Devices thru Material Innovation

NEC/TOKIN

Vol.04

Permanent Magnets

⚠
- All specifications in this catalog and production status of products are subject to change without notice. Prior to the purchase, please contact NEC TOKIN for updated product data.
- Please request for a specification sheet for detailed product data prior to the purchase.
- Before using the product in this catalog, please read "Precautions" and other safety precautions listed in the printed version catalog.

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When using our products, the following Precautions should be taken.

1. Safety Precautions

(1) Large magnets exert an extremely powerful suction force (and sometimes a repelling force) on other magnets or metal scraps and other magnetically attracted substances. This force is capable of causing you to suddenly lose your balance or suffer serious injury if your hand or other parts of your body become trapped in the magnetic field while carrying or installing the magnets. Please take sufficient care when handling these magnets and always use appropriate tools.

(2) The sharp edges of magnets can cause injury to your fingers and hands especially. Please handle the magnets with care.

(3) When attaching magnets using a hollow-core coil, please be aware that the magnet may suddenly spring away from the coil. For safety's sake, place the magnet in the center area of the coil and secure it.

(4) Keep magnets out of the reach of children so as to avoid accidental swallowing. Should this occur, see a physician immediately.

(5) People whose skin is allergic to metals should avoid working with magnets, as this may cause an adverse reaction (rough, red skin).

(6) It is extremely dangerous to handle magnets near people who are wearing pa cemakers or other electronic medical devices. Take special care when using magnets around medical equipment, as it may impair normal operations.

(7) Magnets are generally susceptible to breakage. Please take care when handling any magnet, and be aware that magnet fragments can easily enter your eyes or cause other serious bodily injury.

2. Handling Precautions

(1) If magnetized magnets are placed one on top of another, they can become diffi cult to pull apart or chip. Separate the magnets by using a spacer such as cardboard.

(2) If a magnetized magnet is allowed to be attracted to a metal plate or if two magnetized magnets are allowed to attract or repel each other, their magnetism may decrease, so use caution.

(3) If a magnetized magnet enters an AC or DC magnetic field, its magnetism may decrease.

(4) A magnetized magnet will attract debris such as iron filings, so unpack it from the case in a dust-free environment.

(5) A magnet can adhere to small magnetic bodies even if unmagnetized, so use caution in handling. In addition, when mounting a magnet in a precision motor, clean it after assembly before use.

(6) Each magnet has its own characteristic Curie temperature, depending on the material. If a magnet is heated to near the Curie temperature, it will lose its magnetism. If it is absolutely necessary to heat a magnet in an assembly process, please consult with us.

(7) If a magnet is held to, for example, a yoke by adhesion, select an appropriate adhesive and adhesion method so that mechanical distortion will not remain after adhesion. If the magnet is used while residual stress is still applied, the magnet may be cracked by even a slight shock.

(8) Magnets are not very resistant to shock and are easily cracked and chipped, so use caution. Cracking and chipping may cause deterioration of the magnet's characteristics, as well as loss of rigidity.

3. Others

(1) Please keep magnets away from magnetic tape, floppy disks, prepaid cards, CRTs, magnetic tickets, electronic watches and similar items. This can result in loss of recorded data or lead to malfunction due to magnetization.

(2) Please keep magnets away from electronic devices such as measuring boards and control panels, as this may cause them to malfunction or result in an accident.

(3) When cutting a magnet, please be aware that resulting magnetic dust can catch fire spontaneously due to the heat produced by friction during cutting. Kkeep magnets away from fire or flammable materials. As a precaution against fire, keep a dry chemical extinguisher, a supply of sand, and any other necessary equipment. Also, do NOT use an electric vacuum cleaner.

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INTRODUCTION

NEC TOKIN, as a leading manufacturer of magnetic materials, has been engaged in R&D of permanent magnets. As a result NEC TOKIN has introduced a superior lineup of products such as "TMK" alnico magnet and Lanthanet® rare-earth magnets. Today, application fields of these permanent magnets is extended to new industrial fields.

LANTHANET® is a super high-performance permanent magnet featuring high energy products. These magnets are best suited for electronic clocks, printers, motors, small-sized coreless motors vehicle applications, etc.

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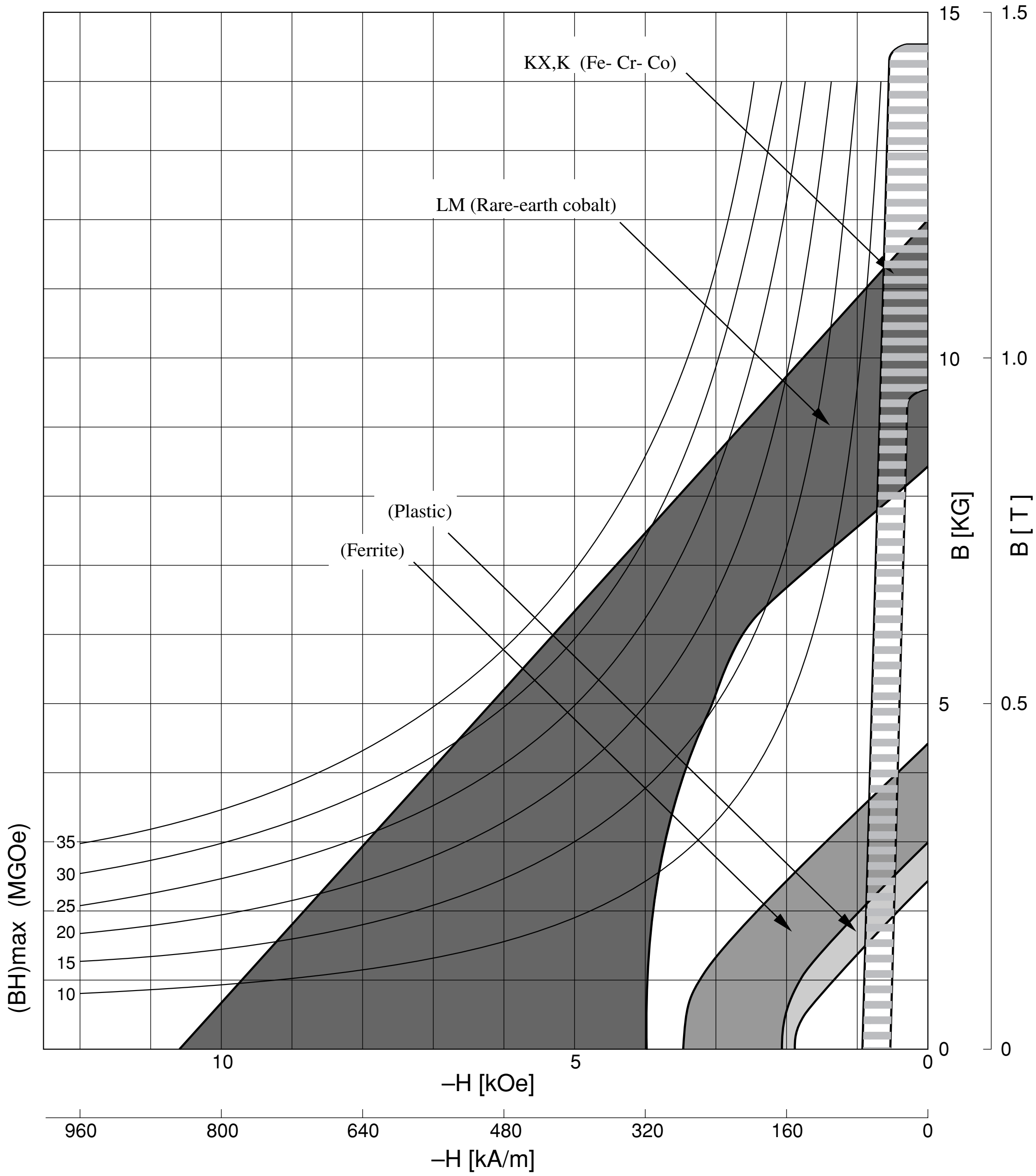

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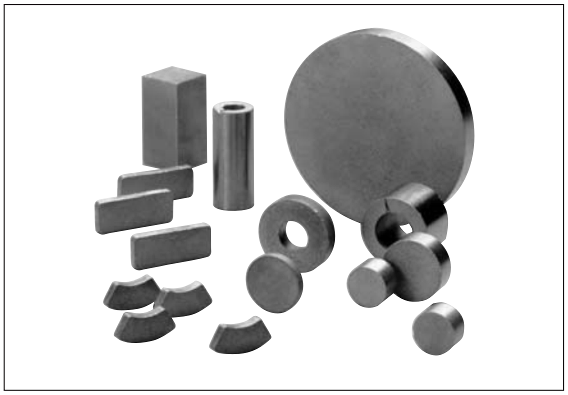
Lanthanet® Rare-earth Magnets



Features

Table 1 presents features and applications for a variety of Lanthanet® magnets.
LM-19: Magnets with large coercive force and high energy products (Type 1-5).
LM-20FB—LM-32FH: Magnets with high Br and high energy product (Type 2-17).
Select the most suitable material that meets your needs.

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Standard Material Characteristics and Applications

Table 1 Standard Material Characteristics

Material	Type	Residual flux density **Br Tesla (kG)**	Coercive force **HCB kA/m (kOe)**	Maximum energy product **(BH)max kJ/m³ (MGOe)**	Intrinsk Coercive force **HCJ kA/m (kOe)**	Density **D kg/m³**	Temperature coefficient **ΔBd/Bd %/ ˚C**	Electrical resistivity **ρ Ω – m**	Application
LM-19	Type 1-5	0.84 ~ 0.90 (8.4 ~ 9.0)	653 ~ 700 (8.2 ~ 8.8)	139 ~ 159 (17.5 ~ 20.0)	796 ~ 2387 (10.0 ~ 30.0)	$8.3 \pm 0.15 \times 10^3$	– 0.043	8×10^{-7}	Printers Motors CD actuators Instruments Traveling wave tube
LM-20FB	Type 2-17	0.96 ~ 1.04 (9.6 ~ 10.4)	517 ~ 716 (6.5 ~ 9.0)	151 ~ 183 (19.0 ~ 23.0)	597 ~ 1194 (7.5 ~ 15.0)	$8.3 \pm 0.15 \times 10^3$	– 0.04	9×10^{-7}	Stepping motors Headphones Loudspeakers
LM-23FB	Type 2-17	1.01 ~ 1.08 (10.1 ~ 10.8)	517 ~ 796 (6.5 ~ 10.0)	175 ~ 207 (22.0 ~ 26.0)	597 ~ 1194 (7.5 ~ 15.0)	$8.3 \pm 0.15 \times 10^3$			
LM-21B	Type 2-17	0.95 ~ 1.00 (9.5 ~ 10.0)	318 ~ 398 (4.0 ~ 5.0)	135 ~ 159 (17.0 ~ 20.0)	358 ~ 477 (4.5 ~ 6.0)	$8.3 \pm 0.15 \times 10^3$	– 0.03	9×10^{-7}	Stepping motors
LM-25B	Type 2-17	1.00 ~ 1.07 (10.0 ~ 10.7)	318 ~ 398 (4.0 ~ 5.0)	151 ~ 183 (19.0 ~ 23.0)	358 ~ 477 (4.5 ~ 6.0)	$8.3 \pm 0.15 \times 10^3$			Headphones Loudspeakers
LM-24F	Type 2-17	0.98 ~ 1.06 (9.8 ~ 10.6)	477 ~ 637 (6.0 ~ 8.0)	175 ~ 207 (22.0 ~ 26.0)	557 ~ 875 (7.0 ~ 11.0)	$8.2 \pm 0.15 \times 10^3$	– 0.03	9×10^{-7}	Flat motors VCM Printers Relays
LM-24FH	Type 2-17	0.98 ~ 1.06 (9.8 ~ 10.6)	597 ~ 796 (7.5 ~ 10.0)	175 ~ 207 (22.0 ~ 26.0)	716 ~ 1432 (9.0 ~ 18.0)	$8.2 \pm 0.15 \times 10^3$			
LM-26FH	Type 2-17	1.02 ~ 1.08 (10.2 ~ 10.8)	637 ~ 796 (8.0 ~ 10.0)	191 ~ 223 (24.0 ~ 28.0)	716 ~ 1432 (9.0 ~ 18.0)	$8.2 \pm 0.15 \times 10^3$	– 0.03	9×10^{-7}	Printers VCM Servo motors
LM-30F	Type 2-17	1.07 ~ 1.15 (10.7 ~ 11.5)	477 ~ 637 (6.0 ~ 8.0)	199 ~ 247 (25.0 ~ 31.0)	517 ~ 875 (6.5 ~ 11.0)	$8.2 \pm 0.15 \times 10^3$	– 0.03	9×10^{-7}	Relays Coreless motors CD actuators VCM Printers Flat motors
LM-30FH	Type 2-17	1.07 ~ 1.15 (10.7 ~ 11.5)	597 ~ 836 (7.5 ~ 10.5)	199 ~ 247 (25.0 ~ 31.0)	637 ~ 1432 (8.0 ~ 18.0)	$8.2 \pm 0.15 \times 10^3$			
LM-26SH	Type 2-17	1.02 ~ 1.07 (10.2 ~ 10.7)	676 ~ 812 (8.5 ~ 10.2)	175 ~ 215 (22.0 ~ 27.0)	1592 ~ (20.0 ~)	$8.2 \pm 0.15 \times 10^3$	– 0.03	9×10^{-7}	Vehicle-use sensors Ignition coils Surface mounting devices
LM-30SH	Type 2-17	1.05 ~ 1.12 (10.5 ~ 11.2)	676 ~ 836 (8.5 ~ 10.5)	199 ~ 247 (25.0 ~ 31.0)	1592 ~ (20.0 ~)	$8.2 \pm 0.15 \times 10^3$			
LM-32F	Type 2-17	1.15 ~ 1.20 (11.5 ~ 12.0)	480 ~ 637 (6.0 ~ 8.0)	224 ~ 256 (28.0 ~ 32.0)	520 ~ 875 (6.5 ~ 11.0)	$8.2 \pm 0.15 \times 10^3$	– 0.03	9×10^{-7}	Sensors Switches Coreless motors Servo motors Actuators
LM-32FH	Type 2-17	1.15 ~ 1.20 (11.5 ~ 12.0)	560 ~ 756 (7.0 ~ 9.5)	224 ~ 256 (28.0 ~ 32.0)	680 ~ 1194 (8.5 ~ 15.0)	$8.2 \pm 0.15 \times 10^3$			

