Magnetics & Materials LLC

GLOSSARY and REFERENCE
for
Magnetism and the Magnetics Industry

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1. EXPLANATIONS, RULES and REFERENCES for the USE of SYMBOLS and TERMS

Guidelines for the use of symbols and terms:

- Symbols representing material characteristics are in italics (example: B_r).
  - However, as a matter of convenience or necessity they are often shown not italicized (example: $\mathrm{B_r}$).
  - For better legibility subscripts are usually not italicized. For convenience or out of necessity, subscripts are often typed as normal text (example: Br).
  - This glossary follows the convention of italicized main letter and non-italicized subscripts.
  - In scientific literature Greek letters are often but not always italicized. They are not italicized herein.
- Symbols which are abbreviations or which represent units are not italicized. For example, the abbreviation of oersted is Oe, the gilbert is Gb, and the ampere is A.
- Names of people when used as units of measurement are not capitalized. However, the first letter of the abbreviation is capitalized. Examples: maxwell (Mx), gauss (G), oersted (Oe), henry (H), joule (J), kelvin (K), and weber (Wb).
- Plurals of units are written in plural form such as oersteds, webers, etc. One exception: the plural of gauss (gausses) is discouraged because the singular naturally ends in "s".

Magnetic fields are vector quantities. For simplicity they are often presented as positive, scalar quantities. For example the operating slope, B_d/H_d, is written as a positive number even though the slope is negative. In another example, the demagnetizing field strength, H, is a negative quantity but often shown as a positive number representing magnitude only.

Reference documents:

- ASTM A340: Standard Terminology of Symbols and Definitions Relating to Magnetic Testing
- IEC 60050-121 and IEC 60050-221: International Electrotechnical Vocabulary
- NIST: Guide for the Use of the International System of Units (SI), 2008 edition
- Numerous textbooks and papers on magnetism – visit: www.magmatllc.com/ref_book_list.html

2. SYMBOLS and TERMS

A	ampere
A_g	area of the air gap cross-section
A_m	area of the magnet cross-section
A/m	ampere per meter (SI unit of coercivity)
B	magnetic flux density magnetic induction
B_d	remanent induction
B_dH_d	energy product (BH product)
$(BH)_{max}$	maximum energy product
B_g	magnetic flux density in the air gap
B_0	value of magnetic induction at maximum energy product
B_0/H_0	coordinates of the maximum energy point
B_i	intrinsic induction
B_r	residual induction residual magnetic flux density remanence
B_s	saturation induction
B_{is}	intrinsic saturation induction
DOM	direction of magnetization
F	leakage factor force
f	reluctance factor
G	gauss (cgs unit of magnetic flux density)
Gb	gilbert, magnetomotive force
H	magnetic field strength
H	henry (unit of inductance)
H_0	value of magnetic field strength at maximum energy product
H_{cB}	(normal) coercive field strength (normal) coercivity
H_{cJ}	intrinsic coercive field strength intrinsic coercivity
H_d	demagnetizing field strength
H_g	air gap magnetic field strength
H_k	(refer to definition)
H_s	saturating magnetic field strength
I	electric current
j	magnetic dipole moment
J	joule
J	polarization (magnetic)
J_d	Intrinsic magnetic flux density
J_s	saturation polarization
L	inductance
L_g	length of air gap
L_m	length of magnet
L_m/D	dimension ratio
m	magnetic moment
M	magnetization
MGOe	megagauss-oersted
MOKE	magneto-optical Kerr effect
M_S	magnetic saturation (saturation magnetization)
Mx	maxwell
N	demagnetizing factor
N_B	ballistic demagnetizing factor
N_F	fluxmetric demagnetizing factor
N_M	magnetometric demagnetizing factor
P	Permeance
P_C	permeance coefficient
P_{CI}	intrinsic permeance coefficient
Oe	oersted
R_M	reluctance
RTC	reversible temperature coefficient (of B_r or H_{cJ})
SCM	symmetrically cyclically magnetized
T	tesla (SI unit of magnetic flux density)
T_C	Curie temperature
T_N	Néel temperature

T_{max}	maximum recommended use temperature; see also T_w
T_{min}	minimum recommended use temperature
T_w	Maximum recommend use temperature
V	volt
V_g	airgap volume (or volume of the gap)
VSM	vibrating sample magnetometer
Wb	weber
α	coefficient of thermal expansion
$\alpha(B_r)$	reversible temperature coefficient of induction
$\alpha(H_{cJ})$	reversible temperature coefficient of coercivity
δ	density
Φ	magnetic flux
μ_B	Bohr magneton
μ	permeability
μ_0	magnetic constant (permeability of a vacuum) = $4\ \pi \times 10^{-7}$ henry per meter
μ_i	initial permeability
μ_{max}	maximum permeability
μ_r	relative permeability
μ_{rec}	recoil permeability
ρ	resistivity
χ	susceptibility

3. GLOSSARY

Note: the following glossary includes terms that do not have corresponding symbols.

Air gap
The region in the flux path of a magnetic circuit where the flux is available for use, as in the gap between the stator and rotor of a motor. The air gap can include non-magnetic materials such as epoxy, plastic structural forms, aluminum, and paint.

Air gap magnetic field strength, H_g
The region in the flux path of a magnetic circuit where the flux is available for use, as in the gap between the stator and rotor of a motor. The air gap can include non-magnetic materials such as epoxy, plastic structural forms, aluminum, and paint.

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

Ampere, A
Unit of electrical current, I, equal to a flow of one coulomb per second.

Antiferromagnetism
Magnetic characteristic of a material where the magnetic moment of neighboring atoms points in the opposite direction. The antiferromagnetic ordering can exist at adequately low temperatures, but disappears above the Néel temperature, T_N, and above the Néel temperature, the material is exhibits paramagnetism.

Area of the air gap, A_g
The cross-sectional area of the air gap perpendicular to the flux path and is the average cross-sectional area of that portion of the air gap within which the application interaction occurs. Area is measured in cm^2 in a plane that is normal to the central flux line of the air gap.

Area of the magnet, A_m
The cross-sectional area of the magnet perpendicular to the central flux line, measured in cm^2 at any point along its length. In design, A_m is usually considered the area at the neutral section of the magnet.

