Iron Powder Core Selection
For
RF Power Applications

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Purpose: The purpose of this article is to present new information that will allow the RF design engineer to select the proper iron powder core for inductors and transformers Handling power in the 250 kHz to 5 MHz frequency range.

Iron powder cores are commonly used to produce high Q inductors and transformers for selective circuits. Iron powder cores used in RF applications are composed of extremely small particles of highly pure carbonyl iron. The distributed air-gap of iron powder cores contributes to their rather low permeability and very good stability. In applications involving low-level signals, the choice of core size, material and winding is normally based on required Q and/or packaging requirements. A listing of the general magnetic properties of carbonyl iron powders are shown in Figure A.

Material Mix No.	Basic Iron powder	Material Permeability (μ_i)	Temperature[1] Stability (ppm/^{0}C)	Relative Cost	Toroidal Color Code
-1	Carbonyl C	20	280	2.7	Blue/Clear
-2	Carbonyl E	10	95	1.7	Red/Clear
-3	Carbonyl HP	35	370	2.5	Gray/Clear
-4	Carbonyl J	9.0	280	2.0	Blue/White
-6	Carbonyl SF	8.5	35	2.0	Yellow/Clear
-7	Carbonyl TH	9.0	30	2.0	White/Clear
-8	Carbonyl GQ4	35	255	2.5	Orange/Clear
-10	Carbonyl W	6.0	150	4.7	Black/Clear
-12*	Synthetic Oxide	4.0	170**	1.5	Green/White
-15	Carbonyl GS6	25	190	3.1	Red/White
-17	Carbonyl	4.0	50	3.1	Blue/Yellow
-42	Hydrogen Reduced	40	550	1.4	Blue/Red
-0	Phenolic	1	0	1.0	Tan/Tan

GENERAL MATERIAL PROPERTIES FOR RF MATERIALS

[1]Temperature stability values, averaged from -55°C to +125°C, are listed for closed magnetic structures.
* Non-linear
** Mix 17 was developed as a temperature stable alternative to mix 12 and is recommended for all new designs.
Note: For information an Mix #'s 8, 18, 26, 28, 33, 40 and 52 see Micrometals Catalog 4 for Power Conversion and Line Filter Applications.

FIGURE A

Low level broadband transformers and RF chokes are commonly built on high permeability ferrite cores. Ferrites are a non-metallic ceramic ferromagnetic compound with a spinel crystalline structure. Ferrite cores have higher permeability than iron powder cores but are less stable. While much of the information presented here will be applicable to ferrite cores, the data presented is primarily intended for iron powder cores.

Inductor and transformer applications involving higher power signals require additional considerations. A common misconception is that core saturation is the primary limiting factor in selecting a core for RF power applications. While it needs to be determined how much voltage drop or current flow a given inductor or transformer can support before a limit is reached, this limit will be either magnetic saturation or excessive temperature rise resulting from both winding (copper) and core material losses.

