

## TRANSFORMER LAMINATIONS, DESIGN CONSIDERATIONS

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Engineers and designers of transformers and inductors will find the information presented in the following helpful in the selection of magnetic materials and core shapes for specific applications.

### Why Magnetic Materials

Magnetic materials are useful for the generation and distribution of electrical power because these materials allow to transmit large power densities at low losses. In addition, voltage and impedance can be easily changed from one level to another, since changes in the flux density of materials induce voltages in copper coils surrounding the magnetic cores (Faraday's law).

The energy density in a magnetic material is

$$E = HB \left( \frac{A}{\text{cm}} \frac{V}{\text{cm}^2} \right) \text{ or } \left( \frac{VA_s}{\text{cm}^3} \right) \quad (1)$$

$H$  is the magnetic field,  $B$  the magnetic induction ( $1 \text{ Vs/cm}^2 = 10^8 \text{ Gauss} = 10^4 \text{ Tesla}$ ). In a field of 500 A turns/cm and an induction of 2 Tesla, an energy density of  $5 \cdot 10^{-2} \text{ W/cm}^3$  can be stored, which is as high as in the best capacitors. By multiplying equation (1) with core volume  $V_c = A_c \cdot l_m$ , where  $A_c$  is the core cross section and  $l_m$  the mean path length and assuming a sinusoidal change of  $B$  at the frequency  $f$ , it can be rewritten as follows. The power handling capacity in VA is

$$VA = 4.44 l_m A_c f B H 10^{-8} \quad (2)$$

Since  $H = ni/l_m$ ,  $n$  number of turns,  $i$  current in the turns and  $ni = S A_w K$ ,  $S$  current density in the copper wire,  $A_w$  core window,  $2K$  copper fill factor (.35% for primary and secondary turns), the power handling capacity of a transformer as derived from the energy storage equation is

$$VA = 4.55 S B f A_c A_w \cdot 10^{-4} \quad (3)$$

in which  $A_c$  and  $A_w$  are in  $\text{in}^2$ ,  $B$  in Tesla,  $S$  in  $\text{A/in}^2$  and  $f$  is the frequency.

The same result is, of course, obtained if we multiply Faraday's law for induction with the current  $i$ .  $E_i = -n A_c dB/dt$ , where  $E_i$  is a voltage induced in  $n$  turns by a flux change  $dB/dt$ . Solving this equation for

sinusoidal flux, we find

$$E_i = 4.44 n f B A_c \cdot 10^{-4} \text{ volts,}$$

in which  $A_c$  is in square cm multiplying with  $i$ , we find for the power VA

$$VA = 4.44 n f B A_c i \cdot 10^{-4} \quad (4),$$

since  $ni = S \cdot A_w \cdot K$ , we can substitute in equation 4 and transform into  $\text{in}^2$ , so that  $VA = 4.55 S B \cdot f A_c A_w \cdot 10^{-4}, (5) = (3)$  in volt amperes.

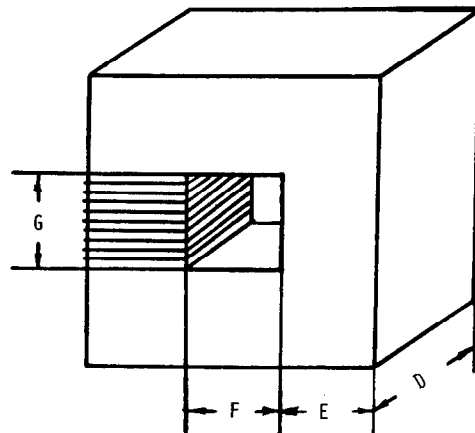


Fig. 1 Transformer Core

$A_c = ED$  = cross section of core  
 $A_w = GF$  = window area

Metallic magnetic materials can be used from low frequencies of a few Hz to high frequencies of few hundred kHz, ferrites and iron powder cores can be used up into the MHz range. With above equations, the designer can select suitable dimensions for the copper coil and the magnetic core cross section at the given frequency which meets the loss requirement. Most manufacturers of core components list in their catalogs the  $A_w A_c$  products for available shapes of core structures. Transformers and inductors can be reduced in weight and volume by operating at higher frequency or by selecting materials which can work at a higher flux density.

