Balancing Material

within the Magnet Industry

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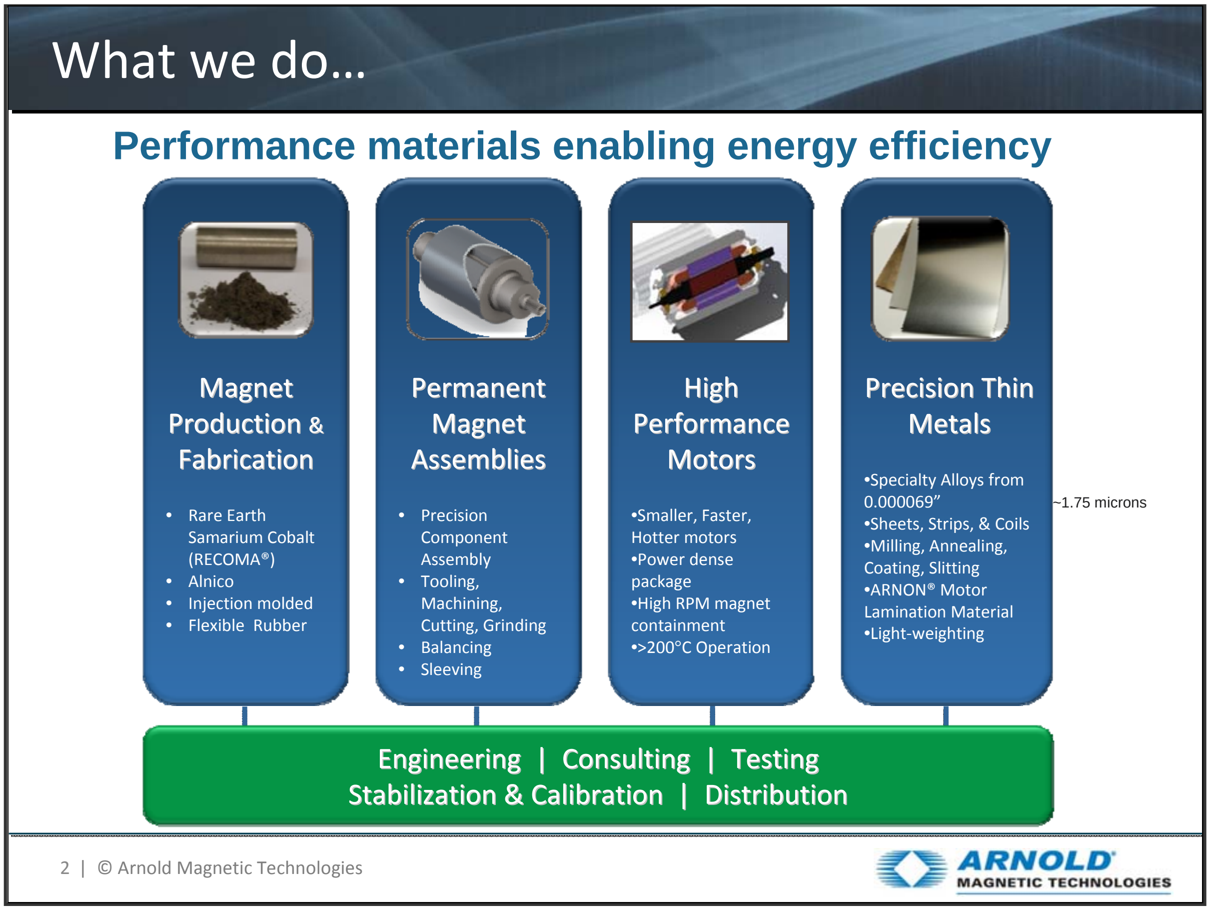
- The need for greater energy efficiency is driving changes toward smaller, lighter and more energy dense devices.
- These have been developed predominantly using neodymium iron boron permanent magnets.
- In 2010-2012 we witnessed disruption to the rare earth raw material supply that echoed through the magnet and motor industries.
- As we expand employment of technologies to harvest, transmit and utilize electric energy more efficiently, what will happen to the supply/demand balance and the pricing changes that result?



- First, a brief introduction to Arnold.
- Arnold started largely as a magnetic products manufacturer.
- Over the years we have evolved into an integrated producer as shown here – still manufacturing magnets, but increasingly producing assemblies and finished devices that use magnetic materials.

Role of Magnetic Materials

Facilitate the efficient…

- **Conversion of mechanical into electrical energy**
  Both soft and permanent magnetic materials
- **Transmission of electrical energy**
  Primarily soft magnetic materials
- **Conversion of electrical into mechanical energy**
  Both soft and permanent magnetic materials

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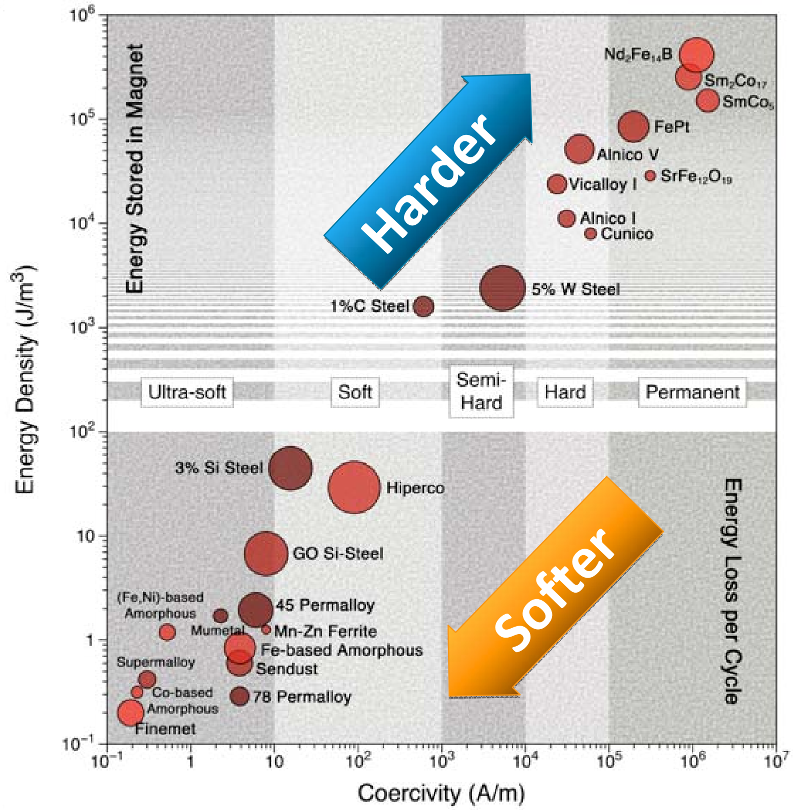
- Magnetic materials are important elements in the production, transmission and consumption of electrical energy.
- The industry is pursuing improvements in manufacture of magnetic products and improvement to the devices that use them.

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.



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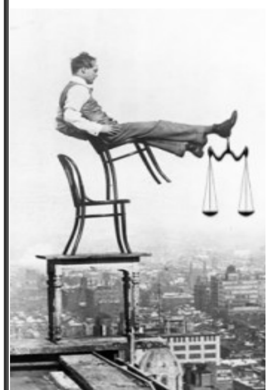
- This chart from Matt Willard of Case Western Reserve University, shows many important details.
- First, there is a continuum from the very "soft" magnetic materials to the very "hard" permanent magnet materials - with an intermediate region we call "semi-hard".
- Soft magnetic materials are better performers when the energy consumed (lost) per cycle is very low. Thus the generally best performing soft magnetic materials may be seen at the bottom left of the chart.
- Conversely, permanent magnets are expected to retain their properties and are useful for their "stored" energy with the best performers found at the upper right of the chart.

Issues

- Permanent magnets: current options
- Key raw materials
- Market volatility



Balance is important in our lives
….and sometimes our wellbeing depends upon it.

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- The "magnet industry" involves permanent, semi-hard magnets and soft magnetic materials.
- Soft magnetic materials require high saturation most often achieved by using iron, iron-cobalt, and iron-nickel based alloys.
- Motors and transformers primarily use silicon-iron, nano-crystalline and amorphous iron alloys in quantities at least 20x that of all the permanent magnets combined.
- Iron, as one of the most abundant raw materials, has witnessed minimal supply and price disruption.
- Permanent magnets, on the other hand, require high coercivity. That is accomplished through the use of additives and special thermal processing.
- It is the permanent magnet industry that has experienced the greatest turmoil and is the focus of this presentation.

