Division of Spang & Company

Core Selection for Saturating Transformers

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The advent of semiconductors opened the door to a wide variety of applications using semi-conductors and saturating transformers, such as dc to ac inverters and dc to dc converters. Presented is information on the various saturable core materials and how the various material characteristics relate to inverter size, efficiency and cost.

The ideal core material would have high flux density, low coercive force, high permeability when not saturated and very low saturated permeability as shown in Figure 1.

Many available core materials have one or more characteristics illustrated by the ideal B-H loop of Figure 1. To approach ideal material characteristics requires a core geometry having a minimum air gap, such as strip wound toroids, ferrite toroids, ring laminations or DU laminations. Gapped structures, such as E-I laminations, ferrite pot cores and cut-cores, reduce the unsaturated core permeability, leading to increased core losses, and also increase the saturated permeability, leading to increased transistor switching losses. Shown in Figure 2 are the exciting current waveforms and B-H Loops of a MAGNESIL® toroid and of a comparable MAGNESIL cut core used as a saturating inverter transformer.

Note that the toroid has lower exciting current and a shorter duration switching spike. In spite of the higher core loss and switching loss of the gapped cores, they are often used effectively at lower frequencies to permit using low cost coil winding techniques.

Figure 1

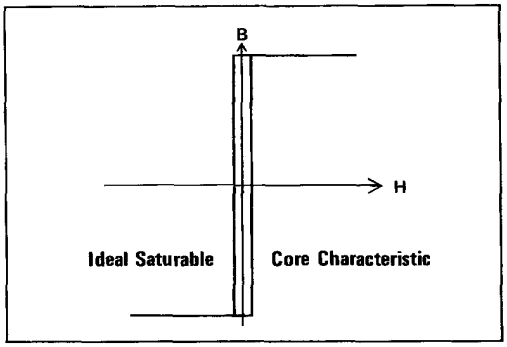


Figure 2

Exciting Current Waveform and B-H Loop for Toroid and Cut Core

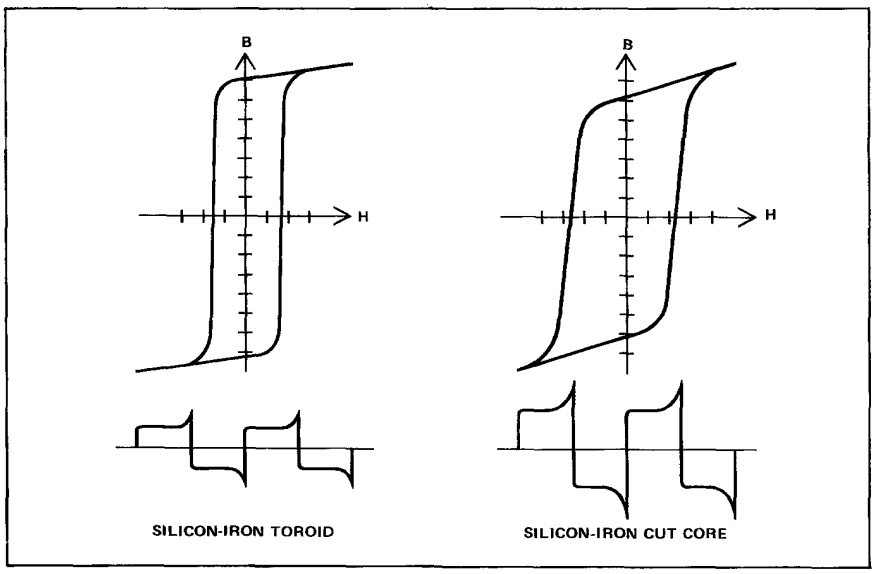
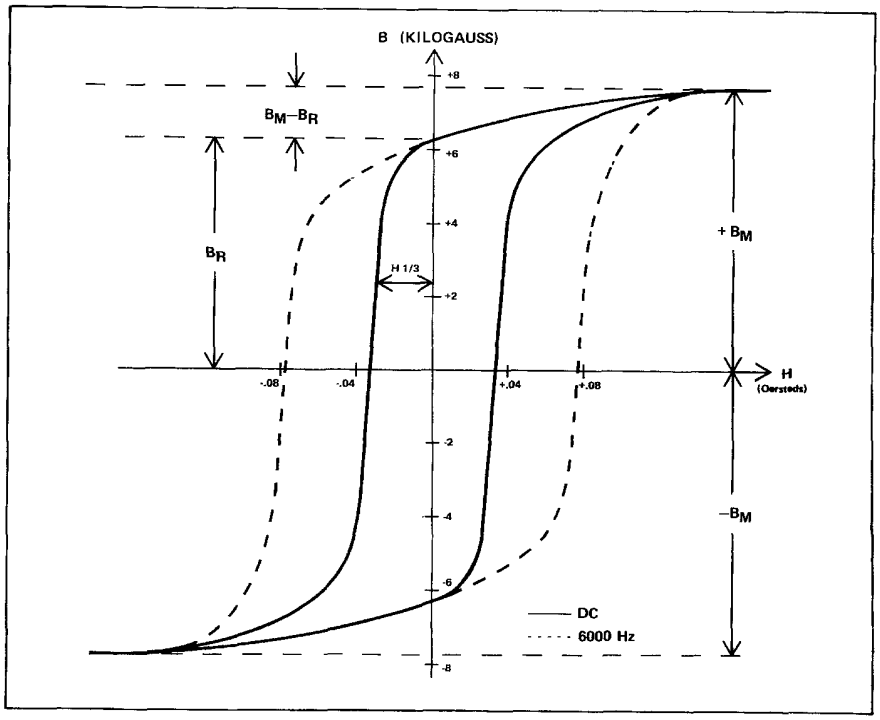


Figure 3 shows a typical B-H loop of Square Permalloy 80 material and describes the various parameters that are normally tested and defined by the core manufacturers. The B_M designation is the core saturation flux density; the higher the flux density, the smaller the size of the inverter transformer will be in a particular design. B_M is normally given in kilogauss and it is the distance from the origin to saturation in one direction. Under normal operation, the total flux density swing would be two times the B_M. The B_M in kilogauss as shown in the diagram, however, is the number that would be used in Faraday's law ($V = 4B_M NAF \times 10^{-8}$) to determine how many volts a given transformer winding can support. The B_M minus B_R is the difference between the maximum flux density (B_M) and the residual flux density (B_R). The lower this number, the lower the permeability in saturation and the lower the switching losses for a given core material. $H_{1/3}$ defines the width of the B-H loop when resetting the core 1/3 of the way from positive saturation with a negative dc bias applied to a core being excited with a half-wave ac signal. $H_{1/3}$ relates to the core loss; the smaller the $H_{1/3}$ the lower the core loss. These two parameters are of most interest in designing inverter transformers.

Also shown in Figure 3 is a B-H loop for the same material at 6,000 hertz showing how the loop width expands and the core loss increases with increasing frequency. This increase in core loss depends on the strip thickness and the resistivity of the core material used. The higher the resistivity of the core material, the less core loss increases with increasing frequency for a given material thickness.

Figure 3

Hysteresis Loops for .002" Thick Permalloy 80



Shown in Figure 4 are dc B-H loops of all the commercially available core materials which are suitable for saturating type transformers. As can be seen, there is a wide range of magnetic characteristics available to the saturating core designer. The problem is to pick the right material for the parameters required in your inverter design.

