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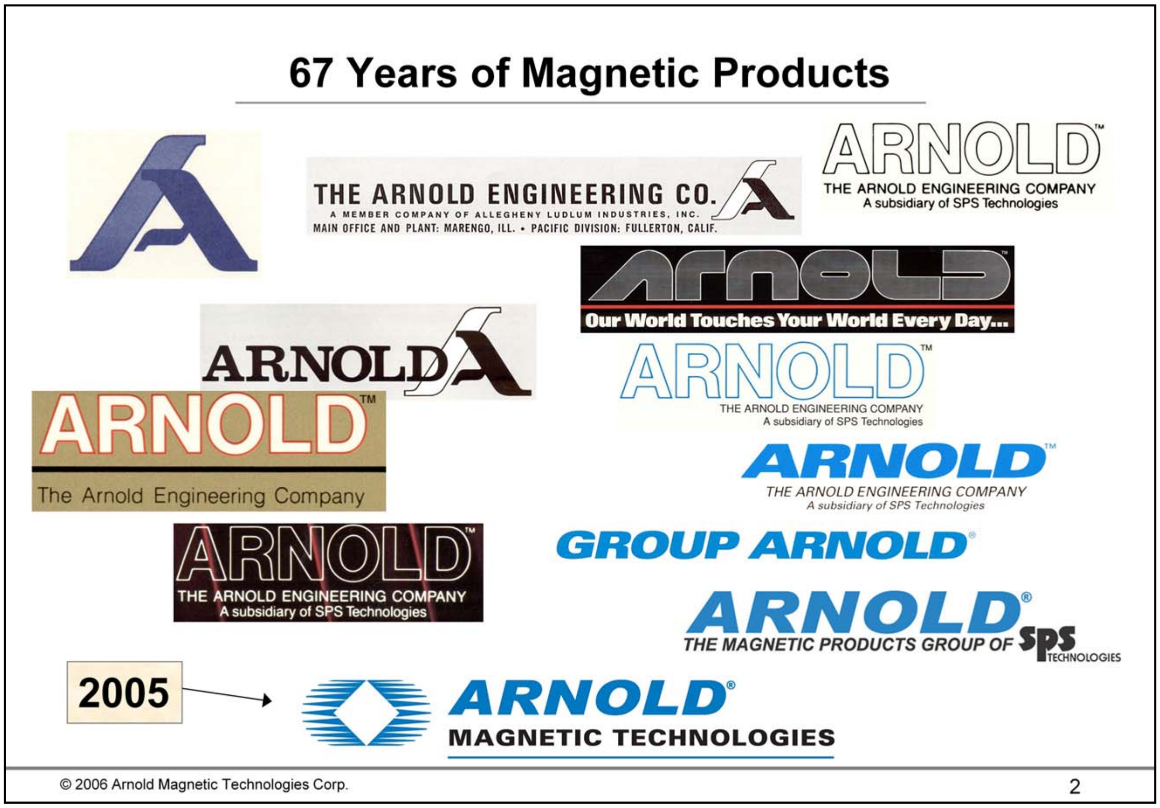
A Manufacturing and Performance Comparison
Between
Bonded and Sintered Permanent Magnets

Presented at **APEEM**
April 4, 2006
By Steve Constantinides



- First a quick update on who Arnold is…
- Our company is over 100 years old and has been making magnetic products since 1938.
- Originally called The Arnold Company, our name was changed to Arnold Magnetic Technologies Corporation in 2005 when we became a privately owned company.

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Commercially Available Permanent Magnets

	Manufacturing Process						
	METALLURGY and PM			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 and CuNiCo		Y					
SmCo			Y	Y	Y		
SmFeN				Y	Y		
NdFeB			Y	Y	Y	Y	Y
Ferrite			Y	Y		Y	
Hybrids				Y	Y	Y	

* SmCo: Available in both SmCo5 and Sm2Co17 grades
**Extruded Ferrite can be mechanically or magnetically oriented; numerous grades are available

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- These are the most common commercially available permanent magnetic materials and Arnold manufactures and supplies everything marked with a “Y” except: rigid extruded NdFeB and CuNiFe and CuNiCo.

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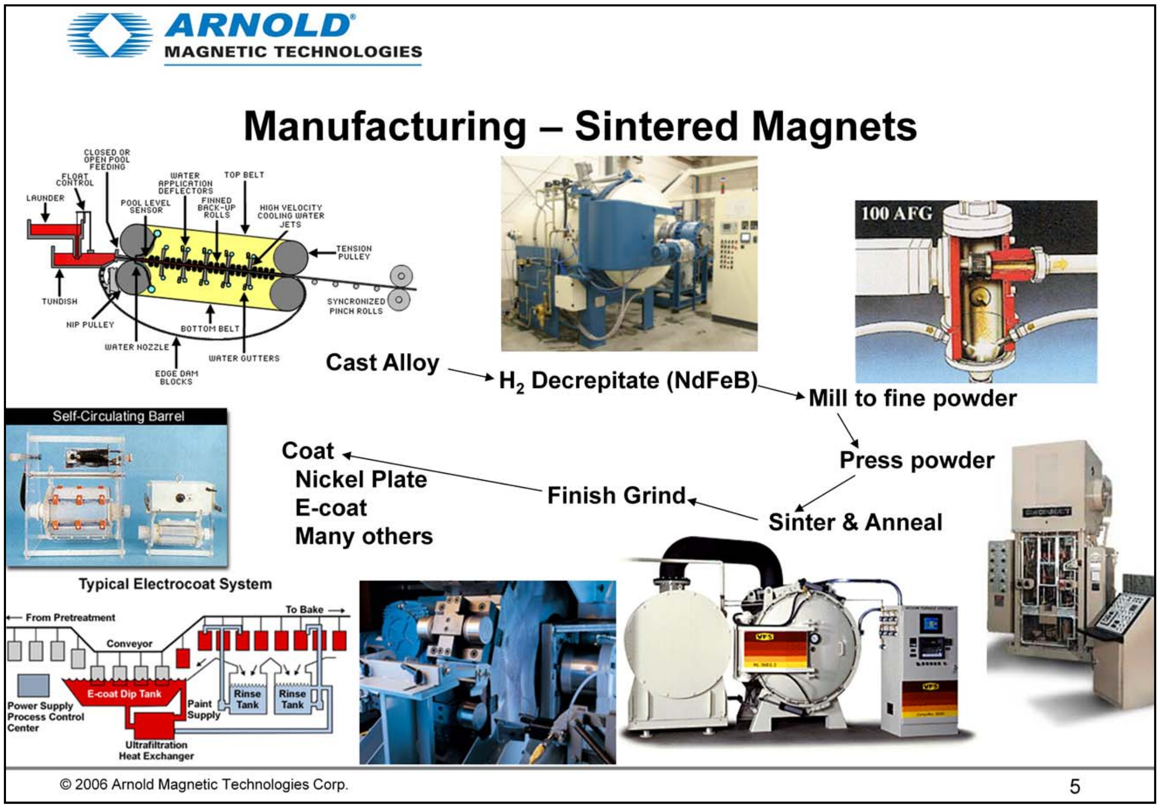
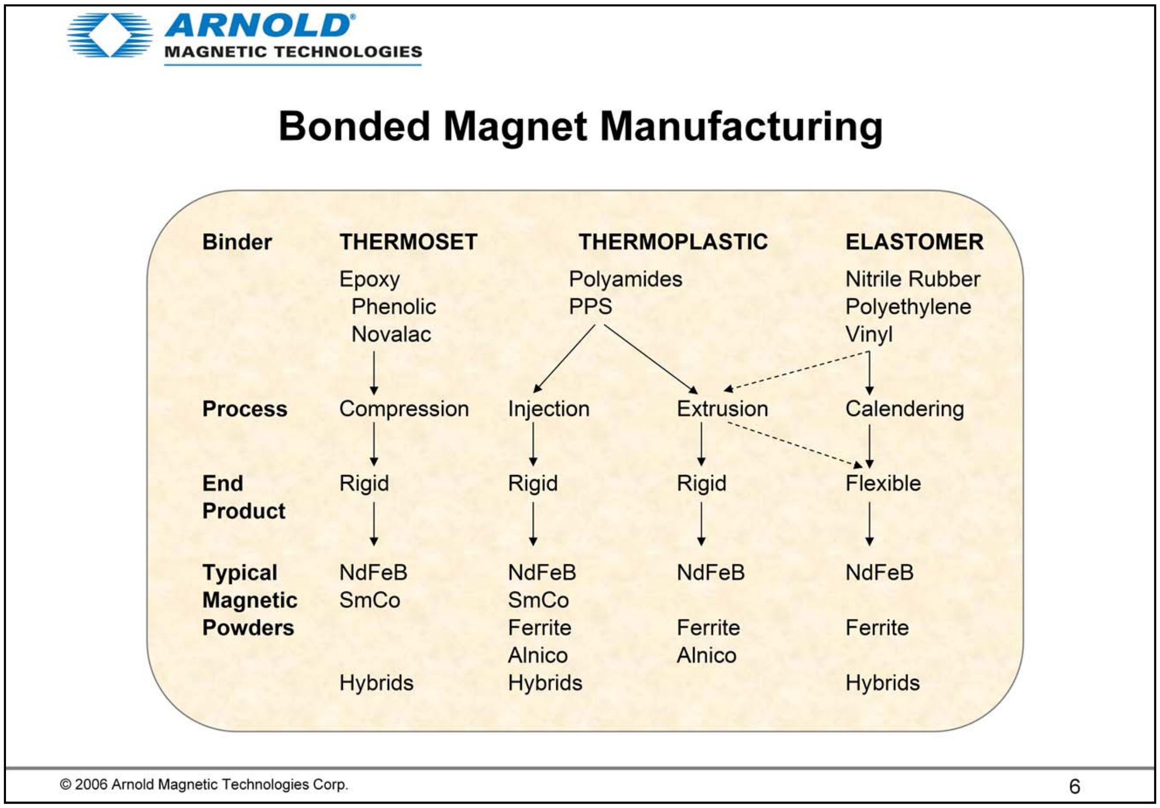
Topics

- ♦ Manufacturing Methods
- ♦ Key Magnetic Characteristics
- ♦ Magnetic Comparisons
- ♦ Corrosion & Chemical Compatibility
- ♦ Physical Configuration
- ♦ Cost Comparison

- Topics we will cover in comparing sintered and bonded magnet materials.



- Sintered NdFeB enjoys more sales on a $ basis than any other material. (Ferrite is still #1 on a tonnage basis).
- NdFeB (Neo) magnets are manufactured following the process of:
- Casting the alloy
- Hydrogen decrepitation (to make milling easier and more effective)
- Fine particle milling (2-3 microns in diameter)
- Compaction via hydraulic, mechanical or isostatic pressing
- Sintering and annealing
- Grinding and machining (poles and sometimes the perimeter of magnets)
- Coating (plating, e-coat, epoxy, etc.).



- Bonded magnets come in rigid or flexible form and may be manufactured by one of four methods shown here.
- Each process and final product benefits from certain characteristics of the raw material magnetic powder such that not all materials are suitable for all products. Ferrite, for example, is too fine to use effectively in a compression bonded magnet.
- Final product characteristics are a function of both the magnet powder and of the binder.

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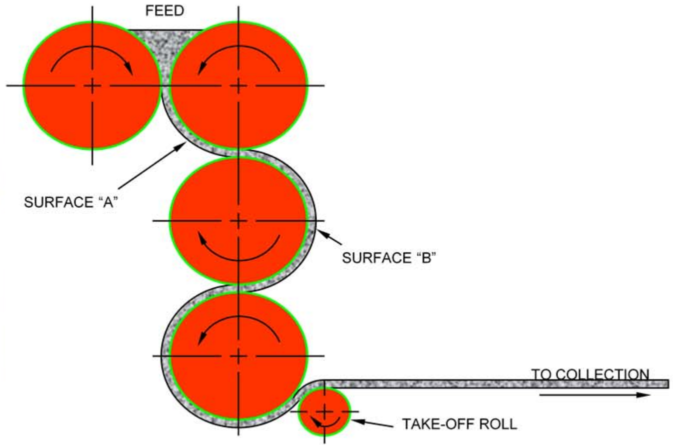
Bonded Manufacturing: Calendering

Automated Sheet Calendering System



- The calendering process utilizes highly loaded elastomeric compound to produce wide sheet.
- The magnetic powder is typically ferrite which is oriented mechanically during the calendering to produce anisotropy through the sheet thickness.
- This photo is the output from an automated calender system.

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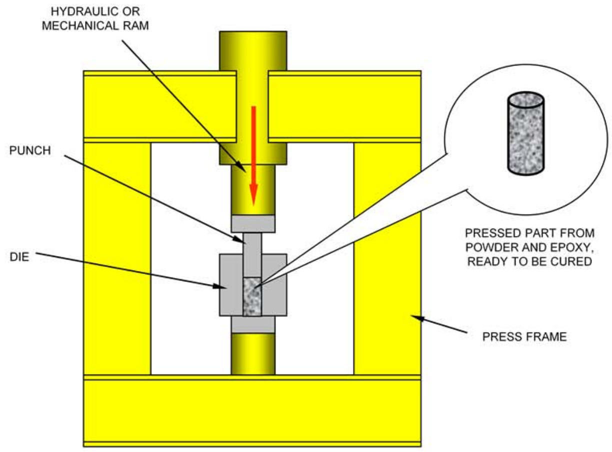
Bonded Manufacturing: Compression Bonded

High Volume Compaction Press



- Uniaxial pressing is used to manufacture compression (compaction) bonded magnets.
- The binder is usually a thermosetting phenolic epoxy.
- The magnetic material is normally neodymium-iron-boron, though SmCo can be used.
- It is rather straightforward to manufacture product of simple geometry
- Compression bonded magnets have higher loading than injection molded magnets, 79 versus 65 volume percent, resulting in higher BHmax.

