EXPLANATION OF TERMS AND FORMULAS

Symbols and units

SYMBOL	UNIT	DESCRIPTION
A_e	mm^2	effective cross-sectional area of a core
A_{min}	mm^2	minimum cross-sectional area of a core
A_L	nH	inductance factor
B	T	magnetic flux density
B_r	T	remanence
B_s	T	saturation flux density
$\hat{B}$	T	peak flux density
C	F	capacitance
D_F	-	disaccomodation factor
f	Hz	frequency
G	μm	gap length
H	A/m	magnetic field strength
H_c	A/m	coercivity
$\hat{H}$	A/m	peak magnetic field strength
I	A	current
l_e	mm	effective magnetic path length
L	H	inductance
N	-	number of turns
P_v	kW/m^3	specific power loss of core material
Q	-	quality factor
T_c	°C	Curie temperature
V_e	mm^3	effective volume of core
α_F	K^{-1}	temperature factor of permeability
$\tan\delta / \mu_i$	-	loss factor
η_B	T^{-1}	hysteresis material constant
μ	-	absolute permeability
μ_o	Hm^{-1}	magnetic constant ($4\pi.10^{-7}$)
μ_s'	-	real component of complex series permeability
μ_s''	-	imaginary component of complex series permeability
μ_a	-	amplitude permeability
μ_e	-	effective permeability
μ_i	-	initial permeability
μ_r	-	relative permeability
μ_Δ	-	incremental permeability
ρ	Ωm	resistivity
$\Sigma(l/A)$	mm^{-1}	core factor (C1)

Definition of terms

PERMEABILITY

When a magnetic field is applied to a soft magnetic material, the resulting flux density is composed of that of free space plus the contribution of the aligned domains.

$$B = \mu_0 H + J \quad \text{or} \quad B = \mu_0 (H + M) \qquad (1)$$

where $\mu_0 = 4\pi.10^{-7}$ H/m, J is the magnetic polarization and M is the magnetization.

The ratio of flux density and applied field is called absolute permeability.

$$\frac{B}{H} = \mu_0\left(1 + \frac{M}{H}\right) = \mu_{absolute} \qquad (2)$$

It is usual to express this absolute permeability as the product of the magnetic constant of free space and the relative permeability (μ_r).

$$\frac{B}{H} = \mu_0 \mu_r \qquad (3)$$

Since there are several versions of μ_r depending on conditions the index "r" is generally removed and replaced by the applicable symbol e.g. μ_i, μ_a, μ_Δ etc.

INITIAL PERMEABILITY

The initial permeability is measured in a closed magnetic circuit (ring core) using a very low field strength.

$$\mu_i = \frac{1}{\mu_0} \cdot \frac{\Delta B}{\Delta H} \; (\Delta H \to 0) \qquad (4)$$

Initial permeability is dependent on temperature and frequency.

EFFECTIVE PERMEABILITY

If the air-gap is introduced in a closed magnetic circuit, magnetic polarization becomes more difficult. As a result, the flux density for a given magnetic field strength is lower.

Effective permeability is dependent on the initial permeability of the soft magnetic material and the dimensions of air-gap and circuit.

$$\mu_e = \frac{\mu_i}{1 + \frac{G \cdot \mu_i}{l_e}} \qquad (5)$$

where G is the gap length and l_e is the effective length of magnetic circuit. This simple formula is a good approximation only for small air-gaps. For longer air-gaps some flux will cross the gap outside its normal area (stray flux) causing an increase of the effective permeability.

AMPLITUDE PERMEABILITY

The relationship between higher field strength and flux densities without the presence of a bias field is given by the amplitude permeability.

$$\mu_a = \frac{1}{\mu_0} \cdot \frac{\hat{B}}{\hat{H}} \qquad (6)$$

Since the BH loop is far from linear, values depend on the applied field peak strength.

INCREMENTAL PERMEABILITY

The permeability observed when an alternating magnetic field is superimposed on a static bias field is called the incremental permeability.

$$\mu_\Delta = \frac{1}{\mu_0}\left[\frac{\Delta B}{\Delta H}\right]_{H_{DC}} \qquad (7)$$

If the amplitude of the alternating field is negligibly small, the permeability is then called the reversible permeability (μ_{rev}).

COMPLEX PERMEABILITY

A coil consisting of windings on a soft magnetic core will never be an ideal inductance with a phase angle of 90°. There will always be losses of some kind, causing a phase shift, which can be represented by a series or parallel resistance as shown in Figs 3 and 4.

