Chapter 2

Magnetic Materials

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Introduction

The magnetic material is the paramount player in the design of magnetic components. The magnetics design engineer has three standard words when making the normal design trade-off study: cost, size, and performance. The engineer will be happy to stuff any two in the bag. The magnetics design engineer is now designing magnetic components that operate from below the audio range to the megahertz range. He is normally asked to design for maximum performance, with the minimum of his parasitic friends' capacitance and leakage inductance. Today, the magnetic materials, the engineer has to work with, are silicon steel, nickel iron (permalloy), cobalt iron (permendur), amorphous metallic alloys, and ferrites. These also have spin-off material variants, such as moly-permalloy powder, sendust powder, and iron powder cores. From this group of magnetic materials, the engineer will make trade-offs with the magnetic properties for his design. These properties are: saturation B_s, permeability μ, resistivity ρ (core loss), remanence B_r, and coercivity H_c.

Saturation

A typical hysteresis loop of a soft magnetic material is shown in Figure 2-1. When a high magnetizing force is encountered, a point is reached where further increase in H does not cause, useful increase in B. This point is known as the saturation point of that material. The saturation flux density, B_s, and the required magnetizing force, H_s, to saturate the core is shown with dashed lines.

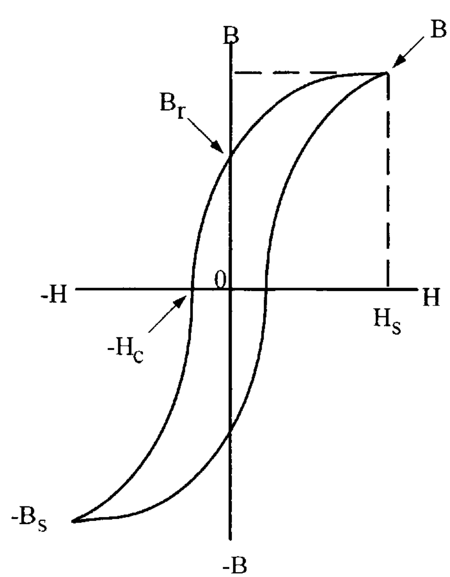

Figure 2-1. Typical B-H or Hysteresis Loop of a Soft Magnetic Material.

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Remanence Flux, B_r, and Coercivity H_c

The hysteresis loop in Figure 2-1 clearly shows the remanence flux density, B_r. The remanence flux is the polarized flux remaining in the core after the excitation has been removed. The magnetizing force, $-H_c$ is called coercivity. It is the amount of magnetizing force required to bring the remanence flux density back to zero.

Permeability, μ

The permeability of a magnetic material is a measure of the ease in magnetizing the material. Permeability μ, is the ratio of the flux density, B, to the magnetizing force, H.

$$\mu = \frac{B}{H}, \quad \text{[permeability]}$$

The relationship between B and H is not linear, as shown in the hysteresis loop in Figure 2-1. Then it is evident that the ratio, B/H (permeability) also varies. The variation of permeability with flux density B is shown in Figure 2-2. It also shows the flux density at which the permeability is at a maximum.

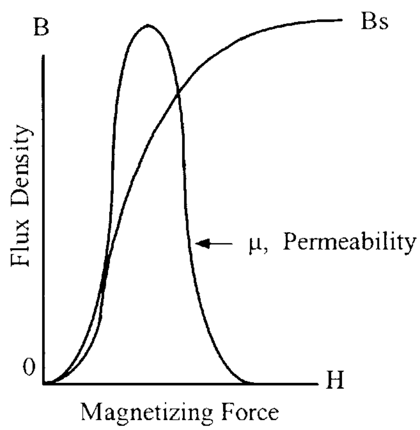

Figure 2-2. Variation in Permeability μ with B and H.

Hysteresis Loss, Resistivity, ρ, (core loss)

The enclosed area within the hysteresis, shown in Figure 2-1, is a measure of the energy lost in the core material during that cycle. This loss is made up in two components: (1) the hysteresis loss and (2) eddy current loss. The hysteresis loss is the energy loss when the magnetic material is going through a cycling state. The eddy current loss is caused when the lines of flux pass through the core, inducing electrical currents in it. These currents are called eddy currents and produce heat in the core. If the electrical resistance of the core is high, the current will be low; therefore, a feature of low-loss material is high

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electrical resistance. In the norm, when designing magnetics components the core loss is a major design factor. Core loss, can be controlled by selecting the right material and thickness. Selecting the correct material, and operating within its limits, will prevent overheating that could result in damage to the wire insulation and/or the potting compound.

Introduction to Silicon Steel

Silicon steel was one of the first alloys to be used in transformers and inductors. It has been greatly improved over the years and is probably, pound for pound, the most, widely used magnetic material. One of the drawbacks in using steel in the early years was, as the material became older, the losses would increase. With the addition of silicon to the steel, the advantages were twofold: it increased the electrical resistivity, therefore, reducing the eddy current losses, and it also improved the material stability with age.

Silicon steel offers high saturation flux density, a relatively good permeability at high flux density, and a moderate loss at audio frequency. One of the important improvements made to the silicon steel was in the process called cold rolled, grain-oriented, AISI type M6. This M6 grain oriented steel has exceptionally low losses and high permeability. It is used in applications requiring high performance and the losses will be at a minimum.

Introduction to Thin Tape Nickel Alloys

High permeability metal alloys are based primarily on the nickel-iron system. Although Hopkinson investigated nickel-iron alloys as early as 1889, it was not until the studies by Elmen, starting in about 1913, on properties in weak magnetic fields and effects of heat-treatments, that the importance of the Ni-Fe alloys was realized. Elmen called his Ni-Fe alloys, "Permalloys," and his first patent was filed in 1916. His preferred composition was the 78 Ni-Fe alloy. Shortly after Elmen, Yensen started an independent investigation that resulted in the 50Ni-50Fe alloy, "Hipernik," which has lower permeability and resistivity but higher saturation than the 78-Permalloy, (1.5 tesla compared to 0.75 tesla), making it more useful in power equipment.

Improvements in the Ni-Fe alloys were achieved by high temperature anneals in hydrogen atmosphere, as first reported by Yensen. The next improvement was done by using grain-oriented material and annealing it, in a magnetic field, which was also in a hydrogen atmosphere. This work was done by Kelsall and Bozorth. Using these two methods, a new material, called Supermalloy, was achieved. It has a higher permeability, a lower coercive force, and about the same flux density as 78-Permalloy. Perhaps the most important of these factors is the magnetic anneal, which, not only increases permeability, but also provides a "square" magnetization curve, important in high frequency power conversion equipment.

