Coil and Transformer Design and Manufacturing

Ottawa Vintage Radio Club
June 11, 2025
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Coil and Transformer Design and Manufacturing

- Why did I choose this as a career?
- How did I acquire the skills necessary to design magnetic components and was it a long process?
- How many components did I design from 1976-2005?
- Any regrets?

Typical Coil and Transformer Constructions

- All consist of one or more windings wound on some sort of bobbin or former. The windings could be copper foil or either round or rectangular magnet wire (enameled wire). Litz wire can be used to reduce high frequency losses if necessary.
- A winding which consists of multiple layers of wire may or may not have insulation between the layers for mechanical strength.
- Windings which are wound concentrically will almost always have insulation between them.

Typical Coil and Transformer Construction Cont’d

- Insulation between windings usually consists of several layers of insulating paper such as Kraft paper, synthetics such as Nomex 410 or 411 or flame retardant tapes such as 3M types 1350 or 20+, in order to meet regulatory requirements.
- Coil form materials are largely plastics, or Nomex which must meet UL94-V0 flammability requirements.

Magnetics Units

- Magnetic Flux Density B in Teslas (MKS) or gauss(CGS) or lines/sq.in. (English)

  1 Tesla = 10000 gauss = 64.5 Kilolines/sq.in.

- Magnetic Flux ϕ in webers (MKS), Maxwells (CGS) and Lines (English).

  1 weber = 10^8 Maxwells = 10^8 Lines

- $\Phi = B \times A_c$ where Ac is the core cross-sectional area

Magnetics Units Cont'd

- Magnetizing force H in Amps/meter (MKS) or in Oersteds (CGS) where 1oe = 79.577 A/m
- Magnetic permeability of free space

  Uo = 4 pi x 10^-7 Henrys/amp-m

When working with Gauss and Oersteds in cgs,

Uo is set =1.0 gauss/oersted and all of the inductance formulae are "fudged" by adding a

4 pi x 10^-9 in front of them.

Don't forget B =UH is true in free space but use with care in magnetic circuits.

Core Materials for Inductors and Transformers

- Air Core (for IF and RF transformers).
- Silicon steel, in the form of either E-I laminations, toroids or C-Cores. These cores are suitable for power, audio output or driver transformers and also power supply inductors).
- Nickel-Iron alloys available as E-I laminations, toroids and C-cores. Depending on the alloy, they may be used for low level audio transformers, magnetic amplifiers or wideband transformers.

Core Materials for Inductors and Transformers (2)

- Amorphous metals. Two distinct types, iron based and cobalt based. Each can be heat treated to provide superior magnetic characteristics. Applications include low and high level audio transformers, inductors for active PFC, utility distribution and substation transformers and EMI suppression inductors. Can be obtained in either toroidal or C-Core form.
- Powdered Iron, Molybdenum Permalloy Powder (aka MPP) and Kool Mu are all materials used to produce toroids . For powdered iron , the application depends on the powdered iron mix, with some mixes good for RF up into the VHF region. Other mixes are well suited to output chokes in switched-

Core Materials (3)

- mode power supplies. Powdered iron can suffer from thermal aging at high temperatures (perm and core loss increase...possible thermal runaway). The molybdenum permalloy and Kool-Mu powder cores are excellent in many applications (think telephone line loading coils) and also switched-mode power supply inductors where size is important and thermal runaway would be a problem with powdered iron.
- Ferrites. There are two distinct types again. Nickel-Zinc and Manganese-Zinc. The former is good for RF applications and the Mn-Zn is the material of choice for most switched-mode power supply inductors and transformers. Available in many core shapes including E-cores, toroids, pot cores, rods, multi-aperture cores and many others.

The Importance of Insulation

- To produce a reliable and safe transformer or inductor we require winding insulation that will withstand the temperature and environmental conditions under which the device will operate. The National Electrical Manufacturer's Association (NEMA) has established insulation classes for transformers and motors. The classes of insulation are also associated with different types of materials, which have different physical and chemical properties. Some examples of materials used for each class of insulation are:
- **Class Y (90 °C):** Silk, cotton, certain thermoplastics that soften above 90 °C.
- **Class A (105 °C):** Reinforced silk, cotton and paper (with impregnated varnish or insulation oil).
- **Class E (120 °C):** Powder plastics, polyurethane, molded polyvinyl epoxy resins, polyethylene terephthalate.
- **Class B (130 °C):** Inorganic materials such as asbestos, glass fibers, mica with varnish.
- **Class F (155 °C):** Mica, class B materials that perform well at higher temperatures.
- **Class H (180 °C):** Fiberglass, mica, asbestos impregnated in silicone rubber.
- **Class C (180 °C+):** Polyimide films, quartz, mica, teflon, polyimide enamel.
- Insulating materials are may be in the form of solid, liquid and gas.
- **Solid** - Mica, teflon, cotton tape, PVC tape, etc.
- **Liquid** - Insulating Oil.
- **Gases** - SF6 Gas, inert gases, etc.

Insulation Cont’d

- In order to determine which insulation system you need to use, you must first know what the maximum operating temperature of your transformer or inductor will be. This is usually determined by consulting with the customer on the maximum physical size of the device, its required efficiency, the maximum ambient temperature, and any forced air flow. In addition we must keep the maximum transformer or inductor temperature at least 15 degrees C below the insulation class to account for “hot spots” within the device so that we have a safety margin.
- Here would be the steps:

1) Choose a package size for the transformer acceptable to the customer and calculate its radiating area in square inches.

2) From the customer’s efficiency information calculate the acceptable losses in watts.

3) Calculate the watts/sq in for the device.

4) Calculate the temperature rise above Tamb degrees C as:

$$T_{rise} \text{ in degrees C} = (112.5 - T_{amb}/2) \times (\text{watts/sq in})^{0.833}$$

Insulation Cont’d

- So, using the preceding formula, if we had a transformer with a radiating area of 10sq in, and a total power loss of 2.5 watts, operating in an ambient temperature of 25 degrees C, our temperature rise would be:

  T rise = (112.5-25/2) x (2.5/10)^0.833 = 100 x (0.25)^0.833

  = 31.5 degrees C for a total temperature of 56.5 C

  Now say that this is in a nice hot radio cabinet with an ambient

  of 50 C. Our temperature rise would then be:

  T rise = (112.5-50/2) x (2.5/10)^0.833 = 87.5 x (0.25)^0.833

  = 27.6 degrees for a total temperature of 50+27.6 = 77.6C

  So since 77.6 + 15 = 92.6 degrees, we could use a 105C class A

  system, but my choice would be a 130C class B system due to the

  negligible cost impact and greatly enhance reliability.