B_0
Value of magnetic induction, B, at the point of the maximum energy product $(BH)_{max}$ and is measured in tesla or gauss.

B_0/H_0
Operating slope at the point of the maximum energy product $(BH)_{max}$. H is negative in the second quadrant so the operating slope is negative. However, it is usually written and treated as a positive number.

Ballistic demagnetizing factor, N_B
One of three types of demagnetizing factors, the others being fluxmetric (N_F) and magnetometric (N_M). For additional information see demagnetizing factor.

Barkhausen effect, Barkhausen jump
A discontinuous variation of the magnetic flux density in a material as the applied magnetic field strength is continuously changed.

Bohr magneton, μ_B

A physical constant quantifying the magnetic moment of an electron and named after Niels Bohr, a Danish physicist.

$$\mu_B = e\, h/4\, \pi\, m \approx (9.274\ 078 \pm 0.000\ 036) \times 10^{-24}\ Am^2$$

Where: e = elementary charge of the electron
h = Planck's constant
m = electron rest mass

CGS or cgs (also: "cgs-Gaussian" or "cgs-emu")
The centimeter-gram-second system of units is a variant of the metric system introduced by the British Association for the Advancement of Science in 1874. The cgs system is commonly used in theoretical physics while the related mks and mksa systems (meter-kilogram-second-ampere) is commonly used in engineering. For additional information refer to the Conversion Table at the end of this section.

Closed magnetic circuit, closed circuit condition
An arrangement where the external flux path of a permanent magnet is confined within high permeability material.

Coefficient of thermal expansion, α
The measure of the average change in length over a specified temperature range. Calculated as: $(L_2 - L_1) / L_1 / (T_2 - T_1)$ where L is length and T is temperature in °C or K.

Coercive field strength, H_{cB}
This is equal to the demagnetizing field strength, $-H$, required after magnetizing to saturation, to reduce the value of magnetic flux density, B, to zero and is measured in amperes per meter (A/m) or oersteds (Oe).

Coercivity, H
The value of the coercive magnetic field strength in a material when the induction, magnetic polarization or magnetization is brought from saturation to zero by a monotonically changing magnetic field. The parameter that is varied should be stated, and the appropriate symbol used as follows: H_{cB} for the coercivity relating to the induction, H_{cJ} for the coercivity relating to the polarization, H_{cM} for the coercivity relating to the magnetization. Coercivity is measured in units of amperes per meter (A/m) or oersteds (Oe).

Curie temperature, T_C
Also called the Curie point. It is the transition temperature below which a magnetic material is ferro- or ferrimagnetic and above which the material is paramagnetic. Above the Curie temperature magnetic domains become randomly oriented, providing no net external magnetic field.

Current, I
An electric current is a flow of electric charge measured in units of amperes (A).

Demagnetization curve
The second quadrant of a hysteresis loop. Points on this curve are designated by the coordinates B_d and H_d.

Demagnetizing factor, N
The ratio of the self-demagnetizing field strength to the magnetization in a uniformly magnetized material. For magnets of ellipsoidal shape, solid cylinders and rectangular cross-section, demagnetizing factors can be calculated. Several methods have been utilized – the three common demagnetizing factors are the ballistic factor, N_B, the magnetometric factor, N_M, and the fluxmetric factor, N_F.

The permeance coefficient (operating slope, load line) can be calculated from N by the formula:

$$P_C = B_d / H_d = 1 - (1 / N)$$

Demagnetizing field strength, H_d
The magnitude of the magnetic field strength in the second quadrant of a normal hysteresis loop. Points on the normal curve are designated by the coordinates (B_d, H_d).

Density, δ
Mass per unit volume expressed in grams per cubic centimeter or the numerically equivalent kilograms per cubic meter.

Diamagnetism
A negative (repulsive) response to an applied magnetic field. A diamagnetic material consists of atoms with no net magnetic moment but which responds negatively to an applied magnetic field.

Dimension ratio, L_m/D
The ratio of the length of a magnet to its diameter, or to the diameter of a circle of equivalent cross-sectional area. The dimension ratio is related to the slope of the operating line of the magnet, B_d/H_d.

Direction of magnetization, DOM
Alignment of the magnetic field within a magnet product. It is typically understood to be the field alignment along the central axis of the magnet. It is also quantitatively interpreted as the direction of the vector sum of the field produced at some defined point on or in the magnet.

Domain wall
A boundary region, many unit lattice cells in thickness, between adjacent Weiss domains, within which the orientation of the magnetic moment progressively changes from the direction in one domain to the direction in the adjacent domain.

Energy product, B_dH_d
The energy that a magnetic material can supply to an external magnetic circuit when operating at any point on its normal demagnetization curve; measured in kilojoules per cubic meter (kJ/m^3) or megagauss-oersteds (MGOe).

Ferrite
A material composed of oxides containing ferric ions as the main component and exhibiting either ferrimagnetism or antiferromagnetism. Ferrites may be either permanent magnets or soft magnetically. For example, strontium hexaferrite is a widely used permanent magnet. Ferrite permanent magnets are also called ceramic magnets as they are a compound of metals and oxygen.

Ferrimagnetism
The phenomenon where, in the absence of an applied magnetic field, the magnetic moments of neighboring ions in a substance are held by their interactions in a partially cancelling arrangement, such that there remains a resultant magnetic moment. When an external magnetic field is applied, the alignment of the magnetic moments increases.

Ferromagnetism
The phenomenon where the magnetic moments of neighboring ions in a substance are approximately aligned in the same direction due to their electron interactions and in which the alignment of the resultant magnetic moments of the regions increases when an external magnetic field strength is applied.

Fluxmeter
An instrument that measures the change of flux linkage with a search coil. An integrating fluxmeter sums over time the change in coil voltage produced by the coil moving relative to a magnetic field.

Fluxmetric demagnetizing factor, N_F
One of three types of demagnetizing factors, the others being ballistic (N_B) and magnetometric (N_M). For additional information see demagnetizing factor.

Gauss, G
The unit of magnetic flux density and magnetic induction, B, in the cgs electromagnetic system. One gauss is equal to one maxwell per square centimeter (Mx/cm^2).