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 and Cunico*** *have been replaced by FeCrCo*
    - ***PtCo*** *is a specialty item made in very limited quantities due to it's high material cost*

Material	First Reported	BH(max)	Hci
Remalloy	1931	1.1	230
Alnico	1931	1.4	490
PtCo	1936	7.5	4,300
Cunife	1937	1.8	590
Cunico	1938	1.0	450
Alnico, field treated	1938	5.5	640
Vicalloy	1940	3.0	450
Alnico, DG	1948	6.5	680
Ferrite, isotropic	1952	1.0	1,800
Ferrite, anisotropic	1954	3.6	2,200
Lodex®	1955	3.5	940
Alnico 9	1956	9.2	1,500
$RECo_5$	1966	16.0	20,000
$RECo_5$	1970	19.0	25,000
$RE_2(Co,Fe,Zr,Cu)_{17}$	1976	32.0	25,000
$RE_2TM_{14}B$	1984	26.0	**25,000**
		35.0	11,000
$RE_2TM_{14}B$	2015	30.0	**45,000**
		52.0	11,000

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

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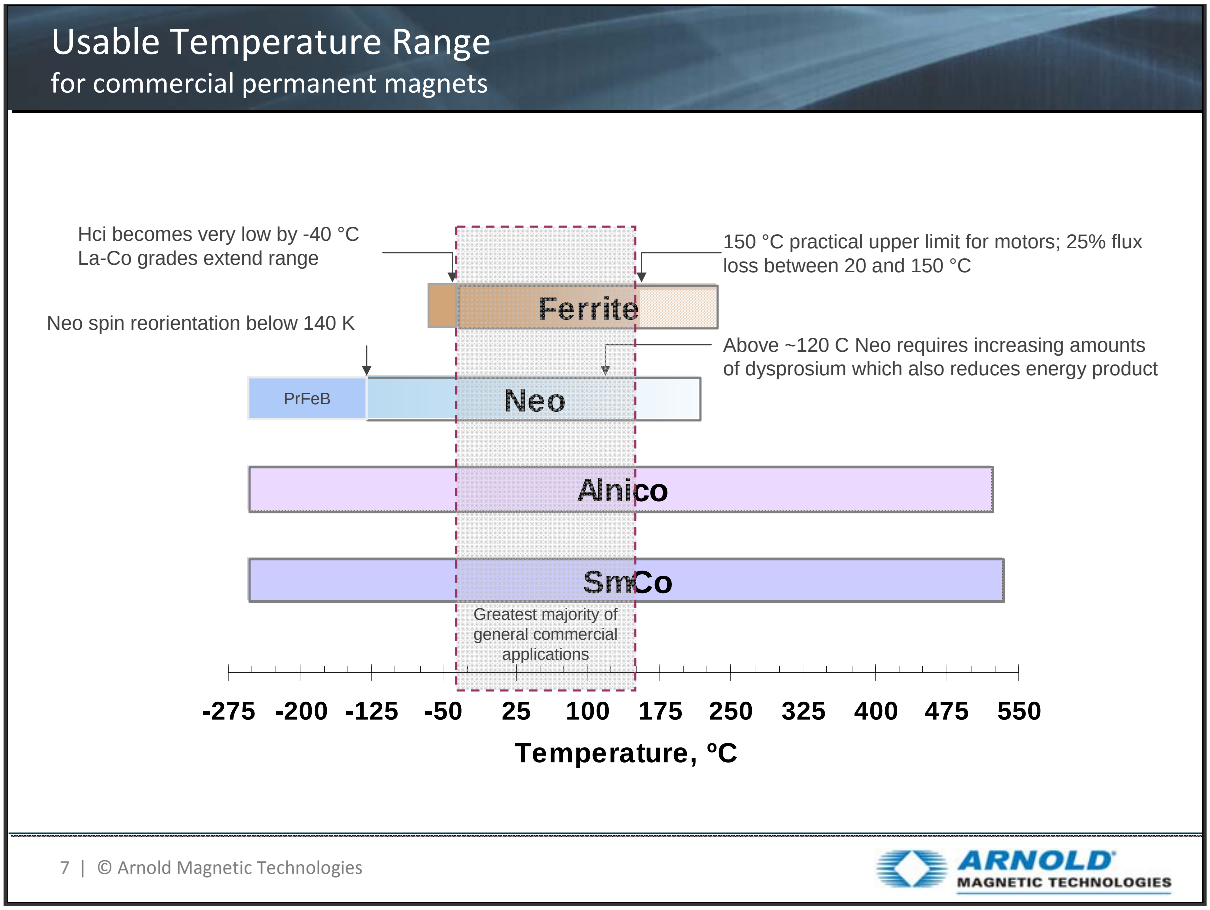
- During the 1900's great strides were made in the development of improved permanent magnets as shown in this table.
- Increased values of both maximum energy product (BHmax) and intrinsic coercivity (Hci), resistance to demagnetization, were made culminating with neo magnets (RE2TM14B) the status for which is provided in 1984 and also for 2015.
- Grades of Neo were developed to maximize energy product while sacrificing some coercivity and conversely, maximizing coercivity (for high temperature use) while sacrificing some energy product.



- 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.
- Fortunate, then, that most consumer applications operate in the range -40 to 150 °C.
- 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.
- On the other hand, Ferrite can be theoretically used to over 350 °C. However, even by 150 °C, it loses 25% of its flux output and that is a practical limit for motor applications – and its coercivity decreases as temperature drops resulting in a minimum use temperature about -40 °C.

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	Magnetfabrik Bonn Magneti Ljubljana SG Magnets Ltd
FERRITE	Anshang Dekang BGRIMM DMEGC Dongyang Gelin Jiangmen **>200 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)

*the 8 listed companies are licensed to sell into the USA

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- This listing shows manufacturers of the four most common permanent magnet materials accurate as of the present.
- There are many additional companies that act as distributors of magnets.
- Chinese companies produce over 80% of each of the magnet materials and consume the greatest portion of them domestically, building them into products for use within China and for export.

Issues

- Permanent magnets: current options
- **Key raw materials**
- Market volatility

Supply and demand are not static, they constantly change
….and often not in the same direction.

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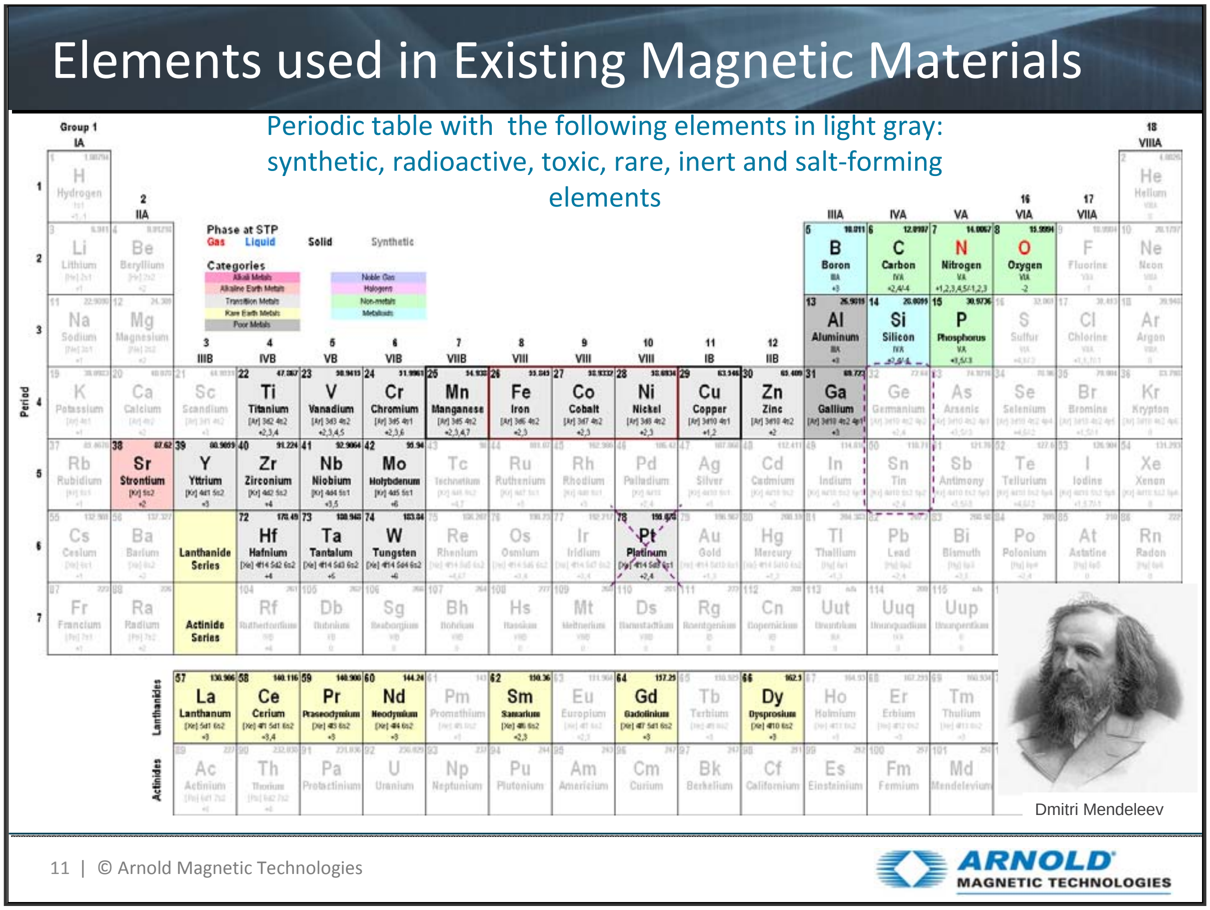
- Certain magnet materials have become critically important from the standpoint of price and availability.