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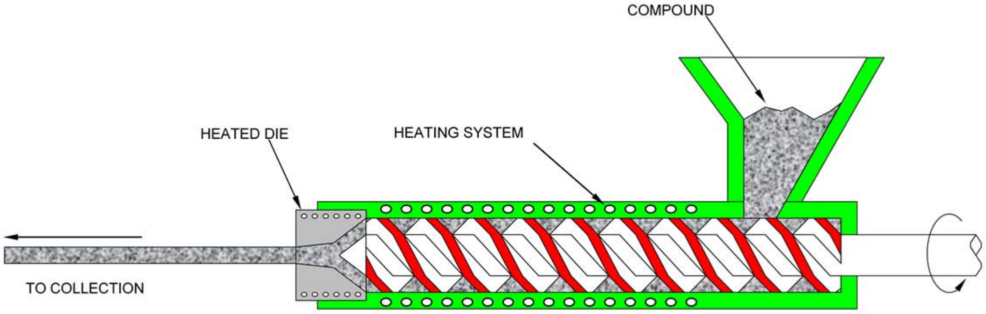
Bonded Manufacturing: Extrusion



Continuous feed Strip Extrusion Line

- Continuous extrusion of a highly loaded elastomeric or thermoplastic compound is used to produce continuous profiles of strip or sheet in a very efficient process.
- A strip extrusion process is shown.
- Although NdFeB can be used, the vast majority of product is manufactured using Ferrite powder.
- Ferrite magnet material is often magnetized as part of the continuous extrusion line.

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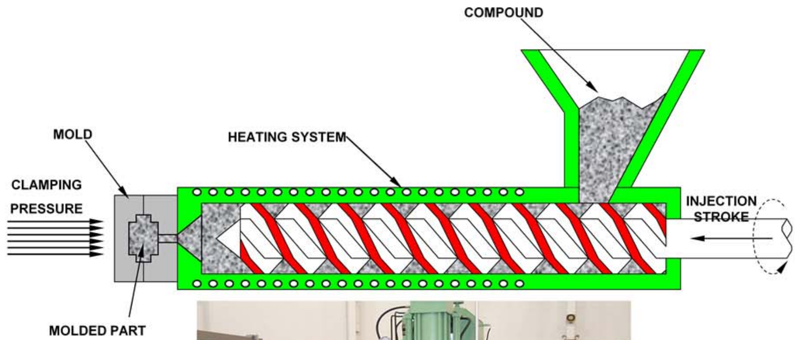
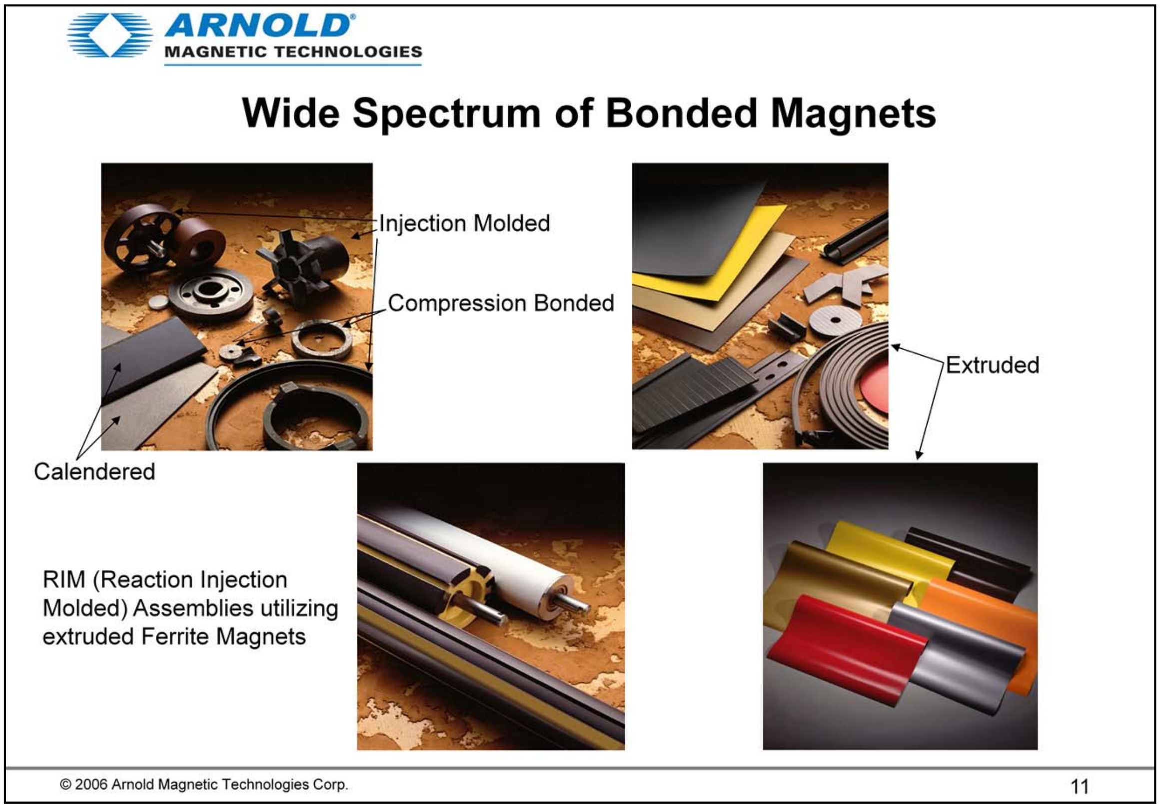
Bonded Manufacturing: Injection Molding



Fully Automated Rotary Injection Molding System

- Injection molding is accomplished by feeding highly loaded Thermoplastic compound into the injection mold.
- The molding may contain magnetic circuit(s) using either permanent magnets or an electromagnetic system to provide an orienting field.
- The process can produce very precise and complex-featured components.
- It has the ability to generate complex orientation patterns.
- Magnetization (during processing) and insert or over-mold capabilities for assemblies are all possible.
- A vertical rotary high volume molding system is shown here.



- This slide is intended to illustrate the diverse applications and markets bonded magnet products serve.
- Flexible sheet products are often laminated with a substrate to accept printed images. The major industry is the Ad Specialties and marketing/promotional market. A typical product is the refrigerator magnet for which magnetic properties are of secondary importance and where flatness, printability, and visuals are more important.
- Extruded magnets of various profiles are used in reprographic magnetic rolls or brushes which have a very stringent set of performance requirements.
- Injection molded magnets are highly engineered parts with tight specifications for magnetics, mechanicals and physicals. They usually require a high capability (Cpk) with tight tolerances and are often used in automotive applications requiring QS 9000 quality systems.

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Application Requirement Checklist

- Magnet dimensions and tolerances
- Magnetic field: orientation, pattern, number of poles, etc.
- Desired or specified magnetics including tolerances
- Range of temperature magnet will see in the application
- Maximum tolerable reversible loss; irreversible loss
- Application design life
- Application sensitivity: casual usage, warranty usage, safety device
- Environment: to what will the magnet be exposed (gas, liquids)
- Coating
- Agreement and correlation of magnetic acceptance testing
- Other test requirements (ASTM, ANSI, SAE, etc.)

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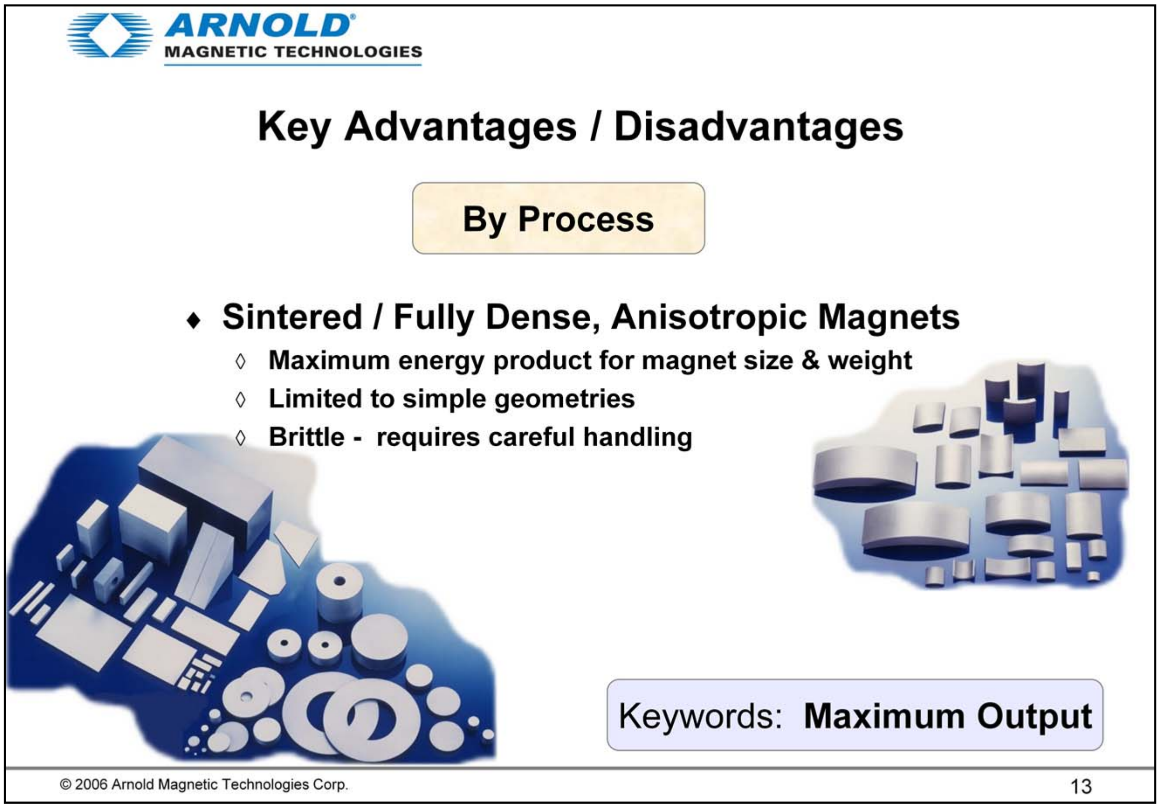
- Before we start our discussion of magnet selection, it is appropriate to focus on a problem endemic in the industry: under-specifying the magnet.
- It is essential for the design engineer, purchasing personnel and manufacturer /supplier to agree to a specification that includes everything necessary 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 all parties.



- 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 high temperatures, 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**

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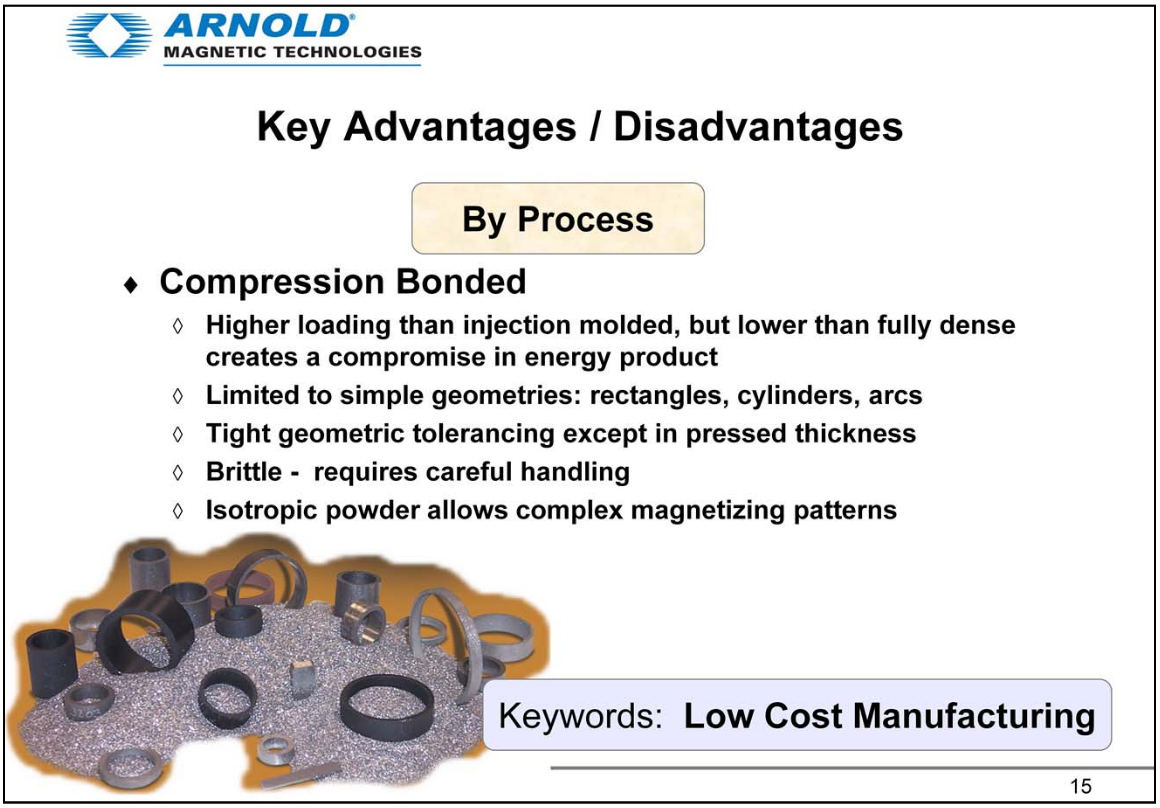
- Injection molded magnets suffer from the greatest dilution effect being 61 to 65% by volume magnetic powder.
- However, their potential for complex shape and magnetic pole configuration possibilities often make them the most desirable choice.
- Tight tolerances are a result of molding to die dimensions - - secondary finishing operations are almost never required.
- Furthermore, assembly can be simplified through the use of insert-, over-, or multi-component injection molding.



- 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 (79 versus 65%), but not as high as sintered, fully dense magnets (99.5%).
- Shape is limited to rather simple cross-sections with no improvement in shape complexity over sintered magnets – e.g., sintered magnets can be EDM'd.
- Perhaps the greatest advantage is that thin wall cylindrical magnets can be manufactured using compression bonding. Thin wall rings or cylinders are usually not practical with the sintering process due to warpage during sintering and breakage during grinding. (Die-upset, back flow magnets can be formed into radially oriented, fully dense hollow cylinders.)
- 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.

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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**

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Considering our choices by material, NdFeB represents the highest magnetic output material up to about 150 degrees centigrade.

It is limited to use above about 135 K, due to a change in magnetic alignment, spin re-orientation, below that temperature. But from 135 K to about 150 centigrade, it provides excellent output. (A variation, PrFeB, is usable to temperatures of a few degrees K.)

One concern with NdFeB is corrosion. It is imperative to obtain material from a quality manufacturer and specify coatings that reduce risk in the application.

Basic patents for compositions and manufacturing techniques are held in all the free-world by two companies: Neomax (Sumitomo) and AMR Technologies (Magnequench). When purchasing NdFeB, it is imperative to positively ascertain that the source is licensed to manufacture and export these products.