Gaussmeter
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.

Gilbert, Gb
The unit of magnetomotive force, F, in the cgs electromagnetic system.

Grain-oriented material
A material in which magnetic texture has been developed by partial or complete orientation of the grains.

H_o
The magnetic field strength at the point of the maximum energy product $(BH)_{max}$ measured in amperes per meter (A/m) or oersteds (Oe).

H_d
Demagnetizing field strength. The value of H corresponding to the remanent induction, B_d, on the normal demagnetization curve in the second quadrant measured in amperes per meter (A/m) or oersteds (Oe).

H_k
The value of H in the second quadrant of a hysteresis loop vertically below the intersection of the polarization curve and a horizontal line drawn from the B-axis starting at the point B=0.9•B_r. H_k will always be less than H_{cJ}. H_k / H_{cJ} provides a measure of the squareness of the demagnetization curve with the upper limit approaching 1. Similar measures are H_x and H_{D10}.

Hall effect transducer
A semiconductor device that produces a voltage dependent on an applied DC voltage and an incident magnetic field. The magnitude of the output is proportional to the field strength and the angle of incidence with the Hall device. This type of sensor is often used to provide an output signal for use in a gauss meter to measure the incident magnetic field strength, H. The output represents the vector sum of the field strength perpendicular to the plane of the Hall chip, over the area of the chip. The output signal is converted to a numeric output representing the magnetic flux density, in units of gauss or tesla.

Henry, H
The SI unit of inductance, equal to an electromotive force of one volt in a closed circuit with a uniform rate of change of current of one ampere per second.

Hysteresigraph
A device for measuring the magnetic characteristics of a material. The output can be numeric or presented as a chart showing hysteresis loops or portions of the loop, such as the second quadrant for permanent magnets.

Hysteresigraphs measure the sample in a closed magnetic circuit.

Hysteresis loop
A closed curve obtained for a material by plotting (usually to rectangular coordinates) corresponding values of magnetic induction, B, polarization, J, or magnetization, M, for ordinates and magnetizing field strength, H, for abscissa when the material is passing through a complete cycle between definite limits of either magnetizing field strength, H, or magnetic induction, polarization or magnetization. It is common for high coercivity materials to measure a limited portion of the hysteresis loop, usually only the second quadrant or occasionally both part of the first and all of the second quadrants.

- The hysteresis loop charting induction (B) versus applied magnetic field strength (H) is often referred to as B (H) – read *B as a function of H*.
- The hysteresis loop charting polarization (J) versus applied magnetic field strength (H) is often referred to as J (H) – read *J as a function of H*. (The J (H) loop is identical to the B_i loop).
- The hysteresis loop charting magnetization (M) versus applied magnetic field strength (H) is often referred to as M (H) – read *M as a function of H*.

Hysteresis loop, major
The closed loop obtained when a material is cycled between positive and negative saturation.

Hysteresis loop, minor
The closed loops obtained when a material is cycled between values of H resulting in less than magnetic saturation.

Hysteresis loop, normal
A hysteresis loop which is symmetrical with respect to the origin of the coordinates.

In the magnetic industry prior to the invention of ferrite magnets, values of H_{cB} and H_{cJ} were similar and only the B (H) loops were measured and reported. With the discovery of high H_{cJ} materials, both the B (H) and the J (H) loops found common use. In order to distinguish which curve is being discussed, the term *normal curve* (loop) was used to identify the B (H) loop while the *intrinsic curve* (loop) represented the J (H) loop.

Inductance, *L*
The property of an electrical conductor by which a change in electric current through it induces an electromotive force (voltage) in the conductor.

Intrinsic coercive field strength, H_{cJ}
Also called intrinsic coercivity. It is a measure of a material's resistance to demagnetization. It is equal to the demagnetizing force, $-H$, which after magnetizing to saturation, reduces the polarization, J, to zero. It is measured in amperes per meter (A/m) or oersteds (Oe). This is currently preferable to H_{ci} which referred to values of B_i on the intrinsic curve.

Initial magnetization curve
The magnetization (hysteresis) curve obtained when a material, initially in a neutral magnetic state, is subjected to a magnetic field, H, the strength of which increases monotonically from zero.

Initial permeability, μ_i
The limiting value of permeability when the magnetic field strength tends to zero. Important for soft magnetic materials it refers to initial magnetization in the first quadrant.

Intrinsic induction, B_i

The contribution of the magnetic material to the total magnetic field strength, B. It is the vector difference between the induced magnetic field strength in the material (the induction) and the magnetic field strength that would exist in a vacuum under the same applied field, H. (See also, Polarization, J, which is preferred over B_i). This relation is expressed by the equation:

$$B_i = B - H$$

Where: B_i = intrinsic induction in gauss
B = magnetic induction in gauss
H = magnetic field strength in oersteds

Intrinsic magnetic flux density, J_d
J_d represents a point on the polarization curve in the second quadrant. It is the value of intrinsic magnetic flux density at that point. This replaces the symbol B_{di}.

Intrinsic permeance coefficient, P_{CI}
Related to the (normal) permeance coefficient by: $P_{CI} = P_C + 1$.

Intrinsic saturation induction, B_{is}
The value of intrinsic magnetic flux density in the first quadrant when the magnetic material is saturated. This term is deprecated in favor of saturation polarization, J_s.

Irreversible loss
Partial demagnetization of a magnet, caused by exposure to high or low temperatures, external fields or other factors. These losses are recoverable by re-magnetization. Magnets can be stabilized against irreversible loss by partial demagnetization induced thermally or by exposure to an external demagnetizing field.

Joule, J
The SI unit of work or energy, equal to the work done by a force of one newton when its point of application moves one meter in the direction of action of the force, equivalent to one 3600th of a watt-hour.

Keeper
A piece (or pieces) of magnetically soft iron 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 makes the magnet less susceptible to spontaneous demagnetization and reduces the effects of external demagnetizing influences.