## Magnetic Materials and Their Properties

Iron, cobalt, nickel and their alloys have atomic spacings in various crystalline or amorphous structures which produce an interchange of some spins of their 3-D shell electrons, so that these spins align in domain patterns and cause a strong magnetism called ferromagnetism. The magnetic material properties like saturation flux density, the ease of magnetization, permeability, the core loss, the changes of these properties with temperature are therefore influenced by the atomic structure, the anisotropies of this structure, its impurity levels and the stress patterns in the material. Improvements in the magnetic properties of materials can be made by controlling the purity or adding certain impurities for grain refinement, by adding alloying elements to increase the resistivity, by influencing grain size and grain orientation, by reducing the thickness of materials and influencing domain wall spacing through stress coatings, laser scratching and crystal orientation.

Figure 2 shows the hysteresis loop of a few commercial grade magnetic materials, low carbon steel, grain oriented 3% Si-Fe and 2V cobalt iron, which in 1984 cost in dollar per pound .30, .75 and .35. The area inside the loop is the core loss per cycle at the measured frequency. For motor and low cost transformer laminations, which are not continuously on-line, the low carbon steel is a suitable material. Low carbon steel has, however, a relatively high core loss (wider loop). For continuous on-line transformers grain oriented steel, with its narrower loop and higher flux density, is the optimum choice and for airborne application, where weight reduction is the main consideration, the 2V cobalt iron is the proper material, since it has the highest saturation flux density. Figure 3 gives the magnetization curves for these and some other alloys. Table 1 lists W/lb., VA/lb. and permeability at 1.5 Tesla (15,000 Gauss) for typical commercial steels.

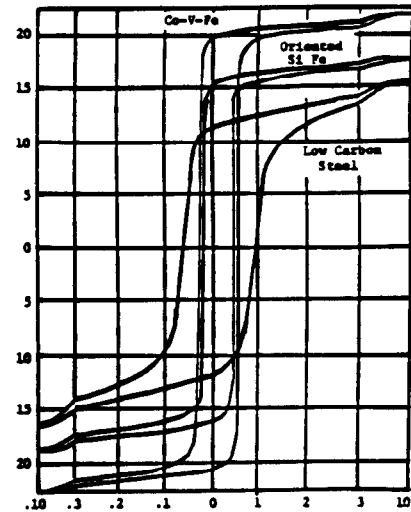


Fig. 2 Hysteresis loops of low carbon, 3% Si grain oriented and 2V cobalt iron steels.

We can expect further improvements of the various carbon and silicon steels in regard to core loss and permeability through improved melting techniques, improved processing and heat treatment. In addition, we can expect improvements in the cutting and stamping characteristics of such steels through better coating techniques and control of their mechanical properties like yield/tensile strength and elongation, which greatly influence the cutting and stamping.

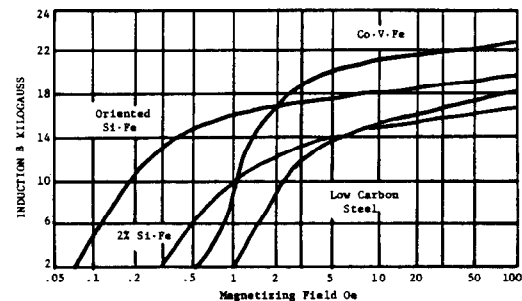


FIGURE 3 - Magnetization curves of cobalt-vanadium-iron, oriented, non-oriented silicon iron and low carbon steel.

Material	Thickness Inches	At 1.5 T, 60 Hz			At 1.0 T, 60 Hz	Comments
		W/#	VA/#	$\mu$	$\mu$	
L.C. Steel	.014, .018, .025	4	6	2,600	5,000	Low cost, moderate core loss
N.O. 5-1% Si Steel	.014, .018, .025	3	6	3,000	6,800	Low cost, improved core loss
N.O. 2-2.5% Si Steel	.014, .018, .025	2	7	2,000	8,000	Low core loss
G.O. 3.2% Si Steel	.014, .0185	.65	.80	30,000	35,900	Best buy for on-line trafo
G.O. 3.2% Si Steel	.008	.2	.60	40,000	42,000	Experimental

Table 1 W/#, VA/# and permeability of low carbon, non oriented and grain oriented Si-Fe steels. Data for underlined thickness.

