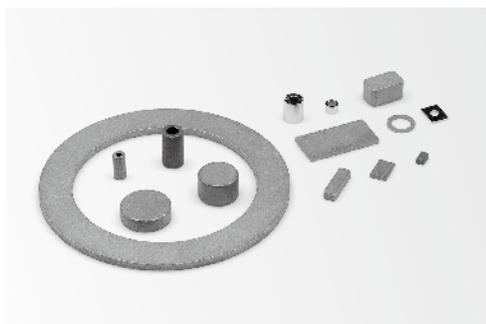


# Permanent Magnets



## Vol. 01



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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 pacemakers 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 difficult 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. Keep 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

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

LANTHANET<sup>®</sup> 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.



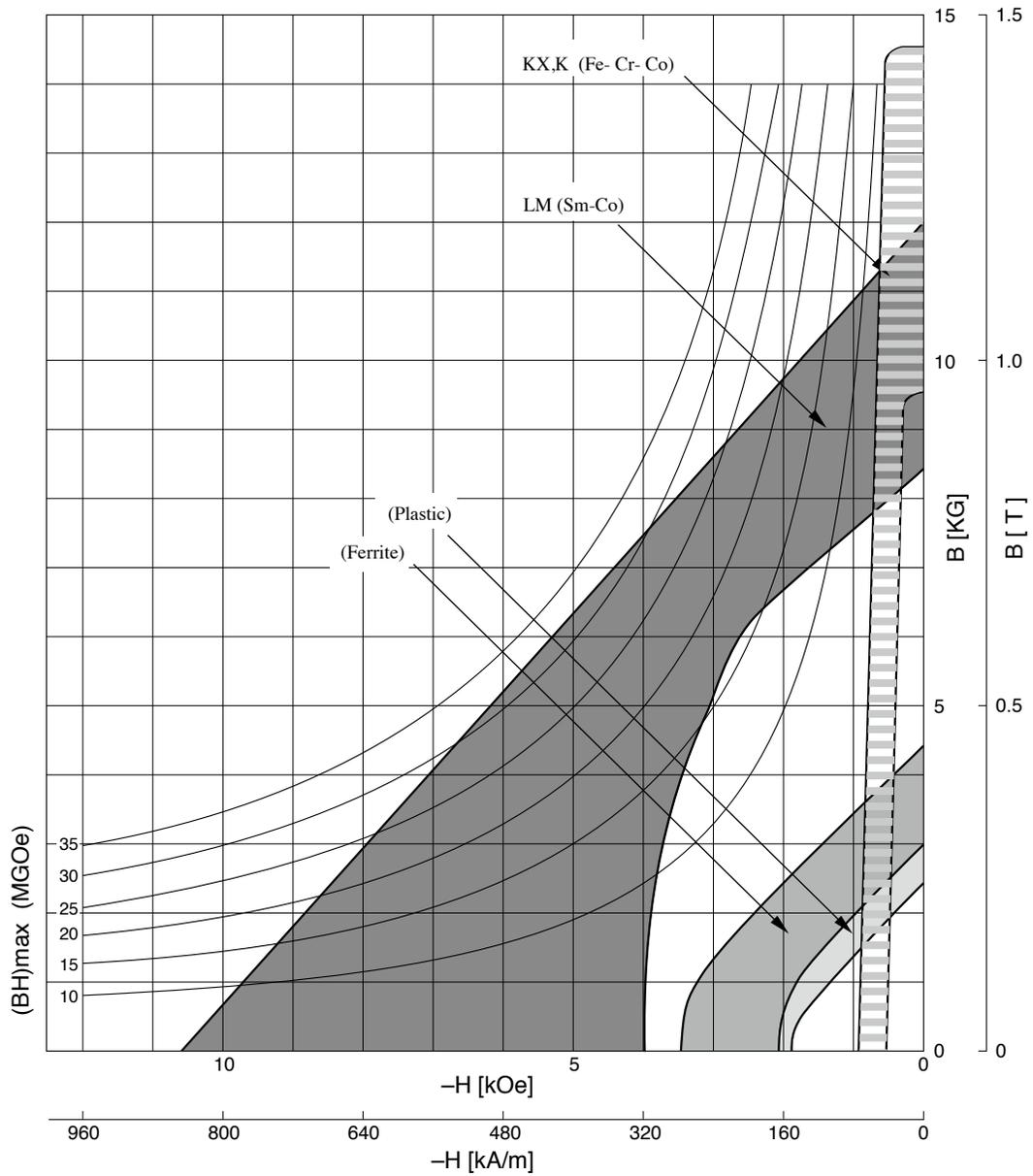
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# "Lanthanet<sup>®</sup>" Sm-Co Magnets

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## Features

Table 1 presents features and applications for a variety of Lanthanet<sup>®</sup> magnets.

LM-19: Magnets with large coercive force and high energy product (Type 1-5).

Other 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/m <sup>3</sup> (MGOe)	Intrinsic Coercive force HcJ kA/m (kOe)	Density D kg/m <sup>3</sup>	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±0.15×10 <sup>3</sup>	-0.043	8×10 <sup>-7</sup>	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±0.15×10 <sup>3</sup>	-0.04	9×10 <sup>-7</sup>	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±0.15×10 <sup>3</sup>			
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±0.15×10 <sup>3</sup>	-0.03	9×10 <sup>-7</sup>	Flat motors 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±0.15×10 <sup>3</sup>			
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±0.15×10 <sup>3</sup>	-0.03	9×10 <sup>-7</sup>	Printers 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±0.15×10 <sup>3</sup>	-0.03	9×10 <sup>-7</sup>	Relays Coreless motors CD actuators 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±0.15×10 <sup>3</sup>			
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±0.15×10 <sup>3</sup>	-0.03	9×10 <sup>-7</sup>	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±0.15×10 <sup>3</sup>			
LM-32SH	Type 2-17	1.12~1.20 (11.2~12.0)	795~875 (10.0~11.0)	223~256 (28.0~32.2)	1592~ (20.0~)	8.2±0.15×10 <sup>3</sup>	-0.04	9×10 <sup>-7</sup>	Vehicle-use sensors Ignition coils Surface mounting devices

