

PERMANENT MAGNET GUIDELINES

- I. Basic physics of **permanent** magnet materials
- II. Design relationships, figures **of** merit and optimizing techniques
- III. Measuring
- IV. Magnetizing
- V. Stabilizing and handling
- VI. Specifications, standards and communications
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MAGNETIC MATERIALS PRODUCERS ASSOCIATION

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INTRODUCTION

This guide is a supplement to our MMPA Standard No. 0100. It relates the information in the Standard to permanent magnet circuit problems. The guide is a bridge between unit property data and a permanent magnet component having a specific size and geometry in order to establish a magnetic field in a given magnetic circuit environment. The MMPA 0100 defines magnetic, thermal, physical and mechanical properties. The properties given are descriptive in nature and not intended as a basis of acceptance or rejection. Magnetic measurements are difficult to make and less accurate than corresponding electrical measurements. A considerable amount of detailed information must be exchanged between producer and user if magnetic quantities are to be compared at two locations. MMPA member companies feel that this publication will be helpful in allowing both user and producer to arrive at a realistic and meaningful specification framework.

Acknowledgment

The Magnetic Materials Producers Association acknowledges the outstanding contribution of Rollin J. Parker to this industry and designers and manufacturers of products using permanent magnet materials. Mr. Parker the Technical Consultant to MMPA compiled and wrote this document. We also wish to thank the Standards and Engineering Committee of MMPA which reviewed and edited this document.

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	Glossary of terms and conversion tables—	
	A very important starting point since the whole basis of communication in the magnetic material industry involves measurement of defined unit properties.1
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	An overview of the physics of permanent magnetism is felt to be an important part of learning about permanent magnets.4
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The sections on measuring, magnetizing and stabilizing contain the basic considerations that allow the user to choose the techniques most suitable for a specific permanent magnet component and operating environment.

GLOSSARY OF TERMS

A_g Area of the air gap, or the cross sectional area of the air gap perpendicular to the flux path, is the average cross sectional area of that portion of the air gap within which the application interaction occurs. Area is measured in sq. cm. in a plane normal to the central flux line of the air gap.

A_m Area of the magnet, is the cross sectional area of the magnet perpendicular to the central flux line, measured in sq. cm. at any point along its length. In design, A_m is usually considered the area at the neutral section of the magnet.

B Magnetic induction, is the magnetic field induced by a field strength, H, at a given point. It is the vector sum, at each point within the substance, of the magnetic field strength and resultant intrinsic induction. Magnetic induction is the flux per unit area normal to the direction of the magnetic path.

B_d Remanent induction, is any magnetic induction that remains in a magnetic material after removal of an applied saturating magnetic field, H. (B_d is the magnetic induction at any point on the demagnetization curve: measured in gauss.)

B_d/H_d Slope of the operating line, is the ratio of the remanent induction, B_d, to a demagnetizing force, H_d. It is also referred to as the permeance coefficient, shear line, load line and unit permeance.

B_dH_d Energy product, indicates the energy that a magnetic material can supply to an external magnetic circuit when operating at any point on its demagnetization curve; measured in megagauss-oersteds.

(BH)_{max} Maximum energy product, is the maximum product of (B_dH_d) which can be obtained on the demagnetization curve.

B_{is} (or J) Saturation intrinsic induction, is the maximum intrinsic induction possible in a material.

B_g Magnetic induction in the air gap, is the average value of magnetic induction over the area of the air gap, A_g; or it is the magnetic induction measured at a specific point within the air gap; measured in gauss.

B_i (or J) Intrinsic induction, is the contribution of the magnetic material to the total magnetic induction, B. It is the vector difference between the magnetic induction in the material and the magnetic induction that would exist in a vacuum under the same field strength, H. This relation is expressed by the equation:

$$B_i = B - H$$

where: B_i = intrinsic induction in gauss; B = magnetic induction in gauss; H = field strength in oersteds.

B_m Recoil induction, is the magnetic induction that remains in a magnetic material after magnetizing and conditioning for final use; measured in gauss.

B_o Magnetic induction, at the point of the maximum energy product (BH)_{max}; measured in gauss.

B_r Residual induction (or flux density), is the magnetic induction corresponding to zero magnetizing force in a magnetic material after saturation in a closed circuit; measured in gauss.

f Reluctance factor, accounts for the apparent magnetic circuit reluctance. This factor is required due to the treatment of H_m and H_g as constants.

F Leakage factor, accounts for flux leakage from the magnetic circuit. It is the ratio between the magnetic flux at the magnet neutral section and the average flux present in the air gap. $F = (B_m A_m) / (B_g A_g)$.

F Magnetomotive force, (magnetic potential difference), is the line integral of the field strength, H, between any two points, p₁ and p₂.

$$F = \int_{p_1}^{p_2} H \, dl$$

F = magnetomotive force in gilberts

H = field strength in oersteds

dl = an element of length between the two points, in centimeters.

H Magnetic field strength, (magnetizing or demagnetizing force), is the measure of the vector magnetic quantity that determines the ability of an electric current, or a magnetic body, to induce a magnetic field at a given point; measured in oersteds.

H_c Coercive force of a material, is equal to the demagnetizing force required to reduce residual induction, B_r, to zero in a magnetic field after magnetizing to saturation; measured in oersteds.

H_{ci} Intrinsic coercive force of a material indicates its resistance to demagnetization. It is equal to the demagnetizing force which reduces the intrinsic induction, B_i, in the material to zero after magnetizing to saturation; measured in oersteds.

H_d is that value of H corresponding to the remanent induction, B_d; on the demagnetization curve, measured in oersteds.

H_m is that value of H corresponding to the recoil induction, B_m; measured in oersteds.

H_o is the magnetic field strength at the point of the maximum energy product (BH)_{max}; measured in oersteds.

H_s Net effective magnetizing force, is the magnetizing force required in the material, to magnetize to saturation measured in oersteds.

J, see B_i Intrinsic induction.

J_s see B_{is} Saturation intrinsic induction.

l_g Length of the air gap, is the length of the path of the central flux line of the air gap; measured in centimeters.

l_m Length of the magnet, is the total length of magnet material traversed in one complete revolution of the center-line of the magnetic circuit; measured in centimeters.

l_m/D Dimension ratio, is the ratio of the length of a magnet to its diameter, or the diameter of a circle of equivalent cross-sectional area. For simple geometries, such as bars and rods, the dimension ratio is related to the slope of the operating line of the magnet, B_d/H_d.

P Permeance, is the reciprocal of the reluctance, R, measured in maxwells per gilbert.

R Reluctance, is somewhat analogous to electrical resistance. It is the quantity that determines the magnetic flux, ϕ , resulting from a given magnetomotive force, F.

$$R = F/\phi$$

where:

R = reluctance, in gilberts per maxwell

F = magnetomotive force, in gilberts

ϕ = flux, in maxwells

T_c Curie temperature, is the transition temperature above which a material loses its magnet properties.

T_{max} Maximum service temperature, is the maximum temperature to which the magnet may be exposed with no significant long range instability or structural changes.

V_g Air gap volume, is the useful volume of air or non-magnetic material between magnetic poles; measured in cubic centimeters.

μ permeability, is the general term used to express various relationships between magnetic induction, B, and the field strength, H.

μ_{re} recoil permeability, is the average slope of the recoil hysteresis loop. Also known as a minor loop.

ϕ magnetic flux, is a contrived but measurable concept that has evolved in an attempt to describe the "flow" of a magnetic field. Mathematically, it is the surface integral of the normal component of the magnetic induction, B, over an area, A.

$$\phi = \int \int B \cdot dA$$

where:

ϕ = magnetic flux, in maxwells

B = magnetic induction, in gauss

dA = an element of area, in square centimeters

When the magnetic induction, B, is uniformly distributed and is normal to the area, A, the flux, $\phi = BA$.

A closed circuit condition exists when the external flux path of a permanent magnet is confined with high permeability material.

The demagnetization curve is the second (or fourth) quadrant of a major hysteresis loop. Points on this curve are designated by the coordinates B_d and H_d.

A fluxmeter is an instrument that measures the change of flux linkage with a search coil.

The gauss is the unit of magnetic induction, B, in the cgs electromagnetic system. One gauss is equal to one maxwell per square centimeter.

A gaussmeter is an instrument that measures the instantaneous value of magnetic induction, B. Its principle of operation is usually based on one of the following: the Hall-effect, nuclear magnetic resonance (NMR), or the rotating coil principle.

The gilbert is the unit of magnetomotive force, F, in the cgs electromagnetic system.

A hysteresis loop is a closed curve obtained for a material by plotting (usually to rectangular coordinates) corresponding values of magnetic induction, B, for ordinates and magnetizing force, H, for abscissa when the material is passing through a complete cycle between definite limits of either magnetizing force, H, or magnetic induction, B.

Irreversible losses are defined as partial demagnetization of the magnet, caused by exposure to high or low temperatures external fields or other factors. These losses are recoverable by remagnetization.

Magnets can be stabilized against irreversible losses by partial demagnetization induced by temperature cycles or by external magnetic fields

A keeper is a piece (or pieces) of soft iron that is placed on or between the pole faces of a permanent magnet to

decrease the reluctance of the air gap and thereby reduce the flux leakage from the magnet. It also makes the magnet less susceptible to demagnetizing influences.

Leakage flux is flux, ϕ , whose path is outside the useful or intended magnetic circuit; measured in maxwells.

The major hysteresis loop of a material is the closed loop obtained when the material is cycled between positive and negative saturation.

The maxwell is the unit of magnetic flux in the cgs electromagnetic system. One maxwell is one line of magnetic flux.

The neutral section of a permanent magnet is defined by a plane passing through the magnet perpendicular to its central flux line at the point of maximum flux.

The oersted is the unit of magnetic field strength, H , in the cgs electromagnetic system. One oersted equals a magnetomotive force of one gilbert per centimeter of flux path.

An open circuit condition exists when a magnetized magnet is by itself with no external flux path of high permeability material.

The operating line for a given permanent magnet circuit is a straight line passing through the origin of the demagnetization curve with a slope of negative B_d/H_d . (Also known as permeance coefficient line.)

The operating point of a permanent magnet is that point on a demagnetization curve defined by the coordi-

nates (B_d, H_d) or that point within the demagnetization curve defined by the coordinates (B_m, H_m).

An oriented (anisotropic) material is one that has better magnetic properties in a given direction.

A permeameter is an instrument that can measure, and often record, the magnetic characteristics of a specimen.

Reversible temperature coefficients are changes in flux which occur with temperature change. These are spontaneously regained when the temperature is returned to its original point.

Magnetic saturation of a material exists when an increase in magnetizing force, H , does not cause an increase in the intrinsic magnetic induction, B , of the material.

A search coil is a coiled conductor, usually of known area and number of turns, that is used with a fluxmeter to measure the change of flux linkage with the coil.

The temperature coefficient is a factor which describes the reversible change in a magnetic property with a change in temperature. The magnetic property spontaneously returns when the temperature is cycled to its original point. It usually is expressed as the percentage change per unit of temperature.

An unoriented (isotropic) material has equal magnetic properties in all directions.

QUANTITIES, SYMBOLS, UNITS AND CONVERSION FACTORS

Quantity	Unit, C.G.S.	Unit, S.I.	(S.I.)/(C.G.S.) Ratio*
Length l	centimeter, cm	meter, m	10^2
Mass	gram, g	kilogram, kg	10^3
Time t	second, s	second, s	1
Electric current I	abampere	ampere, A	10^{-1}
Temperature T	degree Celsius, °C	kelvin, K	(K = °C + 273.16)
Force	dyne, dyn	newton, N	10^5
Work or energy	erg = dyn.cm	joule, J = Nm	10^7
Power	erg/s	watt, W = J/s	10^7
Magnetic flux Φ	maxwell	weber, Wb	10^8
Flux density B	gauss, G	tesla, T = Wb/m ²	10^4
Magnetic constant μ_0 (permeability of space)	(unity)	henry/meter, H/m	$10^7/4\pi$
Intensity of magnetization $J^* *$	e.m.u. = $G/4\pi$ = dyn/cm ² Oe	tesla, T = N/Am	$10^3/4\pi$
Magnetic dipole moment j	e.m.u. = dyn.cm/Oe	Wb m = Nm ² /A	$10^{10}/4\pi$
Magnetic pole strength p	e.m.u.	Wb	$10^8/4\pi$
Magnetic field strength H	oersted, Oe	ampere/meter, Aim	$4\pi/10^3$
Magnetomotive force F	gilbert, Gb	ampere, A	$4\pi/10$
Permeability (abs.) $\mu = B/H$	—	henry/meter, H/m	$10^7/4\pi$
Permeability (rel.) $\mu = B/\mu_0 H$	—	—	1
Reluctance, Rm	gilbert/maxwell	1/henry, H ⁻¹	$4\pi/10^9$
Permeance (inverse of reluctance)	maxwell/gilbert	henry, H	$10^9/4\pi$
Susceptibility (rel. vol.) % = $J/\mu_0 H$	e.m.u.	ratio	$1/4\pi$

* A quantity in S.I. units must be multiplied by this ratio to convert it to C.G.S. units

**Also referred to as magnetic polarization in the S.I. approach.

PART I. BASIC PHYSICS AND ORIGIN OF PERMANENT MAGNET BEHAVIOR

GUIDELINES

About 60 years ago French physicist Pierre Weiss postulated that a ferromagnetic body must be composed of some regions or domains, each of which is magnetized to saturation level, but the direction of the magnetization from domain to domain need not be parallel. Thus a magnet, when demagnetized, was only demagnetized from the viewpoint of an observer outside the material. Man-made fields only serve as a control in changing the balance of potential energy within a magnet. This theory still provides the basis of our highly sophisticated body of knowledge that explains quite satisfactorily the observed properties of ferromagnetic materials and provides an intelligent guide for the search for improved materials.

The inherent atomic magnetic moment associated with such elements as iron, cobalt, nickel and many compounds is believed to originate from a net unbalance of electron spins in certain electron shells. For example, in iron in the third shell there are more electrons spinning in one direction than in the opposite direction. Having an inherent atomic magnetic moment is a necessary but not a sufficient condition for ferromagnetism to be exhibited. Additionally, there must be cooperative interatomic exchange forces that maintain neighboring atoms parallel. Little is known of the exact nature or magnitude of these forces but observations suggest they are electrostatic. It has been pointed out that in ferromagnetic materials the ratio of interatomic distance to the diameter of the shell in which the unbalance exists is unusually large compared to this ratio in materials which do not exhibit ferromagnetism.

In Figure I-1 an exploded view of a ferromagnetic volume is shown. The relative dimensions of the atom, domain, crystal and a measurable volume are noted in the figure.