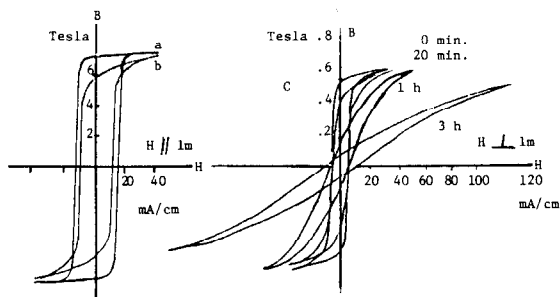


Fig. 4 Hysteresis loops of 80 Ni 5 Mo Re Fe cores annealed to square the loop a) 3h at 420°C, H//lm b) Normal material to flatten the loop c) 20 min.) 1 h ) at 310°C, H⊥lm 3 h )

Inductors and electronic transformers for the telephone industry make use of Ni-Fe alloys containing 50 and 80% nickel, because these alloys have high permeability at low flux densities of .1 to 10 mT. It is well understood today how to influence the permeability and hysteresis loop of such alloys by changing the crystal anisotropies through controlled ordering, so that today flat or very square hysteresis loop materials can be made. In the 80% Ni-Fe alloys, the variation of initial permeability with temperature can be precisely controlled so that inductors and current transformers of great temperature stability can be made. Figure 4 shows the hysteresis loop of 80% Ni-Fe after various heat treatments in magnetic fields applied in the direction or perpendicular to the direction of the operating magnetic field, to either square or flatten the loop by introducing uniaxial atomic anisotropies.

#### Gapped Magnetic Core Structures

High permeability core structures are often out of necessity or deliberately gapped, which flattens the loop and makes the permeability lower, but more constant over B and over a wide temperature range. Figure 5

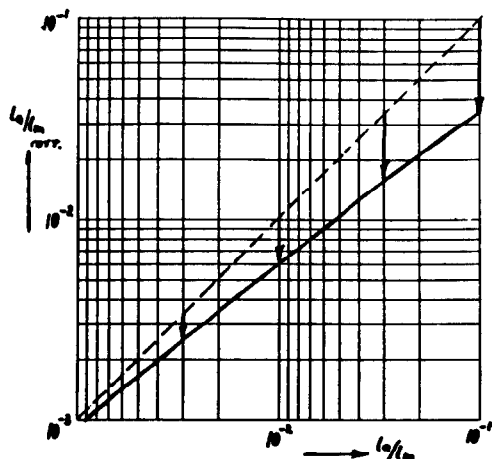


Fig. 6 Corrected effective air gap ratios  $la/lm$  for core structure with larger air gaps.

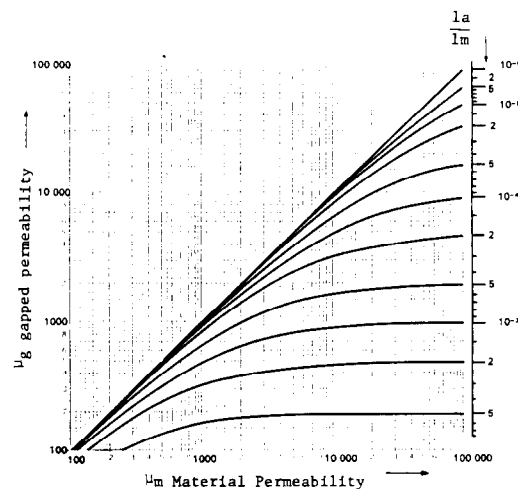


Fig. 5 Effect of air gap upon the gapped core permeability for various ratios of air gap  $la$  to mean path length  $lm$ .

shows the gapped permeability  $\mu_g$  over the material permeability  $\mu_m$ , as calculated by

$$\mu_g = \frac{\mu_m}{1 + \frac{la}{lm} \mu_m} \quad (6)$$

in which  $la/lm$  is the ratio of air gap over mean path length for a given core. For larger air gaps, the B field at the air gap fringes over a larger area and the above equations have to be corrected, as shown in Figure 6.