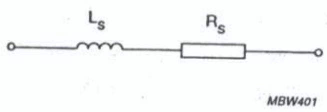

Fig.3 Series representation.

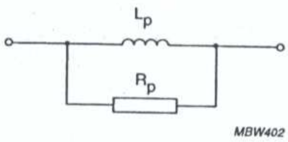

Fig.4 Parallel representation.

For series representation

$$Z = j\omega L_s + R_s \qquad (8)$$

and for parallel representation,

$$Z = \frac{1}{1/(j\omega L_p) + 1/R_p} \qquad (9)$$

The magnetic losses are accounted for if a resistive term is added to the permeability.

$$\mu = \mu_s' - j\mu_s'' \quad \text{or} \quad \frac{1}{\mu} = \frac{1}{\mu'_p} - \frac{1}{\mu''_p} \qquad (10)$$

The phase shift caused by magnetic losses is given by:

$$\tan\delta_m = \frac{R_s}{\omega L_s} = \frac{\mu''_s}{\mu'_s} \quad \text{or} \quad \frac{\omega L_p}{R_p} = \frac{\mu'_p}{\mu''_p} \qquad (11)$$

For calculations on inductors and also to characterise ferrites, the series representations is generally used (μ'_s and μ''_s). In some applications e.g. signal transformers, the use of the parallel representation (μ'_p and μ''_p) is more convenient.

The relationship between the representations is given by

$$\mu'_p = \mu'_s\left(1 + \tan\delta^2\right) \quad \text{and} \quad \mu''_p = \mu''_s\left(1 + \frac{1}{\tan\delta^2}\right) \qquad (12)$$

Loss Factor

The magnetic losses which cause the phase shift can be split up into three components:

- hysteresis losses
- eddy current losses
- residual losses

This gives the formula:

$$\tan\delta_m = \tan\delta_h + \tan\delta_f + \tan\delta_r \qquad (13)$$

Fig.5 shows the magnetic losses as a function of frequency.

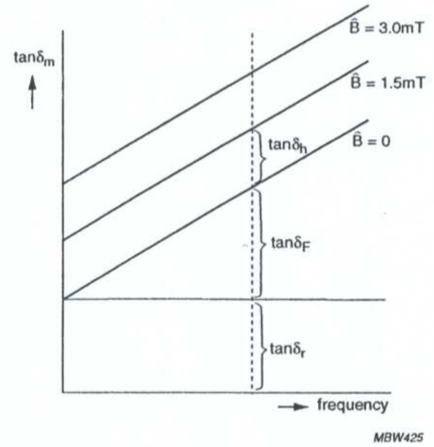

Fig.5 Magnetic losses ($\tan\delta_m$) as a function of frequency.

Hysteresis losses vanish at very low field strengths. Eddy current losses increase with frequency and are negligible at very low frequency. The remaining part is called residual loss. It can be proven that for a gapped magnetic circuit, the following relationship is valid:

$$\frac{(\tan\delta_m)_{gapped}}{\mu_e - 1} = \frac{\tan\delta_m}{\mu_i - 1} \qquad (14)$$

Since μ_i and μ_e are usually much greater than 1, a good approximation is:

$$\frac{(\tan\delta_m)_{gapped}}{\mu_e} = \frac{\tan\delta_m}{\mu_i} \qquad (15)$$

From this formula, the magnetic losses in a gapped circuit can be derived from:

$$(\tan\delta_m)_{gapped} = \frac{\tan\delta_m}{\mu_i} \cdot \mu_e \qquad (16)$$

Normally, the index "m" is dropped when material properties are discussed:

$$(\tan\delta)_{gapped} = \frac{\tan\delta}{\mu_i} \cdot \mu_e \qquad (17)$$

In material specifications, the loss factor ($\tan\delta/\mu_i$) is used to describe the magnetic losses. These include residual and eddy current losses, but not hysteresis losses.

For inductors used in filter applications, the quality factor (Q) is often used as a measure of performance. It is defined as:

$$Q = \frac{1}{\tan\delta} = \frac{\omega L}{R_{tot}} = \frac{\text{reactance}}{\text{total resistance}} \qquad (18)$$

The total resistance includes the effective resistance of the winding at the design frequency.