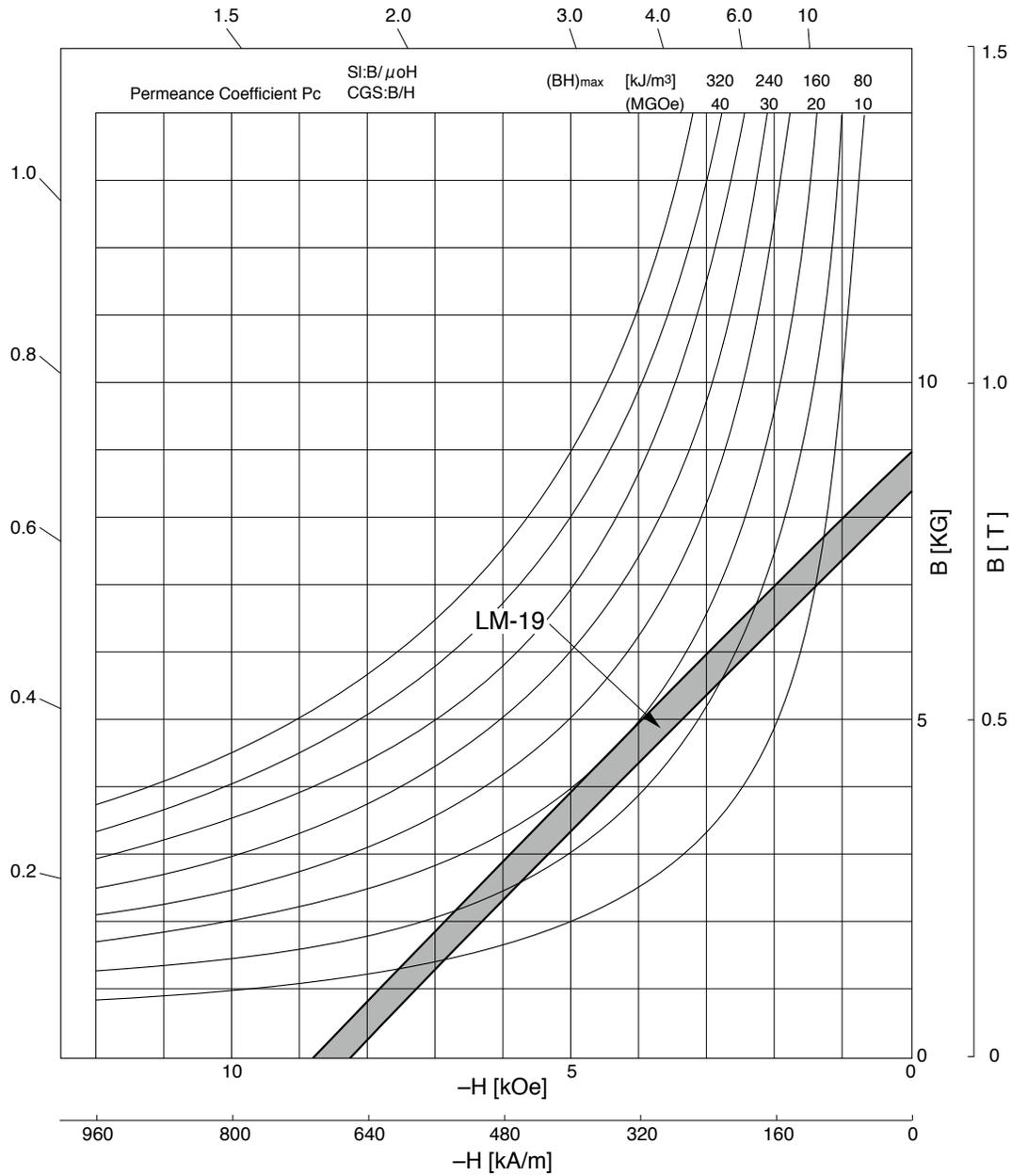


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**Demagnetization Curves**

**Demagnetization Curves of LANTHANET®**

LM-19

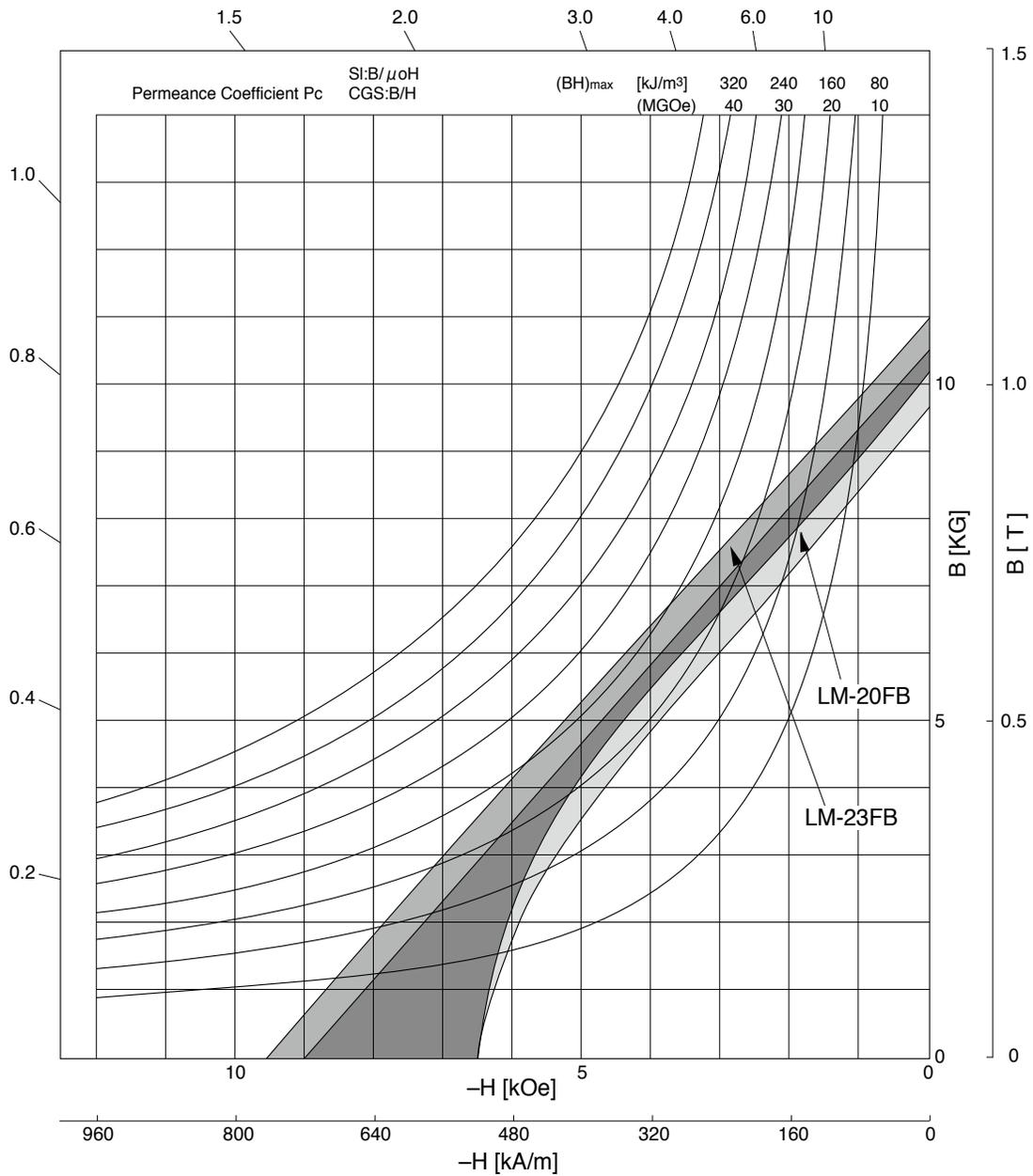


**Fig. 1**



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**Demagnetization Curves of LANTHANET®**  
LM-20FB/LM-23FB

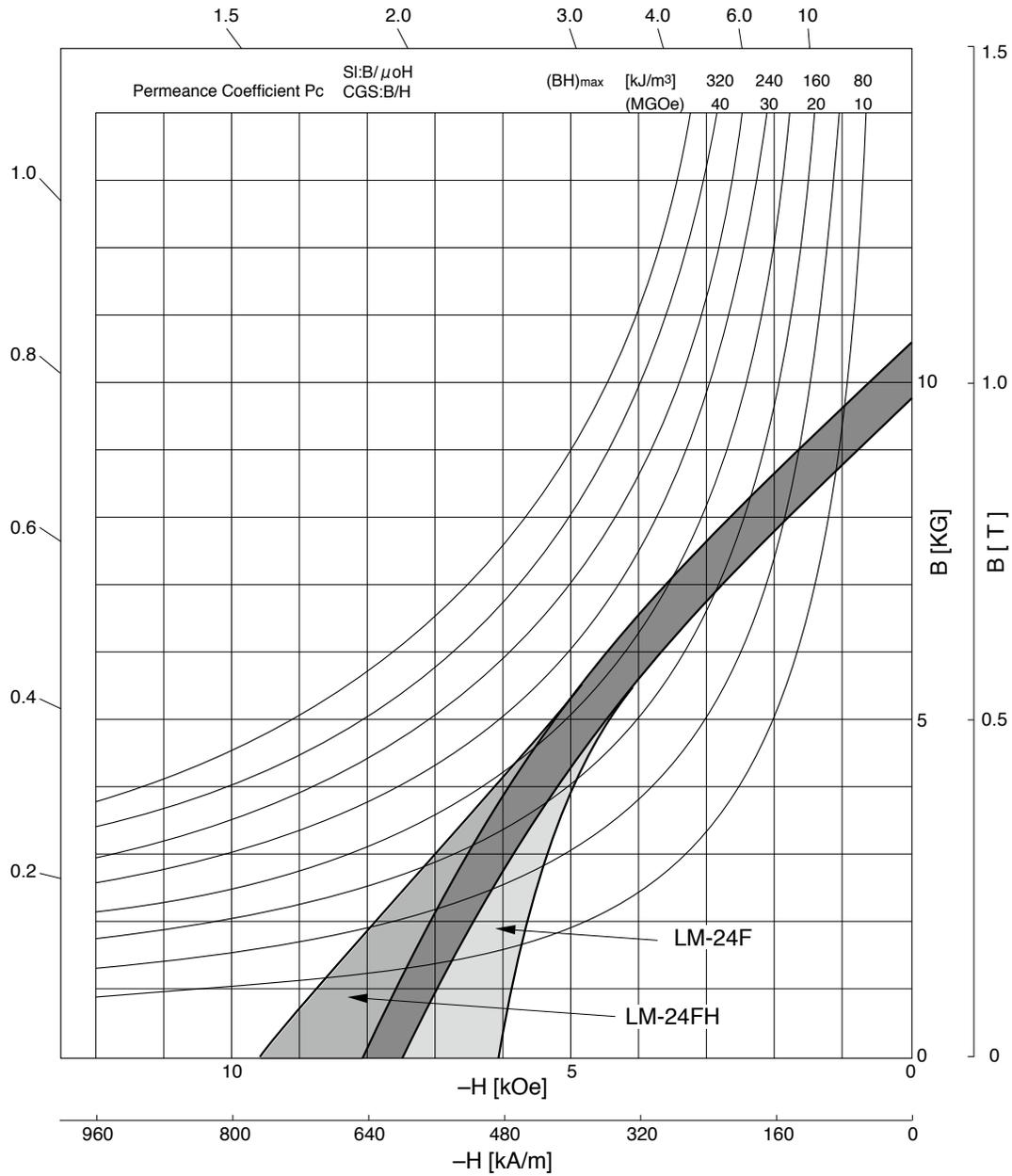


**Fig. 2**



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**Demagnetization Curves of LANTHANET®**  
LM-24F/LM-24FH

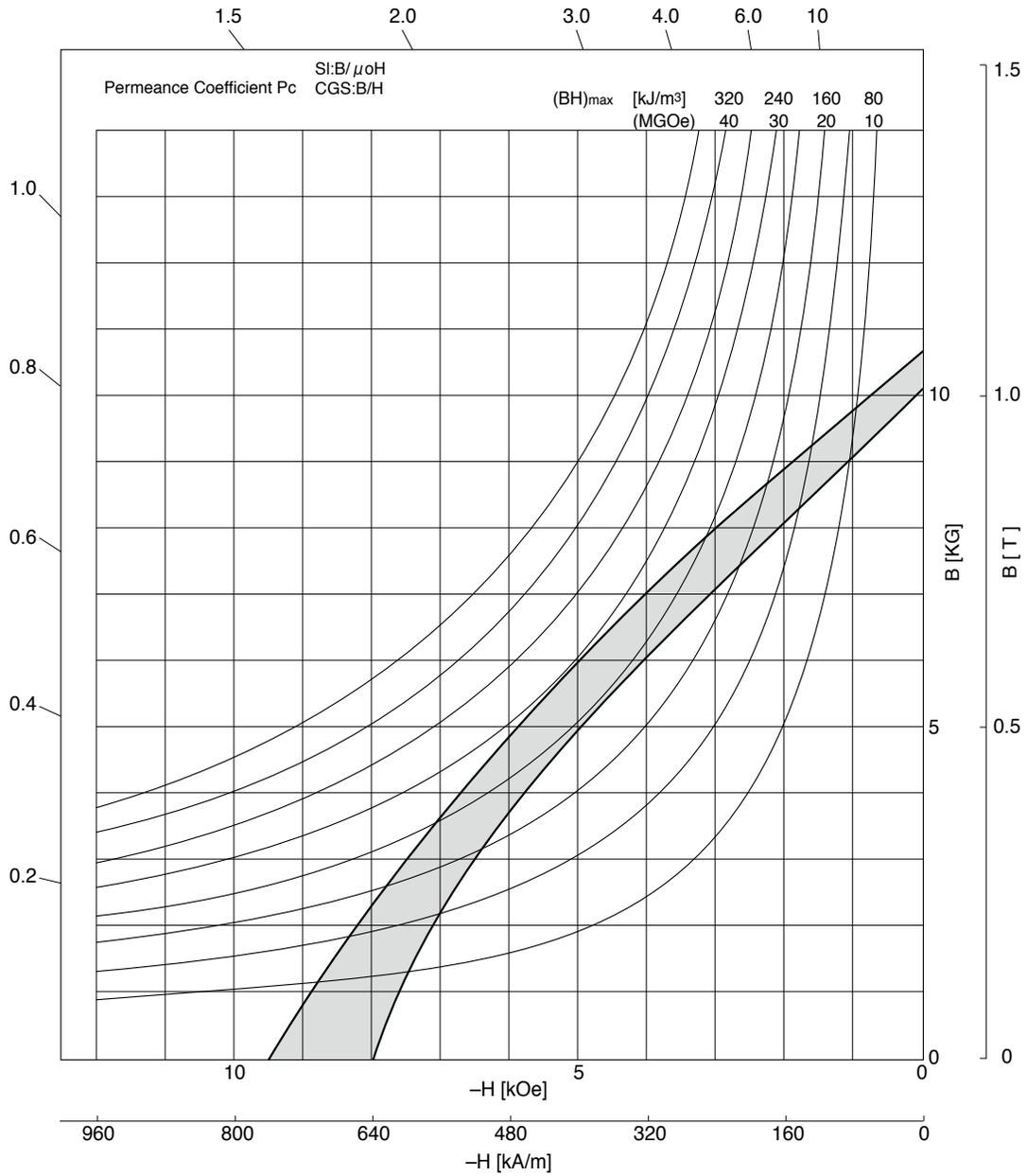


**Fig. 3**



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**Demagnetization Curves of LANTHANET®**  
LM-26FH

