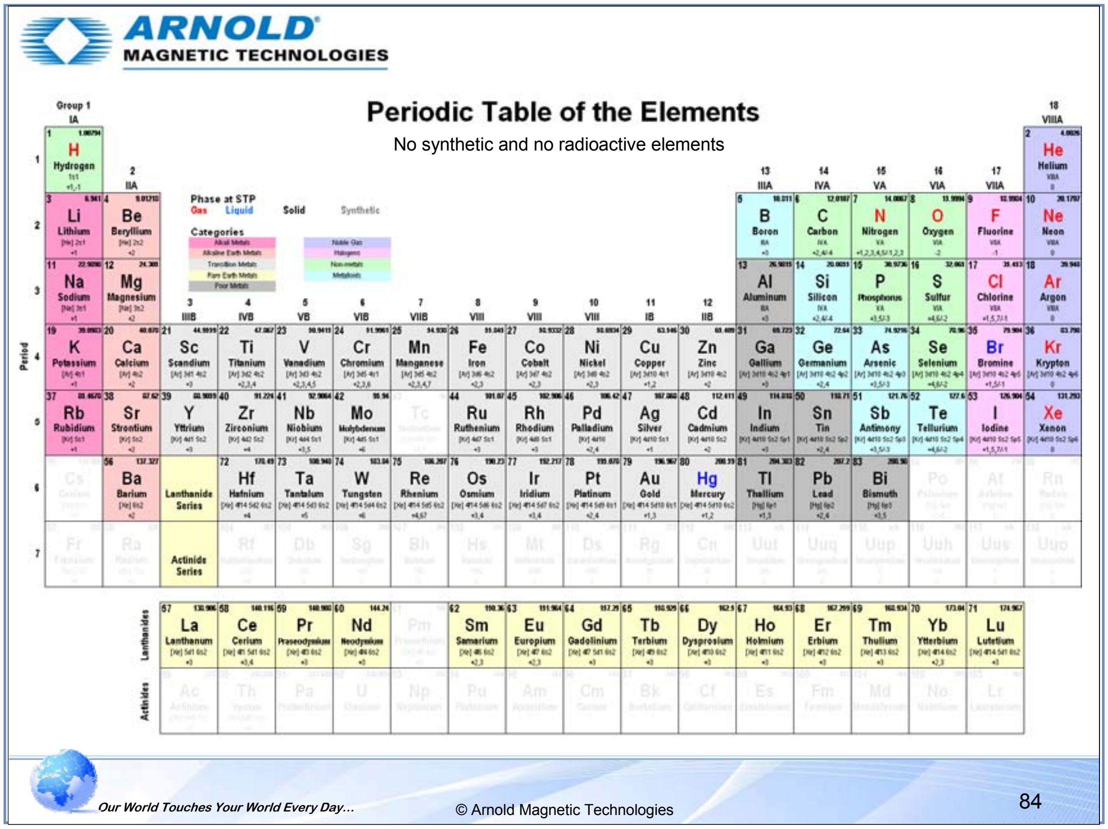
R.M. Bozorth, Ferromagnetism, IEEE, 1993, p.438-441 Color-edited by Dr. Bill McCallum, Ames Lab