Leakage factor, F
The flux leakage from a magnetic circuit. It is the ratio between the magnetic flux at the magnet neutral section and the average flux present in the air gap of a magnetic circuit.

$$F = (B_m A_m)/(B_g A_g)$$

Where B_m = induction in the magnet
A_m = cross-sectional area of the air gap
B_g = induction in the air gap
A_g = cross-sectional area of the magnet
Note: the symbol F is also used to denote magnetomotive force.

Leakage flux
Flux, Φ, whose path is outside the useful or intended magnetic circuit; measured in weber or maxwell.

Length of the air gap, L_g

The length of the path of the central flux line of the air gap; measured in centimeters.

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

Magnetic constant, μ_0
The permeability of a vacuum = $4 \pi \times 10^{-7}$ henry per meter.

Magnetic dipole moment, *j*
A vector quantity given by the volume integral of the magnetic polarization.

Magnetic field strength, *H*
The magnetic vector quantity that determines the ability of an electric current, or a magnetic body, to induce a magnetic field at a given point and is measured in amperes per meter (A/m) or oersteds (Oe). It is the measure of magnetizing (*H*) or demagnetizing (-*H*) field strength.

Magnetic flux, Φ
A contrived but measurable concept that has evolved as 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 weber (SI) or maxwell (cgs)
B = magnetic induction, in tesla (SI) or gauss (cgs)
d*A* = an element of area, in square centimeters

When the magnetic induction, *B*, is uniformly distributed and is normal to the area, *A*, the flux, Φ, = *BA*.

Magnetic flux density, magnetic induction, *B*
The magnetic field induced by a field strength, *H*. It is the vector sum, at each point within the substance, of the applied magnetic field and resultant intrinsic induction. Magnetic field strength is the flux per unit area normal to the direction of the magnetic path (axis of magnetization). Magnetic flux density is preferred when describing the field in a gap (or in space) while induction is acceptable when describing the field within a material especially when resulting from an externally applied field.

Magnetic flux density in the air gap, B_g
The average value of magnetic flux over the area of the air gap, A_g, or the magnetic flux density measured at a specific point within the air gap. It is measured in tesla or gauss.

Magnetic hysteresis
In a ferro- or ferrimagnetic substance, it is the irreversible variation of the induction associated with the change of magnetic field strength; it is the lag of *B* with respect to *H* such that when *H* is returned to zero, *B* returns to B_r.

Magnetic induction, *B*
The magnetic field induced by a field strength, *H*, at a given point. It is the vector sum at each point within a 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.

Magnetic moment, *m*
Magnetic moment can be defined as a vector relating the aligning torque on the object from an externally applied

magnetic field to the field vector itself. The relationship is given by: $\boldsymbol{\tau} = m \times B$

Magnetic saturation
Magnetic saturation is produced in a material when an increase in applied magnetizing field strength, *H*, does not cause an increase in the magnetic induction, *B*, of the material. See also saturation induction, saturation magnetization and saturation polarization.

Magnetic texture
A structural ordering of a polycrystalline magnetic material that produces magnetic anisotropy.

Magnetically hard material, permanent magnet
A magnetic material having a high coercivity which is difficult to demagnetize. It is generally accepted to have an intrinsic coercivity greater than 2 kiloamperes per meter (25 oersteds).

Magnetically soft material
A magnetic material having a low coercivity that is less than about 2 kiloamperes per meter (25 oersteds).

Magnetization, *M*
The vector sum of the magnetic moments of all the atoms in a volume of material, divided by the volume: $M = m / V$. The relationship of *M* to *J* and *B* is: $B = \mu_0 M + \mu_0 H = J + \mu_0 H$.

Magneto-optical Kerr effect, MOKE
The polarization plane of linearly polarized light reflected off the surface of a magnetized material is rotated. The angle of rotation depends on the magnetization of the material. The reflected light produces patterns corresponding to the magnetic domain structure.

Magnetometer
An instrument for measuring, and often recording, the intensity (strength) of a magnetic field.

Magnetometric demagnetizing factor, N_M
One of three types of demagnetizing factors, the others being ballistic (N_B) and fluxmetric (N_F). For additional information see demagnetizing factor.

Magnetomotive force, (magnetic potential difference), *F*
The line integral of the field strength, *H*, between any two points, p_1 and p_2.

$$F = \int_{p_1}^{p_2} H \, \mathrm{d}l$$

Where F = magnetomotive force in amperes or gilberts
H = field strength in amperes per meter or oersteds
dl = an element of length between the two points, measured in meters or centimeters

Magnetostatic
The state in which the magnetic field is non-changing. When the magnetic field is generated by an electric current, the current is non-changing or changing very slowly so as to approximate a static condition.

Magnetostriction
The property of a ferromagnetic or ferrimagnetic material that causes them to change their shape when an external magnetic field is applied. Conversely, the application of compressing physical force causes a change in magnetic susceptibility.

Maximum energy product, $(BH)_{max}$
The maximum product of (B_dH_d) which can be obtained on the demagnetization curve. B_d and H_d at the point of maximum energy product have also been referred to as B_0 and H_0. (B_d,H_d) is the coordinate of the point on the normal curve at maximum energy product.

Maximum permeability, μ_{max}
The maximum value of permeability obtained from the slope of a line extending from the origin to the knee of the normal magnetization curve in the first quadrant.

Maximum recommended use temperature, T_W or T_{max}
The maximum recommended temperature to which the magnet may be exposed without significant long range instability or structural changes. T_W is the more commonly used symbol.

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

Megagauss-oersted, **MGOe**
Million gauss-oersteds. A cgs unit of magnetic energy product equal to SI units of 7.958 kJ/m^3.

Minimum recommended use temperature, T_{min}
The minimum recommended temperature to which the magnet may be exposed without significant instability or structural changes.

Néel temperature, T_N
The temperature below which a magnetic material is antiferromagnetic and above which it is paramagnetic. The susceptibility, χ , of a ferrimagnetic material goes through a maximum at the Néel temperature and decreases both above and below it.

Neutral section
In a permanent magnet it is defined as a plane passing through the magnet perpendicular to its central flux line at the point of maximum flux.

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

Open circuit condition
Exists when a magnetized magnet is by itself with no nearby high permeability material.