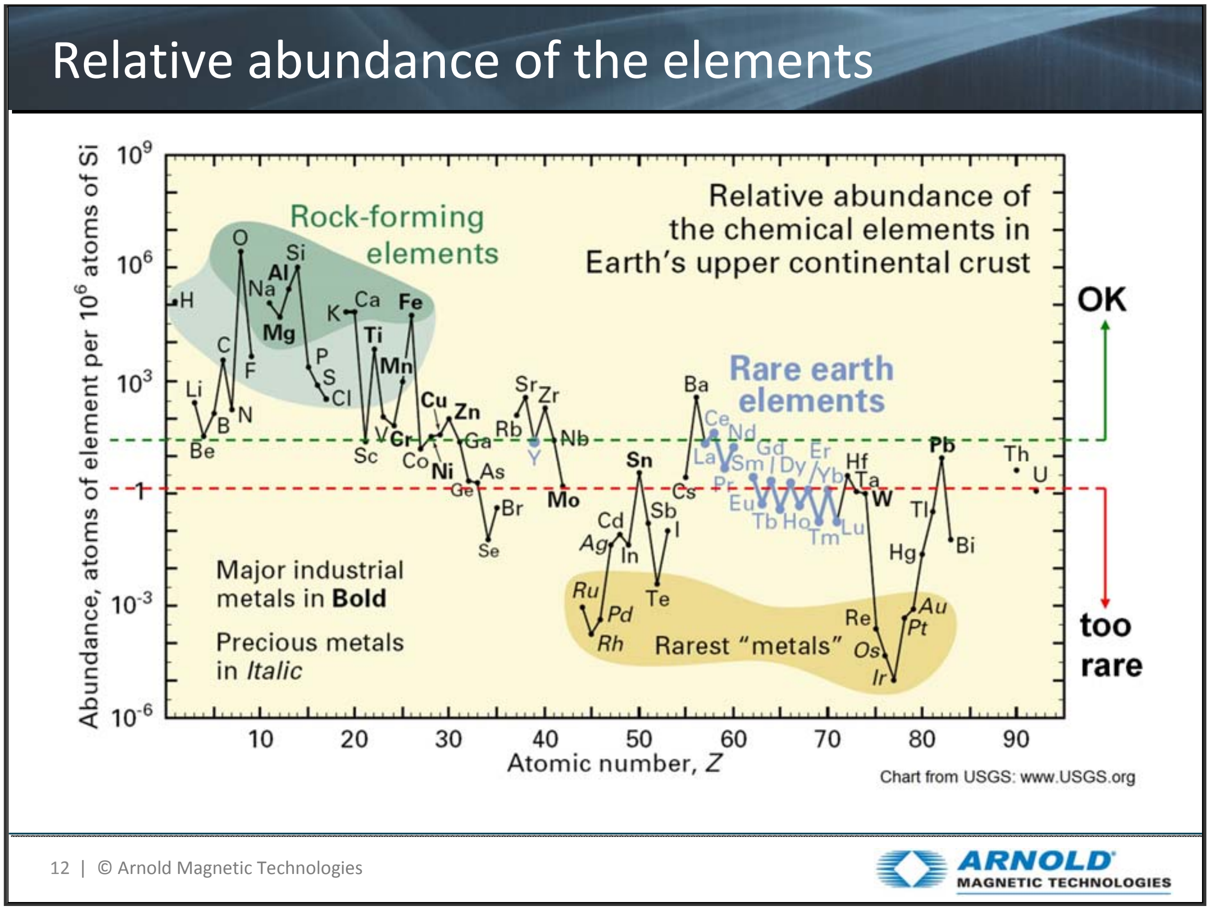
Elements in Existing Magnetic Materials

	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

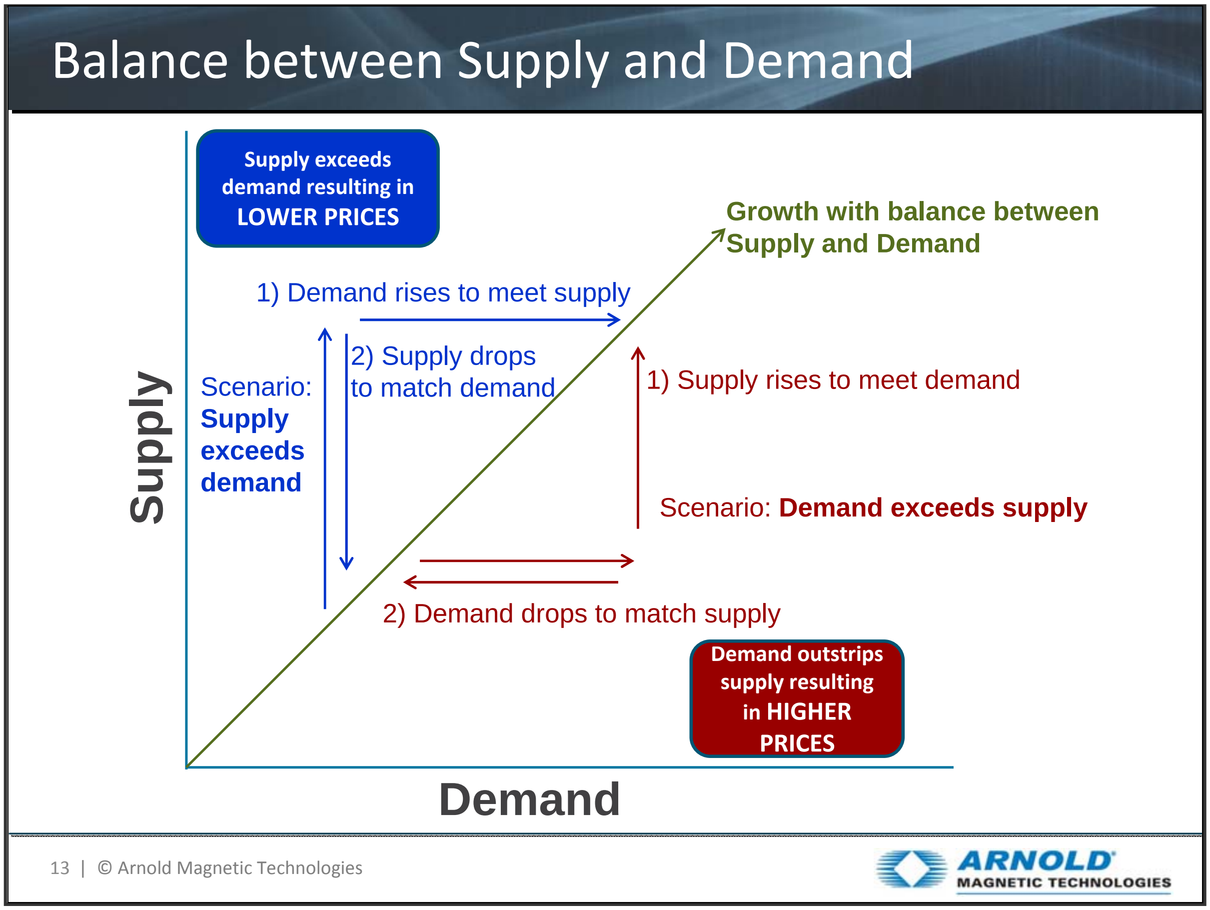
- The majority of magnetic materials are listed along with the elements used in them.



- Many elements in the periodic table are not useful for commercial magnetic products.
- These include: artificially created elements, toxic elements, those elements that are truly rare, those elements that do not contribute to the magnetic moment, inert elements, and elements that will react to form salts (rock-forming elements).
- When we eliminate the non-useful elements from the periodic table, we are left with those shown.
- These have been the elements researched individually and in combination for over 150 years and are the same elements shown on the previous slide.
- Current research is therefore focused on creating modified atomic structures via nano-technology with exchange coupling of high saturation magnetization and high anisotropy field (coercivity) materials combined with esoteric manufacturing techniques resulting in modified structures.