Winding Wire and Copper Losses

- Most common by far for electronic applications is round copper magnet wire which is available in all insulation classes with solderable insulation (no need to strip). Easily obtained in sizes between 8 and 45 AWG.
- Bare copper foil is also widely used in switched-mode power magnetics and is supplied annealed soft, cut to width and de-burred. In Europe, enamelled copper foil is also available in many ready to use widths.
- Rectangular (and even square) magnet wire is the choice for higher power 60Hz magnetics and can be bought in custom as well as standard sizes.
- Litz (short for Litzendraht) wire which is ideal for use in the 20 kHz to 1 Mhz range for both RF and power magnetics is available in many different types of strand layouts as well as strand and overall diameters. It can be produced with solderable insulation. A high cost item, but now necessary in many designs in order to minimize skin effect and particularly

Copper Losses Cont'd

- proximity effect losses.

- Regardless of which type of winding conductor used, there is going to be an associated resistance Rw. For 60 Hz and audio transformers, this Rw for each winding is going to be the dc resistance you read on your DVM or VOM. For higher frequency magnetics this resistance will be the ac resistance which is the dc value multiplied by a factor to account for skin and proximity effect losses.
- This resistance Rw and the current flowing through it (Iw) will result in power dissipation in each winding given by :

$$Rw \times Iw^2$$

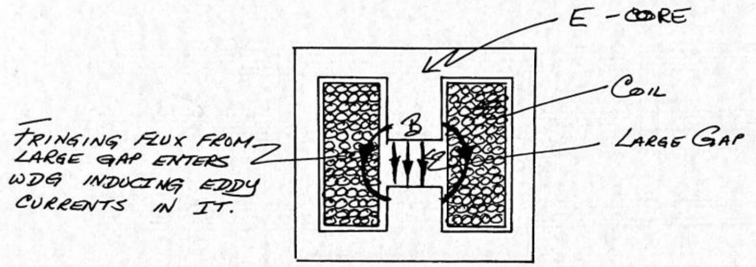
where Iw is the RMS current in the winding

Summing the power losses obtained from the above relationship for all windings yields the total copper loss.

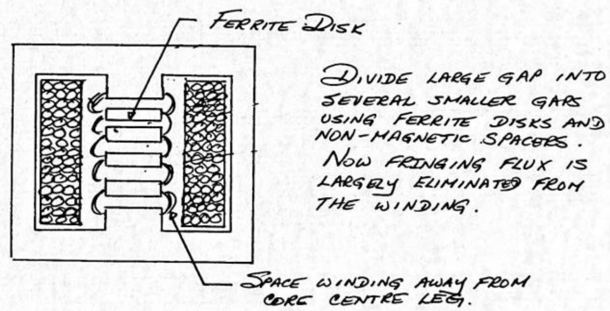
AC Resistance Losses

Other A.C. Resistance Losses.

Gap Induced Eddy Current Losses.



SOLUTION AS BELOW (COSTLY TO ASSEMBLE HOWEVER)



Minimizing AC Resistance

MINIMIZATION OF A.C. RESISTANCE

The following steps will minimize the a.c resistance losses in a transformer or inductor. They are listed in order of increasing production cost.

(1) Keep wire strand diameter $d \leq 2\Delta$

(2) Use the least number of layers possible for each winding to minimize proximity effect losses. One layer is best, with several strands of small wire being used.

(3) Avoid the use of electrostatic shields (screens).

(4) If you "MUST" use copper foil (the worst possible conductor to use for proximity effect), consider alternating layers of primary and secondary for more complete MMF cancellation and reduced proximity effect.

(5) If your windings have to be multiple layer – consider using LITZ wire.

How Hot is my Transformer??

- The temperature of prototype magnetic components is often measured by inserting thermocouples into the windings at various points and then operating the device in its intended application and recording the temperatures. There is an equally good method of measurement which is non-invasive, and relies on the characteristics of copper conductors.

- Copper has a temperature coefficient of resistance of +0.393% per degree C which means that its dc resistance rises by 0.393% for every degree of winding temperature increase. We can exploit this property to measure temperature rise.

Let's use a vintage radio as an example, a nice 7 tube ac set having an 80 as a rectifier, and determine the temperature rise of the power transformer. The set must be in good working order to perform this test.

1) With radio turned off and unplugged, remove chassis from cabinet if necessary to access the 80 rectifier. Chassis to be tubes upright. Remove 80 from from its socket. Make sure that radio has not been used for several hours and chassis is at room temp.

How Hot is my Transformer

2) Using either your DVM or VOM, measure the resistance between pins 2 and 3 of the 80 socket. Let's say it reads 300 ohms. Write this value down as Rlow = 300 ohms.

3) Now reinstall the 80 and reinstall the chassis in the cabinet.

4) Fire up the radio and allow it to play for an hour or two.

5) Unplug the radio, pull the chassis, pull the 80 and repeat the measurement that you made in (2). You have to do all of this fast before the radio gets a chance to cool appreciably. Write down the new resistance reading (say it's 350 ohms) as Rhigh.

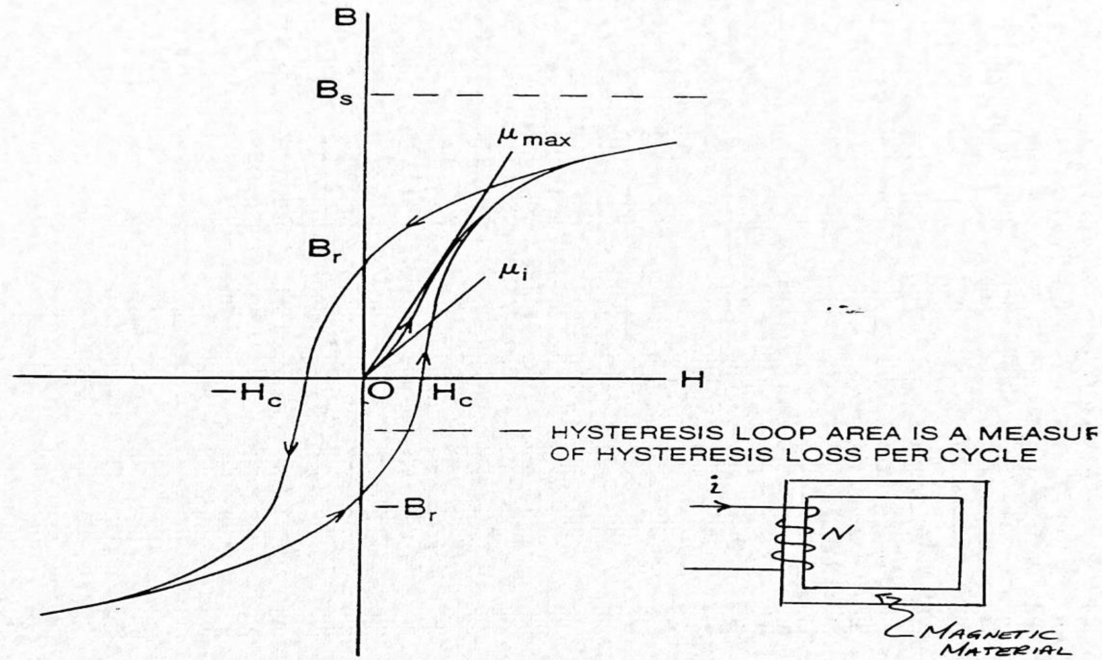
Your temperature rise is Trise = 100 (Rhigh-Rlow)/(0.393xRlow)

= 100 (350-300)/ (0.393x300)

= 42.4 degrees

Core Losses

"B-H Loop" or Hysteresis Loop. (3)



B	MAGNETIC FLUX DENSITY
B_s	SATURATION FLUX DENSITY
B_r	REMANENCE
H	MAGNETIC FIELD STRENGTH
H_c	COERCIVE FORCE
μ_i	INITIAL PERMEABILITY
$\mu_{max.}$	MAXIMUM AMPLITUDE PERMEABILITY

H is related to the current applied to the coil.
V is related to the voltage applied to the coil.

