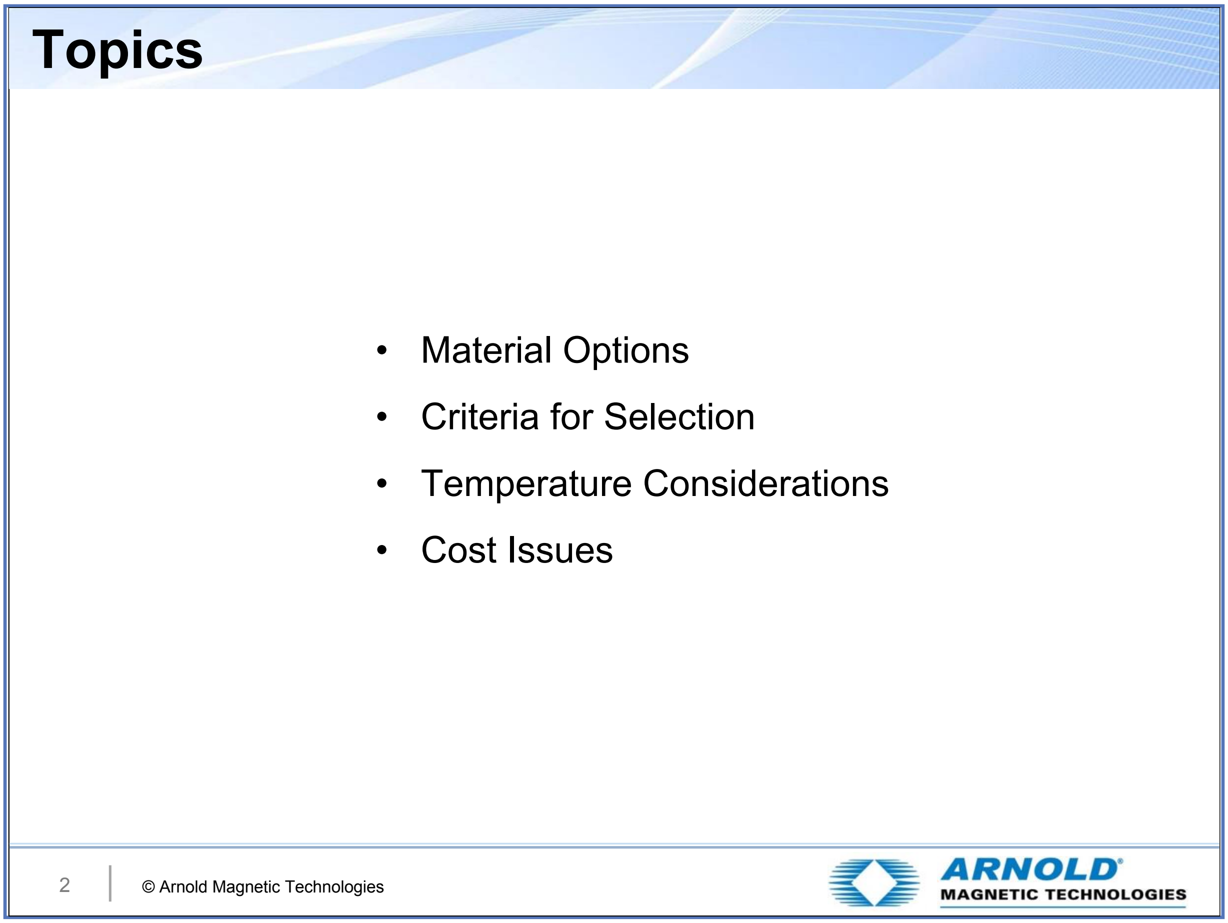
- Today we'll cover several magnetic material characteristics that strongly influence the decision on which material is best-suited for a specific application.



- Key to making that decision is knowing:
- What materials are commercially available
- Which issues are important in considering the various materials. This requires the design engineer and purchasing personnel to understand the requirements of their application.
- Magnetic output changes with temperature. At the extremes, temperature can cause device failure when the wrong material is selected.
- Assuming all else is satisfactory, a design that utilizes a cost-effective magnet is more likely to be successful in the competitive World Market.