- From the standpoint of "balance", we would be well-advised to not utilize rare elements as a major constituent of a magnet material.
- Elements below the red dashed line should be avoided if possible or used in very small amounts.
- For example, PtCo is an excellent material, but is too expensive for all but the smallest magnets.
- There is not enough platinum in the crust of the earth to permit large scale use.



- Unfettered, market forces will seek a balance between supply (production) and demand (consumption).
- For example, when supplies rise to exceed demand, prices fall and demand increases.
- There are two options: either demand rises due to the lower prices or the supply will become more constrained (since the suppliers may not be making an adequate margin on the product and reduce production).
- When demand outstrips supply, prices rise causing either a reduction in demand or an increase in supply to meet demand.
- Changes in demand can be caused by: new technology, market whimsy, government mandate, etc.
- Changes in supply are caused by: adjustment to demand, new or improved technology, new material sources, reduced competitive need, industry consolidation, weather, etc.

Key magnet raw materials – pricing variability

- Alnico
  - Aluminum, Nickel, Cobalt, Iron, Titanium
- Ferrite
  - Strontium, Iron
- SmCo (samarium cobalt)
  - Samarium, Cobalt, Iron, Copper, Zirconium
- NdFeB (neodymium iron boron)
  - Neodymium, Praseodymium, Dysprosium, Terbium, Iron, Cobalt, Boron
  - Minor amounts of Copper, Gallium, Niobium, etc.

Balancing Supply and Demand

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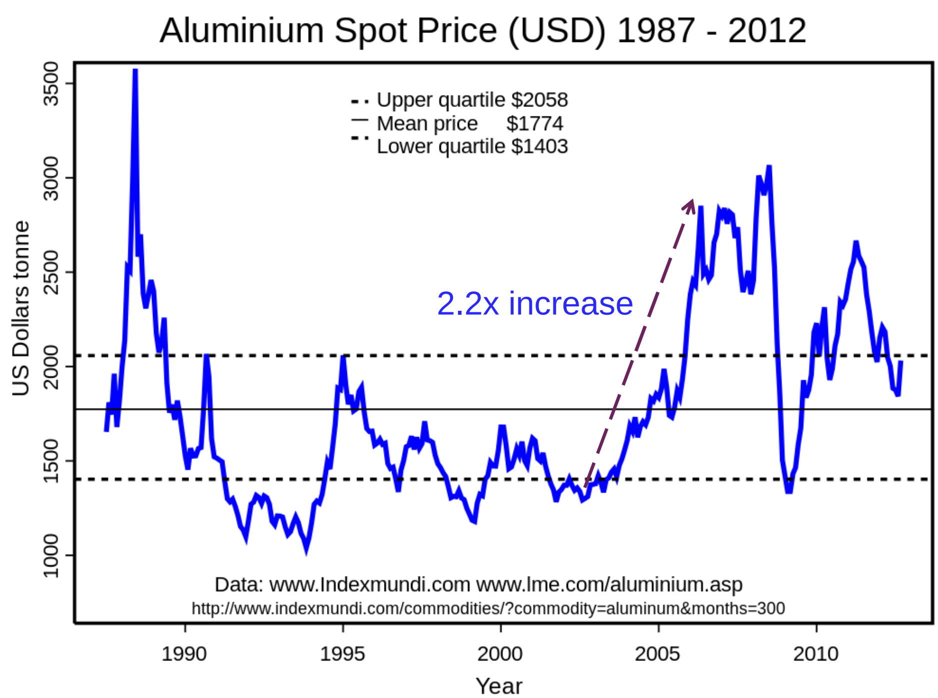
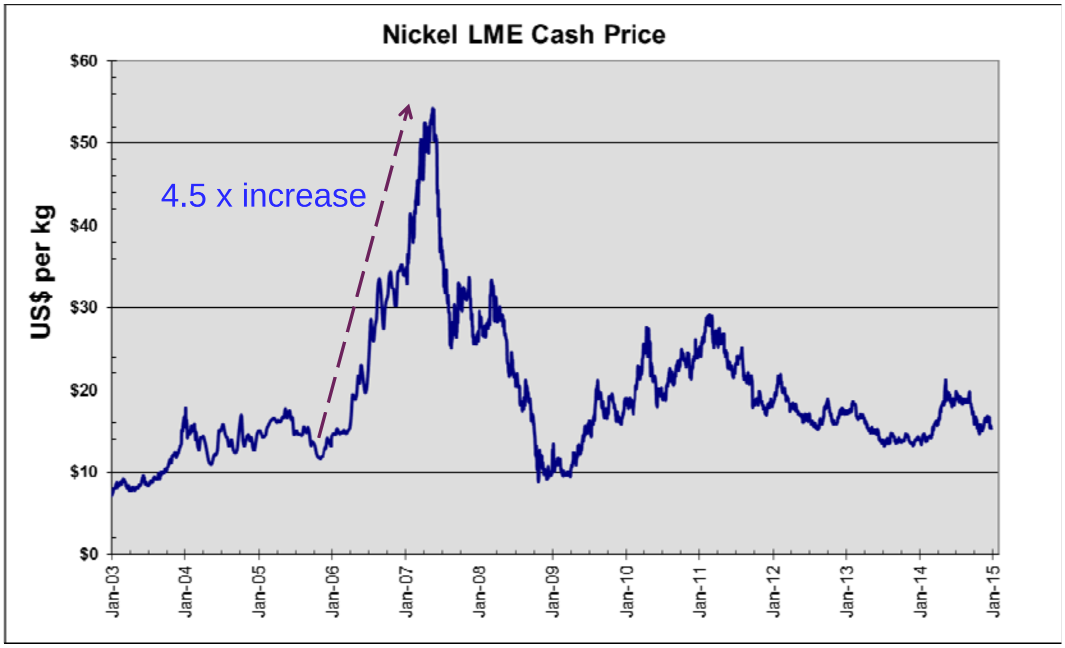
- Let's examine price changes for some of the materials used in the four most common commercial magnets.
- And remember – it's all an issue of balancing supply with demand in markets that are changing.

Material Prices - Aluminum



- Aluminum, one of the most prevalent elements in the crust of the earth, is witness to price swings.
- One might say, from the peak that the price dropped in half – or from the lowest point that the high price was twice the low price – a 2.2x change.

Material Prices - Nickel



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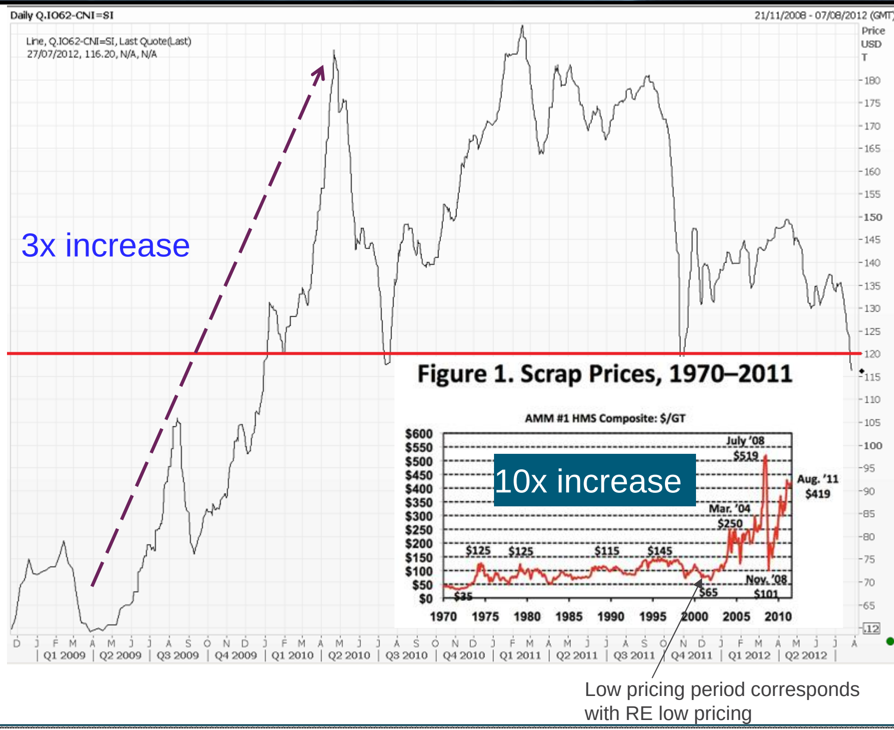
- Nickel has seen a 4.5x market price change up and then back down – all in three years.