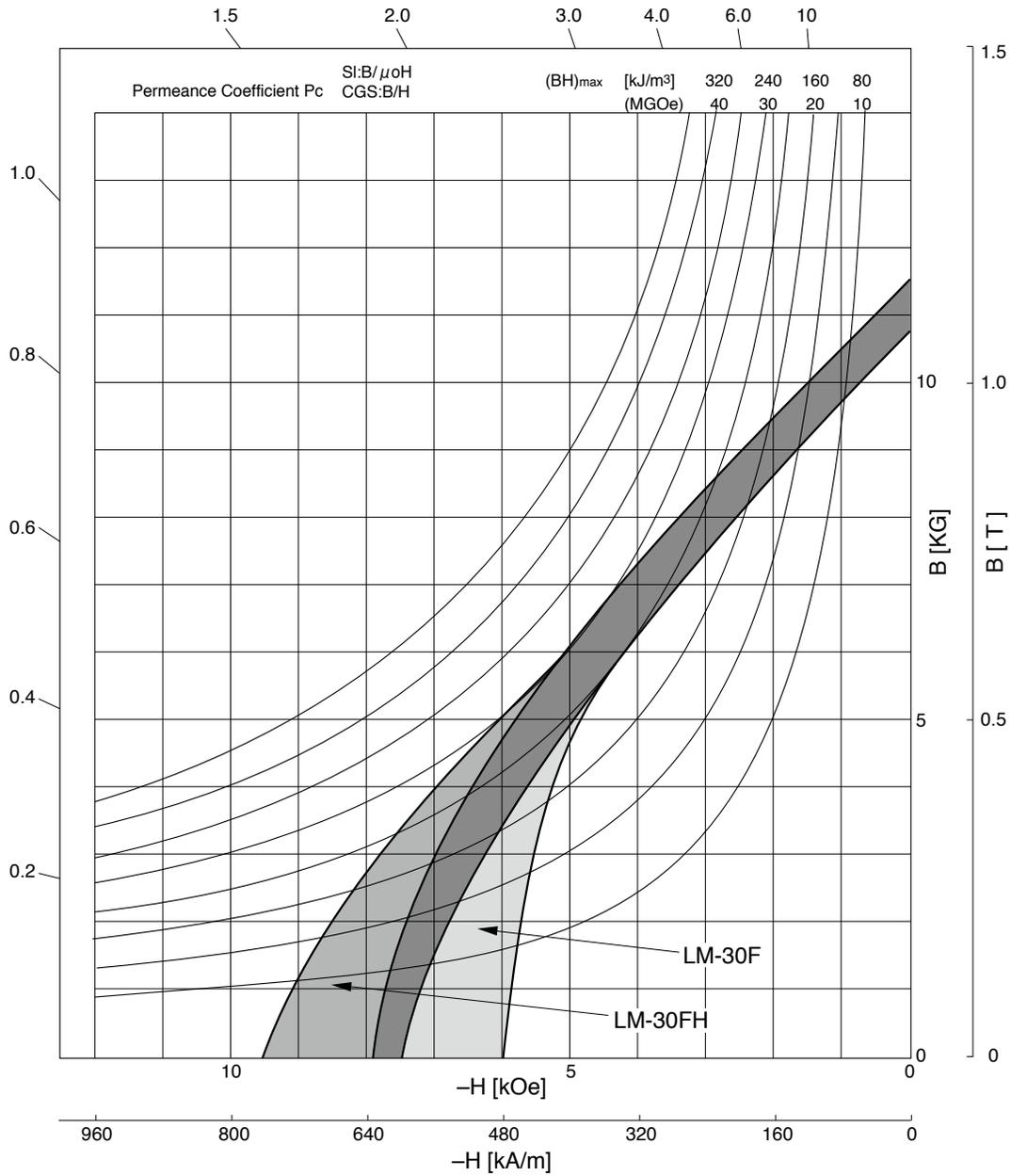


**Fig. 4**



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**Demagnetization Curves of LANTHANET®**  
LM-30F/LM-30FH

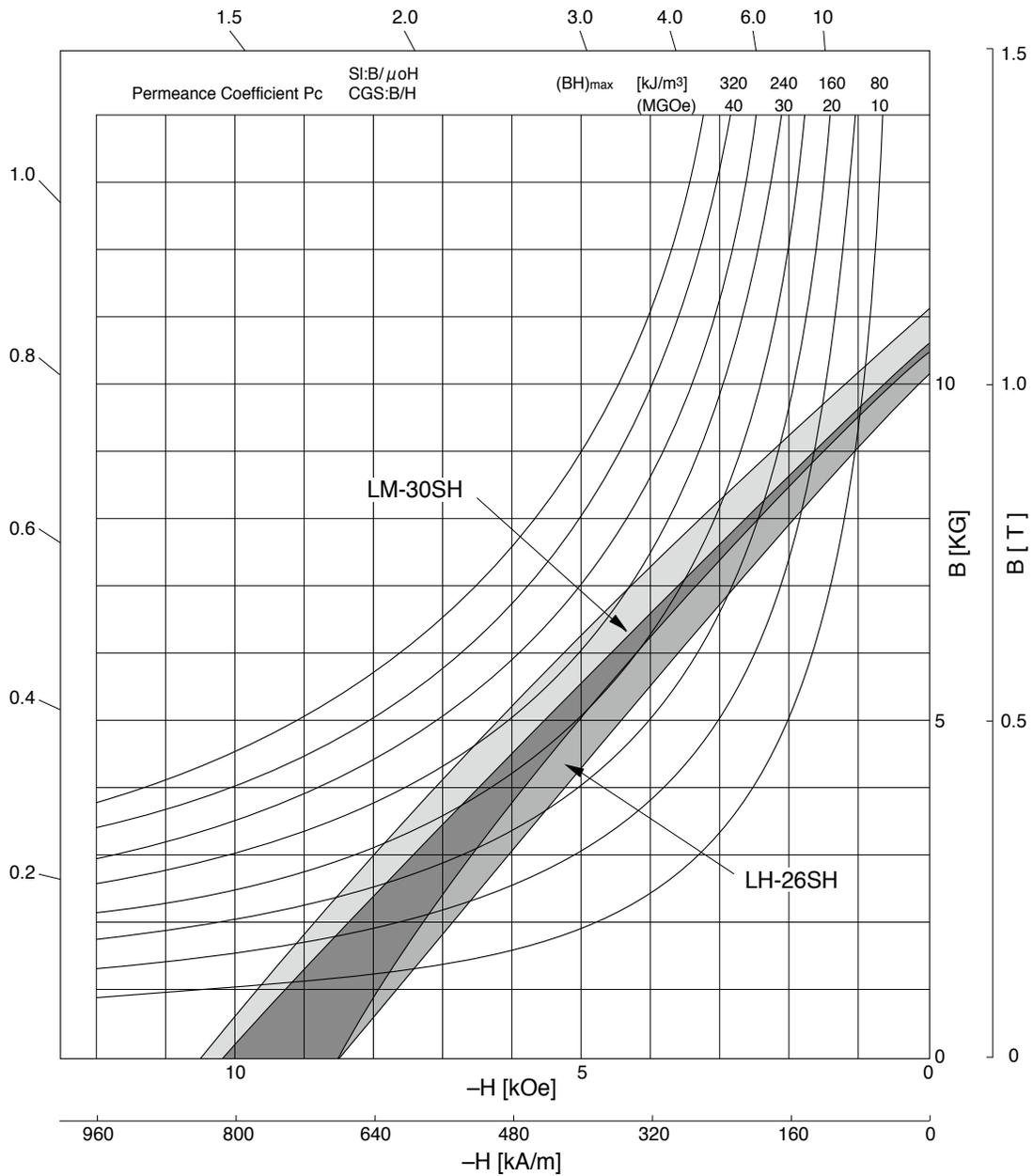


**Fig. 5**



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**Demagnetization Curves of LANTHANET®**  
LM-26SH/LM-30SH