Hysteresis material constant

When the flux density of a core is increased, hysteresis losses are more noticeable. Their contribution to the total losses can be obtained by means of two measurements, usually at the induction levels of 1.5 mT and 3 mT. The hysteresis constant is found from:

$$\eta_B = \frac{\Delta \tan\delta_m}{\mu_e \cdot \Delta\hat{B}} \quad (19)$$

The hysteresis loss factor for a certain flux density can be calculated using:

$$\frac{\tan\delta_h}{\mu_e} = \eta_B \cdot \hat{B} \quad (20)$$

This formula is also the IEC definition for the hysteresis constant.

Effective core dimensions

To facilitate calculations on a non-uniform soft magnetic cores, a set of effective dimensions is given on each data sheet. These dimensions, effective area (A_e), effective length (l_e) and effective volume (V_e) define a hypothetical ring core which would have the same magnetic properties as the non-uniform core.

The reluctance of the ideal ring core would be:

$$\frac{l_e}{\mu \cdot A_e} \quad (21)$$

For the non-uniform core shapes, this is usually written as:

$$\frac{1}{\mu_e} \cdot \Sigma\frac{l}{A} \quad (22)$$

the core factor divided by the permeability. The inductance of the core can now be calculated using this core factor:

$$L = \frac{\mu_0 \cdot N^2}{\frac{1}{\mu_e} \cdot \Sigma\frac{l}{A}} = \frac{1.257 \cdot 10^{-9} \cdot N^2}{\frac{1}{\mu_e} \cdot \Sigma\frac{l}{A}} \text{(in H)} \quad (23)$$

The effective area is used to calculate the flux density in a core,

for sine wave:

$$\hat{B} = \frac{U\sqrt{2} \cdot 10^9}{\omega A_e N} = \frac{2.25U \cdot 10^8}{fNA_e} \text{(in mT)} \quad (24)$$

for square wave:

$$\hat{B} = \frac{0.25\hat{U} \cdot 10^9}{fNA_e} \text{(in mT)} \quad (25)$$

where:

A_e is the effective area in mm^2.

U is the voltage in V

f is the frequency in Hz

N is the number of turns.

The magnetic field strength (H) is calculated using the effective length (l_e):

$$\hat{H} = \frac{IN\sqrt{2}}{l_e} \text{(A/m)} \quad (26)$$

If the cross-sectional area of a core is non-uniform, there will always be a point where the real cross-section is minimal. This value is known as A_{min} and is used to calculate the maximum flux density in a core. A well designed ferrite core avoids a large difference between A_e and A_{min}. Narrow parts of the core could saturate or cause much higher hysteresis losses.

Inductance factor (A_L)

To make the calculation of the inductance of a coil easier, the inductance factor, known as the A_L value, is given in each data sheet (in nano Henry). The inductance of the core is defined as:

$$L = N^2 \cdot A_L \quad \text{(nH)} \quad (27)$$

The value is calculated using the core factor and the effective permeability:

$$A_L = \frac{\mu_0\mu_e \cdot 10^6}{\Sigma(l/A)} = \frac{1.257\mu_e}{\Sigma(l/A)} \quad \text{(nH)} \quad (28)$$

Magnetization curves (H_C, B_R, B_S)

If an alternating field is applied to a soft magnetic material, a hysteresis loop is obtained. For very high field strengths, the maximum attainable flux density is reached. This is known as the saturation flux density (B_s).

If the field is removed, the material returns to a state where, depending on the material grade, a certain flux density remains. This the remanent flux density (B_r).

This remanent flux returns to zero for a certain negative field strength which is referred to a coercivity (H_c).

These points are clearly shown in Fig.6.

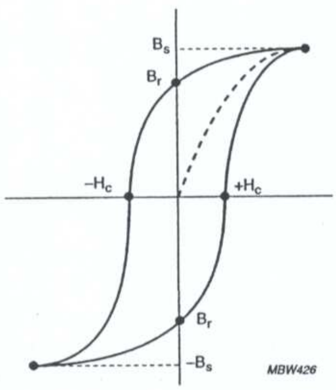

Fig.6 Typical BH curve showing points B_s, B_r and H_c.

TEMPERATURE DEPENDENCE OF THE PERMEABILITY

The permeability of a ferrite is a function of temperature. It generally increases with temperature to a maximum value and then drops sharply to a value of 1. The temperature at which this happens is called the Curie temperature (T_c). Typical curves of our grades are given in the material data section.