Material Prices - Iron



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- Iron, one of the most prevalent elements in the crust of the earth has also experienced pricing excursions, most notably with the high demand for the growing infrastructure within China in the early 2000s.
- Iron is a major constituent of electromagnetic devices on a weight basis so a doubling of cost can have a profound effect on product selling price.

Material Prices - Copper

http://wordpress.mrreid.org/wp-content/uploads/2012/01/copper-price-graph.png

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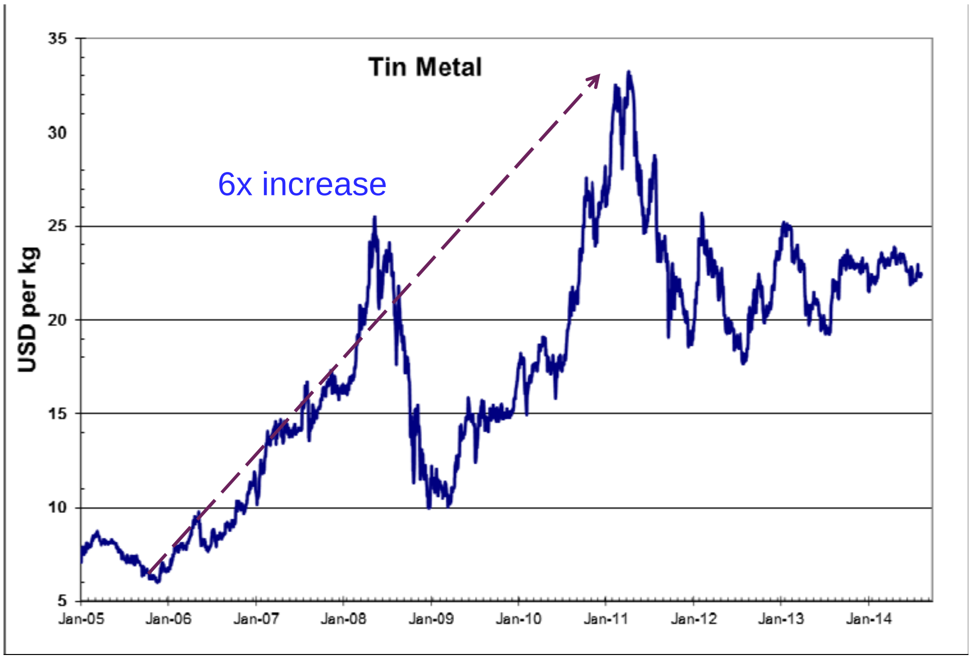
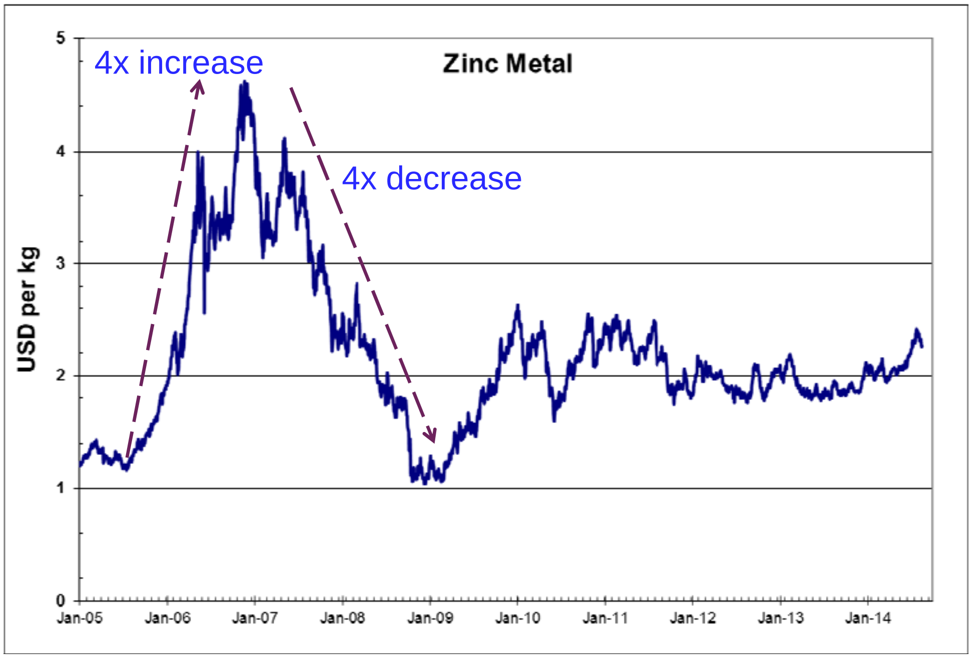
- Even induction and synchronous reluctance motors, which do not use permanent magnets, require field generation from coils of copper wire.
- These charts show a copper price surge of 7x between 2003 and 2011.

Material Prices - Tin



- Materials used in other industries, such as tin, also have seen wide prices swings – it's not just the magnetic materials industry.
- Cumulative increase from 2006 to 2011 is 6X

Material Prices - Zinc



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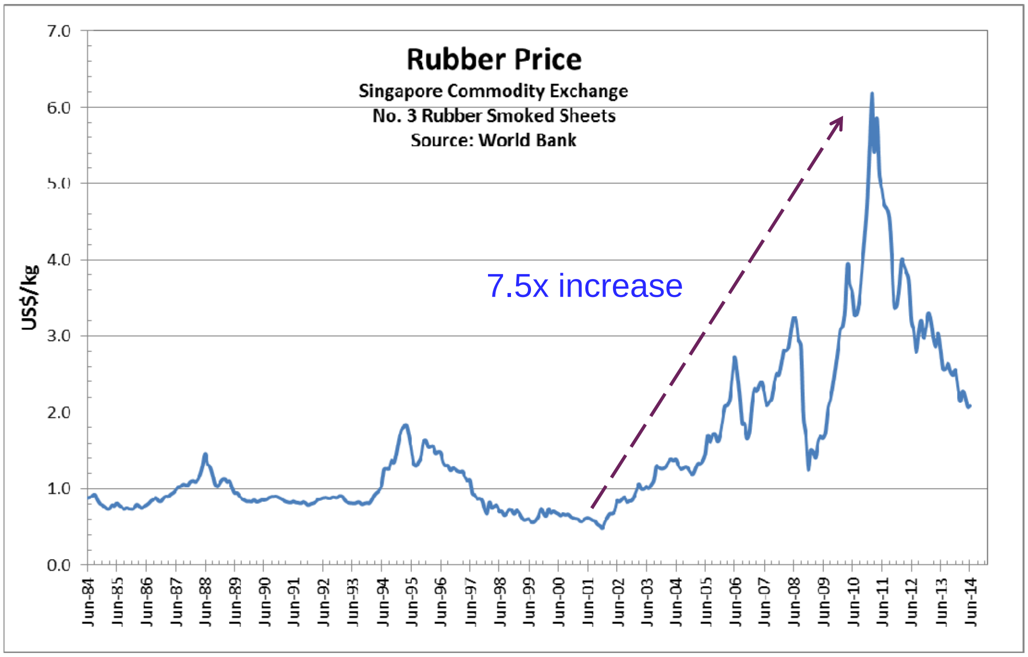
- Zinc also – wide price swings.

Material Prices – Natural Rubber



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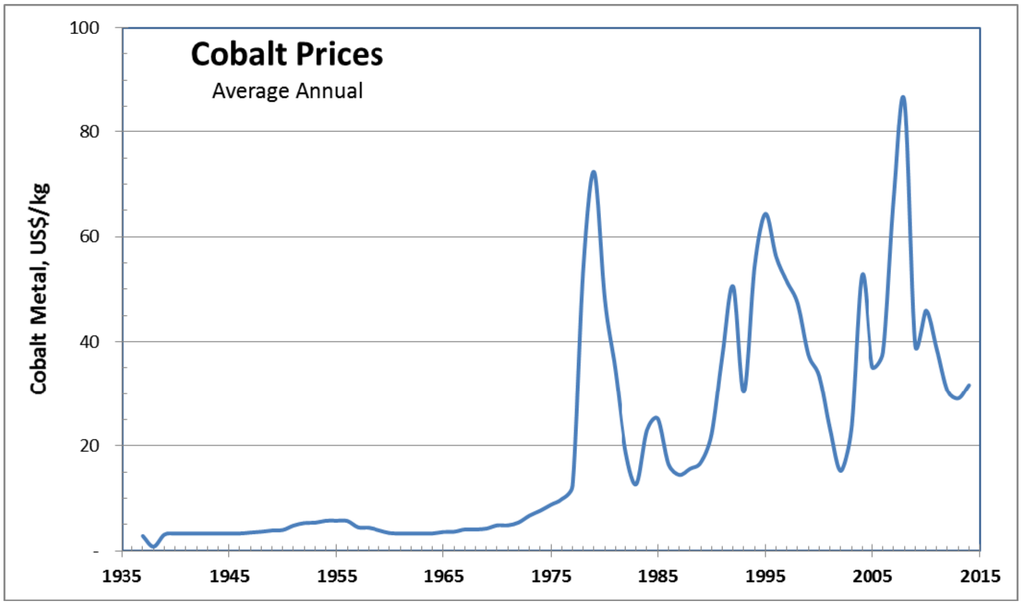
- The natural rubber supply chain is somewhat similar to that for rare earths and other mined metals in that once an increase in demand is noted, it takes between 10 and 12 years to clear the land, plant the trees and wait for them to become productive.
- There is always a risk that the market will shrink before the new assets are producing or that the new production will create an excess supply situation reducing selling prices.