N.B.: as of 2014, the basic composition patents have expired. However, numerous processing patents are still claimed.

Sumitomo's magnet business was purchased by Hitachi between 2004 and 2005.

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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 early late ’60s and switching mostly to the 2-17 type between 1970 and 1990. (Platinum Cobalt pre-dates SmCo, but because of high cost, its usage was limited).
- 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 produced and available for magnet production.
- The biggest advantage of SmCo over NdFeB is that regarding temperature: high temperature capability and temperature stability.

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Key Advantages / Disadvantages

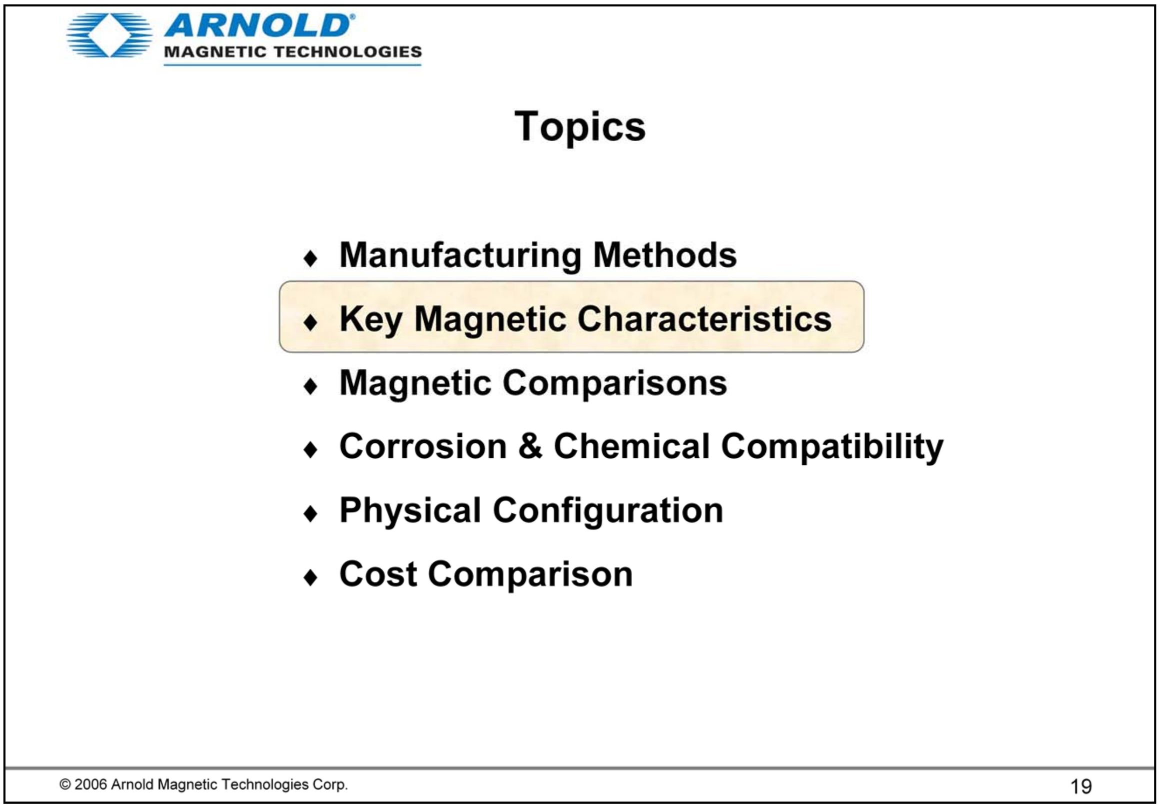
By Magnet Material

- **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

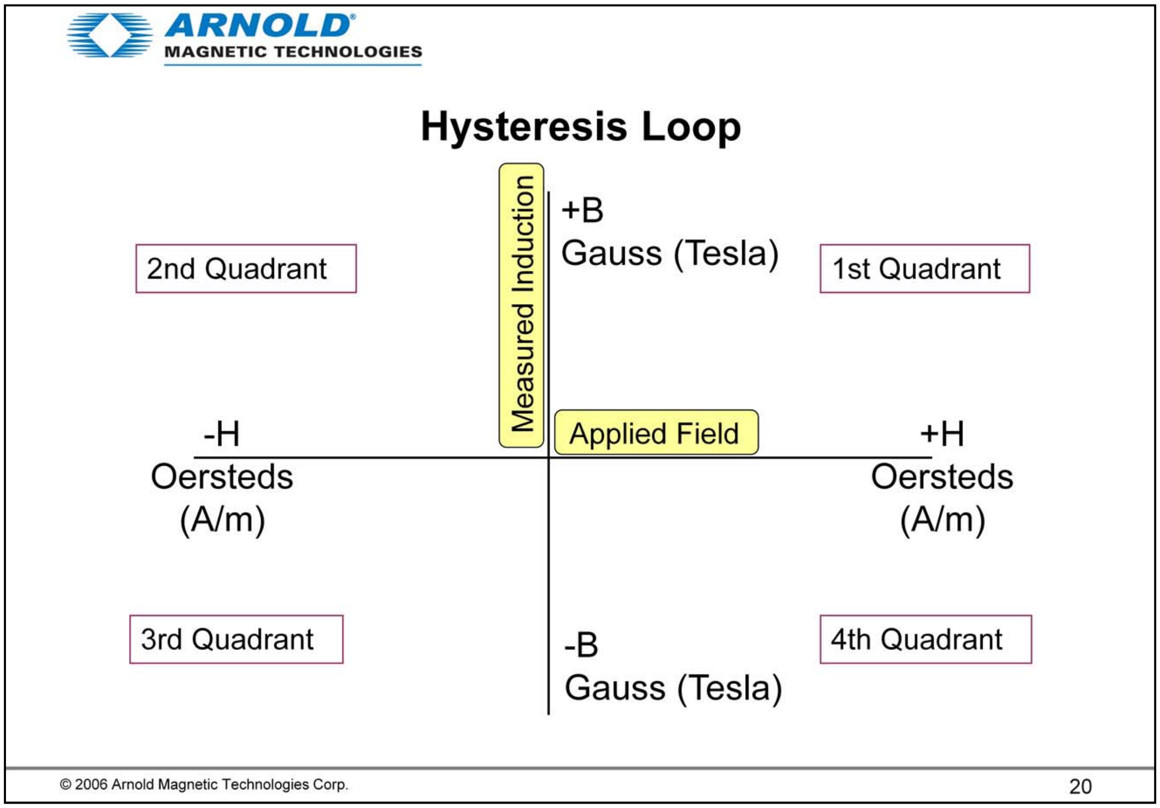
Keywords: **Low Cost**

Ferrite is the Rodney Dangerfield of permanent magnets. We use it in vast quantities and treat it like the "rust" it is - - special rust to be sure, but…

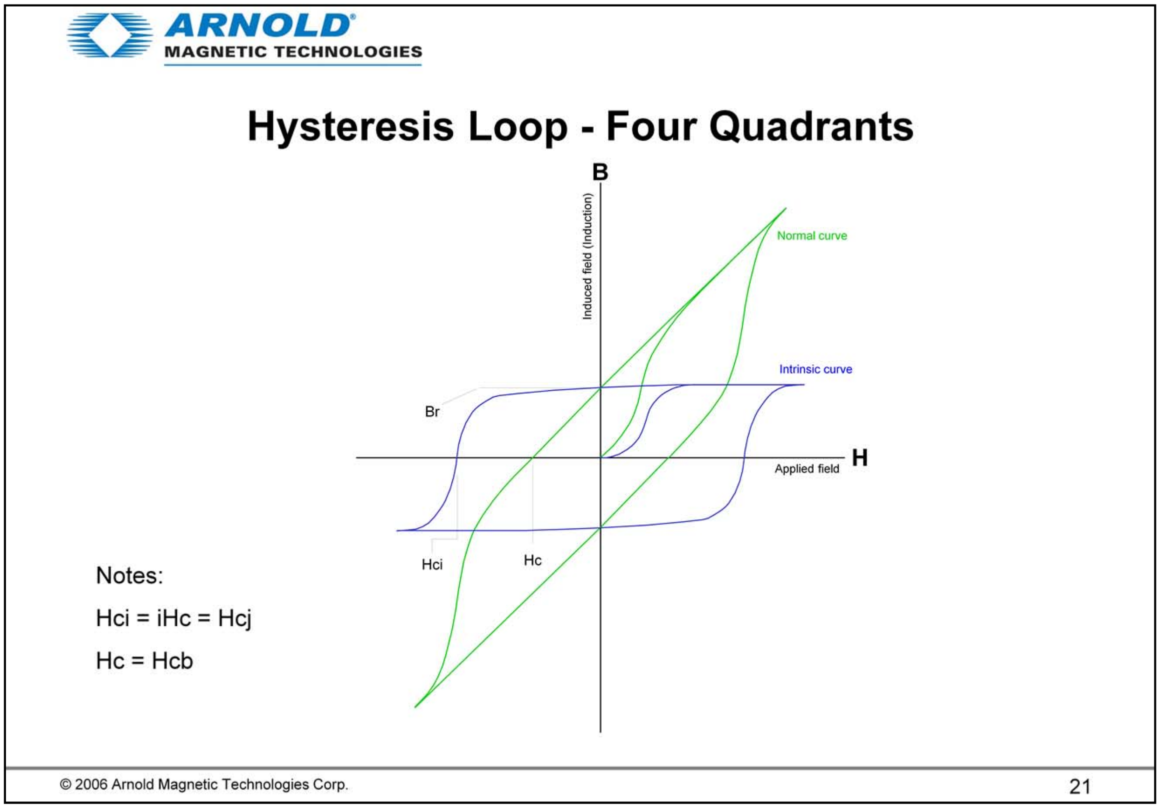
Invented by Philips (Netherlands) and first commercially available in the USA in 1961, it is still used in greater quantity by weight than any of the other materials, primarily due to its very low cost and naturally excellent corrosion resistance.



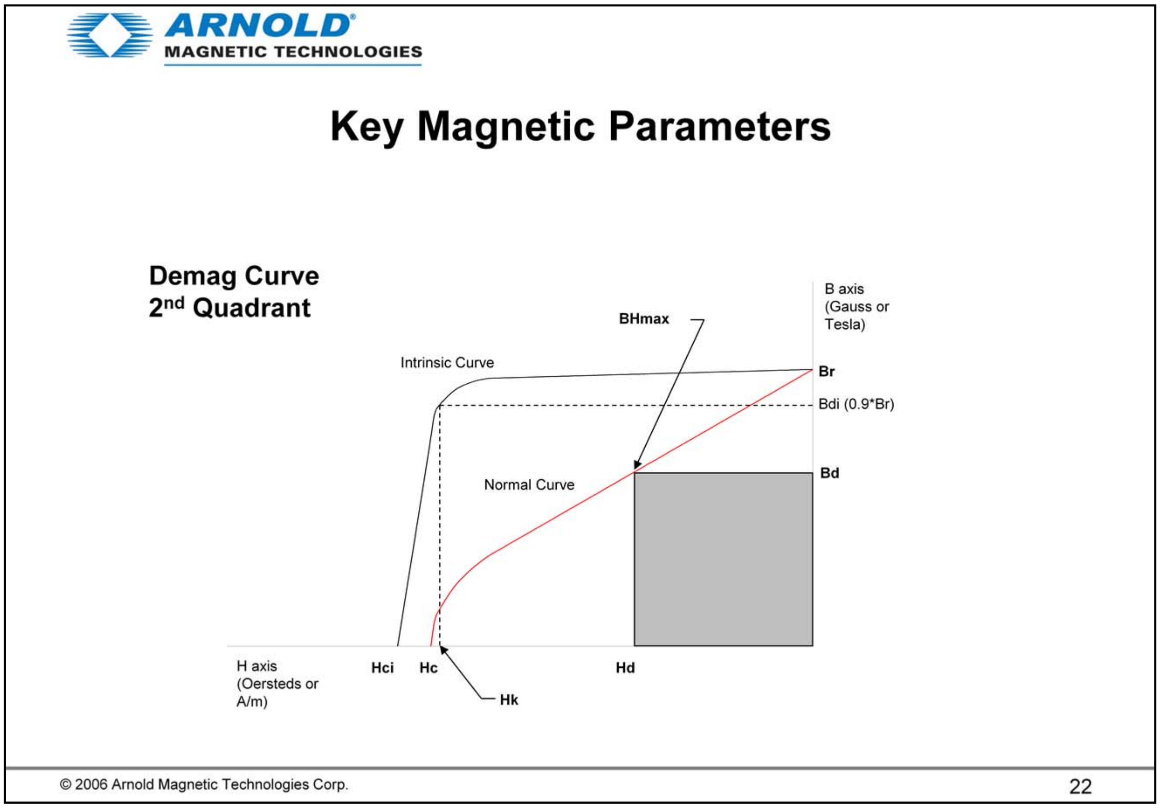
- Let’s examine what parameters we use to distinguish among magnets.