Magnetic saturation is the point at which an increase in magnetization force does not result in any further increase in flux density. This implies that there will be a loss of permeability. An inductor will show a decrease in inductance and a transformer will show both a decrease in impedance and will not transform the additional signal. Carbonyl iron powders typically reach their maximum permeability at about 3000 gauss and then begin to saturate. They reach full saturation at approximately 10,000 gauss. This characteristic is illustrated in Figure B.
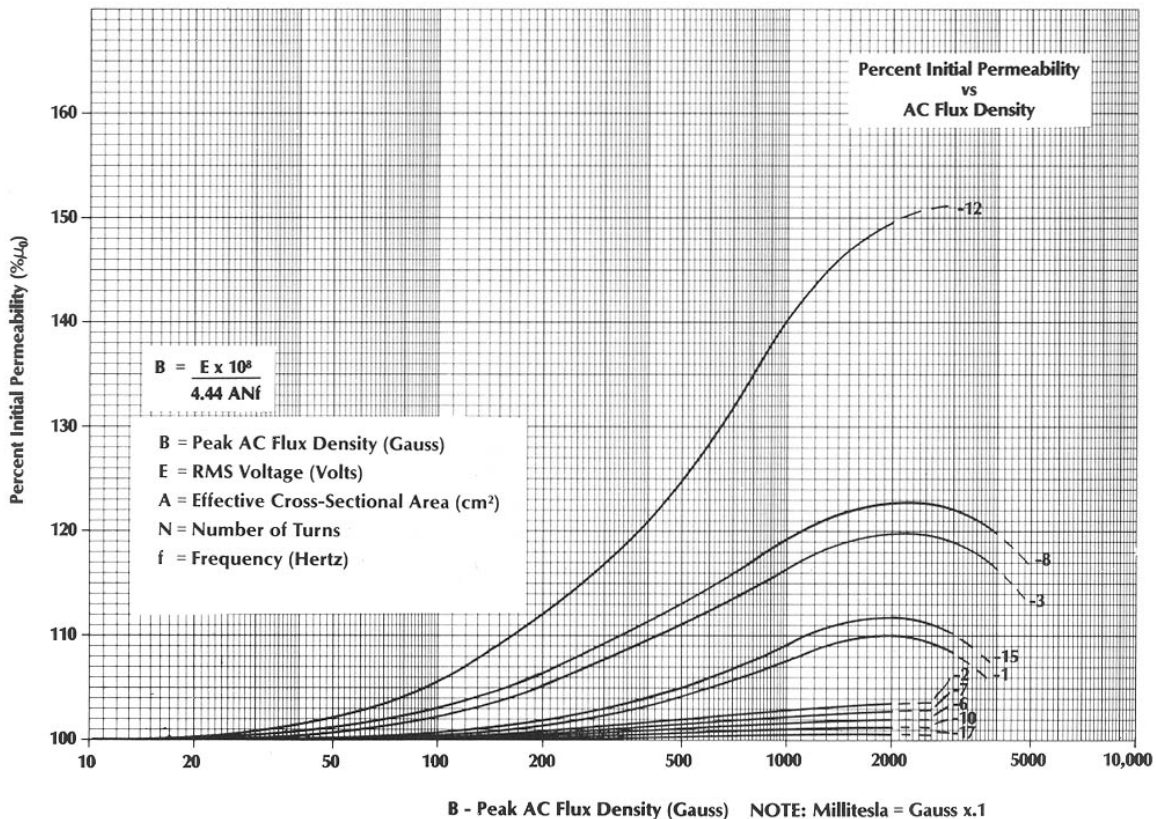

Percent Initial Permeability
vs
AC Flux Density

$$B = \frac{E \times 10^8}{4.44\, ANf}$$

B = Peak AC Flux Density (Gauss)
E = RMS Voltage (Volts)
A = Effective Cross-Sectional Area (cm²)
N = Number of Turns
f = Frequency (Hertz)

B - Peak AC Flux Density (Gauss)   NOTE: Millitesla = Gauss x.1

FIGURE B

With continuous sinewave signals, iron powder cores are limited by temperature rise resulting from losses rather than magnetic saturation. Temperature rise results from losses in both the winding and the core material. The fundamental winding losses are equal to I²R where I is the RMS current flowing in amperes and R is the effective AC resistance. At high frequency the current carried by a conductor tends to be concentrated near the surface. This is known as

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"skin effect". The skin depth of the AC current in a copper conductor at room temperature is described by:

$$\text{Skin Depth (cm)} = 6.62 / f^{.5}$$

where f is frequency in hertz. Figure C is a graphic representation showing AWG wire size versus frequency for a skin depth equal to the conductor radius. For example, at 1 MHz, a wire larger than #35 AWG will not be fully utilized and will thus show an increased AC resistance. Due to this, the use of a large number of strands of fine wire that are insulated from each other and interwoven can be useful in reducing the AC resistance of conductors at high frequency. Such a conductor is known as litz wire. Practical litz conductors are very effective at frequencies below 500 kHz, but begin to lose effect above 3 MHz.
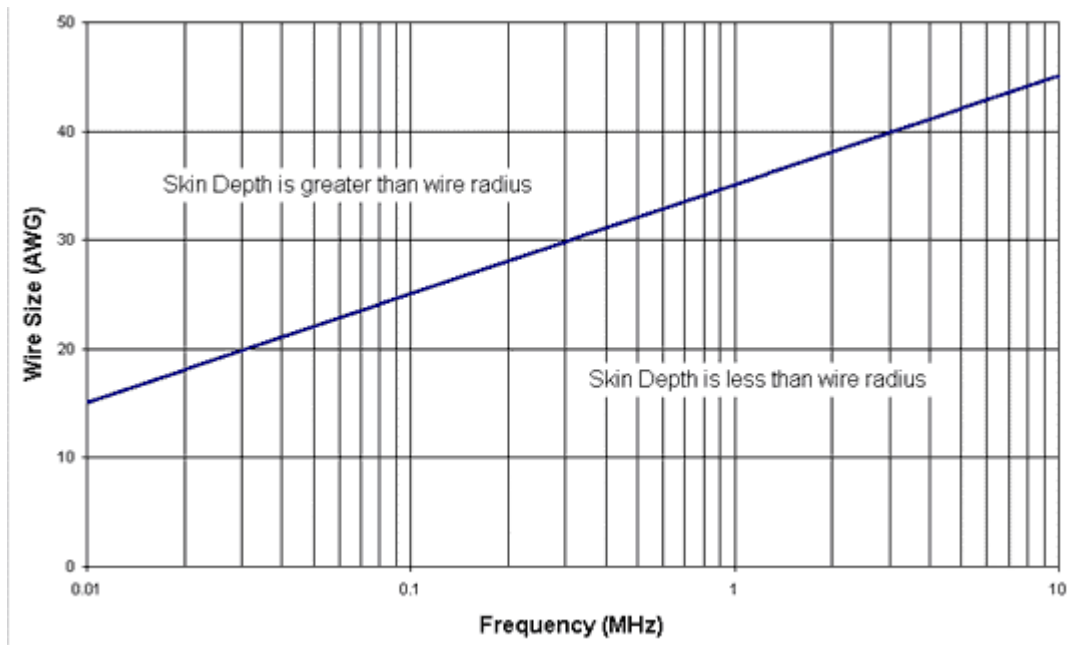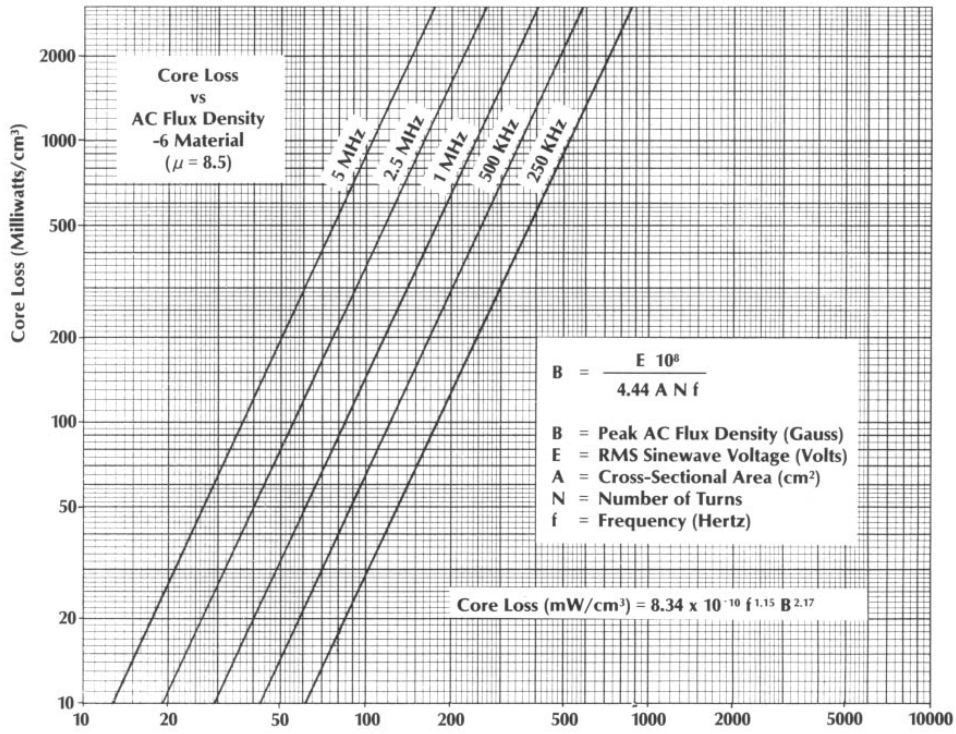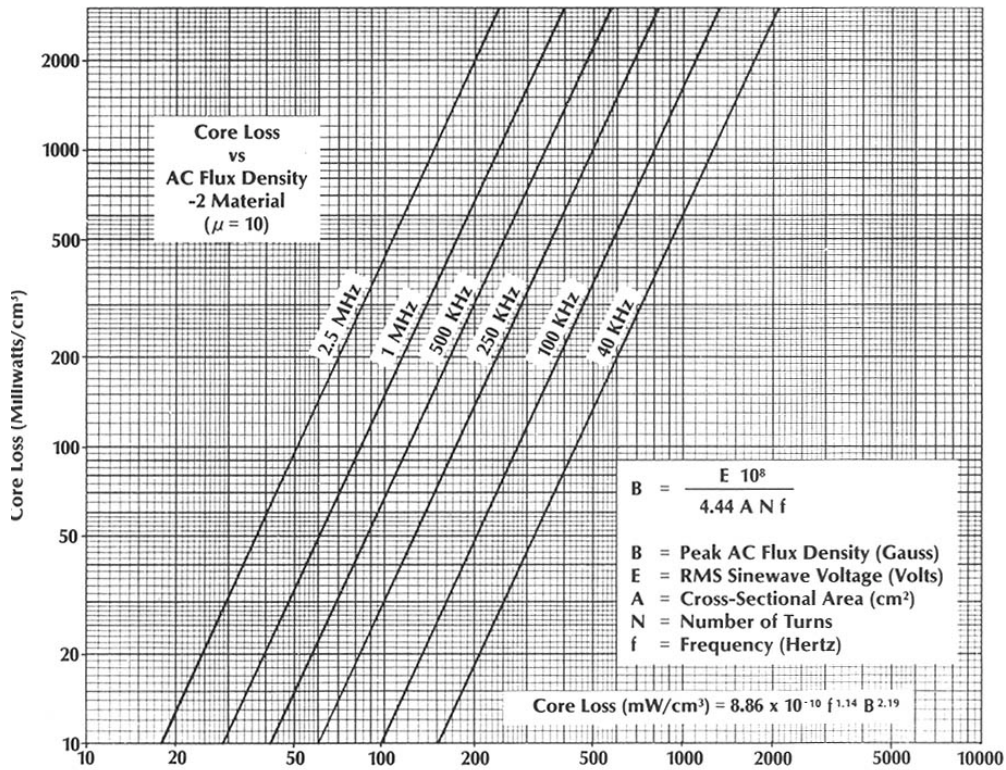

