## Effect of an air gap

A method is described below for the approximate evaluation of the effective permeability, $\mu_e$ of gapped E and U cores, at low flux densities. The $A_L$ values which are of greater direct interest to the user, are related to $\mu_e$ by the formula:

$$A_L = \frac{0.4\pi . \mu_e}{\Sigma \frac{l}{A}} \text{ or } \mu_e = \frac{A_L \Sigma \frac{l}{A}}{0.4\pi} \quad ...(1)$$

where $A_L$ (the inductance of one turn) is in nH.

$\Sigma \frac{l}{A}$ (given in the component pages for specific cores) is in mm-[1].

The demagnetising effect of magnetic poles on both sides of an air gap makes the effective permeability of a gapped core lower than the intrinsic permeability of the core material. The extent of this reduction in value depends on the magnetic reluctance of the flux path in the core and on the reluctance of the air gap. It can be written:

$$\mu_e = \frac{R_m}{R_m + R_{gap}} \cdot \mu_i \quad ...(2)$$

where $R_m$ is the reluctance of the flux path in the core and $R_{gap}$ is the reluctance of the air gap.

The value of $R_m$ can be calculated from the published geometric parameters of the core and the value of the intrinsic permeability of the core material.

$$R_m = \frac{l_e}{A_e} \cdot \frac{1}{\mu_i} \quad ...(3)$$

where $l_e$ is the effective length and $A_e$ is the effective cross-sectional area of magnetic path.

To take the published $l_e$ value for the above expression is not strictly correct; the length of the gap should be subtracted from $l_e$ which is always given for an ungapped core, however the error is generally small.

The value of $R_{gap}$ is:

$$R_{gap} = \frac{l_{gap}}{A_{gap}} (\mu \text{ of air is } 1) \quad ...(4)$$

While the total length of the air gap, $l_{gap}$, presents no problems, the cross-sectional area of the gap, is more difficult to ascertain. The magnetic flux between pole faces on both sides of the gap is not strictly contained within the area of the poles. The magnetic lines barrel out and, therefore, the cross-sectional area of the gap reaches its maximum halfway between the poles.

The effect can be taken into account by introducing a correction factor, K (greater than 1):

$$A_{gap} = k . A_{pole} \quad ...(5)$$

where $A_{pole}$ is the area of this part of the core where the gap is situated.



NEOSID

+61 (0) 2 9660 4566 T
+61 (0) 2 9552 1748 F
sales@neosid.com.au E
www.neosid.com.au W
23-25 Percival Street, Lilyfield NSW 2040, Australia A

In the design of U and E cores, the general tendency is to maintain the same cross-sectional area in all core parts, so that the same flux density is maintained and the losses are not increased in the narrower parts (losses increase with flux density raised to the power of 2.2 to 2.6). Nevertheless, $A_{pole}$ is not necessarily identical with $A_e$. However to simplify the calculations, it can be approximated that $A_{pole} = A_e$.

For an E42 core (32-110-25), $A_e$ = 181mm2. $A_{pole}$ = 178.7mm2

For E56 x 37 x 19 (32-620-25), $A_e$ =211mm2, $A_{pole}$ = 201mm2.

For U 65 x 37 x 19 (34-510-25), $A_e$ =241mm2, $A_{pole}$ = 248mm2.

Formula (4) can now be written as follows:

$$R_{gap} = \frac{l_{gap}}{k.A_e} \quad ...(6)$$

Introducing expressions (3) and (6) into (2):

$$\mu_e = \frac{l_e \cdot \mu_i}{l_e + \frac{l_{gap}}{k} \cdot \mu_i} \quad ...(7)$$

The value of k can be determined only experimentally ( and not very accurately). In approximate calculation, the following values may be taken:

| Gap Length | mm | 0.1 | 0.2 | 0.5 | 1.0 | 2.0 | 3.0 | 4.0 |
|---|---|---|---|---|---|---|---|---|
| k | - | 1.1 | 1.2 | 1.3 | 1.4 | 1.5 | 1.65 | 1.8 |
| $\frac{l_{gap}}{k}$ | mm | 0.009 | 0.17 | 0.38 | 0.71 | 1.33 | 1.82 | 2.22 |

If the total gap consists of two gaps, located in different parts of the magnetic circuit, a value of k should be taken which corresponds to the half length of the total gap.