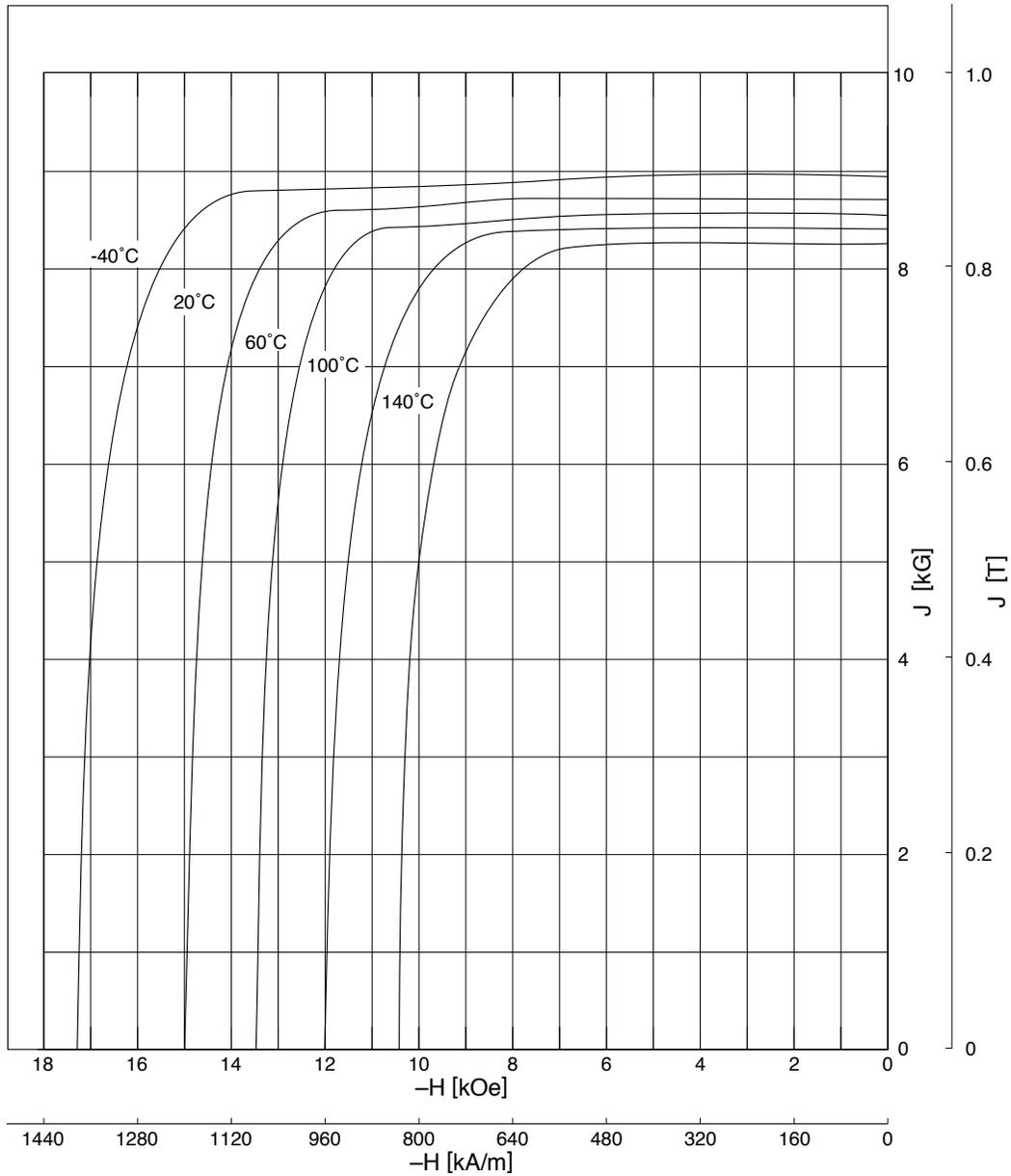


**Fig. 6**



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**Demagnetization Curves of LANTHANET®**  
LM-19

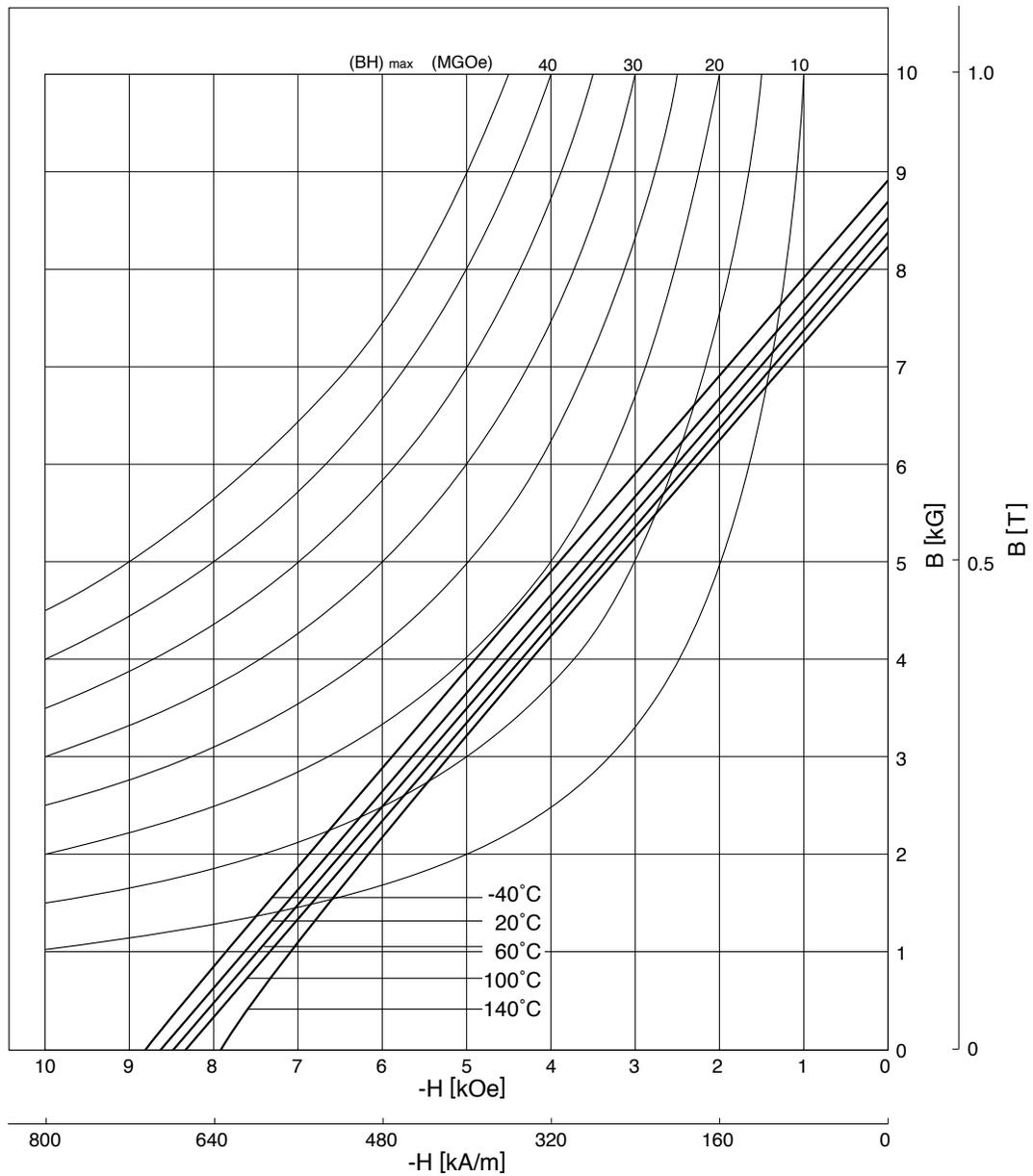


**Fig. 7**



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**Demagnetization Curves of LANTHANET®**  
LM-19

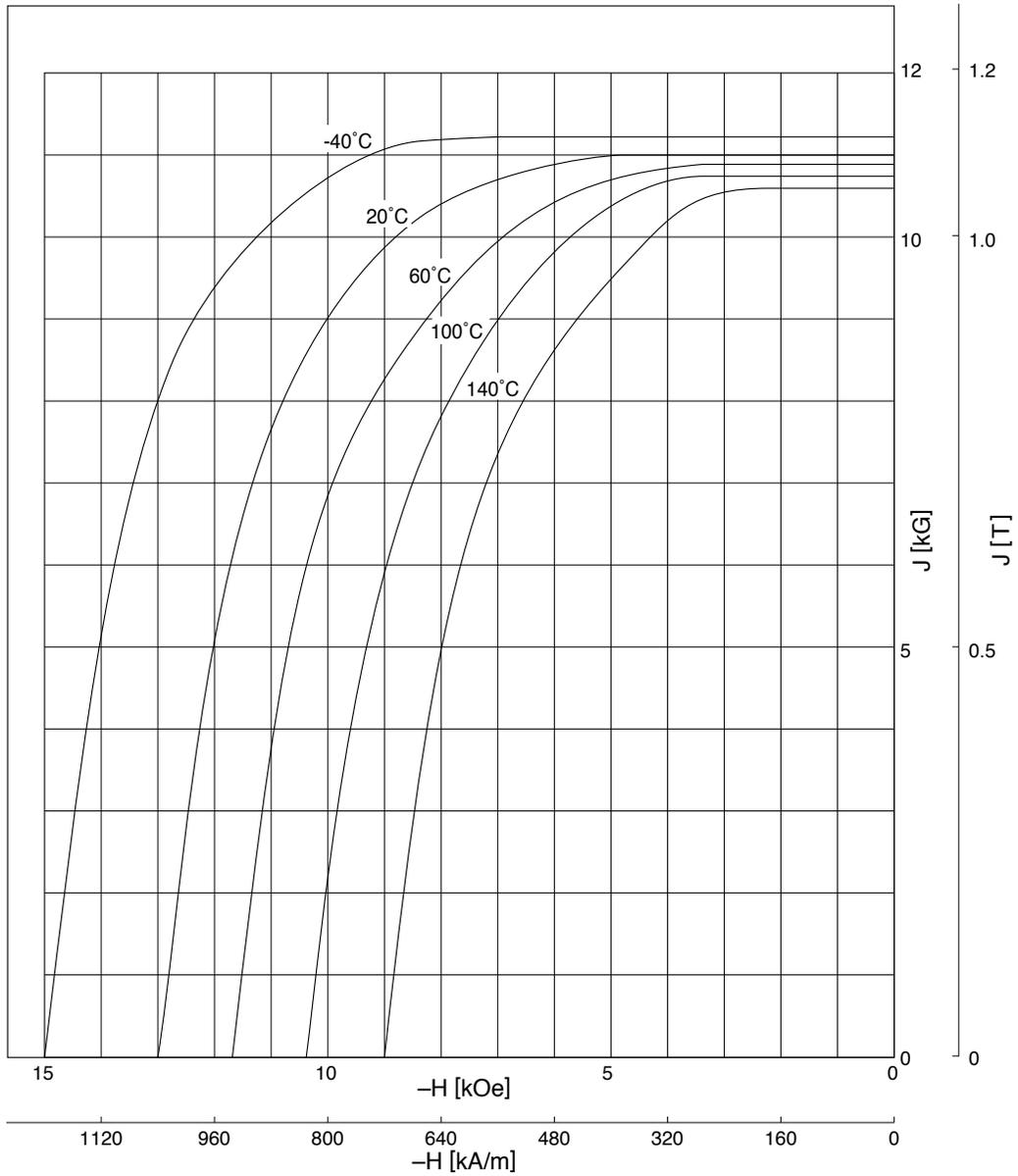


**Fig. 8**



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**Demagnetization Curves of LANTHANET®**  
LM-30FH