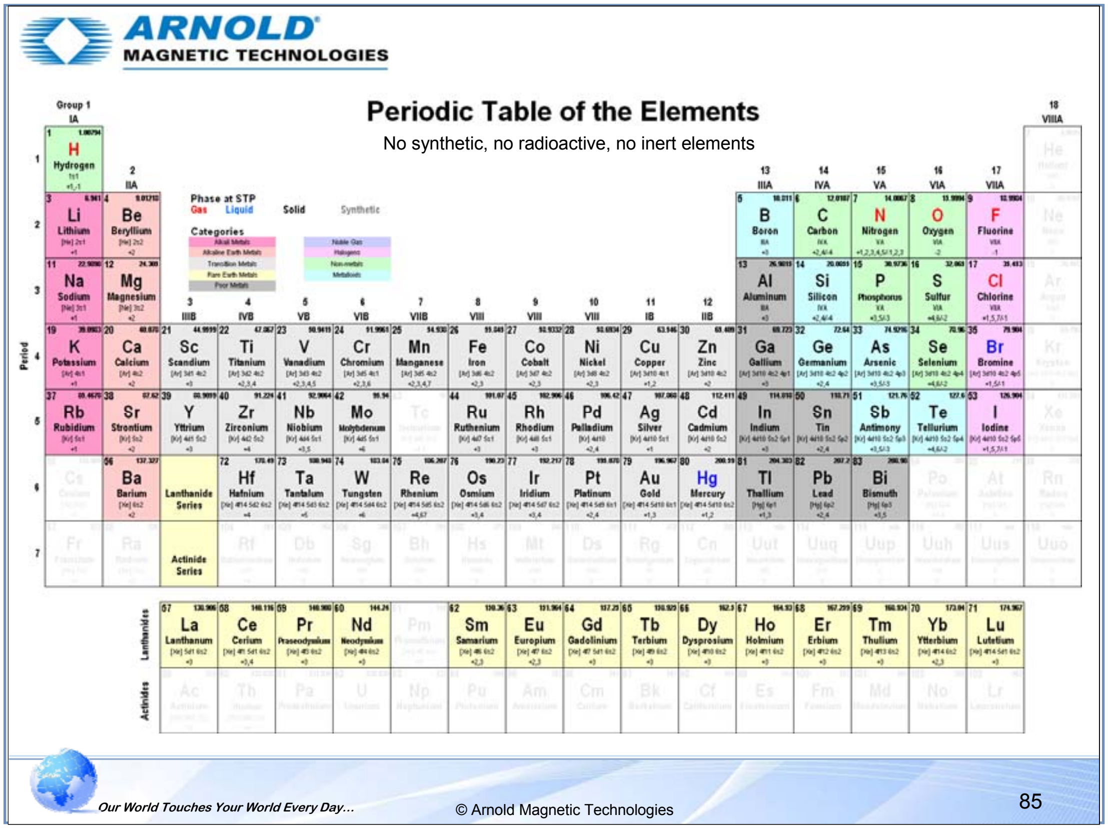
- Let’s work with the periodic table to see what elements are likely candidates for use in magnetic materials.
- I will use a method similar to that of Bill McCallum of Ames Laboratory who kindly shared his notes with me a year or two ago.
- And I should point out that this table was obtained from Vertex 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.



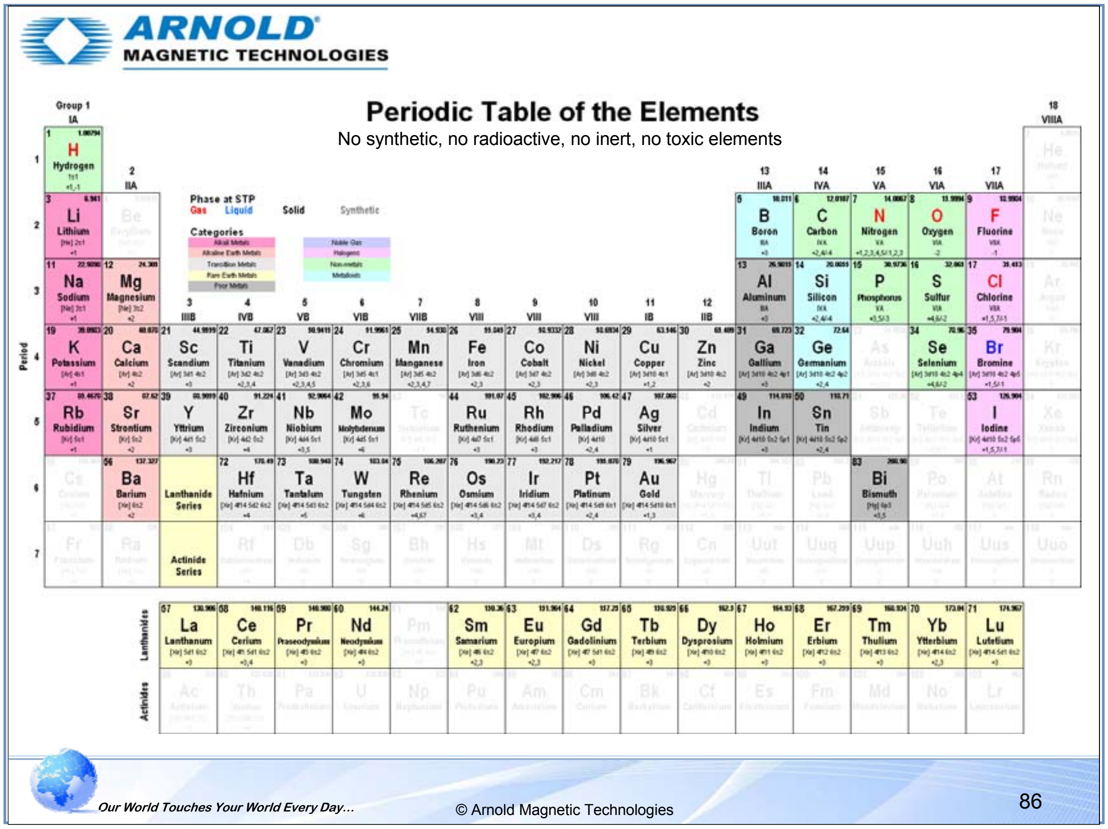
- This chart has eliminated the synthetic elements – those that are man-made and do not survive more than a very short time.