Material Prices - Cobalt



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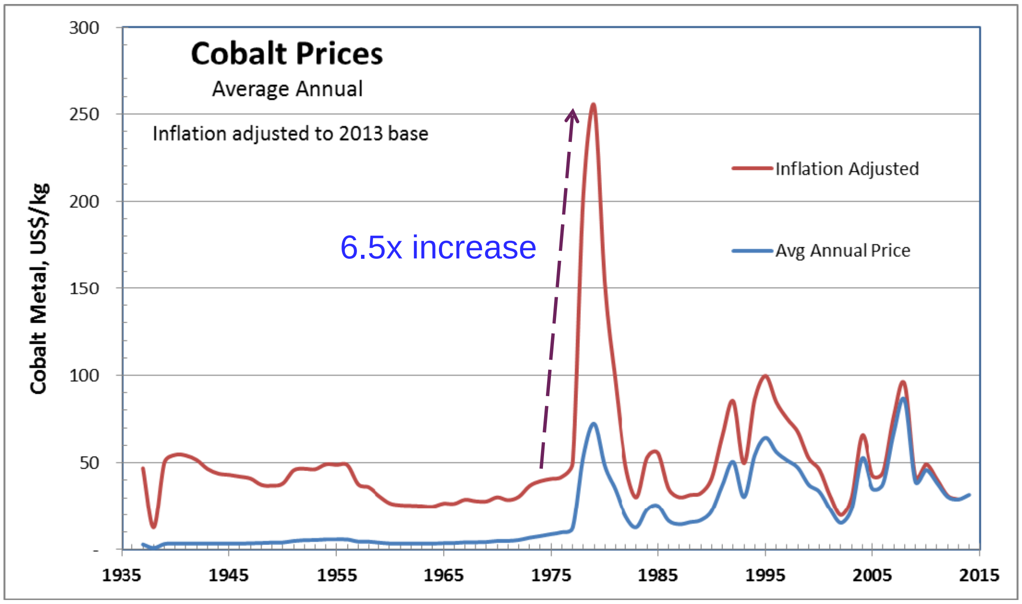
- Cobalt is a key ingredient of several magnetic materials including: alnico, SmCo, Fe-Cr-Co, Vicalloy, Supermendur, 2V-Permendur, and others.
- The magnetics industry consumes between 6 and 7% of the annual production of cobalt.
- Other major uses include specialty steels and batteries.
- Looking at a chart of cobalt prices in current dollars suggests that there is an overarching upward trend and that the price today is higher than it was in the first half of the 20th century and potentially moving higher.
- But the US dollar today does not have the same “value” it had 80, 50 or even 30 years ago. So looking at the data adjusted for inflation as shown on this next chart…

Material Prices - Cobalt, Inflation Adjusted



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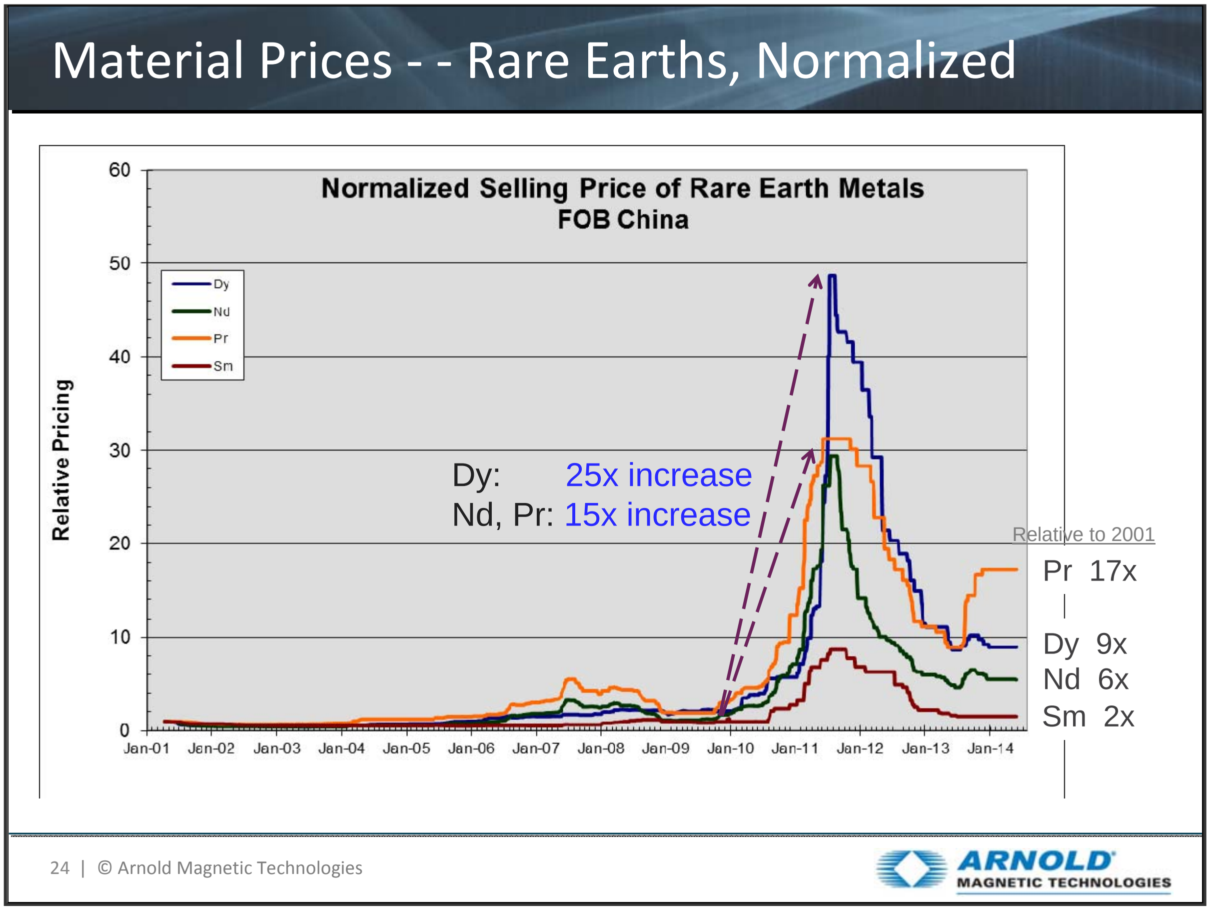
- When the inflation-adjusted prices are plotted, we see that the price of cobalt today is about the same as it was 80 years ago and is only oscillating around the long-term average.
- The red chart also indicates that, although there is moderate price volatility of late, there does not appear to be an upward trend in real pricing.
- Note also that the major peak in 1978, caused by political unrest in the Belgian Congo (ROC), was only a 6.5x rise over the base, similar in magnitude to the other commodity price swings we've been reviewing.



- On the other hand, rare earth material have experienced a major shift in prices.
- Dysprosium's price increase was a large 25x over the base.
- Neodymium and praseodymium also climbed substantially at 15x over base.
- Praseodymium is staying somewhat higher probably due to the extra cost of separating it from neodymium when it is required as a pure element.
- Samarium experienced only a minor increase in price and has recovered far better than the other magnet rare earths.

Dealing with Neo magnets in 2011

Was this a purchasing agent for Neo magnets?

Raw Material Sourcing – comparing REEs & Cobalt

Rare earths

RE Ore

RE Oxide — China, Australia (Lynas), USA (Molycorp)
India, Kazakhstan, Vietnam, etc.