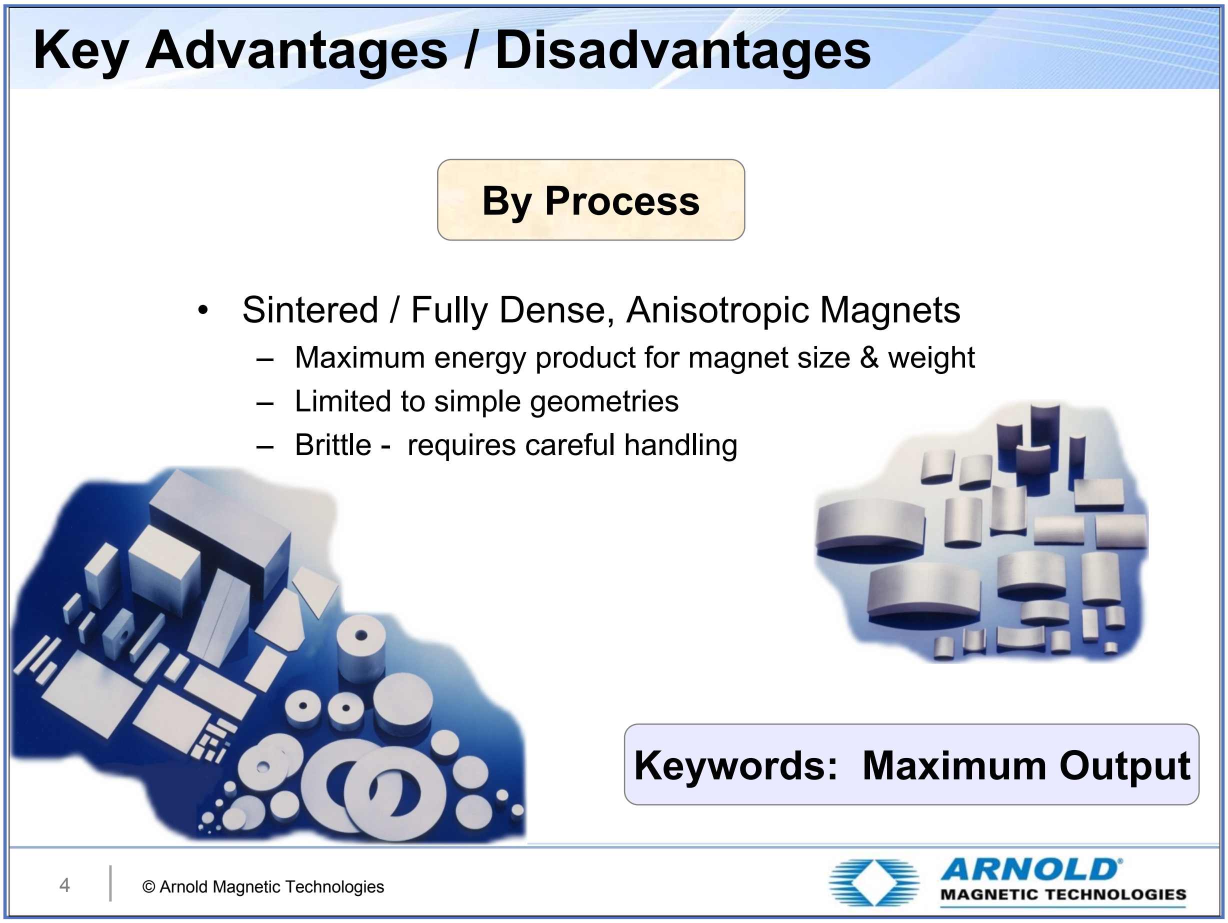
Material Options

Commercially Available Permanent Magnet Materials

○ = Selected for Discussions

				BONDED				
MATERIAL	CAST	EXTRUDED OR ROLLED	SINTERED FULLY DENSE	INJECTION MOLDED	COMPRESSION BONDED	FLEXIBLE	RIGID EXTRUDED
ALNICO	Y		Y	Y			
IRON-CHROME-COBALT	Y	Y					
CuNiFe		Y					
SmCo			(Y)	(Y)	Y		
NdFeB			(Y)	(Y)	(Y)	Y	Y
FERRITE			(Y)	(Y)		Y	
HYBRIDS				Y	Y	Y	

- This chart concisely shows the commercially available permanent magnet materials.
- We will focus today on SmCo, NdFeB and Ferrite. These represent about 85% of all permanent magnets sold on a cost basis.
- Ferrite magnets are extensively used in applications requiring a flexible magnet. On a tonnage basis, these are primarily used for sound-deadening and gasketing applications. Our interest today is in motor and actuator devices which benefit from the unique properties associated with fully dense or rigid bonded magnets.



- Reviewing the Key Advantages and Disadvantages of each of the products as defined by the manufacturing process, we find that fully dense (sintered) permanent magnets offer the highest magnetic output.

- Fully dense means there is no dilution effect from a non-magnetic phase.

- The highest output is available from NdFeB. However, as we will see later, other application requirements, such as elevated temperature, may suggest using the slightly less powerful SmCo magnets.

Key Advantages / Disadvantages

By Process

- Injection Molded
  - Complex geometries
  - Tight geometric tolerancing without finishing operations
  - Relatively “tough” (resistant to chippage)
  - Insert and over molding to reduce assembly costs
  - Variety of pole configurations are possible
  - Multistep and multicomponent molding to produce assemblies
  - Dilution of magnetic phase produces lower energy product
  - Aniso- and isotropic powders provide a wide range of magnetic alignment and output options
  - Relatively high tooling costs make these well-suited to high volume manufacturing

Keywords: Shape Flexibility

- Injection molded products suffer from the greatest magnetic dilution effect.
- However, their shape and magnetic pole configuration possibilities often make them the most desirable choice.
- Tight tolerances are a result of molding to die dimensions - - secondary finishing operations are almost never required.
- Furthermore, assembly can be simplified through the use of insert-, over-, or multi-component injection molding.