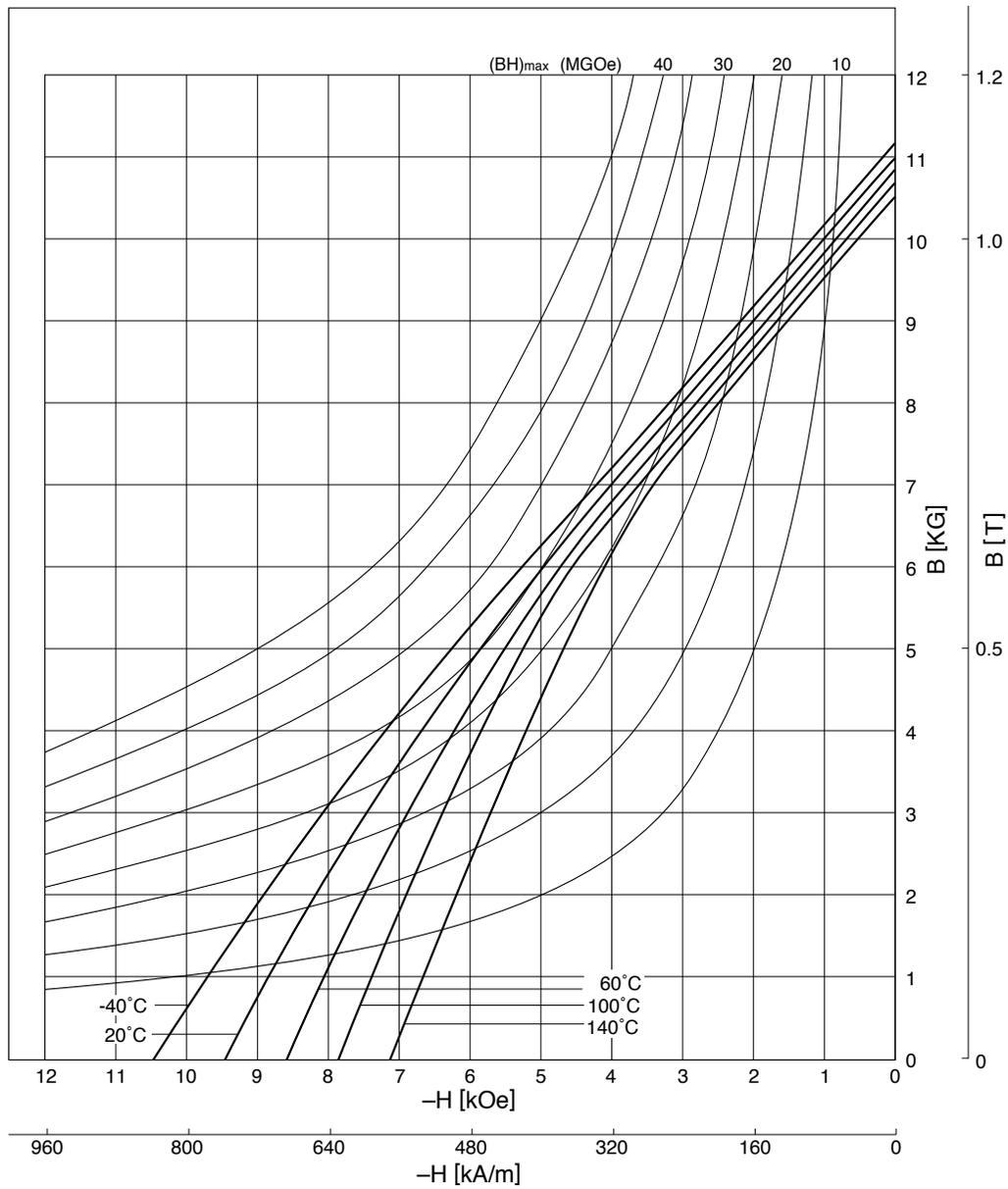


**Fig. 9**



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**Demagnetization Curves of LANTHANET®**  
LM-30FH



**Fig. 10**



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**Demagnetization Curves of LANTHANET®**  
LM-30SH

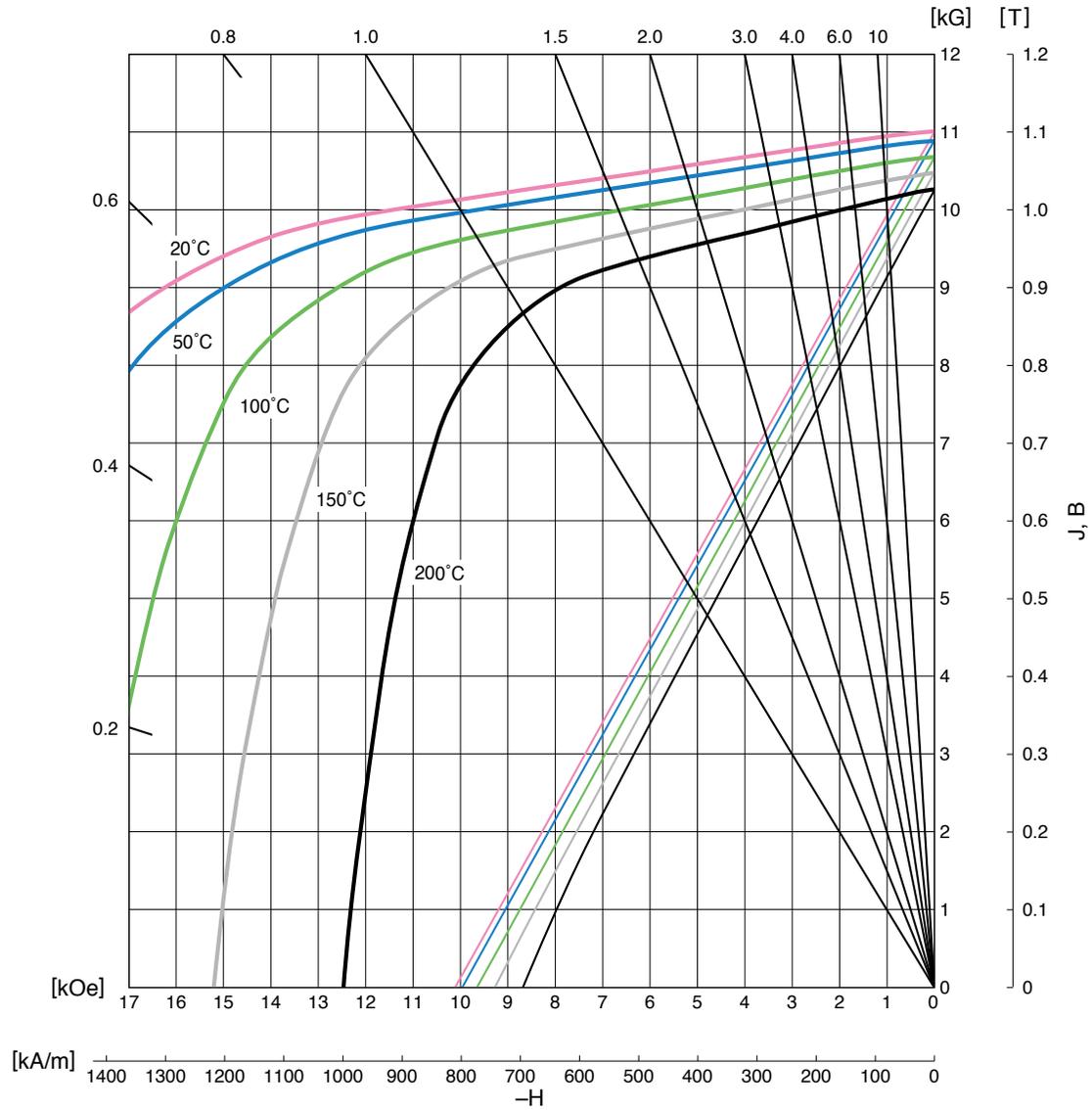
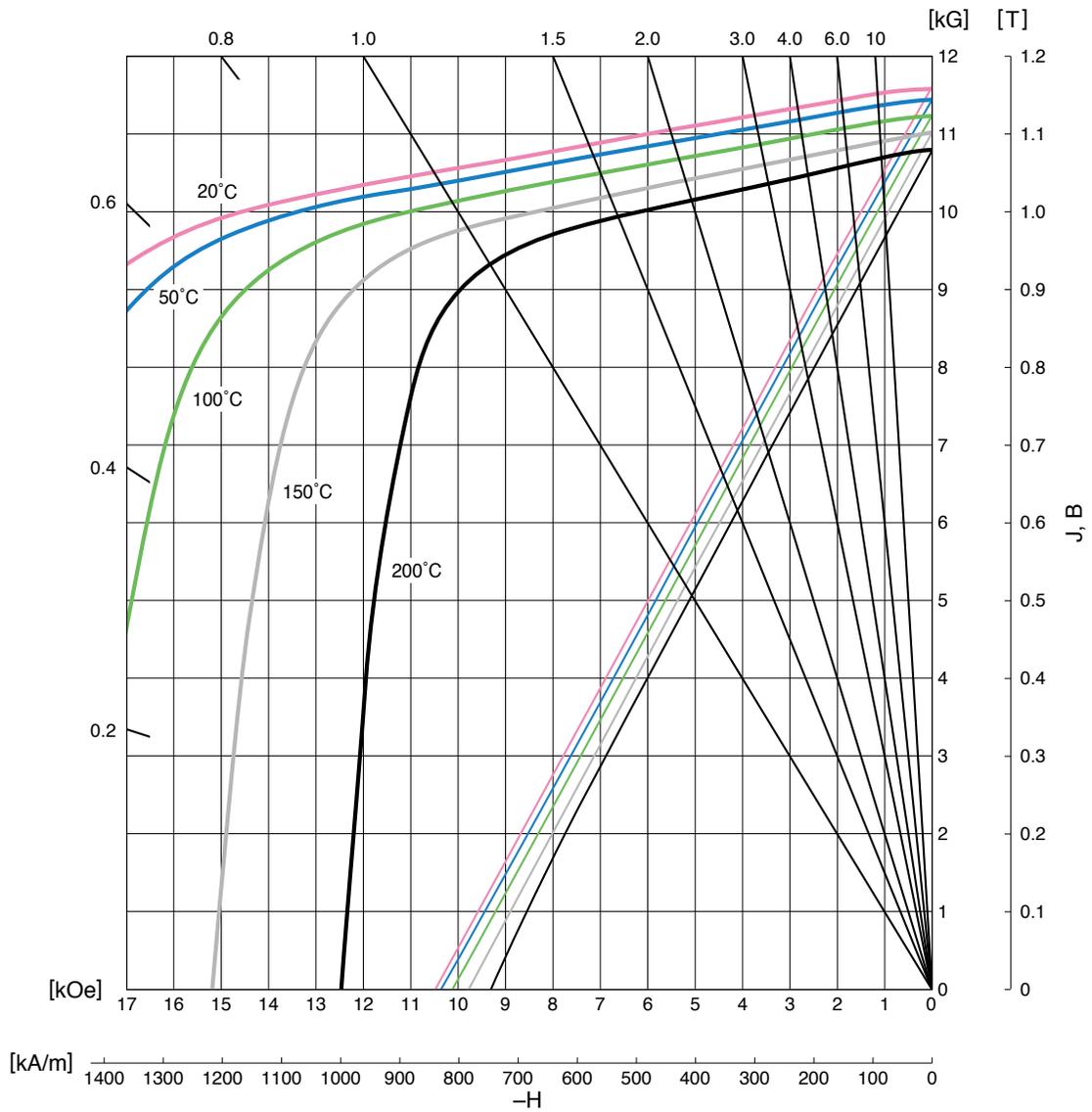