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In order to obtain high resistance, and therefore, lower core losses for high frequency applications, two approaches have been followed: (1) modification of the shape of metallic alloys and (2) development of magnetic oxides. The result was the development of thin tapes and powdered alloys, in the 1920's, and thin films in the 1950's. The development of thin film has been spurred by the requirements of aerospace power conversion electronics from the mid 1960's to the present.

The Ni-Fe alloys are available in thicknesses of 2 mil, 1 mil, 0.5 mil, 0.25 and 0.125 mil. The material comes with a round or square B-H loop. This gives the engineer a wide range of sizes and configurations from which to select for his/her design. The iron alloy properties for some of the most popular materials are shown in Table 2-1. Also given in Table 2-1 is the Figure number for the B-H loop of each of the magnetic materials.

Table 2-1 Magnetic Properties for Selected Iron Alloys Materials.

Iron Alloy Material Properties							
Material Name	Composition	Initial Permeability μ_i	Flux Density Tesla B_s	Curie Temperture °C	dc, Coercive Force, Hc Oersteds	Density grams/cm^3 δ	Typical B-H Loop Figures
Silicon	3% Si 97% Fe	1.5 K	1.5-1.8	750	0.4-0.6	7.3	(2-3)
Supermendur*	49% Co 49% Fe 2% V	0.8 K	1.9-2.2	940	0.15-0.35	8.15	(2-4)
Orthonol	50% Ni 50% Fe	2 K	1.42-1.58	500	0.1-0.2	8.24	(2-5)
Permalloy	79% Ni 17% Fe 4% Mo	12 K-100 K	0.66-0.82	460	0.02-0.04	8.73	(2-6)
Supermalloy	78% Ni 17% Fe 5% Mo	10 K-50 K	0.65-0.82	460	0.003-0.008	8.76	(2-7)
* Field Anneal							

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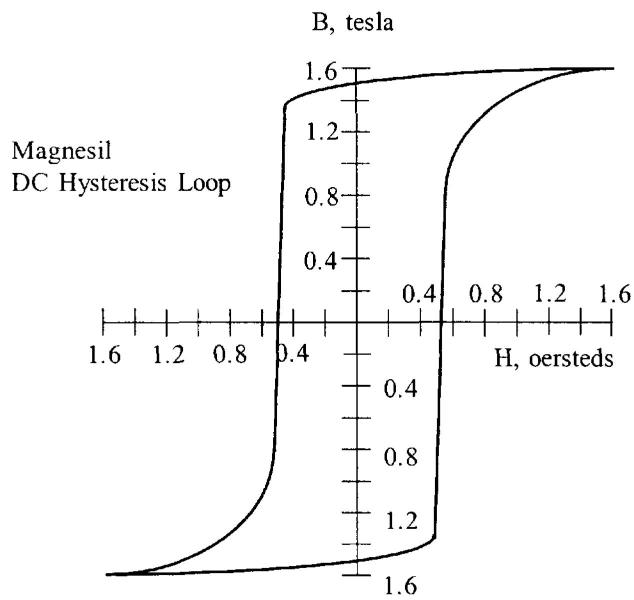

Figure 2-3. Silicon B-H Loop: 97% Fe 3% Si.

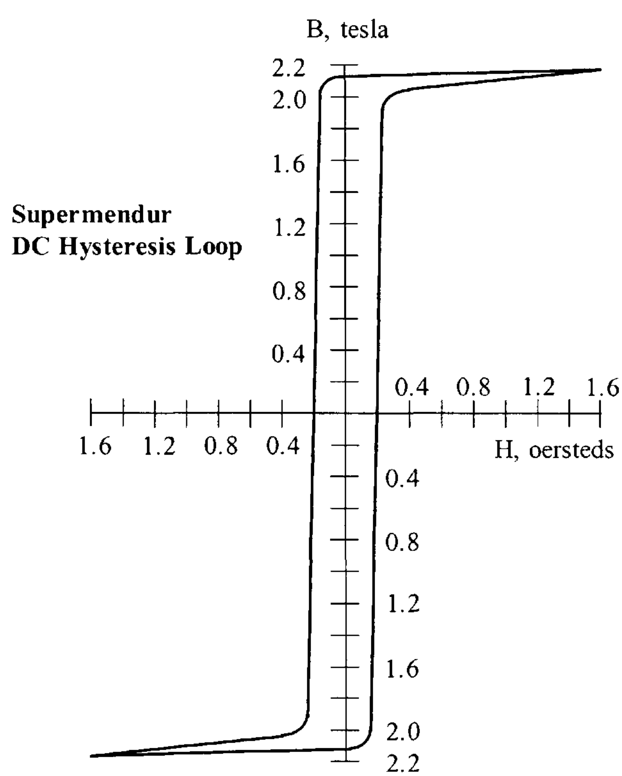

Figure 2-4. Supermendur B-H Loop: 49% Fe 49% Co 2% V.

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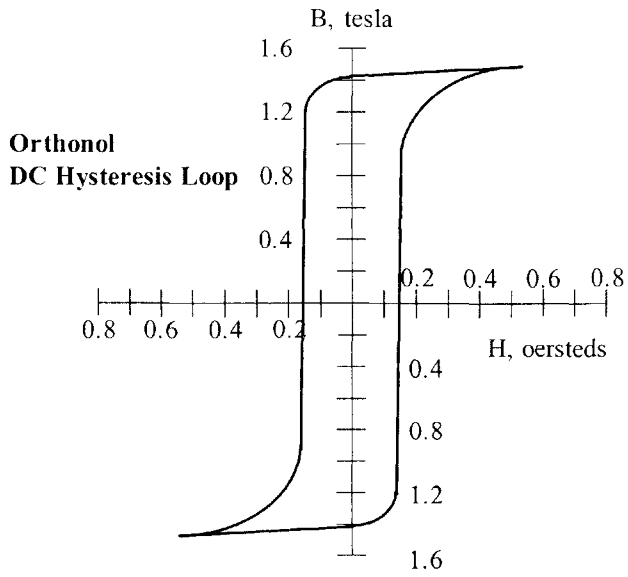

Figure 2-5. Orthonol B-H loop: 50% Fe 50% Ni.