Formula (7) can be rearranged to show directly the value of $e_{gap}/k$ as a function of $\mu_e$ and $\mu_i$ :

$$\frac{l_{gap}}{k} = l_e \left(\frac{1}{\mu_e} - \frac{1}{\mu_i}\right)$$

or in terms of $A_L$:

$$\frac{l_{gap}}{k} = l_e \left(\frac{0.4\pi}{A_L.\Sigma\frac{l}{A}} - \frac{1}{\mu_i}\right)$$

Since the value of k depends on $l_{gap}$, some trial calculations may be needed before the physical length of the air gap can be calculated for a required value of $A_L$; the third row of figures in the table relating $l_{gap}$ and k, will help these calculations.



NEOSID

+61 (0) 2 9660 4566 T
+61 (0) 2 9552 1748 F
sales@neosid.com.au E
www.neosid.com.au W
23-25 Percival Street, Lilyfield NSW 2040, Australia A

## Gapped Cores

When the magnetic circuit of an E or U core has no intentional air gaps, the roughness of the mating surfaces produces an effect equivalent to the existence of a very small gap. The length of this gap is of the order of 0.01mm for U cores and 0.015mm for E cores. For this length of the gap, k is obviously 1.

Since the initial permeabilities of the ferrite grades used for U and E cores are in the order of 1500-3000, even very small gaps seriously reduce the effective permeability, as the following example will show:

$$\mu_e = \frac{50}{50 + 0.015 \times 2000} = 1250$$

assume $l_{gap}$ = 0.015mm, $\mu_i$ = 2000, $l_e$ = 50mm

Obviously the larger the core is (and its $l_e$), the higher the $\mu_e$.

The above method for evaluating the effect of the air gap is only approximate and can be used only for the preliminary calculation, but not as a source of exact design data. This can only be obtained experimentally from careful measurement of the gapped cores.

This method can also be used for preliminary evaluation of the amplitude permeability at high flux densities, although the errors will be greater because the determination of reluctance under the conditions of large cyclic variations of the magnetising field strength is more difficult than when the flux density is very low.

## DC Loading

An approximate method is described below for finding the length of the gap required to ensure that the inductance remains constant when a DC current flows through the winding on a given core. Conversely the method can be used to determine the DC loading, compatible with constant inductance, when the length of the gap in a core is known.

For a given type of core, both the total DC loading (ampere turns) and the number of turns required for a given inductance vary with the length of the gap.

With a current, I, flowing through n turns of the winding, the total magnetomotive force applied to the magnetic circuit (I.n. ampere turns) generates a magnetic flux which flows through the core and through the gap. This causes the magnetisation of the core to be moved to a point on its B-H curve where the slope of the minor loops (dB/dH, corresponding to the small AC current used for inductance measurements) ceases to be identical with the effective permeability (measured with no DC loading). The point on the B-H curve at which the change in the slope of the minor loop begins, marks the limit of the permissible DC loading.

The flux produced by DC current in a gapped magnetic circuit is:

$$\Phi = \frac{\text{magnetomotive force}}{\text{reluctance of the core} + \text{reluctance of the air gap}}$$

$$= \text{const.} \frac{I.n}{R_{core} + R_{gap}} \quad ...(1)$$

or:

$$(I.n)_{total} = \text{const.} \ (R_{core} + R_{gap}) \cdot \Phi \quad ...(2)$$



NEOSID

+61 (0) 2 9660 4566 T
+61 (0) 2 9552 1748 F
sales@neosid.com.au E
www.neosid.com.au W
23-25 Percival Street, Lilyfield NSW 2040, Australia A

In other words, the total magnetomotive force can be divided into two parts: $(I.n.)_{core}$, required to overcome the reluctance of the core path and the other $(I.n.)_{gap}$, required to overcome the reluctance of the air gap.

The reluctance of any path is proportional to its length and inversely proportional to its cross-sectional area and permeability. This provides the means to separate the above two parts of the magnetomotive force:

$$(I.n.)_{core} = (I.n.)_{total} \cdot \frac{R_{core}}{R_{core} + R_{gap}} \quad ...(3)$$

$$(I.n.)_{gap} = (I.n.)_{total} \cdot \frac{R_{gap}}{R_{core} + R_{gap}} \quad ...(4)$$

Assuming that the cross-sectional areas of the core and of the gap are the same, the separation of the magnetomotive force would be related to the respective lengths and to the ferrite permeability. However, the cross-sectional areas cannot be regarded as identical because of the barrelling effect in the air gap. This effectively increases the crosssectional area of the gap compared with the surface area of the core faces. The core faces bordering on the gap may be approximated to $A_e$ because the error is small and the method itself is an approximation.

The barrelling effect (i.e. the increase in the crosssectional area of the gap) is expressed by a factor, k (see section U,E and I cores - Effect of an air gap). whose value increases with the length of the gap. The reluctance of the air gap therefore decreases by the same factor.