Operating line, operating slope
For a given permanent magnet circuit, it is a straight line passing through the origin of the demagnetization curve with a slope of B_d/H_d. The operating line is more commonly referred to as the permeance coefficient, P_C. Although the slope is negative, it is often presented as a positive number.

Operating point
For a permanent magnet it is that point on the normal demagnetization curve defined by coordinates (B_d,H_d).

Oriented (anisotropic) material
This material has stronger magnetic properties in a given direction. Some materials, at the crystal level, have a preferred direction of orientation called magnetocrystalline anisotropy. If grains of this material are rotated

during manufacture so that all of them align to a preferred direction, it is called oriented. In other materials, such as alnico, magnetic properties are dependent on the shape of the magnetic portion. Elongated structures are separated by a non-magnetic phase. When the elongated structures are aligned parallel, the material is called oriented.

Permeability, μ

The general term used to express various relationships between magnetic induction, *B*, and the magnetic field strength, *H*. There are many specific permeabilities indicated by a subscript following the symbol μ. Permeability is related to susceptibility in SI units by $\mu = 1 + 4\pi\chi$. For permanent magnets in the second quadrant, permeability, μ, and susceptibility, χ, in cgs units are related by: $\mu = 1 + \chi$.

Permeability of a vacuum, μ_0

The permeability of a vacuum = $4\pi \times 10^{-7}$ henry per meter. See also magnetic constant.

Permeameter

An instrument that can measure, and often record, the magnetic permeability of a specimen.

Permeance, *P*

The reciprocal of the reluctance, R_M, measured in maxwells per gilbert. Permeance in a magnetic material is analogous to electrical conductance and indicates the ease with which a magnetic field will be conducted through the material.

Permeance coefficient, P_C

For a given permanent magnetic circuit, the permeance coefficient is the ratio of B_d/H_d. A straight line passing through the point (B_d, H_d), the operating point, and through the origin is called the operating slope, also commonly referred to as the operating line. Although the permeance coefficient is a negative number and represented by a line with a negative slope, it is customary to present the value as a positive number.

Polarization, *J*

That part of the magnetic flux density contributed by the material. It is related to induction, *B*, and magnetization, *M*, by the following: $J = B - \mu_0 H = \mu_0 M$

Recoil permeability, μ_{rec}

The average slope of the recoil hysteresis loop of the normal curve, $B(H)$, and most often refers to the curve in the second quadrant. This is special case of reversible permeability, μ_{rev}, which is the ratio of the change in magnetic flux density, ΔB, to the change in magnetic field strength, ΔH.

Relative permeability, μ_r

Permeability μ is defined as B/H, and so has the units of μ_0. It is instead customary to use the relative permeability which is dimensionless, and is numerically the same as the cgs permeability μ.

$$\mu_r = \mu / \mu_0$$

Reluctance, R_M

The quantity that determines the magnetic flux, ϕ, resulting from a given magnetomotive force, *F*.

$$R_M = F/\Phi$$

where: R_M = reluctance, in amperes per weber or gilberts per maxwell
F = magnetomotive force, in amperes or gilberts
Φ = flux, in webers maxwells

This is analogous to Ohm's law where *R* is electrical resistance in ohms, *I* is current in amperes, and *V* is voltage in volts. The Ohm's law relationship is $R = V / I$

Reluctance factor, *f*
The apparent magnetic circuit reluctance.

Remanent induction, remanence, B_d
The magnetic induction at any point on the normal demagnetization curve, B (H); measured in tesla or gauss.

Residual induction, B_r
The magnetic induction, B, corresponding to zero magnetizing force (H=0) in a magnetic material after saturation; measured in tesla or gauss.

Resistivity, ρ
Electrical resistivity is a fundamental property of a material that quantifies how strongly that material opposes the flow of electric current. Resistivity is commonly represented by the Greek letter ρ (rho) and has units of ohm-meter (Ω·m). Units of micro-ohm-centimeters is also commonly used relating to magnetic materials.

Reversible temperature coefficients, RTC, $\alpha(B_r)$ and **$\alpha(H_{cJ})$**
The reversible temperature coefficients (RTC) quantify the rate of change in induction, $\alpha(B_r)$, and intrinsic coercivity, $\alpha(H_{cJ})$ and are defined between a specified lower and higher temperature. The numeric values are percentages and represent the average rate of change between the temperature limits. As long as critical temperatures are not exceeded, these changes are spontaneously reversible.

Saturating magnetic field strength, H_s
The magnetizing field strength required to magnetize a material to saturation; measured in amperes per meter (A/m) or oersteds (Oe).

Saturation induction, B_s
The maximum induction possible in a material. B_s is often used to mean B_{is} and to be equal to saturation polarization, J_s. Thus, the use of B_s is ambiguous and the usage of J_s is preferred.

Saturation intrinsic induction, B_{is}
The maximum intrinsic induction possible in a material. B_{is} is equal to saturation polarization, J_s. The usage of J_s is preferred.

Saturation magnetization, M_s
The maximum obtainable magnetization for a given substance at a given temperature. It is produced in a material when an increase in applied magnetizing field strength, H, does not cause an increase in the magnetic induction, B, of the material. Similar terms are: 1) saturation polarization, J_s, 2) saturation magnetization, M_s, 3) saturation induction, B_s, and 4) intrinsic saturation induction, B_{is}. Use of terms B_s and B_{is} are discouraged. Technically, an increase in H will continue to cause an increase in magnetization until extremely high values of applied field are reached. By one rule, saturation is reached when a 25% increase in H yields less than a 1% increase in magnetization.

Measurement of induction, B, will continue to increase in the first quadrant with increasing H since it is the sum of H plus the contribution of field from the material: $B = J + \mu_o H$

Saturation polarization, J_s
The maximum polarization possible in a material. J_s is preferred over B_s or B_{is} (saturation intrinsic induction). See also magnetic saturation.

Search coil
A coiled conductor, usually of known area and number of turns that is used with a fluxmeter to measure the change of flux linkage between the coil and a source of magnetic field. A change in flux linkage can be achieved by moving the coil relative to the source of magnetic field or, while holding constant the position of the coil and field source, by varying the strength of the magnetic field from the field source.

SI
The international system of units (Le Système International d'Unités) is the modern metric system of measurement, and is becoming the dominant measurement system in international commerce.

