1.0 Introduction

Magnets are an important part of our daily lives, serving as essential components in everything from electric motors, loudspeakers, computers, compact disc players, microwave ovens and the family car, to instrumentation, production equipment, and research. Their contribution is often overlooked because they are built into devices and are usually out of sight.

Magnets function as transducers, transforming energy from one form to another, without any permanent loss of their own energy. General categories of permanent magnet functions are:

- **Mechanical to mechanical** - such as attraction and repulsion.
- **Mechanical to electrical** - such as generators and microphones.
- **Electrical to mechanical** - such as motors, loudspeakers, charged particle deflection.
- **Mechanical to heat** - such as eddy current and hysteresis torque devices.
- **Special effects** - such as magneto resistance, Hall effect devices, and magnetic resonance.

The following sections will provide a brief insight into the design and application of permanent magnets. The Design Engineering team at Magnet Sales & Manufacturing will be happy to assist you further in your applications.

2.0 Modern Magnet Materials

There are four classes of modern commercialized magnets, each based on their material composition. Within each class is a family of grades with their own magnetic properties. These general classes are:

- Neodymium Iron Boron
- Samarium Cobalt
- Ceramic
- Alnico

NdFeB and SmCo are collectively known as Rare Earth magnets because they are both composed of materials from the Rare Earth group of elements. Neodymium Iron Boron (general composition $Nd_2Fe_{14}B$, often abbreviated to NdFeB) is the most recent commercial addition to the family of modern magnet materials. At room temperatures, NdFeB magnets exhibit the highest properties of all magnet materials. Samarium Cobalt is manufactured in two compositions: Sm_1Co_5 and Sm_2Co_{17} - often referred to as the SmCo 1:5 or SmCo 2:17 types. 2:17 types, with higher H_{ci} values, offer greater inherent stability than the 1:5 types. Ceramic, also known as Ferrite, magnets (general composition $BaFe_2O_3$ or $SrFe_2O_3$) have been commercialized since the 1950s and continue to be extensively used today due to their low cost. A special form of Ceramic magnet is "Flexible" material, made by bonding Ceramic powder in a flexible binder. Alnico magnets (general composition Al-Ni-Co) were commercialized in the 1930s and are still extensively used today.

These materials span a range of properties that accommodate a wide variety of application requirements. The following is intended to give a broad but practical overview of factors that must be considered in selecting the proper material, grade, shape, and size of magnet for a specific application. The chart below shows typical values of the key characteristics for selected grades of various materials for comparison. These values will be discussed in detail in the following sections.

Table 2.1 Magnet Material Comparisons

Material	Grade	Br	Hc	Hci	BHmax	T_{max} (Deg C)*
NdFeB	39H	12,800	12,300	21,000	40	150
SmCo	26	10,500	9,200	10,000	26	300
NdFeB	B10N	6,800	5,780	10,300	10	150
Alnico	5	12,500	640	640	5.5	540
Ceramic	8	3,900	3,200	3,250	3.5	300
Flexible	1	1,600	1,370	1,380	0.6	100

* T_{max} (maximum practical operating temperature) is for reference only. The maximum practical operating temperature of any magnet is dependent on the circuit the magnet is operating in.

3.0 Units of Measure

Three systems of units of measure are common: the cgs (centimeter, gram, second), SI (meter, kilogram, second), and English (inch, pound, second) systems. This catalog uses the cgs system for magnetic units, unless otherwise specified.

Table 3.1 Units of Measure Systems

Unit	Symbol	cgs System	SI System	English System
Flux	ø	maxwell	weber	maxwell
Flux Density	B	gauss	tesla	lines/in^2
Magnetomotive Force	F	gilbert	ampere turn	ampere turn
Magnetizing Force	H	oersted	ampere turns/m	ampere turns/in
Length	L	cm	m	in
Permeability of a vacuum	μ_v	1	$0.4\pi \times 10^{-6}$	3.192

Table 3.2 Conversion Factors

Multiply	By	To obtain
inches	2.54	centimeters
lines/in^2	0.155	Gauss
lines/in^2	1.55×10^{-5}	Tesla
Gauss	6.45	lines/in^2
Gauss	0^{-4}	Tesla
Gilberts	0.79577	ampere turns
Oersteds	79.577	ampere turns /m
ampere turns	0.4π	Gilberts
ampere turns/in	0.495	Oersteds
ampere turns/in	39.37	ampere turns/m

Click here for an interactive version of this conversion table.