Fig. 11



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**Demagnetization Curves of LANTHANET®**  
LM-32SH



**Fig. 12**



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**Thermal Variations of Magnetic Characteristics**

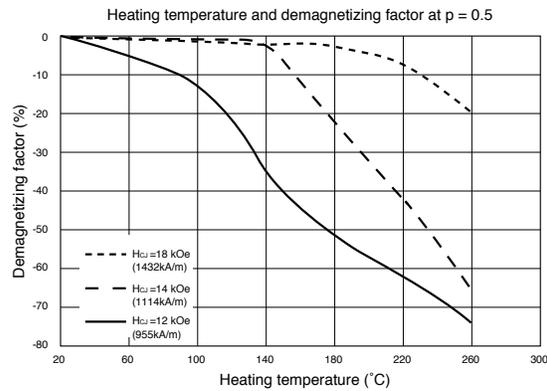
**Irreversible Temperature Variations**

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.

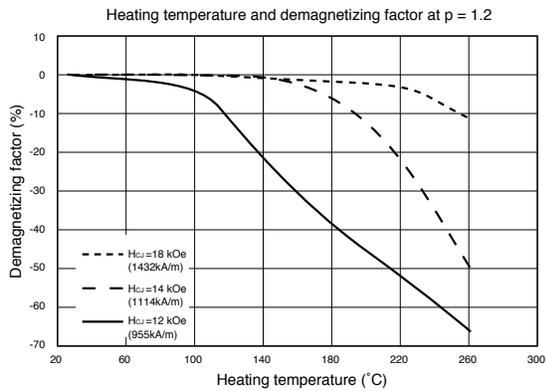
Figures 13-18 present approximate levels of irreversible temperature variations against the coercive force of LANTHANET®. It also shows that irreversible temperature variations are changed by the permanent magnet working point (P). In general, the larger the  $H_{CJ}$  and working point, the smaller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

**Irreversible Temperature Variations of LANTHANET® Fig. 13-18**

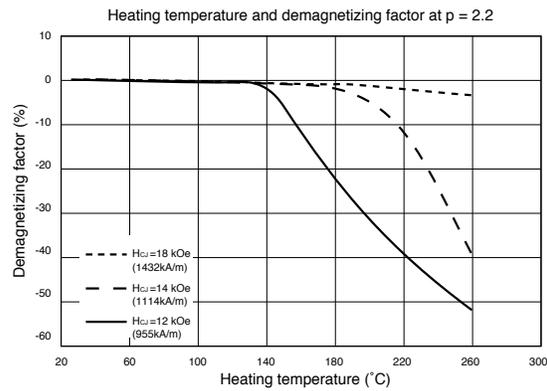
LM19



**Fig. 13**



**Fig. 14**

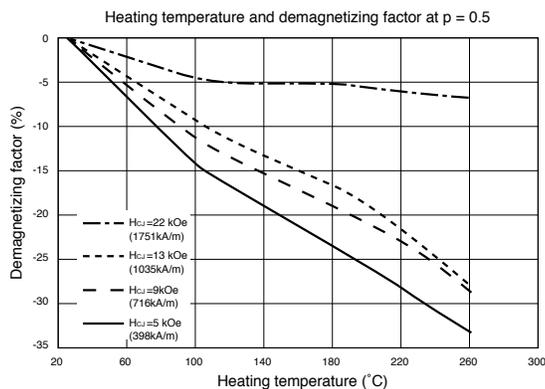


**Fig. 15**

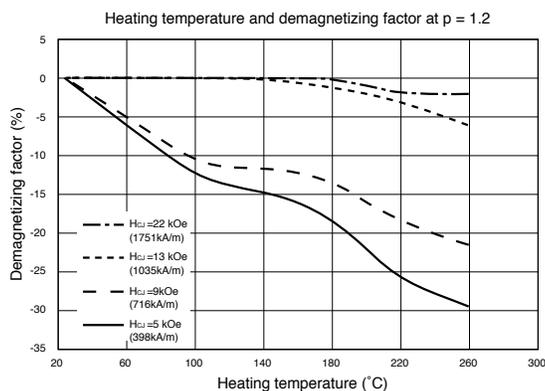


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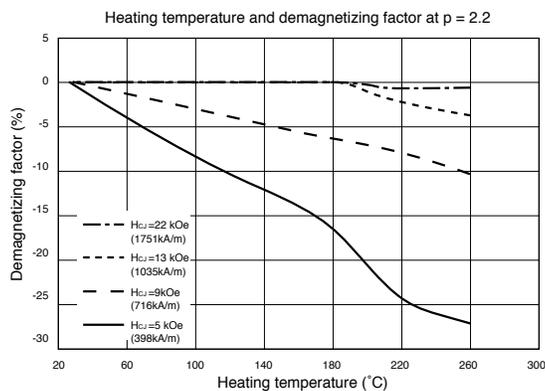
LM24F, 24FH, 26FH, 26SH  
 LM30F, 30FH, 30SH, 32SH



**Fig. 16**



**Fig. 17**



**Fig. 18**



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### Reversible Temperature Variations

Reversible variations of intrinsic magnetic characteristics by temperature change 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.

### 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®.

If you have any questions about the magnetizing method and equipment, please feel free to contact us.

**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	1592 (20)
LM-24FH,LM-26FH,30FH	1989 (25)
LM-26SH,30SH,32SH	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 attractive force of magnetized LANTHANET® is very strong. Careless handling, such as joining or separating two pieces of LANTHANET®, or attaching it to a metal, may damage its edges.

### Ordering Information

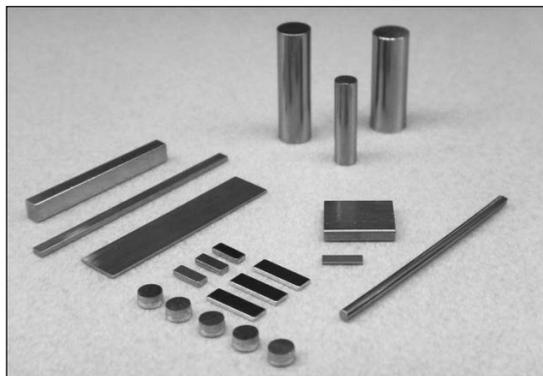
When placing an order with TOKIN LANTHANET®, be sure to specify the following items.

- Material and magnetic characteristics
- Dimensions and tolerances
- Whether or not magnetizing is necessary; direction of magnetization
- Purpose of use
- Usage environment (temperature, atmosphere, etc.)



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# Fe-Cr-Co Magnets



## Outline

Iron-Chromium-Cobalt Magnets were developed by Doctor Kaneko of Tohoku University and have been manufactured by 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 punching, 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 not change due to temperature rise during operation. However, when heated with temperature over 500°C (eg. silver blazing), their magnetic characteristics will be degraded.

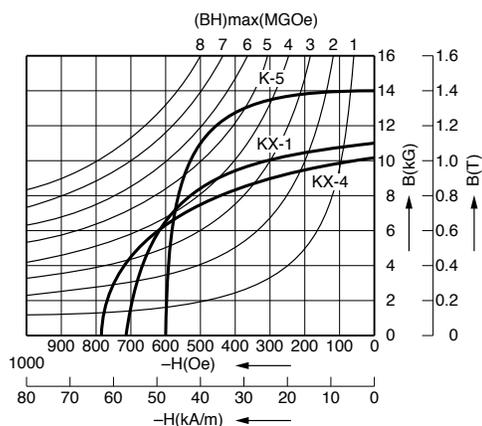


Fig. 19 Demagnetization Curve of Iron-Chromium-Cobalt Magnets



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**Standard Material Characteristics**
**Table 6 Magnetic Characteristics of Iron-Chromium-Cobalt Magnets**

Material	Residual flux density <b>Br</b> T (kG)	Coercive force <b>Hc</b> kA/m (Oe)	Maximum energy product <b>(BH)max</b> kJ/m <sup>3</sup> (MGOe)	Optimum operating point		
				<b>Bd</b> T (kG)	<b>Hd</b> kA/m (Oe)	Permeance coefficient <b>p</b>
<b>KX-1</b>	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
<b>KX-4</b>	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
<b>K-5</b>	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	Tensile strength	Elongation	Density	Electric resistance	Thermal expansion coefficient	Curie temperature
	<b>Hv</b>	<b>N/mm<sup>2</sup></b>	<b>(%)</b>	<b>(kg/m<sup>3</sup>)</b>	<b>(μΩ·m)</b>	<b>(/°C)</b>	<b>(°C)</b>
After solution treatment	200 ~ 230	637 ~ 735	10 ~ 15				
After mag, final heat treatment	450 ~ 500	441 ~ 490	0	7.8 × 10 <sup>3</sup>	0.62	14 × 10 <sup>-6</sup>	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. 20. 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 degraded 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 range of change compared with alnico magnets but much smaller compared with ferrite magnets. In most cases, these value can be ignored.