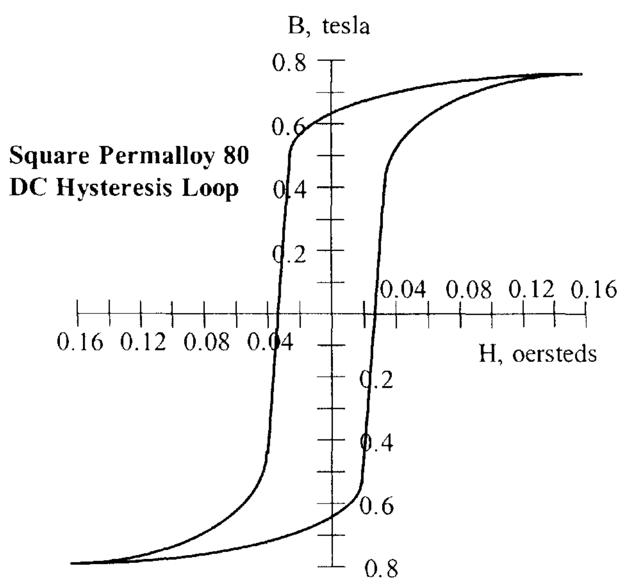

Figure 2-6. Square Permalloy 80 B-H loop: 79% Ni 17% Fe 4% Mo.

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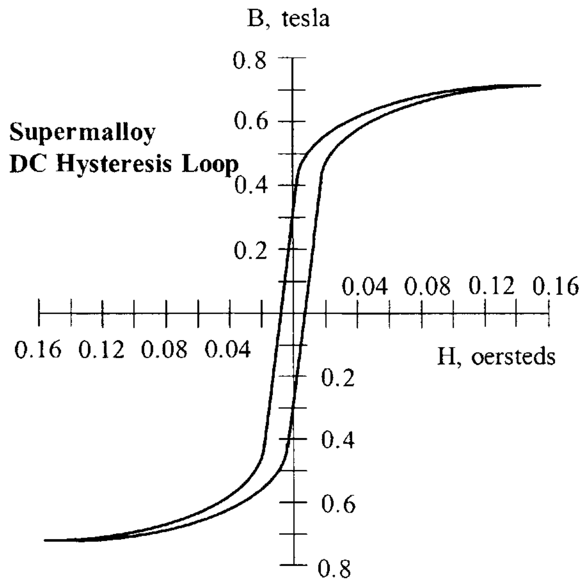

Figure 2-7. Supermalloy B-H Loop: 78% Ni 17% Fe 5% Mo.

Introduction to Metallic Glass

The first synthesis of a metallic glass, drawing wide attention among material scientists, occurred in 1960. Klement, Willens and Duwez reported that a liquid, AuSi alloy, when rapidly quenched to liquid nitrogen temperature, would form an amorphous solid. It was twelve years later that Chen and Polk produced ferrous-based metallic glasses in useful shapes with significant ductility. Metallic glasses have since survived the transition from laboratory curiosities to useful products, and currently, are the focus of intensive technological and fundamental studies.

Metallic glasses are generally produced, by liquid quenching, in which a molten metal alloy is rapidly cooled, at rates on the order of 10^5 degrees/sec.; through the temperature, at which crystallization normally occurs. The basic difference between crystalline, (standard magnetic material), and glassy metals is in their atomic structures. Crystalline metals are composed of regular, three-dimensional arrays of atoms, which exhibit long-range order. Metallic glasses do not have long-range structural order. Despite their structural differences, crystalline and glassy metals of the same compositions exhibit nearly the same densities.

The electrical resistivities of metallic glasses are much larger, (up to three times higher), than those of crystalline metals of similar compositions. The magnitude of the electrical resistivities and their temperature coefficients in the glassy and liquid states are almost identical.

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Metallic glasses are quite soft magnetically. The term, "soft," refers to a large response of the magnetization to a small-applied field. A large magnetic response is desirable in such applications as transformers and inductors. The obvious advantages of these new materials are in high frequency applications with their high induction, high permeability and low core loss.

There are four amorphous materials that have been used in high frequency applications: 2605SC, 2714A, 2714AF and Vitroperm 500F. Material 2605SC offers a unique combination of high resistivity, high saturation induction, and low core loss, making it suitable for designing high frequency dc inductors. Material 2714A is a cobalt material that offers a unique combination of high resistivity, high squareness ratio B_r/B_s, and very low core loss making it suitable for designing high frequency aerospace transformers and mag-amps. The Vitroperm 500F is an iron based material with a saturation of 1.2 tesla and is well-suited for high frequency transformers and gapped inductors. The high frequency core loss for the nanocrystal E 2000 is much lower than ferrite, even operating at a high flux density. The amorphous properties for some of the most popular materials are shown in Table 2-2. Also given in Table 2-2 is the Figure number for the B-H loop of each of the magnetic materials.

Table 2-2. Magnetic Properties for Selected Amorphous Materials.

Amorphous Material Properties							
Material Name	Major Composition	Initial Permeability μ_i	Flux Density Tesla B_s	Curie Temp. °C	dc, Coercive Force, Hc Oersteds	Density grams/cm^3 δ	Typical B-H Loop Figures
2605SC	81% Fe 13.5% B 3.5% Si	1.5K	1.5-1.6	370	0.4-0.6	7.32	(2-8)
2714A E 1000	66% Co 15% Mo 4% Fe	0.8K	0.5-0.65	205	0.15-0.35	7.59	(2-9)
2714AF	66% Co 15% Mo 4% Fe	2K	0.5-0.65	205	0.1-0.2	7.59	(2-10)
Nanocrystal Vitroperm 500F*		30K-80K	1.0-1.2	460	0.02-0.04	8.73	(2-11)

*Vitroperm is the trademark of Vacuumschmelze.

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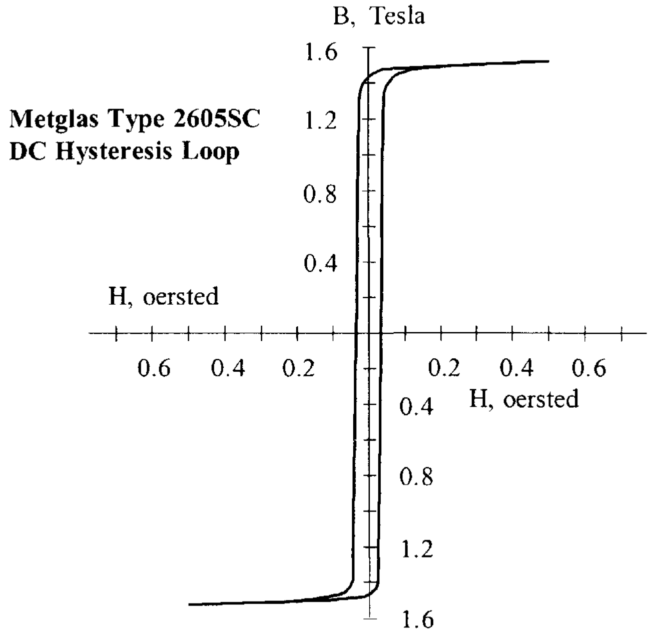

Figure 2-8. Amorphous 2605SC B-H Loop: 78% Ni 17% Fe 5% Mo.