In nickel iron alloys, for instance, the initial permeability of 80% Ni-Fe (Super Perm 80) normally varies from -30 to +60°C by more than 30%. It can be made temperature stable by appropriate heat treatment (Super Therm 80) so that it will not vary by more than 15%. In laminations such as F-shaped laminations, the stability can be further improved by choosing an appropriate air gap  $la/lm$ . This is shown in Figure 7. With this method, lamination stacks can be made temperature stable to a variation of less than 1%.

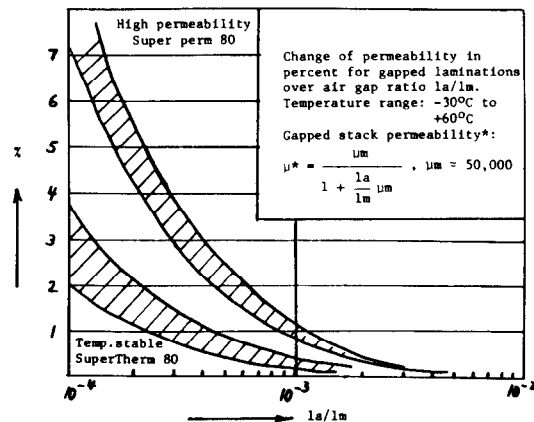


Fig. 7 Change of initial permeability for gapped core structure.

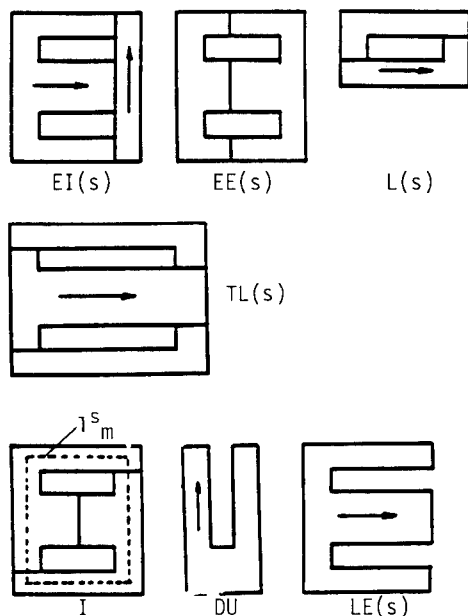
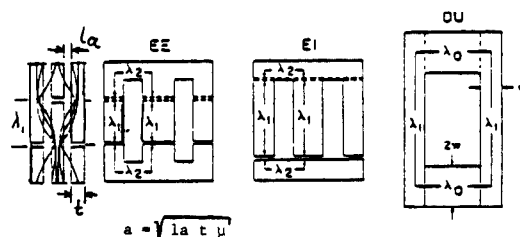


Fig. 8 Typical lamination shapes (s) scrapless configuration possible.

#### Core Structures

Some transformers, like current transformers, can be built with toroidal core structures and toroidal copper windings, to minimize fringing field losses. This is, however, expensive. Most power and electronic transformers use bobbin or stick wound copper coils into which laminations are inserted, often by automatic stacking machines. Figure 8 shows typical shapes of scrapless EI, EE, L and TL laminations which, in most cases, have geometric dimensions providing long flux paths in grain direction. Other non scrapless shapes, like F and EE laminations, are useful because they allow to adjust the air gap in the center of the coil by maintaining a self shielding flux path  $l_m^*$  around the coil, thus preventing cross talk in the electronic coils. Sometimes EE laminations with an air gap stamped in the center leg, often bonded into stacks, are used to minimize cross talk. E-core stacks are available with  $A_L$  values from 160 to 800. DU, DE and Long E laminations minimize effective air gaps when stacked 1 X 1 interleaved, so that the highest possible induction values can be obtained. In Figure 9 is shown how to calculate the stack permeability of EE, EI, DU laminations (per Pfeifer, Brenner) from its geometric configurations.