FIGURE C

Winding losses are an important consideration in properly designing higher power magnetic components. Further information on skin effect and the AC resistance of conductors can be found in the Radio Engineer's Handbook as well as a number of other references.

Figures D, E and F show core loss graphs for three iron powder core materials (Micrometals, Inc. material 6, 2 and 15) ranging in permeability from 8.5 to 25. The losses generated by the core materials were determined experimentally. The total loss of a wound coil was measured and the losses due to the test set-up, the winding, and the core material were separated. The information presented is for the core material alone.

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Core Loss vs AC Flux Density -6 Material ($\mu = 8.5$)

5 MHz 2.5 MHz 1 MHz 500 KHz 250 KHz

$$B = \frac{E\ 10^8}{4.44\ A\ N\ f}$$

B = Peak AC Flux Density (Gauss)
E = RMS Sinewave Voltage (Volts)
A = Cross-Sectional Area (cm²)
N = Number of Turns
f = Frequency (Hertz)

Core Loss (mW/cm³) = $8.34 \times 10^{-10}\ f^{1.15}\ B^{2.17}$

B - Peak AC Flux Density (Gauss)   NOTE: Millitesla = Gauss x.1

FIGURE D

Core Loss vs AC Flux Density -2 Material ($\mu = 10$)

2.5 MHz 1 MHz 500 KHz 250 KHz 100 KHz 40 KHz

$$B = \frac{E\ 10^8}{4.44\ A\ N\ f}$$

B = Peak AC Flux Density (Gauss)
E = RMS Sinewave Voltage (Volts)
A = Cross-Sectional Area (cm²)
N = Number of Turns
f = Frequency (Hertz)

Core Loss (mW/cm³) = $8.86 \times 10^{-10}\ f^{1.14}\ B^{2.19}$

B - Peak AC Flux Density (Gauss)   NOTE: Millitesla = Gauss x.1

FIGURE E

Core Loss (Milliwatts/cm³)

2000

1000

Core Loss
vs
AC Flux Density
-15 Material
(μ = 25)

1 MHz 500 KHz 250 KHz 100 KHz

500

200

$$B = \frac{E\ 10^8}{4.44\ A\ N\ f}$$

100

B = Peak AC Flux Density (Gauss)
E = RMS Sinewave Voltage (Volts)
A = Cross-Sectional Area (cm²)
N = Number of Turns
f = Frequency (Hertz)

50

20

Core Loss (mW/cm³) = 6.98 x 10⁻¹⁰ f¹·¹⁵ B²·²³

10
10   20   50   100   200   500   1000   2000   5000   10000

B - Peak AC Flux Density (Gauss)   NOTE: Millitesla = Gauss x .1

FIGURE F

The core loss expressed in milliwatts per cubic centimeter as a function of peak AC flux density (DC flux does not generate core loss) for a number of frequencies from 40 kHz to 5.0 MHz. The milliwatts per cubic centimeter dissipated by a core will generate temperature rise. The formula used to describe this relationship is:

$$\text{Temp. Rise (C°)} = \left[\frac{\text{Power Dissipation (milliwatts)}}{\text{Surface Area (cm}^2)}\right]^{0.833}$$

This formula provides a reasonable approximation for the temperature rise of a core in free standing air. In other environments such as moving air or an enclosed case, other relationships will need to be used. With constant power dissipation, it typically takes a core about 2 hours to reach its final temperature. Applications involving low-duty or intermittent operation can time average the losses.

It is important to limit the operating temperature of inductors and transformers using iron powder cores. Long term operation of iron powder cores above 80 °C can cause a permanent reduction in both Q and inductance.

A listing of the power dissipation in milliwatts per cubic centimeter for temperature rises of 10, 25 and 40 C° for most of the common iron powder core sizes is shown in Figure G. For those not familiar with the part numbering system: A T30 is a toroidal core with an outside diameter of about 0.30 inches while a T400 is a 4.00 inch outside diameter toroid. It can be seen that the physically small parts can dissipate more power per unit volume than the physically large parts.