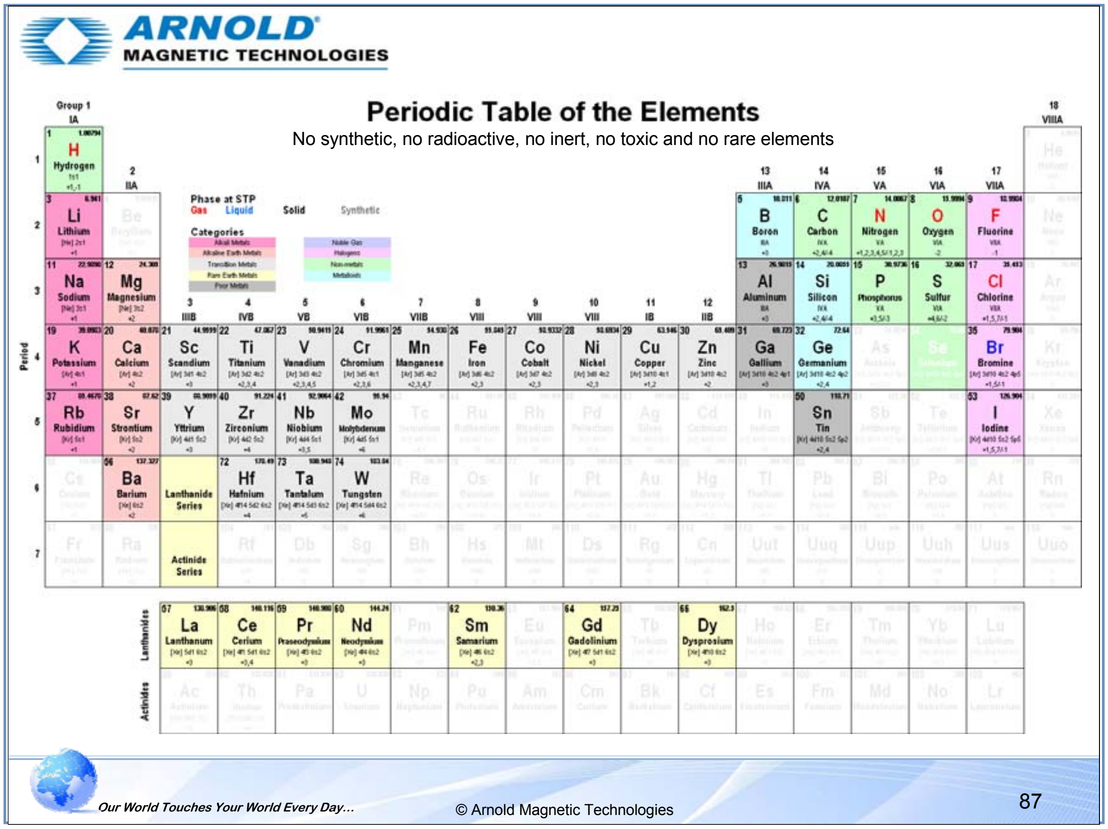
- And let’s eliminate the radioactive elements – we won’t want to put them in commercial magnets!
- As a side note Arnold has patents on Actinide magnets using uranium, iron and boron. They have interesting properties. But every known salt of uranium is either toxic or carcinogenic.