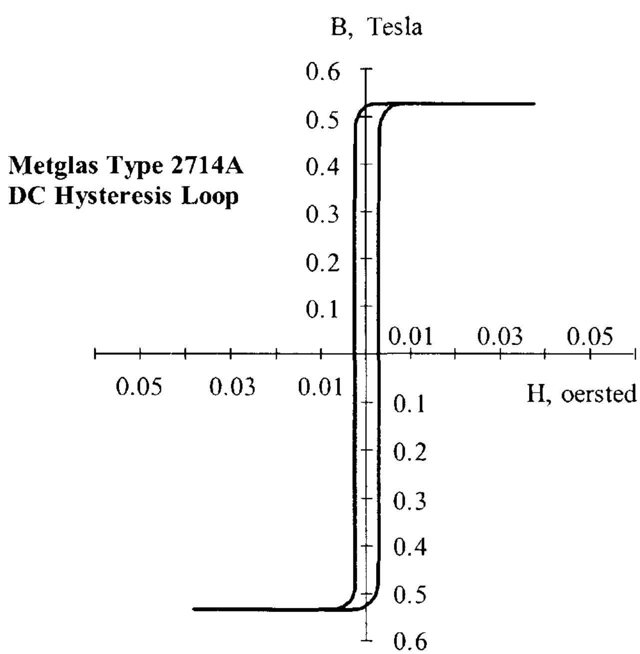

Figure 2-9. Amorphous 2714A B-H Loop: 78% Ni 17% Fe 5% Mo.

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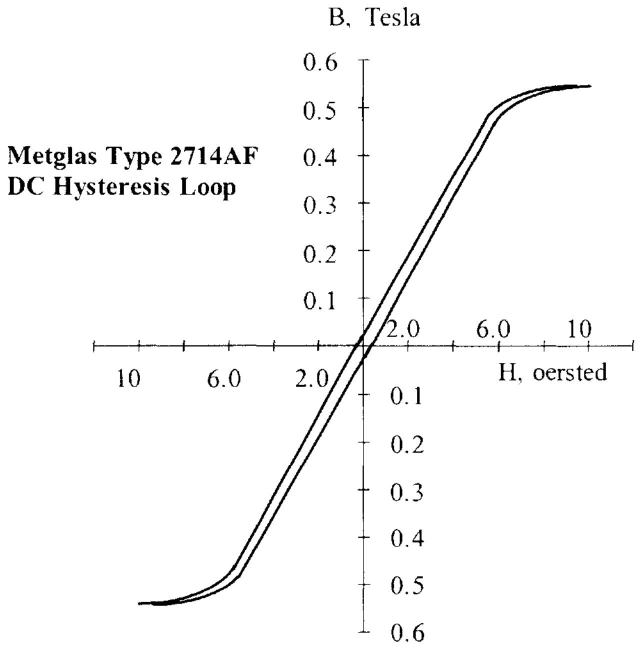

Figure 2-10. Amorphous 2714AF B-H Loop: 78% Ni 17% Fe 5% Mo.

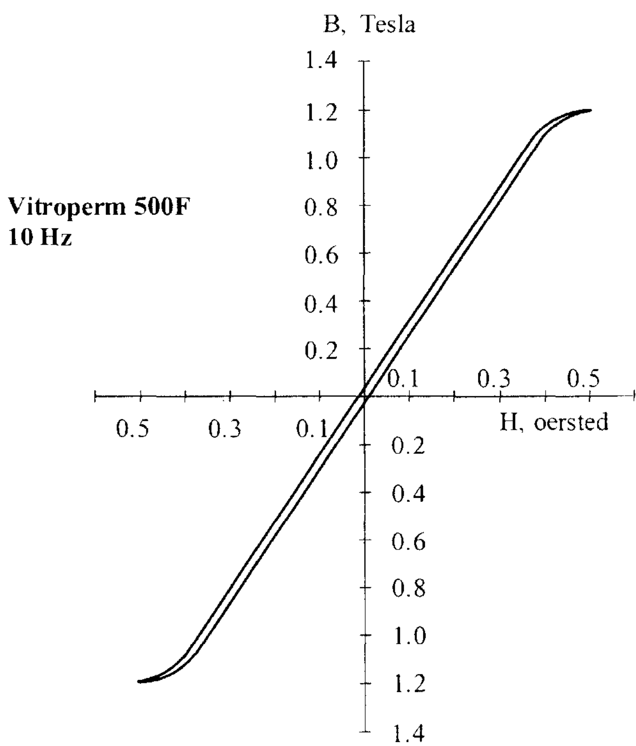

Figure 2-11. Vitroperm 500F B-H loop: 78% Ni 17% Fe 5% Mo.

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Introduction to Soft Ferrites

In the early days of electrical industry, the need for the indispensable magnetic material was served by iron and its magnetic alloys. However, with the advent of higher frequencies, the standard techniques of reducing eddy current losses, (using laminations or iron powder cores), was no longer efficient or cost effective.

This realization stimulated a renewed interest in "magnetic insulators," as first reported by S. Hilpert, in Germany, in 1909. It was readily understood that, if the high electrical resistivity of oxides could be combined with desired magnetic characteristics, a magnetic material that was particularly well-suited for high frequency operation would result.

Research to develop such a material was being performed in various laboratories all over the world, such as, by V. Kato, T. Takei, and N. Kawai in the 1930's in Japan, and by J. Snoek of the Philips' Research Laboratories in the period 1935-1945, in the Netherlands. By 1945, Snoek had laid down the basic fundamentals of the physics and technology of practical ferrite materials. In 1948, the Neel Theory of ferromagnetism provided the theoretical understanding of this type of magnetic material.

Ferrites are ceramic, homogeneous materials composed of oxides; iron oxide is their main constituent. Soft ferrites can be divided into two major categories; manganese-zinc and nickel-zinc. In each of these categories, changing the chemical composition or manufacturing technology can manufacture many different Mn-Zn and Ni-Zn material grades. The two families of Mn-Zn and Ni-Zn ferrite materials complement each other and allow the use of soft ferrites from audio frequencies to several hundred megahertz. Manufacturers do not like to handle manganese-zinc in the same area, or building with nickel-zinc, because one contaminates the other, which leads to poor performance yields. The basic difference between Manganese-Zinc and Nickel-Zinc is shown in Table 2-3. The biggest difference is Manganese-Zinc has a higher permeability and Nickel-Zinc has a higher resistibility. Shown in Table 2-4 are some of the most popular ferrite materials. Also, given in Table 2-4, is the Figure number for the B-H loop of each of the materials.