Key Advantages / Disadvantages

By Process

- Compression Bonded
  - Higher loading than injection molded, but lower than fully dense creates a compromise in energy product
  - Limited to simple geometries: rectangles, cylinders, arcs
  - Tight geometric tolerancing except in pressed thickness
  - Brittle - requires careful handling
  - Isotropic powder allows complex magnetizing patterns

Keywords: Low Cost Manufacturing

- Compression bonded magnets represent a compromise of sorts between fully dense and injection molded magnets. The volumetric loading of magnetic phase is greater than injection molded magnets, but not as high as sintered, fully dense magnets.

- Shape is limited to simple cross-sections such as cylinders, rectangles and other shapes that can be pushed out of a die cavity.

- Perhaps the greatest advantage is that thin wall cylinder magnets can be economically manufactured using compression bonding. Thin wall rings or cylinders are possible, but often not practical with the sintering process due to warpage during sintering and breakage during finish grinding.

- Except in the pressing direction which varies with die fill and press set-up, dimensions are very tight, conforming to the tooling dimensions of the die.

Key Advantages / Disadvantages

By Magnet Material

- Neodymium-Iron-Boron
  - Relatively abundant resource with large proven reserves
  - Refining costs are moderate to low
  - Manufacturing technology is now well-established (some companies still improving)
  - Highest output of all commercially available PM materials
  - High temperature applications require a compromise in energy product
  - Tendency to corrode requires protective coatings
  - China now the dominant manufacturer/supplier of NdFeB magnets:
    - Must buy only from licensed manufacturers - - be sure of your source
    - Quality and supply logistics issues
    - Low selling price

Keywords: High Energy

- Considering our choices by material, NdFeB represents the highest magnetic output material up to about ~150 degrees centigrade.
- It is limited to use to above about 135 K (-138ºC), due to a change in magnetic alignment at that temperature. But from 135 K to about 150 centigrade, it provides excellent output.
- An analog of NdFeB, PrFeB, can be used below 135 K.
- One concern with NdFeB is corrosion. It is imperative to obtain material from a quality manufacturer and specify coatings that mitigate risk in the application.
- Basic patents for compositions and manufacturing techniques are held, in all the free-world, primarily by two companies: Hitachi (previously by Sumitomo) and Magnequench. When purchasing NdFeB, it is imperative to positively ascertain that the source is licensed to manufacture and export these products.

Key Advantages / Disadvantages

By Magnet Material

- Samarium Cobalt
  - Relatively abundant resource with large proven reserves
  - Manufacturing technology is well-established; 2-17 grades now predominate
  - Second only to NdFeB in magnetic output
  - Excellent high temperature performance with grades available for use to 550ºC
  - Corrosion resistance superior to NdFeB, but coatings generally advisable
  - Capable Western sources are available in addition to Chinese Vendors
  - Refining costs are higher than for NdFeB

Keywords: Stable

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- Samarium Cobalt was the first widely used rare earth permanent magnet type, starting with the 1-5 composition in the late ’60s and switching mostly to the 2-17 type in the 1970s.

- When rare earth ore is mined, all the rare earths become available in the refining process, including Cerium, lanthanum, misch metal (a combination of rare earths), Praseodymium, Neodymium, Dysprosium and Samarium. As NdFeB usage goes up, more Samarium is also mined and available for magnet production.

- The biggest advantage of SmCo over NdFeB is that of high temperature capability coupled with temperature stability.

Key Advantages / Disadvantages

By Magnet Material

- Ferrite (Ceramic)
  - Abundant, low cost raw material
  - Magnets are lowest cost option
  - Manufacturing technology is well-established
  - Lower magnetic output than the rare earth materials
  - Excellent high temperature performance with grades available for use to 250ºC
  - Limited low temperature performance (generally to –40ºC)
  - Corrosion resistance is outstanding
  - China is the world's largest manufacturer and supplier of ferrite magnets

Keywords: Low Cost

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- Ferrite is the Rodney Dangerfield of permanent magnets. We use it in vast quantities and treat it (without respect) like the "rust" it is - - special rust to be sure, but…

- Developed in the late 1950s and first commercially available in the USA in 1961, it is still used in greater quantity by weight than any of the other materials, primarily due to its realtively low cost.