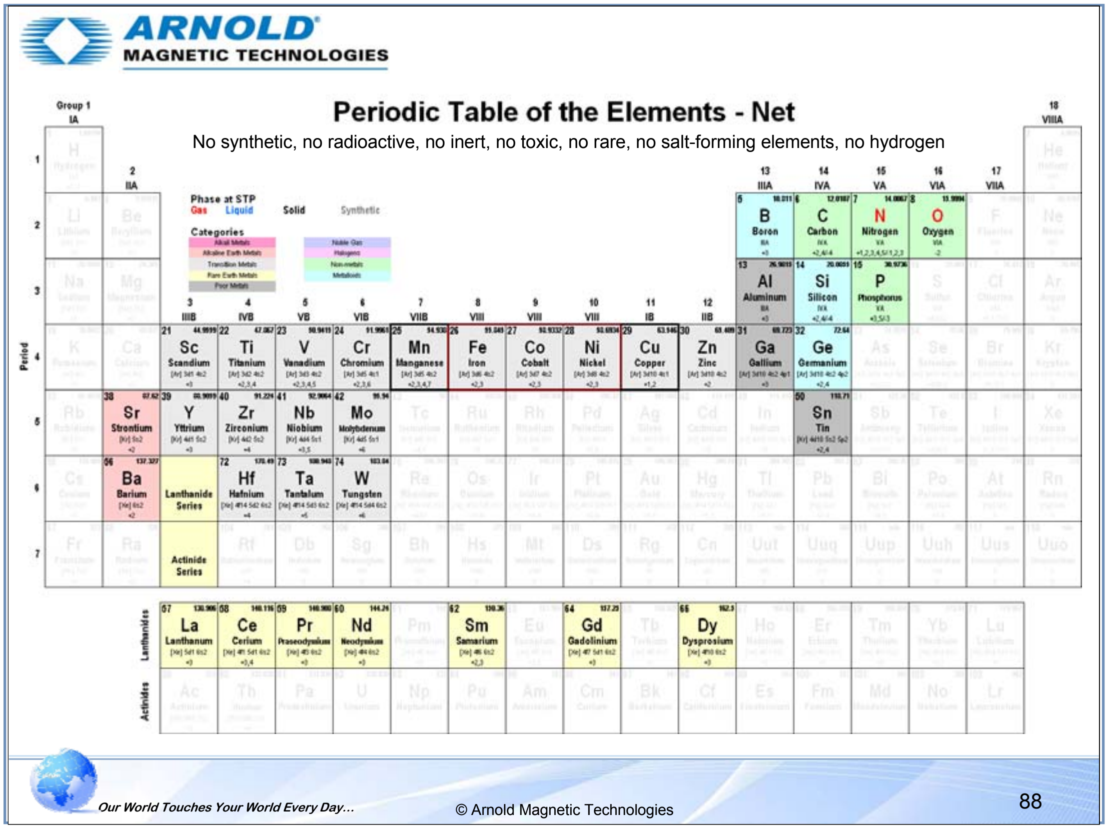
• Let’s also eliminate the noble gases – the inert elements. No magnetics available here.



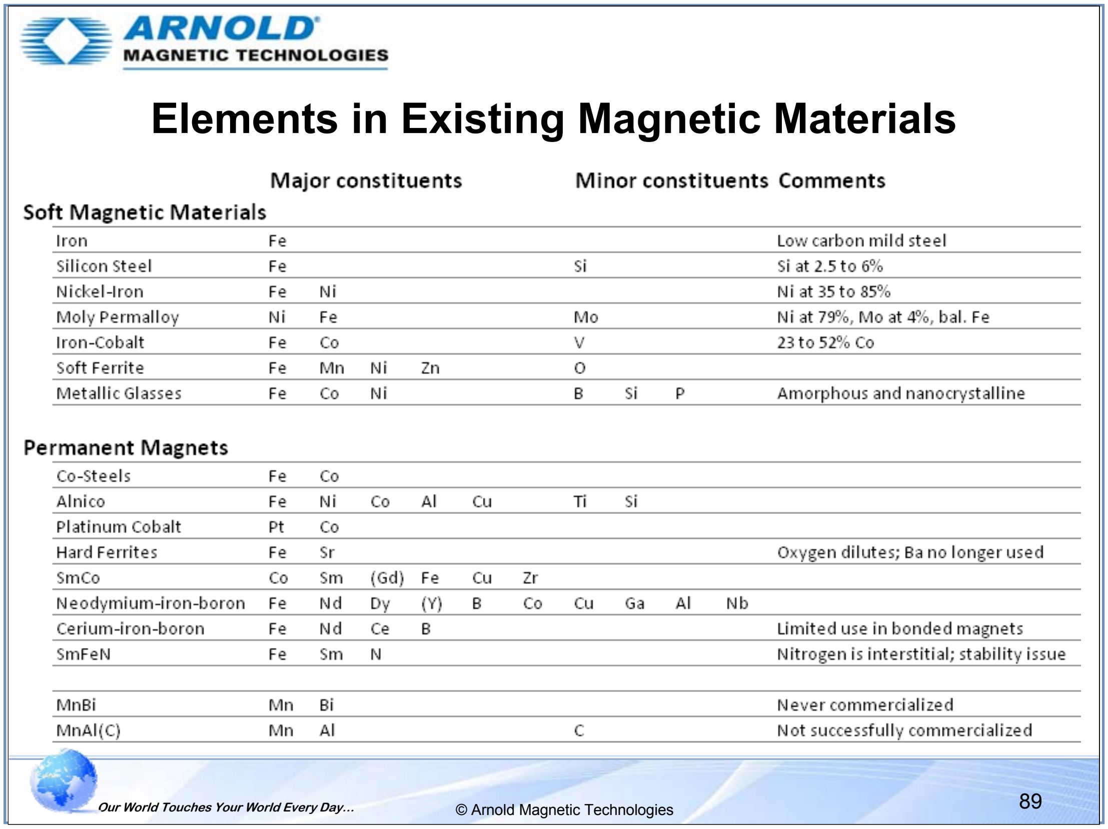
- Here we have eliminated radioactive elements.
- It’s fair to say “no” to toxic materials – so they are gone from this list.