As can be seen from these curves, Supermendur, the 50% iron – 50% cobalt material, has the highest flux density of any of the materials and therefore would give the smallest core size, if size is the most important consideration in an inverter design. Ferrite material, having the lowest flux density, gives the largest size transformer. Amorphous Alloy E has the lowest coercive force, therefore the lowest core loss of any other core materials available. However, dc B-H loops don't necessarily give the true picture of what happens to core loss at higher frequencies. Table 1 lists these various materials by composition, trade names and some of their more important characteristics.

A core size should be selected so that the wire size will completely fill the window opening. If, at low frequencies, additional window area remains, increasing wire size to fill the window area will reduce copper loss and improve the efficiency of the transformer. At high frequencies, cores with unused window area produce excessive core losses due to the unnecessary magnetic path length of the core. It is advisable in this case to select a core with a smaller diameter, but with the same cross-sectional area, to insure that the windings will completely fill the core window.

Figure 4
B-H Loops of Saturable Materials

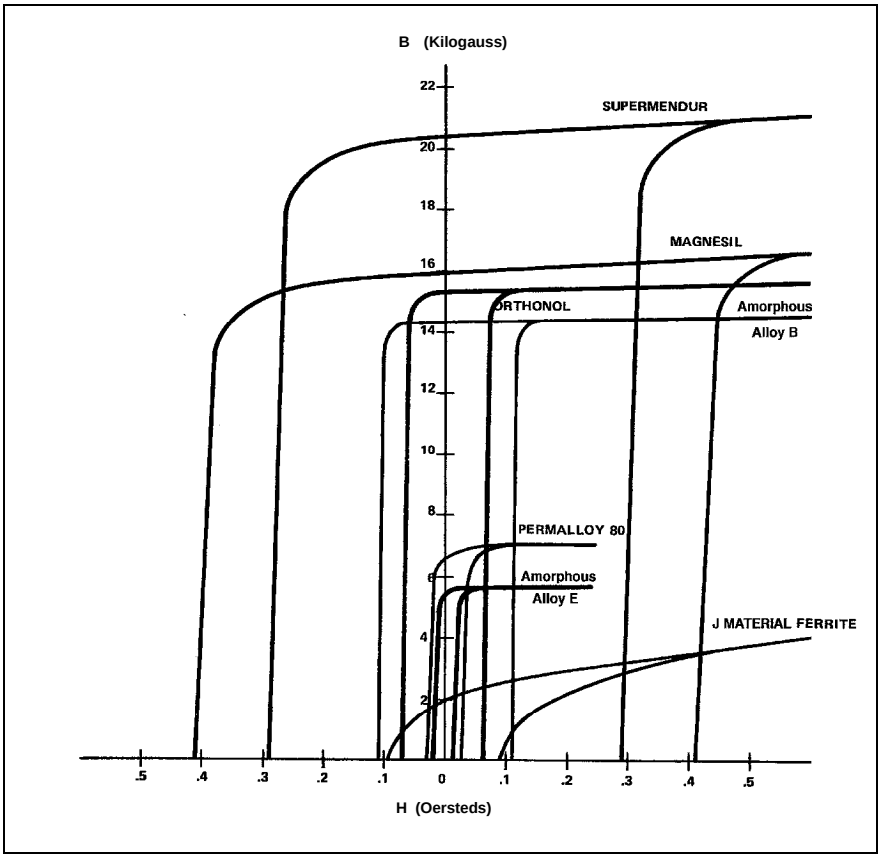


Table 1 — Saturable Core Material Characteristics

METAL OR ALLOY	COMMON TRADE NAMES	COMPOSITION IN % (Balance Iron)	FLUX DENSITY (Kilogauss)	DC COERCIVE FORCE (oersteds)	RESISTIVITY IN MICRO-OHMS CENTIMETERS	CURIE TEMP. °C	Available Thickness and Recommended Upper Frequency for Saturating Transformer	
Silicon-Iron	Hypersil Magnesil Selectron Orthosil Microsil Supersil Square Mu-3	3.5% Si (Grain Oriented)	18	.4-.6	50	750	.012"-.025" .006"-.012" .004" .002" .001"	100 Hz 250 Hz 1000 Hz 2000 Hz 5000 Hz
Cobalt-Iron	Supermendur	49% Co 2% V (Magnetic Anneal)	22	.15-.35	25	940	.004" .002" .001"	800 Hz 1500 Hz 3000 Hz
Nickel-Iron	Orthonol Deltamax Orthonik Hypernik-V HCR 49 Square Mu	45-50% Ni (Grain Oriented)	15	.1	45	500	.014" .004" .002" .001" .0005" .00025" .000125"	100 Hz 1500 Hz 4000 Hz 8000 Hz 20,000 Hz 35,000 Hz 50,000 Hz
Nickel-Iron	Hy Ra 80 4-79 Permalloy Square Permalloy 80 Square Mu-79	79% Ni 4% Mo	7	.02	57	460	.014" .004" .002" .001" .0005" .00025" .000125"	400 Hz 4000 Hz 10,000 Hz 20,000 Hz 40,000 Hz 70,000 Hz 150,000 Hz
Amorphous (iron-base)	METGLAS Alloy 2605SC	3.5% Si 13.5% B 2% C	16	.03-.08	135	370	.001"	25,000 Hz
Amorphous (cobalt-base)	METGLAS Alloy 2714A	66% Co 15% Si 14% B	5	.008-.02	140	205	.001"	500,000 Hz
Ferrites	J 3E2A 0-6 H5B2 T-35 24H	MnZn Permeability equals 5000	4	.1	10×10^6	170		35,000 Hz
Ferrites	G 3B7 N-29	MnZn Permeability equals 2300	4	.2	40×10^6	170		50,000 Hz

Another important consideration is that each half of the primary of a saturating type transformer using the center-tapped configuration to control two transistors, carries current during only one-half of the cycle. Since the winding "sees" only a 50% duty cycle, the selection of the primary wire size is influenced by this factor. For example, if a 12 watt inverter is designed to work from a 12 volt power source, and a primary wire size is chosen to carry 1 ampere continuously, the transformer primary is really capable of supplying 24 watts. Core loss will be comparable to that found in a 24 watt transformer even though the rated output power is only 12 watts because of the increased core diameter required to accommodate the unnecessarily larger wire size used. Therefore the transformer efficiency is reduced.

Another important factor in the operation of a saturating type inverter transformer is the coupling between the primary winding, the feedback winding, and the core. This is best accomplished by winding the center-tapped primary bifilar (2 windings in parallel) completely around the core and then placing the feedback windings, again bifilar wound, directly, uniformly around, and over the primary. Generally it is best to tape over these windings and then apply the secondary winding last. This technique is especially important for good starting when working into a capactive load, which appears like a partial short circuit when attempting to turn the inverter "on".

In the center-tap primary saturating transformer type inverter, the transistors will see twice the battery voltage across the collector-emitter junction and should be rated to withstand at least two times the battery voltage.

To minimize switching losses, the cut-off frequency of the transistors should be at least ten times the desired operating frequency of the inverter.

Normally, inverter transformers are designed for smallest size, highest efficiency, lowest cost, and widest environmental conditions. Unfortunately, the material producing the smallest size may have the poorest efficiency and highest cost. Materials giving the highest efficiency may have high cost and large size. Therefore all designs will tend to be a compromise on material selection to achieve the best characteristic on the most important parameter with some compromise on other parameters.