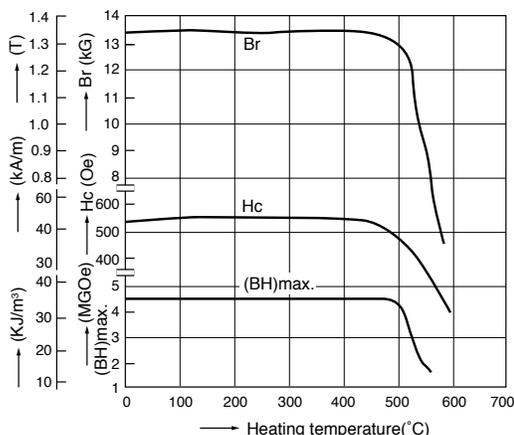


Fig. 20 Irreversible Temperature Change of Fe-Cr-Co Magnets

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
Sm-Co Magnets	- 0.03 ~ - 0.043
Nd-Fe-B Magnets	- 0.09 ~ - 0.12
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 permeability of recoil, recoil curve of Fe-Cr-Co Magnet KX-1 is shown in Fig. 21. From this, you can see Fe-Cr-Co Magnets is superior to alnico magnets regarding magnetic stability. ( $\mu_{rec}$  of alnico 5 is approx. 3.7 max.)

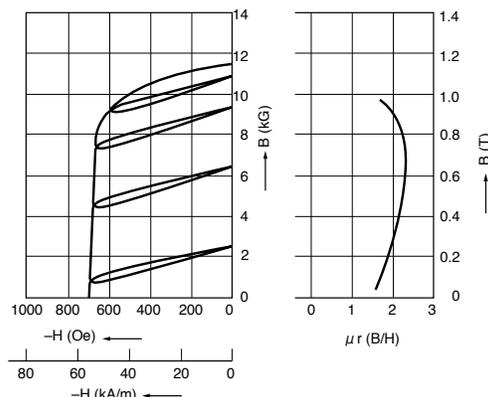


Fig. 21 Recoil Curve of Fe-Cr-Co Magnets KX-1

## 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, Fe-Cr-Co 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 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) Magnetized or Non-magnetized
- 5) Usage environment (temperature, atmosphere, etc.)
- 6) Any other relevant specifications (plating, coating, sealing)

**Table 9 General Shapes and Dimensions**

Shapes	Dimensions	Others
Plate	t0.3 ~ 1.5	Magnets of shapes stated left or molded by die-cutting, or grinding are available.
Rod	ø10 ~	
Line	ø0.5 ~ 8	



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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 field 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 Magnetization

As increasing magnetic fields imposed upon magnetic material, that material will reach saturation. This degree of magnetization is called saturation magnetization. For instance, saturation magnetization 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,  $\mu_{pl}$  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  $B_r$  (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 is 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.

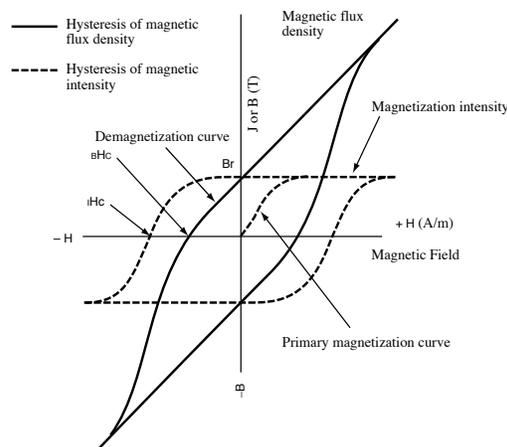


Fig. 22 Hysteresis Loop of Permanent Magnet



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When increasing diamagnetic field beyond coercive force  $H_C$ , 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. 22).

**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**

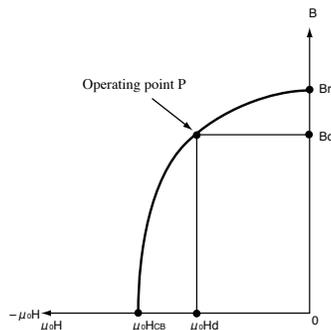
As stated in the section of magnetic flux density, permanent magnet uses its magnetic flux generated through magnetization process. Therefore, as much magnetic flux density remains in the permanent magnet despite large diamagnetic field, it can be said that its feature is more prominent. As a result, the essential condition for superior permanent magnet is that it has large residual magnetic flux density and coercive force  $H_C$ . 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. 22)

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  $H_d$ , the magnet generates magnetic flux density (magnetic induction) which correspond to  $B_d$  on the demagnetization curve. In this way, the point represented by  $H_d$  and  $B_d$  is called the operating point of the permanent magnet. (Refer to Fig. 23). 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. 23 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. 23 Operating Point of Permanent Magnet**  
Operating point P

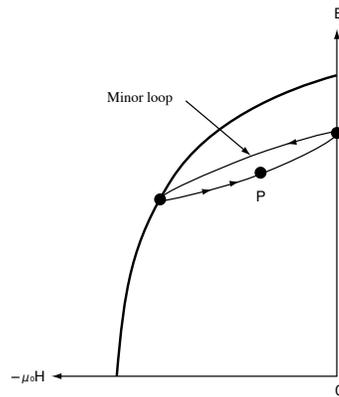
**Maximum Energy Product**

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  $H_d$  exists, it is only necessary to find out how much the magnetic flux density  $B_d$  is. So, best way to judge magnetic properties of permanent magnet is to use maximum product of  $H_d \times B_d$  on operating point. Since  $H_d \times B_d$  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. 24. 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.



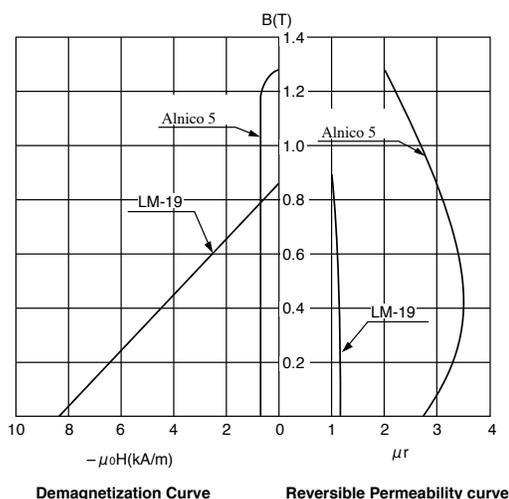
**Fig. 24 Minor Loop and Operating Point**



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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  $\mu r$ . Reversible permeability varies depending upon its starting point on demagnetization curve. Fig. 25 shows comparison of permeability between Lanthnet<sup>®</sup> 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.



**Fig. 25**

**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<sup>®</sup> 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  $B_d$  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  $B_d$  at the point of maximum energy product like reversible permeability.



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# Designing of Permanent Magnets

It is possible to design permanent magnets 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.

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

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

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

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  $Lm \cdot Am$  of permanent magnet, it is necessary to select the point of maximum energy product on demagnetization curve of permanent magnet at which  $Bd \cdot Hd$  is maximized. Then, after selecting  $Hd$  and  $Bd$ , it is required to examine whether magnetic field  $Bd$  which is needed for necessary void (Volume =  $Ag \cdot Lg$ ) 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:

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

$$\phi = Bd \cdot Am = f \cdot Bg \cdot Ag \text{ (Magnetic flux) ----- (2)'}$$

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 from 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:

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

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 $\phi$	Current I
Reluctance Rm	Resistance R
$Rm = \frac{1}{\mu S}$	$R = \frac{1}{\sigma S}$
Permeability $\mu$	Conductivity
Permeance P	Conductance G
$P = \frac{1}{Rm}$	$G = \frac{1}{R}$
$F = NI = Rm \phi$	$V = R \cdot I$



In circuit shown in Table 27, permeance P of external magnet is defined as  $P = \phi/F$ .

On the other hand, from the equation  $F = Hd \cdot Lm$ ,  $\phi = Bd \cdot Am$ , the following equation will be established:

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

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.

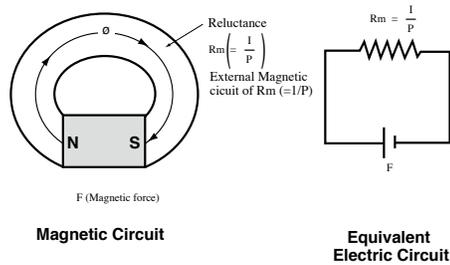


Fig. 26 Magnetic Circuit and Equivalent Electric Circuit

In the next stage, in case external magnetic circuit is separated into two systems, the following equation will be established from Fig. 27.

$$\begin{aligned} F &= \phi g/Pg = \phi f/P_f \\ \phi &= \phi g + \phi_f \\ &= F(Pg + P_f) \end{aligned}$$

When total permeance is set is PT,

$$PT = Pg + P_f.$$

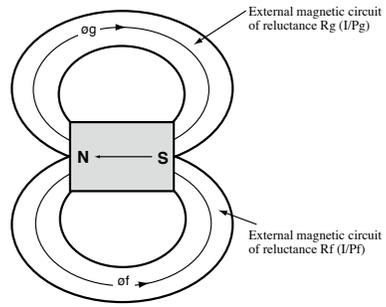
When defining Pg as permeance in gap and Pf as permeance in leakage section, leakage coefficient f will be defined as:

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

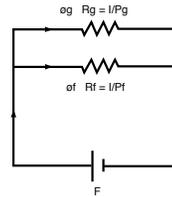
In addition, permeance coefficient of permanent magnet can be defined from equation (3):

$$\rho = Pr \cdot \frac{Lm}{Am \cdot r}$$

Fig. 28 presents an example leakage condition of magnetic circuit.