Table 2-3. Comparing Manganese-Zinc and Nickel-Zinc Basic Properties.

Basic Ferrite Material Properties					
Materials	Initial Permeability μ_i	Flux Density B_{max} Tesla	Curie Temperture, °C	dc, Coercive Force, H_c Oersteds	Resistivity Ω - cm
Manganese Zinc	750-15 K	0.3-0.5	100-300	0.04-0.25	10-100
Nickel Zinc	15-1500	0.3-0.5	150-450	0.3-0.5	10^6

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Manganese-Zinc Ferrites

This type of soft ferrite is the most common, and is used in many more applications than the nickel-zinc ferrites. Within the Mn-Zn category, a large variety of materials are possible. Manganese-zinc ferrites are primarily used at frequencies less than 2 MHz.

Nickel-Zinc Ferrites

This class of soft ferrite is characterized by its high material resistivity, several orders of magnitude higher than Mn-Zn ferrites. Because of its high resistivity, Ni-Zn ferrite is the material of choice for operating from 1-2 MHz to several hundred megahertz.

The material permeability, u_m, has little influence on the effective permeability, u_e, when the gap dimension is relatively large, as shown in Table 2-5.

Table 2-4. Magnetic Properties for Selected Ferrite Materials.

Ferrites Material Properties							
Magnetic Material Name	Initial Permeability μ_i	Flux Density Tesla B_s@15 Oe	Residual Flux Tesla B_r	Curie Temperture °C	dc, Coercive Force, Hc Oersteds	Density grams/cm^3 δ	Typical B-H Loop Figures
K	1500	0.48T	0.08T	>230	0.2	4.7	(2-12)
R	2300	0.50T	0.12T	>230	0.18	4.8	(2-13)
P	2500	0.50T	0.12T	>230	0.18	4.8	(2-13)
F	5000	0.49T	0.10T	>250	0.2	4.8	(2-14)
W	10,000	0.43T	0.07T	>125	0.15	4.8	(2-15)
H	15,000	0.43T	0.07T	>125	0.15	4.8	(2-15)

Table 2-5. Permeability, and its Effect on Gapped Inductors.

Comparing Material Permeabilities					
Material	μ_m	Gap, inch	Gap, cm	*MPL, cm	μ_e
K	1500	0.04	0.101	10.4	96
R	2300	0.04	0.101	10.4	98
P	2500	0.04	0.101	10.4	99
F	3000	0.04	0.101	10.4	100
*Core , ETD44					

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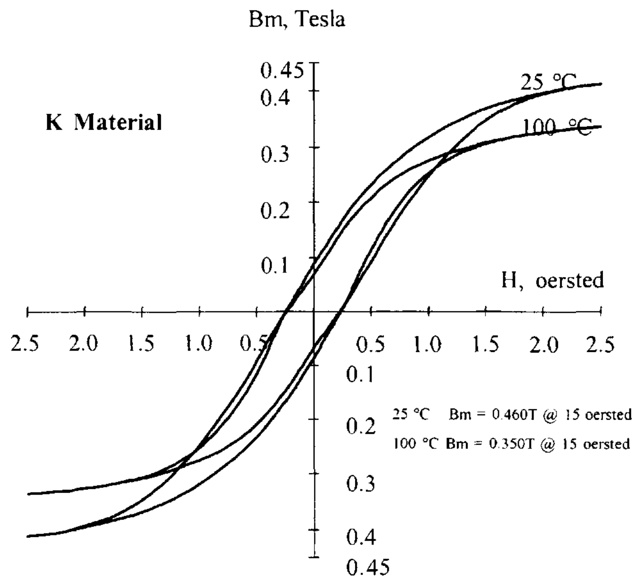

Figure 2-12. Ferrite B-H loop, K Material at 25 and 100 °C.

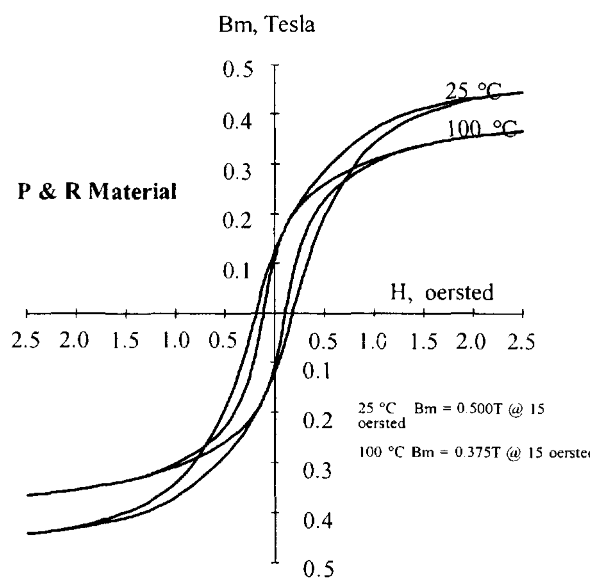

Figure 2-13. Ferrite B-H loop, P & R Material at 25 and 100 °C.

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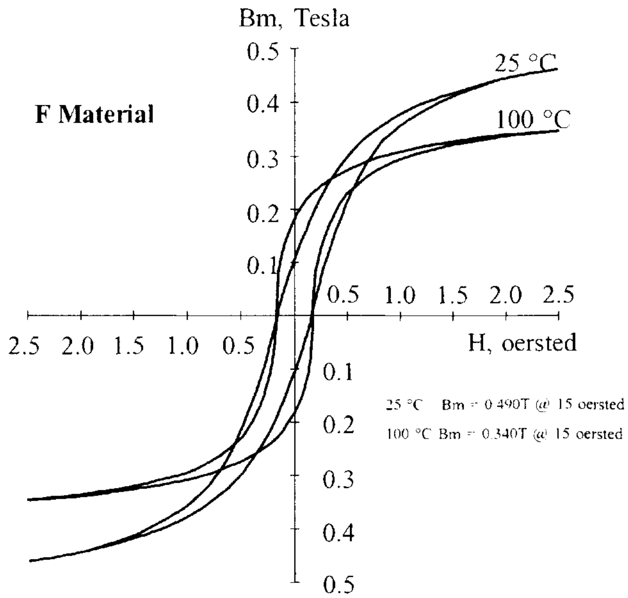

Figure 2-14. Ferrite B-H loop, F Material at 25 and 100 ° C.