Power dissipation in mW/cc As a function of temp rise			
Core	10° C	25° C	40° C
T30	400	1148	2026
T37	412	1170	2065
T44	310	884	1556
T50	307	874	1535
T68	234	664	1167
T80	212	602	1056
T94	160	454	802
T106	114	322	566
T130	117	331	582
T157	94	266	468
T200	87	260	436
T300	62	186	327
T400	43	130	228

FIGURE G

The peak AC flux density (Figures D, E and F) for sinewaves is described by Faraday's Law:

$$B = \frac{E \times 10^8}{4.44 \times A \times N \times f}$$

Where: B = peak AC flux density (gauss)   (I gauss = 10^{-4} tesla)
          E = RMS sinewave voltage (Volts)
          A = core cross-sectional area (cm^2)
          N = number of Turns
          f = frequency (hertz)

This form of Faraday's Law is generally more useful for transformer applications where the applied voltage is normally known. For an inductor,

$$E = 2\pi f L I$$

Where: E = RMS Sinewave Voltage (volts)
          f = Frequency (hertz)
          L = Inductance (henries)
          I = RMS Current (amperes)

Comparing the core loss characteristics of the three materials shown in figures D, E and F at a particular frequency does not indicate a significant difference in the power dissipated in milliwatts per cubic centimeter at a given AC flux density. However, with further investigation it becomes evident that for a given inductance and voltage the lower permeability materials generate less AC flux density and, thus, lower core loss, than the higher permeability materials.

Coils wound on lower permeability materials, however, require more turns than higher permeability materials to produce the same inductance, and will, therefore produce greater winding loss. In general, the best compromise in performance will occur when the winding and core losses are approximately equal.

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While the distribution of total loss between the core and the winding for any given frequency is dependent on the winding details as well as the physical size of the coil, it is useful to have a rough approximation of this distribution. Figure H illustrates this distribution for three iron powder core materials over the frequency range of 250 kHz to 5.0 MHz with a typical single layer winding. This graph shows that at a frequency of 1 MHz, of the total loss generated in a typical coil wound on material 2, that about 40% of that loss is due to the winding. In the higher permeability material 15, at 1 MHz, about 10% of the total loss generated is due to the winding. With this guideline, it is then possible to estimate how much core loss can be tolerated without exceeding reasonable temperature rise limits.
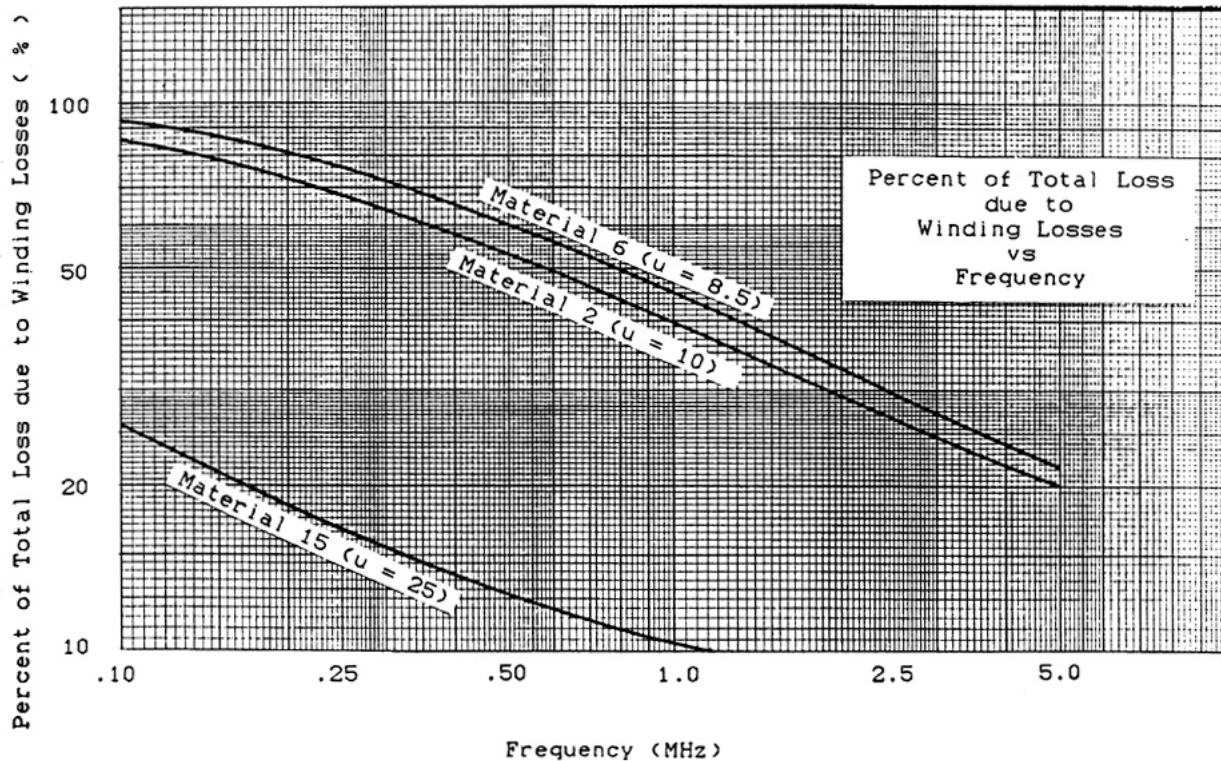