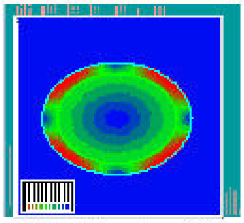
4.0 Design Considerations

Basic problems of permanent magnet design revolve around estimating the distribution of magnetic flux in a magnetic circuit, which may include permanent magnets, air gaps, high permeability conduction elements, and electrical currents. Exact solutions of magnetic fields require complex analysis of many factors, although approximate solutions are possible based on certain simplifying assumptions. Obtaining an optimum magnet design often involves experience and tradeoffs.

4.1 Finite Element Analysis

Finite Element Analysis (FEA) modeling programs are used to analyze magnetic problems in order to arrive at more exact solutions, which can then be tested and fine tuned against a prototype of the magnet structure. Using FEA models flux densities, torques, and forces may be calculated.

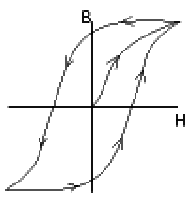
Results can be output in various forms, including plots of vector magnetic potentials, flux density maps, and flux path plots. The Design Engineering team at Magnet Sales & Manufacturing has extensive experience in many types of magnetic designs and is able to assist in the design and execution of FEA models.



Finite Element model

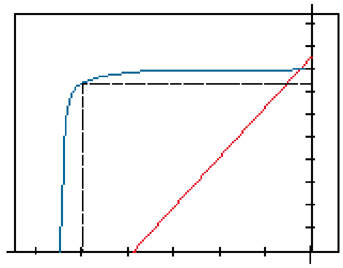
4.2 The B-H Curve

The basis of magnet design is the B-H curve, or hysteresis loop, which characterizes each magnet material. This curve describes the cycling of a magnet in a closed circuit as it is brought to saturation, demagnetized, saturated in the opposite direction, and then demagnetized again under the influence of an external magnetic field.



The second quadrant of the B-H curve, commonly referred to as the "Demagnetization Curve", describes the conditions under which permanent magnets are used in practice. A permanent magnet will have a unique, static operating point if air-gap dimensions are fixed and if any adjacent fields are held constant. Otherwise, the operating point will move about the demagnetization curve, the manner of which must be accounted for in the design of the device.

The three most important characteristics of the B-H curve are the points at which it intersects the B and H axes (at B_r - the residual induction - and H_c - the coercive force - respectively), and the point at which the product of B and H are at a maximum (BH_{max} - the maximum energy product). B_r represents the maximum flux the magnet is able to produce under closed circuit conditions. In actual useful operation permanent magnets can only approach this point. H_c represents the point at which the magnet becomes demagnetized under the influence of an externally applied magnetic field. BH_{max} represents the point at which the product of B and H, and the energy density of the magnetic field into the air gap surrounding the magnet, is at a maximum. The higher this product, the smaller need be the volume of the magnet. Designs should also account for the variation of the B-H curve with temperature. This effect is more closely examined in the section entitled "Permanent Magnet Stability".



When plotting a B-H curve, the value of B is obtained by measuring the total flux in the magnet (ø)and then dividing this by the magnet pole area (A) to obtain the flux density (B=ø/A). The total flux is composed of the flux produced in the magnet by the magnetizing field (H), and the intrinsic ability of the magnet material to produce more flux due to the orientation of the domains. The flux density of the magnet is therefore composed of two components, one equal to the applied H, and the other created by the intrinsic ability of ferromagnetic materials to produce flux. The intrinsic flux density is given the symbol B_i where total flux $B = H + B_i$, or, $B_i = B - H$. In normal operating conditions, no external magnetizing field is present, and the magnet operates in the second quadrant, where H has a negative value. Although strictly negative, H is usually referred to as a positive number, and therefore, in normal practice, $B_i = B + H$. It is possible to plot an intrinsic as well as a normal B-H curve. The point at which the intrinsic curve crosses the H axis is the intrinsic coercive force, and is given the symbol H_{ci}. High H_{ci} values are an indicator of inherent stability of the magnet material. The normal curve can be derived from the intrinsic curve and vice versa. In practice, if a magnet is operated in a static manner with no external fields present, the normal curve is sufficient for design purposes. When external fields are present, the normal and intrinsic curves are used to determine the changes in the intrinsic properties of the material.

4.3 Magnet Calculations

In the absence of any coil excitation, the magnet length and pole area may be determined by the following equations:

$$L_m = \frac{B_g L_g}{H_m}$$ Equation 1

and

$$A_m = \frac{B_g A_g}{B_m}$$ Equation 2

where B_m = the flux density at the operating point,

H_m = the magnetizing force at the operating point,

A_g, = the air-gap area,

L_g = the air-gap length,

B_g = the gap flux density,

A_m = the magnet pole area,

and L_m = the magnet length.