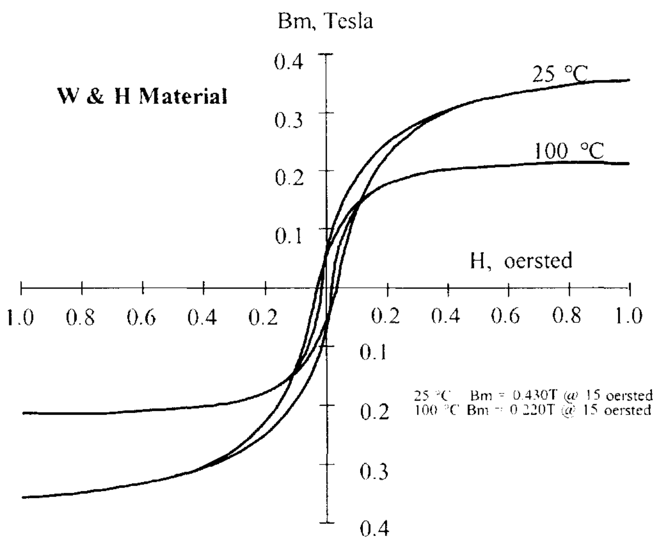

Figure 2-15. Ferrite B-H loop, W & H Material at 25 and 100 ° C.

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Table 2-6. Ferrite Materials, Manufacturers' Cross Reference.

Ferrite Material Cross Reference							
Permeability	1500	2300	2500	3000	5000	10,000	15,000
Application	Power	Power	Power	Power	Filter	Filter	Filter
Manufacturer's	Material Designation						
Magnetics	1 K	2 R	3 P	F	J	W	H
Thomson LCC		L2	B2	B1	A4	A2	
Philips Comp.	3F4	3F3	3C85	3C81	3E2A	3E5	
Fair-Rite		78	77		75	76	
Siemens	N47	N67	N27	N41	T35	T38	T46
TDK Corp.	PC50	PC44	PC44	H7A	HP5	H5C2	H5D
MMG		F44	F5	F5C	F-10	F-39	
Ceramic Mag	MN67	MN80		MN8CX	MN60	MC25	
Tokin		HBM	2500B	3100B	5000B	12001H	
Ferrite Int.			TSF-05	TSF-10	TSF-15		

1. High Frequency power material 250 kHz & up.
2. Lowest loss at 80°-100°C, 25 kHz to 250 kHz.
3. Lowest loss at 60°C-80°C.

Introduction to Molypermalloy Powder Cores

The nickel-iron (Ni-Fe) high permeability magnetic alloys (permalloy) were discovered in 1923, and in 1927. Permalloy alloys were successfully used in powder cores, greatly contributing to the carrier wave communications of the time.

In the early 1940's, a new material, trademarked molybdenum permalloy powder, (MPP), was developed into cores by the Bell Telephone Laboratory and the Western Electric Company. This new material was developed for loading coils, and filtering coils, and transformers at audio and carrier frequencies in the telephone facility. The use of such cores has been extended to many industrial and military circuits. The stability of permeability and core losses, with time, temperature, and flux level, are particularly important to engineers designing tuned circuits and timing circuits. This new material has given reliable and superior performance over all past powder core materials.

Molybdenum permalloy powder, [2 Molybdenum (Mo)-82 Nickel (Ni)-16 Iron (Fe)], is made by grinding hot-rolled and embrittled cast ingots; then, the alloy is insulated and screened to a fineness of 120 mesh for use in audio frequency applications, and 400 mesh for use at high frequencies.

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In the power conversion field, the MPP core has made its greatest impact in switching power supplies. The use of MPP cores and power MOSFET transistors has permitted increased frequency, resulting in greater compactness and weight reduction in computer systems. The power supply is the heart of the system. When the power supply is designed correctly, using a moderate temperature rise, the system will last until it becomes obsolete. In these power systems there are switching inductors, smoothing choke coils, common mode filters, input filters, output filters, power transformers, current transformers and pulse transformers. They cannot all be optimally designed, using MPP cores. But, in some cases, MPP cores are the only ones that will perform in the available space with the proper temperature rise.

Introduction to Iron Powder Cores

The development of compressed iron powder cores as a magnetic material for inductance coils stemmed from efforts of Bell Telephone Laboratory engineers to find a substitute for fine iron-wire cores. The use of iron powder cores was suggested by Heaviside, in 1887, and again, by Dolezalek in 1900.

The first iron powder cores of commercially valuable properties were described by Buckner Speed, in U.S. Patent No. 1274952, issued in 1918. Buckner Speed and G.W. Elman published a paper in the A.I.E.E. Transactions, "Magnetic Properties of Compressed Powdered Iron," in 1921. This paper describes a magnetic material, which is well-suited to the construction of cores in small inductance coils and transformers, such as those used in a telephone system. These iron powder cores were made from 80 Mesh Electrolytic Iron Powder. The material was annealed, then, insulated by oxidizing the surface of the individual particles. In this way, a very thin and tough insulation of grains of iron was obtained; this did not break down when the cores were compressed. A shellac solution was applied to the insulated powder as a further insulator and binder. This was how toroidal iron powder cores were manufactured by Western Electric Company, until about 1929. Today's iron powder cores are manufactured much the same way, using highly pure iron powder and a more exotic insulator and binder. The prepared powder is compressed under extremely high pressures to produce a solid-looking core. This process creates a magnetic structure with a distributed air-gap. The inherent high saturation flux density of iron combined with the distributed air-gap produces a core material with initial permeability of less than 100, and with high-energy storage capabilities.

The dc current does not generate core loss, but an ac or ripple current does generate core loss. Iron powder material has higher core loss than some other more expensive core materials. Most dc-biased inductors have a relatively small percentage of ripple current and, thus, core loss will be minimal. However, core loss will sometimes become a limiting factor in applications with a relatively high percentage of ripple current at

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very high frequency. Iron powder is not recommended for inductors with discontinuous current or transformers with large ac flux swings.

Low cost, iron powder cores are typically used in today's, low and high frequency power switching conversion applications, for differential-mode, input and output power inductors. Because iron powder cores have such low permeability, a relatively large number of turns are required for the proper inductance, thus keeping the ac flux at a minimum. The penalty for using iron powder cores is usually found in the size and efficiency of the magnetic component.

There are four standard powder materials available for power magnetic devices: Molypermalloy (MPP) Powder Cores with a family of curves, as shown in Figure 2-20; High flux (HF) Powder Cores with a family of curves, as shown in Figure 2-21; Sendust Powder Cores, (Kool Mu), with a family of curves, as shown in Figure 2-22; and Iron Powder Cores, with a family of curves, as shown in Figure 2-23. The powder cores come in a variety of permeabilities. This gives the engineer a wide range in which to optimize the design. The powder core properties for the most popular materials are shown in Table 2-7. Also, given in Table 2-7, is the Figure number for the B-H loop of each of the powder core materials. In Table 2-8 is a listing of the most popular permeabilities for each of the powder core materials.