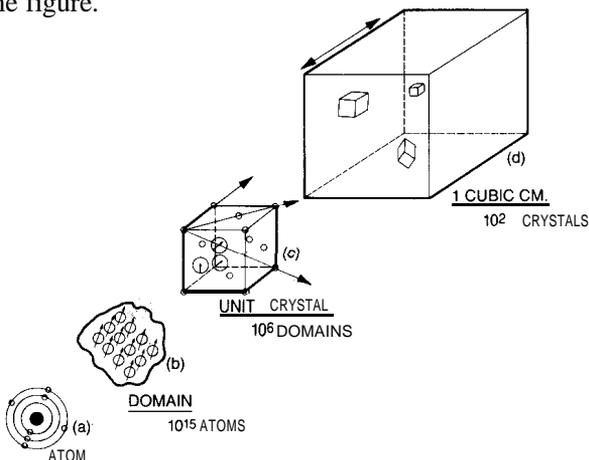


Figure I-1. Exploded assembly of ferromagnetic volume.

The atomic exchange force also produces magnetostrictive effects and is associated with the crystalline structure of magnetic materials in a way that exhibits anisotropy or directional dependence with respect to the crystal axis.

In Figure I-2 the directional dependence is shown for iron. The easy axis of magnetization is the cube (100) edge.

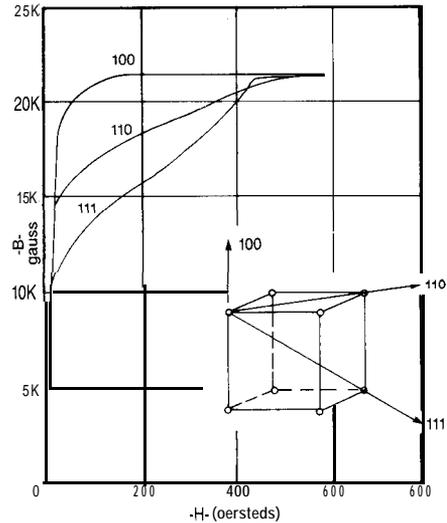


Figure I-2. Directional dependence (iron).

We can view the magnetic domain as a region in which the atomic moments cooperate to allow a common magnetic moment which may be rotated by externally applied fields. Domain size, not a fundamental constant of physics, varies widely depending on composition, purity and state of strain of the material as well as some very important energy relationships. Figure I-3 shows a boundary region between two domains. This boundary region and its significance was first proposed by Bloch.

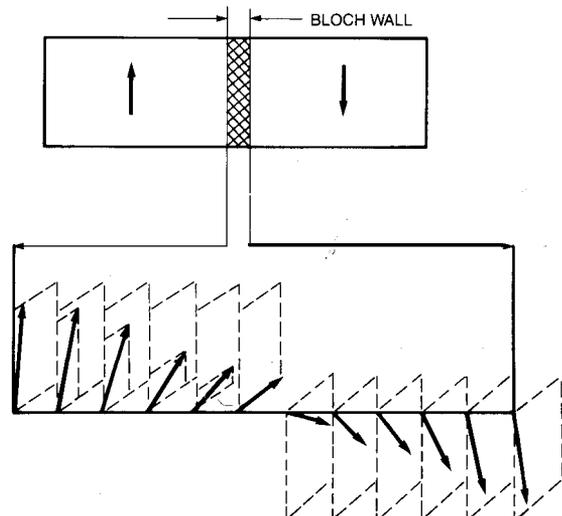


Figure I-3. Bloch wall between ferromagnetic domains.

The Bloch wall is a transition region containing many atomic planes. The 180 degree change in magnetization must occur over a considerable distance to minimize the potential energy in the wall. However, the width of the wall will be restricted because of the restraining influence of crystal anisotropy (directional dependence of magnetism with respect to crystalline axis). Figure I-4 illustrates an additional energy relationship which influences the size of the domain and involves the magneto-static or field energy surrounding a magnetized volume. A magnetized volume tends to subdivide itself. It will be energetically possible for subdivision to occur as shown in Figure I-4 until the decrease in magnetostatic energy is less than the potential energy associated with the Bloch wall foundation. At this point we might say that the magnetization vector arrangement associated with domain volumes in a ferromagnetic material results from a complex energy balance so arranged that the total potential energy of the system is a minimum. Externally applied fields to magnetize or demagnetize only disturb the balance of the potential energies involved and our familiar S-shaped magnetization curves are records of the change in balance with respect to the external influence. Figure I-5 shows the action pictorially as a bar of ferromagnetic material is magnetized.

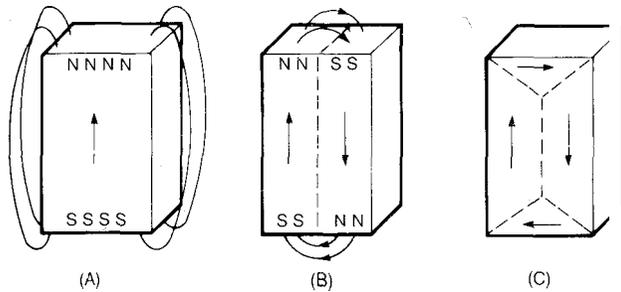


Figure I-4. Domain subdivision.

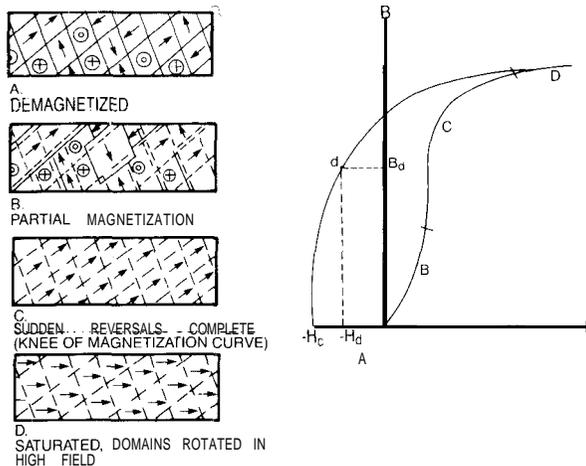


Figure I-5. Pictorial explanation of magnetization curve in a ferromagnetic bar.

The demagnetized condition (A) results from an internal arrangement with mutually cancelling directions of magnetization vectors. In region (B) with low values of external field the action is primarily one of domain boundary stretching, usually around imperfections.

This is a reversible process (reversible magnetization process is one in which the magnetization vectors reorient to their original position after the field (H) is removed). As the field is increased, region (C) domain boundaries break away and move through the material. The more favorably oriented regions grow at the expense of their less favorably oriented neighbors. As a result, a large increase in magnetic induction occurs. This is an irreversible process in which the magnetization vectors tend to keep their new position after a field (H) is removed.

In region (D) at still higher values of magnetizing force, the magnetization vectors are rotated against the forces of strain and crystalline anisotropy into alignment with the direction of the applied field, and saturation occurs. Removing the magnetizing force causes some relaxation; the domains rotate back to the easy direction of magnetization (a reversible process). This relaxation can be minimized by making the direction of easy magnetization coincident with the desired direction of magnetization.

Subjecting the magnet to a demagnetizing force returns the domain boundaries to a condition similar to their original positions in (A) and hence the magnet is demagnetized. In normal use a permanent magnet operates in the second quadrant of the hysteresis loop. The magnet will operate at some point such as (d) in Figure I-5 where a magnetic potential $-H_d$ per unit length and induction $+B_d$ per unit area will be established. For outstanding permanent magnets, domain wall motion and rotation of the magnetization vectors should be made difficult. The more external energy required to magnetize the system, the more will be required to demagnetize the system and hence a better permanent magnet.

Figure I-5 describes the magnetizing process satisfactorily for magnetic materials having coercive force (H) values up to approximately 300 oersteds. The coercive force of the early carbon, tungsten and cobalt steel permanent magnets is believed to be a result of impeding domain wall motion. These quench hardened magnets have nonmagnetic inclusions building up at the domain boundaries, obstructing wall motion. This mechanism is believed to be of significance only at relatively low field strength.

Today's modern permanent magnets exhibit coercive forces well above the level explained by domain wall motion. One therefore must look for magnetization mechanisms requiring greater energy input. A significant milestone in understanding permanent magnet properties occurred with the suggestion of Frenkel and Dorfman that, if small particles were prepared with dimensions less than the width of a domain boundary, such particles would contain no boundaries. This explanation forms the central concept in fine particle magnet theory and provides a satisfactory explanation of modern high coercive force magnets such as alnico, ferrite, rare earth cobalt and rare earth iron magnets.

The dimensions of a single domain volume are predictable from a consideration of the wall energy and magnetostatic energy. For a sphere the wall energy is proportional to the cross section or to the square of the radius. The magnetostatic energy is proportional to the sphere volume or to the radius cubed. A critical radius exists where the two energies are balanced. For this value and below, it is energetically impossible for a boundary to exist. Without domain boundaries the magnetization of a permanent magnet can be changed only by rotation of the magnetic moments associated with each domain volume. This process requires higher energy input than domain wall movement. The degree of difficulty in rotating the magnetic moments depends on the anisotropy, or the forces that give direction to a domain's magnetization.

In alnico magnets, during precipitation, elongated domain regions are formed in a less magnetic matrix phase. The major axis is the easy axis of magnetization and the elongated regions exhibit greater coercive force than spherical regions. Today most research in permanent magnets is in the area of materials exhibiting crystalline anisotropy. Ferrite magnets, rare earth cobalt and rare earth iron magnets all exhibit high coercive force because of the strong attachment of the magnetization to a crystal axis.

The two principle types of anisotropy and the property interrelationships which result are shown in Figure I-6. With particles having shape anisotropy it is necessary to retain spacing between adjacent particles so that the elongated regions will not short each other. Maximum energy density occurs with packing fractions of about 0.6. With a system relying on crystal anisotropy the properties continue to increase as the packing fraction increases. Real permanent magnets often have coercive forces due to several kinds of anisotropy.

associated with the permanent magnet is independent of time unless the magnet is subjected to some form of additional energy input such as heat or demagnetization energy.

The permanent magnet is a unique component in the energy conversion process. A permanent magnet in a stabilized condition is a reversible medium for energy transformation. Potential energy is stored both in the magnet volume and in the external field associated with the magnet. Permanent magnets often operate over a dynamic cycle where energy is converted from electrical or mechanical form to field energy and then returned to the original form.

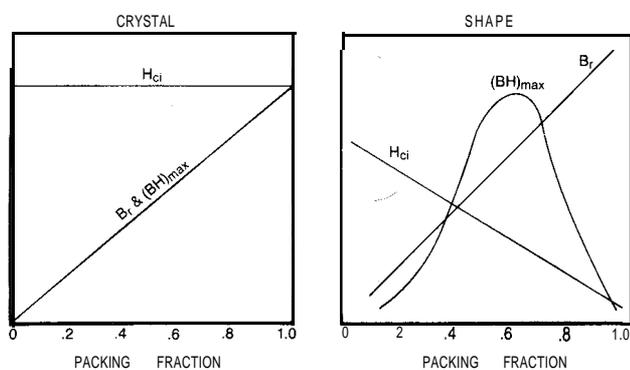


Figure I-6. Two kinds of anisotropy.

When a permanent magnet is magnetized energy is dissipated in changing the internal potential energy balance. For a magnet to establish external field energy additional input energy is required to set up the free poles and establish the magnet's magnetomotive force. Energy is only involved in changing a magnetic field, not in maintaining the field. Hence the field energy

PART II. DESIGN RELATIONSHIPS, FIGURES OF MERIT AND OPTIMIZING

TECHNIQUES

Permanent magnets are characterized and compared in terms of defined unit properties which are obtained from the hysteresis loop of the magnet material. The hysteresis loops for a typical permanent magnet material are shown in Figure II-1. These relationships are determined by measurements as detailed in section III of this guide. The relationship between B , the magnetic induction, and H is known as the normal curve. The relationship between J , the intrinsic magnetization, and H is known as the intrinsic curve. The curves are related at every point by the equation $B = J + H$ in absolute values. *

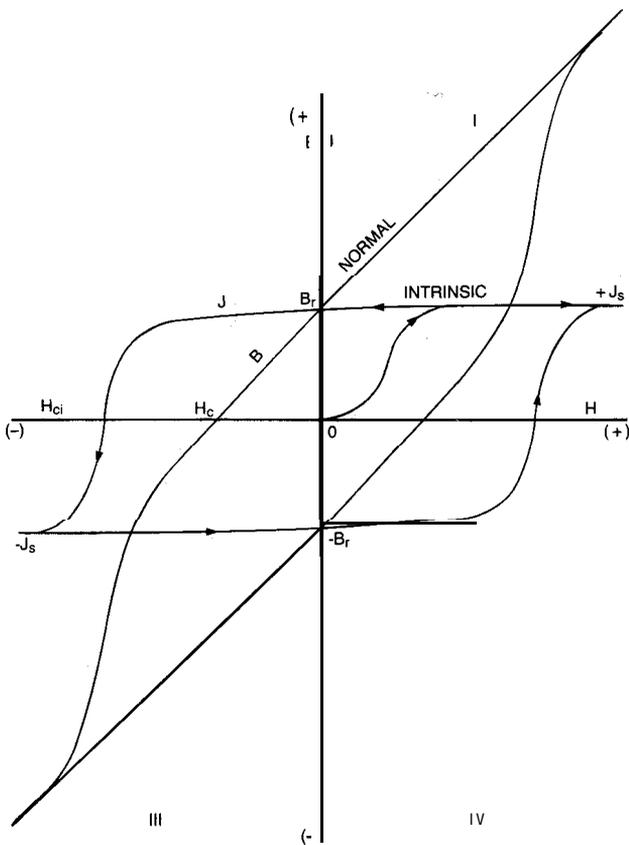


Figure 11-1. Magnet hysteresis loop.

*Note: 1st Quadrant: $B = J + (+H) = J + H$
2nd Quadrant: $B = J + (-H) = J - H$

The permanent magnet is uniquely different from an electromagnet. An electromagnet establishes a field H by having a current in a winding. If a ferromagnetic body is placed in the coil, magnetic induction (B) is born. H and B vectors are parallel to each other and additive. When a field is applied to a permanent magnet intrinsic induction (J) is born. Again J and H are parallel. If the permanent magnet is removed from the mag-

netizer free poles are established and a field potential $-H_d$ exists between the free poles. The field potential in this case is due to some of the magnetization J returning internally. The field potential $-H_d$ associated with a permanent magnet is a product of the magnetization J and is 180° opposed to J . The magnitude of $-H_d$ depends on the geometry of the magnet and thus the spacing of the poles. These relationships are shown pictorially in Figure 11-2.