Criteria for Selection

- Environment
  - Temperature of the application
  - Materials to which exposed: acids, salts, hydrogen, etc.
- Device Size / Weight
- Magnet Size & Shape
- Integration of Magnet in the Device
  - Attachment method
  - Encapsulation or protective coating(s)
- Cost (Magnet & Total System)

Marked items to be discussed in detail

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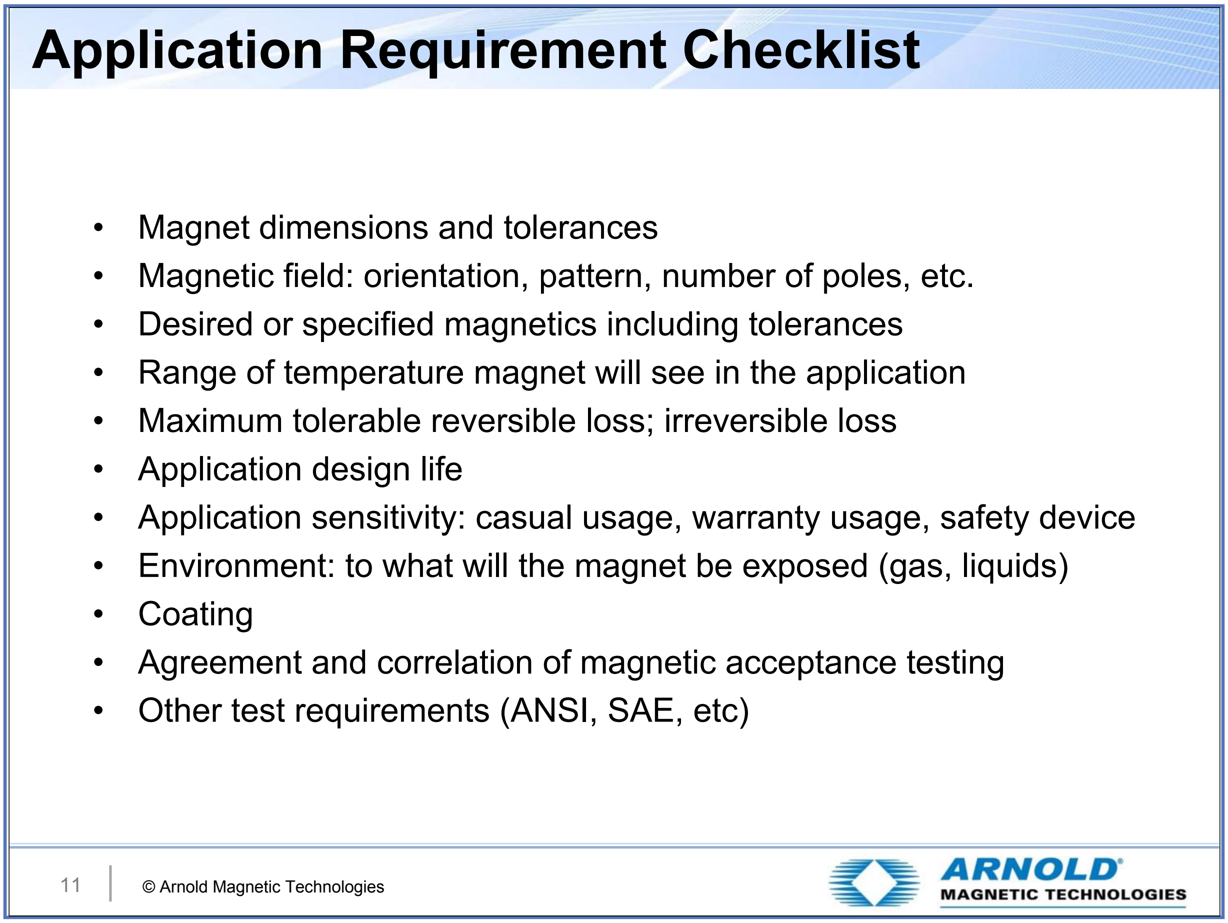
- How does an engineer start the process of selecting a magnet?

- Most start by ruling out magnets that cannot be used due to one or another limitation such as temperature, magnetic output or material cost.

- Magnetic output, temperature capability and cost are probably the predominant selection criteria. Device size and weight are also used in the final decision.

- We will see later in this talk that magnet material, size/weight and system cost are all interrelated.



- Before we launch into a discussion on the three highlighted items from the last slide, it is appropriate to focus on a problem endemic in the industry: underspecifying the magnet.

- The design engineer, purchasing personnel and manufacturer /supplier must agree to a specification that includes everything necessary to ensure proper device function over the design life.

- The list above should be considered as the bare minimum and can serve to initiate dialogue and agreement among producer and user.