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Demagnetization Curves

Demagnetization Curves of LANTHANET® (1) (Reference)

LM-19

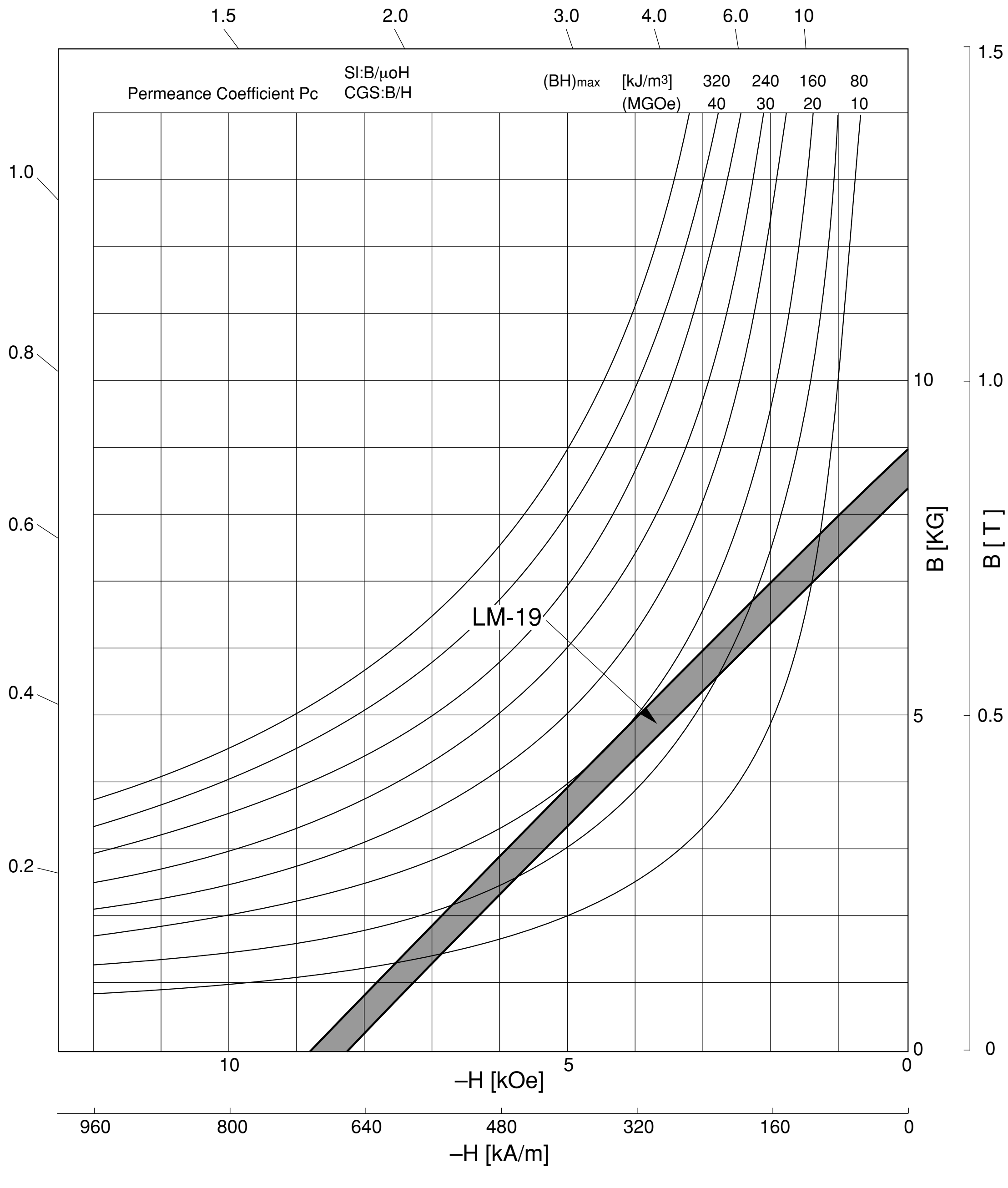

Fig. 1

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Demagnetization Curves of LANTHANET® (2) (Reference)

LM-20FB/LM-23FB

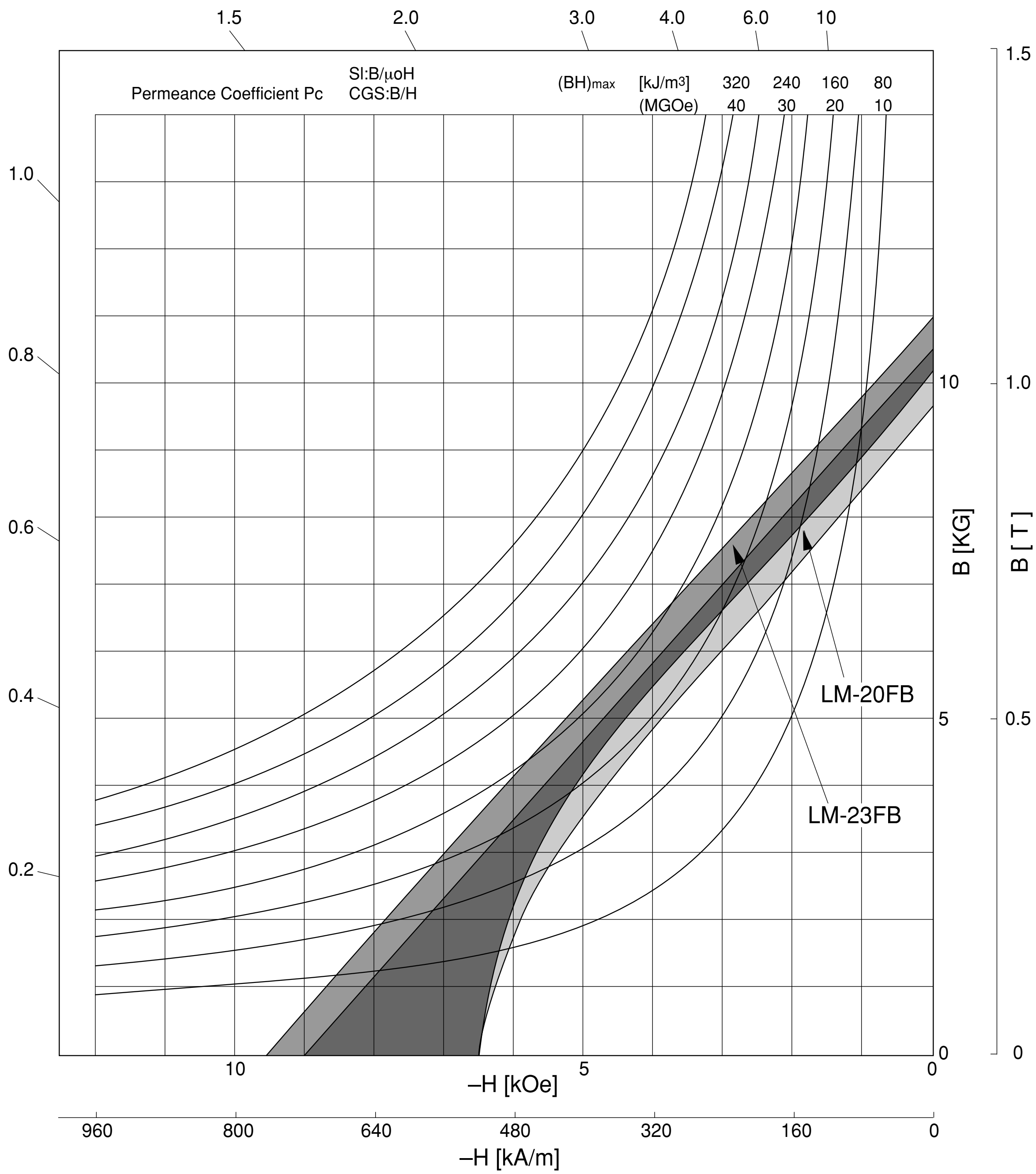

Fig. 2

• LM-20FB/LM-23FB are ideal for stepping motors, headphones and loudspeakers.

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Demagnetization Curves of LANTHANET® (3) (Reference)

LM-21B/LM-25B

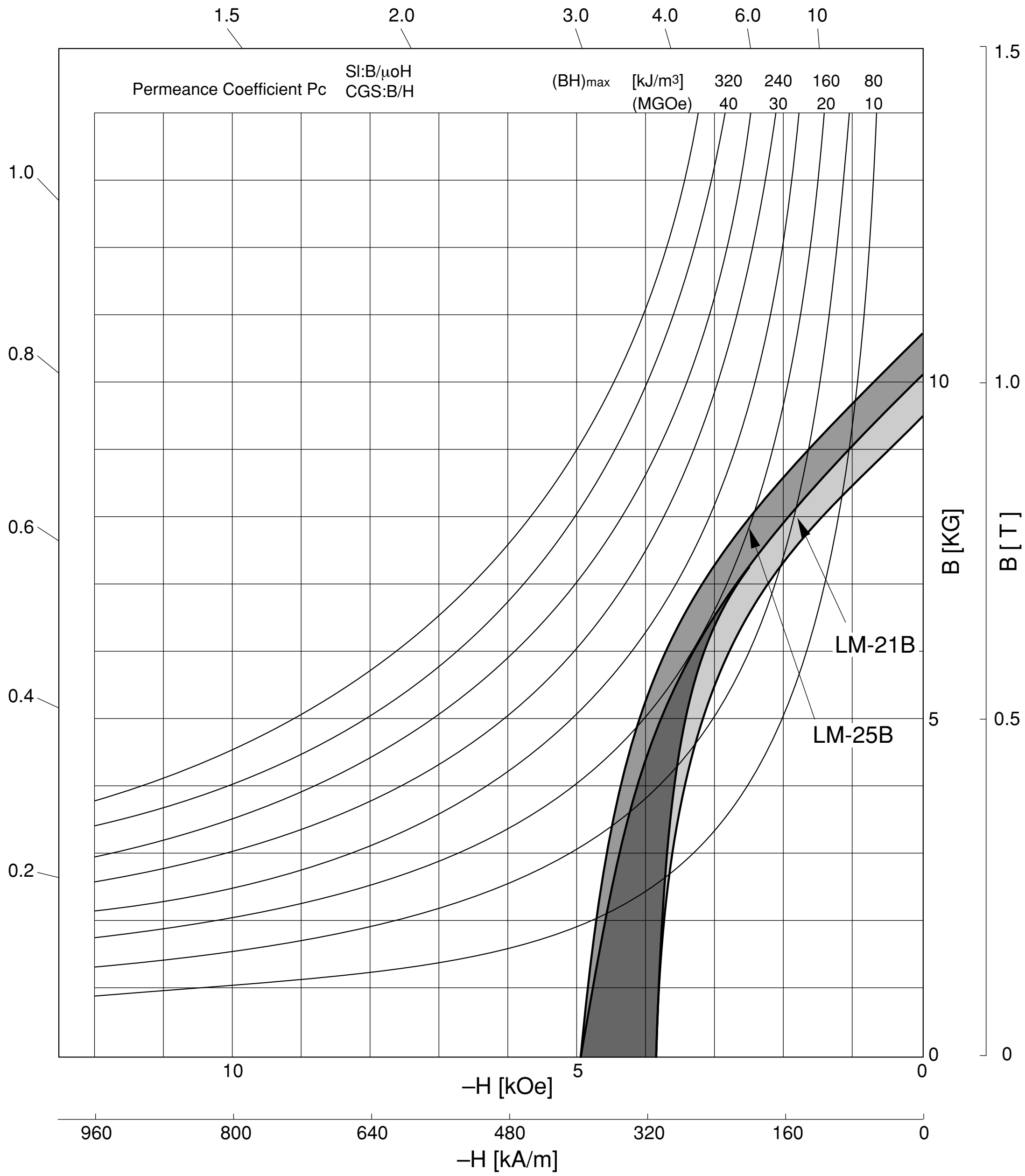

Fig. 3

- LM-21B/LM-25B are ideal for stepping motors, headphones and loudspeakers.
- Easy alternating-current demagnetization.