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Table 2-7. Powder Core Material Properties.

Powder Core Material Properties							
Material Name	Composition	Initial Permeability μ_i	Flux Density Tesla B_s	Curie Temperture °C	dc, Coercive Force, Hc Oersteds	Density grams/cm^3 δ	Typical B-H Loop Figures
MPP	80% Ni 20% Fe	14-550	0.7	450	0.3	8.5	(2-16)
High Flux	50% Ni 50% Fe	14 - 160	1.5	360	1	8	(2-17)
Sendust (Kool Mu)	85% Fe 9% Si 6% Al	26 - 125	1	740	0.5	6.15	(2-18)
Iron Powder	100% Fe	4.0 - 100	0.5 - 1.4	770	5.0 - 9.0	3.3 - 7.2	(2-19)

Table 2-8. Standard Powder Core Permeabilities.

Standard Powder Core Permeabilities				
Powder Material	MPP	High Flux	Sendust (Kool Mu)	Iron Powder
Initial Permeability, μ_i				
10				X
14	X	X		
26	X	X	X	
35				X
55				X
60	X	X	X	X
75			X	X
90			X	
100				X
125	X	X	X	
147	X	X		
160	X	X		
173	X			
200	X			
300	X			
550	X			

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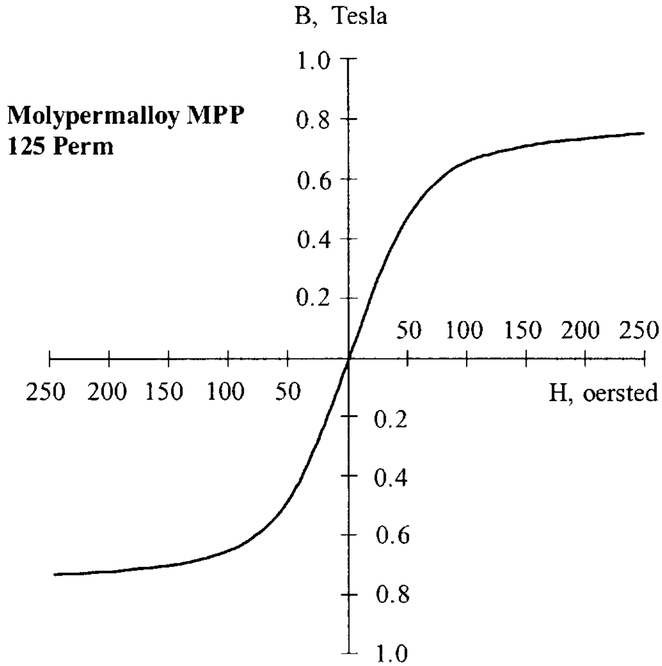

Figure 2-16. Molypermalloy Powder Core, 125 Perm.

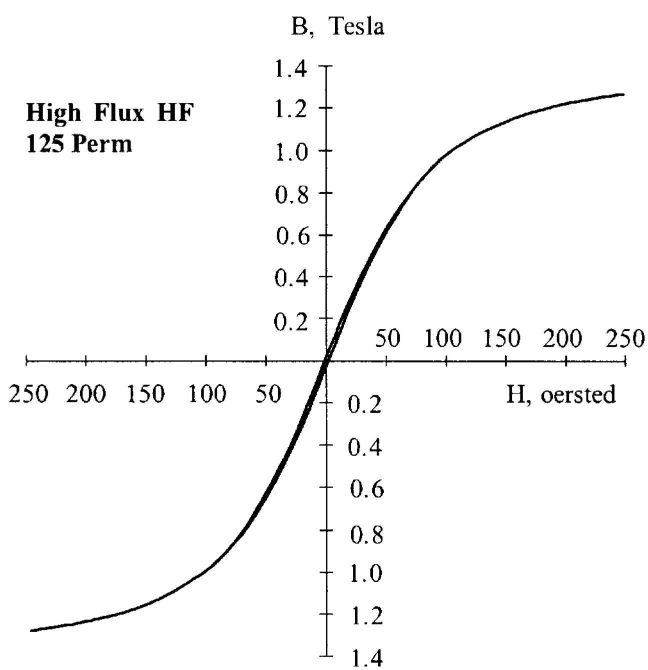

Figure 2-17. High Flux Powder Core, 125 Perm.

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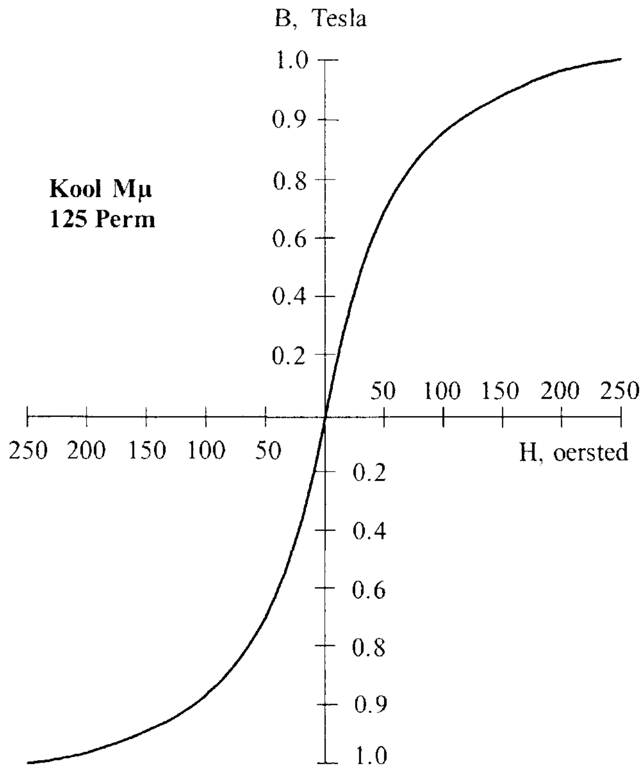

Figure 2-18. Sendust (Kool Mu) Powder Core, 125 Perm.