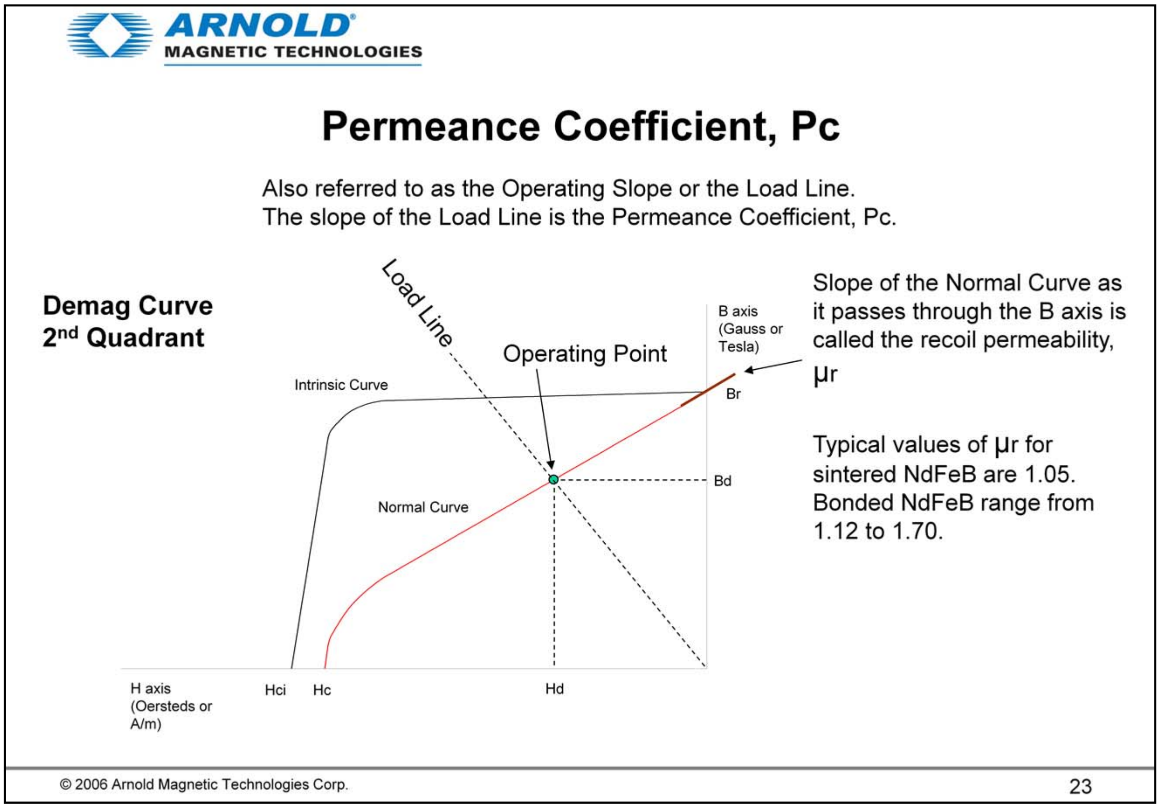
- First we will define magnetic parameters.
- We describe the hysteresis "loop" on a grid with X and Y axes except that we call the horizontal axis the "H" axis measured in Oersteds (or kA/m); the vertical axis is the "B" axis measured in Gauss (or Tesla, T).
- The H axis represents the magnitude of an externally applied field to the magnet material. The B axis represents the magnetic output either of the magnet or the combination of the magnet and the applied field.
- In air, one Gauss = one Oersted. Note the distinction that Oersted refers to applied field and Gauss to the measured (induced) field.
- The grid is divided into quadrants. The first quadrant is often referred to as the magnetizing quadrant, and the second is often referred to as the demagnetizing quadrant.
- The 1st and 3rd quadrants are identical except for sign (negative H and B).
- The 2nd and 4th quadrants are identical (except for sign).



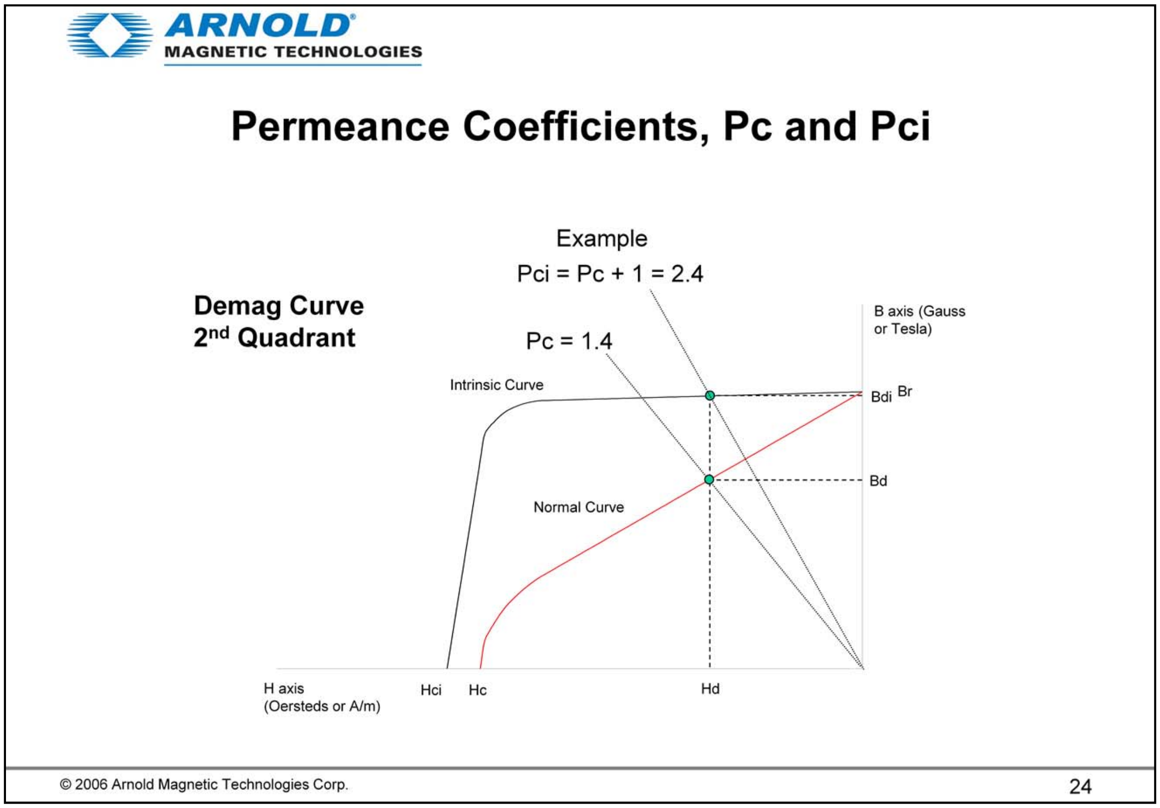
- This chart displays the two types of hysteresis loops for a permanent magnet material: the Normal Curve and the Intrinsic Curve.
- At every point the two hysteresis loops will differ by the value of H: (B = Bi + H). In the first quadrant B = Bi +(+ H) or B=Bi +H. In the second quadrant B=Bi+(-H) or B=Bi-H. If you have one curve (e.g., B vs. H), you can calculate the other (e.g., Bi vs. H).
- The Bi curve is often referred to as polarization, J, or magnetization, M.
- The hysteresis curve shown is typical of a “straight line demagnetization” material, a.k.a., “square loop” material. “Straight line” refers to the normal curve’s linear response in the second quadrant. ”Square loop” describes the knee shape of the intrinsic curve.
- This behavior is typical of ferrite and sintered rare-earth magnets (NdFeB and SmCo). For Alnico and Iron Chrome Cobalt, the intrinsic curve is very similar to the normal curve. They are so similar on these alloys that the Hci is approximately the same as the Hc and only the Normal curve is shown.
- Bonded rare earth magnets exhibit a hysteresis loop somewhat less than “straight line.”



- Most permanent magnet circuits are designed to operate in the 2nd quadrant on the demag curve. With the exception of hysteresis devices (hysteresis clutch, brakes, etc.), where the material sees the whole cycle of magnetization within in the application, the typical magnet, in operation, works only within the region known as the 2nd quadrant of the hysteresis curve.
- As a result, understanding of the demagnetization curves is very important. The demagnetization curves provide specific information about how a given material performs under a variety of magnetic loading and temperature conditions.
- One should remember that the curve is representative of the specific material used to make the magnet, and is independent of the geometry the magnet is made into.
- The key parameters of Br, Hc, Hci, Hk and BHmax are all shown.



- This illustration shows a plot of a Load Line and its intersection with the Normal Curve. That intersection is known as the Operating Point.
- The slope of the line is referred to as the Permeance Coefficient (Pc). While the slope of the line is negative, by convention the Pc is a positive number.
- The second item of note is the Recoil Permeability. Typical values of Recoil Permeability are about 1.05 for sintered Ferrite, SmCo and NdFeB. Bonded ferrite is also about 1.05. Isotropic, bonded Neo magnets range from about 1.1 to 1.7, depending upon grade. Alnico ranges from 1.3 to 6.



- The B value for the Operating Point on the Normal Curve is Bd.
- If a vertical line is drawn from the Operating Point up to the Intrinsic curve and down to the H axis, a point is obtained on the Intrinsic curve which is at a level of B referred to as Bdi.
- If a straight line is drawn from the origin to the Bdi point, the resulting line is called the Intrinsic Permeance Coefficient, Pci. Because of the special relationship between the Normal and the Intrinsic curves, Pci is equal to Pc plus 1 (cgs system).

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Types of "Loss"

Reversible	**Change in output as a function of temperature or stress**
Irreversible-Recoverable	**Critical conditions exceeded, magnet partially de-magnetized**
Structural **(Irreversible-Unrecoverable)**	**Permanent loss due to corrosion or excessive temperature (or radiation) causing structural change**

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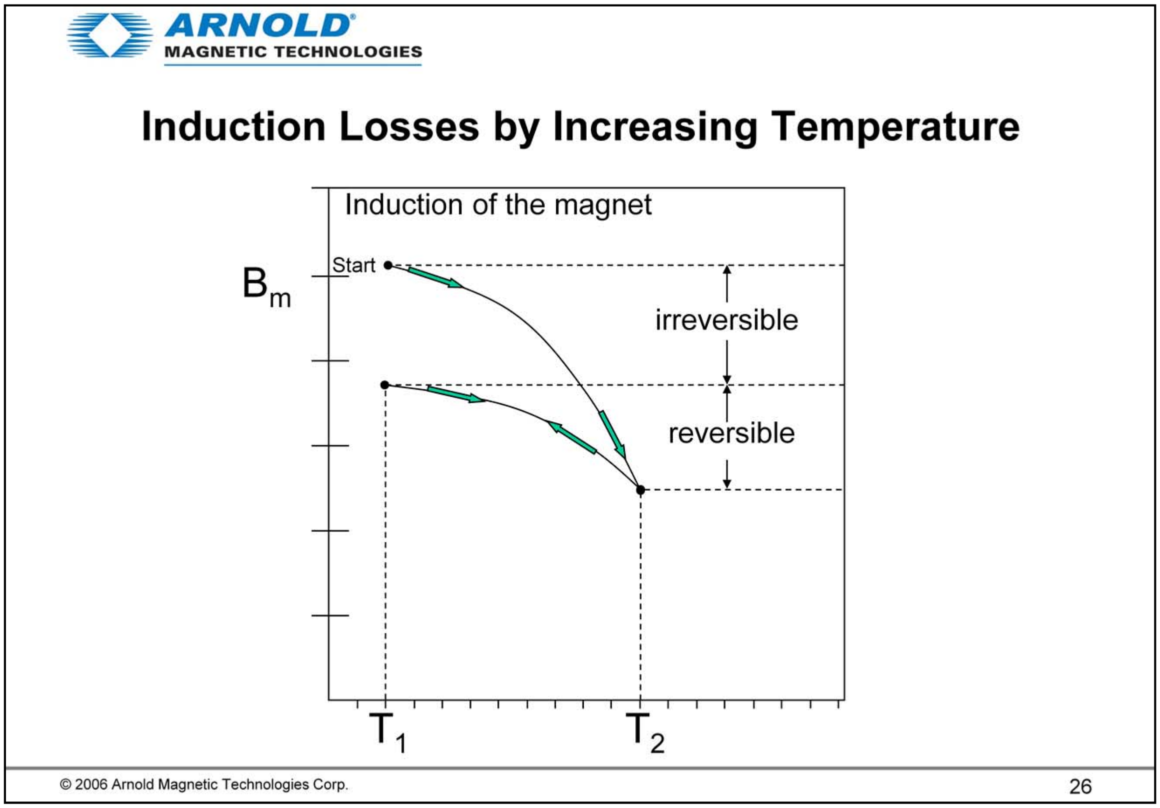
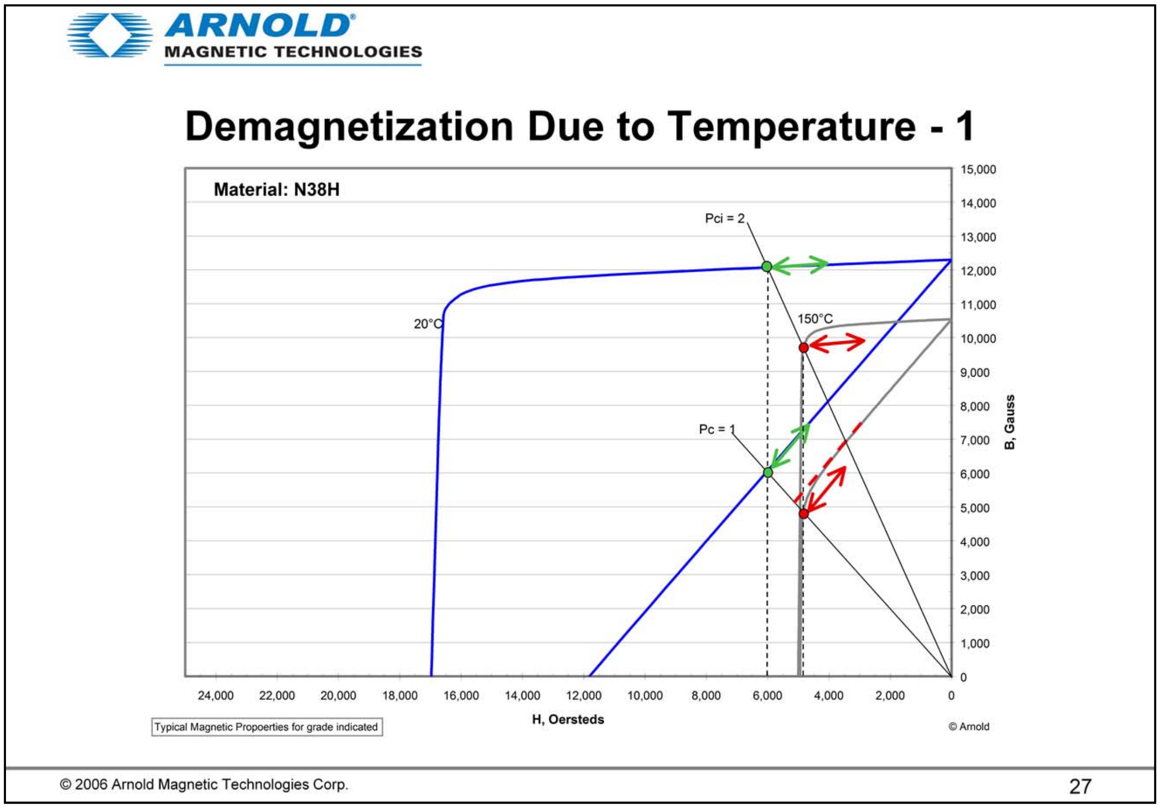
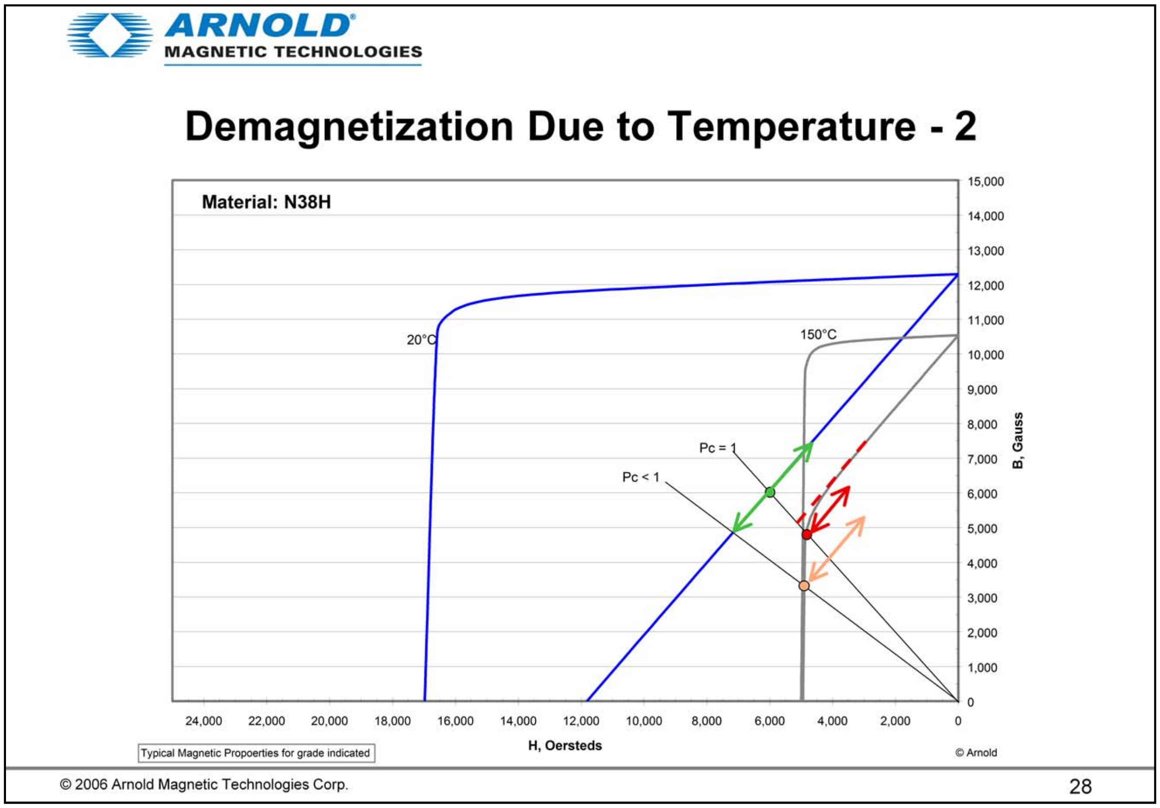
- When a magnet suffers loss in output, it may be one of several types.
  - Reversible: a change in output which disappears when the magnet is returned to its original state.
  - Irreversible: the change is output is permanent.
    - Irreversible, recoverable: the magnet may be re-magnetized and all output recovered.
    - Structural (irreversible, unrecoverable): there is permanent change in output which cannot be recovered except by reprocessing the magnet.
- An example of reversible change is the change in output as a magnet is raised to a higher temperature within the recommended maximum for the material and then returned to room temperature.
- An example of irreversible, unrecoverable loss is that due to corrosion of the magnet.
- Reversible losses can almost always be accommodated in the design. However, un-planned large irreversible losses are not acceptable.
- To accommodate exposure to temperatures at which mild de-magnetization occurs, magnets are sometimes "pre-stabilized".
- Structural loss is not acceptable and can result in system failure. For example, corrosion not only results in lower magnetic output, but can also result in physical destruction of the device.