The magnetomotive force for the air gap can now be written:

$$(I.n.)_{gap} = (I.n.)_{total} \cdot \frac{l_{gap}/k.A_e}{l_e/A_e \cdot \mu_i + l_{gap}/k.A_e}$$

$$= (I.n.)_{total} \cdot \frac{l_{gap}/k}{l_e/\mu_i + l_{gap}/k} \quad ...(5)$$

where $\mu_i$ is the intrinsic permeability of the core material.

An inductance of L requires n=1000, √L/AL turns, where L is in mH and $A_L$ in nH.

$$\text{the value of } A_L = \frac{0.4\pi.\mu_e}{\Sigma l/A} = \frac{0.4\pi.\mu_e}{l_e/A_e} \text{ (nH)}$$

where $l_e$ is in mm and $A_e$ in $mm^2$ as given in the product data section and $\mu_e$ is the effective permeability:

$$\mu_e = \frac{le.\mu_i}{l_e + \mu_i.l_{gap}/k}$$

so that,

$$A_L = \frac{0.4\pi}{l_e/A_e} \cdot \frac{le.\mu_i}{l_e + \mu_i.l_{gap}/k} = \frac{0.4\pi.A_e}{l_e/\mu_i + l_{gap}/k} \quad ...(6)$$



NEOSID

+61 (0) 2 9660 4566 T
+61 (0) 2 9552 1748 F
sales@neosid.com.au E
www.neosid.com.au W
23-25 Percival Street, Lilyfield NSW 2040, Australia A

Using the above formula for the calculation of the number of turns (n) required for an inductance of L mH, equation (5) for the $(I.n.)_{gap}$ becomes, after some rearrangements and substituting 0.892 for the square root of $1/(0.4\pi)$ and $V_e$ for $A_e \cdot l_e$:-

$$(I.n)_{gap} = 1000.\, I.\, \frac{l_{gap}/k}{l_e/\mu_i + l_{gap}/k} \sqrt{\frac{L}{0.4\,\pi.A_e}\,(l_e/\mu_i + l_{gap}/k)}$$

$$= 892.\, I.\, \frac{l_{gap}}{k} \sqrt{\frac{L}{V_e} \cdot \frac{\mu_i}{1 + \mu_i \cdot \frac{l_{gap}}{l_e.k}}} \qquad ...(7)$$

The magnetic field strength in the gap, H, is:

$$H_{gap} = \frac{(I.n.)_{gap}}{l_{gap}} = \frac{10.(I.n.)_{gap}}{l_{gap}} \left(\frac{A}{cm}\right)$$

where, $l_{gap}$ is in mm. When equation (7) is combined with the above,

$$H_{gap} = 8920.\, I.\, \frac{l_{gap}}{k} \sqrt{\frac{L}{V_e} \cdot \frac{\mu_i}{1 + \mu_i \cdot \frac{l_{gap}}{l_e.k}}} \qquad ...(8)$$

The above equation states the relationship between the DC loading current, the type of core ($V_e$ and $l_e$), the required inductance and the length of the air gap.

The survey of various available data for the permissible DC loading shows that for typical ferrite grades with an intrinsic permeability of about 2000 and saturation induction of 400mT or higher, the inductance hardly varies until the DC current brings the core material to a flux density of about one half of the saturation induction, i.e. to 200mT. The flux density in the gap is somewhat lower than in the core, because of the barrelling effect.

A more conservative value would therefore assume that the flux density in the air gap must not exceed 170mT (1700 Gauss) and the maximum permitted field strength in the air gap is 1700 Gauss or 1350A/ m.

Putting this value into (8), taking $\mu_i$ = 2000 and transforming the equation so as to show the maximum permitted DC current, we obtain:

$$I_{max} = 0.00338k \sqrt{\frac{V_e}{L}\left(1 + 2000 \cdot \frac{l_{gap}}{l_e.k}\right)} \qquad ...(9)$$

To facilitate the calculations, the number of turns, required for L mH, can be obtained from equation (6),

$$n = 1000. \sqrt{\frac{L}{0.4\,\pi.V_e.l_e} \cdot l_e \left(\frac{1}{\mu_i} + \frac{l_{gap}}{l_e.k}\right)}$$

$$= 19.95\; l_e \sqrt{\frac{L}{V_e}\left(1 + 2000 \cdot \frac{l_{gap}}{l_e.k}\right)} \qquad ...(10)$$

Equation (9) gives only a very approximate value for the maximum DC loading permitted for constant inductance, and equation (10) gives a smaller number of turns for a given L than the number which would be derived, taking into account the bottom limit of intrinsic permeability. Using equations (9) and (10), $I_{max}$ and n have been calculated for a range of air gaps found in common core types that may be used with a DC load. The results are shown in the table below based on L = 1mH. For E cores which have, nearly always, only one gap in the centre leg, factor k has been taken from data shown in on page 2.