Temperature Considerations

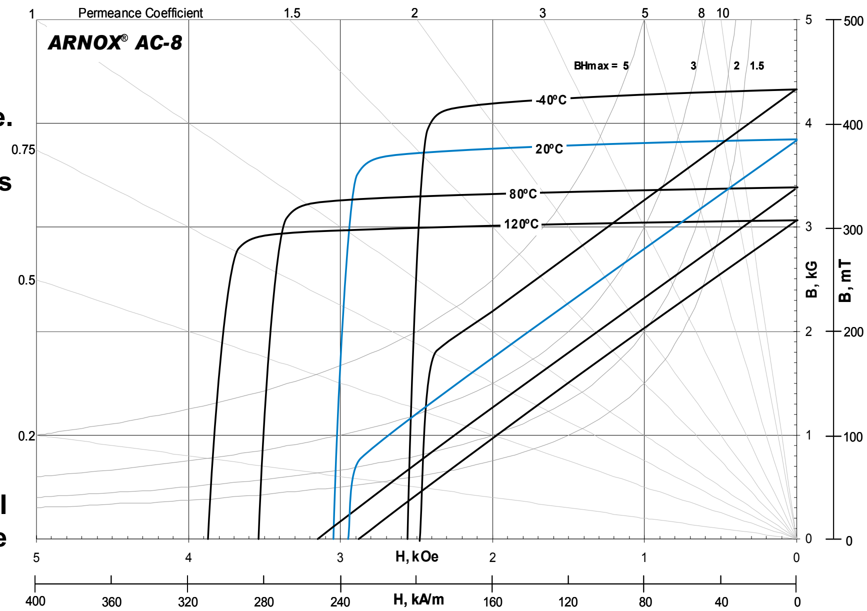
Reversible Temperature Coefficients

A common Ferrite grade is shown in this example.

Magnetic output changes as a function of temperature.

Both flux output and resistance to demagnetization are affected.

Material grades must be selected to have minimal irreversible loss over the application temperature range.



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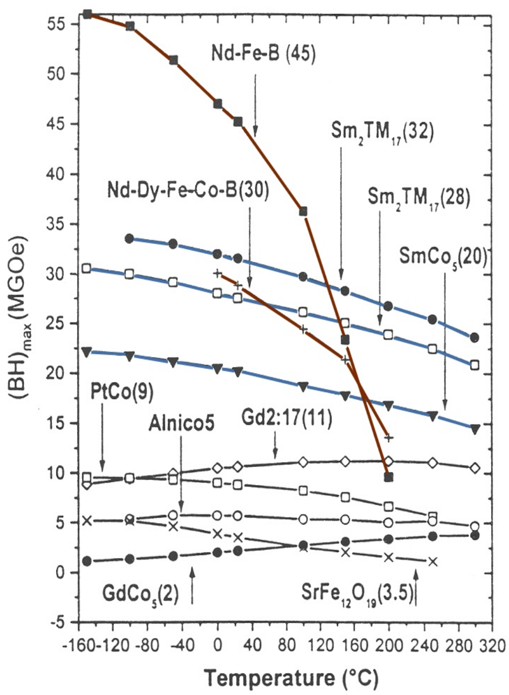
- Most of you are probably familiar with reversible temperature coefficients - - the amount the magnetic output changes as a function of temperature. There are two coefficients: one for Br (induction) and one for Hci (intrinsic coercivity).
- I show ferrite here because, unlike rare earths magnets, ferrite (intrinsic) coercivity increases as temperature increases. Conversely, as temperature drops, coercivity becomes less. Where rare earth magnets have a practical upper temperature limit, ferrite has a lower use limit. A practical lower use temperature limit is –40 degrees centigrade. Below –40, there is substantial risk of demagnetization.
- Changes in Br (induction) are greater than with NdFeB or SmCo. For that reason, ferrite is seldom used in sensor applications. However, it is widely used in motors.
- In the range 0 to 135 K (-138ºC), SmCo is the material of choice with PrFeB being an alternate. Between 135 K and 150ºC, NdFeB is preferred. Over 180º and up to 350ºC standard grades of SmCo provide the best performance. Above 350ºC and up to 550ºC, high temperature grades of SmCo are available.
- Alnico magnets can be used from near 0 K up to 550 °C but have far lower resistance to demagnetization.
- Between –40 and 180ºC, we have other trade-offs that dictate which of the three materials is best.
- Bonded magnets are generally limited to the range of –40 to 180ºC.

Temperature Considerations

BHmax vs Temperature



Between –138ºC (135 K) and 150ºC, NdFeB outperforms SmCo for flux output. Above ~150ºC NdFeB suffers sufficient loss in induction that SmCo is superior.

Where induction must be stable over a wide temperature range, SmCo is superior.

(Numbers in parens are the room temperature BHmax)

Graph is: Summary of magnetic properties for most commercial permanent magnetic materials at –160ºC to 300ºC.

Graph is by Chen, et al
Electron Energy Corporation, 1999

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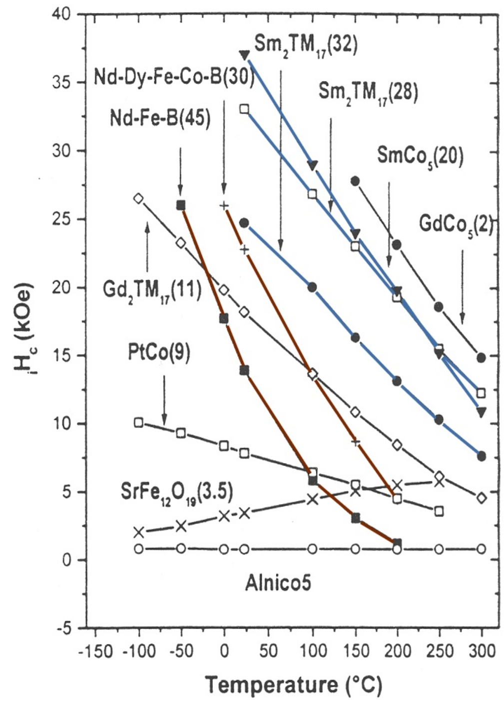
- This chart, from a poster presentation in 1999 by Christina Chen of EEC, dramatically shows the change in energy product (BHmax) as a function of temperature. Because SmCo is more temperature stable than NdFeB, NdFeB drops below the output of SmCo, by ~150ºC.