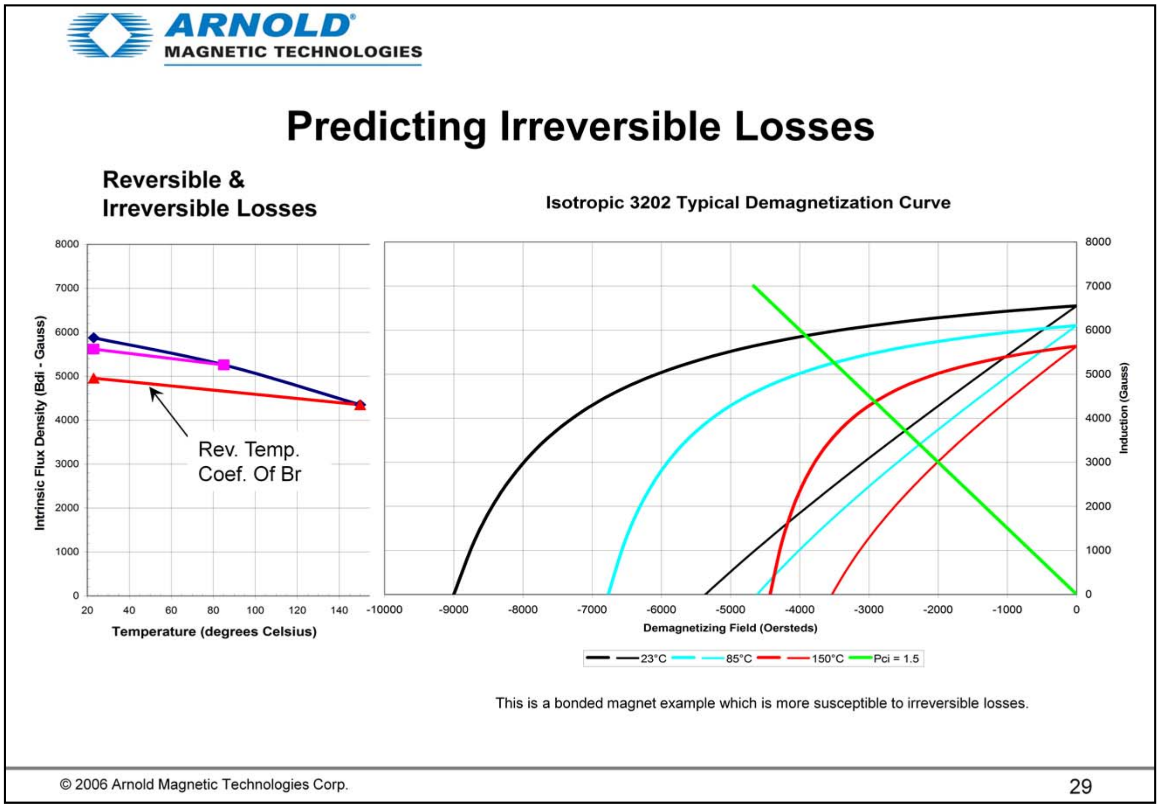
- Flux losses in a magnet, due to increasing temperature, can be separated into irreversible and reversible losses.
- The reversible loss is the portion of loss at the elevated temperature which is recovered when the magnet returns to its initial temperature.
- The irreversible loss is the part of the flux loss at the elevated temperature that is not recovered when the magnet returns to its initial temperature. To regain the "recoverable" portion of the lost flux, the magnet will have to be re-magnetized.
- The irreversible loss in an application can be minimized by cycling the magnet above the use temperature or by magnetically stabilizing (by approximately 1.5-2 times the expected irreversible loss).
- The irreversible loss can be precisely measured when prototypes are made, but predicting the expected irreversible losses requires other design tools.



- It is possible to view performance at elevated temperatures on both the Normal and the Intrinsic curves by drawing a vertical through the Normal Operating Point and up to intersect with the Intrinsic curve.
- A line drawn from this new point to the origin will have a slope of Pc + 1 (ignoring signs) and is referred to as Pci (as seen on the previous slide).
- Recoil along the Intrinsic curve is at a slope of the Recoil Permeability minus one.
- Where only the effects of temperature are experienced, either the Normal or the Intrinsic curve may be used to make calculations regarding loss in flux as the result of exposure to elevated temperature.



- If, in the application, the Pc drops lower than 1:
  - At room temperature the magnetic output will move back and forth approximately along the Normal curve.
  - At 150 degrees, in this example, additional loss will occur as the Operating Point moves further around the Knee of the curve.



- Predicting irreversible losses is a necessary process during the design phase. Knowing the losses one may expect allows for calculation of long term effects on the magnet. While these approximations are easy when the permeance coefficient of the device is close to a permeance coefficient tested on along-term test, it is much more difficult when the test data for that Pc is not available.
- The chart on the left demonstrates plotting of the following points:

Temperature	Bdi at temp	Bdi @ 23 °C after recoil
23 °C	5876 Gauss	N.A.
85 °C	5260 Gauss	5619 Gauss
150 °C	4350 Gauss	4958 Gauss

- The values for Bdi @ 23 °C after recoil are calculated by applying the reversible temperature coefficient of induction to the at temperature values of Bdi. By doing this, the recoil slope due to temperature is set by the reversible temperature coefficient of induction.
- This irreversible loss amount is approximately the same as the value measured in a short-term loss data set. Multiply x 2 to approximate long term losses.

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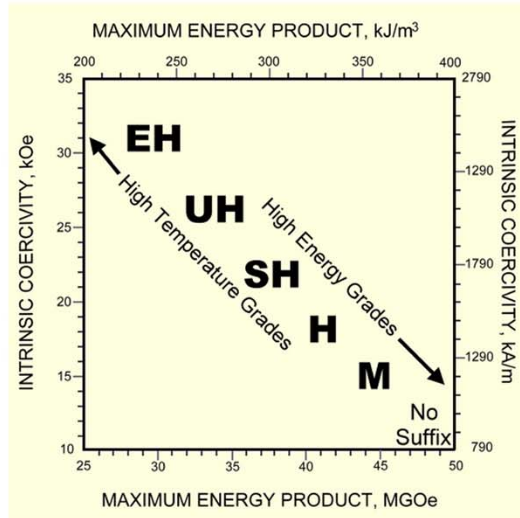
NdFeB Grade Designation

- 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 iHc - - 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
- New, high temperature grades such as L-38UHT have recently been introduced



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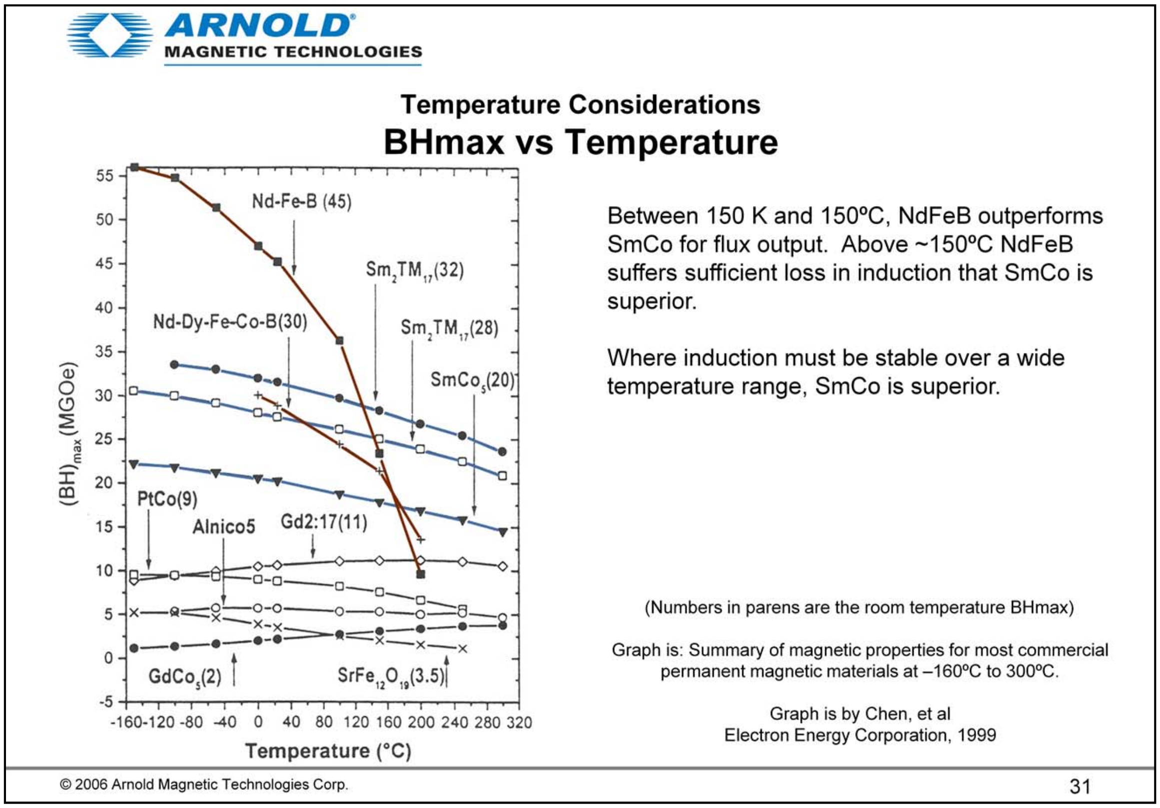
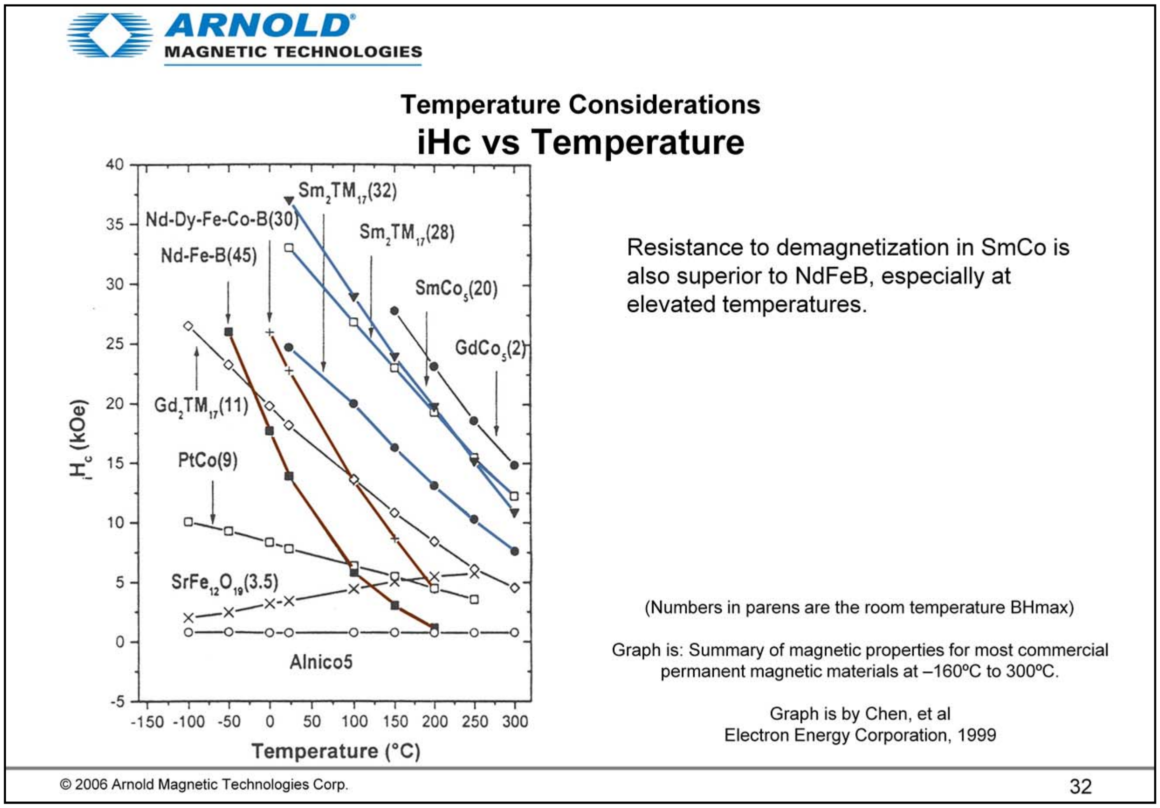
- Grade designations are shown on the plot at the approximate location to denote representative Br and Hci. Note the compromise between intrinsic coercivity and Maximum Energy Product.
- The maximum recommended use temperature follows with coercivity:
  - No suffix **- -** 80ºC maximum
  - **M - -** 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 or even be the best material choice. 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 or rounded intrinsic curve.