Slope of the operating line, B_d/H_d
The ratio of the remanent induction, B_d, to a demagnetizing magnetic field, H_d. It is also referred to as the permeance coefficient, shear line, load line or unit permeance. The point on the normal demagnetization curve represented by the coordinates (B_d,H_d) is called the operating point.

Spontaneous magnetization
Magnetization resulting from the alignment of atomic magnetic moments without the application of an external magnetic field.

Susceptibility, χ
Change of M (or J) with change in H.

$$\chi = \frac{M}{H} \frac{\text{emu}}{\text{Oe} \cdot \text{cm}^3}$$

Permeability is related to susceptibility as follows.

$$\mu = \frac{B}{H}$$

Since $B = H + 4\pi M$, we have

$$\frac{B}{H} = 1 + 4\pi\left(\frac{M}{H}\right)$$

$$\mu = 1 + 4\pi\chi$$

For permanent magnets in the second quadrant, permeability, μ, and susceptibility, χ, in cgs units are related by: $\mu = \chi + 1$.

Symmetrically cyclically magnetized, SCM
Magnetic condition resulting from exposure to a magnetic field that varies cyclically between equal positive and negative limits of applied field strength, H, when successive hysteresis loops are identical and symmetric with respect to the origin of the B and H axes.

Temperature coefficient
A factor which describes the reversible change in a magnetic or physical property of a material with a change in temperature. It is expressed as the percentage change per unit of temperature.

Tesla, T
In the SI system, a number representing the magnetic flux density or magnetic induction.

Un-oriented (isotropic) material
Usually expresses the magnetic property of the material where it has equal magnetic properties in all directions; that is, there is no preferred direction of magnetization.

- Uniaxial crystalline anisotropy: the property of a magnetic material wherein a magnetic field is aligned with a crystal axis such that there is only one possible direction of magnetization. This is the case for ferrite, samarium cobalt, neodymium iron boron and samarium iron nitride magnets.
- Isotropic material: a material in which the crystals – and therefore the magnetic domains – are aligned randomly such that magnetic properties are equal regardless of the direction in which the material is magnetized. Attempts to orient this material during manufacture are unsuccessful. An example is melt-spun neodymium-iron-boron produced in powder form to make bonded magnets.
- Oriented and un-oriented (isotropic material is naturally un-oriented). When the powder used in the manufacture of magnets is of one crystalline (domain) orientation per particle, it can be oriented during manufacture and the resulting magnet is said to be oriented. If no attempt is made to orient the powder, the magnet is said to be un-oriented

Vibrating sample magnetometer, VSM
A device, similar to a hysteresigraph, for measuring the magnetic properties of a material. However, unlike for a hysteresigraph, the sample is supported in near open circuit within a magnetic field. In the measurement setup, a magnet sample is caused to move in the proximity of two pickup coils. Output is based on Faraday's law which states that an electromotive force is generated in a coil when there is a change in flux through the coil such as that created by the moving magnetic material.

Volt, V
Electric potential difference (voltage). One volt is the potential difference between two points that will impart one joule of energy per coulomb of charge that passes between the two points.

Voltage, *V*
Electric potential difference (voltage) measured in units of volts (V).

Volume of the gap, V_g
The volume of the air gap in region between adjacent magnetic pole faces in a magnetic circuit. It is the product of the cross-sectional area of the pole faces and the distance between them.

Weber, Wb
The unit of magnetic flux in the SI system. One weber equals 10^8 maxwells.

4. UNITS AND CONVERSION FACTORS for MAGNETIC PROPERTIES

The following is the foreword to the presentation of a table of units and conversions published in 1986 and which is very similar to the table presented below. The foreword was written by Ron B. Goldfarb of the National Bureau of Standards (NBS). The NBS became the National Institute of Standards and Technology (NIST) in 1988.

> "Historically, the Gaussian (cgs-emu) system has been used in magnetic materials research. One problem that arises is that there are no names for certain quantities. Thus, for example, both mass magnetization and mass susceptibility may be expressed as "emu per gram". Here "emu" is used as an indicator of electromagnetic units; it is not itself a unit.
>
> "In recent years, there has been an effort to unify electromagnetic disciplines and this has meant the use of SI (rationalized mks) for magnetics. One problem with rationalized mks is that there are two acceptable ways to relate the flux density (*B*) to the field strength (*H*) and either magnetization (*M*) or magnetic polarization (*J*): $B=\mu_O(H + M)$ and $B = \mu_O H + J$. Generally, the use of *M* rather than *J* is preferred in SI [ed. *J* is now preferred], which determines the SI units for those quantities derived from *M*: mass magnetization, volume susceptibility, and mass susceptibility. However, *J* itself is an approved SI quantity, as is magnetic dipole moment (*j*).
>
> "Another problem with SI is that the unit for *H*, ampere per meter, is usually quantitatively awkward and recourse is often made to the unit for *B*, tesla (equal to weber per square meter). Thus, we often hear about one-tesla electromagnets, for example, but rarely hear about 800-kiloampere-per meter electromagnets. The problem does not arise in the Gaussian system since the units for *B* and *H* have the same dimensionality; at worst, "gauss", the unit of *B*, is improperly used in place of "oersted", the unit for *H*.
>
> "In spite of these perceived problems, it is more convenient to use SI when dealing with applications that combine electricity and magnetism, such as in applied superconductivity. In such cases, SI is perfectly compatible with both disciplines, while cgs is not. For one thing, in electricity, the Gaussian and emu systems are no longer equivalent. For example, the Gaussian unit for current is "statamp" and the emu [unit] for current is "abamp".
>
> "The NBS [ed. Now the National Institute of Standards and Technology] has adopted SI. Most [NIST] authors give magnetic quantities in SI, followed by the cgs quantity in parentheses, when reporting data on magnetic materials. Perhaps some good advice is for us magneticians to become bilingual."