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Demagnetization Curves of LANTHANET® (4) (Reference)

LM-24F/LM-24FH

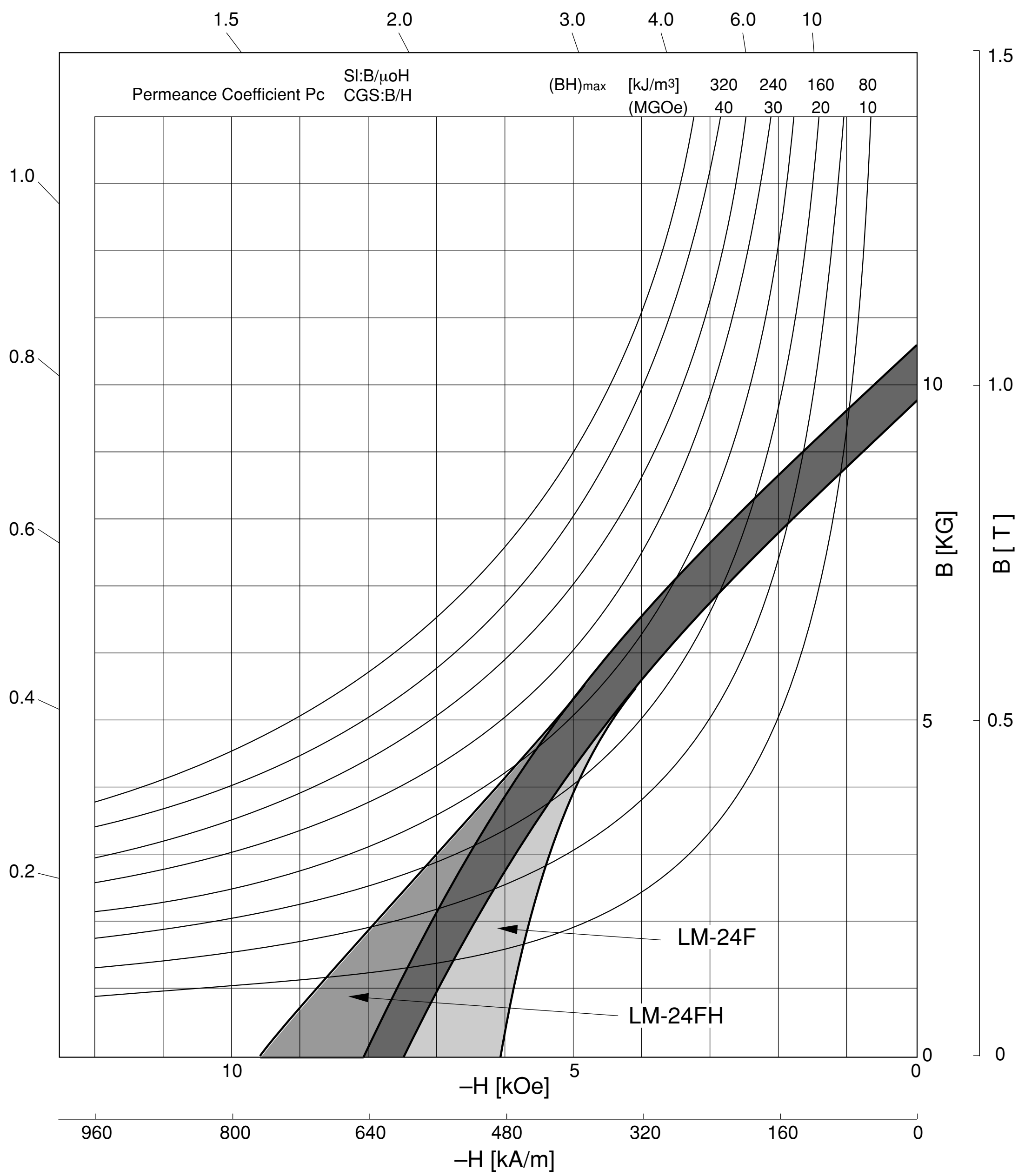

Fig. 4

- LM-24F is ideal for motors that use flat-ring type magnets.
- LM-24FH is ideal for printers.

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Demagnetization Curves of LANTHANET® (5) (Reference)

LM-26FH

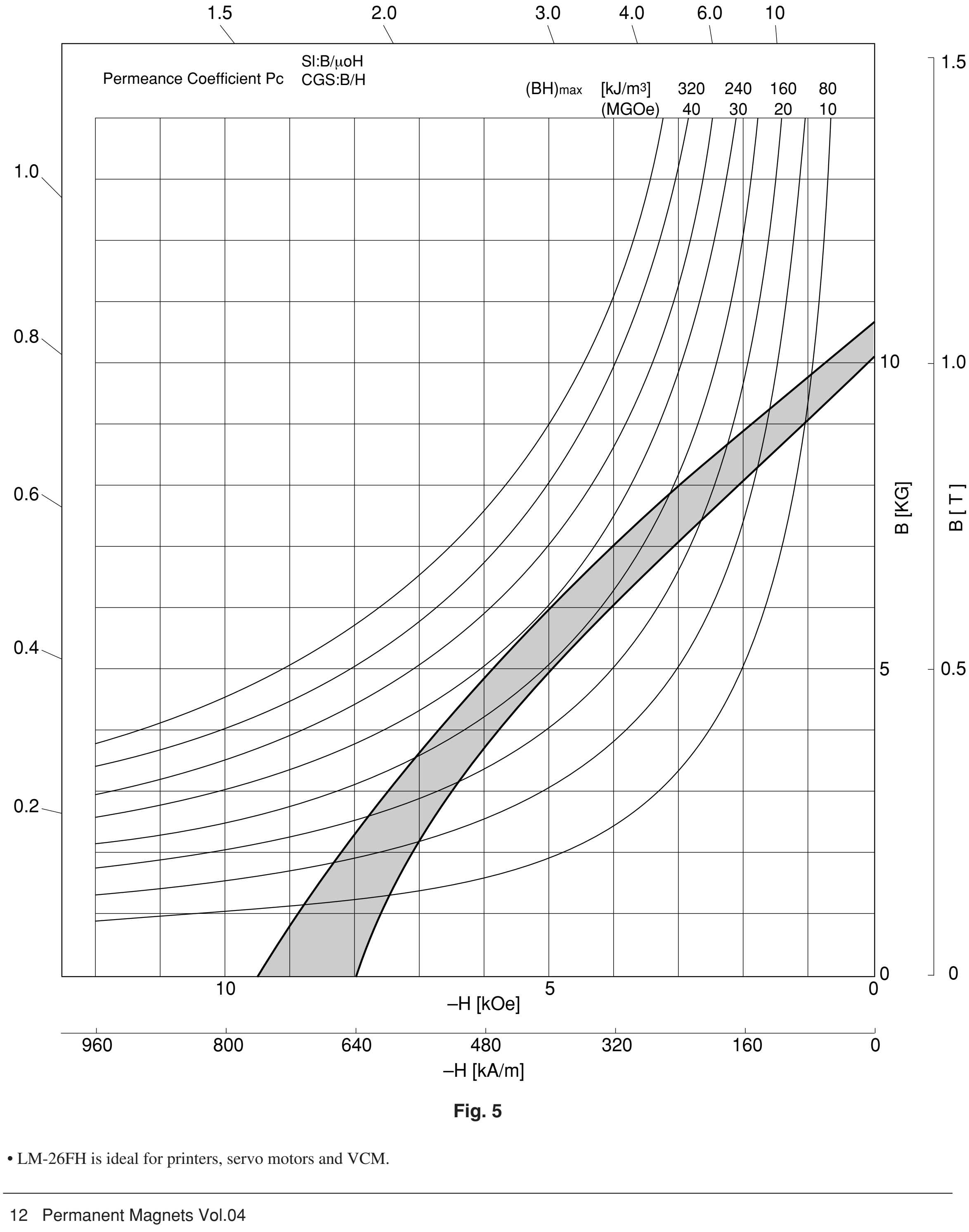

Fig. 5

• LM-26FH is ideal for printers, servo motors and VCM.

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Demagnetization Curves of LANTHANET® (6) (Reference)

LM-30F/LM-30FH

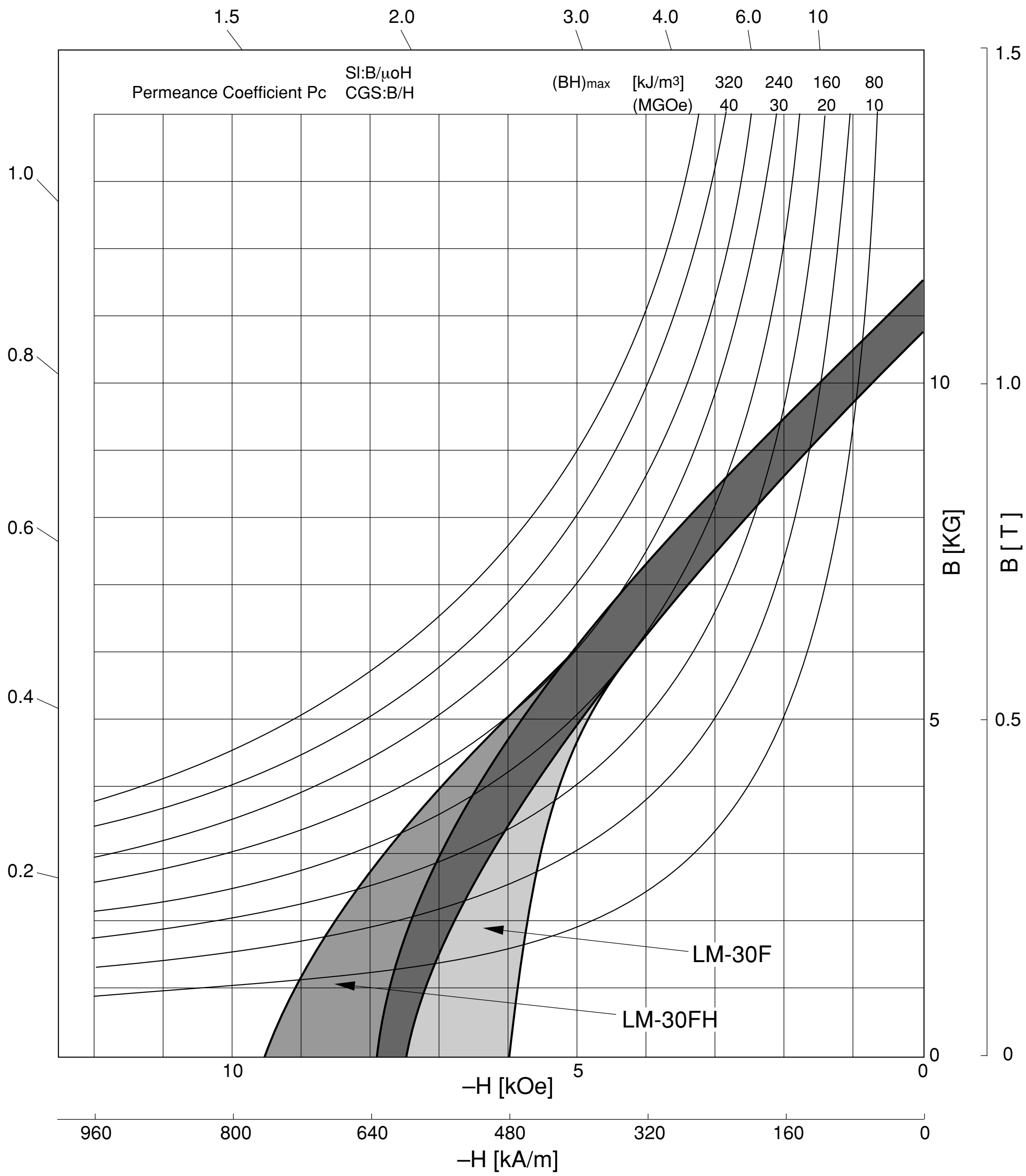

Fig. 6

- LM-30F is ideal for careless motors and relays.
- LM-30FH is ideal for flat motors and line printers.

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Demagnetization Curves of LANTHANET® (7) (Reference)

LM-32F/LM-32FH

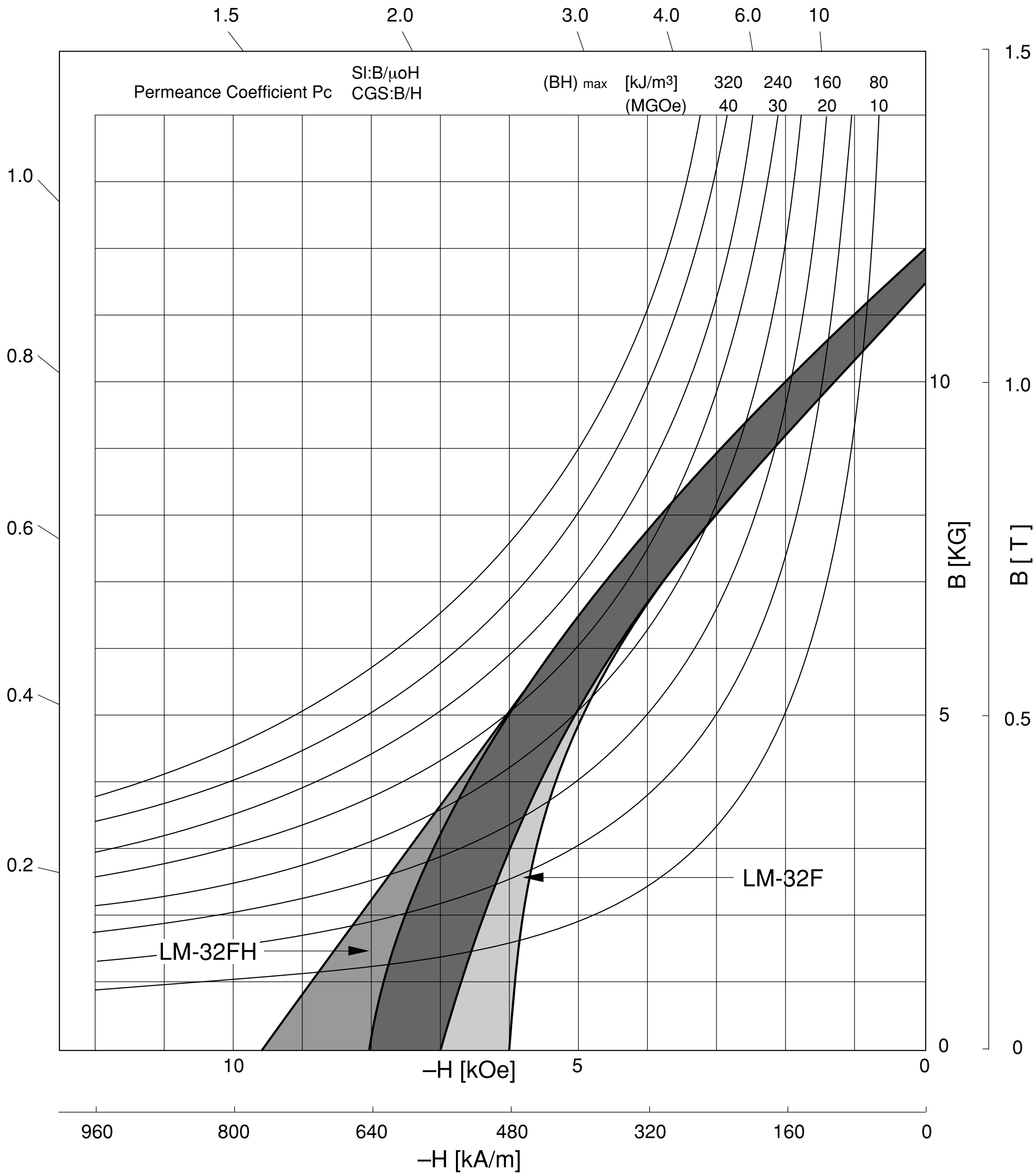

Fig. 7

- LM-32F is ideal for coreless motors and relays.
- LM-32FH is ideal for serbo-motors, HDDs, and latching magnets.