- An important consideration regarding use of magnets at elevated temperature is that of Reversible Temperature Coefficients.
- 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, most high temperature grades of NdFeB are no stronger than high grades of SmCo even at room temperature.



- 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 may be preferred.

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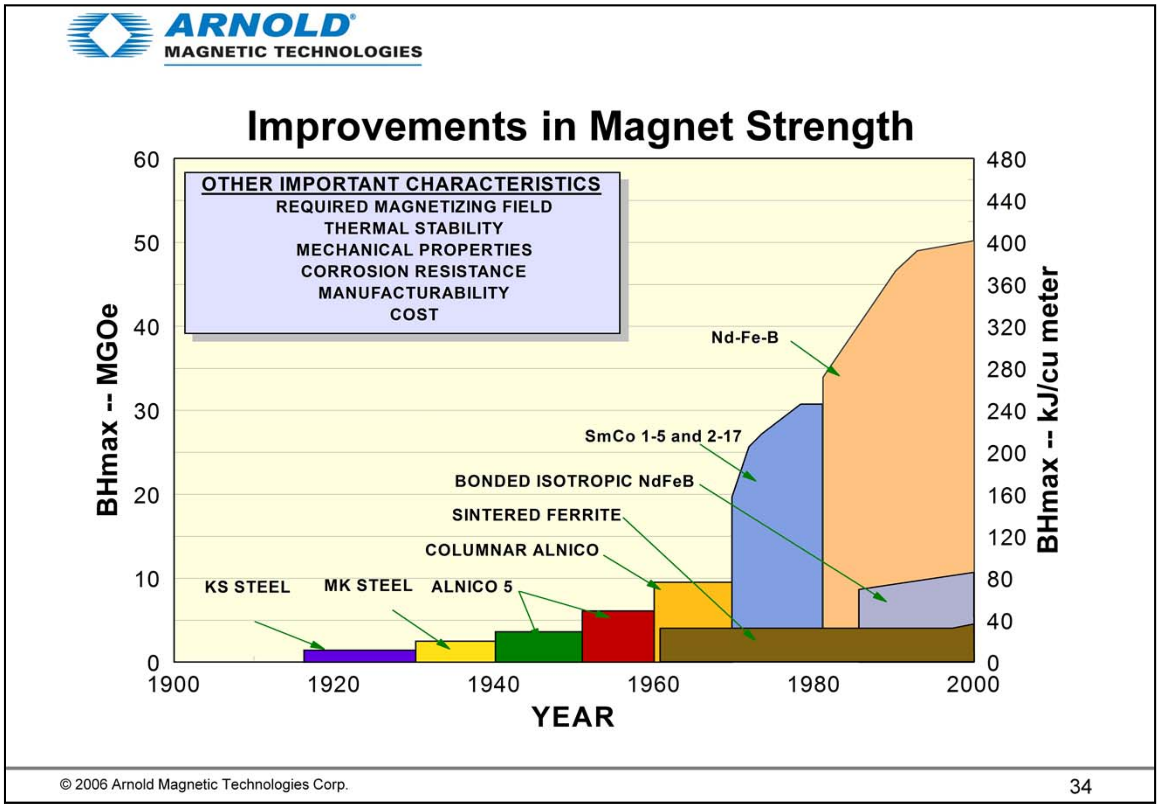
Topics

- Manufacturing Methods
- Key Magnetic Characteristics
- **Magnetic Comparisons**
- Corrosion & Chemical Compatibility
- Physical Configuration
- Cost Comparison



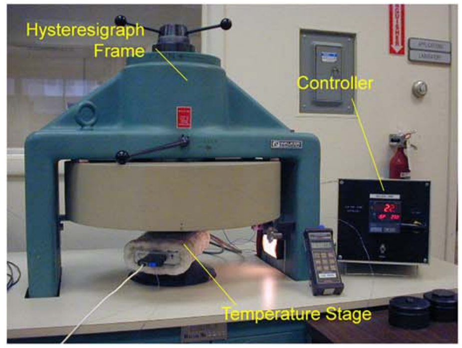
- At the start of the 20th century, the best magnets were made from iron alloys (steel) and had very low magnetic strength compared with today's materials.
- In the 1930's, alnico was invented and this permitted the development of devices with which we are familiar today such as efficient and small motors, high quality loudspeakers, hard disk drives, etc.
- But it was the invention of ferrite (ceramic) magnets in the late 1950s that revolutionized the industry. Ferrite remains predominant today representing about 85% of permanent magnets made on a weight basis.
- The reason: ferrite material cost is very low, especially compared with the rare earth magnets (SmCo and NdFeB).
- However, rare earth compositions provide very high magnetic energy allowing design of miniature equipment and small, light weight consumer electronics.
- The theoretical maximum strength for "Neo" magnets is 64 MGOe. Laboratories have reported achieving BHmax of 57 MGOe and >50 MGOe is available commercially.

ARNOLD®
MAGNETIC TECHNOLOGIES

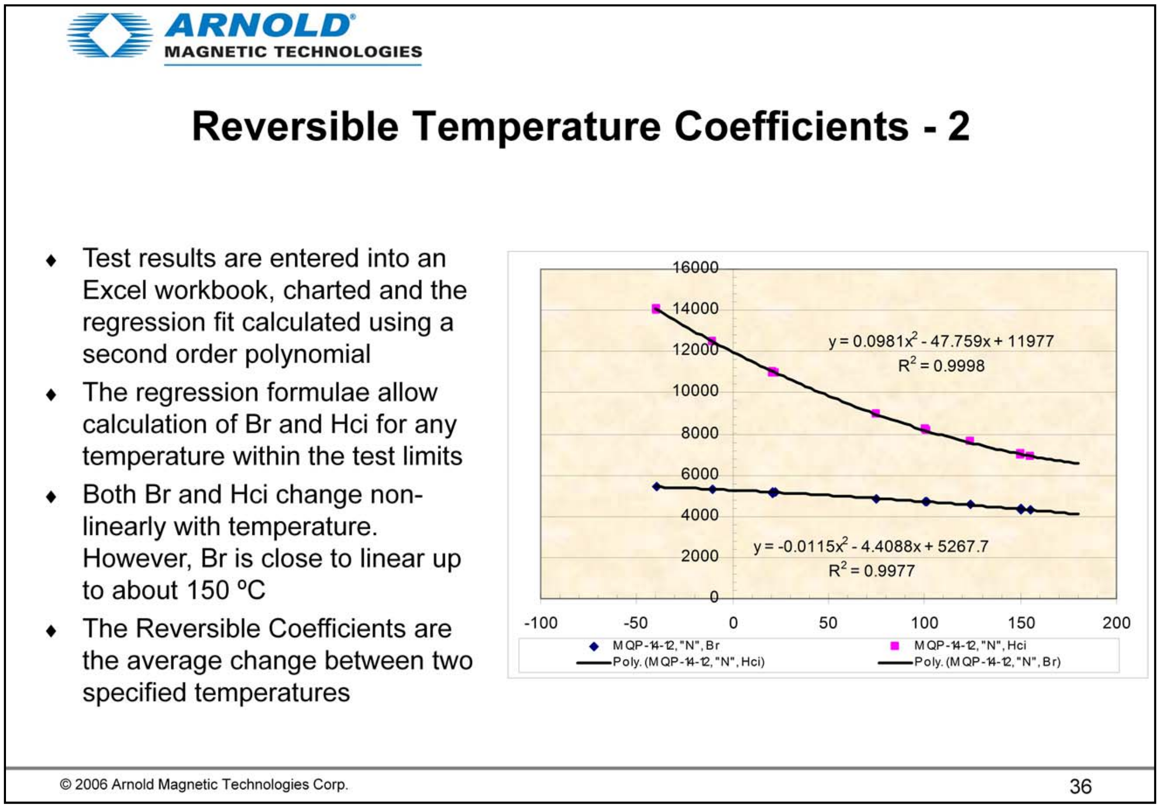
Reversible Temperature Coefficients - 1

Temperature Stage for a Hysteresigraph

- The Stage is an add-on device which allows the magnetic material to be tested at low and high temperatures
- Uses liquid nitrogen and resistance heaters to control the temperature
- Provides direct magnetic data: Br, Hc, Hci & BHmax at temperature.
- Used for measuring reversible temperature coefficients for Br (Alpha) and Hci (Beta).



- We saw earlier that temperature affects magnetic output. How does one measure magnets at temperatures other than ambient? Devices such as a SQUID, Vibrating Sample Magnetometer or Hysteresigraph with Temperature Stage (such as shown here) are used.



Using the hysteresigraph, it is normal to make multiple measurements at selected temperatures to improve on the accuracy of the calculations.

For almost all materials measured between -40 and 300 °C, a 2nd order polynomial provides a good fit with the data (R^2>0.998).

ARNOLD MAGNETIC TECHNOLOGIES

Reversible Temperature Coefficients - 3

Using the regression coefficients, Values for Br and Hci can be calculated for a range of temperatures.

Calculated Br and Hci

	MQP-14-12, "N"	
Temp	**Br**	**Hci**
-40	5,426	14,044
20	5,175	11,061
100	4,712	8,182
120	4,573	7,659
150	4,348	7,020
180	4,102	6,559
200	3,926	6,349

Regression Coefficients

x2	-0.0115	0.0981
x	-4.4088	-47.759
k	5267.7	11977

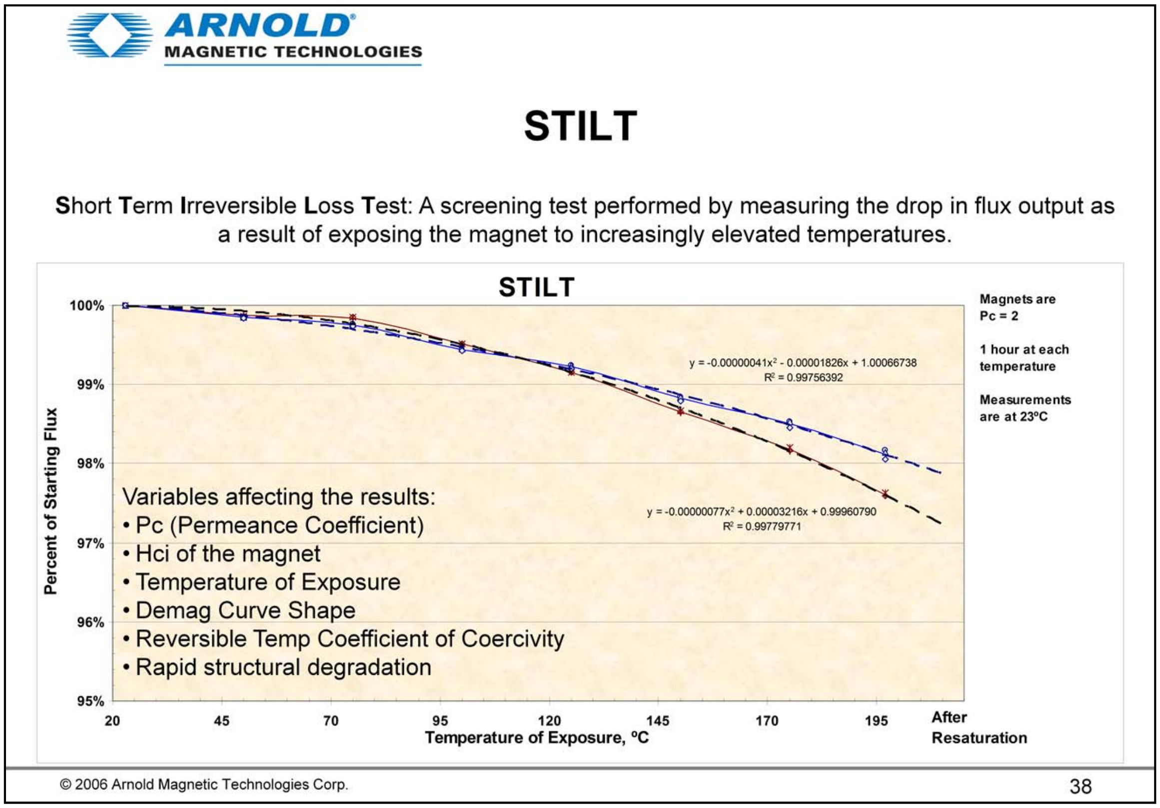
Then the Reversible Temperature Coefficients can be calculated between selected temperatures.