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



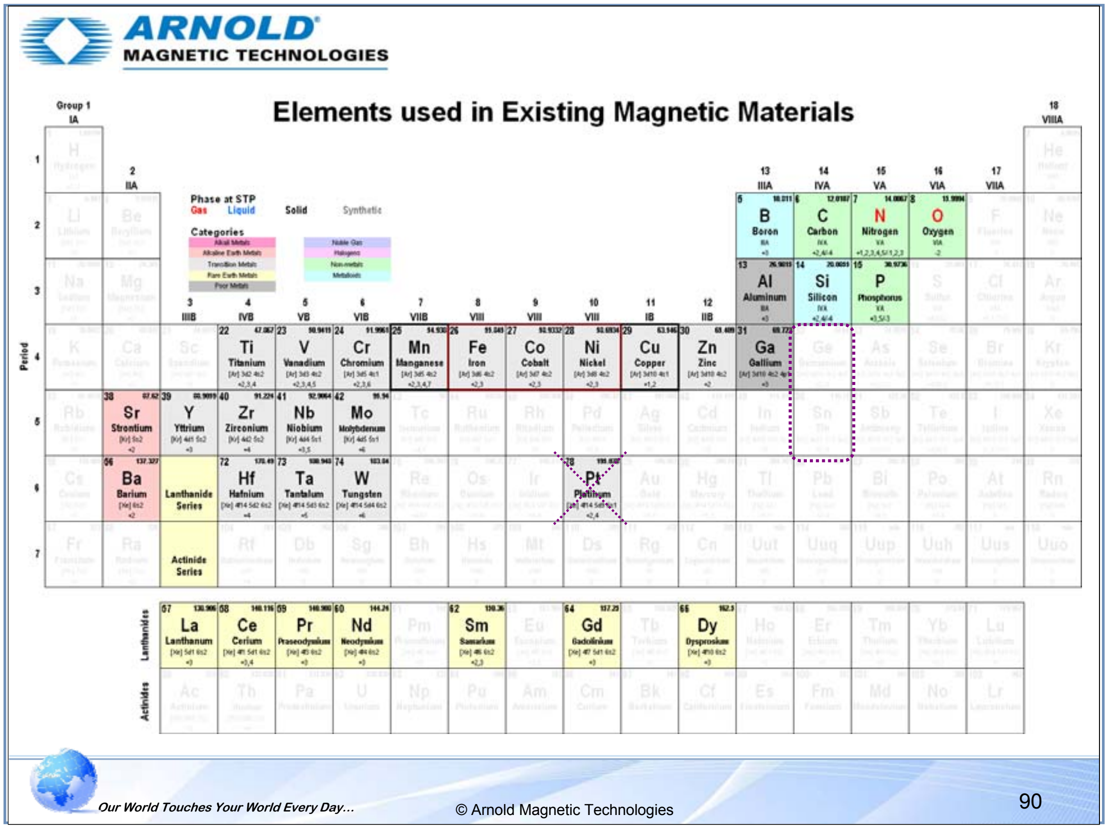
- Oh and hydrogen and the rock-forming elements won’t do us any good either – at least that’s our tentative belief.
- So we’re down from 90 naturally occurring elements to 36 – still a lot to work with.
- Let’s ask a question: what elements have been used over the last 150 years to make magnetic materials?