Magnetic Circuit



Equivalent Electric Circuit

Fig. 27 Magnetic Circuit with 2 External Magnetic Fields

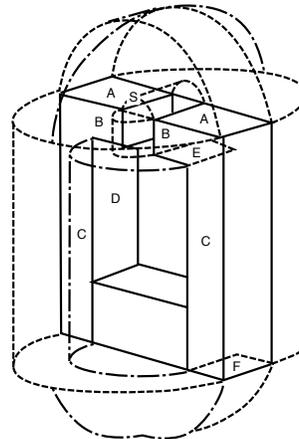
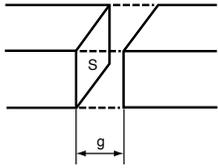
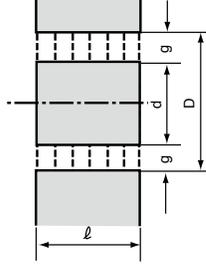
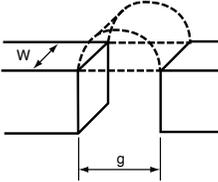
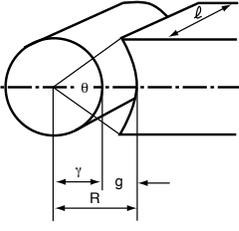
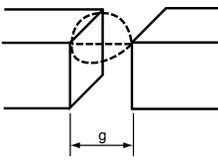
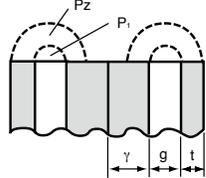
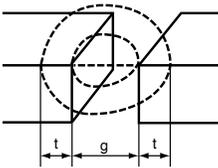
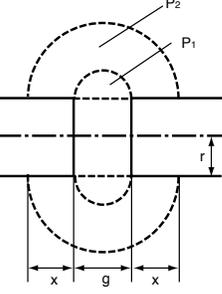
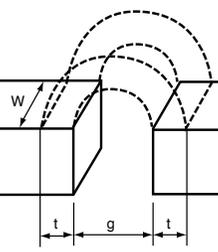


Fig. 28 Example of Leakage Flux



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Place	Equation	Place	Equation
Parallel, plain Permeance between two surfaces 	$S$ : Area of magnetic pole $g$ : Void distance $P = \frac{S}{g}$	Peameance between surfaces of concentric tubes 	$\ell$ : 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 $g/d < 0.01$ : $P = \pi d\ell/g$ )
Barrel-shape permeance from straight line 	$W$ : Width of yoke or magnet $P = 0.264W$	Permeance between circular surfaces 	$\ell$ : Length of arc $R, \gamma$ : Radius of arc $\theta$ : Angle of arc (Radian) $g$ : Void distance $P = \theta\ell/\ell n \frac{R}{\gamma}$ (When $g$ is smaller than $\gamma$ , $P = \theta\gamma\ell/g$ )
Permeance corresponding to a quarter of the ball from the corner 	$g$ : Void distance $P = 0.077g$	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 corresponding to a quarter of the ball from side line 	$t$ : Distance considered $g$ : Void distance $P = \frac{t}{4}$	Permeance between surfaces of cylindrical side panels 	$P = P_1 + P_2$ $= 1.65(\gamma + 0.212g)$ $+ \{2r + \sqrt{g(g+2x)}\} \ell n(1+2x/g)$
Barrel-shape permeance from side panels 	$W$ : Width of yoke or magnet $t$ : Distance considered $g$ : Void distance ① When $g \geq 3t$ , $P = 0.637 \frac{W}{1+g/t}$ ② When $g < 3t$ , $P = \frac{W}{\pi} \ell n \frac{g+2t}{g}$		

**Fig. 29 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. 29. (including gap)
- 2) Using Fig. 29, find permeance  $P_g, P_{f1} \dots P_{fn}$  of each section.
- 3) Find  $P_1 = P_g + P_{f1} + \dots + P_{fn}$
- 4) Find  $f = PT/P_g$
- 5) Find  $A_m$  so that  $p = PT \times (L_m/A_m)$  can be optimum considering Demagnetizing properties. In this case,  $L_m = (rBg \cdot Lg)/Hd$ .
- 6) Confirm  $f$  again when dimensions is decided.

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

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:

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

Therefore, if surface density I 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:

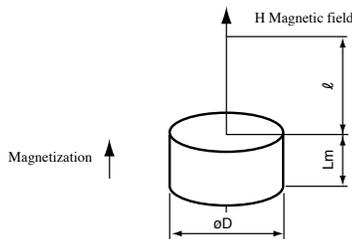
$$H = 2\pi I \left( 1 - \frac{\ell}{\sqrt{\ell^2 + r_0^2}} \right) \text{ (Oe)} \quad \text{-----(4)}$$

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. 30 and  $2\pi I = \frac{Br}{2}$  and  $\gamma_0 = \frac{D}{2}$  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. 30 Cylindrical Magnets**

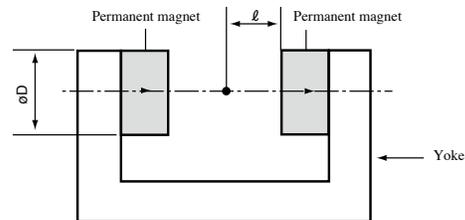
**Example 2 In Case of Facing Cylindrical Magnets**

In case of facing magnets shown in Fig. 30, 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. 31 will be erased. Therefore double of equation (4) can be used.

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



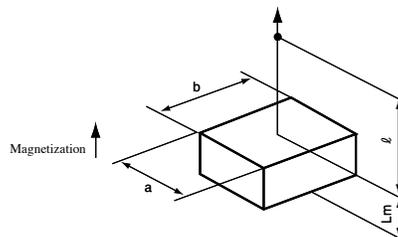
**Fig. 31 In Case of Connecting Yokes**

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. 32 (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. 32 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 equation:

$$\rho = \frac{Bd}{Hd} = \frac{Br-Hd}{Hd}$$

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

### Permeance coefficient of cylindrical magnet

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

### Permeance coefficient of square magnet (angle is radian)

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

(Refer to Fig. 30 and Fig. 32. for dimensions)

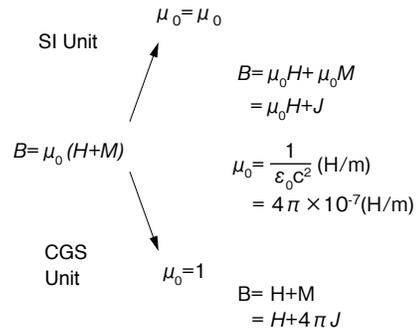
This calculation uses charge method. Therefore, when permeance coefficient is below turning point of demagnetization curve, it is necessary to use apparent Bd minor loop in case of drawing minor loop from that point.



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# Units of Magnets

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



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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	$\Phi$	Weber ( $\Phi=BA$ )	Wb	Maxwell ( $\Phi=BA$ )	Maxwell	1Wb=10 <sup>8</sup> Maxwell	1 Maxwell=10 <sup>-8</sup> Wb
Magnetic flux density	$B$	Tesla	T	Gauss	G	1T=10 <sup>4</sup> G	1G=10 <sup>-4</sup> T
Magnetic induction							
Magnetic constant (Vacuum permeability)	$\mu_0$	Henry per meter	H/m	Absolute number ( $\mu_0=1$ )	-	-	-
Magnetic intensity	$H$	Ampere per meter	A/m	Oersted	Oe	1A/m= $\frac{4\pi}{10}$ Oe=1.25664×10 <sup>-2</sup> Oe	1Oe= $\frac{10^3}{4\pi}$ A/m=79.5775A/m
Magnetic flux density compatible with magnetic intensity		Tesla ( $\mu_0 H$ )	T	Oersted	Oe	1T=10 <sup>4</sup> Oe	1Oe=10 <sup>-4</sup> T
Magnetization *	$M$	Ampere per meter ( $M=\frac{J}{\mu_0}$ )	A/m	Gauss ( $M=4\pi J$ )	G	1A/m=10 <sup>3</sup> G	1G=10 <sup>-3</sup> A/m
Magnetic polarization	$J$	Tesla ( $J=\mu_0 M$ )	T	Gauss ( $J=\frac{M}{4\pi}$ )	G	1T= $\frac{10^4}{4\pi}$ G	1G=4 $\pi$ ×10 <sup>-4</sup> T
Permeability (Absolute permeability)	$\mu$	Henry per meter	H/m	Absolute number	-	1H/m= $\frac{10^7}{4\pi}$ =7.95775×10 <sup>5</sup>	1= $\frac{4\pi}{10^7}$ H/m=1.25664×10 <sup>-6</sup> H/m
Permeability (Permeance coefficient)	$\mu_r$	Absolute number ( $\mu_r=\frac{\mu}{\mu_0}$ )	-	Absolute number ( $\mu_r=\mu$ )	-	SI and CGS Unit are identical	
Magnetomotive force	$F_m$	Ampere ** ( $F_m=HL$ ) ( $Um=H\Delta L$ )	A	Gilbert ( $F_m=HL$ ) ( $Um=H\Delta L$ )	Gilbert	1A= $\frac{4\pi}{10}$ Gilbert	1 Gilbert= $\frac{10}{4\pi}$ A
Magnetic difference	$Um$					=1.25664 Gilbert	=0.795775A
Permeance	$A$	Henry ( $A=\frac{\Phi}{F_m}$ )	H	Maxwell per Gilbert ( $A=\frac{\Phi}{F_m}$ )	$\frac{\text{Maxwell}}{\text{Gilbert}}$	1H= $\frac{10^9}{4\pi}$ Maxwell/Gilbert =7.95775×10 <sup>8</sup> $\frac{\text{Gilbert}}{\text{Maxwell}}$	1 Gilbert= $\frac{4\pi}{\text{Maxwell}}$ H =1.25664×10 <sup>8</sup> H
Magnetic resistivity	$R_m$	Henry ( $R_m=\frac{F_m}{\Phi}$ )	H <sup>-1</sup>	Maxwell per Gilbert ( $R_m=\frac{F_m}{\Phi}$ )	$\frac{\text{Gilbert}}{\text{Maxwell}}$	1H <sup>-1</sup> = $\frac{4\pi}{10^9}$ Gilbert/Maxwell =1.25664×10 <sup>-8</sup> $\frac{\text{Gilbert}}{\text{Maxwell}}$	1 Gilbert= $\frac{10^9}{\text{Maxwell}}$ H <sup>-1</sup> =7.95775×10 <sup>7</sup> H <sup>-1</sup>
Magnetic energy product		Joule per cubic meter ( $BH$ )	J/m <sup>3</sup>	Gauss Oersted or Erg per cubic centimeter ( $BH$ )	G Oe erg/cm <sup>3</sup>	1J/m <sup>3</sup> =4 $\pi$ ×10GOe =1.25664×10 <sup>2</sup> GOe =1.25664×10 <sup>2</sup> erg/cm <sup>3</sup>	1GOe= $\frac{1}{4\pi}$ ×10 <sup>-1</sup> J/m <sup>3</sup> =7.95775×10 <sup>-3</sup> J/m <sup>3</sup> =1erg/cm <sup>3</sup>
Magnetic energy	$E$	Joule ( $\frac{BH\cdot AL}{2}$ )	J	Erg ( $\frac{BH\cdot AL}{8\pi}$ )	erg	1J=10 <sup>7</sup> erg	1erg=10 <sup>-7</sup> J
Magnetic absorption	$F$	Newton ( $\frac{B^2 A}{2\mu_0}$ )	N.	Dyne ( $\frac{B^2 A}{8\pi}$ )	dyn	1N=10 <sup>5</sup> dyn (1N=0.101972kgf)	1dyn=10 <sup>-5</sup> N (1kgf=9.80665N)

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



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