Core Losses

1.3.2 CORE LOSSES.

If we apply an alternating magnetic field to a magnetic material, it becomes alternately magnetized and demagnetized, following its B-H loop (or some portion of it). In a practical magnetic material, this requires energy to be expended which is proportional to the area inside the B-H loop. This energy is lost as heat, and is known as "core loss".

Core loss consists of three major components:

(1) HYSTERESIS LOSS:

This loss represents the energy expended in flipping the "magnetic domains" in the material back and forth. It may be represented by:

$$P_h = K_h B_{max}^n f$$

where n is an exponent dependent on the magnetic material varying from ~ 1.5 to 2.5. K_h is a constant once again dependent on the core material, and f is the frequency of the alternating field.

Hysteresis loss is generally minimum in a magnetic material having a fine crystal structure.

Core Losses Cont'd

1.3.2 CORE LOSSES

(2) EDDY CURRENT LOSS:

Any conducting surface normal to the magnetic field created by an alternating current in a winding will have a voltage and hence a current induced in it. The core is no exception if it happens to be a conductor! This current, called an "eddy current" is a source of power loss in the core, and is described by:

$$P_e = K_e B_{max}^2 f^2$$

where K_e is a constant related to the core material.

Losses from eddy currents may be minimized by:

(a) Using a material having high resistivity such as ferrite.

(b) Ferromagnetic materials which are usually fairly good conductors may be divided into thin strips (laminations), which are insulated from one another, usually by an oxide coating. These strips are arranged to be in the plane of the magnetic field, and as a result eddy currents are significantly reduced.

Core Losses Cont'd

1.3.2 CORE LOSSES.

(3) RESIDUAL (OR "OTHER") LOSSES:

These are due to a number of causes, chiefly:

(a) Eddy current losses in individual crystals within the crystal structure.

(b) Dielectric losses in magnetic materials which exhibit high permittivities (ε_r) such as ferrites.

To put things in perspective, most of the losses in ferromagnetic materials (iron, nickel etc.) tend to be caused by hysteresis and eddy currents. Most of the losses in ferrites however tend to be caused by hysteresis and residual losses, as the eddy current losses are very low.

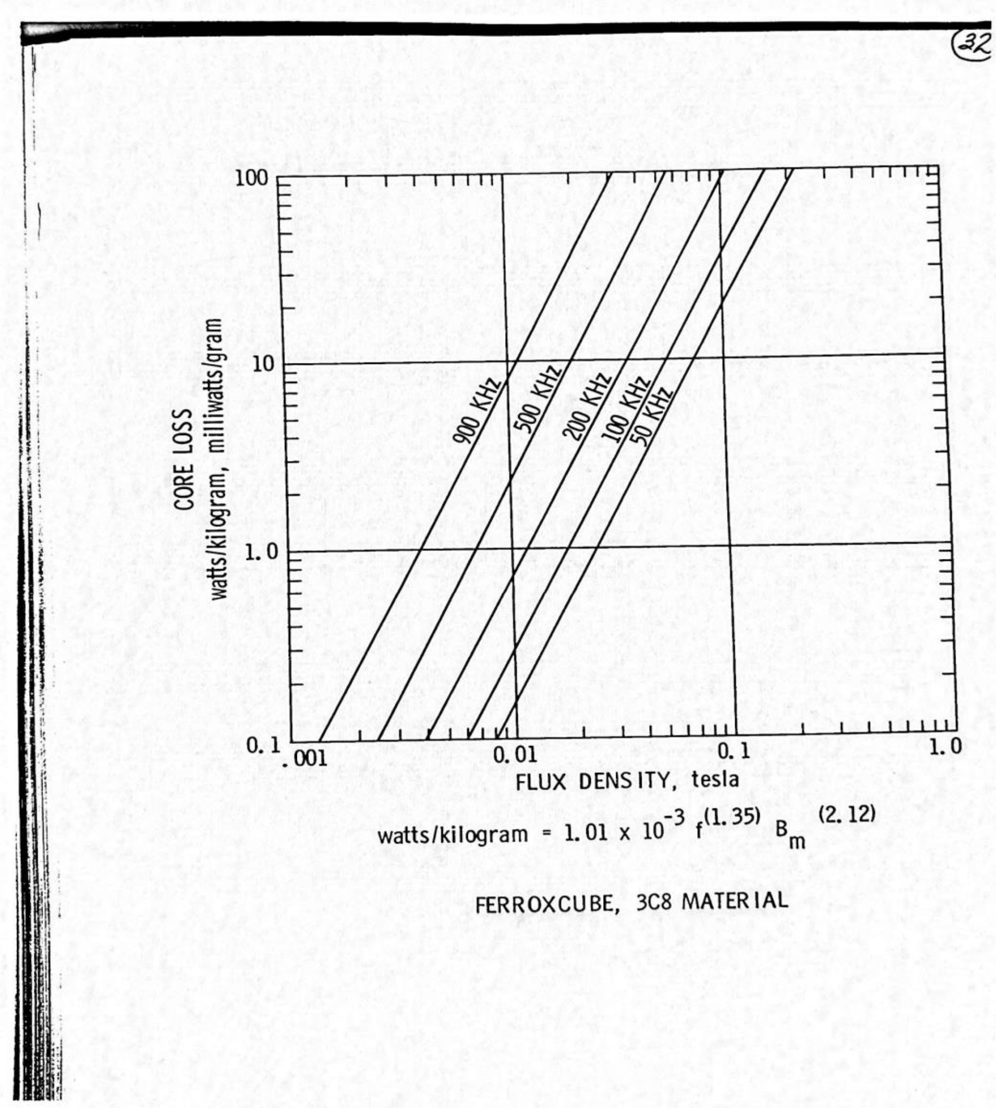
TOTAL LOSSES.