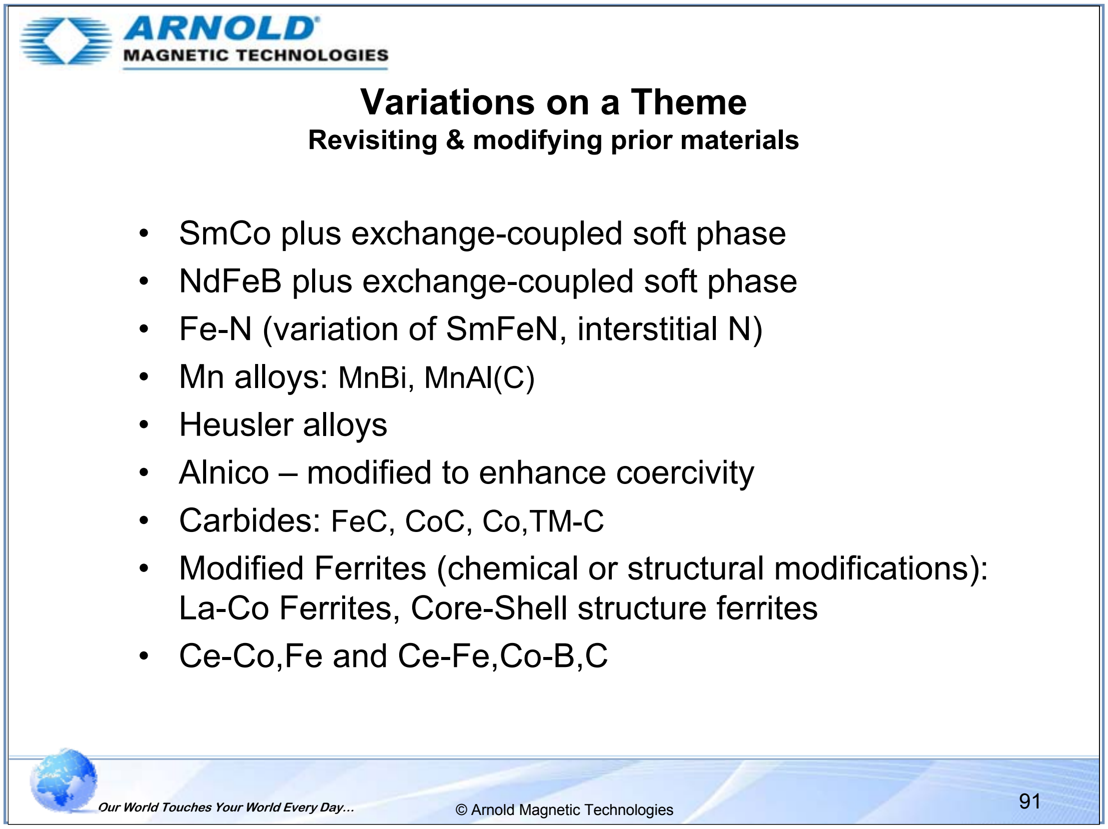
Elements in Existing Magnetic Materials

	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.



- 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.