1. Minimum Size and Weight

Supermendur, the oriented 50% iron – 50% cobalt material, with its 22 kilogauss flux density, gives the smallest size and weight, particularly at lower frequencies. Under 1000 hertz, Supermendur will give a real size and weight reduction, with MAGNESIL® being the second best choice. At frequencies above 2500 hertz, the ORTHONOL® material becomes a good choice. This material has much lower core loss than Supermendur or MAGNESIL materials and generally a thicker gauge material can be used at higher frequencies. At 3000 hertz for example, 2 mil thick ORTHONOL material would have lower core loss than would 1 mil Supermendur material or 1 mil MAGNESIL material. The difference in stacking factor essentially offsets the higher flux density of MAGNESIL and Supermendur.

The stacking factor for a strip wound core is the ratio of the effective core cross sectional area to the gross cross section of magnetic core material. The standard stacking factor for the various material thickness is as follows:

IEEE STANDARD FACTORS	
MATERIAL THICKNESS	STACKING FACTOR
.010" - .014"	.95
.004" - .009"	.90
.002"	.85
.001"	.75
.0005"	.50
.00025"	
.000125"	.25

2. Maximum Efficiency

At frequencies below 1000 hertz the MAGNESIL material, or the ORTHONOL material, is the best choice for a high efficiency transformer. Even though these materials have higher core loss than square Permalloy 80, their much higher flux density allows a significant reduction in copper loss. At low frequencies, the copper loss is the predominant loss factor in the transformer. This reduction in copper loss more than offsets the increased core loss using these core materials. Above five kilohertz, where core loss is the predominant transformer loss, Square Permalloy 80 is the best choice. Above 25 kHz, Amorphous Alloy E is best.

3. Minimum Cost

For low frequency applications under 100 hertz, MAGNESIL is by far the least expensive core material. If "X" represents the $ cost per pound of 12 mil thick Silicon - Iron, the relative costs per pound of the other materials would be about 2x for ferrite, 11 x for ORTHONOL and Amorphous Alloy B, 10.5x for Square Permalloy, 25x for Supermender, and 60x for Amorphous Alloy E.

As operating frequency is increased, thinner gauge materials must be used; at thinner gauges, the MAGNESIL material loses much of its cost advantage. For example, a 2,000 hertz transformer using MAGNESIL should use 1 mil thick material. However, 2 mil thick ORTHONOL would have essentially the same core loss as 1 mil MAGNESIL. The cost of 2 mil

ORTHONOL versus 1 mil MAGNESIL could be less.

When designing above 2,000-3,000 hertz, ORTHONOL becomes the most economical material. Ferrite material, although inexpensive, does not save money at low frequencies as the savings in core costs are more than offset by the additional copper and the larger core size required to compensate for the ferrite's low flux density (4,000-5,000 gauss). Above ten kilohertz, the ferrite material may become more attractive from a cost standpoint.

4. Minimizing Audible Noise

Audible noise can be reduced by designing the inverter for operation above ten kilohertz, where audible noise is not a problem. If the operating frequency must be in the 60 hertz to 10 kilohertz region, where audible noise is a problem, Square Permalloy 80 or cobalt - based Amorphous Alloy E tend to give the lowest audible noise in a saturating transformer because of low magnetostriction and low saturation flux density.

5. Operation Over Extreme Temperature Ranges

For operation over an extreme temperature range of -65 degrees C to +200 degrees C, any of the metal strip wound cores in an aluminum core box with silicone dampening compounds are quite suitable. These magnetic materials have relatively high Curie temperatures, and their flux density change with temperature is such that from -65 degrees C to +200 degrees C there would be less than a 30% change in operating frequency. The core loss in these materials varies in such a way that transformer efficiency will tend to be self-compensating over the temperature range. Although core loss increases at lower temperatures, the frequency will decrease because of increasing flux density, thus reducing the amount of core loss increase.

Copper loss decreases, tending to offset the higher core loss. With increasing temperatures the core loss decreases, while copper loss and frequency+ increase, tending to give a stable efficiency over a wide temperature range.

Ferrites are not generally suitable over wide temperature ranges due to their very low Curie temperature.

Core Size Selection

Upon selecting the transformer core material and material thickness, the next step is to select the proper size core for a transformer with a given operating frequency and output power. The power handling capability of a toroid core can be determined by its $W_A A_C$ product where W_A is the available core window area in circular mils and A_C is the core effective cross sectional area in cm². The curves in Table 2 show the required core $W_A A_C$ product for some of the common core materials plotted against transformer output power for a given frequency.

The $W_A A_C$ relationships are obtained by solving Faraday's Law in the following manner:

FOR SATURATING TYPE TRANSFORMERS,

Faraday's Law = $E = 4 B_M A_C N f \times 10^{-8}$

Solving for $NA_C = \dfrac{E}{4 B_M f \times 1 0^{-8}}$ However,

the Window Utilization Factor $K = \dfrac{NA_W}{W_A} = .1$, $NA_W = .1 W_A$

Multiply both sides by A_c and transpose:

$$NA_C = \frac{.1 W_A A_C}{A_W}$$

Combining and solving for $W_A A_C$:

$$\frac{.1 W_A A_C}{A_W} = \frac{E}{4 x B_M x f x 10^{-8}} \qquad W_A A_C = \frac{E A_W}{.4 x B_M x f x 10^{-8}}$$

$$W_A A_C = \frac{2.5 x E x A_W}{B_M x f x 10^{-8}}$$ Assume 85% efficiency

and 750 $\dfrac{\text{cir mils}}{\text{amp}}$ current capacity of wire.

However, the primary winding has a 50% duty factor

giving a current capacity of 375 $\dfrac{\text{cir mils}}{\text{amp}}$

Therefore the formula becomes:

$$W_A A_C = \frac{1.1 \text{ Power Output}}{B_M x f x 10^{-11}}$$

Since the inverter is a saturating device,

B_M = 21,000 (50% cobalt) B_M = 14,500 (50% nickel & Amorphous Alloy B)

B_M 17,000 (3% silicon) B_M = 7,000 (80% nickel)

B_M = 3,500 (Ferrites) B_M = 4,500 (Amorphous Alloy E)

FORMULAS USED FOR INVERTER CURVES ARE:

$$W_A A_C = \frac{5.25 \times \text{Power Output} \times 10^6}{\text{frequency}}$$ 50% cobalt)

$$W_A A_C = \frac{6.5 \times \text{Power Output} \times 10^6}{\text{frequency}}$$ (3% silicon)

$$W_A A_C = \frac{7.6 \times \text{Power Output} \times 10^6}{\text{frequency}}$$ (50% nickel & Amorphous Alloy B)

$$W_A A_C = \frac{15.7 \times \text{Power Output} \times 10^6}{\text{frequency}}$$ (80% nickel)

$$W_A A_C = \frac{24.4 \times \text{Power Output} \times 10^6}{\text{frequency}}$$ (Amorphous Alloy E)

$$W_A A_C = \frac{31.5 \times \text{Power Output} \times 10^6}{\text{frequency}}$$ (Ferrites)

Core Loss Calculations

Shown in Table 3 are core loss curves for several materials and material thicknesses. These curves show typical core loss in watts per pound versus operating flux density levels for various frequencies. To find the weight of a given toroidal core size, determine the core volume in cubic inches from:

Volume = .75(O.D. + I.D.)(O.D.-I.D.)(Ht) where the bare core inside diameter, outside diameter, and height are in inches.