It is common to express the above three losses by a single mathematical expression as:

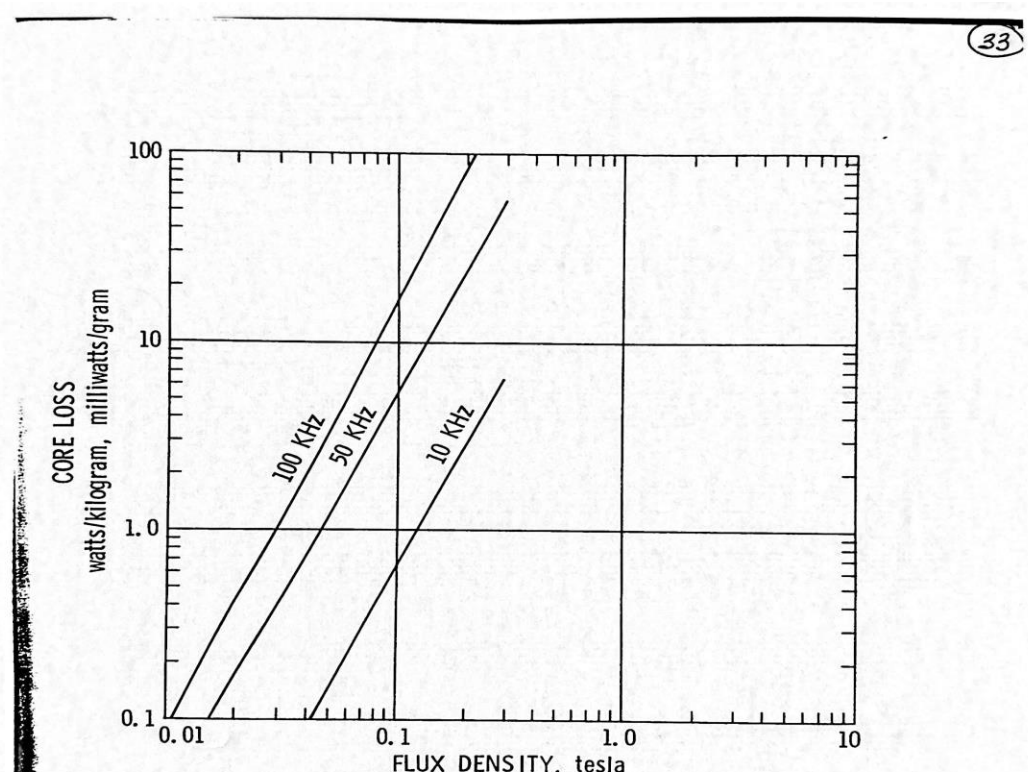
$$P_c = K_1 B^x f^y \quad \ldots (2)$$

Where K is a constant depending on the core material (and may also be core shape dependent).

Core Losses Cont'd



Core Losses Cont'd



$$\text{watts/kilogram} = 0.262 \times 10^{-3} f^{(1.39)} B_m^{(2.19)}$$

SIEMENS SIFERRIT N27

Transformer Efficiency

1.3.2 CORE LOSSES

The value of K, as well as the exponents X and Y may be obtained from the core supplier, but can also be determined from the core loss program in mainframe "MAGNET" by entering data points from the core loss graphs supplied in core data books.

MAXIMIZING TRANSFORMER EFFICIENCY

The most efficient transformer will be the one with the lowest losses. If we are supplying a load power P_o with our transformer, then:

EFFICIENCY → $$\eta = \frac{P_o}{P_{IN} + P_{CORE} + P_{COPPER}} \quad \ldots (3)$$

P_{IN}: INPUT POWER; P_{CORE}: CORE LOSS; P_{COPPER}: COPPER LOSS.

The copper loss in the transformer will be given by:

$$P_{COPPER} = I^2 R_W \text{, where:} \quad \ldots (4)$$

$\underline{I}$ is the winding current referred to one winding. This is the total RMS winding current, consisting of the load current AND magnetizing current as we shall see later.

Transformer Efficiency

MAXIMIZING TRANSFORMER EFFICIENCY.

R_W is the total AC winding resistance, referred to one winding (the same winding used for I) and is given by:

$$R_W = K_{AC} R_{DC}, \quad \text{where } K_{AC} = \frac{R_{AC}}{R_{DC}}$$

Taking the above, and substituting it into the expression (1) on P14:

$$R_W = \frac{K_{AC} \rho_C N^2 MT}{A_W F_C} \quad \ldots \text{(5)}$$

So substituting (5) into (4) we get:

$$P_{COPPER} = \frac{I^2 K_{AC} \rho_C N^2 MT}{A_W F_C} \quad \ldots \text{(6)}$$

Now when we are designing a transformer, we know I, and we have already chosen a package* (ETD, EC, RM, etc. etc.) so we have the following information also known:

A_W
MT
F_C
ρ_C

* THE CHOICE OF A PACKAGE SIZE IS OFTEN A MATTER OF EXPERIENCE, AND USING MANUFACTURER'S GUIDELINES. IN GENERAL HOWEVER $P_O \propto A_W A_C$

and, with experience and the help of pages 15 through 28, we can establish a value of K_{AC}.

Transformer Efficiency

MAXIMIZING TRANSFORMER EFFICIENCY

This means that for a given package size, we can reduce equation (6) to:

$$\boxed{P_{COPPER} = K_2 N^2 I^2} \quad \text{where: } \ldots\ldots (7)$$

$$K_2 = \frac{K_{AC}\, P_C\, MT}{A_W\, F_C}$$

Now we can combine the core and copper loss from equations (2) and (7) to obtain the total losses.

$$P_L = P_C + P_{COPPER} = K_1 B^x f^y + K_2 N^2 I^2$$

Since for a constant applied a.c. voltage V, the flux density $B \propto \frac{V}{N}$, we can re-write the above expression as:

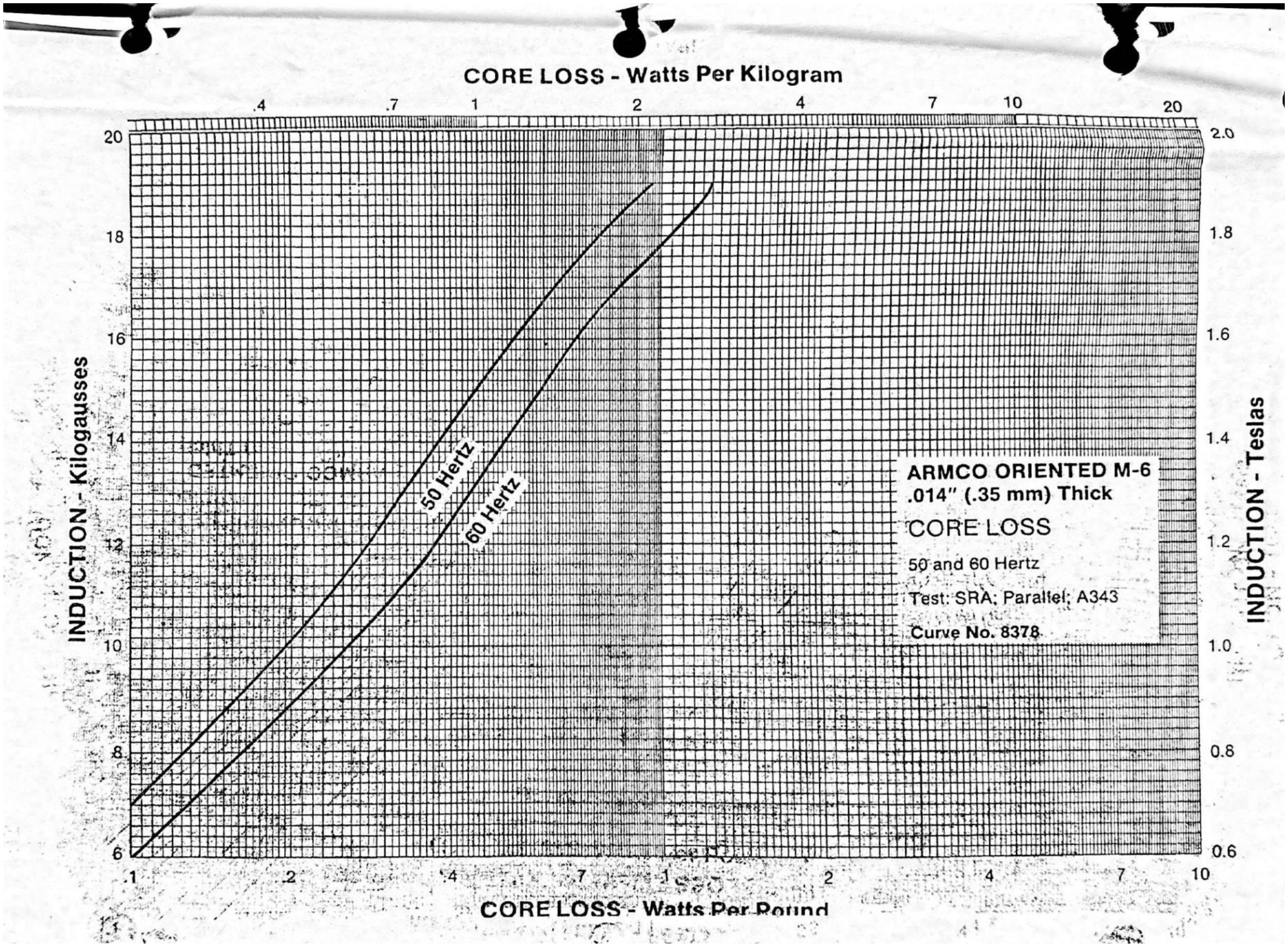
$$P_L = K_1 (K_3 V N^{-1})^x f^y + K_2 N^2 I^2$$

If we were to differentiate this expression with respect to N and set it equal to zero:

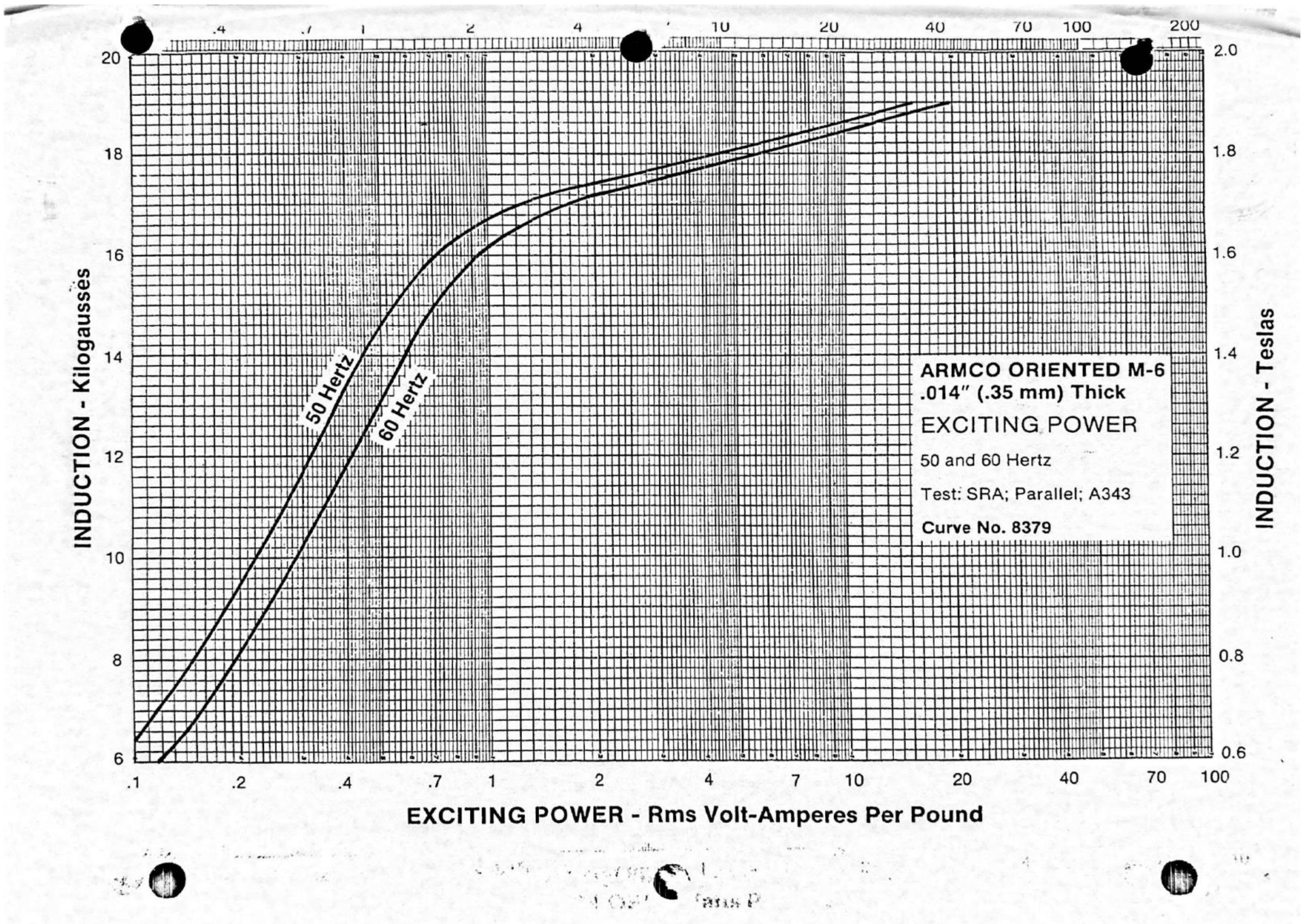
$$\text{Set } \frac{dP_L}{dN} = 0$$

and solve for N, this solution would give us a value of N for minimum total loss.