Quantity	Symbol	Gaussian & cgs emu [a]	cgs to SI Conversion[b]	SI & rationalized mksa [c]
electric current	I	abampere, abA	10	ampere, A
force	F	dyne, dyn	10^{-5}	newton, N
work or energy	erg	erg=dyn•cm	10^{-7}	joule, J=N•m
power	P	erg/s	10^{-7}	watt, W=J/s
magnetic flux	N	maxwell (Mx), G•cm^2	10^{-8}	weber (Wb), volt second (V•s)
magnetic flux density, magnetic induction	B	gauss (G), Mx/cm^2	10^{-4}	tesla (T), Wb/m^2
magnetic field strength, magnetizing force	H	oersted (Oe)	$10^3/4\pi$	A/m
magnetization (volume)	M	emu/cm^3	10^3	A/m
magnetization (volume)	$4\pi M$	gauss (G)	$10^3/4\pi$	A/m
magnetic polarization	J	emu/cm^3	4π x 10^{-4}	tesla (T), Wb/m^2
magnetization (mass)	σ, M	emu/g	1 4π x 10^{-7}	A•m^2/kg Wb•m/kg
magnetic moment	m	emu, erg/G	10^{-3}	A•m^2, joule per tesla (J/T)
magnetic dipole moment	j	emu, erg/G	4π x 10^{-10}	Wb•m
susceptibility (volume)	χ	dimensionless, emu/cm^3	4π	dimensionless
susceptibility (mass)	χ_ρ	cm^3/g	4π x 10^{-3}	m^3/kg
permeability	μ	dimensionless	4π x 10^{-7}	H/m, Wb/(A•m)
permeability (relative)	μ_r	not defined	-	dimensionless
permeance (inverse of reluctance)	-	maxwell/gilbert	10^9 / 4π	henry
Reluctance	R_m	gilbert/maxwell	4π / 10^9	1/henry
energy density (volume), energy product	W	erg/cm^3	10^{-1}	J/m^3
demagnetization factor	N	dimensionless	$1/4\pi$	dimensionless

a. Gaussian units and cgs emu are the same for magnetic properties. The defining relation is $B = 4\pi M + H$.

b. Multiply a number in Gaussian units by the conversion factor to convert to SI (e.g., 1 G x 10^{-4} T/G = 10^{-4} T).

c. SI (*Système International d'Unitès*) has been adopted. Where two conversion factors are given, the upper one is recognized under, or consistent with, SI and is based on the definition $B = \mu_o(M + H)$, where $\mu_o = 4\pi \times 10^{-7}$ H/m. The lower one is not recognized under SI and is based on the definition $B = \mu_o H + J$.

Adapted from R. B. Goldfarb and F. R. Fickett, U.S. Department of Commerce, National Bureau of Standards, Boulder, Colorado 80303, March 1985, NBS Special Publication 696.

5. EVOLUTION of MAGNETIC SYMBOLS and TERMINOLOGY

Symbols and names for magnetic characteristics present a challenge: they continue to evolve and they vary by author, country and company. A few equivalent symbols for selected characteristics are shown below. Additional detail is available in the section: Basics of Magnetics.

Subscripts: subscripts in symbols are often ignored so as to simplify writing and typing. The subscripted letters are sometimes capital letters in order to be more legible. In some situations (such as plain text e-mail and mobile device texting) subscripts, italics and bold face are not available.

Italics: symbols are italicized in ASTM A340. According to NIST's guide for the use of SI, symbols are not italicized. IEC uses italics for the main part of the symbol, but not for the subscripts.

For additional information:

- ASTM standard A340, Standard Terminology of Symbols and Definitions Relating to Magnetic Testing. Refer to the latest edition of ASTM A340 as it is undergoing continual updating to be made consistent with current industry, NIST and IEC usage.
- IEC 60050 - International Electrotechnical Vocabulary available online at: www.electropedia.org/iev/iev.nsf/index?openform&part=221
- NIST Guide to the use of SI available for download at: https://physics.nist.gov/cuu/pdf/sp811.pdf

Symbols are presented below from the older to the more recent; the last abbreviation for each is most consistent with SI and what industry is moving toward and is presented in bold face and blue color. Refer to their usage in the two following Figures.

- Br = $\boldsymbol{B_r}$ = **Residual induction** and is equal to J_r (residual polarization) and $4\pi M_r$ (residual magnetization). Though B_r remains the more common symbol J_r is increasingly used. Units of B_r are tesla, T (in SI units), and gauss, G (in cgs units), where 10,000 gauss = one tesla. Residual induction may also be called residual magnetic flux density.
- Hc = Hcb = $\boldsymbol{H_{cB}}$ = **coercivity** or normal coercivity or normal coercive field strength. "b" or "B" are probably used because the H_{cB} point is the intersection of the normal (B versus H) curve and the H axis. Units of coercivity are A/m (SI) and oersted, Oe (cgs), where 1 Oe = 4•π•kA/m = 12.566•kA/m.
- Hci = iHc = jHc = Hcj = $\boldsymbol{H_{cJ}}$ = **intrinsic coercivity**, a measure of a magnet's resistance to demagnetization. The "I" or "J" are probably used as these points are on the intrinsic curve, also called the polarization (J) curve. It is at the intersection of the intrinsic curve with the H axis. Units of coercivity are A/m (SI) and oersteds, Oe (cgs).
- (BdHd)m = (BdHd)max = BHmax = (BH)max = $\boldsymbol{(BH)_{max}}$ = **maximum energy product**. Every point on the normal curve has a value of B and a corresponding value of H. There is a product of B•H for every point on the curve. This product is called the energy product. The point in the second quadrant where the product of B•H is maximum is called the maximum energy point and the value of B•H at this point is the maximum energy product. The point is sometimes represented by its coordinates, (B_d,H_d) or (B_0,H_0). Units of maximum energy product are kilojoules per cubic meter, kJ/m^3 (SI) and megagauss-oersteds, MGOe (cgs).
- μ_r = $\boldsymbol{\mu_{rec}}$ = **recoil permeability** is measured on the normal curve. It has also been called relative recoil permeability. When referring to the corresponding slope on the intrinsic curve it is called the intrinsic recoil permeability. (See susceptibility). In the cgs system where one gauss equals one oersted, the intrinsic recoil equals the normal recoil minus one. For example, a typical rare earth magnet might have a μ_{rec} = 1.05 and the corresponding intrinsic recoil = 0.05. The symbol μ_r is currently used to represent relative permeability. There are several other permeabilities, including initial permeability (μ_i) and maximum permeability, μ_{max}.