Core weight in pounds = Volume x Stacking Factor x Density.

The densities of various core materials are as follows:

MATERIALS	DENSITY (LBS. / CU. IN.)
3% Silicon	.29
50% Ni & 50% Co	.31
80% Nickel	.33
Amorphous Alloy B	.26
Amorphous Alloy E	.27
Ferrites (MnZn)	.19

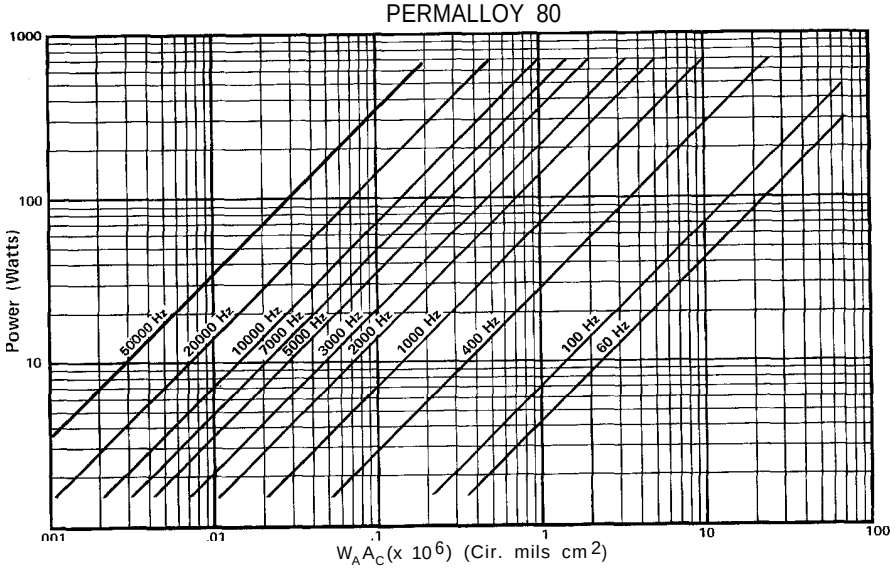
Knowing the core weight, the expected core loss can be found from these curves.

Core selection for inverter transformers often involves compromises which affect inverter performance. Hopefully, by following the steps outlined, the designer will optimize the final inverter performance.

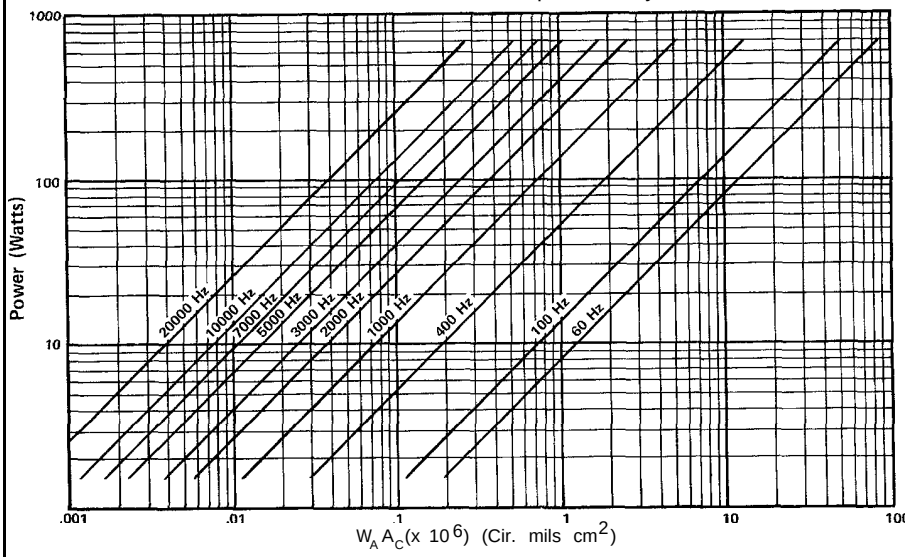
Table 2

Relationship of Core W_AA_C to Output Power Capability

PERMALLOY 80



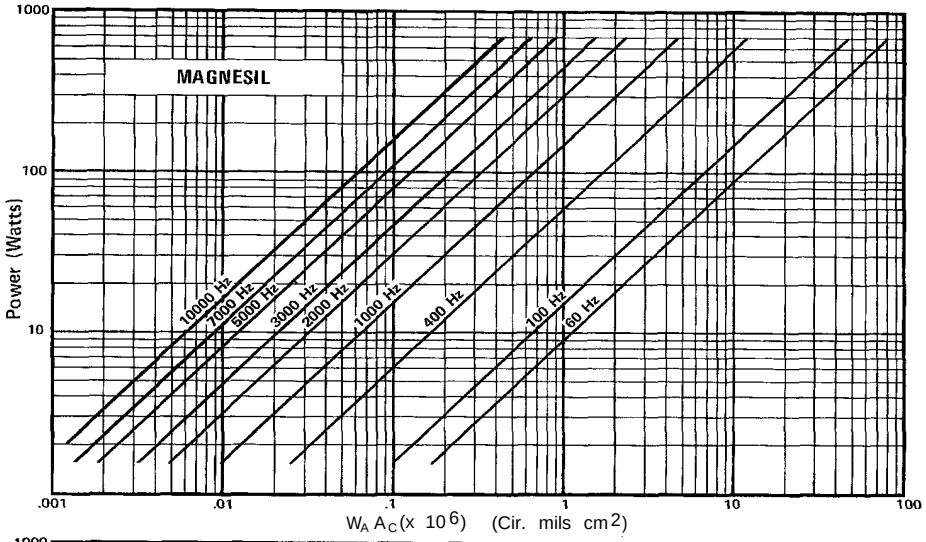
ORTHONOL and Amorphous Alloy B

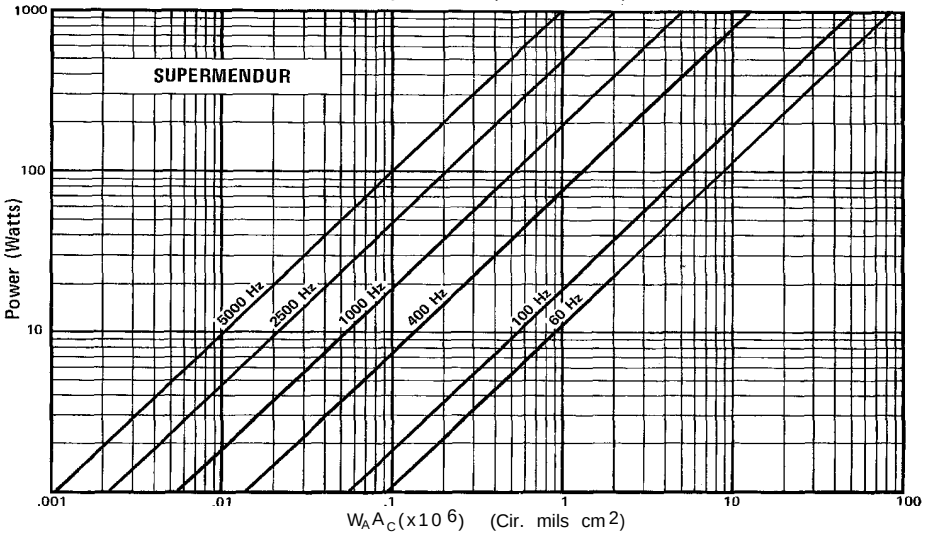


For Amorphous Alloy E, multiply W_AA_C determined from the formula by 1.55 and use Permalloy curves above.