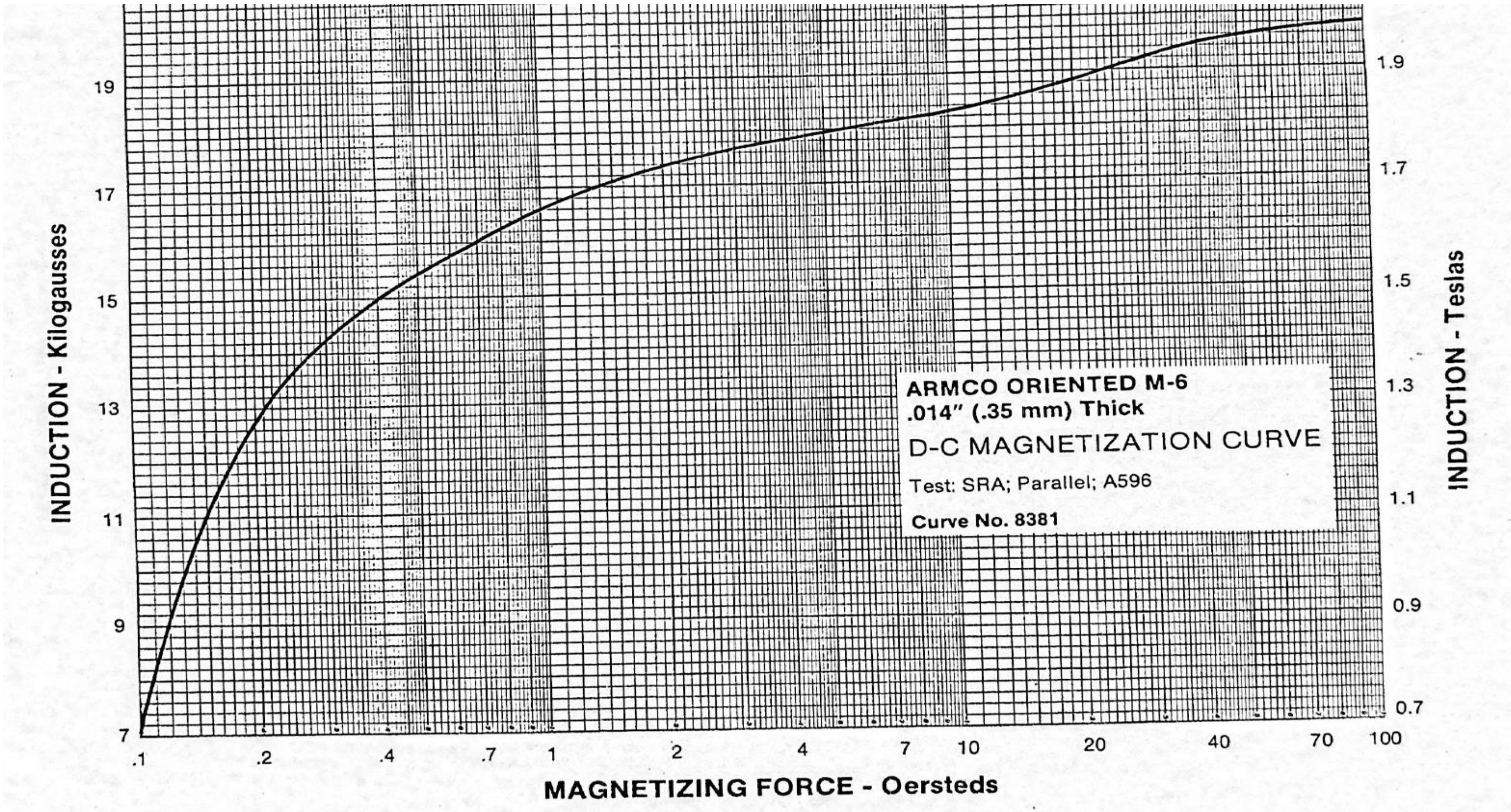
Core Losses for Laminations



Exciting Volt-Amps for Laminations



DC Magnetization for Laminations



Ferrite Core Materials

1 SERIES 3F3 FERRITE MATERIALS

(5)

3F3 Material

A Manganese Zinc material specifically designed for high frequency power applications, up to 750 kHz. This medium permeability material has the lowest losses of any of our power ferrites. Saturation characteristics and Curie temperature are equivalent to other power ferrite materials.

Available in:

- POT CORES
- E, U & I CORES
- TOROIDS
- EP CORES
- ETD CORES

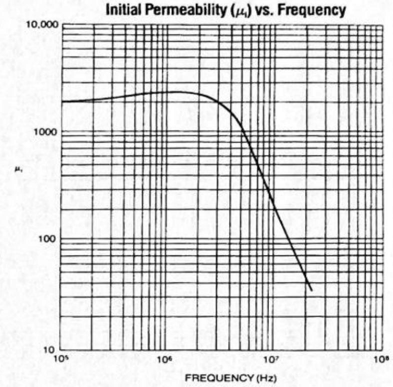
3F3 Characteristics

Parameters shown are based upon measurements of a medium toroid.

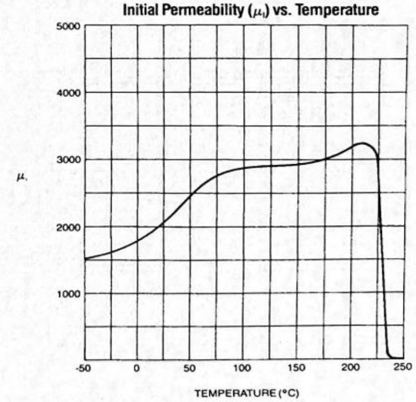
Initial Permeability at 25°C	μ_i	1800 (± 20%)
Saturation Flux Density		
H = 37.5 oersted at 25°C	B_s	5000 gauss*
H = 3 oersted at 100°C	B_s	≥ 3300 gauss
Coercive Force	H_c	0.2 oersted*
Residual Flux Density	B_r	1300 gauss*
Losses	P	
100 kHz, 1000G & 25°C		≤ 110 mW/cm³
100 kHz, 1000G & 100°C		≤ 80 mW/cm³
400 kHz, 500G & 25°C		≤ 150 mW/cm³
400 kHz, 500G & 100°C		≤ 150 mW/cm³
Curie Temperature	T_c	≥ 200°C