ARNOLD
MAGNETIC TECHNOLOGIES

“Greenfield” Magnets

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

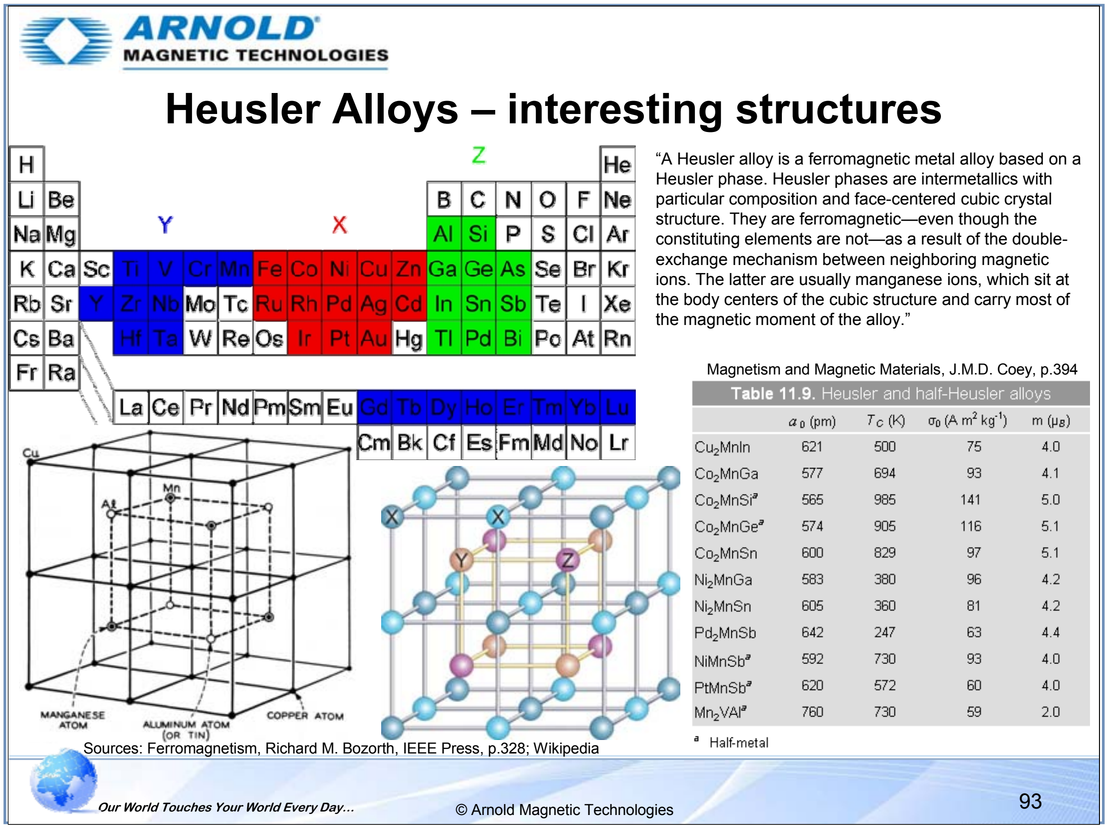


Table 11.9. Heusler and half-Heusler alloys

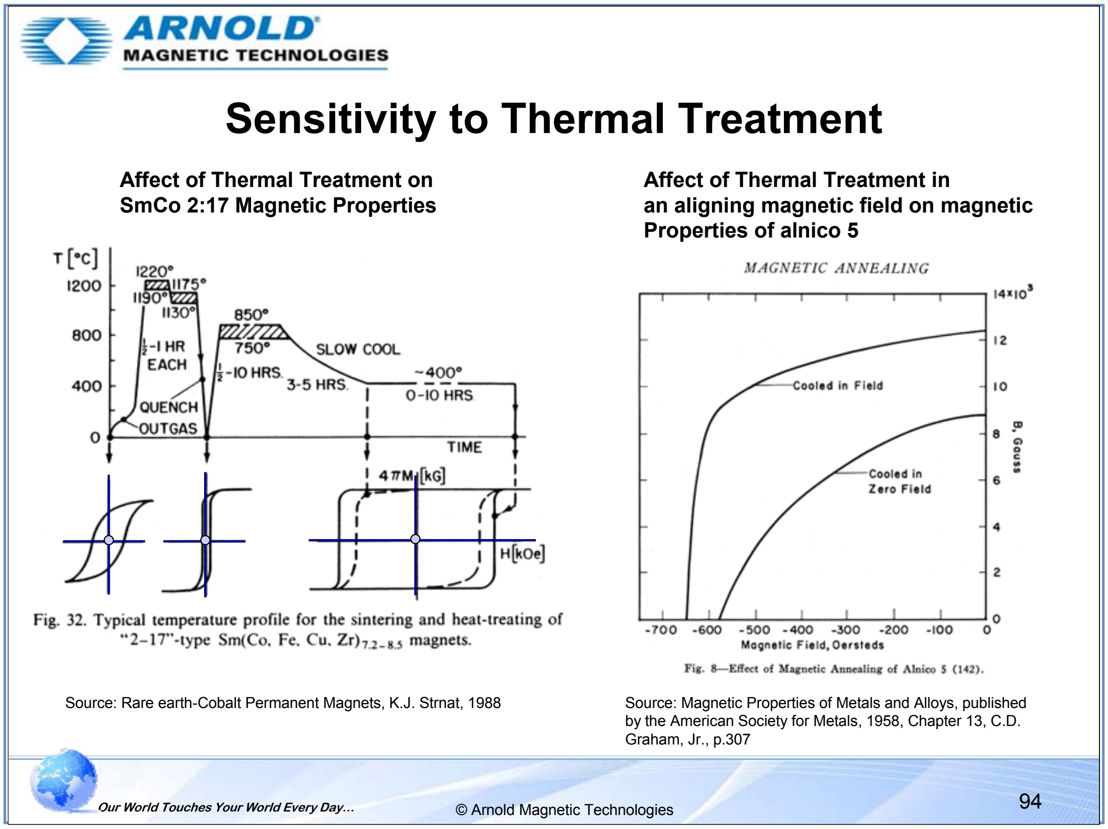
	a_0 (pm)	T_C (K)	σ_0 (A m^2 kg^{-1})	m (μ_B)
Cu_2MnIn	621	500	75	4.0
Co_2MnGa	577	694	93	4.1
Co_2MnSi^a	565	985	141	5.0
Co_2MnGe^a	574	905	116	5.1
Co_2MnSn	600	829	97	5.1
Ni_2MnGa	583	380	96	4.2
Ni_2MnSn	605	360	81	4.2
Pd_2MnSb	642	247	63	4.4
$NiMnSb^a$	592	730	93	4.0
$PtMnSb^a$	620	572	60	4.0
Mn_2VAl^a	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)



- 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.