RE Metal — China, (Japan, France, other minor)

RE Alloy — China, Japan, Molycorp (USA), LCM (UK), "in-house"

Figure 42: Estimated number of facilities and REO separation and refining capacity by country

Country	Estimated Number of Facilities	Estimated TREO Production Capacity (tonnes)	Current Rare Earth Products Yielded	Estimated Capacity Utilization (%)
China	59+	320,000	Separated REOs, mixed REOs	33%
Brazil	1	2,000	Separated REOs, mixed REOs	8%
Estonia	1	3,000	Separated REOs	90%
France	1	9,000	Separated REOs	25%
India	2	2,500	Mineral concentrates	80%
Kazakhstan	1	4,000	RE chloride	0%
Malaysia	2	22,600	Separated REOs, mixed REOs, mineral concentrates	45%
Russia	1	4,000	Separated REOs, RE chloride, RE carbonate	60%
U.S.	1	20,000	Separated REOs	75%
Vietnam	2	2,500	Separated REOs, mixed REOs, mineral concentrates	9%

Adamas Intelligence - Rare Earth Market Outlook - October 1, 2014

Cobalt

Country	2011 Mine Production Metric tonnes Co-contained	2011 Refinery Production Metric tonnes Co content
Australia	3,850	4,720
Belgium	-	3,187
Botswana	149	-
Brazil	3,500	1,613
Canada	7,071	6,038
China	6,800	43% 35,000
Congo (Kinshasa)	55% 60,000	3,083
Cuba	4,000	-
Finland	535	10,441
France	-	354
India	-	1,299
Indonesia	1,600	-
Japan	-	2,007
Madagascar	500	-
Morocco	2,159	1,788
New Caledonia	3,240	-
Norway	-	3,067
Philippines	2,200	-
Russia	6,300	2,337
South Africa	1,600	840
Uganda	-	661
Zambia	5,400	5,756
Zimbabwe	86	-
Totals	**109,000**	**82,200**

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- Why did REEs experience such an increase in pricing while cobalt did not? Perhaps the answer lies in the supply chain's ability to react to market needs.
- Converting REO to metal is a constraint-point in the REE supply chain.
- There are few facilities outside China with the capability of processing rare earths on a commercial scale.
- On the other hand, cobalt is widely available – not to say that a disruption in the Republic of the Congo (ROC) wouldn't have as impact on supply and pricing, but the market would be able to adjust relatively more quickly and effectively than for the current rare earth metal supply.

Calculating Neo Magnet Production from REO

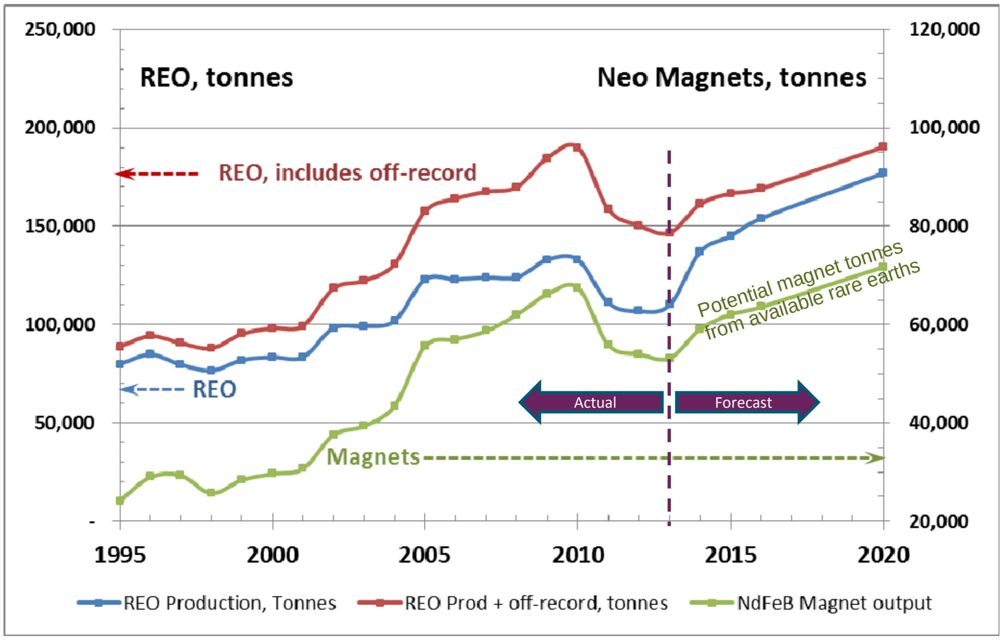
A modest attempt to confirm Neo magnet production statistics

Assumptions

1. 92 to 95% of available Nd, Pr, Dy, Tb from REO is used in magnets
2. Off-record (black market) production of REO variable between 7 and 30% of on-record production, combination of LREO and HREO
3. TRE metal content of neo magnets is 32.5 weight %
4. Oxide-to-metal conversion yield 78% rising to 82% (theoretical limit is ~85%)
5. Alloy melt yield 95% rising to 97.5%
6. Magnet material manufacturing yield 70% rising to 76%
7. Magnets use from year-to-year between 19 and 24% of total produced REO

- What is the supply situation for REEs and what does that mean for the permanent magnet industry?
- In order to forecast future performance, a level of confidence is necessary for numbers representing the recent past.
- I thought it might be worthwhile to make a top-down estimate of potential magnet output as a function of published information for production of REO and compare that to the bottoms-up estimates for the market derived by several industry sources.
- Possible factors for discrepancies in reported production by various industry persons may be due to omission of manufacturing process losses and for off-record production – my assumptions regarding these are shown on the slide.
- Another source of variation is the assumed level of off-record (black market) production.

Neo Magnet Production – past and potential



Caveat: this does not account for raw materials pulled from the supply chain by commodities traders or material stockpiled by manufacturers.

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Chart explained:

•The blue line indicates published quantities of REO production (left scale).

•The red line adds-in the off-record (black market) REO content with assumed values of between 7 and 30% of total.

•The green line is the estimated quantity of Neo magnets than can be made with the available REO (right scale).

•Magnet output apparently reached a peak in 2010 prior to the run-up in raw material prices.

•Demand continues to be slack due to several factors including 1) users moving away from Neo magnets due to high prices and instability in the supply chain, 2) alternate (non-permanent magnet) technologies being implemented, 3) world economy is in slow/sporadic recovery from the "great recession".

•As magnet users again utilize Neo magnets, consumption is expected to rise – perhaps far faster than shown here, pending adequate supply of raw material.

Major PM Materials

	2010 Actual				2015 Forecast			
	2010				2015			
	tons	%	$$$	%	tons	%	$$$	%
NdFeB	67,300	10.5%	5,700	65.1%	61,750	6.5%	8,479	60.4%
SmCo	2,310	0.4%	270	3.1%	3,510	0.4%	540	3.8%
Ferrite	567,000	88.2%	2,600	29.7%	881,120	92.4%	4,760	33.9%
Alnico	5,555	0.9%	125	1.4%	6,440	0.7%	185	1.3%
Other	540	0.1%	65	0.7%	580	0.1%	75	0.5%
Totals	**642,705**	100.0%	**8,760**	100.0%	**953,400**	100.0%	**14,039**	100.0%

Sales $$$ are in millions

Per calculations on the previous slides, 2015 NdFeB production is limited to 61,750 tons based on available REO.

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- A separate and earlier breakout of permanent magnet production (produced during 2011-2012) shows Neo magnet production in 2010 at 67,300 tons (bottom-up calculation).
- The forecast for 2015 shows neo at lower tonnage than in 2010 – due to constrained supply of neodymium and dysprosium (and terbium).
- In this forecast, sale of ferrite rises to over 92% of all permanent magnets, due in part to improved ferrite properties (La-Co additions).
- The higher price of these La-Co ferrite magnets pushes the dollar percentage to ~34%.