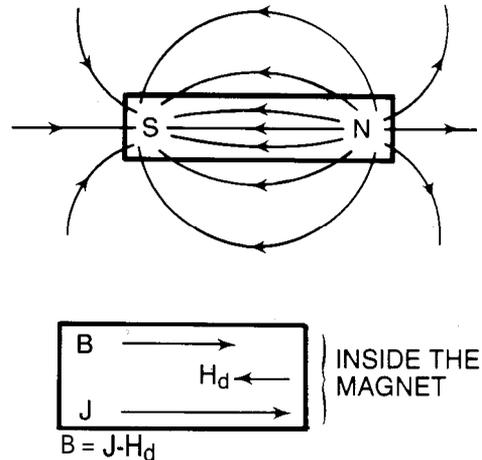


Figure II-Z. BH relationships in a permanent magnet.

Generally, the second quadrant of the hysteresis loop is used in analysis of permanent magnet behavior. Both the intrinsic curve and the normal curve are used. The normal B curve is used for designing since it represents the net output of the magnet when the magnet's use is to establish energy in an air gap. When the magnet is placed in an external field, the intrinsic curve is used to determine how the external field changes the intrinsic properties. The change in normal properties can be constructed from the equation relating the two curves. While it is true that having one curve allows construction of the other, everything is due to the intrinsic magnetization. In the development of permanent magnet materials, intrinsic values are universally used to report progress.

Figure II-3 shows the second quadrant demagnetization curves. B_r , the residual induction, is defined as the flux density of the magnet in a closed magnetic circuit after removal of the magnetizing force. H_c is that demagnetizing force which will reduce B to zero. $(BH)_{max}$, probably the most important single criterion of magnet performance, is obtained by constructing the energy product curve, i.e., the product of abscissa and ordinate plotted against the value of B or sometimes H at appropriate points on the demagnetization curve. The energy product curve starts at the origin, rises to a maximum

point, $(BH)_{\max}$ and then falls again to zero. An alternate and more widely used display is also shown in Figure II-3 where energy product contours are constructed on the demagnetization curves and allows one to compare the energy product of a family of demagnetization curves by inspection.

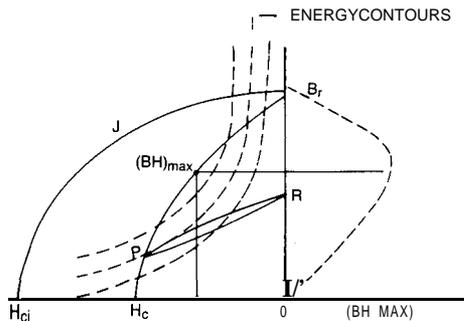


Figure 11-3. Second quadrant demagnetization curves.

An important characteristic of a permanent magnet is termed its recoil permeability (μ_{re}). If at any point, such as P in Figure 11-3, the cycle in H is reversed in direction, then the flux density changes along an interior curve PR. If, from R the field H retraces its values, the flux density traverses the upper half of the loop RP until it again reaches P, after which the major hysteresis loop is followed. Such a minor loop is known as a recoil loop and the slope of the loop is the recoil permeability or reversible permeability. In many materials the slope is fairly constant whatever the point of origin and is very closely approximated by the slope of the major hysteresis loop at point $H = 0$ where $B = B_r$.

Demagnetization Factors-Loadlines and Circuit Concepts

The field H inside the magnet at any point is the result of the applied field H_a , and the self demagnetizing field H_d . As we have seen H_d is a result of pole formation and is proportional to the magnetization J. Therefore $H = H_a + H_d = H_a - NJ$ where N is termed the demagnetization factor. If the magnet is in a closed magnetic circuit H_d will be zero since the free poles do not exist. For a magnet in an open circuit condition or for a magnet circuit containing an air gap the effect of H_d will be to lower the magnetization J. The factor N is dependent on magnet geometry. Joseph¹⁵ has derived both ballistic and magnetometric values for N for cylinders as shown in Figure 11-4. N_b , the ballistic value must be used in determining properties for the central or neutral section of the cylinder. The magnetometric value N_m is used when the average properties of the entire cylinder are being determined. If the demagnetizing field is expressed as $H_d = -NJ$ and (B_d, H_d) is substituted for J, rearranging one has:

$$H_d = \frac{B_d}{\uparrow - N} \text{ and also } \frac{B_d}{H_d} = 1 - \frac{1}{N}$$

This is an important relationship relating the demagnetizing factor to the load line.

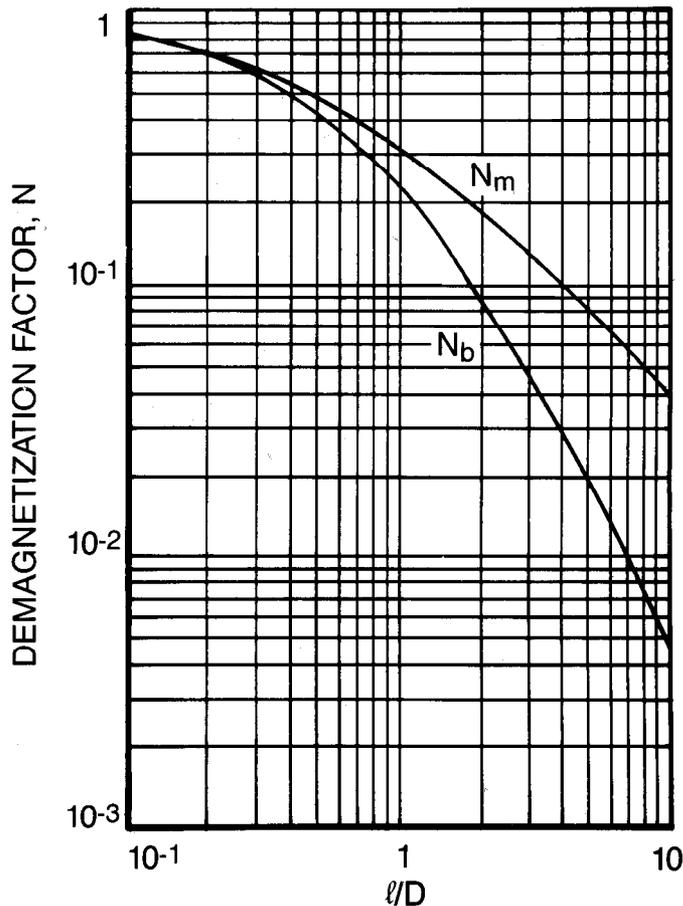


Figure 11-4. Ballistic (N_b) and magnetometric (N_m) demagnetizing factors for cylindrical rods.

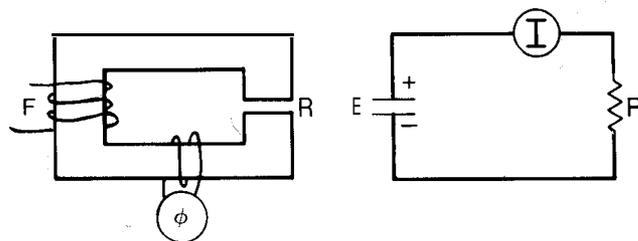


Figure 11-5. Interrelationships between magnetic and electrical circuits.

To establish the relationship between the unit properties of the magnet material and the physical dimensions, consider the magnetic circuit of Figure 11-5. The following equations are based on the CGS system. The magnetic circuit analogy of Ohms law is:

$$\text{flux} = \frac{\text{Magnetomotive Force}}{\text{Reluctance}} \text{ or } \phi = F/R \quad (1)$$

In Figure II-5 the Magnetomotive Force (F) is supplied by electromagnetic ampere turns. In Figure II-6 a permanent magnet is substituted to supply F. By applying the well known line integral theorem to magnet and gap, a basic equation involving magnetomotive forces in the magnet and air gap can be written. The small magnetomotive force drop associated with the steel pole pieces can be neglected for the moment.

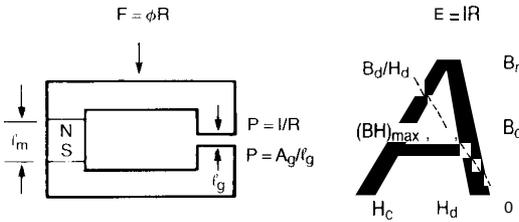


Figure II-6. Magnetic circuit analysis.

$$\ell_m H_d - \ell_g H_g = 0 \quad (2)$$

where ℓ_m = magnet length
 H_d = magnetic potential of magnet per unit length
 ℓ_g = length of air gap
 H_g = air gap magnetic potential per unit length

Another fundamental equation involving magnet dimensions and unit properties results from the premise that flux lines are continuous and may be equated at any two points in a magnetic circuit. Choosing a point in the center of the gap and a point in the center of the magnet one may write:

$$A_m B_d = A_g B_g \quad (3)$$

where A_m = magnet area
 B_d = magnet flux density
 A_g = area of air gap
 B_g = air gap flux density

from equations (2) and (3)

$$\ell_m = \frac{\ell_g H_g}{H_d} \quad (4)$$

$$A_m = \frac{A_g B_g}{B_d} \quad (5)$$

$$V_m = \ell_m A_m = \frac{\ell_g H_g^2 A_g}{B_d H_d} \quad (6)$$

where V_m = magnet volume and $B_g = H_g$ numerically in the cgs system.

Now using the magnetic analogy of Ohms law, we have:

$$\phi = \frac{F}{R} = B_d A_m = \frac{H_d \ell_m}{\ell_g / \mu A_g} \quad (7)$$

Where μ = permeability of gap and will be considered as unity for air, therefore the gap reluctance is ℓ_g / A_g . Rewriting equation (7)

$$B_d = H_d \frac{\ell_m A_g}{A_m \ell_g} \quad (8)$$

Equation (8) is in terms of B and H and can be plotted as a straight line with a negative slope on a magnet demagnetization curve. The intersection of this line with the demagnetization curve represents the operating point of the magnet. In terms of the demagnetization curve the flux density has decreased from B_r to B_d and a negative potential $\ell_m H_d$ has developed which is equal to the potential drop in the air gap $\ell_g H_g$. The slope represented by equation (8) may be expressed as:

$$\frac{B_d}{H_d} = \frac{\ell_m A_g}{A_m \ell_g} = \frac{\ell_m}{A_m R} = \frac{\ell_m}{A_m} P \quad (9)$$

The reciprocal of $1/R$ is permeance (P), and is widely used in actual calculations. The concept of permeance reduced to a unit volume of magnet material is simply the slope of the load line.

$$P_u = \frac{B_d}{H_d} = \frac{\ell_m}{A_m} P \quad (10)$$

Usually the designer will select the dimensions so as to operate at given B_d/H_d ratio. Often it is the point $(BH)_{max}$ where the product $B_d H_d$ is at a maximum and consequently the V_m used will be a minimum. [Refer to equation (6).] For the case of the magnet by itself outside of its return path the B_d/H_d will be set entirely by the geometry of the magnet and B_d/H_d must be determined from the demagnetization factor N as previously developed. The total permeance is usually broken up into a value for each region. For example our simple circuit could be analyzed by breaking total permeance P into $P_l + P_p + P_g$ where P_p is the magnet limb permeance obtained from N. P_p is the permeance of the pole pieces and P_g is the air gap permeance A_g/ℓ_g . Equation (10) can be rewritten as follows:

$$\frac{B_d}{H_d} = \frac{\ell_m}{A_m} P_p + P_p + P_g \quad (11)$$

The design equations were developed under the ideal but unobtainable assumption that all of the magnet potential was used across the air gap and all of the magnet flux was confined in the circuit. In practice it is difficult to determine the true permeance. For example, for a short air gap of large area the permeance will be A_g/ℓ_g . In practice the true permeance will be more than this value since part of the flux is leakage. This is equivalent to a proportionate increase in gap area which may be considered as a leakage factor F. Similarly it is often advisable to apply a correction factor to the gap length to allow for losses introduced by joints in the magnetic circuit and potential loss in the pole piece material.

The reluctance factor f is convenient to use. Consequently the corrected permeance would be:

$$P_g = \frac{A_g F}{\ell_g f} \quad (12)$$

F can vary widely from 1.5 to 10 in typical magnet designs. Usually f is much smaller and would have a typical range of 1.1 to 1.3 in most magnetic circuits.

In using permanent magnets the influence of external fields in changing the flux level is an important consideration. The geometry of the magnet and return path sets the self demagnetization (B_d/H_d ratio) and has considerable effect on the interaction of a magnet and an external field. To predict the change in flux density of a magnet in the presence of an external field, both the normal and intrinsic curves of the magnet material are required. Refer to Figure 11-7. If the unit permeance B_d/H_d is known, a line with a slope $B_d/H_d + 1$ will intersect the intrinsic curve and give the correct level of intrinsic magnetization. Now the magnitude of an external field $-H_a$ is laid off parallel to $B_d/H_d + 1$ slope. The intersection with the intrinsic curve is projected down to the normal curve to yield the new level of flux density in the presence of this external field influence. In Figure II-7 ΔB is the loss of flux density for $-H_a$ applied external field influence.

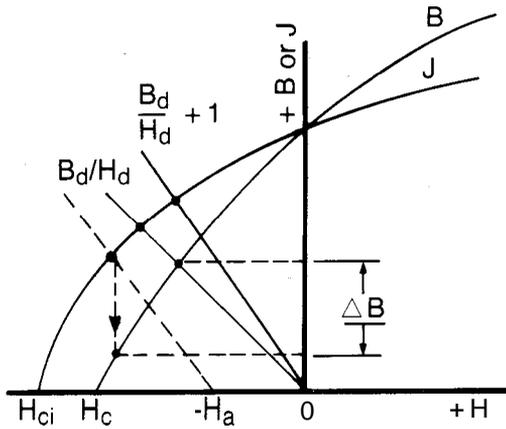


Figure 11-7. ΔB is the loss of flux density for $-H_a$ external applied field influence.

Use of Flux Conducting Materials in Permanent Magnet Circuits

Flux conducting members in a permanent magnet circuit are used to 1) complete a return path for the flux, 2) change the flux density in a circuit, or 3) form multiple magnet poles. Figure II-8 shows the circuits involved. In Figure II-9 some widely used high permeability materials are shown. Usually cost is an important factor in the choice of material. A high percentage of permanent magnet circuit elements are ordinary cold rolled steel. Cobalt-iron alloy is used in some high performance circuits. It is well to operate these materials near their maximum permeability. This will tend to minimize the cross sectional area and at the same time keep the magnetic potential loss to a low level. If the cross section is too small then the H drop in the material will tend to be high. This will cause an appreciable part of the

magnet's potential to be dropped in the circuit member and be unavailable as potential to use across the air gap. The longer the circuit member the more serious the problem.