NOTE that, if the considered value of inductance is L mH and not 1 mH, the value of I shown in the table must be divided by √L while the number of turns, n, must be multiplied by √L. The product (I.n.) (= magnetomotive force) remains constant, since it is a function of the effective magnetic path length of the core, $l_e$, of the length of the air gap and of the intrinsic permeability of the core material.

## Permissible DC Current (A) and number of turns required for 1 mH

Assumptions:

1. Intrinsic Permeability = 2000.
2. Area of core faces bordering the air gap = $A_e$.
3. Maximum permitted field strength in the air gap = 135000A/m.
4. Effective magnetic path length of cores not changed by the introduction of the air gap.
5. Numerical values of the factor k expressing the barrelling effect of flux lines in the gap.

| Gap | E 42/15 | | E42/20 | | E55/21 | | E55/25 | | E65/27 | |
|---|---|---|---|---|---|---|---|---|---|---|
| (mm) | I | n | I | n | I | n | I | n | I | n |
| 0.05 | 0.68 | 21 | 0.78 | 18 | 1.02 | 16 | 1.08 | 14 | 1.27 | 13 |
| 0.10 | 0.87 | 25 | 1.00 | 21 | 1.27 | 19 | 1.33 | 17 | 1.55 | 16 |
| 0.15 | 1.01 | 28 | 1.16 | 24 | 1.46 | 21 | 1.57 | 19 | 1.81 | 17 |
| 0.20 | 1.13 | 31 | 1.30 | 27 | 1.63 | 23 | 1.78 | 21 | 2.05 | 19 |
| 0.25 | 1.25 | 34 | 1.44 | 29 | 1.79 | 25 | 1.95 | 22 | 2.24 | 20 |
| 0.30 | 1.35 | 36 | 1.56 | 31 | 1.94 | 27 | 2.12 | 24 | 2.42 | 22 |
| 0.40 | 1.56 | 40 | 1.79 | 35 | 2.22 | 29 | 2.42 | 27 | 2.76 | 24 |
| 0.50 | 1.74 | 44 | 2.00 | 38 | 2.47 | 32 | 2.70 | 29 | 3.07 | 26 |
| 0.60 | 1.91 | 47 | 2.19 | 41 | 2.70 | 34 | 2.95 | 31 | 3.34 | 28 |
| 0.70 | 2.06 | 50 | 2.37 | 44 | 2.92 | 36 | 3.18 | 33 | 3.61 | 30 |
| 0.80 | 2.21 | 53 | 2.54 | 46 | 3.12 | 38 | 3.41 | 35 | 3.86 | 31 |
| 0.90 | 2.35 | 56 | 2.71 | 49 | 3.32 | 40 | 3.62 | 37 | 4.10 | 33 |
| 1.00 | 2.49 | 58 | 2.86 | 51 | 3.51 | 42 | 3.83 | 38 | 4.33 | 34 |
| 1.10 | 2.62 | 60 | 3.02 | 53 | 3.70 | 44 | 4.02 | 40 | 4.54 | 36 |
| 1.20 | 2.75 | 63 | 3.17 | 54 | 3.88 | 45 | 4.20 | 41 | 4.74 | 37 |
| 1.30 | 2.87 | 65 | 3.30 | 56 | 4.04 | 47 | 4.38 | 43 | 4.94 | 38 |
| 1.40 | 2.98 | 67 | 3.43 | 58 | 4.20 | 48 | 4.55 | 44 | 5.13 | 40 |
| 1.50 | 3.09 | 69 | 3.56 | 60 | 4.36 | 50 | 4.72 | 45 | 5.32 | 41 |
| 1.60 | 3.20 | 71 | 3.68 | 62 | 4.51 | 51 | 4.88 | 47 | 5.50 | 42 |
| 1.80 | 3.42 | 74 | 3.94 | 64 | 4.82 | 53 | 5.20 | 49 | 5.86 | 44 |
| 2.00 | 3.62 | 77 | 4.17 | 67 | 5.10 | 56 | 5.51 | 51 | 6.20 | 46 |



NEOSID

+61 (0) 2 9660 4566 T
+61 (0) 2 9552 1748 F
sales@neosid.com.au E
www.neosid.com.au W
23-25 Percival Street, Lilyfield NSW 2040, Australia A