Average Temperature Coefficients

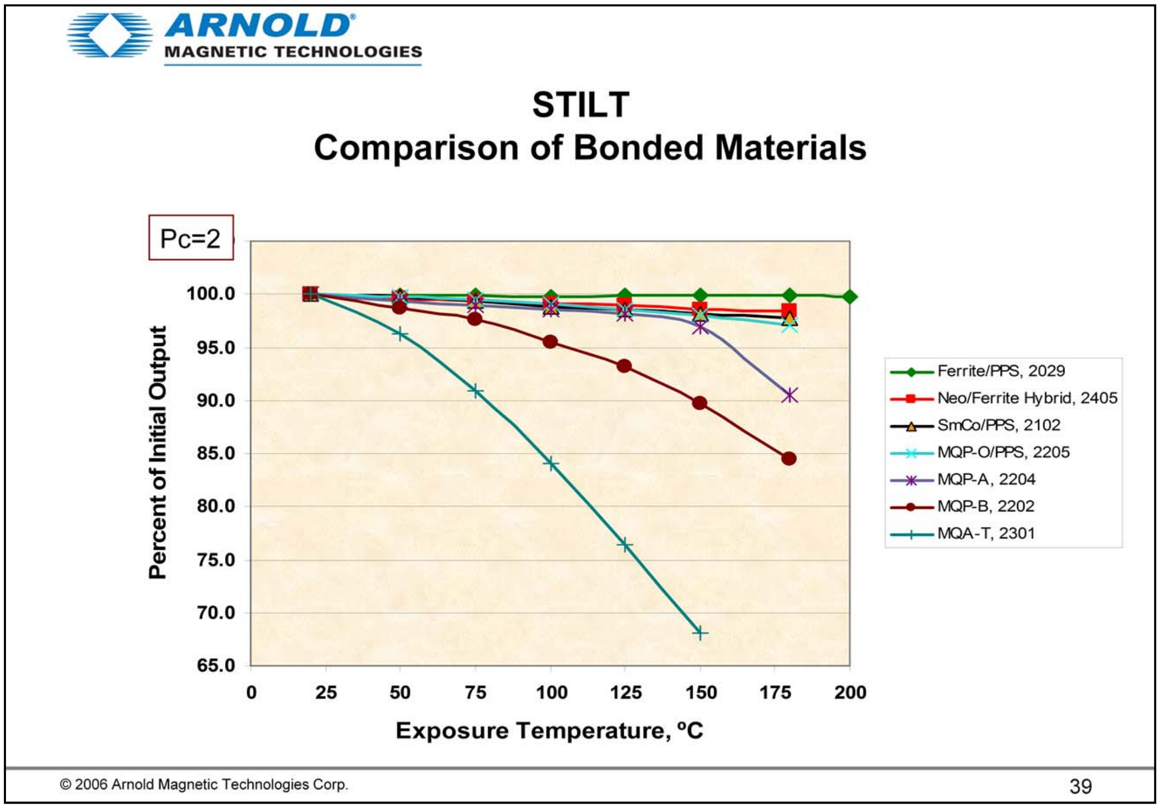
Coefficients Calc		MQP-14-12, "N"	
From	**To**	Br	Hci
-40	100	-0.094%	-0.298%
20	100	-0.112%	-0.325%
20	150	-0.123%	-0.281%
20	180	-0.130%	-0.254%
20	200	-0.134%	-0.237%
22	150	-0.124%	-0.281%

Coefficients are in %/ºC.

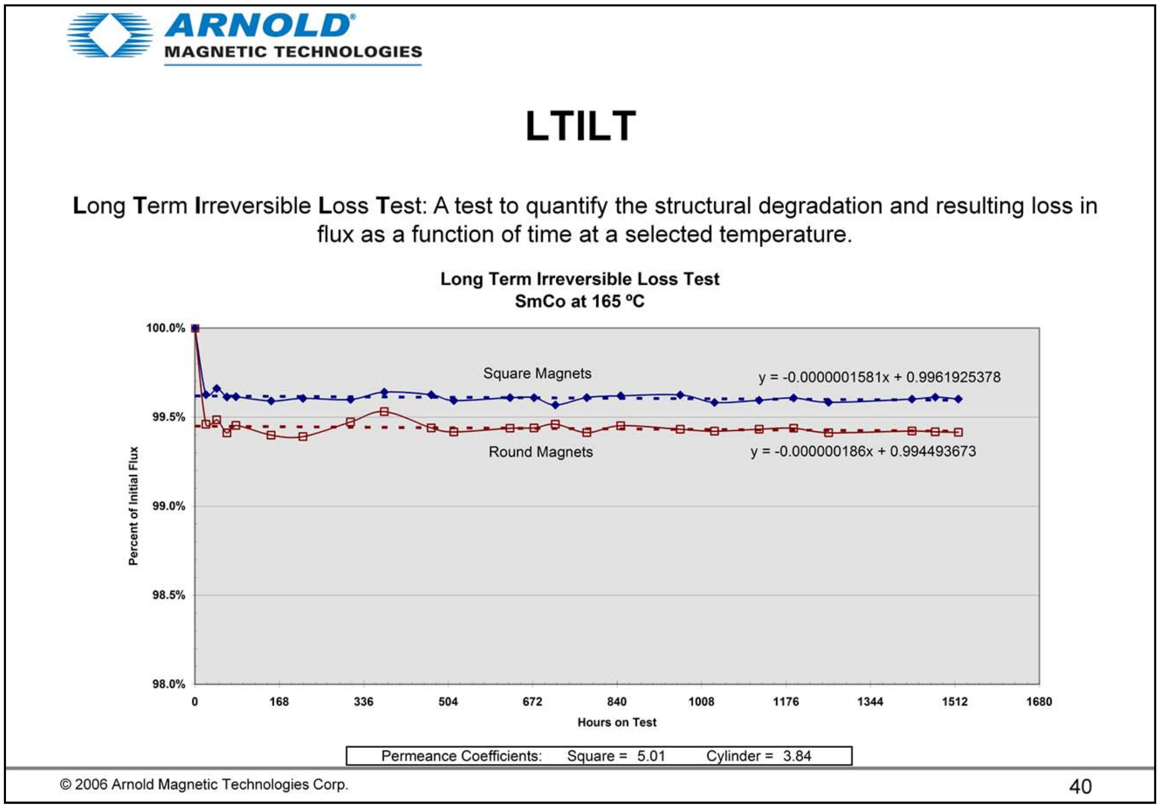
- Having established the best-fit equation, values of Br and Hcj can be calculated for any temperature with the original test temperature range.
- Average rate of change for induction (Br) and coercivity (Hcj) can also be calculated for any two temperatures, e.g., 20 to 150 °C.



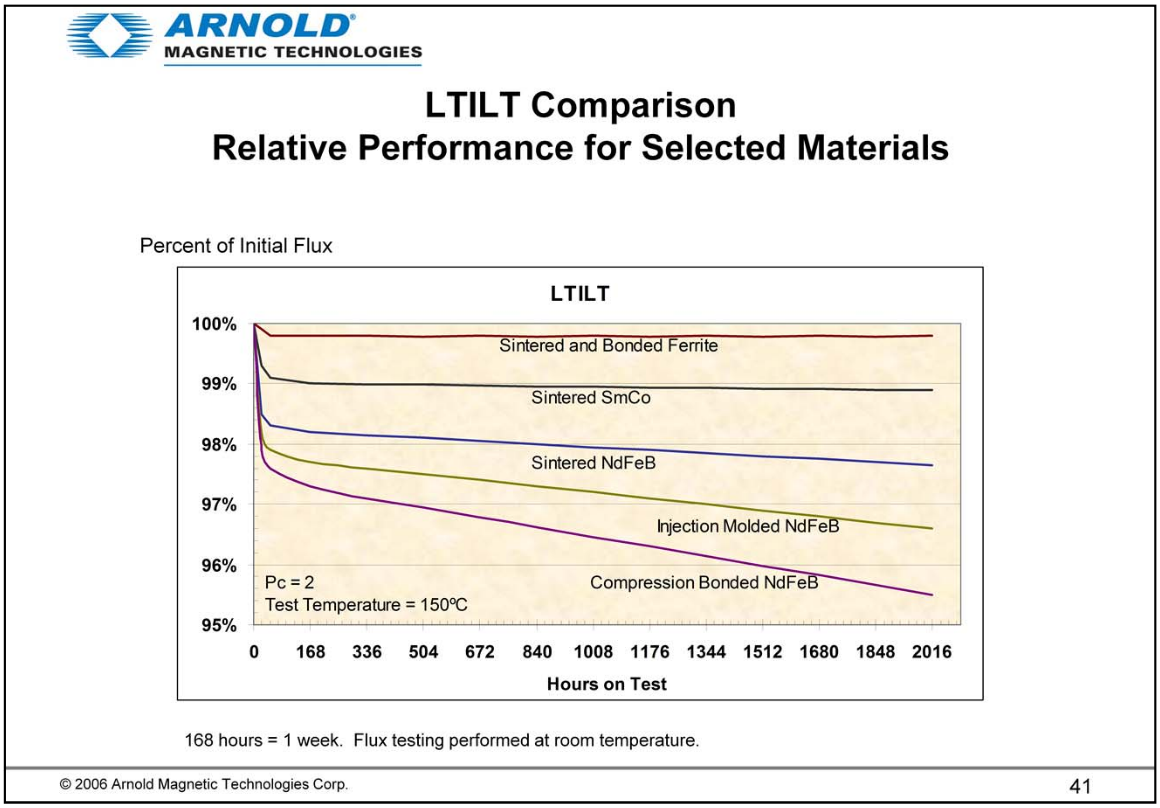
- The STILT (Short Term Irreversible Loss) test was established as a quick way to identify magnet materials with the inability to perform at elevated temperatures.
- Successful candidates would then go on to LTILT (long term) test.
- The procedure is to take magnets of a common Pc (=2) so that doesn't influence the test, measure the Helmholtz flux of the magnets (at room temperature), place the magnets in an oven in open circuit and at a defined elevated temperature (e.g., 75 ºC) for one hour, remove them and let them cool to ambient, re-measure them, put them back in the oven at the next higher temperature for one hour, remove and re-measure them – repeating this process to the highest desired exposure temperature.
- Factors affecting drop in flux are shown on the slide.
- It is sometimes advantageous to re-magnetize after testing at the highest temperature to determine if there has been any permanent (structural) damage to the magnet.



- A typical STILT result is plotted here (c.1993), showing drop in flux output as a function of temperature for a number of bonded magnets.
- Magnets made from the anisotropic NdFeB material above will rapidly lose more than 20 percent of their flux output when exposed to 125 ºC.
- Ferrite coercivity increases with temperature and is resistant to degradation from exposure to elevated temperatures. The result is a magnet that is stable to very high temperatures as illustrated above.



- The Long Term Test involves selecting an appropriate test temperature, exposing the magnets to this temperature and periodically extracting the magnets for measurement.
- Magnets must be of a known Pc, usually 2, and placed in the oven widely separated to minimize magnetic interaction.
- The testing is very sensitive. Fine resolution requires extreme steps be taken to control the measurement process including the testing environment.



- These curves are generally representative of the specific magnet types. However, there is significant variability within each category.
- The LTILT curve consists of two parts:
  - Initial loss, the great majority of which is irreversible-recoverable.
  - Continuing loss which is almost totally the result of structural degradation.
- The slope of the curves between 168 and 2000 hours is virtually straight except for compression bonded where it is straight between 500 and 2000 hours.

ARNOLD MAGNETIC TECHNOLOGIES

Topics

- Manufacturing Methods
- Key Magnetic Characteristics
- Magnetic Comparisons
- Corrosion & Chemical Compatibility
- Physical Configuration
- Cost Comparison

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MAGNETIC TECHNOLOGIES

Corrosion

- Corrosion can be caused by exposure to water or other corrosive liquids and gases such as acids or caustic materials
- It can be exacerbated by the presence of dissolved salts or contaminants
- In general terms, the most common permanent magnet materials can be rated from best to worst regarding corrosion in water or humid environments
  - Ferrite
  - Iron-Chrome-Cobalt
  - Alnico
  - Samarium Cobalt
  - Neodymium-Iron-Boron