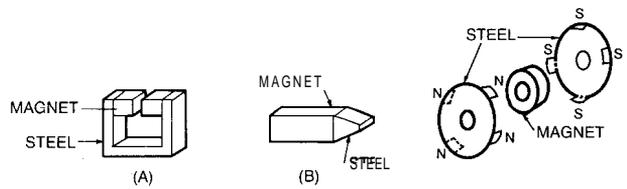


Figure II-8. The use of high permeability steel in permanent magnet circuits.

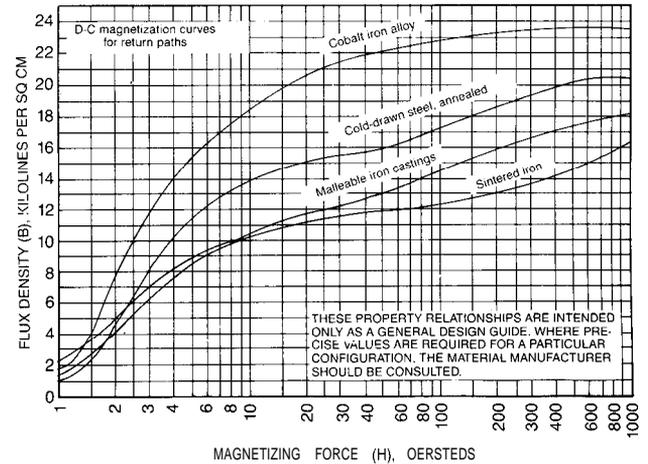


Figure II-9. Magnetization curves for some high permeability materials.

Another fundamental principle in permanent magnet circuits is illustrated in Figure 11-10. Here the location of the magnet in the circuit is of importance. The magnet should be as close to the gap as possible, otherwise the magnet's full potential will lead to excessive flux leakage between the circuit elements or pole pieces.

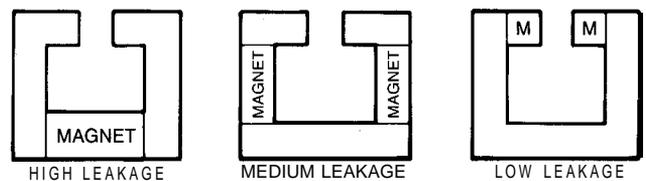


Figure 11-10. Circuit element location.

Some Important Figures of Merit

In developing the design relationships, mention was made of a magnet's volumetric efficiency. For a fixed static air gap it is desirable to operate at a particular B_d/H_d slope where the product of B_d and H_d is a maximum. This particular point on the normal demagnetization curve is defined at $(BH)_{max}$. Refer to Figure II-11(a). Depending on how the magnet is used there are some other important figures of merit to consider. If the magnet is used in an application that converts field

energy to mechanical work such as a holding or lifting magnet, it is a dynamic load situation. The cycle of events is shown in Figure II-11(b). In the design process we must control both P_2 and P_3 . Area $0 P_2 B_p$ represents the magnetic energy per unit that can be converted to mechanical work. This value, multiplied by magnet volume, would be the total area under a force-distance curve for a holding magnet. At a particular air gap between magnet and armature, or load represented by P_3 , the product of force and distance would be a maximum. We define the shaded rectangular area as (BH) , or useful energy. It will be less than $(BH)_{max}$ which is the total available energy per unit volume.

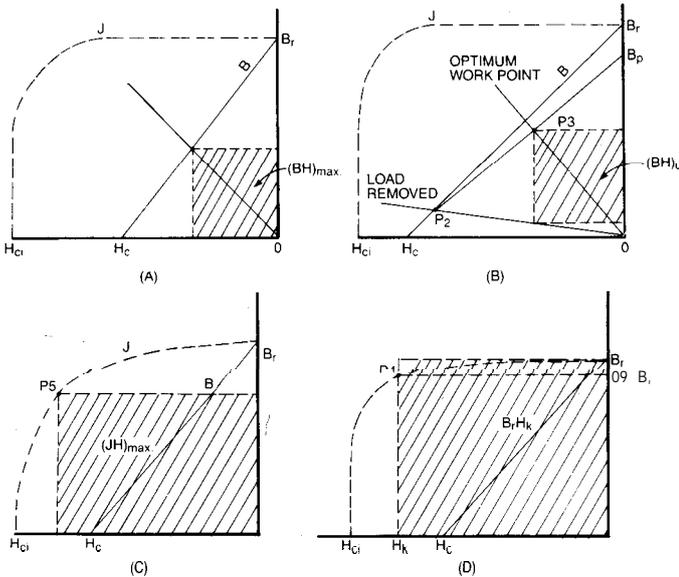


Figure II-11. Permanent magnet figures of merit.

Another type of permanent magnet use involves the exposure to a very high external field for a short time duration followed by a much lower self demagnetization field during continuous operation. The typical d.c. motor application subjects a magnet to the above described events. At start or stall the armature draws many times the normal running current. The figure of merit under such conditions is approximated by $(JH)_{max}$ as shown in Figure II-11(c). This is the largest rectangle which can be drawn under the J vs H demagnetization curve. The length of the magnet in a d.c. motor is inversely proportional to coercive force and the magnet area inversely proportional to B_r . Consequently the magnet volume will be inversely proportional to the rectangular area. A similar figure of merit $B_r H_k$ is shown in Figure II-11(d). Here we define H_k as the demagnetization field that reduces the intrinsic magnetization by 10%. In this case the knockdown is arbitrarily specified: in the case of the largest rectangular area a somewhat more intrinsic quantity as shown in Figure II-11(c) is involved.

Optimizing Permanent Magnet Circuits-Estimating Permeance and Finite Element Modeling

Over the years several analytical techniques have been used to give approximate solutions to magnetic field

problems. In the simplest cases the analytical solution can be exact, but in any practical problem analytical solutions are approximate and a large error between calculation and measurement can exist. In practice we have lumped circuit constants and electrical analog methods. For two dimensional analysis flux plotting on conducting paper has been useful. A simple modeling technique uses three dimensional foam and aluminum-wrap scale models to simulate the capacitance between circuit elements. Since capacitance is the analog of magnetic permeance one can easily arrive at accurate permeance values. Zoning can be used to improve the accuracy. Today most designs are optimized by measurement and reference to experiences with similar magnetic circuits.

Now the availability of digital computers means that very accurate numerical techniques such as finite element modeling can be used to study circuits, devices and systems. The timing is fortunate because rare earth permanent magnets are expensive. They tend to be used in sophisticated and costly systems. Accurate solutions are rather imperative if one is to fully exploit the potential of these new magnets and to arrive at cost effective solutions. The permanent magnet is a very interactive component and digital techniques allow us to explore many alternatives that can minimize material cost and the manufacturing events to arrive at a high-performance energy-conversion system. As the cost of computerized solutions improve and as the ease of getting the problem on to the computer improves, numerical analysis of magnetic circuits will be extensively used.

PART III. MEASURING

Some Basic Systems for Measuring Flux or Flux Density

Man's early attempts to express a magnetic field in quantitative terms involved force relationships between magnetic bodies. One early system used the force resulting from the magnet under test reacting with a moving magnet free to rotate to indicate relative strength. Figure III-1 shows the elements of a permanent magnet gaussmeter that is sometimes used to measure field strength.

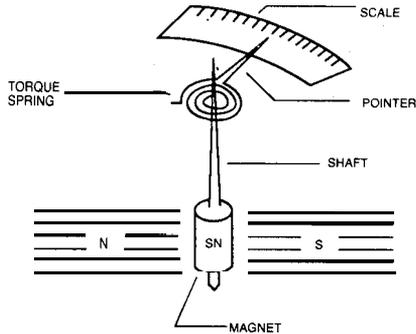


Figure III-1. Permanent magnet gaussmeter or magnetometer

A second system, based on Faraday's law, is the induced voltage method. An e.m.f. is induced in a coil when the magnetic flux within the coil changes.

$$e = n \frac{d\phi}{dt} 10^{-8} \text{ volts}$$

Where n is turns of the coil. Since the voltage changes with the rate of change of flux, the practice is not to measure voltage but to measure the time integral of voltage $\int e dt$. The above expression can be rewritten to give:

$$d\phi = \frac{10^8}{n} \int e dt \text{ by integration}$$

$$\Delta\phi = \int_{\phi_1}^{\phi_2} d\phi = \frac{10^8}{n} \int_0^t e dt = \text{maxwells}$$

Knowing the number of turns, one is able to calculate the total flux change from the $\int e dt$ measurement. The electronic integrating fluxmeter shown in Figure III-2 is an example of the induced voltage method.

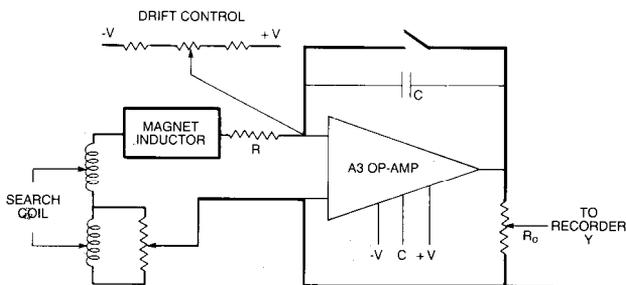


Figure III-2. B signal integration circuit (fluxmeter).

An interesting variation of the induced voltage method is to use a Helmholtz coil pair instead of a tight fitting coil around a magnet. A magnet being measured under open circuit conditions may be considered to be a magnetic dipole with orientation parallel to the axis of the coil set. The magnetic moment is B_i/V_m where V_m is sample volume. The coil arrangement and sample relationship is shown in Figure 111-3. As the magnet is moved from the center of the coil set to a point well outside the coils the time integrated voltage $\int e dt$ is measured with a fluxmeter or electronic integrator. The wave form is shown at the bottom of the figure. The value of $\int e dt$ is proportional to the magnetic moment of

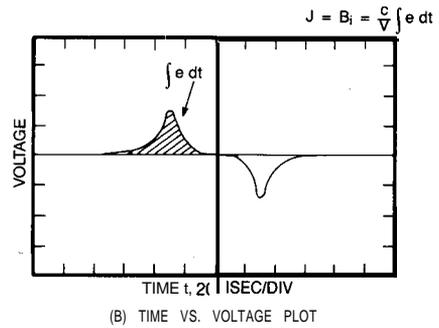
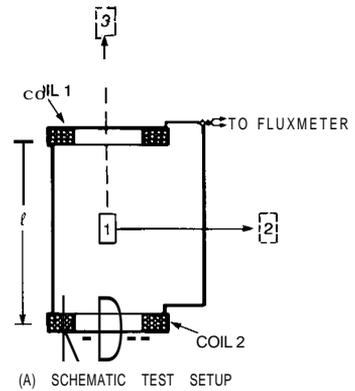


Figure 111-3. Measurement of magnetization in a Helmholtz coil.

the sample. Since B_i is the magnetic moment per unit volume it follows that,

$$B_i = \frac{c}{V_m} \int e dt$$

where c is a proportionality constant for the coil pair. This constant is independent of sample volume and shape if the sample is small with respect to coil diameter. The Helmholtz pair is a very convenient detector for use with high coercive force magnets where the typical sample is short. This technique frees one from tight fitting coils and corrections for high self demagnetizing fields. One coil set can measure a wide range of magnet volumes and shapes. However, one must know the load line rather accurately since it is necessary to subtract H_d from B_i to obtain B_d .

A third widely used system involves the Hall effect. The use of Hall generators in measurements has found wide acceptance. The small size of the field sensor element and the static characteristic (no relative motion is required) enables the Hall probe to be used in areas where measurements with the induced voltage method would not be feasible. Figure III-4 shows the principle elements of the measuring system using the Hall effect. The Hall output voltage (e) is given by the following equation:

$$e = \frac{R H i}{d}$$

Where R = Hall constant (material constant)
 H = field strength
 i = current across Hall element
 d = thickness of Hall element

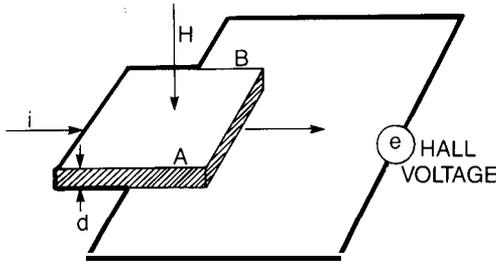


Figure 1114. The Hall effect, with a thin plate of material such as indium arsenide, placed in a magnetic field with its plane perpendicular to the field, a coincidental longitudinal current i , through the material produces a proportional transverse voltage e , between surfaces A and B.

When a thin plate of material exhibiting the Hall effect is placed in a magnetic field with its plane perpendicular to the field, a longitudinal current (i) through the material produces a proportional transverse voltage (e) between surfaces (A) and (B). The Hall elements can measure D.C. fields or A.C. fields. The output voltage is a function of the current and field characteristics. Because of its small size a Hall probe is ideally suited to check field homogeneity and is useful in flux plotting. The Hall output voltage is a sine function of the angle between the lines of force and the plane of the Hall element. At any point in a field where the output is zero, it follows that the lines are parallel to the Hall element. When the element is oriented for maximum output, the lines are perpendicular to the element.

Direct and continuous reading of field strength coupled with relatively low equipment investment cost have made the Hall system widely used in production measurements.

To measure magnetic potential (F) between two points, a special coil known as the Chattock magnetic potential coil is used. Physically the Chattock coil consists of a flexible strip of non-metallic material of uniform cross section, uniformly wound with fine wire. The coil is connected to an integrating instrument such as an electronic flux meter. The Chattock coil is essentially the

magnetic equivalent of a voltmeter. Referring to Figure III-5 the magnetic potential between two points x_1 and x_2 is defined as the work done in moving a unit pole between the two points. We can express the potential difference between x_1 and x_2 as:

$$\int_{x_1}^{x_2} H \cos \theta dx$$

Measurement of Magnetic Potential Between Two Points

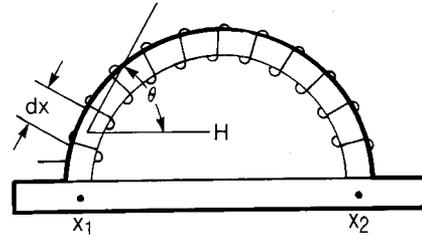


Figure III-5. A Chattock coil to measure the magnetic potential difference between points x_1 and x_2 of a bar magnet.