FIGURE H

In an effort to take the basic core loss data that is expressed in magnetic terms and present it in more common engineering terms, application curves have been generated by Micrometals, Inc. The set of curves shown in Figure I graphs the maximum voltage as a function of inductance (and inductive reactance) for various core sizes in Micrometals material 2 at a frequency of 1 MHz for a temperature rise of 25 C° due to core loss. These curves are based on continuous sinewave signals. A similar set of curves in terms of current as a function of inductance appears in figure J. Similar graphs are available for other frequencies and core materials from Micrometals, Inc.
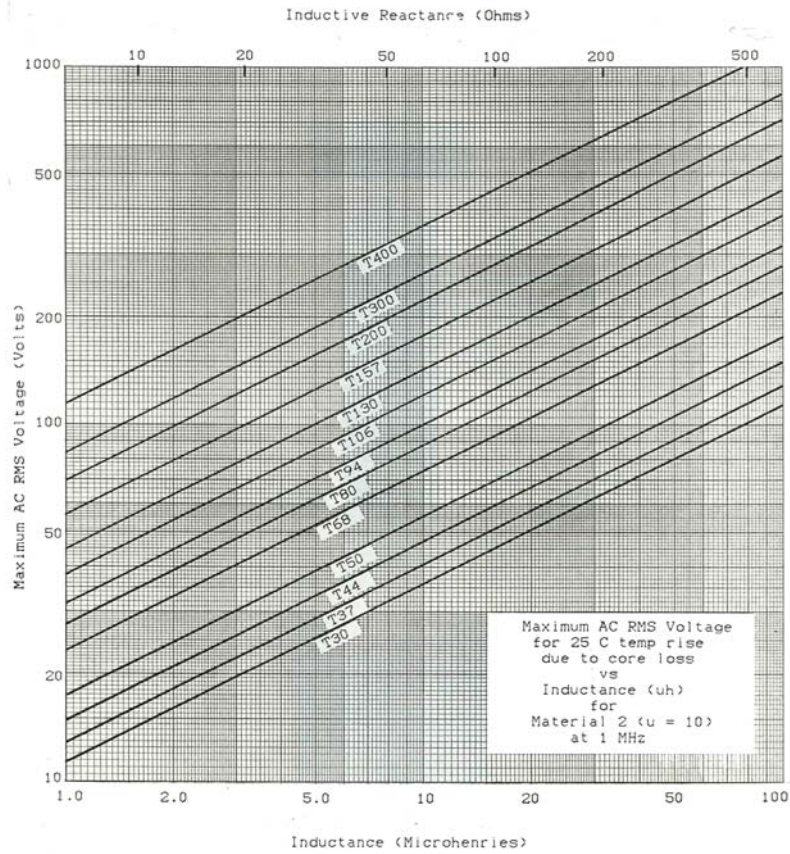
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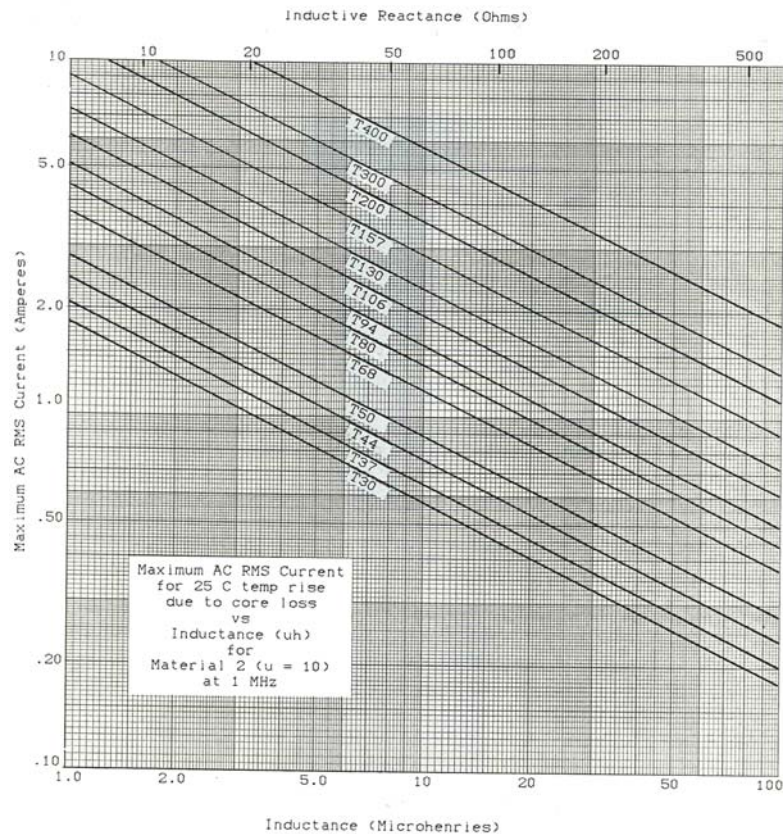
FIGURE I