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Demagnetization Curves of LANTHANET® (8) (Reference)

LM-26SH/LM-30SH

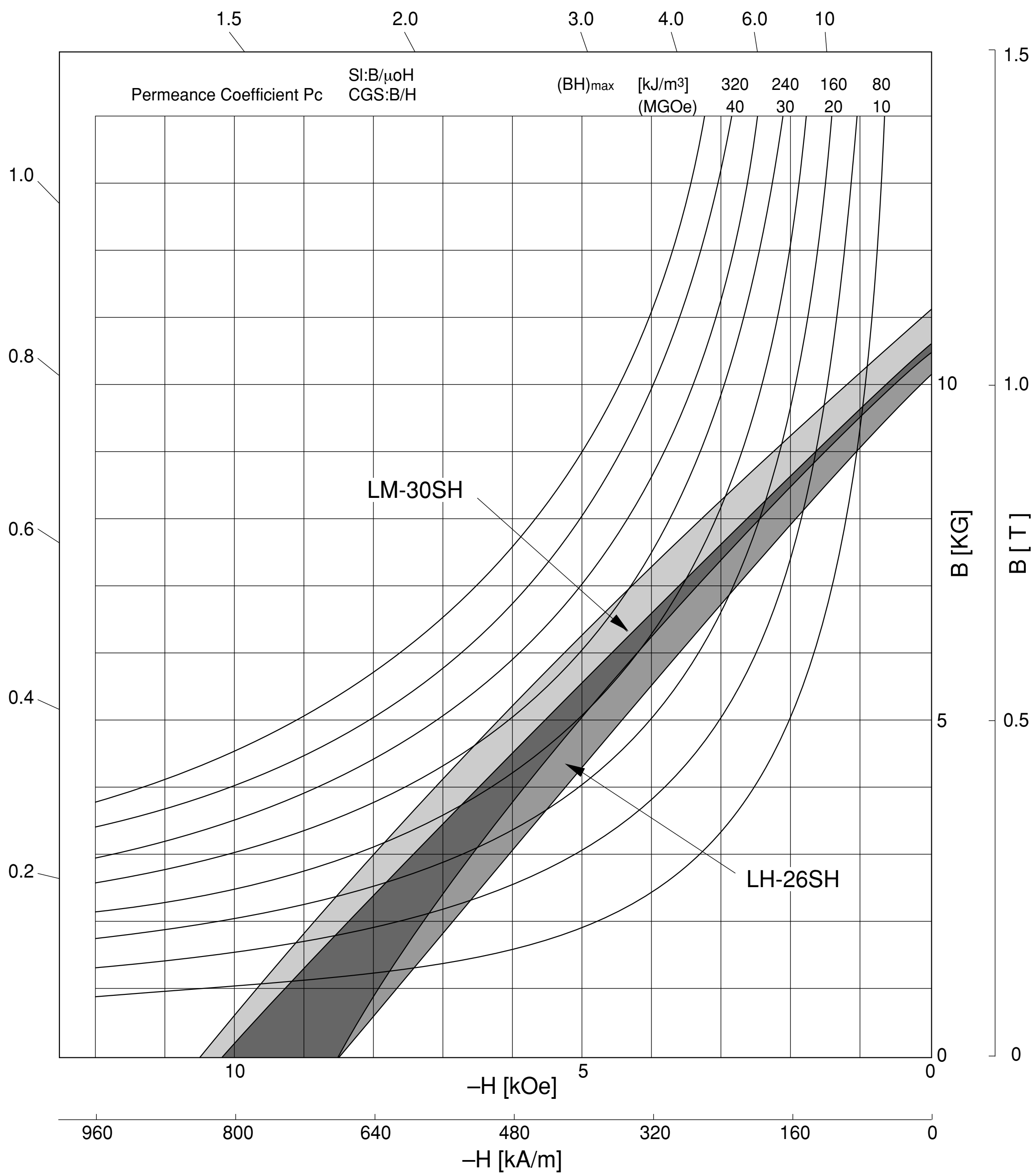

Fig. 8

- Vehicle applications: speed sensors, ABS sensors, ignition coils
- Surface mounting applications: relays, sounders

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Demagnetization Curves of LANTHANET® (9)

LM-19

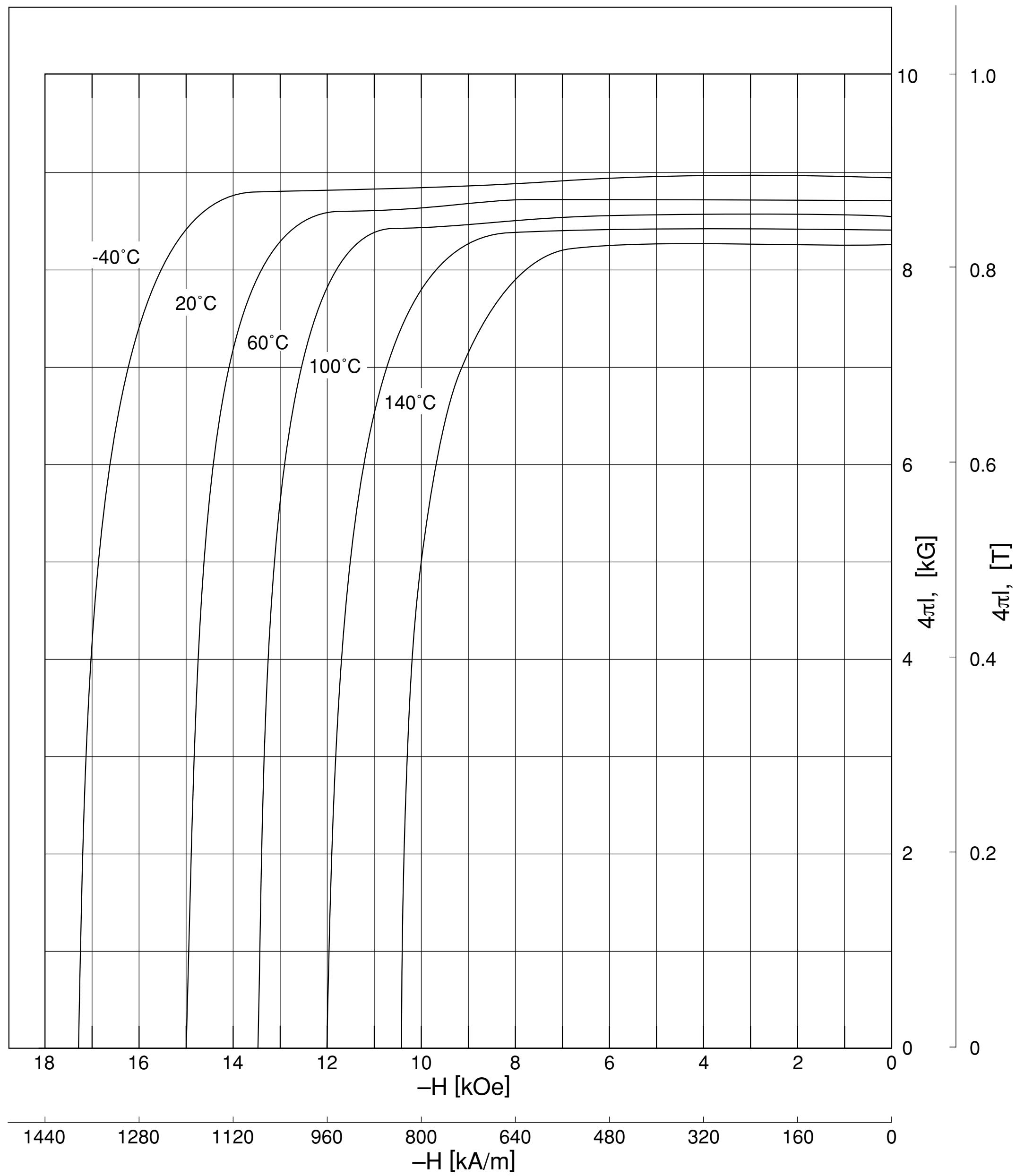

Fig. 9

Demagnetization Curves of LANTHANET® (10)

LM-19

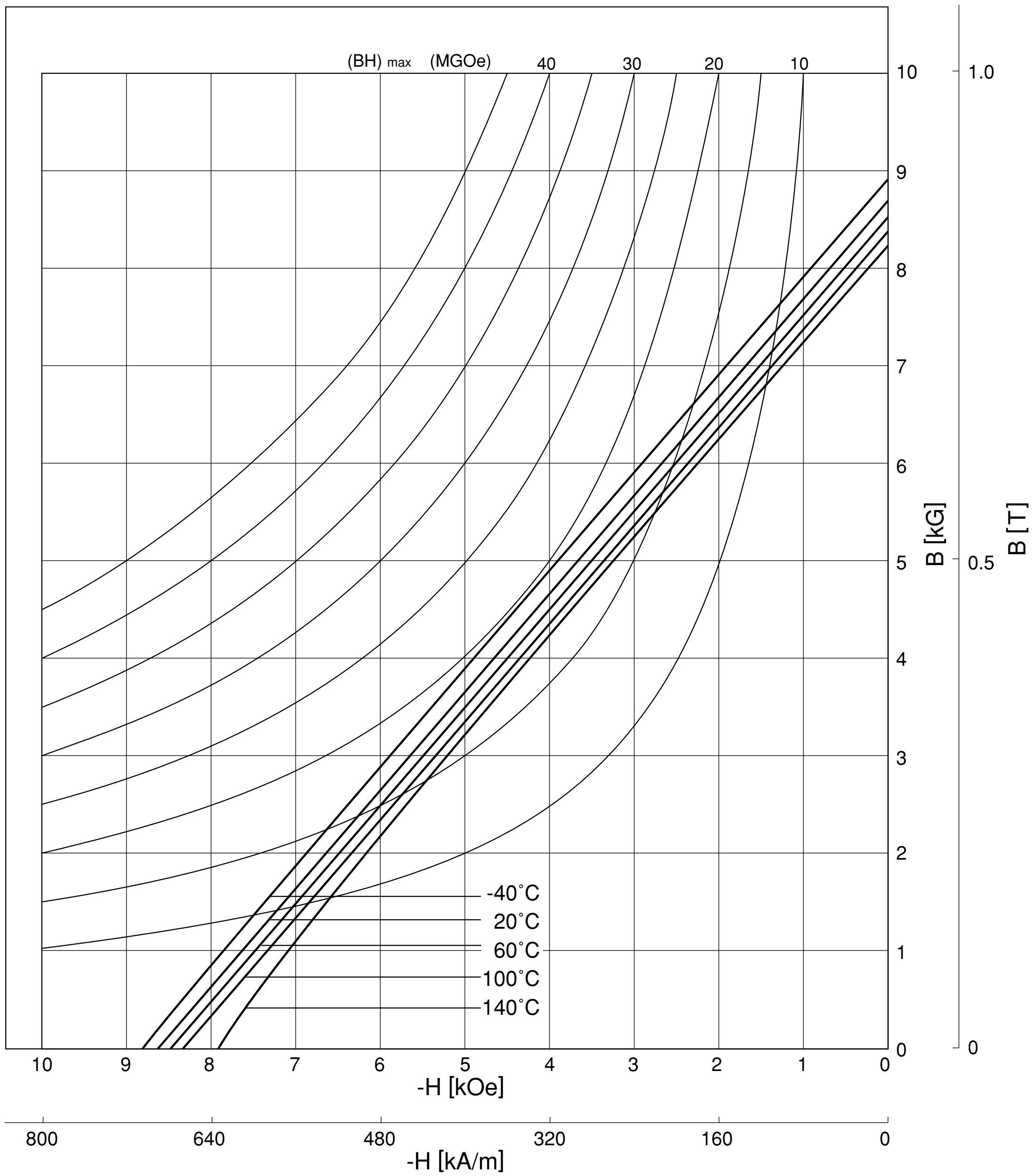

Fig. 10

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Demagnetization Curves of LANTHANET® (11)