- Indeed, the higher temperature grade of NdFeB is no stronger than SmCo - even for some grades at room temperature.

Temperature Considerations

Hci vs Temperature



Resistance to demagnetization in SmCo is also superior to NdFeB, especially at elevated temperatures.

(Numbers in parens are the room temperature BHmax)

Graph is: Summary of magnetic properties for most commercial permanent magnetic materials at –160ºC to 300ºC.

Graph is by Chen, et al
Electron Energy Corporation, 1999

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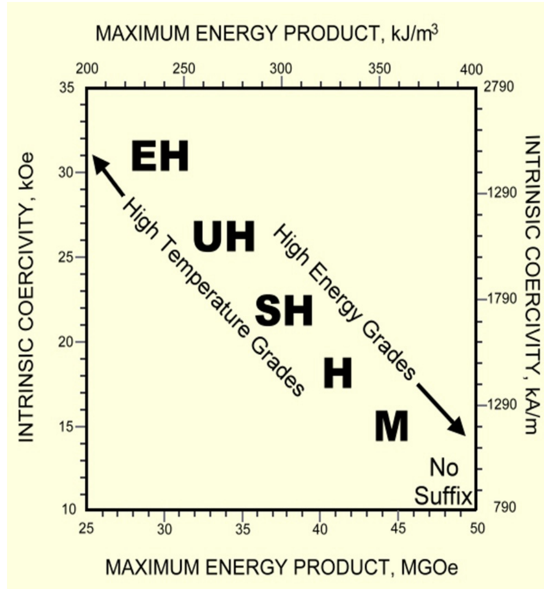
- In this chart, from the same poster presentation, we see the profound affect of temperature on (intrinsic) coercivity.
- Thus, where the magnet is subjected to high temperatures, especially where demagnetizing stress is expected, SmCo is likely to be preferred or required.

NdFeB Grade Designation

- In addition to MMPA and IEC grade designations, we now have Chinese NdFeB grades as denoted by:
  - A number representing the energy product in MGOe
  - A suffix indicating the Hci (or Hcj - - intrinsic coercivity)
- Since almost all NdFeB is now supplied from China and the designations are descriptive and easy to use, it makes sense to apply them



- Grade designations are shown on the plot at the approximate location to denote representative Br and Hci. Note the compromise between intrinsic coercivity and Maximum Energy Product.

- The maximum recommended use temperature follows with coercivity:
- No suffix - - 80ºC maximum
- **M** - - 100º
- **H** - - 120º
- **SH** - - 150º
- **UH** - - 180º
- **EH** - - 200º
- **AH** - - 220 to 230°

- Just because a magnet "can" be used at this high a temperature, does not mean it will function well in the application. Other considerations include operating slope (or load line) and demagnetizing stress.

- Minimizing irreversible loss also requires a true "square loop" - - not one with a drooping intrinsic curve.

Market Changes

- Manufacturing base shifting to China
- Dramatic price reductions have been experienced, especially in Rare Earth permanent magnets
- Industry Consolidation
  - Ferrite manufacturers cease operations: General Magnetic, Sumitoc, Crumax, Arnold
  - NdFeB manufacturers cease US operations: Magnequench (Anderson), Magnequench (Ugimag), VAC USA (Elizabethtown)
  - Hitachi-Sumitomo joint operations

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- We mentioned that almost all NdFeB is today coming from China.
- China produces 75% of the world's rare earth magnets
- Manufacturing costs are substantially lower than that of the Japan, North America and Europe

- Prices have been driven down to-date not because Chinese manufacturers are competing with US or European companies, but because the Chinese manufacturers are competing against each other for the Western market.

- This has forced major changes in the supply of magnets and magnetic assemblies.

- But difficulties remain in sourcing from the Far East that are best served by companies experienced in trading with China.