The hysteresis loop can be sheared to improve the incremental permeability with superposed d.c. by stacking E laminations in groups of 2 X 2 or 3 X 3 or 4 X 4. Figure 10 shows the incremental permeability of .014" thick, 2425EE laminations made of 50% Ni-Fe, stacked 1 X 1, 2 X 2, 3 X 3 or 4 X 4 interleaved over and butt



$$\begin{aligned} & \text{EE} \quad \mu_s = \frac{\mu_m l_m}{l_m + 2a \left( \coth \frac{\lambda_1}{a} + \tanh \frac{\lambda_2}{a} \right)} \\ & \text{EI} \end{aligned}$$

$$\begin{aligned} & \text{DU} \quad \mu_s = \frac{\mu l_m}{l_m - w + a \frac{2 - \tanh \frac{\lambda_1}{a} \tanh \frac{w}{a} - \tanh^2 \frac{w}{a}}{\tanh \frac{\lambda_1}{a} + \tanh \frac{w}{a} - 2 \tanh \frac{\lambda_1}{a} \tanh^2 \frac{w}{a}}} \end{aligned}$$

Fig. 9 Stack permeability  $\mu_s$  for 1 X 1 overlapped EI, EE, DU, DE laminations

$t$  = thickness  
 $l_a$  = air gap between lamination layer  
 $a = \sqrt{l_a t \mu_m}$  effective shearing length  
 $\lambda_1$  = overlap length  
 $\lambda_2$  = shunt length  
 $\mu_m$  = permeability

stacked with various gaps, the d.c. premagnetization. Such stacking methods allow to maximize the inductance for a.c. signals with superposed d.c. at a very low cost. To calculate the permeability for lamination stacks, stacked 2 X 2 or 3 X 3, the thickness  $t$  and the air gap  $l_a$  in Figure 8 have to be doubled.

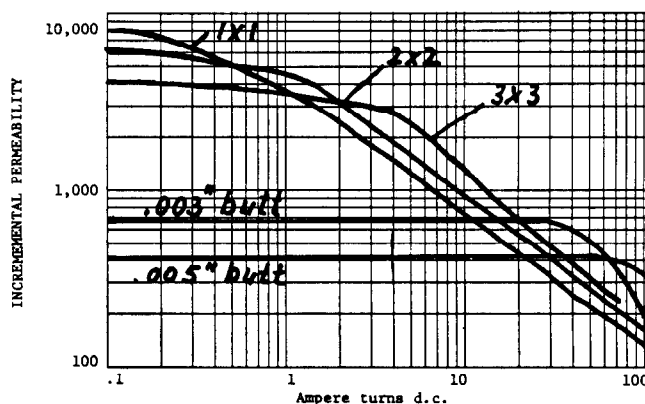


Fig. 10 Incremental a.c. permeability for .014" EE2425, 50% Ni-Fe over superposed d.c. field, stacked 1 X 1, 2 X 2, 3 X 3 and butt gapped.

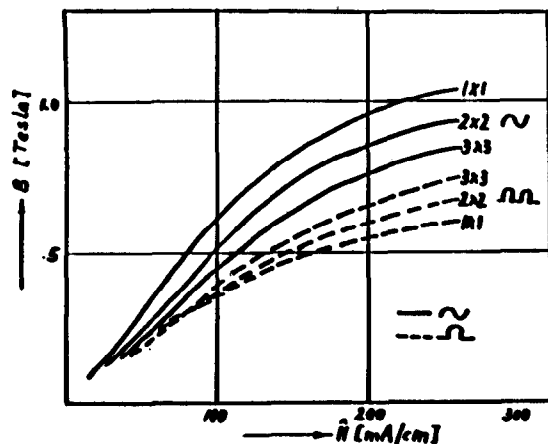


Fig. 11 Magnetization curves of 124DU, .014", 50% NiFe stacked 1 X 1, 2 X 2, 3 X 3. Magnetization  $\sim$  sinusoidal Magnetization  $\text{---}$  halfwave ( $B_r \rightarrow B_m$ )

Figure 11 shows the magnetization curves of 124DU laminations made of 4914, stacked in packs of 1 X 1 to 3 X 3 laminations and magnetized with full sinewave and halfwaves. These examples show how powerful a tool controlled stacking of laminations is in the control of the hysteresis loop and the permeability. Above considerations will hopefully inspire designers to use all these tools available to maximize the efficiency of power and electronic transformers. Proper selection of material, lamination shape and stacking method. Consultation with the Engineering Departments of suppliers, to optimize designs, is always recommended and has normally great paybacks.

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