LM-30FH

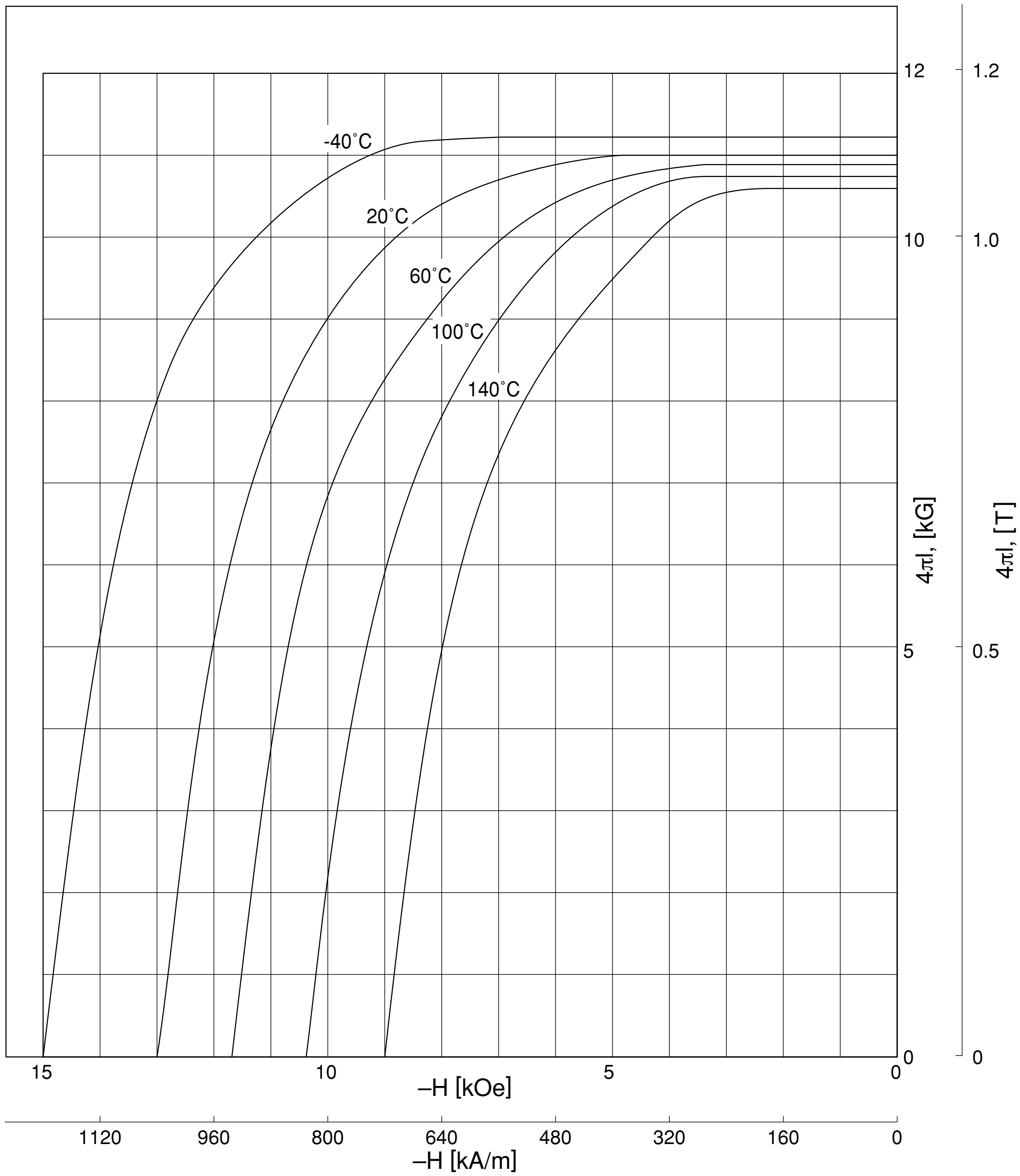

Fig. 11

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Demagnetization Curves of LANTHANET® (12)

LM-30FH

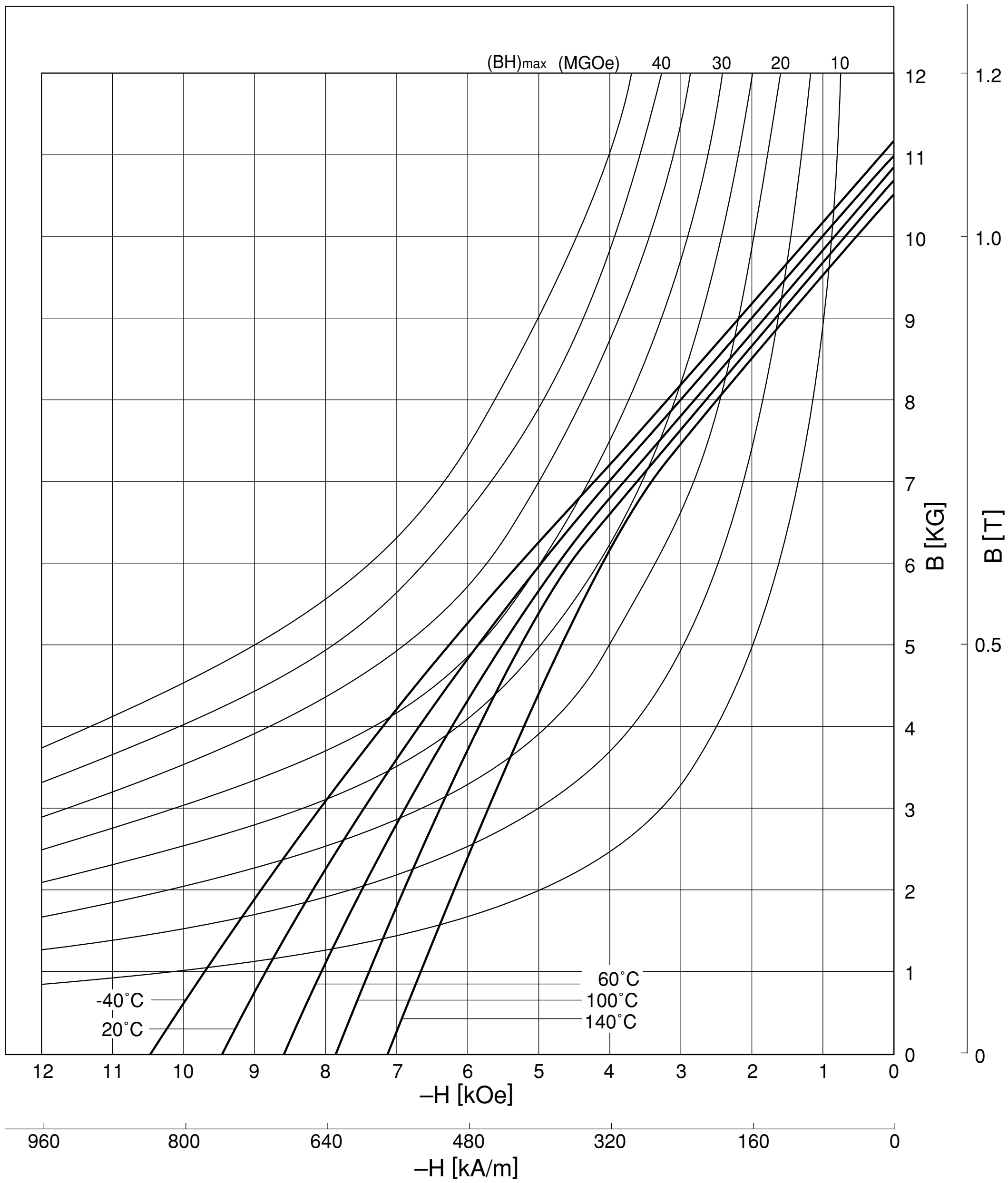

Fig. 12

Thermal Variations of Magnetic Characteristics

Irreversible Temperature Variations

The magnetic flux density generated by a permanent magnet decreases even without a change in the material if a permanent magnet is exposed to a high temperature and then returned to normal temperature. The variation ratio of the magnetic flux density gradually decreases commensurate to the time it is exposed to a high temperature and reaches saturation soon (30 minutes to 4 hours) after the variations stop. The variation ratio of the first magnetic flux density at this time is called the irreversible temperature variation ratio, and the variation width differs a great deal due to the holding temperature and magnet operating point position.

Figures 13-18 present approximate levels of irreversible temperature variations asainst the coercive force of LANTHANET®. It also shows that irreversible temperature variations are changed by the permanent magnet working point (P). In general, the larger the H_{CJ} and working point, the smaller the irreversible variations will be.

Irreversible Temperature Variations of LANTHANET® Fig. 13-18

LM19

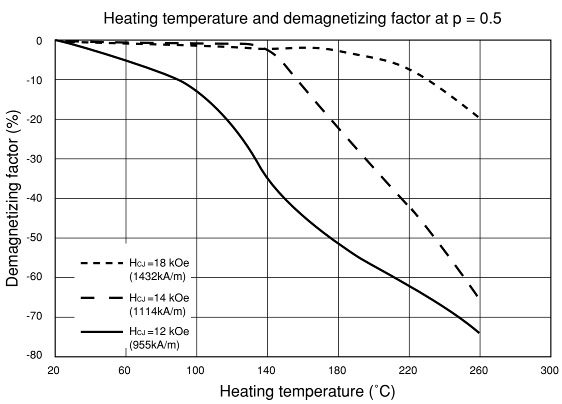

Fig. 13

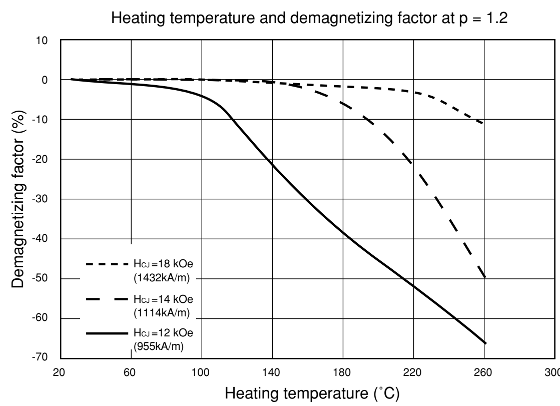

Fig. 14

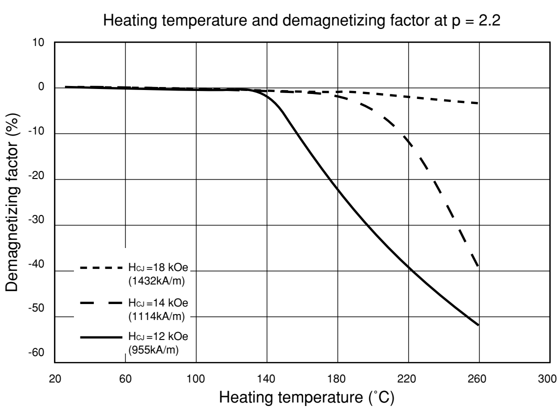

Fig. 15

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LM24F, 24FH, 26FH, 26SH
LM30F, 30FH, 30SH

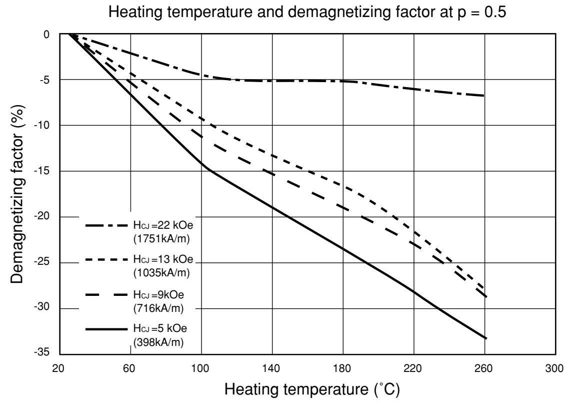

Fig. 16

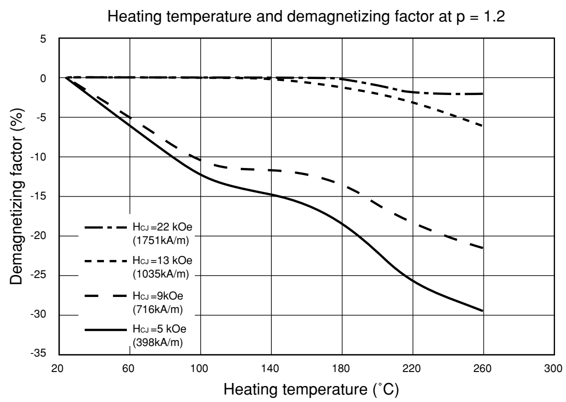

Fig. 17

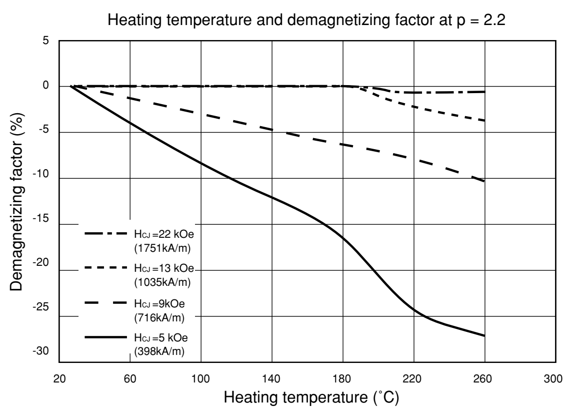

Fig. 18

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Reversible Temperature Variations

Reversible variations of magnetic characteristics intrinsic to materials due to temperature variations are called reversible temperature variations. The variation factor of magnetic flux density per degree centigrade is called the reversible temperature coefficient. The reversible temperature variations are measured after completing irreversible temperature variations at each temperature.

The temperature coefficients in Table 1 show the reversible temperature variations. The LM-20BT, the magnetic material with the swallest temperature variations, is a specially made by NEC TOKIN.

Magnetizing Field

Compared with alnico and ferrite magnets, LANTHANET® requires a high magnetizing field, and the magnetic field requires careful attention. Table 2 shows the required magnetic fields for LANTHANET®.

NEC TOKIN also manufactures and sells various magnetizing equipment. Do not hesitate to consult NEC TOKIN about your magnetizing requirements and equipment.

Table 2 Required Magnetizing Field for LANTHANET®

Material	Magnetic field kA/m(kOe)
LM-19	1273 (16)
LM-21B,25B	1194 (15)
LM-20FB,23FB	1989 (25)
LM-24F,30F,32F	1592 (20)
LM-24FH,LM-26FH,30FH,32FH	1989 (25)
LM-26SH,30SH	3183 (40)

If the demagnetizing field to a permanent magnet product is large, a larger magnetic field may be required to compensate the field.

Precaution

The force of attraction of magnetized LANTHANET® is very large. Careless handling, such as joining or separating two pieces of LANTHANET®, or attaching it to a metal, may damage its edges.

Ordering Information

When placing an order with NEC TOKIN LANTHANET®, be sure to specify the following items.