Permanent Magnet Imports into the USA
"Other than of Metal"

U.S. International Trade Commission - - 2003 Tariff Database

Sorted in Descending Value for 2002 Imports

8505.1900 Permanent Magnets other than of metal (Ferrite)

Source	1998	1999	2000	2001	2002		2003		Percent change YTD2002-YTD2003
	--thousand dollars--					Percent of total	January-June --thousand dollars--		
All sources	$82,745	$87,097	$83,721	$78,810	$83,308	100.0%	$40,904	$43,342	6.0%
China	$29,089	$32,478	$31,913	$28,445	$31,130	37.4%	$14,443	$18,027	24.8%
Mexico	$10,366	$12,311	$11,001	$10,938	$11,282	13.5%	$5,795	$4,575	-21.1%
Japan	$17,977	$18,931	$16,088	$9,717	$9,569	11.5%	$5,060	$5,672	12.1%
Dominican Republic	$0	$0	$1,551	$9,175	$7,424	8.9%	$3,671	$5,155	40.4%
Korea, Republic of	$4,840	$5,097	$4,322	$3,783	$6,148	7.4%	$2,774	$2,939	5.9%
Canada	$5,847	$4,766	$3,626	$2,132	$3,708	4.5%	$1,362	$1,576	15.8%
Taiwan	$3,305	$3,079	$3,751	$2,967	$2,977	3.6%	$1,750	$1,091	-37.7%
United Kingdom	$1,490	$1,258	$1,258	$1,394	$2,152	2.6%	$1,091	$763	-30.1%
Hong Kong	$1,221	$663	$2,352	$3,135	$2,037	2.4%	$1,051	$790	-24.9%
Germany	$1,720	$1,570	$1,195	$1,835	$1,533	1.8%	$756	$987	30.6%
Indonesia	$645	$1,488	$1,131	$1,178	$1,324	1.6%	$871	$466	-46.5%
France	$1,250	$259	$603	$1,171	$1,323	1.6%	$889	$351	-60.5%

Countries from which $1 million or more was imported.

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- The US International Trade Commission has maintained information on imports of two categories of permanent magnets (into the US):
  - Magnets made from metal (8505.1100) such as Alnico, SmCo and NdFeB
  - Magnets made Other than of Metal (8505.1900) such as ferrite
- Note that the Dominican Republic and Canada are not manufacturing ferrite magnets, but are acting as a pass-through into the US marketplace, possibly to avoid tariffs.
- China is by far, the largest foreign source of ferrite magnets, especially when the pass-through amounts are considered.

N.B.: c.2006 the ITC ceased to track imports of magnets other than of metal.

Permanent Magnet Imports into the USA
“Magnets of Metal”

U.S. International Trade Commission - - 2003 Tariff Database

Sorted in Descending Value for 2002 Imports

8505.1100 Permanent Magnets of metal (Rare Earths, Alnico)

Source	1998	1999	2000	2001	2002			2003	Percent change YTD2002-YTD2003
	--thousand dollars--					Percent of total	January-June --thousand dollars--		
All sources	$95,353	$105,350	$116,680	$94,318	$182,608	100.0%	$60,597	$79,939	31.9%
Mexico	$1,693	$1,075	$1,702	$952	$86,841	47.6%	$17,464	$26,779	53.3%
Japan	$25,413	$30,499	$44,130	$30,289	$30,930	16.9%	$12,863	$18,193	41.4%
China	$25,713	$31,732	$28,002	$31,229	$30,753	16.8%	$14,425	$19,467	35.0%
United Kingdom	$13,952	$14,984	$16,161	$10,433	$10,656	5.8%	$5,082	$4,560	-10.3%
Germany	$8,087	$10,014	$11,217	$6,459	$10,484	5.7%	$4,347	$4,585	5.5%
Taiwan	$3,024	$3,919	$3,777	$3,070	$3,005	1.6%	$1,353	$1,652	22.1%
Korea, Republic of	$659	$779	$2,070	$1,814	$2,001	1.1%	$863	$987	14.4%
Switzerland	$3,509	$3,529	$3,041	$2,180	$1,879	1.0%	$826	$905	9.6%

Countries from which $1 million or more was imported.

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- This table shows the dramatic increase of importation of permanent magnets, especially NdFeB, rising from $95 million in 1998 to $182 million in 2002.

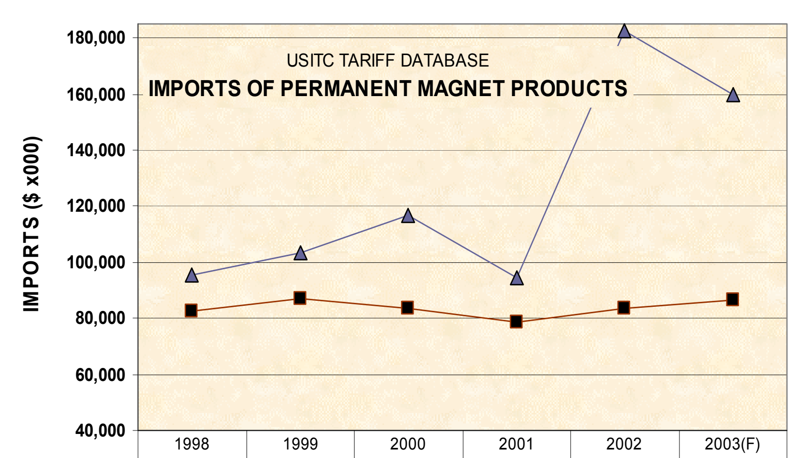
- The total for 2003 appears as though it may be considerably lower. Is that because the assemblies containing magnets are now made overseas?