Where dx is a small increment of the path and θ is the angular displacement between the directions of H and dx . If the Chattock coil has an area A and n_u turns per unit length, the flux linkages in length dx are equal to $A n_u H \cos \theta dx$ and the total interlinkages from x_1 to x_2 are:

$$n\theta = A n_u \int_{x_1}^{x_2} H \cos \theta dx$$

or:

$$\theta n = A n_u \text{ (potential between points)}$$

$$\text{potential between } x_1 \text{ and } x_2 = \frac{\theta n}{A n_u}$$

Unit Property Measurements

The basis of information exchange in the permanent magnet industry is the relationships between B_1 , B and H and the unit property intercepts B_r , H_c , H_{ci} and $(BH)_{max}$. To determine this data the demagnetization curves or second and third quadrants of the hysteresis loop must be plotted.

The procedure outlined in the following section on unit property measurement focuses on a uniform set of procedures regarding sample selection, field uniformity conditions and arrangement of sensors and instrumentation.

Introduction

The following information is intended to help users obtain accurate unit property measurements on permanent magnets. Lack of accepted magnetization references and non-uniform techniques and procedures have long been severe problems in industry. At present we have the technology to permit both producer and user to measure magnetic properties based on length, area and

volume unit dimensions within a very narrow error band provided due attention is paid to several sensitive issues, which can introduce errors. The procedures discussed call attention to these issues while providing techniques flexible enough to permit use of a wide range of equipment.

The focus is on obtaining the demagnetization curve (second quadrant of the hysteresis loop) of a specimen. The relationships between the magnetic induction (B), the field strength (H) and the intrinsic induction (B_i) are shown by the demagnetization characteristic (Figure III-6). Important unit property values for residual induction B_r , coercive force H_c , intrinsic coercive force H_{ci} and maximum energy product $(BH)_{max}$ can be obtained from the demagnetization curves.

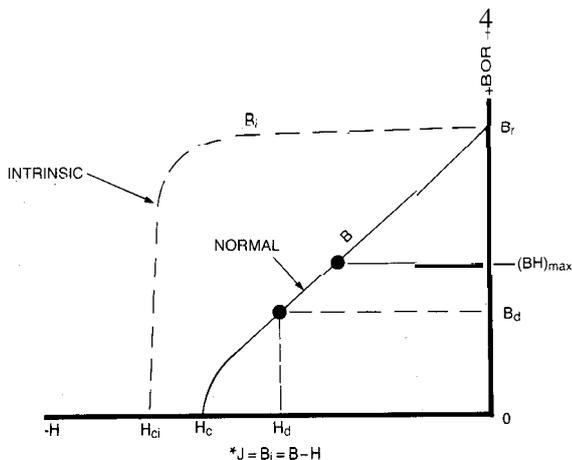


Figure III-6. Property relationships (second quadrant).

1. Electromagnetic Yoke

The measurements are carried out in a closed circuit consisting of the test specimen and a yoke or return path made of soft magnetic material. The yoke should be of symmetrical construction and at least one pole should be movable to accommodate various specimen lengths and ensure minimum air gap between specimen and pole pieces (Figure 111-7). The coercivity of the yoke and pole pieces should not be more than 2 oersteds.

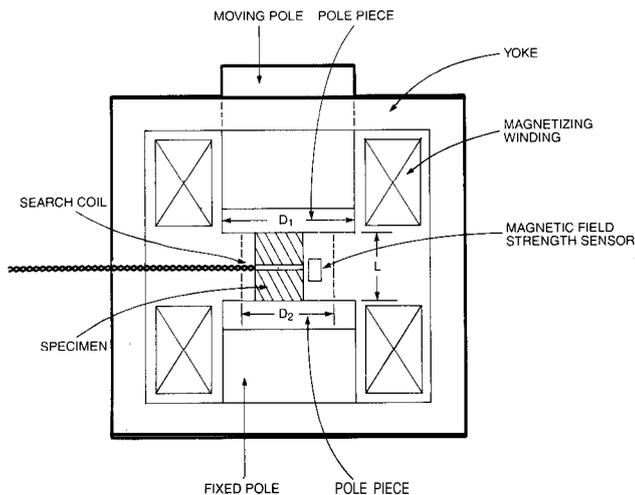


Figure III-7. Electromagnet and specimen arrangement.

2. Field Uniformity Requirements

To obtain uniform magnetization in the region occupied by the specimen, certain geometric relationships linking specimen dimensions and electromagnet gap dimensions must be maintained. See Figure 111-7.

$$D_1 \geq D_2 + 1.2 L \quad (1)$$

$$\text{Also } D_1 \geq 2.0 L \quad (2)$$

Where D_1 = diameter of a circular pole piece or the shortest dimension of a rectangular pole piece.

L = Distance between pole pieces.

D_2 = Maximum diameter of the cylindrical volume with a uniform field.

It is necessary that the flux density in the pole pieces be well below the saturation level of the poles, so that the pole faces shall be near equipotential conditions. The recommended practice is to limit the flux density to 10 kilogauss in iron and 12 kilogauss in iron cobalt (Permendur) pole pieces. If the foregoing conditions are met, the field in the specified volume is uniform to within 2% in both radial and axial directions. However, these recommended kilogauss levels are often unreasonably low at the pole tips for high coercive force materials. Consequently, field distortion must be considered when higher flux density levels are used.

3. Field Strength Requirements

The value of the field strength varies according to the nature of the permanent magnet material and its prior history. Generally saturation is achieved with fields of the order of 3-5 times the intrinsic coercive force (H_{ci}). With SmCo_5 and many other rare earth PM materials this ratio is less when magnetizing specimens that have had no prior exposure to a magnetic field. A practical way to determine saturation is to expose a specimen to a value of field H_1 and note the level of magnetic induction, then apply a field H_2 25% greater than H_1 . If the magnetic induction increases less than 1%, one can conclude that level H_1 was adequate to saturate the material. For extremely high field requirements an alternative procedure is to magnetize the specimen by impulse in a solenoid and transfer it to the electromagnetic yoke. In this situation it is imperative that the specimen geometry be such that an irreversible loss of magnetization does not occur due to self demagnetizing influence of the free poles. This is of great concern if the material has a non-linear shaped demagnetization curve. However, most of this loss can be recovered by remagnetizing the sample (in the closed yoke structure) before generating the demagnetization curve.

4. Test Specimen Considerations

The test specimen should have a simple configuration (cylinder or parallelepiped) whose dimensions are chosen according to equations (1) and (2). The length L should not be less than 5 mm. The faces should be ground parallel to each other and perpendicular to the specimen axis to reduce air gap between specimen and poles. The cross sectional area should be uniform over the length of the specimen.

5. Integration of the Flux Density

The change in flux density in the specimen is determined by integration of the induced voltage in a search coil around the specimen. The coil should be wound as closely as possible on the magnet and should be symmetrical with respect to the pole pieces. The leads must be tightly twisted to avoid voltage being induced in the lead loops. It is possible to minimize error in the flux density measurement by following the above. Acceptable error in the flux density measurement is of the order of $\pm 1\%$. The variation of flux density B in the specimen between time t_1 and t_2 is given by:

$$\Delta B = B_2 - B_1 = \frac{10^{-8}}{AN} \int_{t_1}^{t_2} edt \quad (3)$$

Where B_2 = the flux density in gauss at time t_2 .
 B_1 = the flux density in gauss at time t_1 .
 A = cross section of specimen in sq. cm.
 N = number of coil turns.
 edt = the induced voltage in volt seconds.

It is necessary to correct the change in flux density by taking into account the flux included in the search coil. The corrected change is given by:

$$\Delta B_{\text{corr}} = \frac{10^{-8}}{AN} \int_{t_1}^{t_2} edt - \Delta H \frac{A_t - A}{A} \quad (4)$$

Where ΔH = the change in field strength in oersteds.

A , = effective cross section area of coil in sq. cm. based on mean coil diameter.

6. Measurement of Field Strength

The field strength at the specimen surface is equal to the field strength inside the specimen only in that part of space where the field strength vector is parallel to the side surface of the specimen. Therefore the field sensor must be placed in the homogeneous field zone as near the specimen as possible and symmetrical with respect to the poles. The field strength can be determined by using a search coil, a magnetic potentiometer, or a Hall probe. A suitable readout instrument must be used. The dimensions of the field sensor and its location must be within the area limited by diameter D_2 [refer to equations (1) and (2)]. The field sensor or transducer must be calibrated so that the total error is within $\pm 1\%$.

When using Hall probes, non-linearity must be considered, especially above 10,000 gauss.

7. Determination of Demagnetization Curve

For the measurements described below a low-drift fluxmeter or a ballistic galvanometer is used to measure the voltage integral. The test specimen is assembled in the electromagnet and saturated at a high magnetic field strength H_{max} . At this field strength, the induction in the specimen is equal to B_{max} , Figure III-g(a). Then the current is switched off and the change of magnetic flux density $\Delta B_1 = B_{\text{max}} - B'$, can be measured. The magnetic field strength in the absence of the magnetizing current is not zero ($H'_r \neq 0$) due to the permanent magnetization of the poles and yoke. Consequently, $B' \neq B_r$. The value H'_r , like any other value of magnetic field strength, may be measured with the magnetic field strength sensor inserted into the space between the pole pieces. By increasing the negative magnetizing

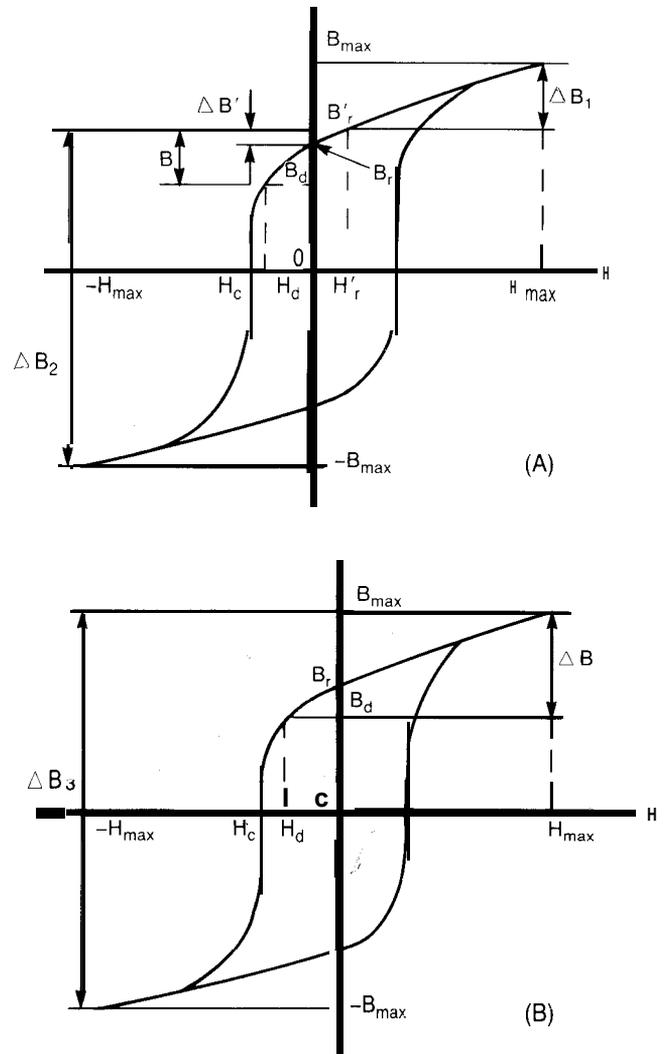


Figure III-8. Principal points on the hysteresis loop.

current to obtain the value $-H_{\max}$, the change of flux density $\Delta B_2 = B' + B_{\max}$ can be measured. The value of the magnetic flux density B'_r is calculated from:

$$B'_r = \frac{\Delta B_2 - \Delta B_1}{2} \quad (5)$$

The test specimen is again magnetized to the point B_{\max} , H_{\max} and after switching off the magnetizing current the magnetic flux density returns to the point B'_r , H'_r . After a negative magnetic field has been applied, the magnetic flux density at any point B_d , H_d can be calculated from the flux density change ΔB according to the equation:

$$B_d = B'_r - \Delta B \quad (6)$$

The determination of any pair of associated values B and H on the demagnetization curve shall start from the point B'_r , H'_r , and necessitates magnetizing the specimen to B_{\max} , H_{\max} . The actual value of the residual flux density B'_r may be obtained by the linear interpolation of the nearest points. To avoid the repetition of magnetizing to B_{\max} , H_{\max} several points B , H can be determined by successive changes ΔB , ΔH between the points, but this method increases the measuring error.

Together with the above mentioned procedures, the following measurement order is recommended:

The value of B_{\max} corresponding to the maximum magnetizing current, is determined by reversing the maximum magnetizing current without changing its value:

$$B_{\max} = \frac{\Delta B_3}{2} \quad [\text{Figure III-8(b)}] \quad (7)$$

To determine value of the magnetic flux density B at any point on the demagnetization curve, the value of the demagnetizing current should be such as to produce the field strength H corresponding to this point on the curve. Then the cyclic remagnetization of the specimen is repeated. After that the change of the magnetic flux density ΔB is determined by changing the magnetizing current from the value corresponding to the required value up to its maximum value.

The magnetic flux density is calculated from the equation:

$$B_d = B_{\max} - \Delta B \quad (8)$$

An alternative method for determining the demagnetization curve is the use of an electronic integrator. The integrator is connected to the search coil and is adjusted to zero. Then the demagnetized test specimen is put into the search coil and the assembly mounted in the electromagnet. After magnetizing to the required magnetic field strength the magnetizing current is switched off. However, the values of the magnetic flux density B'_r and the magnetic field strength H'_r may still be in the

first quadrant because of the permanent magnetization of the poles and the yoke. The current is then reversed and increased until the magnetic field has passed the coercivity H_C or H_{Ci} . The speed of the variation of the magnetic field strength shall be sufficiently slow to avoid producing a phase difference between H and B . With some materials there is a considerable delay between the change in the magnetic flux density and the magnetic field strength. In this case, the time constant of the flux integrator should be long enough to ensure accurate integration. Although the procedure detailed is for obtaining the $B(H)$ demagnetization curve, one can easily obtain the $B_i(H)$ by arranging to add H to the B value at every point. (In the second quadrant $B_i = B + H$.) Measuring $B_i(H)$ demagnetization characteristic is of major importance when a permanent magnet is subjected to external demagnetization influences in service.

8. Calibration Techniques and Standards

The calibration of the integrating flux meter or galvanometer can be achieved by one of the following:

- (1) Use of a calibrated volt-second source. A very stable voltage source and an accurate timer are combined into a calibration device. An accuracy of $\pm 0.1\%$ is achievable with a volt-second reference.
- (2) Use of a mutual inductance standard with the switching on and off of the primary current, which can be read with good precision. A known flux change is produced in the inductor secondary which can be used for calibration purposes. An accuracy of $\pm 0.1\%$ is achievable with the mutual inductor.
- (3) Use of search coil of known area turns in a known homogenous magnetic field that is measured with nuclear resonance technique. An accuracy of $\pm 0.01\%$ is possible with this approach.
- (4) For convenience a secondary standard reference is often used in calibration of magnetic test equipment. A specimen of pure nickel makes a very good reference. The saturation magnetization of nickel is quite invariant and if the area is determined accurately there will be a known level of flux for calibration. Additionally, a permanent magnet that has been stabilized and temperature cycled makes a very good flux reference. An error of $\pm 0.5\%$ in the calibration procedure is to be expected with secondary references.