- Material and magnetic characteristics
- Dimensions and tolerances
- Whether or not magnetizing is necessary; direction of magnetization
- Whether or not grinding is necessary
- The purpose for which the material will be used
- The conditions under which the material will be used
- Any other relevant specifications

We welcome your queries regarding the shapes and dimensions of LANTHANET®. Please note however, the following limitations:

1) Upper limit of shape (monolithic construction)
   Round shape : Less than ϕ65mm
   Rectangular shape : Length - less than 75mm
   Width – less than 30mm

2) Accuracy
   Standard tolerance : ±1/10mm
   Special tolerance : ±5/100mm
   (Further accuracy depends on the shape of magnet)

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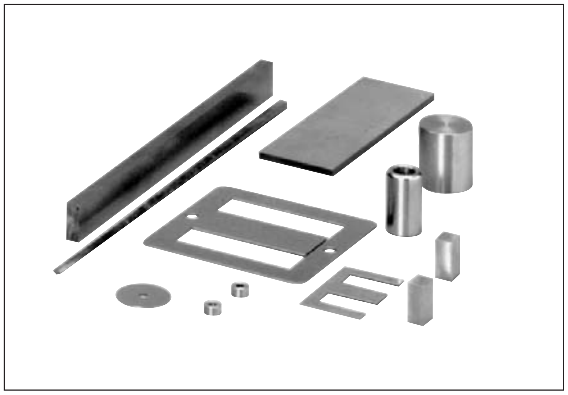
Fe-Cr-Co Magnets



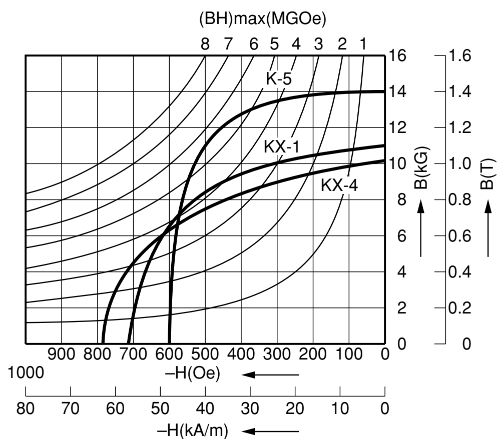


Fig. 29 Demagnetization Curve of Iron-Chromium-Cobalt Magnets

Outline

Iron-Chromium-Cobalt Magnets were developed by Professor Kaneko of Tohoku University and have been manufactured by NEC TOKIN. Their most prominent features are that they have equivalent performance to that of casting alnico magnets and economical magnets that have low content of Co and can be easily machine processed. In addition these magnets have the following features:

1) Plastic working is possible. Therefore, can be manufactured into thin plate or fine wire. Further, machining such as cutting, die parching, and drilling, which allows free designing of magnetic circuit and applications for new fields.

2) Since Iron-Chromium-Cobalt Magnets are manufactured in the process of rolling and drawing, they have no gross porosity or cracks and cannot be cracked or broken due to shocks.

3) They can be soldered. Their magnetic characteristics does no change due to temperature rise during operation. However, when heated with temperature over 500˚C (eg. silver blazing), their magnetic characteristics will be degraded.

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Standard Material Characteristics

Table 6 Magnetic Characteristics of Iron-Chromium-Cobalt Magnets

Material	Residual flux density Br T (kG)	Coercive force Hc kA/m (Oe)	Maximum energy product (BH)max kJ/m^3 (MGOe)	Optimum operating point		
				Bd T (kG)	Hd kA/m (Oe)	Permeance coefficient p
KX-1	1.05 ~ 1.25 (10.5 ~ 12.5)	47.7 ~ 59.7 (600 ~ 750)	25.5 ~ 41.4 (3.2 ~ 5.2)	0.85 (8.5)	39.8 (500)	17
KX-4	0.85 ~ 1.05 (8.5 ~ 10.5)	53.3 ~ 65.3 (670 ~ 820)	23.9 ~ 39.8 (3.0 ~ 5.0)	0.70 (7.0)	43.8 (550)	14
K-5	1.30 ~ 1.50 (13.0 ~ 15.0)	37.4 ~ 49.3 (470 ~ 620)	39.8 ~ 55.7 (5.0 ~ 7.0)	1.3 (13.0)	35.8 (450)	29

Mechanical and Physical Characteristics

Mechanical and physical characteristics of Fe-Cr-Co Magnets shown in table 7 is measured as solution treatment and mag, final heat treatment. Thermal expansion coefficient is average of temperature range from 0 to 500˚C.

Table 7 Mechanical and Physical Properties of Iron-Chromium-Cobalt Magnets

	Mechanical properties			Physical properties			
	Hardness Hv	Tensil strength N/mm^2	Elongation (%)	Density (kg/m^3)	Electric resistance ($\mu\Omega \cdot m$)	Thermal expansion coefficient (/˚C)	Curie temperature (˚C)
After solution treatment	200 ~ 230	637 ~ 735	10 ~ 15				
After mag, final heat treatment	450 ~ 500	441 ~ 490	0	7.8×10^3	0.62	14×10^{-6}	670

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Magnetic Stability

Generally speaking, when heating permanent magnet with high temperature, magnet materials appear irreversible demagnetization and also appear reversible demagnetization along with temperature change. Once you heat the material above operational temperature and the irreversible demagnetization is finished, you have only to pay attention to reversible change responding to temperature coefficient. Fe-Cr-Co Magnets do not generate irreversible demagnetization under temperature below 500˚C as shown in Fig. 30. However, when used under temperature above 500˚C, they show drastic decrease in flux value. (Keep magnets within each temperature range for an hour and measure flux value after temperature is lowered to room temperature). Therefore, magnets can be soldered but magnetism will be degradated when silver-soldered.

Table 8 presents rate of temperature change in Br of permanent magnetic materials under temperature range below 400˚C where degradation of irreversible characteristics is not generated. Fe-Cr-Co magnets show a bit larger rage of change compared with alnico magnets but much smaller compared with ferrite magnets. In most cases, these value can be ignored.

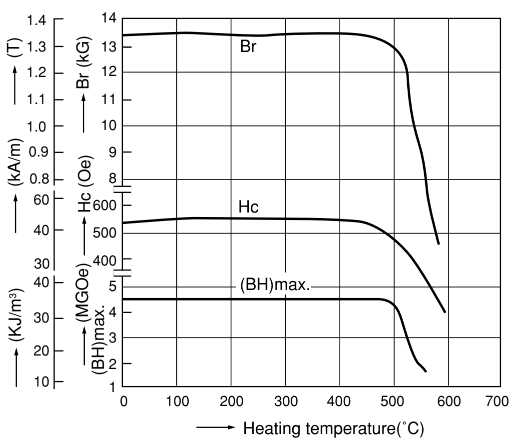

Fig. 30 Irreversible Temperature Change of Fe-Cr-Co Magnets

Table 8 Rate of Change in Br of Various Permanent Magnetic Materials (Irreversible Change)

Materials	Rate of Temperature Change in Br (%/˚C)
Alnico 5	– 0.021
Fe-Cr-Co Magnets	– 0.040
Rare-earth Magnets	– 0.043
Barium Ferrites	– 0.019

Change in Magnetic Resistance of Magnetic Circuit

The flux density at operating point will change in case magnetic resistance of magnetic circuit under operation changes. And since the rate of change is interrelated with permeablilty of recoil, recoil curve of Fe-Cr-Co Magnet KX-1 is shown in Fig. 31. From this, you can see Fe-Cr-Co Magnets is superior to alnico magnets regarding magnetic stability. (μrec. of alnico 5 is approx. 3.7 max.)

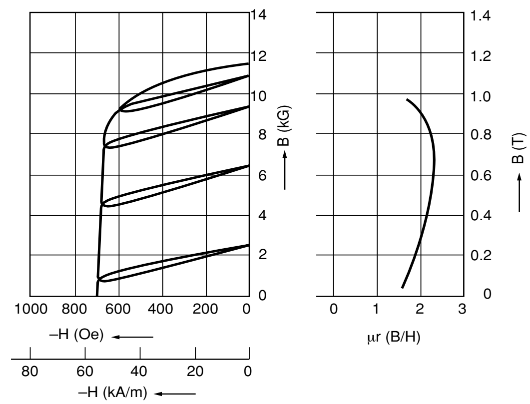

Fig. 31 Recoil Curve of Fe-Cr-Co Magnets KX-1

Magnetization and Demagnetization

Magnetization

Magnetized magnets may be demagnetized upon influence from diamagnetic fields or handling of products when transported. And, regarding their performance, it is advantageous to magnetize product after they are assembled. Therefore, we deliver general magnets without being magnetized. Approximately 3kOe of the magnetic field is necessary for the saturation magnetization. However, in reality, half that value is needed for actual magnetization.

Demagnetization

Generally, magnets generate a few percent of demagnetization due to contact demagnetization. Therefore, when designing magnetic circuit, it is possible to take optimum margin for demagnetizing and demagnetize that margin in order to ensure the performance of the circuit under operation.

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Ordering Information

When placing an order with NEC TOKIN Iron-Chromium-Cobalt Magnets, be sure to specify the following items.
1) Shapes and dimensions
2) Necessary magnetic properties
3) Direction of magnetization
4) Whether or not magnetizing is necessary
5) Conditions under which the material will be used.
6) Any other relevant specifications (plating, coating, sealing)

Table 9 General Shapes and Dimensions

Shapes	Dimensions	Others
Plate	t0.3 ~ 4.0	Magnets of shapes stated left or molded by die-cutting, or grinding are available.
Rod	ø10 ~	
Line	ø0.5 ~ 10	

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Technical Terms

The following are terms describing magnetic volumes by SI units which are necessary for using permanent magnets.

Magnetic Properties

Magnetic Fields

There exists magnetic fields on earth. This exists not only in permanent magnets but also around electric conductors.
Magnetic field is represented by H. The unit (SI) is represented by A/m. For instance, earth magnetic field is approximately 24A/m. It is possible to create easily magnetic filed of 1.6MA/m by using electromagnets. However it needs some device to create stronger magnetic fields.

Magnetization

When placing magnetic materials in magnetic fields, that material will generate magnetic changes. This is called magnetization. Further, the rate of magnetization is called "intensity of magnetization". And its strength is represented by M. Its unit is T.

Saturation Magnitization

As increasing magnetic fields imposed upon magnetic material, that material will reach saturation. This degree of magnetization is called saturation magnitization. For instance, saturation magnitization of barium ferrite magnet is approximately 0.44T and that of Lanthanet® [LM-19] is approximately 0.86T.

Magnetizing

The operation to apply magnetic field enough for magnetic material to reach saturation is called magnetizing. And when remove magnetic field used for magnetizing from the material, it will keep the state of being magnetized. After going through this process, magnetic material will be permanent magnet.

Magnetic Flux Density (Magnetic Induction)

As stated above, magnetic material is magnetized by magnetizing. In this case, magnetic flux goes through the material. Magnetic flux per unit area is called magnetic flux density (magnetic induction) and it is represented by B. The unit is represented by gauss, equal to that of intensity of magnetization. This magnetic flux density is represented by $B = J + \mu_0 H$. Briefly speaking, this value is equivalent to magnetic field given to the material plus intensity of magnetization. The intensity of magnetization in the air is nearly zero regardless of the intensity of the magnetic field (In another words, 4pl of the air is nearly zero.). Therefore, after taking the magnets used for magnetizing out of the magnetic field, the intensity of magnetization around the magnet will be equal to the magnetic field on site. Practically, the most important matter is the value of this magnetic flux density.

Residual Magnetic Flux Density,

This section explains the change in the intensity of magnetic field and the magnetic flux density when exerting magnetic field to the magnetic material gradually or conducting the reverse process by decreasing magnetic field.
At first, as stated in the previous section, when gradually adding magnetic field to magnetic material, it will gradually gain magnetization and finally reaches saturation magnetization. This process is called primary magnetizing process. In the next stage, the magnetic flux density gained by decreasing magnetic fields and eliminating external magnetic field exerted upon the magnetic material is called residual magnetic flux density Br (residual magnetic induction). Further, by exerting magnetic field to the material without external magnetic field towards the reverse direction, the magnetizing and magnetic flux density will decrease. Then the magnetic flux will not go through the magnetic material. The intensity of magnetic field exerted upon the material on this stage in called coercive force H_{CB}. Further, when increasing magnetic field of reverse direction, the magnetic flux will flow toward reverse direction and then magnetization intensity will be eliminated. In another word, there are two kinds of coercive force. One is magnetic field H_{CB} gained by decreasing magnetic flux density B to zero. Another is magnetic field H_{CJ}, gained by decreasing the intensity of magnetization intensity J to zero.

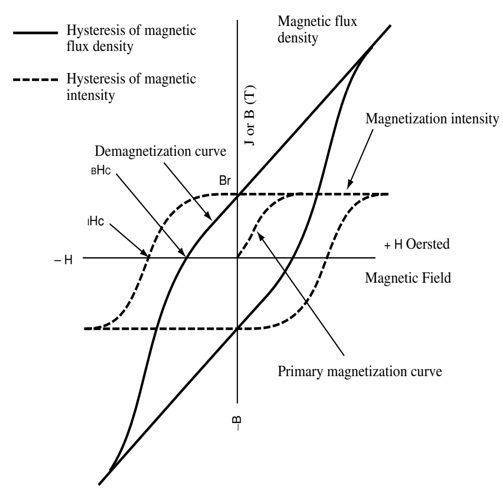

Fig. 32 Hysteresis Loop of Permanent Magnet

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When increasing diamagnetic field beyond coercive force H_{CJ}, the magnetization intensity will turn around to the opposite direction and correspond to the direction of diamagnetic field, and finally the magnetization intensity will be saturated. The curve describing repetition of these processes is called Hysteresis Loop (Refer to Fig. 32).

Diamagnetic Field

Permanent magnet generates external magnetic field by its N and S pole. On the other hand, the magnetic field exists within the magnet generated by the same N and S pole. This is called diamagnetic field (demagnetization field). The size and direction is different from magnetic flux density inside the magnet. Diamagnetization field tends to decrease its own magnetic intensity. And as near as N and S pole exists (the length of magnet is short), demagnetization field gets larger.

Demagnetization Curve

As stated in the section of magnetic flux density, permanent magnet uses its magnetic flux generated through magnetization process. Therefore, as much magnetic flux density remains in the permanent magnet despite large diamagnetic field, it can be said that its feature is more prominent. As a result, the essential condition for superior permanent magnet is that it has large residual magnetic flux density and coercive force BHC. Demagnetization curve is used in order to find out how magnetic flux density changes according to the intensity of diamagnetic field. This curve is identical to the second quadrant of hysteresis loop which explains the relationship between magnetic flux density and magnetic field.
(Refer to Fig. 32)
The first step to evaluate the permanent magnet is to see its hysteresis Loop.