Note: To convert circular mils to cm^2, multiply by 5.07×10^{-6}.

Relationship of Core $W_A A_C$ to Output Power Capability (cont.)





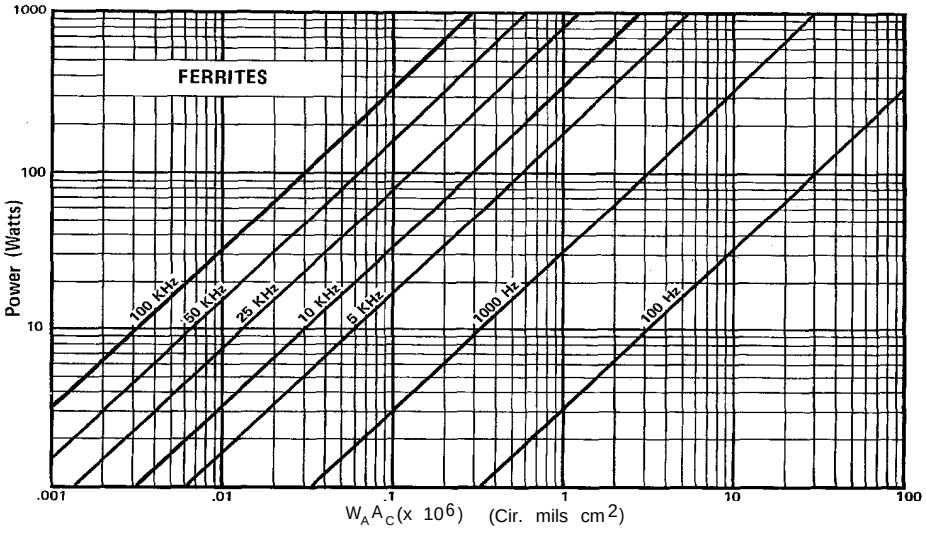
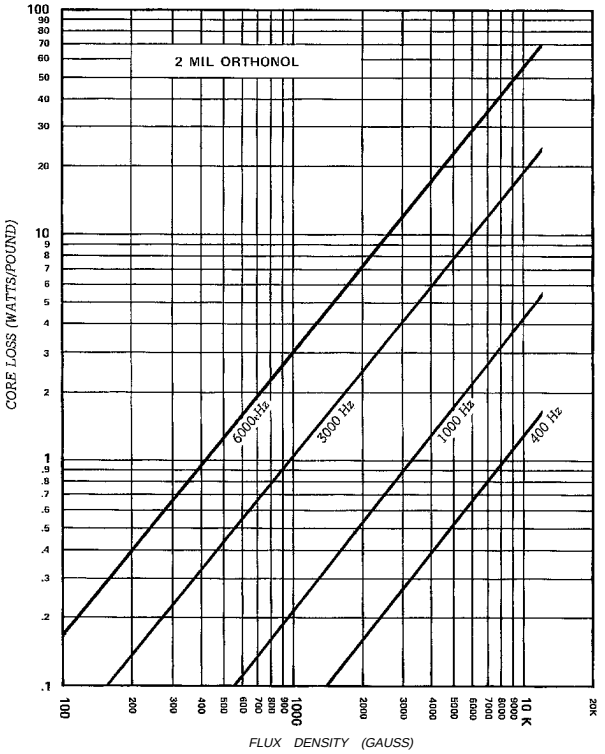
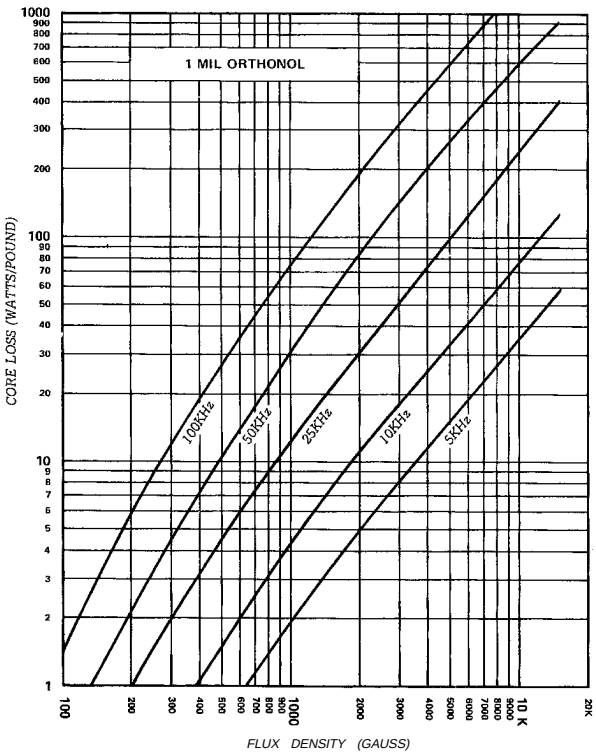
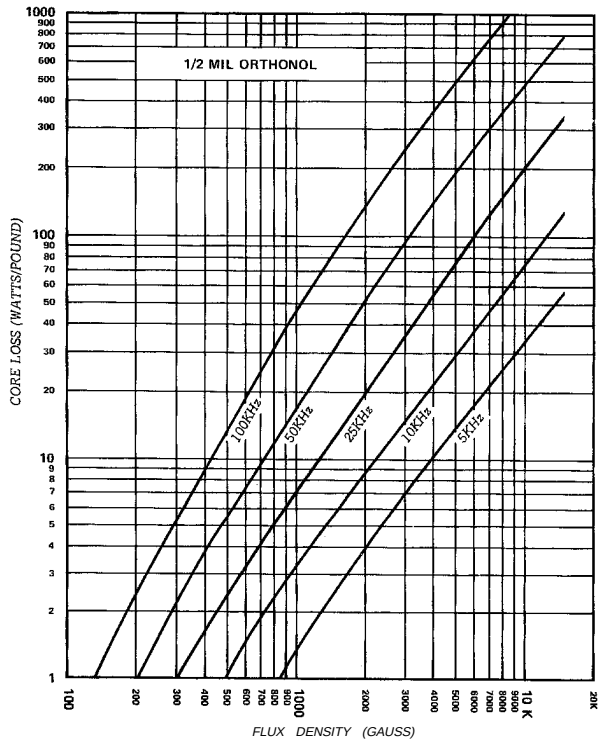