For filter applications, the temperature dependence of the permeability is a very important parameter. A filter coil should be designed in such a way that the combination it forms with a high quality capacitor results in an LC filter with excellent temperature stability.

The temperature coefficient (TC) of the permeability is given by:

$$TC = \frac{(\mu_i)_{T2} - (\mu_i)_{T1}}{(\mu_i)_{T1}} \cdot \frac{1}{T_2 - T_1} \quad (29)$$

For a gapped magnetic circuit, the influence of the permeability temperature dependence is reduced by the factor μ_e/μ_i. Hence:

$$TC_{gap} = \frac{\mu_e}{(\mu_i)_{T1}} \cdot \frac{(\mu_i)_{T2} - (\mu_i)_{T1}}{(\mu_i)^2_{T1}} \cdot \frac{1}{T_2 - T_1} = \mu_e \cdot \alpha_F \quad (30)$$

So α_F is defined as:

$$\alpha_F = \frac{(\mu_i)_{T2} - (\mu_i)_{T1}}{(\mu_i)^2_{T1}} \cdot \frac{1}{T_2 - T_1} \quad (31)$$

Or, to be more precise, if the change in permeability over the specified area is rather large:

$$\alpha_F = \frac{(\mu_i)_{T2} - (\mu_i)_{T1}}{(\mu_i)_{T1} \cdot (\mu_i)_{T2}} \cdot \frac{1}{T_2 - T_1} \quad (32)$$

The temperature factors for several temperature trajectories of the grades intended for filter applications are given in the material specifications. They offer a simple means to calculate the temperature coefficient of any coil made with these ferrites.

TIME STABILITY

When a soft magnetic material is given a magnetic or thermal disturbance, the permeability rises suddenly and then decreases slowly with time. For a defined time interval, this "disaccommodation" can be expressed as:

$$D = \frac{\mu_1 - \mu_2}{\mu_1} \quad (33)$$

The decrease of permeability appears to be almost proportional to the logarithm of time. For this reason, IEC has defined a disaccommodation coefficient:

$$d = \frac{\mu_1 - \mu_2}{\mu_1 \cdot \log(t_2/t_1)} \quad (34)$$

As with temperature dependence, the influence of disaccommodation on the inductance drift of a coil will be reduced by μ_e/μ_i.

Therefore, a disaccommodation factor D_F is defined:

$$D_F = \frac{d}{\mu_i} = \frac{\mu_1 - \mu_2}{\mu_1^2 \cdot \log(t_2/t_1)} \quad (35)$$

The variability with time of a coil can now be predicted by:

$$\frac{L_1 - L_2}{L_1} = \mu_e \cdot D_F \quad (36)$$

RESISTIVITY

Ferrite is a semiconductor with a DC resistivity in the crystallites of the order of 10^{-3} Ωm for a MnZn type ferrite, and about 30 Ωm for a NiZn ferrite.

Since there is an isolating layer between the crystals, the bulk resistivity is much higher: 0.1 - 10 Ωm for MnZn ferrites and 10^4 - 10^6 Ωm for NiZn an MgZn ferrites.

Material grade specification 3C80

SYMBOL	CONDITIONS	VALUE	UNIT
μ_i	25 °C; ≤10 kHz; 0.1 mT	2000 ±20%	
μ_a	100 °C; 25 kHz; 200 mT	5500 ±25%	
B	25 °C; 10 kHz; 250 A/ m	≈420	mT
	100 °C; 10 kHz; 250 A/ m	≈330	
P_V	100 °C; 25 kHz; 200 mT	≤200	kW/m³
ρ	DC; 25 °C	≈1	Ωm
T_C		≥200	°C
density		≈4800	kg/m³

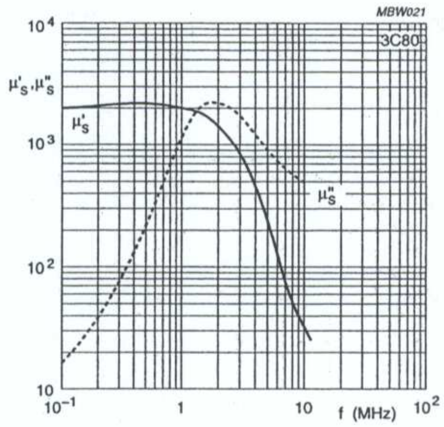

Fig.1 Complex permeability as a function of frequency.