9. Reference Documents

- ASTM A-34, Testing Magnetic Materials
- ASTM A-340, Standard Terminology of Symbols and Definitions Relating to Magnetic Testing

Acceptance Testing of Production Quantities

Unit properties determined by obtaining demagnetization curves are generally not used in acceptance testing. Obtaining the complete demagnetization curves is time consuming and costly. Often the closed circuit test does not identify the range of operating field conditions in a device. Samples for unit property testing must be of a critical size and shape. If the actual magnet component involved is large or non-uniform in cross section samples must be cut from it which are suitable for the unit property tests. This obviously leads to destructive testing. In acceptance testing a test is required that will classify magnets into acceptable or unacceptable categories for a specific application. This kind of test is useful for quality control in the magnet producing plant and also as an incoming inspection test in the user's plant. A satisfactory acceptance test must simulate the magnetic circuit conditions and the field environment of the actual device or system in which the magnet is used. In some applications a magnet must be subjected to demagnetizing conditions set up by the end device. Often a magnet is used in a circuit where it is magnetized in place and its load line is higher than the open circuit load line. In such a situation it may be necessary to remagnetize the magnet if for any reason it is removed from its magnetic circuit. This situation is dependent on the H_{ci} of the material. Often high H_{ci} materials are specified when open circuit conditions and low load lines are involved.

Acceptance testing generally requires a fixture that can be adjusted so the magnet under test is working at the same load conditions as in the actual device.

Reference Magnets

It is suggested that a reference magnet be used in acceptance testing rather than exchanging and using absolute magnetic quantities. Reference magnets are magnets selected and approved by the producer and user to allow satisfactory function of the end device.

In addition to magnetic measurements it is at times desirable to test for related variables—for example, force or torque between magnets or between a magnet and a soft iron armature. A generated voltage test is at times useful for testing magnets and magnet assemblies used in motors, generators and tachometers. In multi-pole structures the average flux is measured. At constant speed and load conditions the generated voltage is proportional to average magnetic flux.

Measurements for Optimizing a Permanent Magnet Structure

An important category of measurements is involved in the analysis of a permanent magnet circuit. For example in the simple circuit shown in Figure III-9 one would like to check the load line of the device. Additionally there may be questions about the potential loss in the pole pieces and the air gap flux density H_g . An indicating instrument such as a fluxmeter or electronic digital integrator and some simple coils are all that is needed to completely analyze the structure. As indicated in Figure III-S(a) the H_g of the gap can be measured with a gaussmeter or a small coil and fluxmeter. Another test method uses a potential coil to measure total magnetomotive force F across the gap. Dividing F by l_g , the gap length, gives a value for H_g . This technique can be used when the gap is very short and a thin enough Hall probe or search coil is not available. To determine the load line, wrap a few turns of wire around the magnet and pull the magnet from the assembly and the coil [Figure III-S(b)]. Knowing the magnet area, B_d can be computed. H_d can be determined by moving a potential coil from point a to b and shown in Figure III-9(c). With known values for both H_d and B_d , the slope of the operating line, B_d/H_d , can be calculated. Perhaps there is a question about pole piece material or the magnetomotive force (F) loss in the pole pieces (has the designer selected the iron cross section for optimum H drop in the iron?). In Figure III-S(d) the use of the potential coil allows one to measure the F drop between point a and b and by dividing F by the length of iron the unit potential drop in the iron can be determined. From magnetization curves for various flux conducting materials one can then make a determination regarding how reasonable is the potential loss in the iron.

MEASUREMENT TO BE MADE	TECHNIQUE
Measure H_g in magnet assembly air gap $H_g = F/l_g$ Alternate way is use Hall probe or small search coil.	(A) FLUXMETER
Measure B_d in magnet measure H_d as shown in (c) below Determine load line B_d/H_d	(B) FLUXMETER
Measure internal field H_d in magnet $H_d = F_m/l_m$	(C) FLUXMETER
Measure magnetic potential loss in iron pole piece.	(D) FLUXMETER

Figure 1118. Measurements for design analysis.

PART IV. MAGNETIZING AND DEMAGNETIZING

Changing the state of magnetization is a very important consideration in using permanent magnets. For a permanent magnet to exhibit full properties, it must be fully magnetized or saturated. Partial magnetization results in reduced properties, and efficiency and stability are compromised.

The magnet producer generally ships demagnetized magnets to the user. The principle reason for this practice is that most magnets are designed for magnetization in the environment of a completed magnetic circuit. Additionally, shipping costs of magnetized magnets are greater and the danger of collecting small magnetic particles in air gaps is reduced with a demagnetized magnet.

Recent progress in property development has been largely in terms of increased coercivity. With increased resistance to demagnetization, such materials are proportionately more difficult to magnetize. Successful use of the newer high coercive force magnets requires magnetizing equipment capable of producing very high field levels as well as a good understanding of the magnetization process. Early low coercive force permanent magnets were magnetized with rather modest levels of field. Little consideration was necessary as to how magnetization was achieved. In considering high H_{ci} rare earth magnets one needs to be aware of the high field requirements and of the flux density levels the magnetizing path must be capable of handling. The basic design often will be influenced by how to magnetize. It is very easy to design structures that simply will not allow in-place magnetization.

Magnetizing Requirements

To fully magnetize the following must be considered: (a) External field magnitudes, (b) The effective net field seen by the permanent magnet due to self demagnetization and magnetic circuit influences, (c) Conformance of the shape of the field to the magnet geometry being magnetized, (d) The time required to magnetize and the problem of field penetration, (e) Field distortion events after magnetization that may leave the magnet partially demagnetized

(a) The net effective field required to saturate a given permanent magnet material can be determined from the hysteresis loop. Figure IV-1 shows a typical relationship between intrinsic magnetization (J) and magnetizing force (H). As the field is increased J will approach some maximum value (J_s) characteristic of the material. The value of saturation field strength (H_s) is usually of the order of 3 to 5 times the H_{ci} of the material. Figure IV-1 represents the conditions of a closed magnetic circuit. The influence of self demagnetization will be developed later.

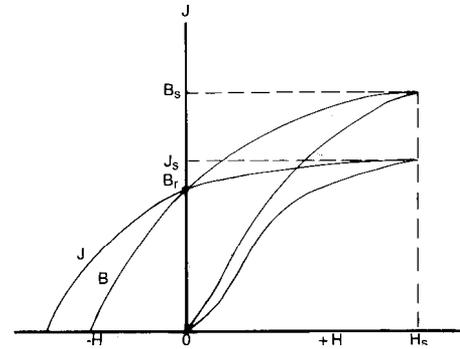


Figure IV-1. Magnetization curves.

The demagnetization curves of J and B versus H supplied by magnet producers are measured with the material in a saturated condition. Failure to properly saturate a magnet designed on the basis of the given property curve will lead to disappointing results. In order to evaluate and compare permanent magnet materials each must be fully magnetized. Figure IV-2 shows the sensitivity of magnet properties to levels of magnetizing force for SmCo_5 . It is clear from this example that partial magnetization would be wasteful and that properties achieved are non linear with applied field level.

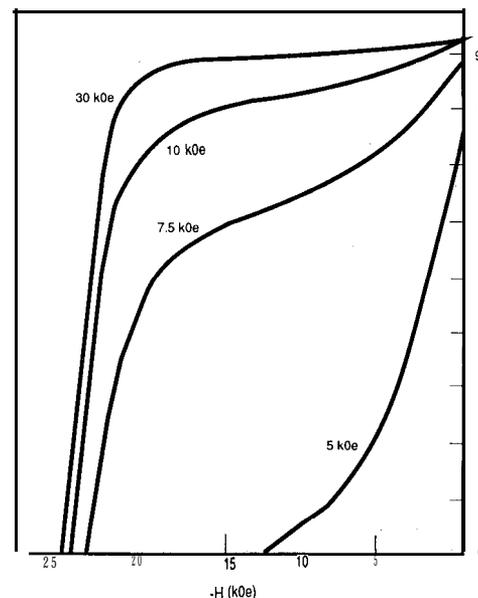


Figure IV-2. SmCo_5 magnetized at various levels of field.

Several methods can be used to determine when a magnet is saturated. It is quite easy to check the applied field level with a gaussmeter in the case of d.c. fields. With pulse fields, a Hall probe operated in the d.c. mode in conjunction with an oscilloscope can be used. Another technique is to check for saturation by field reversal. This check is performed by magnetizing and measurement in a specified manner and then the same field is applied in the opposite direction. The magnet is tested again and if the

results are the same, the field level may be considered adequate. It is also possible to apply an initial field level and make a reference measurement. Then, a field level larger by perhaps 25% is used and if the magnetization does not increase it is safe to assume that the initial field level is adequate.

- (b) The field levels suggested by magnet producers are always the actual or net field levels as seen by the permanent magnet. In practice, the only time the applied field is the same as the actual field is when the magnet is in essentially a closed low reluctance circuit such as magnetization in an iron yoke electromagnet. In this case the total F applied will be very close to the F across the magnet. The general problem is one of magnetizing in a magnetic circuit which is designed to handle the operating flux from the magnet and not the higher flux level associated with magnetization. Air gaps are present and often parallel return paths must be saturated, which means extra flux lines during magnetization. Consider the case of a short rectangular magnet being magnetized in an air solenoid Figure IV-3. The permeance coefficient $-B/H$ is determined from the magnet geometry as developed in the design section. If a line is drawn through the J_s, H_s point having a slope $B/Y + 1$ the intersection of this line with the H axis will give the total field necessary to magnetize. $H_t - H_s$ is the field necessary to overcome the magnet's self demagnetizing influence and allow a net H_s to be experienced by the magnet. For open circuit conditions with low B/H values, the total field requirements can be reduced by magnetizing several magnets in series.

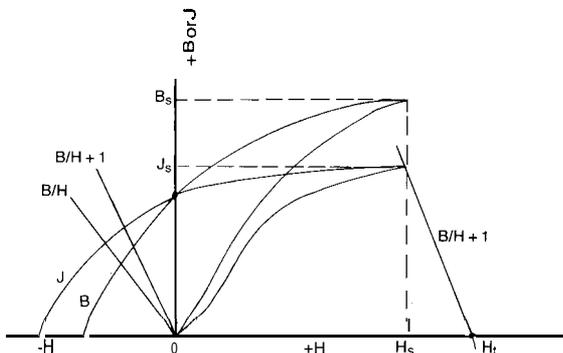


Figure IV-3. Analysis of self demagnetizing field.

- (c) Partial magnetization may occur if the field generated does not conform to the configuration of the magnet. The permeability of most permanent magnets is very low and hence, the presence of the magnet does little to shape an applied field. The field should always coincide with the easy axis of the permanent magnet. When magnet configuration and field do not coincide, it is possible to have fields that are too great, which in effect, leave regions magnetized off axis and the result appears as partial magnetization. Figure IV-4 shows the influence of a field applied at various angles to alnico 5-7, which is a highly anisotropic material.

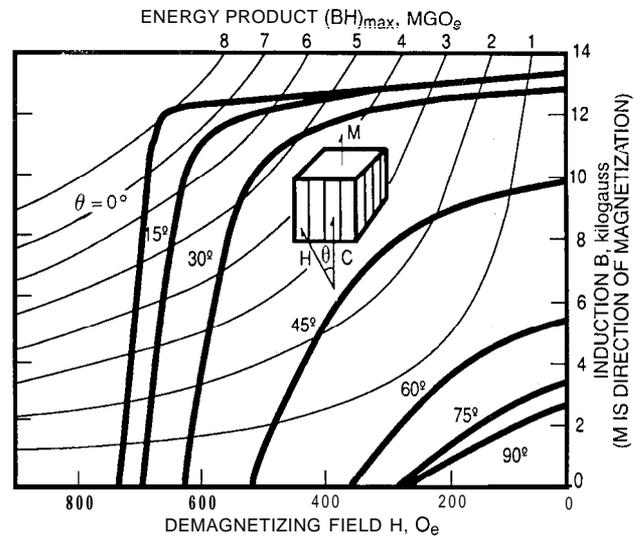


Figure IV-4. Influence of various angles of field application (alnico 5-7).

- (d) Although the magnetization process is essentially instantaneous, the time duration of the applied field is important because of the existence of eddy currents in metallic materials. Also, with highly inductive electromagnets, the current rise time may be of the order of 1-2 seconds.

Figure IV-5 shows a relationship inter-relating depth of penetration with resistivity, permeability and frequency of wave form. In general, the frequency must be chosen so that the magnetizing pulse lasts longer than the eddy current. The eddy current path is a function of geometry and for large metallic magnets there are problems with penetration. The general experience with alnico and rare earth magnets has been to use about 10 millisecond minimum pulse width. This width of pulse allows a wide range of magnet configurations and sizes to be fully magnetized.

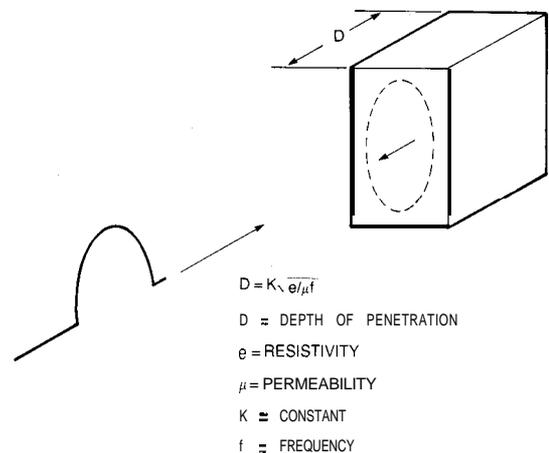


Figure IV-5. Effects of eddy currents.

- (e) After calibration it is possible to inadvertently demagnetize a magnet with improper handling; therefore care must be taken to preserve the original condition of magnetization. A magnetized magnet should not be touched along its length with ferro-

magnetic objects. Such action will produce consequent poles which alters the main flux pattern and reduces the useful flux in the gap or at the pole surface of the magnet. Also magnets can be demagnetized by repeated contact with poles in repulsion. Improper handling is most serious with magnets having H_{ci} appreciably less than B_r .