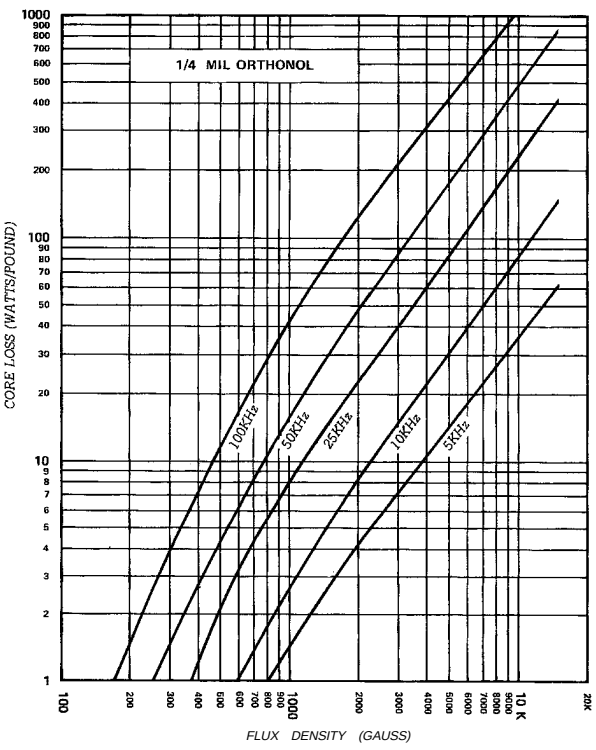
Table 3

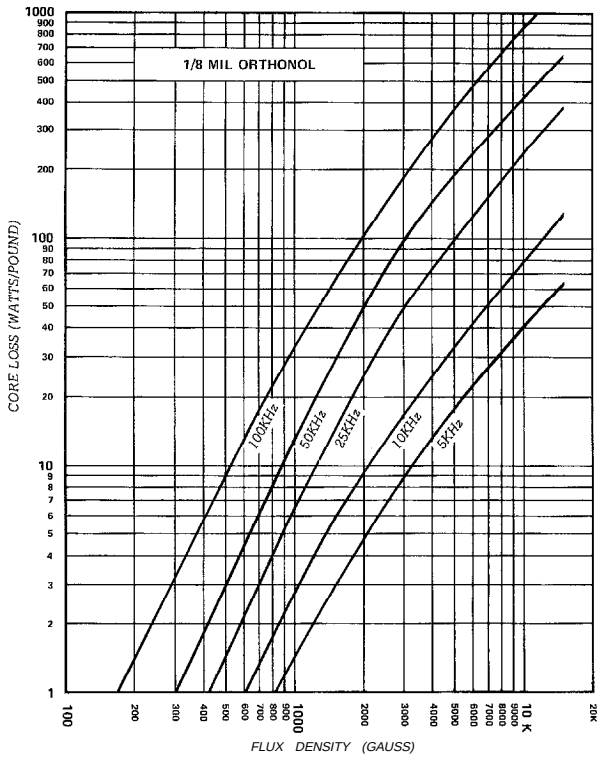
Core Loss Curves

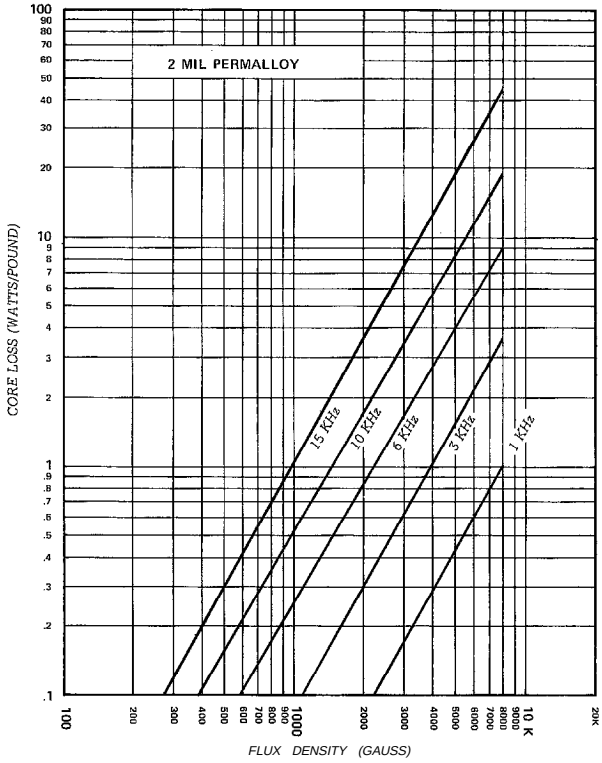


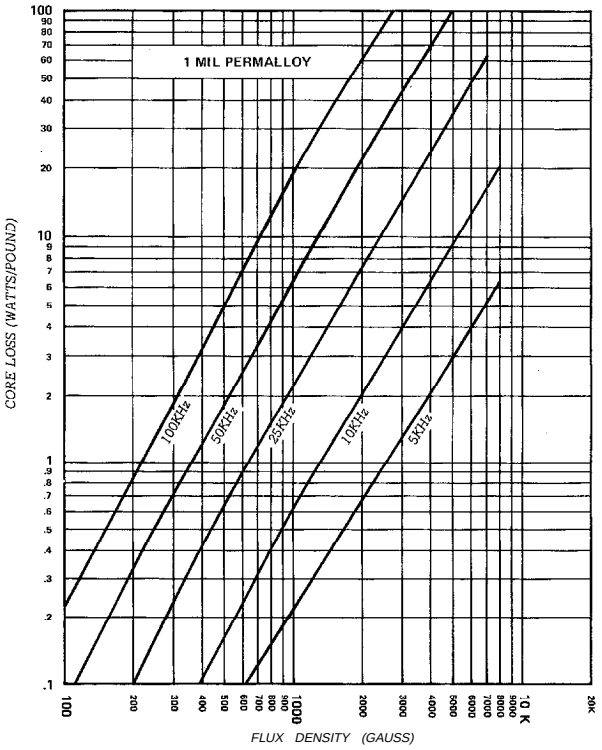


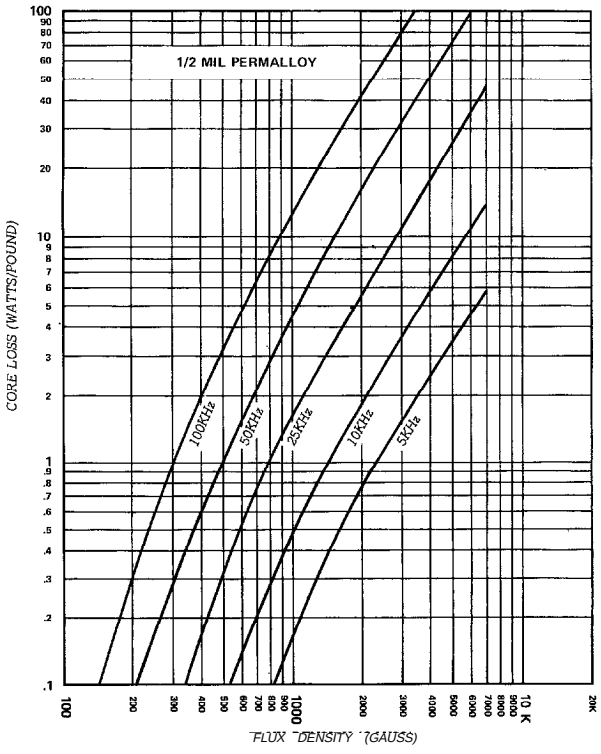





1/8 MIL ORTHONOL
CORE LOSS (WATTS/POUND)
FLUX DENSITY (GAUSS)
100KHz
50KHz
25KHz
10KHz
5KHz


2 MIL PERMALLOY
CORE LOSS (WATTS/POUND)
FLUX DENSITY (GAUSS)
15 KHz
10 KHz
6 KHz