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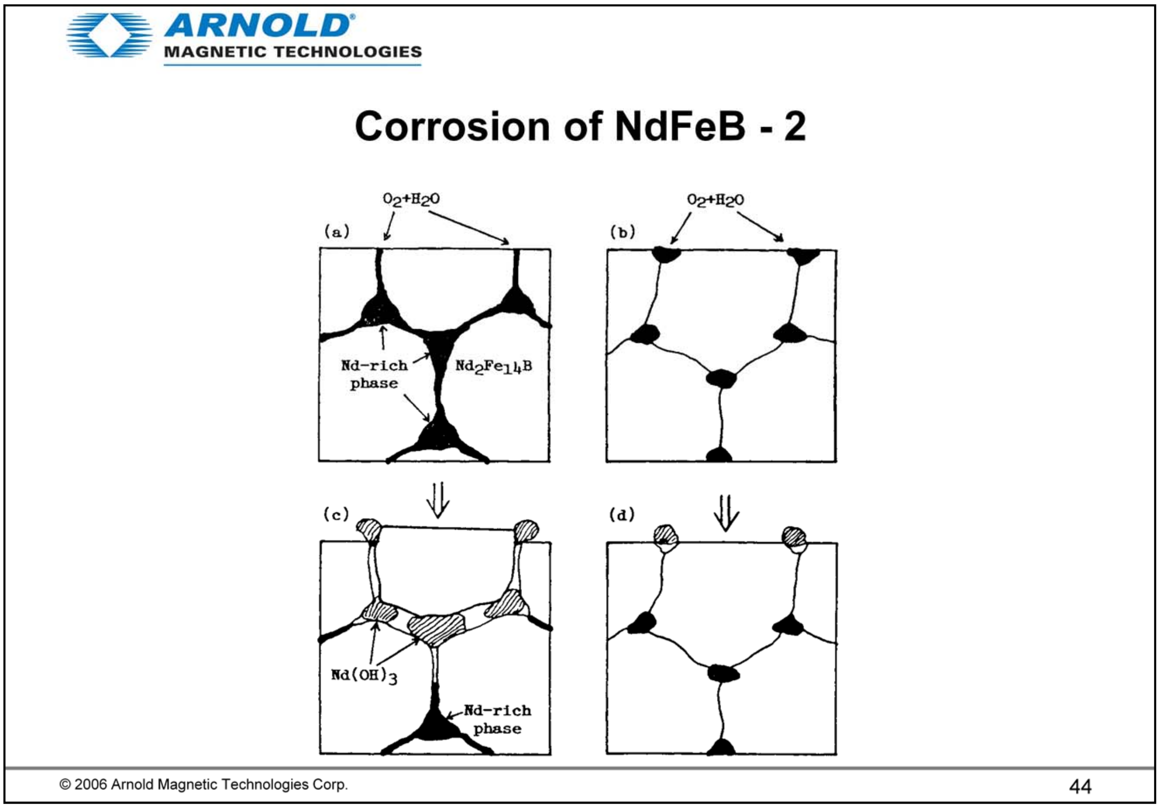
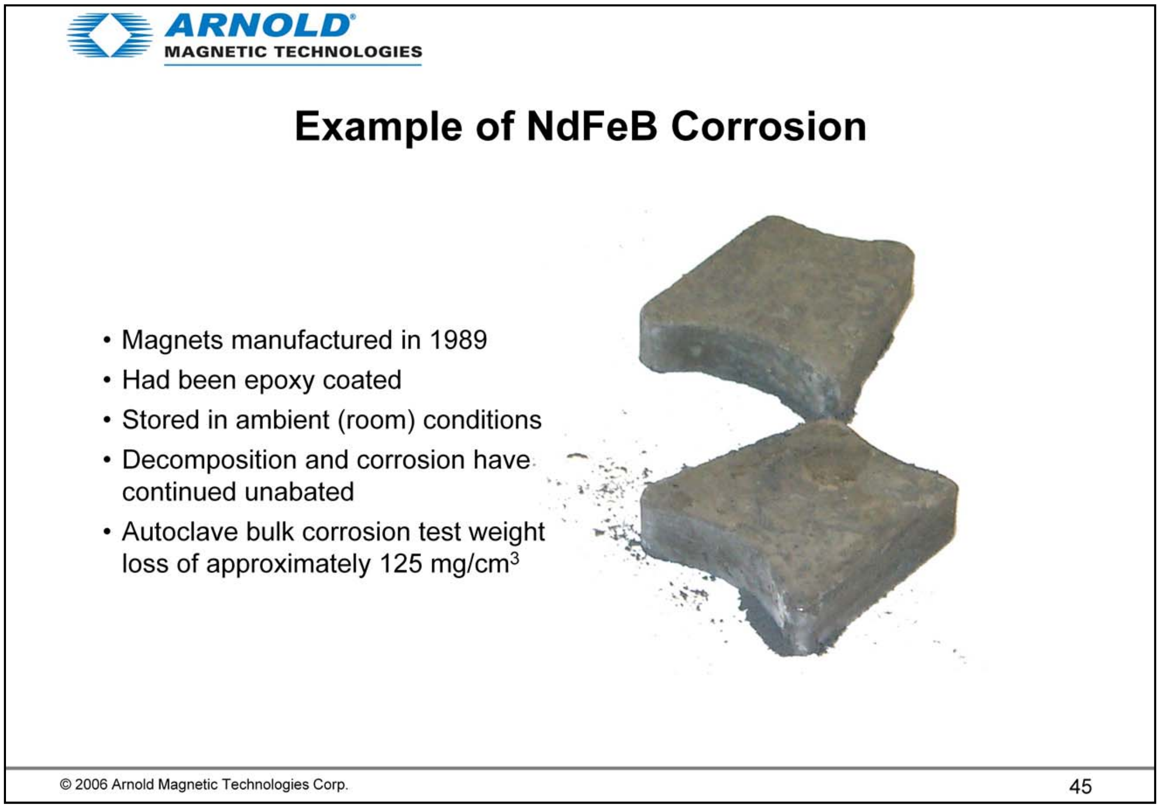
- Corrosion is defined as: “To wear away gradually usually by chemical action.”
- In water the process is almost always through galvanic corrosion. That is, an electric potential exists between dissimilar alloy phases wherein one functions as the cathode and one as the anode. The anodic material becomes sacrificial, and is reacted so that it no longer functions as originally designed.
- This problem is especially severe in conventional neodymium-iron-boron alloys.



- In early NdFeB magnets, the grain boundaries were heavily laden with a rare-earth-rich phase. The corrosion of NdFeB magnets tended to occur along the grain boundaries where this phase exists.
- As the grain boundary material is corroded away, the grains themselves become loose. The magnet would quickly disintegrate into loose particles.
- More modern alloys minimize this phase at the grain boundary; as a result, corrosion proceeds slowly through the material. The resulting magnet is less likely to disintegrate due to the effects of corrosion. Alternatively the grain boundary composition is modified to minimize the galvanic couple.
- However, not all companies have learned to produce stable alloy structures. Therefore, it is advised to establish a corrosion specification when purchasing NdFeB and to work closely with the supplier to ensure that it is consistently met.



- This photo represents typical decomposition / corrosion of NdFeB magnets when the base composition has an excess of rare earth.
- These magnets were manufactured about 1989 for a hard disk drive application.
- Since that time many, but not all, manufacturers have made great improvements in alloy composition and processing to minimize this problem.
- Additionally, the use of a nickel plating to provide a hermetic barrier extends the life of the magnet. Importantly, successful nickel plating requires at least moderately good corrosion resistance in the NdFeB alloy.

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MAGNETIC TECHNOLOGIES

Coating for Corrosion Protection

Nickel plated magnets and steel return paths.

- Although great strides have been made in improving the base NdFeB alloy, corrosion remains a serious issue. One method of reducing corrosion for all magnet types is coating. Both powder spray epoxies and E-coat have been used with moderate success, but the best protection all-around protection for NdFeB is achieved with electrolytic nickel plating. The samples above are voice coil motors (VCM) for disk drives.
- A good alloy structure with 0.0008 to 0.0012" (0.020 to 0.030 mm) of electrolytic nickel plate can remain free of rust for 2000+ hours at 85°C and 85% relative humidity or 1000+ hours in an autoclave at 121 °C.
- Both the 1-5 and 2-17 SmCo alloy compositions are generally superior to NdFeB with regard to "rusting", but they still obtain some benefit in extreme conditions from coating or nickel plating.
- Alnicos, significantly more corrosion resistant, are generally coated with paint for aesthetics, cleanliness or to prevent outgassing.
- Ferrite magnets are "rust" to begin with (strontium, iron oxide). Corrosion is so minimal that these compositions are almost always used without coating.
- Galvanic coupling which produces corrosion is an "electric" phenomenon, enhanced in the presence of a magnetic field: a general rule is that magnetized magnets corrode faster than un-magnetized ones.
- Polished or very fine ground materials rust more slowly than rough finish materials.

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MAGNETIC TECHNOLOGIES

Solvents and Organic Liquids

- Solvents have little to no affect on Sintered Magnets
- Solvents do affect organic polymers (Nylon more, PPS less)
  - Tensile strength
  - Swelling
  - Elongation
  - Stress-cracking
  - Softening -- weakening
  - Flexibility
  - Weight
  - Appearance

Examples: Gasoline, Transmission Fluid, Oils, Grease, Cleaners….

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- Modern Polymer Bonded Magnet binders include polyamides (nylons), PPS (polyphenylene sulfide), chlorinated polyethylene (CPE), nitrile rubber, etc. The list in this chart provides some of the attributes affected by solvents.
- All organic binders will absorb some amount of solvent (including moisture). However, there is a great variability among them as to how much is picked up and the resulting volume expansion (swelling) and loss of strength.
- All the basic materials are manufactured with additives intended to improve flowability, strength, chemical stability, flammability, adhesion, etc. Added to the variety of basic materials, the number of combinations is almost infinite. It is, therefore, imperative to obtain the manufacturer's material compatibility data.
- Organic polymers are mildly to greatly crystalline in structure. However, as-made materials may not have crystallinity fully developed, such as in un-vulcanized rubber. In addition to affecting in-use shrinkage, solvent compatibility is affected by the degree of crystallinity.
- Nylons are popular for bonded magnets. Nylon 12 has moderate resistance to water absorption; nylon 6 has better high temperature capability. Compromises can be achieved with formulation variants such as nylon 6/12 or nylon 6/6.
- PPS is very resistant to water absorption. It is compatible with ferrites, but not with all of the rare earth materials. To use rare earths with PPS, surface treatment of the powder is required. The untreated rare earth alloy powder will catalyze a decomposition of the PPS.

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MAGNETIC TECHNOLOGIES

Topics

- Manufacturing Methods
- Key Magnetic Characteristics
- Magnetic Comparisons
- Corrosion & Chemical Compatibility
- **Physical Characteristics**
- Cost Comparison

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MAGNETIC TECHNOLOGIES

Physical Stress

MATERIAL	Shock/Impact	Bending Stress
Alnico	**Tough, but brittle**	**8,000-30,000 psi bend strength (55,000-206,000 kPa)**
Ferrite	**Chips, cracks easily**	**Brittle failure at moderate stress**
SmCo	**Chips, cracks easily**	**5,000-6,000 psi Tensile strength (35,000-42,000 kPa)**
NdFeB	**Chips and cracks**	**10,000-14,000 psi Tensile strength (69,000-97,000 kPa)**
Bonded Magnets	**Generally chip & break resistant**	**3,000-12,000 psi tensile strength (20,700-82,700 kPa)**
Fe-Cr-Co	**Strong, hard, tough, but brittle**	**40,000-80,000 psi bend strength (280,000-550,000 kPa)**

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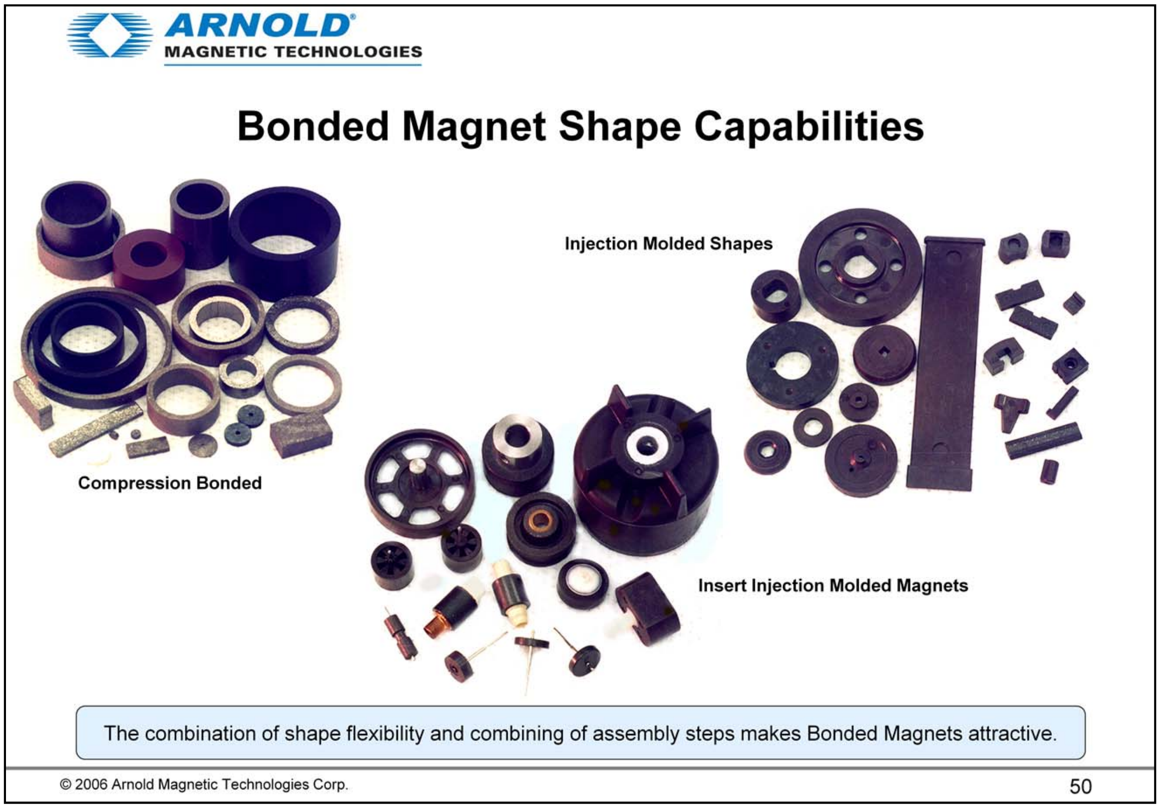
- As a general rule, magnets should not be considered a mechanical part of the assembly structure nor should they be subjected to mechanical shock, bending moment or load.
- Under loads, the material will change in magnetic properties.
- Most magnetic materials are brittle and tend to break under impact or bending stress. Even when total failure does not occur, particulate may be released into the mechanism causing device failure.
- Additionally, rare earth materials are pyrophoric: cracking or striking may cause sparking.
- Note: Machining of rare earth materials in finishing operations such as a clean-up grind after motor rotor assembly requires care. The grind swarf is pyrophoric when dry.



- Bonded magnets are magnetically weaker and are, for the rare earths, more prone to corrosion. Why use them at all?
- They are extremely useful due to shape complexity and the potential for elimination of assembly steps. Also, dimensional tolerances can be very tight right out of the mold avoiding subsequent machining.

Topics

- Manufacturing Methods
- Key Magnetic Characteristics
- Magnetic Comparisons
- Corrosion & Chemical Compatibility
- Physical Configuration
- **Cost Comparison**

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**

- It is necessary for the design engineer to be able to respond efficiently 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.

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MAGNETIC TECHNOLOGIES

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 December 2005. 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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- Our calculations have resulted in the above relative costs and weights when calculations were made at 23ºC. Minor shifts are seen to 150ºC. Above 150, SmCo compares favorably with NdFeB.
- “Magnet Material” refers to the relative cost per pound. “Magnet in the System” refers to the cost of the weight of magnet used in the system. For example, less NdFeB would be used than ferrite for equivalent output. Therefore the “Magnet in the System” NdFeB cost is of 2.7x is relatively closer to Ferrite than the bulk material cost of 20x.
- 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, a change in the soft magnetic return path and the copper (electric circuit).
- This model does not consider assembly costs. It does consider most of the required design changes associated with different materials.

Summary

- Both Sintered and Bonded Magnets have a place in product designs
  - ◊ Sintered magnets are generally capable of superior performance at elevated temperatures
  - ◊ Bonded Magnets have greater shape flexibility and can be made into very complex structures