Combining the two equations, the permeance coefficient P_c may be determined as follows:

$$P_c = \frac{B_m}{H_m} = \frac{A_g L_m}{A_m L_g}$$. Equation 3

Strictly, $$P_c = \frac{B_m}{H_m} = \mu\left(\frac{A_g L_m}{A_m L_g}\right)k$$

where μ is the permeability of the medium, and k is a factor which takes account of leakage and reluctance that are functions of the geometry and composition of the magnetic circuit.

Click here to calculate Permeance Coefficients of Disc, Rectangle, Ring

(The intrinsic permeance coefficient $P_{ci} = B_i/H$. Since the normal permeance coefficient $P_c = B/H$, and $B = H + B_i$, $P_c = (H + B_i)/H$ or $P_c = 1 + B_i/H$. Even though the value of H in the second quadrant is actually negative, H is conventionally referred to as a positive number. Taking account of this convention, $P_c = 1 - B_i/H$, or $B_i/H = P_{ci} = P_c + 1$. In other words, the intrinsic permeance coefficient is equal to the normal permeance coefficient plus 1. This is a useful relationship when working on magnet systems that involve the presence of external fields.)

The permeance coefficient is a useful first order relationship, helpful in pointing towards the appropriate magnet material, and to the approximate dimensions of the magnet. The objective of good magnet design is usually to minimize the required volume of magnet material by operating the magnet at BH_{max}. The permeance coefficient at which BH_{max} occurs is given in the material properties tables .

We can compare the varios magnet materials for general characteristics using equation 3 above.

Consider that a particular field is required in a given air-gap, so that the parameters B_g, H_g (air-gap magnetizing force), A_g, and L_g are known.

- Alnico 5 has the ability to provide very high levels of flux density B_m,
- Alnico 8 operates at a higher magnetizing force, H_m, needing a smaller

- Rare Earth materials offer reasonable to high values of flux density at very high values of magnetizing force. Consequently, very short magnet lengths are needed, and the required volume of this material will be small.

- Ceramic operates at relatively low flux densities, and will therefore need a correspondingly greater pole face area, A_m.

The permeance coefficient method using the demagnetization curves allows for initial selection of magnet material, based upon the space available in the device, this determining allowable magnet dimensions.

4.3.1 Calculation Of Flux Density On A Magnet's Central Line

Click here to calculate flux density of rectangular or cylindrical magnets in various configurations (equations 4 through 9).

For magnet materials with straight-line normal demagnetization curves such as Rare Earths and Ceramics, it is possible to calculate with reasonable accuracy the flux density at a distance X from the pole surface (where X>0) on the magnet's centerline under a variety of conditions.

a. Cylindrical Magnets

$$B_x = \frac{B_r}{2}\left(\frac{(L+X)}{\sqrt{R^2+(L+X)^2}} - \frac{X}{\sqrt{R^2+X^2}}\right)$$

Equation 4

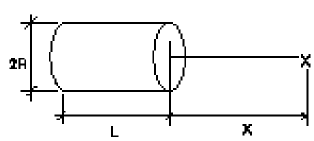


Table 4.1 shows flux density calculations for a magnet 0.500" in diameter by 0.250" long at a distance of 0.050" from the pole surface, for various materials. Note that you may use any unit of measure for dimensions; since the equation is a ratio of dimensions, the result is the same using any unit system. The resultant flux density is in units of gauss.

Table 4.1 Flux Density vs. Material

Material and Grade	Residual Flux Density, Br	Flux at distance of 0.050" from surface of magnet
Ceramic 1	2,200	629
Ceramic 5	3,950	1,130
SmCo 18	8,600	2,460
SmCo 26	10,500	3,004
NdFeB 35	12,300	3,518
NdFeB 42H	13,300	3,804

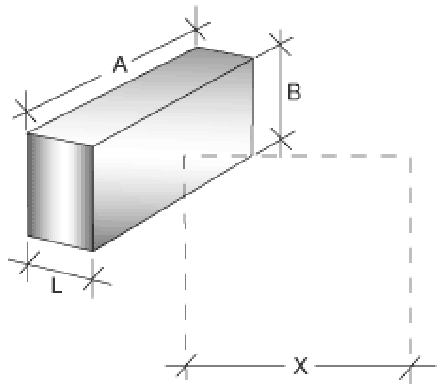
NdFeB 42H	13,300	3,804

b. Rectangular Magnets

$$B_x = \frac{B_r}{\pi}\left(\tan^{-1}\frac{AB}{2X\sqrt{4X^2+A^2+B^2}} - \tan^{-1}\frac{AB}{2(L+X)\sqrt{4(L+X)^2+A^2+B^2}}\right)$$