Issues

- Permanent magnets: current options
- Key raw materials
- **Market volatility**

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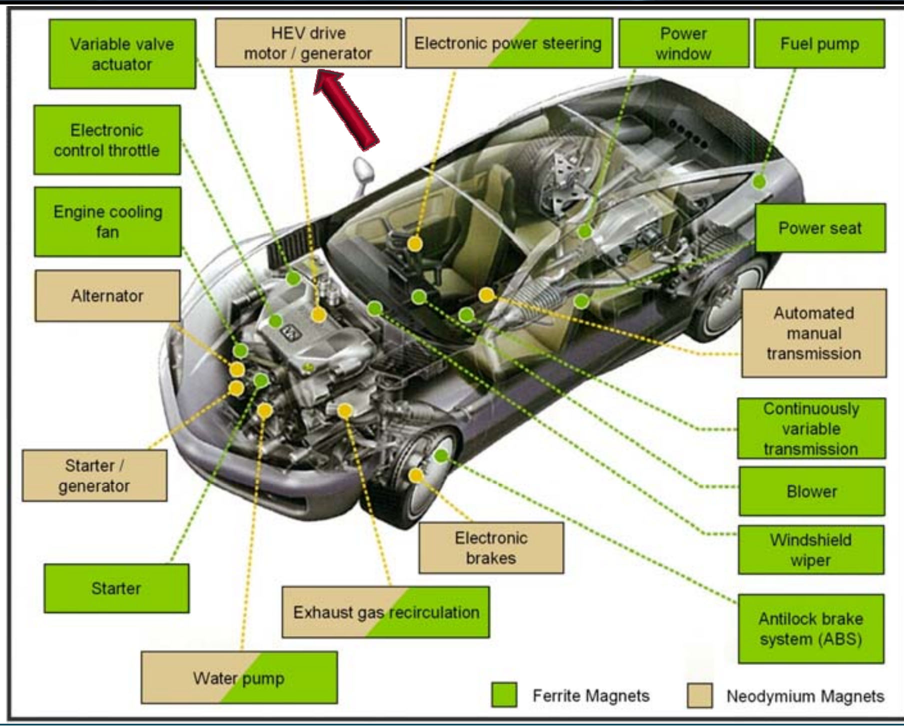
- Rapid market changes are disruptive.
- In the following slides, we'll look at just one market that is changing quickly, in part due to fuel prices and in part due to government mandates.

Automotive Motors & Actuators

Illustration from Hitachi Magnetics



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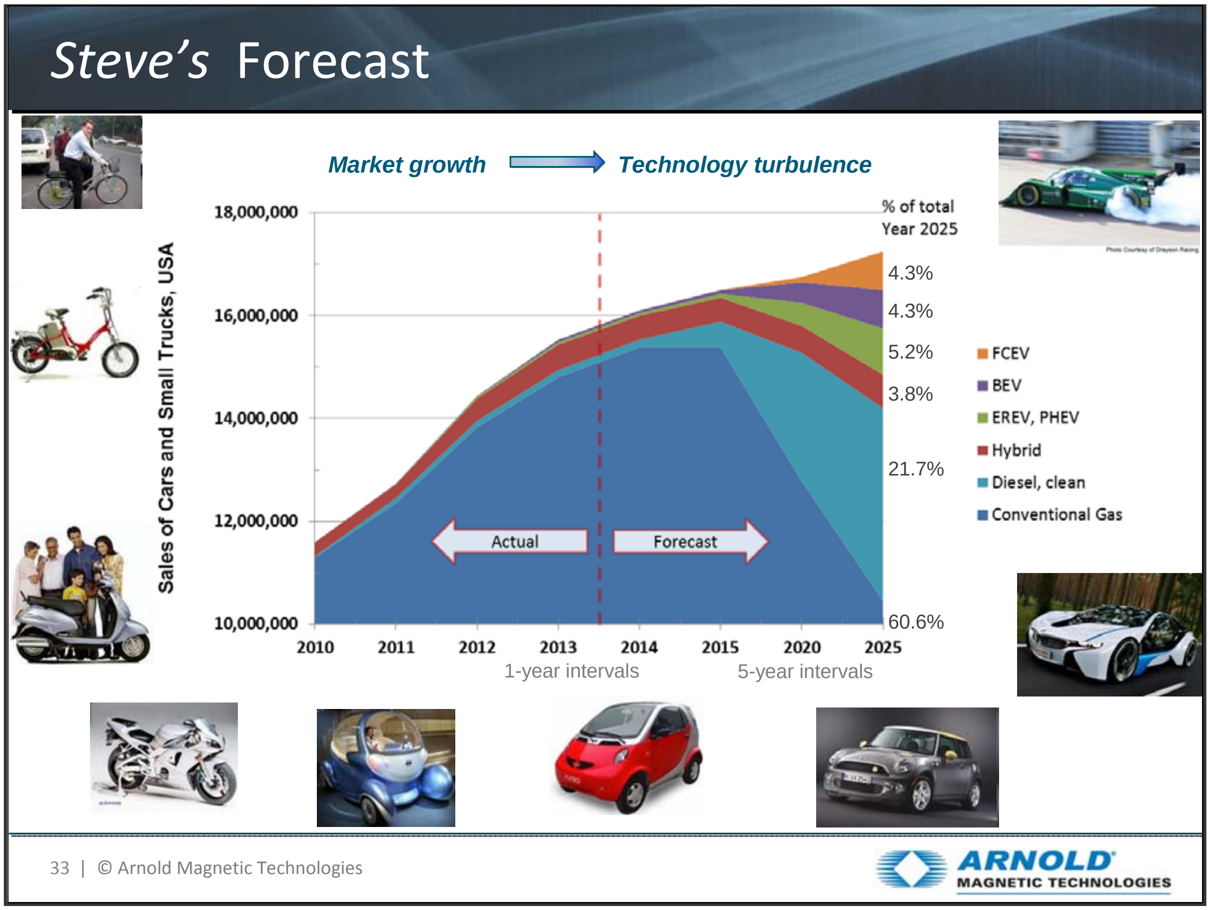
- We are, of course, talking of the transportation industry.
- It is tempting to focus on rare earth magnets such as NdFeB for use in automotive motors.
- However, many vehicular systems still rely on ferrite magnets as they are less expensive, adequately strong, and naturally corrosion resistant, including to road salt.
- This illustration from Hitachi provides applications and likely magnet type(s) with green representing ferrite and tan representing rare earth magnets, most of which are neodymium iron boron, although a few SmCo magnets are used (primarily in sensors).
- When a motor is mentioned, most of us will immediately think of a device that drives a spinning shaft, but there are linear motors as well, such as door-lock actuators and entertainment system speakers.
- Note the red arrow pointing to the traction drive motor…

Alternative Powertrain Types

		Examples
HEV	**Hybrid Electric Vehicle** Uses both an electric motor and an internal combustion engine to propel the vehicle.	Prius
PHEV	**Plug-In Hybrid Electric Vehicle (PHEV)** Plugs into the electric grid to charge battery - is similar to a pure hybrid and also utilizes an internal combustion engine.	Plug-in Prius
EREV	**Extended Range Electric Vehicle (EREV)** Operates as a battery electric vehicle for a certain number of miles and switches to an internal combustion engine when the battery is depleted.	Volt
BEV	**Battery Electric Vehicle BEV)** Powered exclusively by electricity from it's on-board battery, charged by plugging into the grid	Leaf; Tesla Model S
FCEV	**Fuel Cell (Electric) Vehicle (FCEV)** Converts the chemical energy from a fuel, such as hydrogen, into electricity.	Honda FCX Clarity; Hyundai Tuscon

- There are many “alternative drive” types.
- This list shows most of them including one or more examples of each that are in production.
- Some use permanent magnet motors such as the Prius and Nissan Leaf, while some use induction motors such as the Tesla Model S.



- In response to other overly optimistic forecasts, over the last few months data and opinions have been sought regarding the development of the transportation industry.
- This chart is my humble attempt to show a consensus of the development of alternate drive systems by type. It should be taken only as directionally accurate.
- One reason why ICE (internal combustion engine) including clean diesel will remain the primary source of tractive power is the technological advances being made with those technologies to provide ever more efficient drive systems at modest price increases and while using the existing fuel distribution infrastructure.
- Expansion in use of any type drive depends upon a range of factors including economic, political, and technical.

N.B.: the scale at the bottom is by year to 2015 and then by 5-year increments.

Summary

- Material Prices fluctuate – select the best material for the job
  - We need to select materials for their advantages rather than avoid them due to temporary changes in pricing
- Markets that use rare earth magnets are highly dynamic
  - New demands and new technologies are driving changes, sometimes very quickly
- We need to manage the supply chain
  - R&D into new permanent magnets has yet to produce substitutes for Neo or SmCo magnets
  - Market elasticity: Where alternative technologies exist and are value-competitive, they will be used

It's a question of balance

- Production, transmission and use of electrical energy is dependent upon both soft and permanent magnet materials.
- Commodity pricing variability is a "fact of life". We must learn to manage supply and price issues, not run from them. Magnetic materials should be selected based on optimal performance over the expected life of the product.
- Pricing is largely a result of supply-demand imbalance. If either changes too quickly to permit the other to adjust, price-swings will occur.
- At any price level, the user community will select the device that offers the best value.
- We are all hoping for a wonderful new permanent magnet material that will be made from abundant and cheap raw materials and have strong output over a wide temperature range. Key word is "**hope**".
- R&D is a lengthy process (10 years+ from invention to large-scale commercial production). While we are awaiting the next material's arrival, we must also work on optimizing use of the materials we have.

Thank you!