Magnetizing Equipment

Direct current structures such as electromagnets are the oldest and still an important equipment category to consider in magnetizing permanent magnets. An example of the field developed as a function of current and pole spacing in an electromagnet yoke magnetizer is shown in Figure IV-6. Such a unit with a controllable power supply can serve many laboratory measurement functions, including obtaining hysteresis loops and demagnetization curves to characterize permanent magnets. Due to penetration problems mentioned previously a d.c. magnetizer can be used advantageously to magnetize large section metallic magnets. An electromagnet yoke magnetizer is somewhat limited to rectangular or cylindrical form magnets having straight-through direction of magnetization.

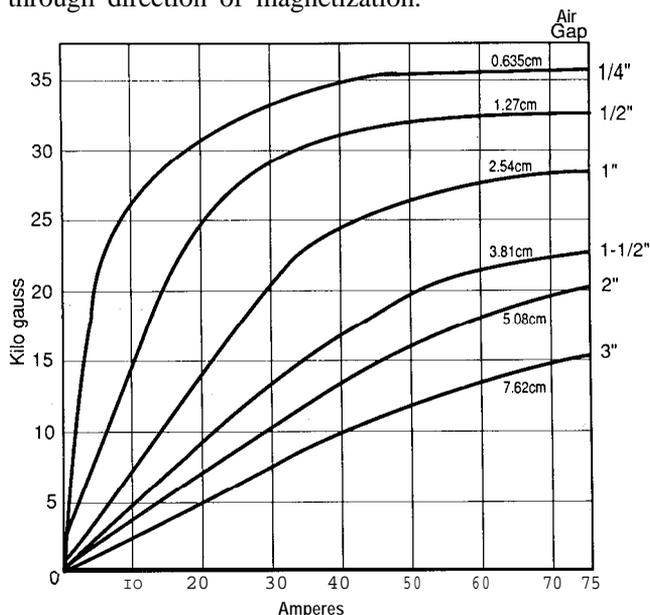


Figure IV-6. Electromagnet gap fields.

Another widely used d.c. structure is the open solenoid often used in production since it permits magnets to move through in a continuous stream.

In some instances the steady state field of one permanent magnet is used to magnetize another permanent magnet. However, there are problems in avoiding distortion as the magnet being magnetized is removed from the larger magnet supplying the field. In this case the magnetizing energy is supplied in terms of mechanical input from the person removing the magnetized magnet.

Since the time interval required to magnetize is extremely short, magnetization can be achieved by a

current pulse, provided its magnitude is sufficient to deliver the peak H requirement. The development of materials with high coercive force has led to short magnet lengths and parallel circuits. There are also many magnet configurations with multiple poles that cannot be magnetized by placing them in contact with conventional electromagnetic structures. The use of a single conductor or a few conductors threading through the magnetic circuit is necessary.

Impulse magnetization has become popular not only for its necessity in some circuits but generally for nearly all types of magnetization because of the modest investment requirements. The basic components of a capacitor discharge magnetizer are shown in Figure IV-7. The capacitor is charged to voltage V at a rate determined by R. The capacitor (C) is switched to discharge into a coil having inductance (L) and resistance (R). If R is greater than $2\sqrt{L/C}$, the current will be unidirectional without oscillations.

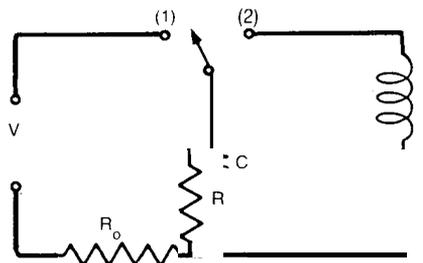


Figure IV-7. Basic elements of capacitor discharge magnetizer.

Another type of impulse magnetizer is the half cycle magnetizer shown in Figure IV-8. Such a system has the disadvantage of drawing the current surge directly from the power line. It, however, offers a very rapid repetition rate and is often used in production. The timing and phase shifting control features allow the current level to be adjusted. Figure IV-9 shows voltage, current and flux changes for various firing points in the half cycle. Figure IV-10 shows several conductor arrangements used to achieve specific magnetization patterns with current pulses.

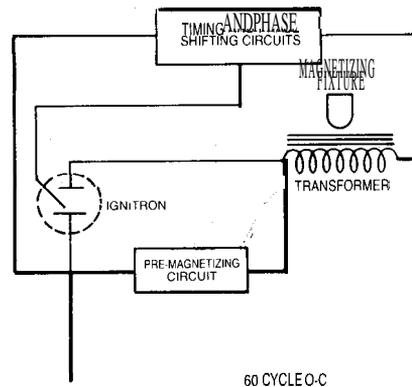


Figure IV-8. Half-cycle magnetizer circuit passes half-cycle current impulses whose amplitude and duration is controlled by the firing of a thyatron in the ignitor circuit. For currents above 10,000 amp a transformer is used. To prevent flux reversal, a pre-magnetizing circuit saturates the transformer with d-c pulses of opposite polarity to the main pulse.

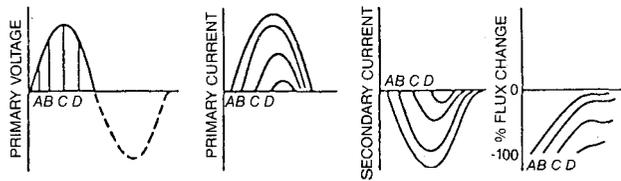


Figure IV-9. Voltage, current and flux change for various firing points on a half-cycle magnetizer with transformer.

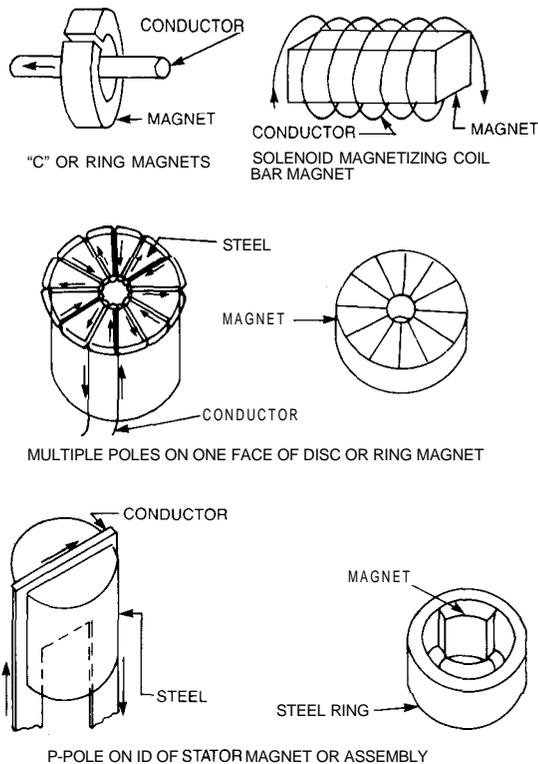


Figure IV-10. Magnetizing conductor arrangements.

Demagnetization

Both producers and users of permanent magnets find it necessary to demagnetize magnets. The producer magnetizes magnets to check quality and must then demagnetize prior to shipping. The magnet user will often find need to partially demagnetize to calibrate or to stabilize against adverse fields or temperature variations. The most common method of demagnetization is to subject the magnet to an a.c. field of a magnitude sufficient to nearly fully magnetize and then gradually reduce this field by pulling the magnet slowly from the field or by slowly reducing the a.c. current. It is also useful to produce a damped wave form by charging a capacitor and discharging into a coil. By proper choice of R, L and C an oscillatory wave form can be obtained, Figure IV-7.

With large metallic magnets a.c. fields are often ineffective due to eddy current shielding. A d.c. supply with some means to vary current and a reversing switch, is the best way to demagnetize very large magnets. The technique involves applying the field in alternate directions at the same time the field magnitude is slowly reduced. By experimenting with the cycles and field reduction per cycle, fairly complete demagnetization can be obtained.

With rare earth magnets some success in demagnetization has been achieved by using both thermal and field energy to demagnetize. Exposing the magnet to perhaps 150°-200°C in conjunction with a.c. field of 1000 oersteds has been useful. If the temperature of a magnetized magnet is raised above its Curie temperature and then returned to room temperature complete demagnetization occurs. This procedure works well with ceramic magnets but with metallic magnets structural changes may occur at the higher temperatures that cause properties to be changed.

PART V. STABILIZING AND HANDLING

Introduction and Clarification of Magnetization Changes

A compelling reason to use permanent magnets in many devices and systems is the magnet's ability to maintain a constant flux output over a very long period of time. In most uses the magnet is subjected to influences that tend to alter the flux output to some extent. If the nature and extent of these influences is known it is possible to predict the amount of the flux change. It is also possible, by exposing the magnet to the influence in advance, to render the magnet insensitive to subsequent changes during the life span of the device. Using special stabilization techniques it is common to achieve field constancy of 1 part change in 105. To achieve this order of stability with a regulated electromagnet would be prohibitively complex and costly. Today's stability achievements with modern permanent magnets are in sharp contrast to very early permanent magnets which exhibited structural or metallurgical change with time.

It is helpful to classify the magnetization changes as to their nature and cause:

(1) **Reversible Changes**-The reversible change in flux as a function of temperature originates from the change in spontaneous magnetization. These changes obey the same temperature law as does saturation magnetization. Reversible changes are functions of temperature and are not time dependent. They disappear completely without need for remagnetization when the magnet is returned to its initial temperature.

(2) **Irreversible Change Resulting from a Change in The Magnetic State**-In this type of change after removal of the disturbing influence the magnetization does not return to the original value. Examples of such changes are:

- (A) Ambient temperature changes
- (B) After-effects
- (C) Magnetic field induced changes such as an external field or change in magnetic circuit permeance or load line

In the above changes, magnetization may be fully restored by remagnetization at room temperature.

(3) **Permanent Irreversible Change Resulting From a Change in the Structural or Metallurgical State.** Examples of such changes which are generally time-temperature dependent are:

- (A) Oxidation
- (B) Phase Change

Remagnetization does not restore the original state of magnetization after this type of change. In the literature this type change is often referred to as aging since there may be time dependence. The temperature at which change in properties first occur corresponds closely to the maximum recommended service temperature.

No energy is required to maintain a magnetic field. Energy is only required to change a field. Thermal, mechanical, magnetic field and radiation are energy input forms that may change a permanent magnet field.

The magnetization in a permanent magnet is held by a net internal field ($H_{ci} - H_d$). There is a dynamic energy balance which involves thermal energy and internal field energy. The magnetic state is stable when the thermal energy is low compared to the internal field. We are concerned with the coercive force mechanism and the temperature dependence of H_{ci} . If, for example, there is a difference between room temperature H_{ci} and H_{ci} at an elevated temperature, the formation of reversed domains will take place as soon as the temperature changes, until a new internal energy balance is achieved.

Time Effects at Constant Temperature

These changes are known as after effects or sometimes magnetic viscosity. The domain regions of a freshly magnetized magnet are in a self imposed internal field. They are also in a field that fluctuates in time. At a particular site in the magnet small local temperature excursions occur. The temperature change causes a field change and an energy unbalance and hence a time adjustment of magnetization. Because the change is thermally activated it can be accelerated with increased temperature. The after effect can also be anticipated and stabilization can be achieved by subjecting the magnet to an alternating field sufficient to demagnetize to the extent of the loss which would occur during the time period of interest. In practice demagnetizing 3-5% is usual. Table V-1 shows the constant temperature (room temperature) adjustment with respect to time for four widely used permanent magnet materials. The magnitude of the change is of little concern unless one is working with a calibrated device.

Table V-1.
Examples of property changes with time.

Material	Loss Per Log Cycle	LOSS At 100,000 Hrs (11.4 years)
C e r a m i c	Essentially Zero	Essentially Zero
Alnico 5 (near residual)	0.01%	0.06%
Alnico 5 (near max. energy).	0.15%	0.9%
Alnico 5 (near coercive)	0.4%	2.4%
Alnico 8—no data (expected to be less than Alnico 5)		
SmCo ₅	0.08%	0.5%

Structural and Metallurgical Changes

Alnico magnets are very stable and have no oxidation problems up to about 500°C. Ferrite magnets are not subject to oxidation but due to their lower Curie temperature are not used above 400°C.

Rare earth magnets have oxidation problems which limit their use to between 200°C and 300°C. For example with SmCo₅ as temperature and time increase, oxygen diffuses into the material causing an oxidized layer to form. This oxidized layer has a changed composition and a much lower coercive force. The internal field of the magnet will reverse the magnetization of the outer layer. This leads to a compounding of flux loss since the outer layer represents a flux loss because of its volume which is not effective and also it acts as a shunt in reducing the output of the interior magnet. For SmCo₅ to be used above 200°C some kind of surface protection is needed. An appropriate plating or coating is effective in some applications.

Irreversible Losses

Complete demagnetization curves at various temperatures are necessary to understand the irreversible changes as a function of temperature. From material to material there is a wide range of behavior. For example alnico 5 characteristics show curves at various temperatures crossing each other, leading to both positive and negative coefficients.

For NdFeB magnets H_{ci} decreases with increasing temperature. The relatively high positive H_{ci} coefficient limits the usefulness of NdFeB in high temperature applications.

In the case of ferrite magnets the coercive force diminishes with decreasing temperature so irreversibility at low temperatures becomes a concern.

Table V-2 shows a general comparison of temperature parameters for several materials. Curie temperature, maximum use temperature, reversible coefficient of B_r and reversible coefficient of H_{ci} with respect to temperature are compared in the table.

Table V-2. Temperature Characteristics Comparison

Magnet Material	Curie Temperature °C	B_r Reversible Coefficient %/°C	H_{ci} Reversible Coefficient %/°C	Max. Service Temperature °C
Alnico 5	720	-0.02	-0.03	525
Ferrite	450	-0.20	0.40	800
SmCo ₅	725	-0.04	-0.30	250
Sm(Co,Cu,Fe,Zr) _{7.5}	825	-0.035	-0.30	300
NdFeB	310	0.12	-0.60	150

To form a perspective of how the various materials change flux output with temperature variations, Table V-3 was constructed. The different materials have been

compared near their point of $(BH)_{max}$. One must remember that irreversible loss is a strong function of B/H since the change is sensitive to the internal field of the magnet H_d . In the table the magnet is referenced to room temperature and the percent irreversible loss shown is determined by exposure to the indicated temperature and then returning to room temperature to measure the percent loss. Table V-3 shows that the various materials have a wide range of behavior in response to temperature. To predict change it is necessary to find the change in the intrinsic magnetization J and then by graphical construction project the change in B.