Equation 5

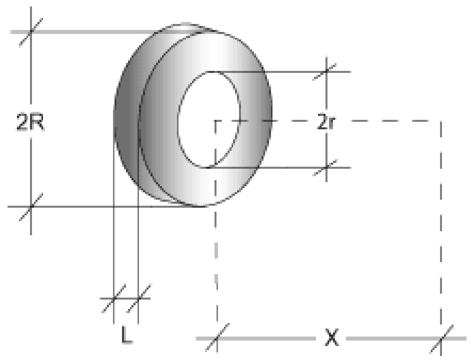
(where all angles are in radians)



c. For Ring Shaped Magnets

$$\frac{B_r}{2}\left(\left(\left(\frac{L+x}{\sqrt{R^2+(L+x)^2}}\right)-\left(\frac{L+x}{\sqrt{r^2+(L+x)^2}}\right)\right)-\left(\left(\frac{x}{\sqrt{R^2+x^2}}\right)-\left(\frac{x}{\sqrt{r^2+x^2}}\right)\right)\right)$$

Equation 6



d. For a Magnet on a Steel Back plate

Equation 7 Substitute 2L for L in the above formulae.

e. For Identical Magnets Facing Each Other in Attracting Positions

Equation 8 The value of B_x at the gap center is double the value of B_x in case 3. At a point P, B_p is the sum of $B_{(x-p)}$ and $B_{(x-p)}$, where (X+P) and (X-P) substitute for X in case 3.

f. For Identical, Yoked Magnets Facing Each Other in Attracting Positions

Equation 9 Substitute 2L for L in case 4, and adopt the same procedure to calculate B_p.

4.3.2 Force Calculations

The attractive force exerted by a magnet to a ferromagnetic material may be calculated by:

$$F = 0.577B^2A$$ **Equation 10**

where F is the force in pounds, B is the flux density in Kilogauss, and A is the pole area in square inches. Calculating B is a complicated task if it is to be done in a rigorous manner. However, it is possible to **approximate** the holding force of certain magnets in contact with a piece of steel using the relationship:

$$F \approx 0.58B_r^2L_m\sqrt{A}$$ **Equation 11**

where B_r is the residual flux density of the material, A is the pole area in square inches, and L_m is the magnetic length (also in inches).

Click here to calculate approximate pull of a rectangular or disc magnet.

This formula is only intended to give an order of magnitude for the holding force that is available from a magnet with one pole in direct contact with a flat, machined, steel surface. The formula can only be used with straight-line demagnetization curve materials - i.e. for rare earth and ceramic materials - and where the magnet length, L_m, is kept within the bounds of normal, standard magnet configurations.

Click here to go to the next section of the Design Guide, Permanent Magnet Stability.

5.0 Permanent Magnet Stability

Table 5.1 Reversible Temperature Coefficients of B_r and H_c

Material	T_c of B_r	T_c of H_c
NdFeB	-0.12	-0.6
SmCo	-0.04	-0.3
Alnico	-0.02	0.01
Ceramic	-0.2	0.3

5.2.2. Irreversible but recoverable losses.

These losses are defined as partial demagnetization of the magnet from exposure to high or low temperatures. These losses are only recoverable by remagnetization, and are not recovered when the temperature returns to its original value. These losses occur when the operating point of the magnet falls below the knee of the demagnetization curve. An efficient permanent magnet design should have a magnetic circuit in which the magnet operates at a permeance coefficient above the knee of the demagnetization curve at expected elevated temperatures. This will prevent performance variations at elevated temperatures.

5.2.3. Irreversible and unrecoverable losses.

Metallurgical changes occur in magnets exposed to very high temperatures and are not recoverable by remagnetization. Table 5.2 shows critical temperatures for the various materials, where

- T_{Curie} is the Curie temperature at which the elementary magnetic moments are randomized and the material is demagnetized; and
- T_{max} is the maximum practical operating temperatures for general classes of major materials. Different grades of each material exhibit values differing slightly from the values shown here.

Table 5.2 Critical Temperatures for Various Materials

Material	T_{Curie}	T_{max}*
Neodymium Iron Boron	310 (590)	150 (302)
Samarium Cobalt	750 (1382)	300 (572)
Alnico	860 (1580)	540 (1004)
Ceramic	460 (860)	300 (572)

(Temperatures are shown in degrees Centigrade with the Fahrenheit equivalent in parentheses.)

*Note that the maximum practical operating temperature is dependent on the operating point of the magnet in the circuit. The higher the operating point on the Demagnetization Curve, the higher the temperature at which the magnet may operate.

Flexible materials are not included in this table since the binders that are used to render the magnet flexible break down before metallurgical changes occur in the magnetic ferrite powder that provides flexible magnets with their magnetic properties.

Partially demagnetizing a magnet by exposure to elevated temperatures in a controlled manner stabilizes the magnet with respect to temperature. The slight reduction in flux density improves a magnetís stability because domains with low commitment to orientation are the first to lose their