FIGURE J

The use of these curves can be illustrated with the following examples:

1) If an inductor application at 1 MHz requires 10 µH (microhenries) and the AC RMS current level is 1 ampere, figure J shows that a T68 size core will be required (Part number T68-2). It can also be seen in figure I that this condition corresponds to a voltage drop across this coil of about 70 volts.

2) To select a core for a transformer requiring 100 ohms of primary inductive reactance and capable of supporting 200 volts rms, Figure I should be used. This shows that 100 ohms of reactance is equal to 15.9 µH and that a T157 size core will be required to support the 200 volts rms.

Inductance ratings in microhenries for 100 turns are commonly provided by iron powder core manufacturers. The number of turns required to produce a desired inductance for a core with a known inductance rating is given by:

$$\text{required turns} = 100\left[\frac{\text{desired L }(\mu H)}{\text{L rating }(\mu H/100\text{ turns})}\right]^{\frac{1}{2}}$$

In example (1) the T68-2 has an inductance rating of 57 µH for 100 turns and will thus require 42 turns for 10 µH. The T157-2 in example (2) has an inductance rating of 140 µH for 100 turns. The 15.9 µH will require 34 turns. In general, for inductors, the largest wire which will fit in a full single layer will produce the best results. A winding table with this information is available.

It is further possible to define a "power rating" for the various core sizes. This "power rating" will be defined to be the product of the current flowing through a coil times the voltage being dropped across that coil. For a given temperature rise due to core loss, this product is independent of the number of turns wound on the core. Figure K shows this information for material at 2 MHz.

"Power Rating" for 25° C temp rise due to core loss Material 2 – 1 MHz	
Core	Watts
T30	21
T37	26
T44	37
T50	49
T68	88
T80	125
T94	160
T106	236
T130	331
T157	515
T200	794
T300	1127
T400	2108

FIGURE K

Conclusion: The selection of the core size and material for RF power inductors and transformers has typically relied on the "cut and try" method. New data and application information is now available which allows the design engineer to more easily and accurately select the optimum iron powder core size and material for these applications.