Table V-3. Comparison of Irreversible Loss

Material	-60°C	+100°C	+200°C	+300°C	+400°C	+500°C
Alnico 5	-1.4%	0.4	0.8	1.1	1.7	-2.1%
Ferrite (C-5)	-27.1%	0	0	0		
SmCo ₅	0	0.5	1.7			
Sm(Co,Cu,Fe,Zr) _{7.5}	0	0.5	1.8	3.6	11	
NdFeB	0	6.5	65.0			

The table indicates the irreversible loss of permeance measured at 20°C after exposure to the indicated temperature. B/H is near $(BH)_{max}$ for all materials.

The ideal way to stabilize against irreversible losses is to subject the magnet to several temperature cycles which are to be the temperature limits expected in use. However, this is time consuming and an acceptable alternate is to partially demagnetize by means of an a.c. field. Depending on the material, it may be necessary to field demagnetize to an extent greater than the loss due to the temperature cycle to completely stabilize against the loss due to the temperature.

Reversible Losses

One cannot eliminate these reversible changes by stabilization. However, temperature compensation materials may be used as a shunt in parallel with a magnet to reduce the reversible loss to a negligible level. The watt-hour meter and the automotive speedometer are examples of devices that normally use temperature compensation materials.

It is also possible to compensate a permanent magnet internally, at the atomic level. Light rare earth elements such as Sm, Pr and Nd exhibit a negative temperature coefficient in the range of most interest (-40°C to +150°C). Heavy rare earth elements such as Gd, Tb, Dy, Ho and Er have a positive coefficient because of a different mode of coupling between magnetic atoms. By combining both light and heavy rare earth atoms one can produce a near zero reversible coefficient over a limited temperature range. However, since the magnetic moments of the heavy atoms are lower, the overall properties are lower than for the uncompensated magnet.

Adverse Fields and Permeance Change

If a magnet is subjected to adverse magnetic fields partial demagnetization can result. Permeance or reluc-

tance change in a magnetic circuit can also result in partial demagnetization. The extent to which these changes are irreversible depends on the magnitude of the change and the reversible permeability of the material.

Shock and Vibration

Mechanical shock and vibration add energy to a permanent magnet to decrease the magnetization in much the same manner as discussed for the case of thermal after-effect. While our earliest magnets were magnetized and demagnetized by shock in the earth's field, today's high energy density magnets require much higher energy input levels to change the level of magnetization. For almost all but the most closely calibrated devices, mechanical energy input is not a magnetic problem with today's magnets. However, magnetic material may be brittle and subject to fracture from mechanical impacts.

Radiation

There are limited reported radiation tests for both soft and hard magnetic materials. For soft magnetic materials the evidence is the coercivity increases. For permanent magnets there is little evidence that the flux loss is anything beyond that which can be attributed to temperature effects.

PART VI. SPECIFICATIONS, STANDARDS AND COMMUNICATIONS

The Guide to this point has been concerned largely with the functional aspects of understanding, designing and measuring a permanent magnet. Magnet volume, magnet geometry and magnet stability in a system or device are influenced by the unit properties of the magnet material chosen. Figure VI-1 is an attempt to show the scope of information involved in working with a multi-disciplined subject such as permanent magnetism. This section focuses on how user and producer can exchange information and develop a complete specification. The specification involves much more than choice of magnet material, volume and geometry. To define acceptability it must include dimensional tolerances, magnetic test information and visual acceptance criteria. The cost of the magnet is greatly influenced by the level and degree specified for the required parameters. A good specification:

- (1) Allows the magnet producer to respond to inquiries quickly and constructively with a minimum number of changes or exceptions.
- (2) Simplifies correspondence and improves understanding between the user and magnet supplier.
- (3) Prevents over specification which could result in higher than necessary costs.
- (4) Results in usable and functional magnets.

The specification is an important control vehicle as it interrelates a wide range of events occurring in both user and producer facilities as illustrated by Figure VI-1.

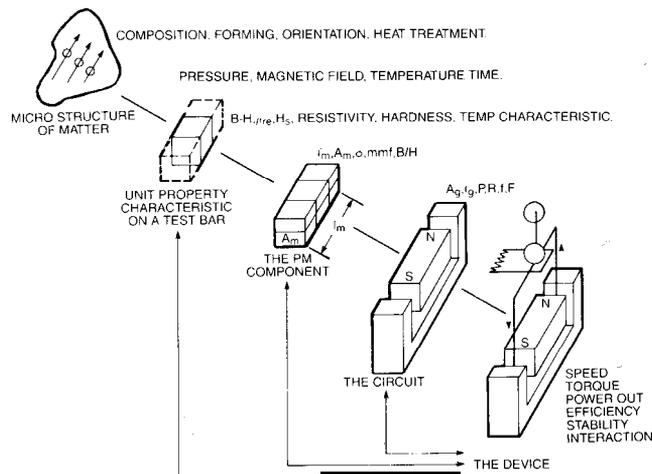


Figure VI-1. The universe of information required in specifying.

MMPA Standard Specifications for Permanent Magnet Materials-0100 is an important specification tool. It describes:

- Definitions and terms used in the magnet industry
- Classification and designation of magnet materials

- Magnetic properties, thermal properties surface characteristics and other physical properties
- Mechanical characteristics
- Dimensions and tolerances
- Inspection and testing.

Individual sections are devoted to alnico, ceramic, rare earth and iron-chromium-cobalt magnets. Each of these gives information on composition, manufacturing methods, magnetic properties, dimensions and tolerances, mechanical characteristics, physical properties, thermal properties and inspection sampling plans for each class of material.

Manufacturing processes vary considerably for each of the magnet classes. What is possible to achieve in one class is often not possible in others. There can also be considerable variation between magnet suppliers due to scale, investment, knowledge and experience. It is impossible to describe all of the tolerances, shape factors and physical parameters covering all the classes of magnets in this publication.

To facilitate development of a good specification the following technique and checklists are offered. There are three categories of information involved. The first category is:

- (1) General magnetic properties
- (2) Nominal dimensions
- (3) Direction of orientation
- (4) State of magnetization
- (5) Quantity and delivery

These are essential items to be initially supplied by the user when directing inquiries or requesting cost information. In effect they constitute the bare minimum of information. The general magnetic properties and nominal dimensions are a result of the design process.

Reference to MMPA Standard Specifications for Permanent Magnet Materials 0100 or producers' literature will help you select the class and grade of magnet material to be used as the general magnetic properties. A drawing covering the nominal dimensions, configuration and direction of orientation is required. Figure VI-2 shows several examples. State of magnetization indicates whether the magnets are to be shipped magnetized or demagnetized. If magnetized, the number of

poles and pole positions should be indicated. Delivery information should include total quantity for quotation, estimated annual requirement, date when initial parts are required and rate of delivery. This latter information is essential to the magnet producer for determining the type of tooling, the number of cavities and the rate at which the magnets must be built.

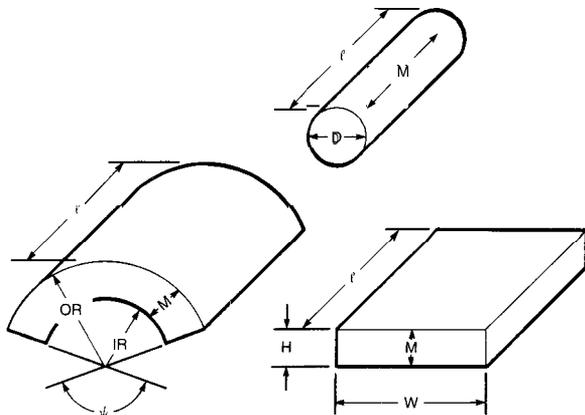


Figure VI-2. Dimensions, configurations and direction of orientation (J).

The second category of information is essential information supplied by the magnet producer. It is suggested that the magnet producer respond with this information as part of his quotation.

(6) Specific magnetic specification

(7) Dimensional tolerances

In some instances the user may want or need to include some of the above in his initial inquiry. The magnetic specification may involve a defined test procedure checking for total flux, flux density, coercive force or performance at a specific load line. A simulated circuit and use of correlation samples may be described. The following example of a simple holding magnet shows how important it is to integrate both magnetic and dimensional tolerances into the specification. Figure VI-3 shows a rectangular magnet having dimensions of H, W and ℓ . The force function is proportional to ϕ_m^2/A_g where ϕ_m = the total magnet flux and A_g is the area of the gap. In turn, $\phi_m \propto B_m HW$, where B_m is the flux density of the magnet. The chart lists an example with individual magnetic and dimensional tolerances and the accumulated tolerances for ϕ_m and force. Such a broad range in flux may not be acceptable and the magnet producer may agree to hold tighter flux control than the accumulation indicates. The best approach is to avoid trying to control magnetics through extra tight and costly ground tolerances. By looking at the total design the magnet producer will be able to offer the most cost effective approach.

A generalized summary of dimensional tolerances for each magnet class is described in Standard Specifications 0100. The recommended procedure is to allow the

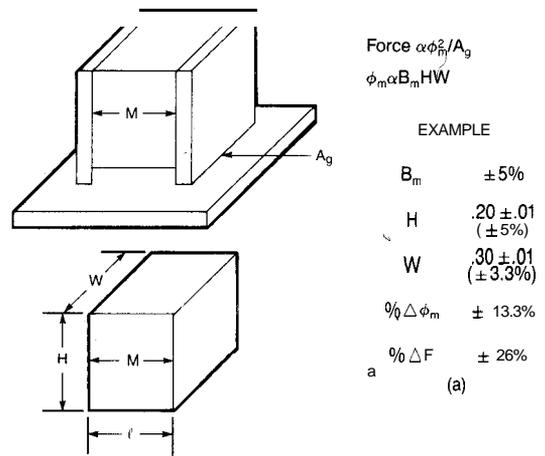


Figure W-3. Simple holding magnet.

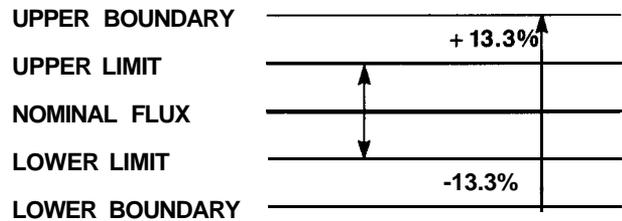


Figure VI-4. Flux specification.

magnet producer to quote and suggest the specific magnet test and test limits along with dimensional tolerances which represent the best overall magnet value.

The third category of information is several optional items that may be important enough to be included in the specifications. The magnet user should include any of these items that require special consideration with his initial inquiry when requesting cost information.

(8) Visual characteristics

(9) Sampling plan, AQL levels or statistical process control plan.

(10) Identification

(11) Protective or decorative finish

(12) Special performance requirements

Visual characteristics and inspection sampling plans for the various magnet classes are included in the Standard Specification booklet 0100. If other than these are to apply they should be described and included with the initial cost request inquiry. The use of mutually agreed upon visual standards is recommended if it is critical to the application. Sample boards have proven effective in this respect.

When more than one material of the same size or more than one supplier of same part is involved some kind of identification may be needed. Color code or imprint from tooling are suggested forms of identification.

To summarize items which may pertain to the development of a magnet specification are:

- (1) General magnetic properties
- (2) Nominal dimensions
- (3) Direction of orientation
- (4) State of magnetization
- (5) Quantity and delivery
- (6) Specific magnetic specification
- (7) Dimensional tolerances
- (8) Visual characteristics
- (9) Sampling plan, AQL levels or statistical process control plan
- (10) Identification
- (11) Protective or decorative finish
- (12) Special performance requirements

Bibliography

1. *Permanent Magnets in Theory and Practice*. Malcolm McCaig. Halsted Press, Div. of J. Wiley and Sons, New York, NY (1977)
2. *Permanent Magnet Design and Application Handbook*. L. Moskowitz. Cahners Book International. Boston, Massachusetts (1976)
3. *Introduction to Magnetic Materials*. B. D. Cullity. Addison-Wesley Publishing Co., Reading, Massachusetts (1972)
4. *Dauermagnete- Werkstoffe and Anwendungen*. K. Schuler and K. Brinkman. Springer-Verlag, Berlin-Heidelberg-NY (1970)
5. *Permanent Magnets and Their Applications*. R. J. Parker and R. J. Studders. J. Wiley and Sons, New York (1962)
6. *Permanent Magnets and Magnetism*. D. Hadfield, editor. Iliffe Books, Ltd., London and J. Wiley and Sons, New York (1962)
7. *Permanent Magnets, F. G. Spreadbury*, Pitman and Sons Ltd., London, 1949
8. *Proc. 2nd Intl. Workshop Rare Earth-Co Perm Mag.*, K. J. Strnat, Editor. Univ. of Dayton, Dayton, OH (1976)
9. *Proc. 3rd Intl. Workshop Rare Earth-Co Perm Mag.*, K. J. Strnat, Editor. Univ. of Dayton, Dayton, OH (1978)
10. *Proc. 4th Intl. Workshop Rare Earth-Co Perm Mag.*, H. Kaneko and T. Kurino, editors. The Soc. of Non-Traditional Technology, Tokyo, Japan (1979)
11. *Proc. 5th Intl. Workshop Rare Earth-Co Perm Mag.*, K. J. Strnat, editor. Univ. of Dayton, Dayton, OH (1981)
12. *Proc. 6th Intl. Workshop Rare Earth-Co Perm Mag.*, J. Fidler, editor. Tech. University Vienna, Austria (1982)
13. *Proc. 7th Intl. Workshop Rare Earth-Co Perm Mag.*, X. Pan, W. Ho and C. Yu, editors. China Academic Publishers, Beijing, P.R. of China (1983). Available through University of Dayton, OH, Magnetics Laboratory.
14. *Proc. 8th Intl. Workshop Rare Earth-Co Perm Mag.*, K. J. Strnat, editor. University of Dayton, Dayton, OH (1985)
15. R. I. Joseph, "Ballistic Demagnetizing Factor in Uniformly Magnetized Cylinders." *J. Applied Physics*, vol. 37, p. 4639, (1966)
16. *Evaluation of Long-Term Magnet Stability*, W. L. Zingery et. al., *J. Appl. Phys.*, 1, March, 1966
17. *Radiation Damage Thresholds for Permanent Magnets*, R. S. Sery, R. H. Lundsten and D. I. Gordon, Naval Ordnance Laboratory TR-61-45 Silver Springs, Md., May 18, 1961
18. *Environmental Evaluation of Magnetic Materials*, D. I. Gordon, *Electra-Technology*, 67, No. 1, January 1961, pp. 118-125
19. *Irradiating Magnetic Materials*, D. I. Gordon, *Electro-Technology*, June 1965, pp. 42-45
20. *Proc. 9th Intl. Workshop Rare Earth Permanent Magnets*, Bud Soden, W. Germany (1987)

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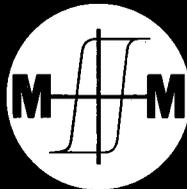
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