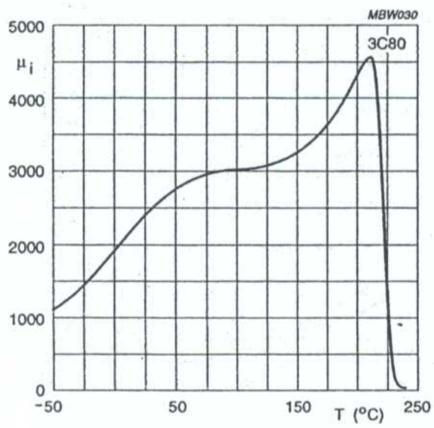

Fig.2 Initial permeability as a function of temperature.

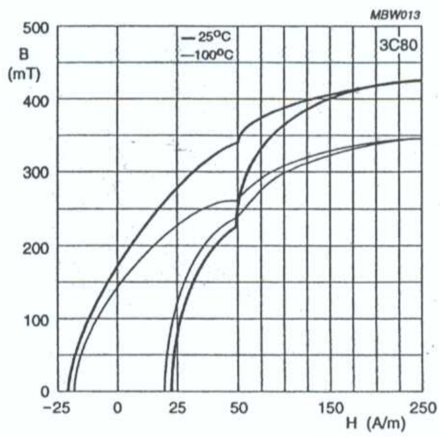

Fig.3 Typical B-H loops.

Material grade specification

3C80

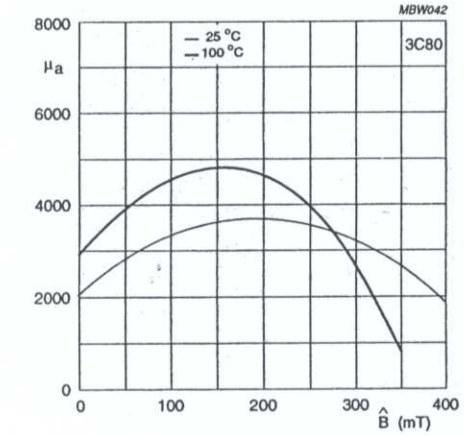

Fig.4 Amplitude permeability as function of peak flux density.

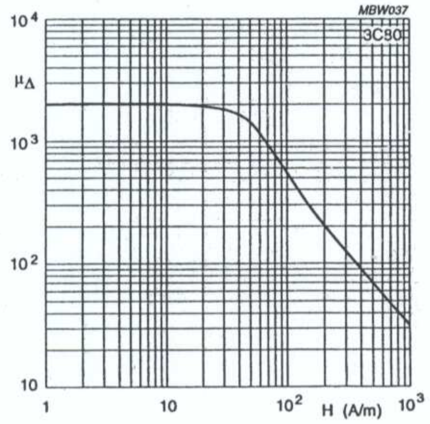

Fig.5 Incremental permeability as a function of magnetic field strenght.

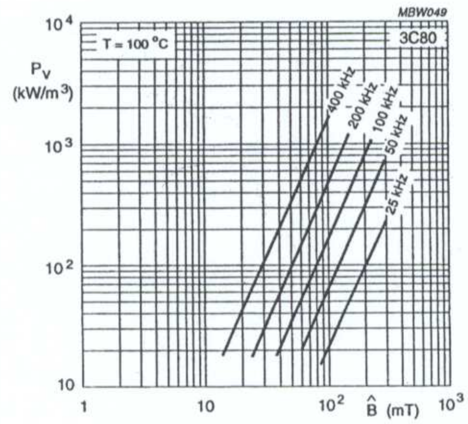

Fig.6 Specific power loss as a function of peak flux density with frequency as a parameter

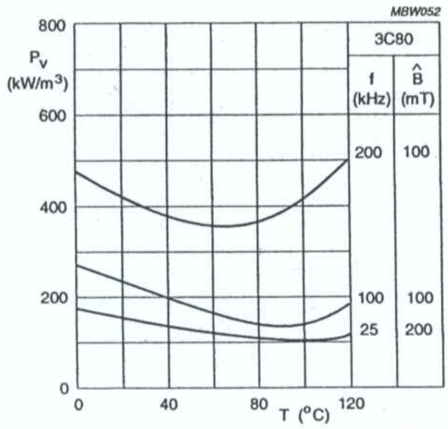

Fig.7 Specific power loss for several frequency/flux density combinations as a function of temperature