Operating Point

When diamagnetic field exerted upon the permanent magnet is equal to Hd, the magnet generates magnetic flux density (magnetic induction) which correspond to Bd on the demagnetization curve. In this way, the point represented by Hd and Bd is called the operating point of the permanent magnet. (Refer to Fig. 33). However, in practical use, this point changes according to the environmental conditions. For example, the operating point of magnet is positioned at P in Fig. 33 after being magnetized, it will move to area in which diamagnetic field decreases and magnetic flux density increases when attaching iron piece to the magnet.

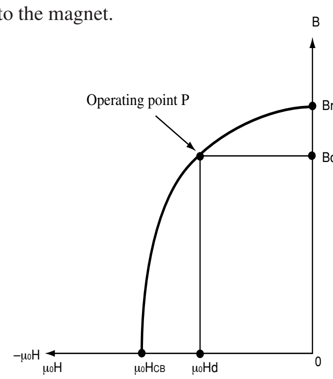

Fig. 33 Operating Point of Permanet Magnet Operating point P

Maximum Energy Product

As stated in the section of demagnetization curve, the criteria to judge the magnetic properties of permanent magnet is to see demagnetization curve. In another words, if some diamagnetic field Hd exists, it is only necessary to find out how much the magnetic flux density Bd is. So, best way to judge magnetic properties of permanent magnet is to use maximum product of Hd x Bd on operating point. Since Hd x Bd is proportional to energy per magnet volume which magnet enables to give off into outer space, that value is called maximum energy product. The unit of maximum energy product is J/m^3.
Optimum method to design permanent magnet is to make sure that the operating point is identical to the point of maximum energy product. The reason is that it is possible to minimize the volume of permanent magnet required to gain necessary energy.

Minor Loop

In the previous section, it is stated that operating point moves according to operational conditions of permanent magnet. This does not mean the operating point moves exactly on demagnetization curve. But it moves on hysteresis Loop which are formed with the primary operating point as the datum point as shown in Fig. 34. This small hysteresis Loop which starts from demagnetization curve is called minor loop. The operating point of permanent magnet should generally be on minor loop. However, in case the operating point does not move such as that of magnet for speaker, it is naturally on demagnetization curve.

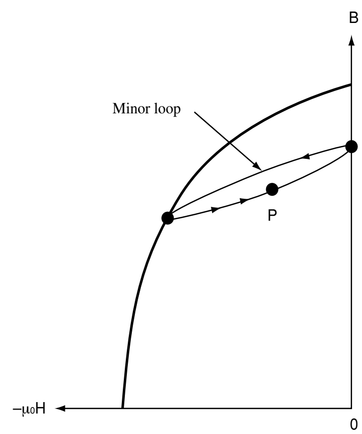

Fig. 34 Minor Loop and Operating Point

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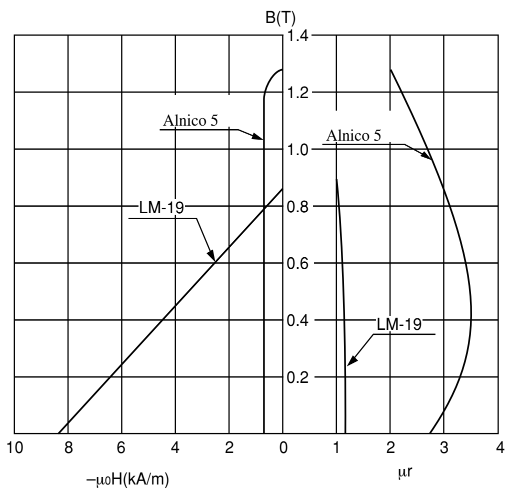
Reversible Permeability

Since the area of minor loop is small, generally round trip of the loop can be represented by one line. The angle of this line B/H is called reversible permeability and represented by μr. Reversible permeability varies depending upon its starting point on demagnetization curve. Fig. 35 shows comparison of permeability between Lanthnet® and Alnico magnet on the same scale. Usually, when representing reversible permeability by one figure, the value showing maximum energy product on operating point is used. The reason is that the magnetic material whose angle of demagnetization curve is close to 45˚ has reversible permeability which is close to 1. And since its coercive force is large, the operating point will return to the primary position even though strong diamagnetic field is exerted. Therefore, it is advantageous to use this value when generating magnetic field and using power of absorption as well as using repulsive power.



Demagnetization Curve **Reversible Permeability curve**

Fig. 35

Thermal Variations of Magnetic Properties

Irreversible Thermal change

Magnetic flux density of permanent magnet decreases when it is exposed to high temperature even though the quality of material does not change. This rate of change in magnetic flux density gradually gets smaller proportional to the length of the time during which the magnet is exposed to high temperature. And it reaches saturation in relatively short period of time and stop to change. The rate of change at this stage corresponding to primary value of magnetic flux density is called irreversible thermal variations. The irreversible thermal variations, whether small or large, is found in any permanent magnet. The degree of variation varies in a large scale depending upon retention temperature and position of operating point of magnet. Although barium ferrite is demagnetized when exposed to low temperature, Lanthanet® is not.

Heat treatment and AC Demagnetization

Since permanent magnet incurs irreversible thermal variation, its magnetic properties will be deteriorated when exposed to high temperature during operation. In order to avoid this, it is necessary to allow the magnetic flux density to be compatible with rate of irreversible thermal variations for maximum operating temperature when designing permanent magnet. And then expose the magnet to the maximum operating temperature for several hours after magnetized. This process to stabilize magnet is called thermal seasoning. For alnico magnet, stabilizing process is performed by exerting AC magnetic fields (AC demagnetization).

Reversible thermal change (Temperature Coefficient)

So far, magnetic properties at room temperature is stated. Conditions of magnetic properties when magnet is exposed to low or high temperature is extremely important upon practical operation. In order to find thermal change of magnetic properties, demagnetization curve at each temperature is required. By simplifying this process, changes in operating point Bd per 1˚C is called rate of irreversible thermal change(temperature coefficient). This rate should be measured after irreversible thermal variations at every temperature is completed.
In addition, regarding general magnets, rate of irreversible thermal variations will change according to the position of operating point of the magnet. However, when this rate is represented by one figure, the value should be based on the variations of Bd at the point of maximum energy product like reversible permeability.

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Designing of Permanent Magnets

It is possible to design permanet magents in a highly accurate scale without using electronic calculator. The following is the basic concept of designing permanent magnets.

Basic Concept of Designing Permanent Magnets

When creating magnetic fields using permanent magnets, it is necessary to prevent loss of magnetomotive force by using combination of permanent magnet and a yoke. The problem regarding design of magnetic circuit is how to decide minimum required dimensions of permanent magnets. There are two equations to solve above problem.

a) Magnetomotive force of permanent magnets is equal to loss of magnetomotive force in void.

$$Hd \bullet Lm = Hg \bullet Lg \quad \text{------------ (1)}$$

b) Total magnetic flux going through center of permanent magnet is equal to magnetic flux going through void.

$$Bd \bullet Am = Bg \bullet Ag \quad \text{------------ (2)}$$

Using CGS unit, it can be said that Hg = Bg. Therefore, if (1) x (2),

$$Hd \cdot Bd = \frac{Bg^2 \cdot Lg \cdot Ag}{Lm \cdot Am}$$

On condition that:

Am: Cross section of magnet
Lm : Length of magnet
Bd : Magnetic flux density at an operating point
Hd : Intensity of magnetic field at an operating point
Ag : Cross section of void
Lg : Length of void
Bg : Magnetic flux density in void
Hg : Intensity of magnetic field in void

Therefore, in order to minimize Lm • Am of permanent magnet, it is necessary to select the point of maximum energy product on demagnetization curve of permanent magnet at which Bd • Hd is maximized. Then, after selecting Hd and Bd, it is required to examine whether magnetic field Bd which is needed for necessary void (Volume = Ag • Lg) can be generated. But actually, loss of magnetomotive force and leakage of magnetic flux is so large the drastic modification of equation (1) and (2) will be required. This modification method is known as loss coefficient of magnetomotive force (reluctance coefficient) and leakage coefficient.

When these values are represented as:

f: Leakage coefficient
r: Reluctance coefficient

The following equation will be established:

$$F = Hd \bullet Lm = r \bullet Bg \bullet Lg \text{ (Magnetomotive force) ------ (1)'}$$

$$ø = Bd \bullet Am = f \bullet Bg \bullet Ag \text{ (Magneic flux) ---------------- (2)'}$$

Reluctance coefficient r is the correction coefficient to be used for the case in which magnetomotive force generated from permanent magnet is consumed in yoke or joint section between yoke and magnet. Except when design of the magnet is not ordinal, the value should be between 1.1 and 1.5 (usually 1.3).

Leakage coefficient is the correction coefficient to be used for the case in which magnetic flux generated from permanent magnet is leaked form around void or yoke. This value varies depending upon the state of magnetic circuit.

Example 1: Find the value of Bg

Now, in case shape and dimensions of magnetic circuit is already decided, and f is found, the equation established from (1)' and (2)' will be:

$$p = \frac{Bd}{Hd} = \frac{Lm \cdot Ag \cdot f}{Am \cdot Lg \cdot r}$$

Since Lm and Lg are already decided, permeance coefficient can also be decided. On the other hand, Bd and Hd can be found from demagnetization curve.

From (2)', $Bg = \frac{Bd \cdot Am}{f \cdot Ag}$

Therefore the value of Bg can be found. The case of finding Bg using this equation is only when f can be estimated using similar magnetic circuit.

Leakage Coefficient and Permeance

Leakage coefficient f can be found by closely assuming flow of magnetic flux and calculate it as equivalent circuit related in Table 11.

Leakage Coefficient vs. Magnetic Circuit

Table 11

Magnetomotive force F	Electromotive force V
Magnetic flux ø	Current I
Reluctance Rm	Resistance R
$Rm = \frac{1}{\mu S}$	$R = \frac{1}{\sigma S}$
Permeability μ	Conductivity
Permeance P	Conductance G
$P = \frac{1}{Rm}$	$G = \frac{1}{R}$
F=NI=Rm ø	V=R • I

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In circuit shown in Table 27, permeance P of external magnet is defined as P = ø/F.
On the other hand, from the equation F = Hd • Lm, ø = Bd • Am, the following equation will be established:

$$p = \frac{Bd}{Hd} = P \cdot \frac{Lm}{Am} \quad \text{-------------- (3)}$$

Therefore, permeance coefficient P is equivalent to Permeance P in case length of magnet Lm and cross section Sm is equal to the size of the unit. So it can also be called unit permeance.

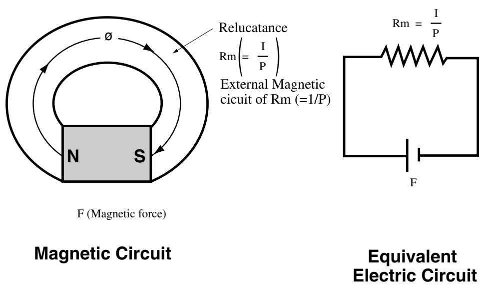

Fig. 27. Magnetic Circuit and Equivalent Electric Circuit

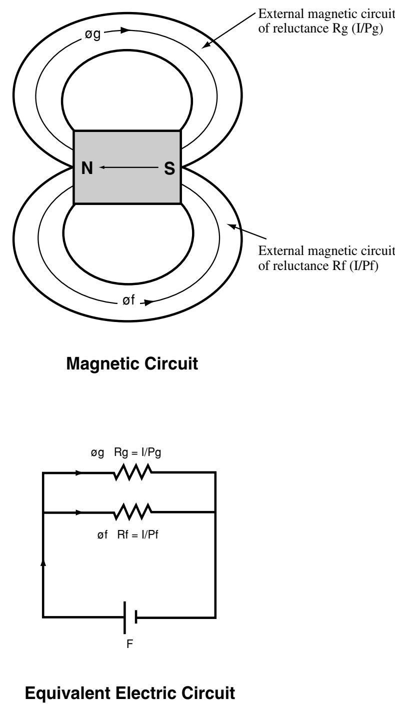

Fig. 28 Magnetic Circuit with 2 External Magnetic Fields

In the next stage, in case external magnetic circuit is separated into two systems, the following equation will be established from Fig. 28.

$$F = \phi g/Pg = \phi f/P_f$$
$$\phi = \phi g + \phi_f$$
$$= F(Pg + P_f)$$

When total permeance is set is PT,

$$PT = Pg + P_f.$$

When defining Pg as permeance in gap and Pf as permeance in leakage section, leakage coefficient f will be defined as:

$$f = \frac{\text{Total magnetic flux } (\phi)}{\text{Total magnetic flux in the gap}} = \frac{Pg + Pf}{Pg} = \frac{P_T}{Pg}$$

In addition, permeance coefficient of permanent magnet can be defined from equation (3):

$$p = P_T \cdot \frac{Lm}{Am \cdot r}$$

Fig. 29 presents an example leakage condtion of magnetic circuit.