3 KHz
1 KHz


1 MIL PERMALLOY
CORE LOSS (WATTS/POUND)
FLUX DENSITY (GAUSS)
100KHz
50KHz
25KHz
10KHz
5KHz


1/2 MIL PERMALLOY
CORE LOSS (WATTS/POUND)
FLUX DENSITY (GAUSS)
100KHz
50KHz
25KHz
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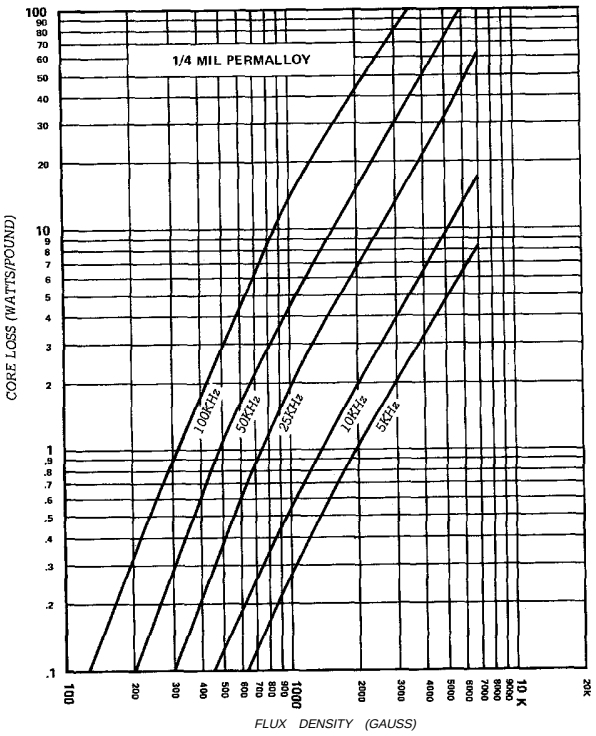
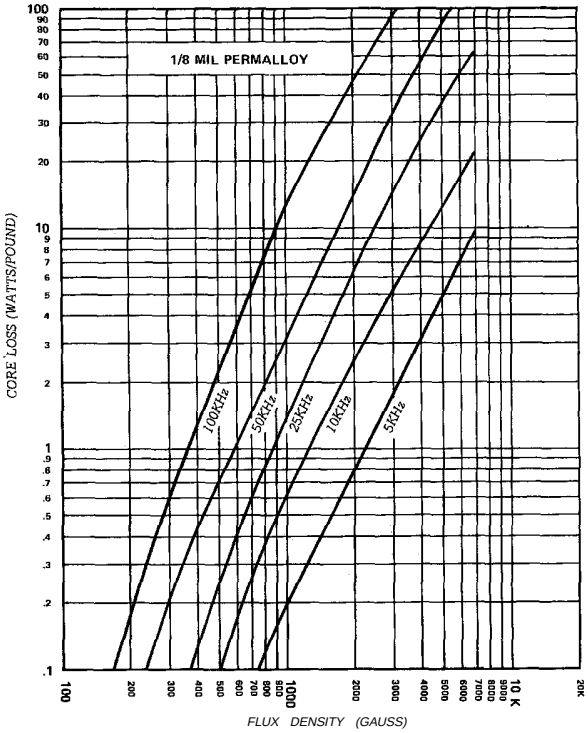
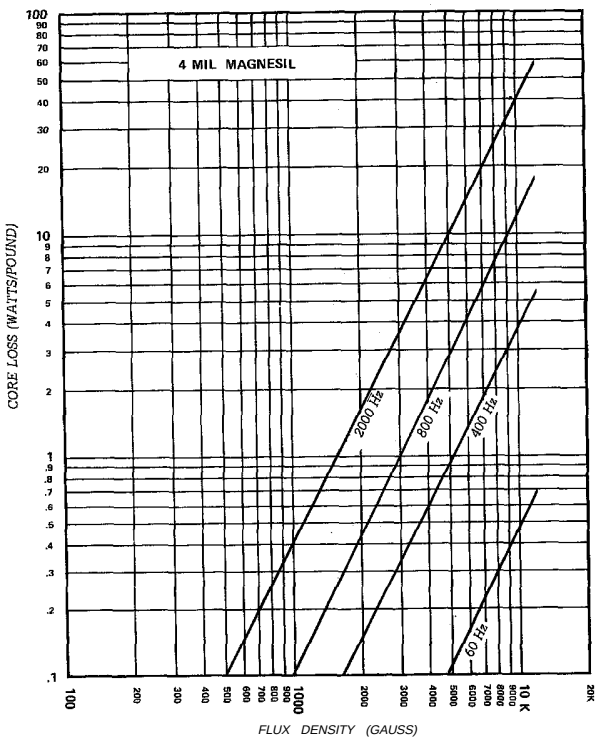
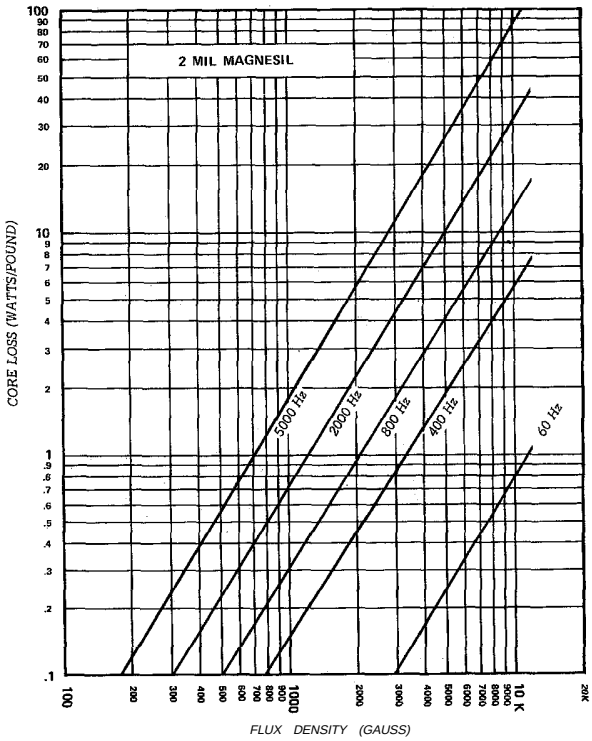
5KHz