Strictly speaking, recoil permeability is without units as it is a ratio.

- Pc = P_C = **permeance coefficient**. This is a calculated value dependent on the dimensions of the magnetic circuit and on the dimensions of the magnet alone when the magnet is in open circuit. Calculation of P_C is also dependent upon the magnetic material for which the effects can be large such as in alnico, FeCrCo, Vicalloy and similar semi-hard materials due to flux leakage near the poles. For "straight line" materials such as ferrite, SmCo and NdFeB, the effects are minor and usually ignored. Calculation of permeance are based on one of the following: the Evershed polar model (N_B, ballistic demagnetizing factor); Joseph's uniform material (N_M magnetometric demagnetizing factor); or the fluxmetric (N_F, fluxmetric demagnetizing factor) the latter of which is similar to N_B but incorporates the materials' susceptibility. P_C is related to the demagnetizing factor by the relationship: $P_C = 1-(1/N)$ where N is any of the above demagnetization factors. In the cgs system, the intrinsic permeance coefficient is equal to the permeance coefficient plus one: $P_{CI} = P_C+1$. The value of P_C is negative, but almost always presented and used as a positive number.
- H_X and H_k. In these cases, the symbol is also the name of the parameter. Both parameters are meant to indicate the value of H corresponding to the location of the knee of the intrinsic curve, that value of H where the intrinsic curve falls quickly toward the H axis.
- H_k/H_{cJ} = **squareness** (ratio). Since H_k is an indication of the onset of demagnetization and H_{cJ} is a measure of a magnet's resistance to demagnetization, a value of H_k approaching H_{cJ} is considered beneficial. The ratio of H_k to H_{cJ} is the squareness ratio with 1 as an upper limit and values greater than 0.85 considered typical for oriented, anisotropic square loop materials such as permanent magnet ferrites, NdFeB and SmCo.
- Hs = H_s. The value of the applied field strength, H, where the material becomes magnetically saturated.
- $4\pi M_S$ = Bis = Bs = J_S = **Saturation polarization.** This is the maximum value of intrinsic magnetic flux density achievable by a ferro- or ferrimagnetic material. It is observed in the first quadrant and is one of the key figures of merit for soft magnetic materials. Refer to Figure 1. The use of B_S has been associated with both the normal and intrinsic curves. In part to avoid this ambiguity, J_s is strongly advised.
- $M_S/M_R = B_{IS}/B_R = J_S/J_R$ = first quadrant **squareness ratio**. Less frequently used in industry but often used in magnetics research. It is a measure of a permanent magnet's resistance to spontaneous demagnetization and is often an indicator of a potentially strong permanent magnet material.

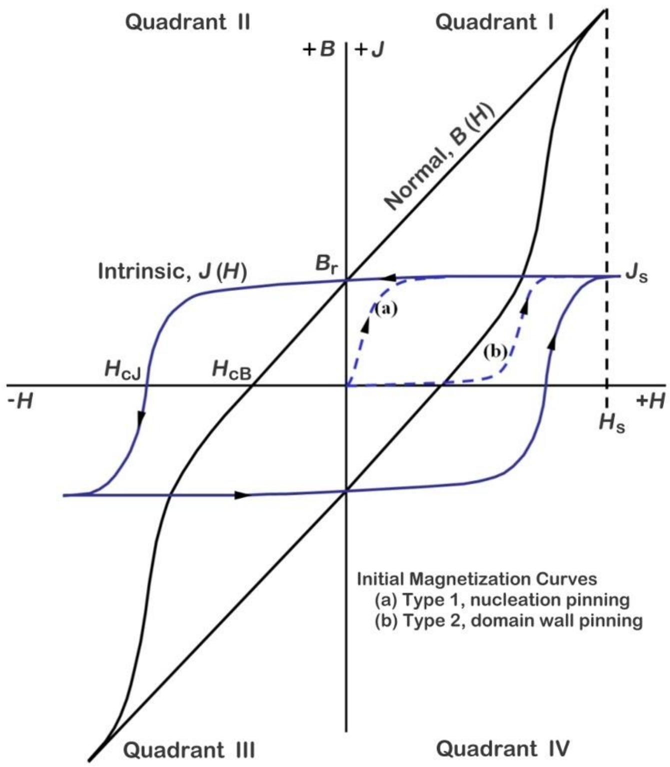

Figure 1. Normal and intrinsic magnetic hysteresis loops showing all four quadrants and indicating many key figures of merit. This chart is based on Figure 1 of *ASTM A977M Standard Test Method for Magnetic Properties of High-Coercivity Permanent Magnet Materials Using Hysteresigraphs*.

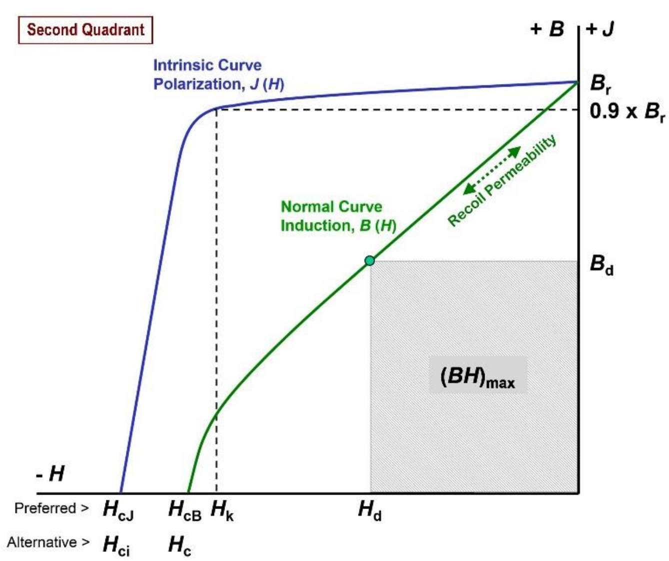

Figure 2. Second quadrant showing both normal and intrinsic hysteresis curves and figures of merit. Maximum energy product, $(BH)_{max}$, is represented by the shaded area.