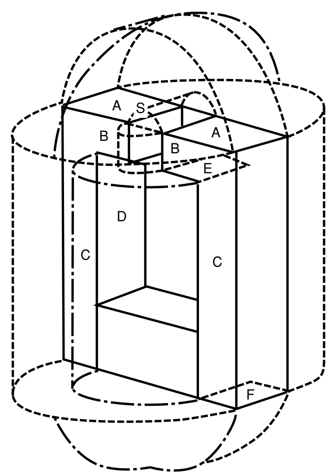

Fig. 29 Example of Leakage Flux

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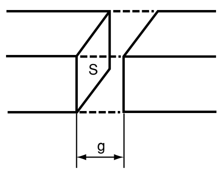
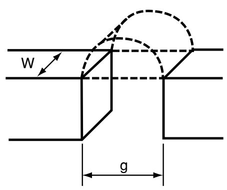
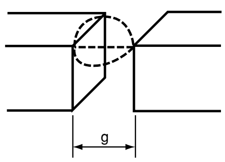
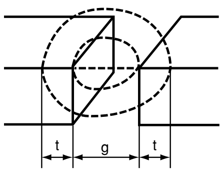
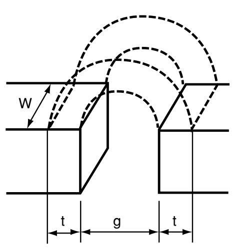
Place	Equation
Parallel, plain Permeance between two surfaces 	S ; Area of magnetic pole g ; Void distance $P = \frac{S}{g}$
Barrel-shape permeance from straight line 	W; Width of yoke or magent $P = 0.264W$
Permeance corresponding to a quater of the ball from the corner 	g ; Void distance $P = 0.077g$
Permeance correspoding to a quater of the ball from side line 	t ; Distance considered g ; Void distance $P = \frac{t}{4}$
Barrel-shape permeance from side panels 	W; Width of yoke or magnet t ; Distance considered g ; Void distance ① When g≥3t, $P = 0.637\frac{W}{1+g/t}$ ② When g<3t, $P = \frac{W}{\pi}\ell n\frac{g+2t}{g}$

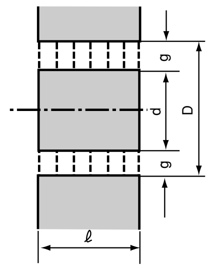
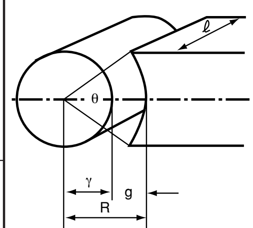
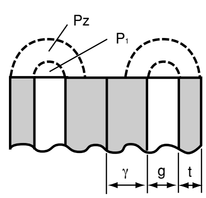
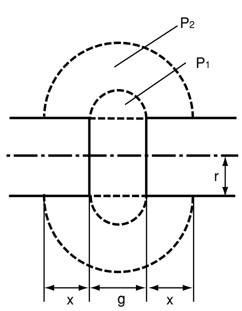
Place	Equation
Peameance between surfaces of concentric tubes 	ℓ ; Length of cylindrical tube D, d ; Outer/inner diameter of cylindrical tube g ; Void distance $P = 2\pi\ell/\ell n\frac{D}{d}$ (When g is smaller than d and g/d<0.01: $P = \pi d\,\ell/g$)
Permeance between circular surfaces 	ℓ ; Length of arc R, γ ; Radius of arc θ ; Angle of arc (Radian) g ; Void distance $P = \theta\ell/\ell n\frac{R}{\gamma}$ (When g is smaller than γ, $P = \theta\gamma\ell/g$)
Permeance between surfaces of cylindrical void 	$P = P_1 + P_2$ ($\gamma > t$) $= (\gamma + \frac{g}{2})\{1.66 + 2\ell n(1+2t/g)\}$ ($\gamma < t$) $= (\gamma + \frac{g}{2})\{1.66 + 2\ell n(1+2\gamma/g)\}$
Permeance between surfaces of cylindrical side panels 	$P = P_1+P_2$ $= 1.65(\gamma + 0.212g)$ $+\{2r + \sqrt{g(g+2x)}\}\,\ell n(1+2x/g)$

Fig. 30 Permeance of Various Void

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Example 2 Finding Leakage Coefficient

Design method in case permeance is parallel and exists in large numbers:

1) Flow of magnetic field around the void should be set as close as to Fig. 30. (including gap)
2) Using Fig. 30, find permeance Pg, Pf1 ------ Pfm of each section.
3) Find P1 = Pg + Pf1 + ----------- + Pfm
4) Find f = PT/Pg
5) Find Am so that p = PT X (Lm/Am) can be optimum considering Demagnetizing properties. In this case, Lm = (rBg • Lg)/Hd.
6) Confirm f again when dimensions is decided.

This methods uses the fact in which permanent magnets are uniformerly magnetized and, if the strenght of those magnets are I, their magnetic density per unit area in cross section perpendicular to the direction of magenetization.

When there is magnetic pole I at one point, magnetic field generated by that magnetic pole at the point with distance of R from the original point will be the following based on Coulomb's law:

$$H = \frac{I}{\ell^2}$$

Therefore, if surface density l are distributed on a disk whose diameter is ro, the magnetic field at the point on its central axis with distance of R will be:

$$H = 2\pi I \left(1 - \frac{\ell}{\sqrt{\ell^2 + r_0^2}}\right) \text{(Oe)} \quad \text{--------(4)}$$

The essential condition using this method is that magnetic poles are uniformly distributed. Therefore, this method is effective only when the operating point exists in the region when angle of demagnetization curve is 45˚. In another words, it is effective for all ferrite magnets and rare-earth magnets if the operating point exists above turning point of demagnetization curve.

Example 1 Magnetic Field of Central Axis of Cylindrical Magnets

In this case, substitute dimensions shown in Fig. 31 and $2\pi I = \frac{Br}{2}$ and $\gamma_O = \frac{D}{2}$ into equation (4). Plus adding these to the sum of magnetic fields generated by magnetic poles of the front and rear circle. Therefore magnetic field will be the following equation:

$$H = \frac{Br}{2}\left(\frac{(\ell + Lm)}{\sqrt{(\ell + Lm)^2 + \frac{D^2}{4}}} - \frac{\ell}{\sqrt{\ell^2 + \frac{D^2}{4}}}\right) \quad \text{---------(5)}$$

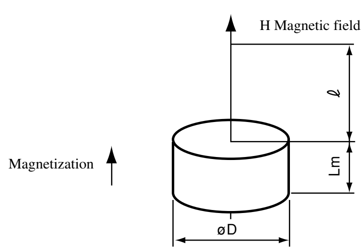

Fig. 31 Cylindrical Magnets

Example 2 In Case of Facing Cylindrical Magnets

In case of facing magnets shown in Fig. 31, magnetic field on their central point will be twice the equation (5).

Example 3 In Case of Facing Cylindrical Magnets and Connecting Their Rear Surface by Yoke

In this case, magnetic field on rear surface of Fig. 32 will be erased. Therefore double of equation (4) can be used.

$$H = Br\left(1 - \frac{\ell}{\sqrt{\ell^2 + \frac{D^2}{4}}}\right)$$

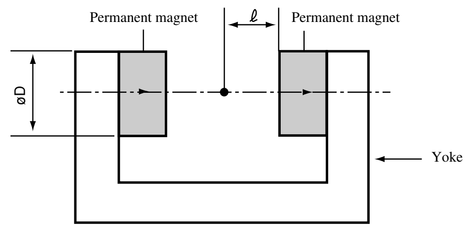

Fig. 32 n Case of Connecting Yokes

The smaller ratio of dimensions of magnet (D/L), error rate is smaller.

Example 4 In Case of Square Magnets

By applying dimensions shown in Fig. 33 (angle is radian), the following equation is established:

$$H = \frac{Br}{\pi}\left[\tan^{-1}\frac{ab}{2\ell\sqrt{4\ell^2 + a^2 + b^2}} - \tan^{-1}\frac{ab}{2(\ell + Lm)\sqrt{4(\ell + Lm)^2 + a^2 + b^2}}\right] \quad \text{---------(6)}$$

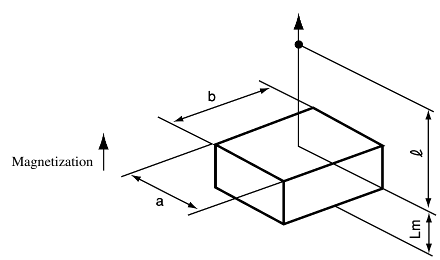

Fig. 33 Square Magnets

Applying these methods, magnetic fields inside and outside perforated magnets can be found.

In every cases, error compared with practical value occurs. The reason is that magnetic poles are not distributed uniformly and they exists on other faces mentioned in this section.

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Method to Find Permeance Coefficient of Single Magnets

Permeance coefficient of all single magnets can be found using equation (5) and (6). First, substitute $\ell = -\frac{Lm}{2}$ for these equations and find H. And this will be diamagnetic field Hd. Secondly, if demagnetization curve has gradient of 45˚, *Bd = Br - Hd* is established. Therefore permeance coefficient can be found using the following equasion:

$$p = \frac{Bd}{Hd} = \frac{Br\text{-}Hd}{Hd}$$

By adding correction coefficient to improve accuracy, the following equation will be established.

Permeance coefficient of cylindrical magnet

$$p = 1.3\,\frac{Lm}{D}\left(\sqrt{1+\left(\frac{Lm}{D}\right)^2} + \frac{Lm}{D}\right)$$

Permeance coefficient of square magnet (angle is radian)

$$p = 1.2\left[\frac{\pi}{2}\left\{\tan^{-1}\frac{ab}{Lm\sqrt{a^2+b^2+Lm^2}}\right\}^{-1} - 1\right]$$

(Refer to Fig. 31 and Fig. 33. for dimensions)

This calculation uses charge method. Therefore, when permeance coefficient is below turning point of demagnetization curve, it is necessary to use apparent Bd minor loop in case of drawing minor loop form that point.

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Units of Magnets

The following equation represents SI Unit (International Unit) and CGS Unit.

$$B = \mu_0 (H+M)$$

SI Unit: $\mu_0 = \mu_0$

$$B = \mu_0 H + \mu_0 M$$
$$= \mu_0 H + J$$

$$\mu_0 = \frac{1}{\varepsilon_0 c^2} \text{ (H/m)}$$
$$= 4\pi \times 10^{-7} \text{(H/m)}$$

CGS Unit: $\mu_0 = 1$

$$B = H + M$$
$$= H + 4\pi J$$

Please refer to the following page for details.

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Conversion of SI and CGS Unit

Volume	Symbol	Unit				SI to CGS Unit	CGS to SI Unit
		SI Unit		CGS Unit			
		Name (Equation)	Symbol	Name (Equation)	Symbol		
Magnetic flux	Φ	Weber ($\Phi = BA$)	Wb	Maxwell ($\Phi = BA$)	Maxwell	1Wb=10^8 Maxwell	1 Maxwell=10^{-8} Wb
Magnetic flux density Magnetic induction	B	Tesla	T	Gauss	G	1T=10^4 G	1G=10^{-4} T
Magnetic constant (Vaccum permeability)	μ_o	Henry per meter	H/m	Absolute number (μ_o=1)	—	—	—
Magnetic intensity	H	Ampere per meter	A/m	Oersted	Oe	1A/m=$\frac{4\pi}{10^3}$Oe=1.25664×10^{-2}Oe	1Oe= $\frac{10^3}{4\pi}$A/m=79.5775A/m
Magnetic flux density compatible with magnetic intensity		Tesla ($\mu_o H$)	T	Oersted	Oe	1T=10^4 Oe	1Oe=10^{-4} T
Magnetization *	M	Ampère per meter ($M = \frac{J}{\mu_o}$)	A/m	Gauss ($M = 4\pi J$)	G	1A/m=10^3 G	1G=10^{-3} A/m
Magnetic polarization	J	Tesla ($J = \mu_o M$)	T	Gauss ($J = \frac{M}{4\pi}$)	G	1T=$\frac{10^4}{4\pi}$G	1G=4π×10^{-4} T
Permeability (Absolute permeability)	μ	Henry per meter	H/m	Absolute number	—	1H/m=$\frac{10^7}{4\pi}$=7.95775×10^5	1=$\frac{4\pi}{10^7}$H/m=1.25664×10^{-6}H/m
Permeability (Permeance coefficient)	μ_r	Absolute number ($\mu_r = \frac{\mu}{\mu_o}$)	—	Absolute number ($\mu_r = \mu$)	—	SI and CGS Unit are identical	
Magnetomotive force Magnetic difference	Fm Um	Amperè ** ($Fm=HL$) ($Um=H\Delta L$)	A	Gilbert ($Fm=HL$) ($Um=H\Delta L$)	Gilbert	1A= $\frac{4\pi}{10}$ Gilbert =1.25664 Gilbert	1 Gilbert=$\frac{10}{4\pi}$A =0.795775A
Permeance	Λ	Henry ($\Lambda = \frac{\Phi}{Fm}$)	H	Maxwell per Gilbert ($\Lambda = \frac{\Phi}{Fm}$)	Maxwell/Gilbert	1H=$\frac{10^9}{4\pi}$ Maxwell/Gilbert =7.95775×10^{-7} Gilbert/Maxwell	1 Gilbert/Maxwell=$\frac{4\pi}{10^9}$ H =1.25664×10^{-8}H
Magnetic resistivity	Rm	Henry ($Rm = \frac{Fm}{\Phi}$)	H^{-1}	Maxwell per Gilbert ($Rm = \frac{Fm}{\Phi}$)	Gilbert/Maxwell	1H^{-1}=$\frac{4\pi}{10^9}$ Gilbert/Maxwell =1.25664×10^{-8} Gilbert/Maxwell	1 Gilbert/Maxwell=$\frac{10^9}{4\pi}$ H^{-1} =7.95775×$10^7$$H^{-1}$
Magnetic energy product		Joule per cubic meter (BH)	J/m^3	Gauss Oersted or Erg per cubic centimeter (BH)	G Oe erg/cm^3	1J/m^3=4π×10GOe =1.25664×10^2 GOe =1.25664×10^2 erg/cm^3	1GOe= $\frac{1}{4\pi}$×10^{-1} J/m^3 =7.95775×10^{-3} J/m^3 =1erg/cm^3
Magnetic energy	E	Joule ($\frac{BH \bullet AL}{2}$)	J	Erg ($\frac{BH \bullet AL}{8\pi}$)	erg	1J=10^7 erg	1erg=10^{-7}J
Magnetic absorption	F	Newton ($\frac{B^2 A}{2\mu_o}$)	N,	Dyne ($\frac{B^2 A}{8\pi}$)	dyn	1N=10^5 dyn (1N=0.101972kgf)	1dyn=10^{-5}N (1kgf=9.80665N)

(Based on Electronic Materials Association standard EMAS-7003)

Note: 1. A= Cross section
2. L = Length of magnetic route
3. ΔL = Length of partial magnetic route
* Magnetization means magnetizing intensity
** Conventionally, Ampère Turn had been used. However, Ampère is used instead for SI Unit.

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