- As in the previous slide, we see significant imports from Mexico, Japan and China. Since there is no manufacture of NdFeB in Mexico outside of Magnequench, one presumes most of this is a pass-through from China.

N.B.: Metal magnets include FeCrCo, Fe-Ni and numerous other materials. However, the permanent magnet alloys of NdFeB, SmCo and Alnico represent the great majority of imported magnetic materials.

Dollar totals are the sum of claimed import values, not expected sales values.

Challenge: Magnet Price Instability



	1998	1999	2000	2001	2002	2003(F)
Ferrite	82,745	87,097	83,721	78,810	83,308	86,684
RE & Alnico	95,353	103,350	116,680	94,318	182,608	159,878

- Changes in the manufacturing base, raw material costs and location of manufacture have brought dramatic reductions in prices of magnets, especially rare earth magnets
- Increasing importation of magnets from China, directly or through third party countries, is largely responsible for price reductions

The fine print: Data from the USITC. Dollar values for imports are claimed values by importers. Categories are not “pure”. That is “Permanent Magnets made from Metal” includes alnico, SmCo and NdFeB. “Permanent Magnets made from other than metal” includes ferrite, whether sintered or bonded. Actual weight of imports has gone up faster as declared values have generally trended down.

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- In summary, on a dollar basis, ferrite imports have remained flat while metal magnets have risen dramatically.
- Selling prices have fallen for all permanent magnet types suggestinga greater importation on a weight basis.
- Lastly, there is an apparent drop-off in 2003 in importation of metal magnets, possibly due to increased overseas assembly.

Comparisons
Magnet and System Costs and Weight

- A spreadsheet model has been created
  - Allows rapid comparisons of magnetic materials in a “motor type” magnetic circuit (small air gap and soft magnetic return path)
- Considerations include
  - Magnet & return path magnetic properties and costs
  - Air gap length (0.040”, 1 mm used in this comparison)
  - Circuit Reluctance
  - Leakage flux
  - Provides comparisons at selected temperatures

- We have seen how pricing and importation (sourcing) is changing rapidly. It is necessary for the design engineer to be able to respond quickly in selection of the most suitable permanent magnet.
- We all recognize how important reducing manufacturing cost is to the success of a design.
- Therefore, we have developed a spreadsheet model to assist in magnet selection. The model includes a small air gap and metal return path similar to what might be found in motors and some solenoid actuators.

Comparisons
Magnet and System Costs and Weight

Calculated at: 23ºC Material	BHmax MGOe (23ºC)	Magnet Material	Relative Cost of Magnet In System	Total System	Relative System Weight
NdFeB 38SH (Sintered)	37.8	20	2.7	1.0	1.0
Ferrite (Sintered)	3.9	1	1.0	1.1	1.5
SmCo 28 (Sintered)	28.8	28	5.5	1.3	1.0
NdFeB (Inj molded)	6.4	23	13.7	2.2	1.3
Ferrite (Inj molded)	1.9	2	3.6	1.5	1.9
SmCo (Inj molded)	9.2	33	13.3	2.2	1.2
NdFeB (Comp bonded)	10.5	23	9.1	1.7	1.2

Disclaimer: Calculations are based on typical magnet prices as of September 2003. Actual comparisons may differ based upon changes in raw magnet pricing, grade of magnet material, non-standard lamination steel, air gap other than as specified, configuration of magnet(s) and return path, etc.

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- The calculations have resulted in the above relative costs and weights with calculations made at 23ºC. Minor shifts are seen to 150ºC. Above 150, SmCo compares more closely with NdFeB.

- Any model has limitations and must be used wisely. Wherever there are questions a knowledgeable applications engineer should be consulted.

- Remember also, that this model is for simple geometry magnets. Where shape complexity occurs, it may be necessary to use a bonded magnet or one that is easier to magnetize in a complicated pattern, such as ferrite.

- In almost every case, one cannot simply substitute one material for another. Substitution requires a re-design.

- This model does not consider assembly costs. It does consider most of the required design changes associated with different materials. The model demonstrates, that for many applications, NdFeB is now fully price competitive with ferrite.

Summary

- There are many permanent magnet materials on which to base a design
- Each material has a mix of advantages & disadvantages that must be considered in the selection process
- Critical parameters include:
  - Application temperature range
  - Device size and weight constraints
  - System Cost
- Magnet sources and pricing have gone through a period of great change: 1998 to present
- Applications exist which benefit from characteristics of each material: temperature stability, corrosion resistance, resistance to demagnetization, molded shape complexity, etc.
- NdFeB has reached a price point where it is the material of choice except at very low (less than -138ºC, 135 K) and very high temperatures (>180ºC)

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- Selecting the best material requires the design engineer to consider a long list of trade-offs in magnetic output, design size, cost, design life, etc.

- This must be done knowledgeably and result in a thorough material specification.

- A company capapable of supplying the full range of products can often facilitate the material decision.