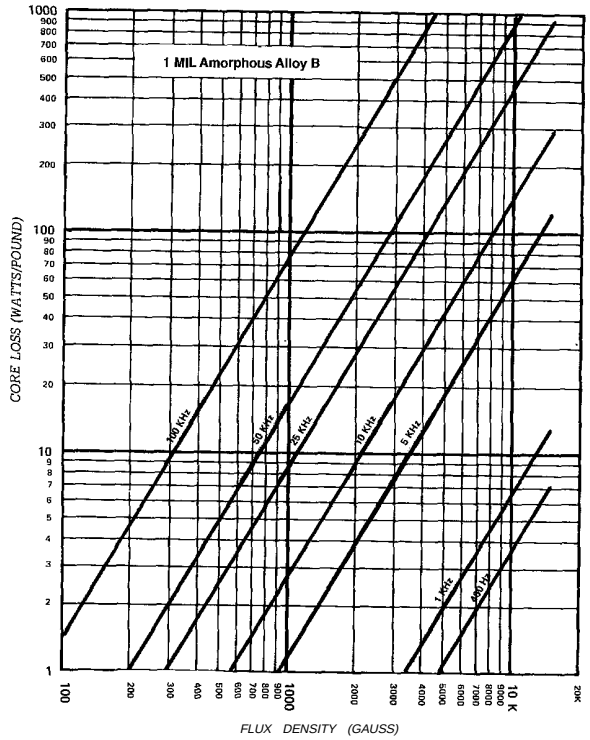
Core Loss Curves










1 MIL Amorphous Alloy B
CORE LOSS (WATTS/POUND)
FLUX DENSITY (GAUSS)
100 KHz
50 KHz
25 KHz
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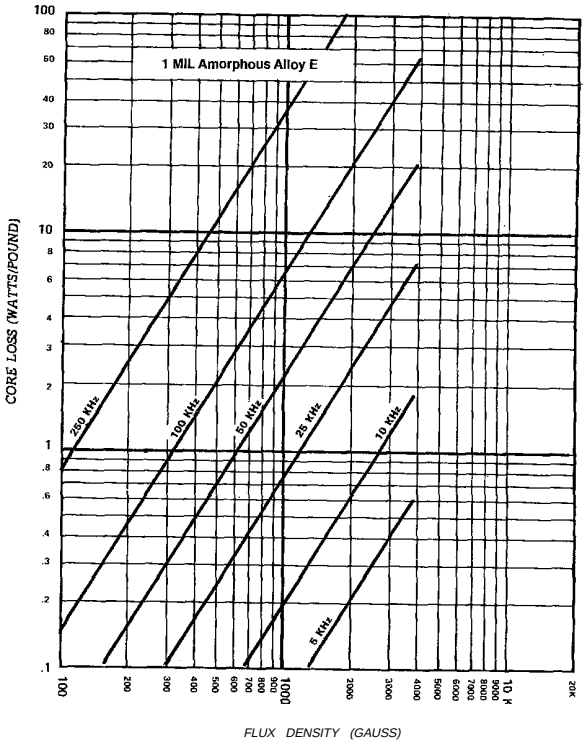
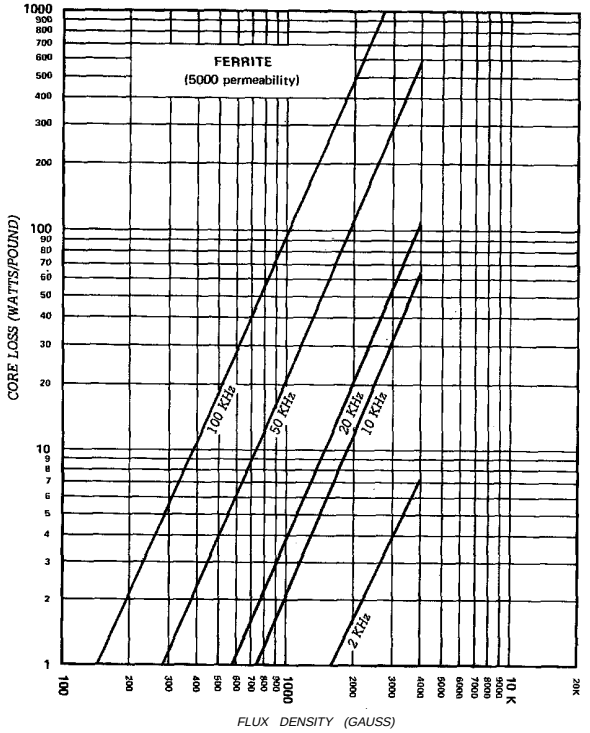
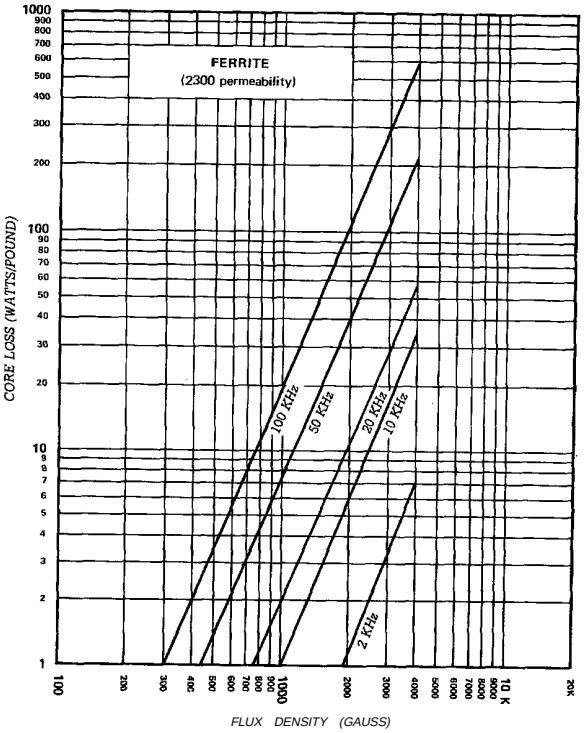
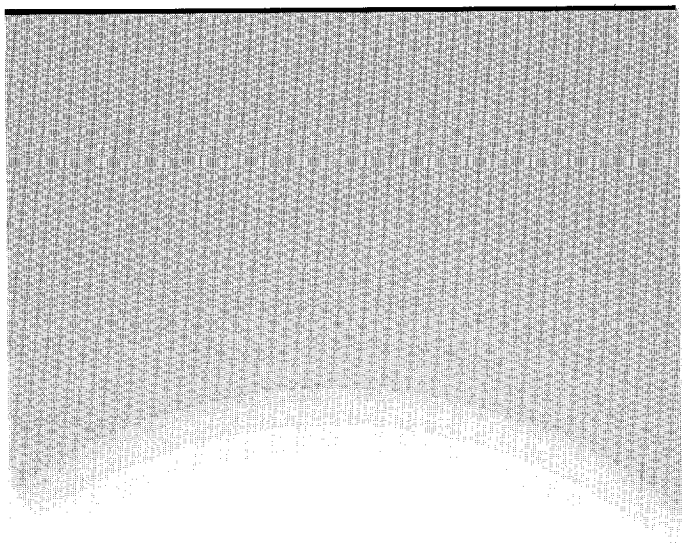
500 Hz


1 MIL Amorphous Alloy E
CORE LOSS (WATTS/POUND)
FLUX DENSITY (GAUSS)
250 KHz
100 KHz
50 KHz
25 KHz
10 KHz
5 KHz


FERRITE
(5000 permeability)
CORE LOSS (WATTS/POUND)
FLUX DENSITY (GAUSS)
100 KHz
50 KHz
20 KHz
10 KHz
2 KHz


FERRITE
(2300 permeability)
CORE LOSS (WATTS/POUND)
FLUX DENSITY (GAUSS)
100 KHz
50 KHz
20 KHz
10 KHz
2 KHz



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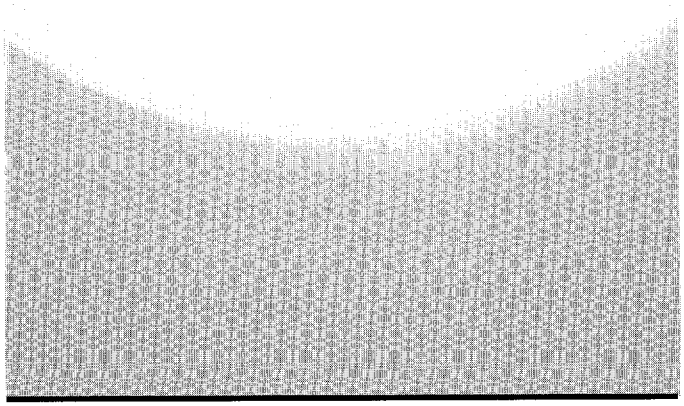

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