* Typical values

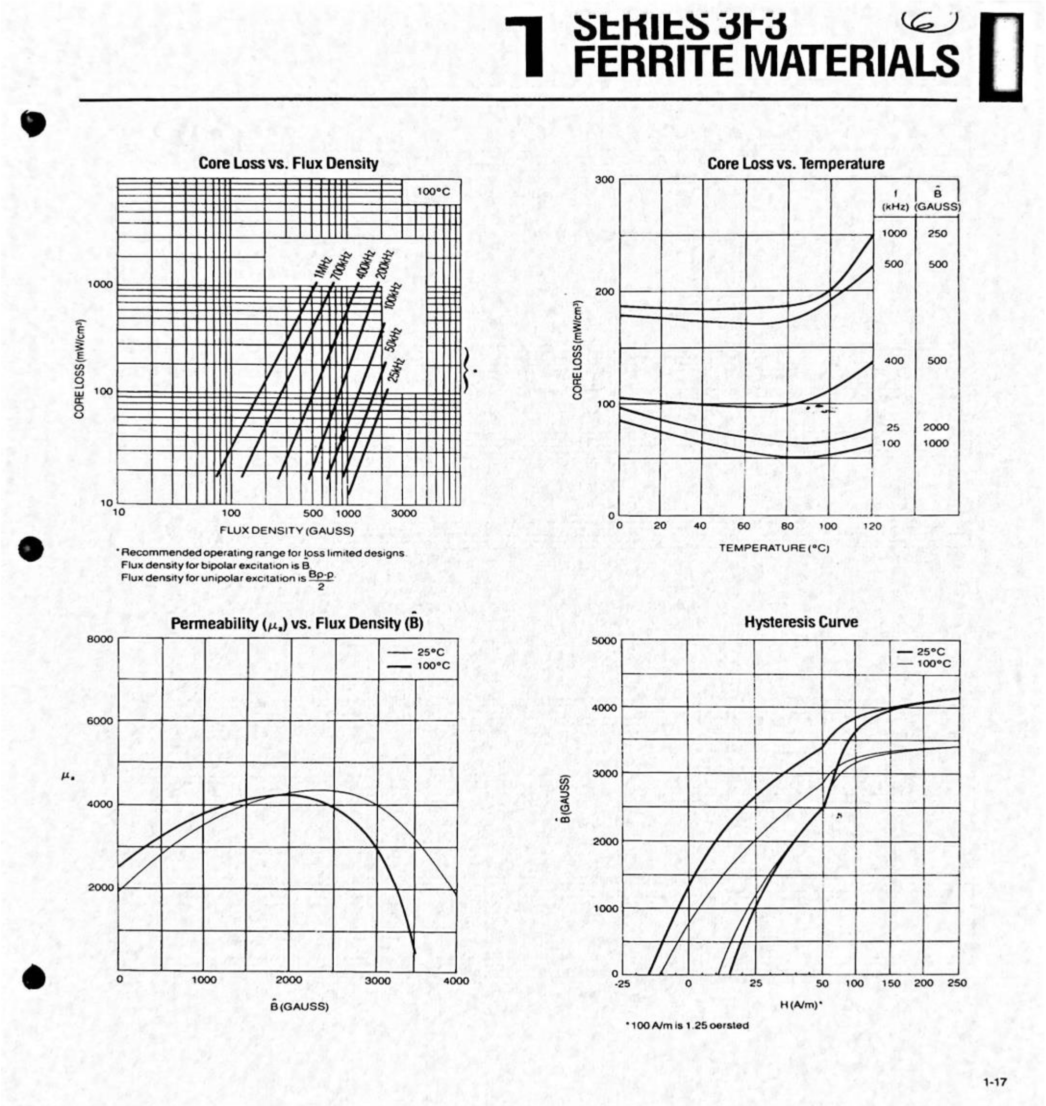
Initial Permeability (μ_i) vs. Frequency



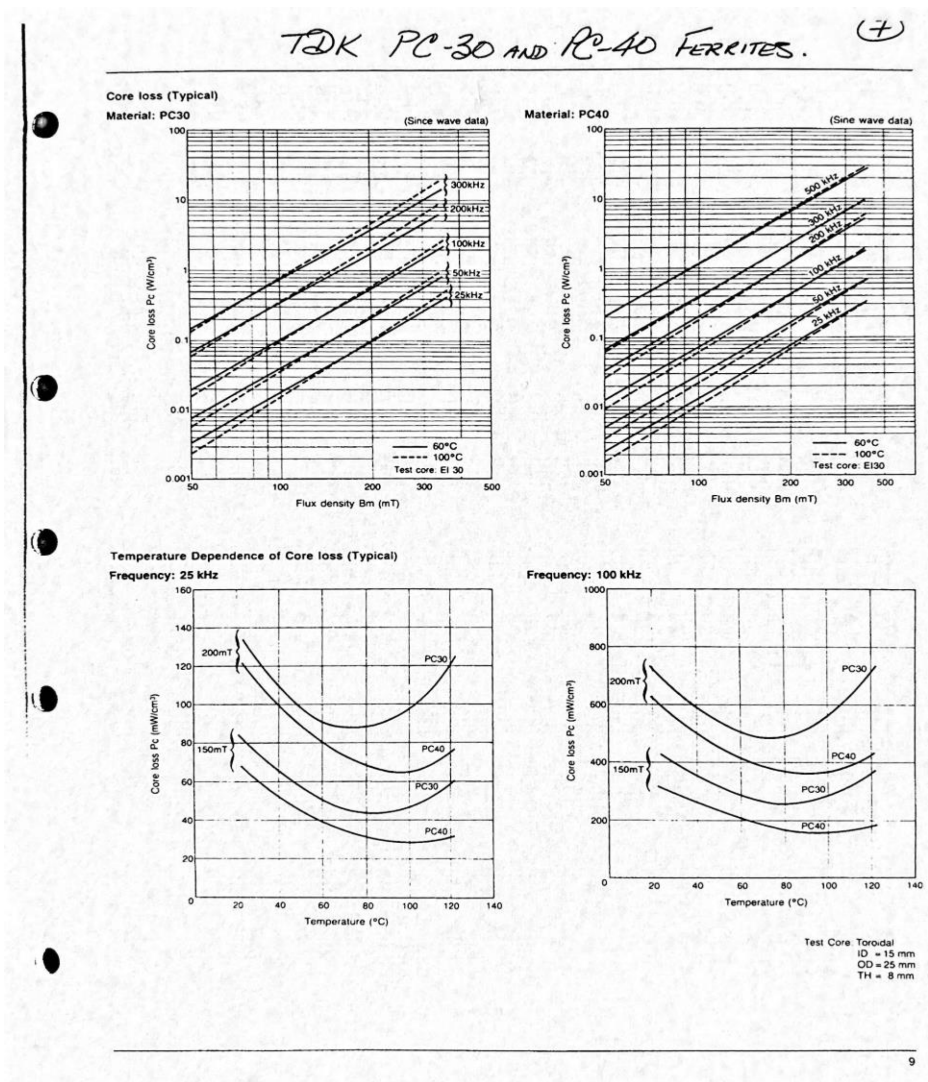
Initial Permeability (μ_i) vs. Temperature