ARNOLD MAGNETIC TECHNOLOGIES

Alnico Thermal Treatment

Three treatments

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

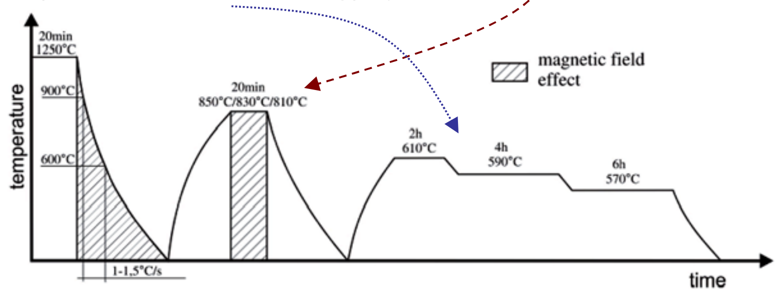
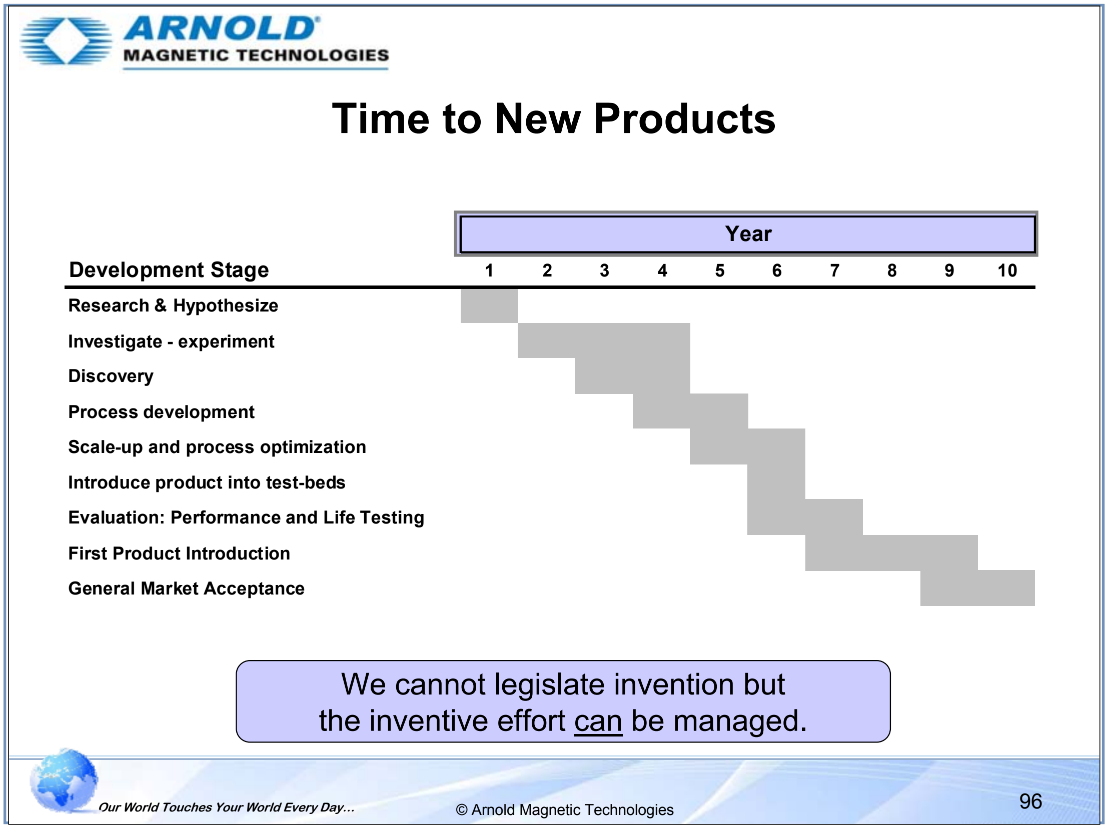


Fig. 3. Scheme of thermo-magnetic treatment of Alnico 8 alloy

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.



- 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