Ferrites Cont'd



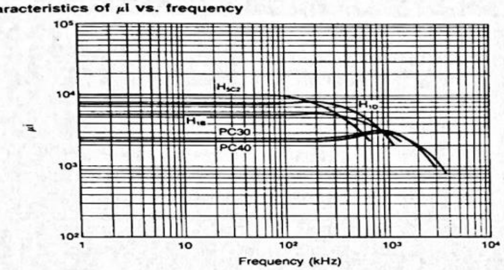
Ferrites Again



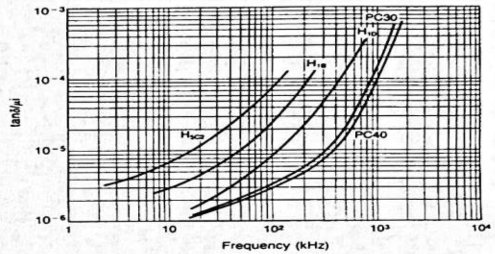
The End of Ferrites

Material Characteristics

Characteristics of μi vs. frequency

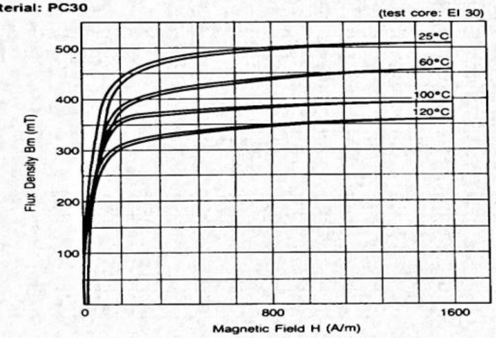


Characteristics of tanδ/μi vs. frequency

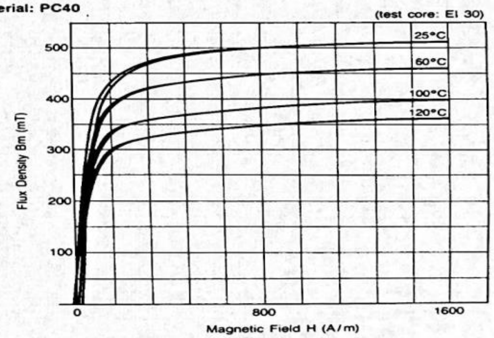


Magnetization Curves (Typical)

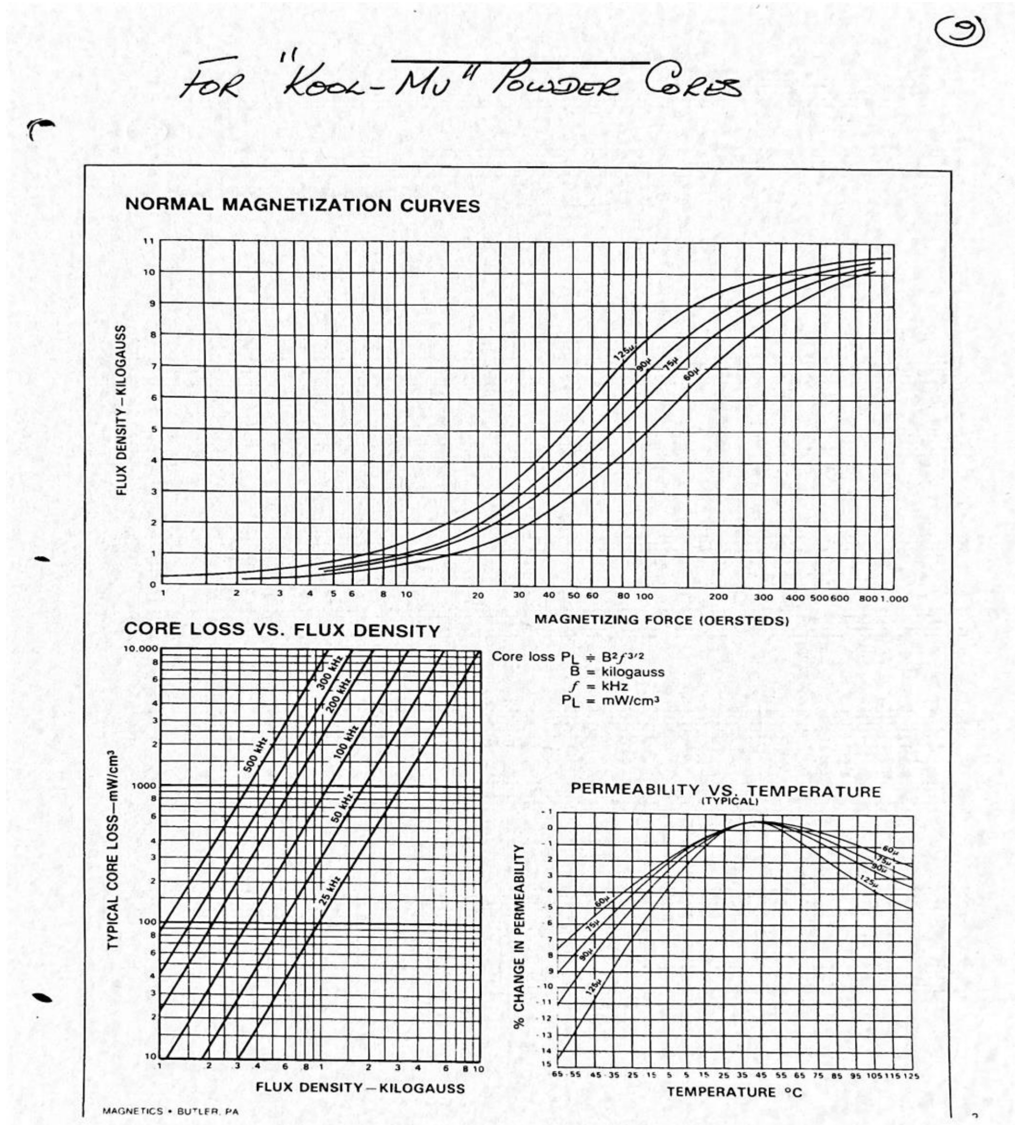
Material: PC30



Material: PC40



Powder Cores (Kool Mu)

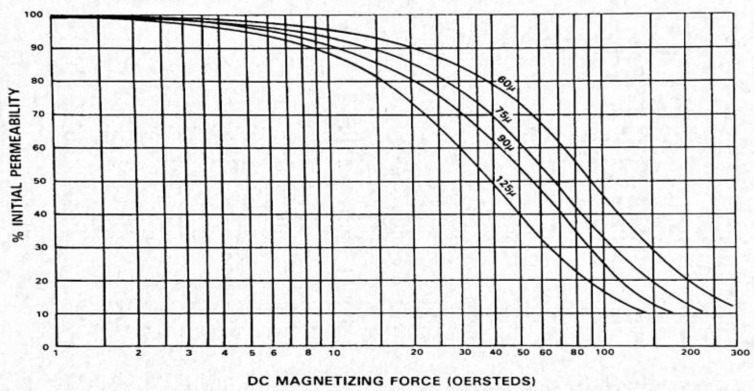


More Powder

(10)

FOR "KOOL-MU" POWDER CORES.

PERMEABILITY VS. DC BIAS
(TYPICAL)



PERMEABILITY VS. FLUX DENSITY
(TYPICAL)