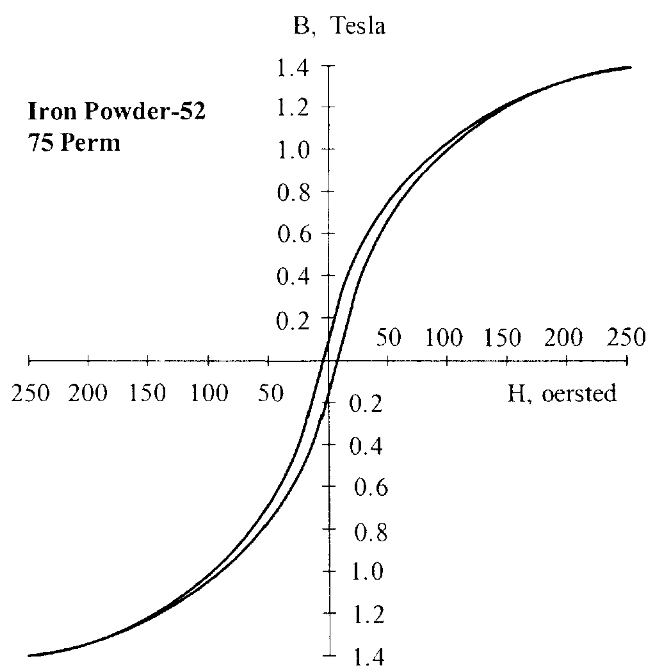

Figure 2-19. Iron Powder (-52) Core, 75 Perm.

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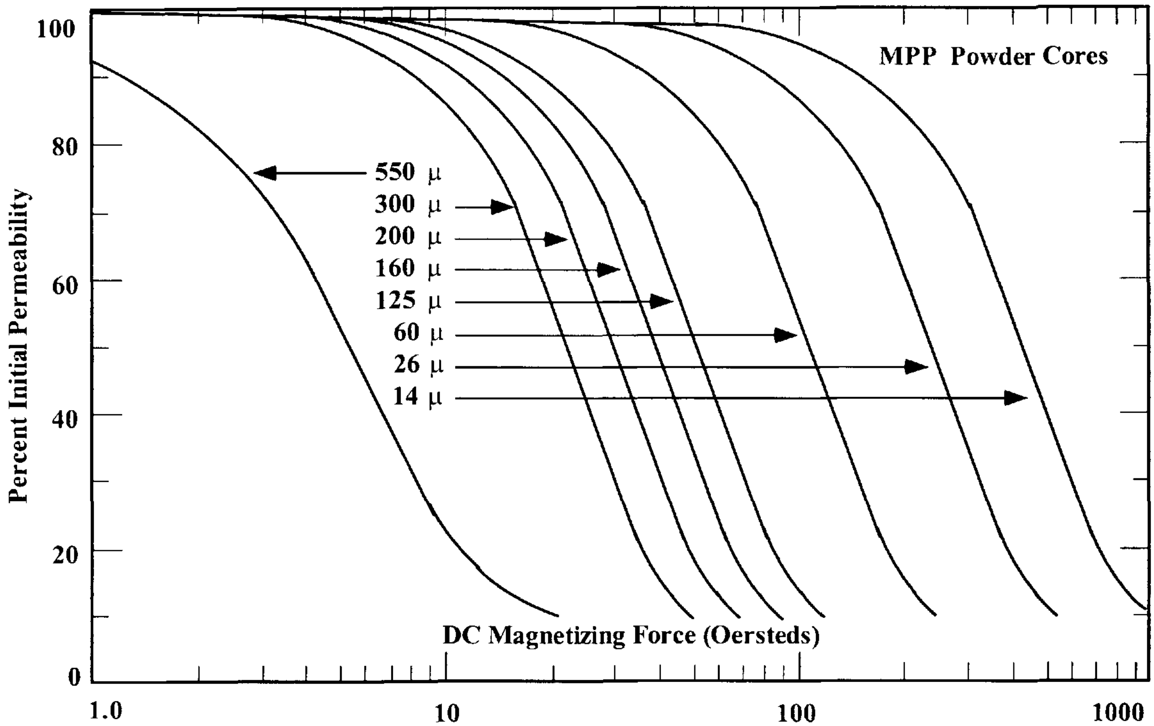

Figure 2-20. Permeability Versus dc Bias for Molypermalloy Powder Cores.

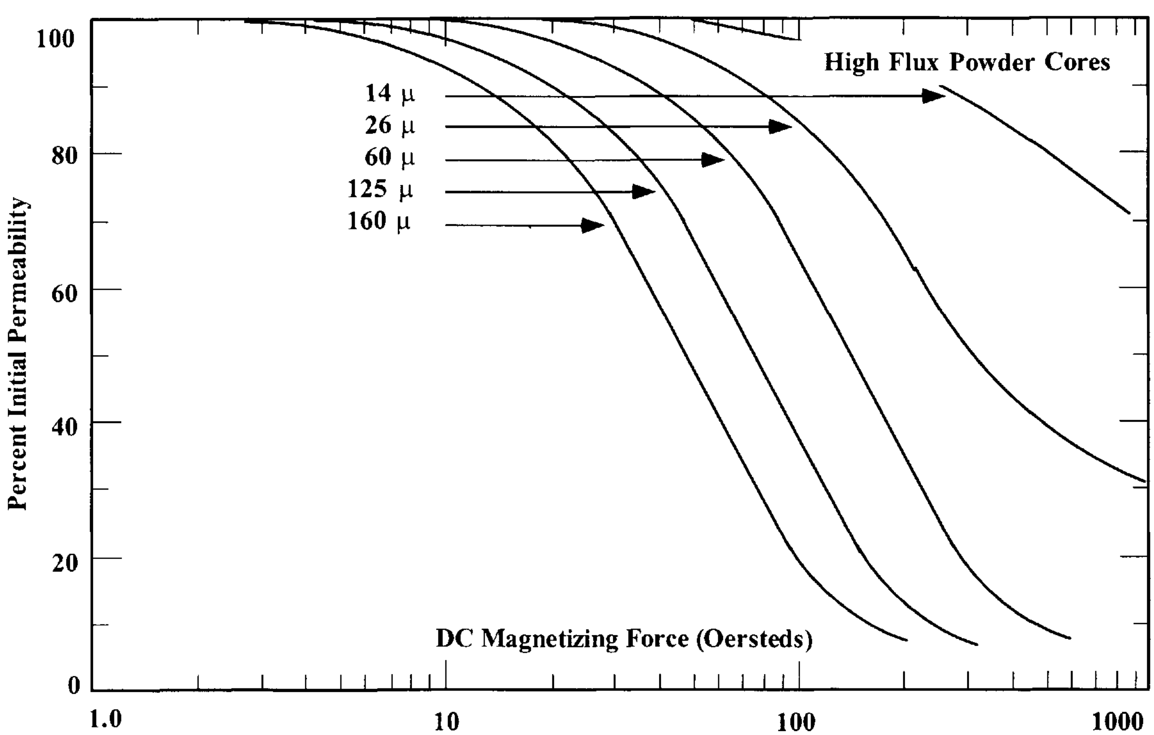

Figure 2-21. Permeability Versus dc Bias for High Flux Powder Cores.

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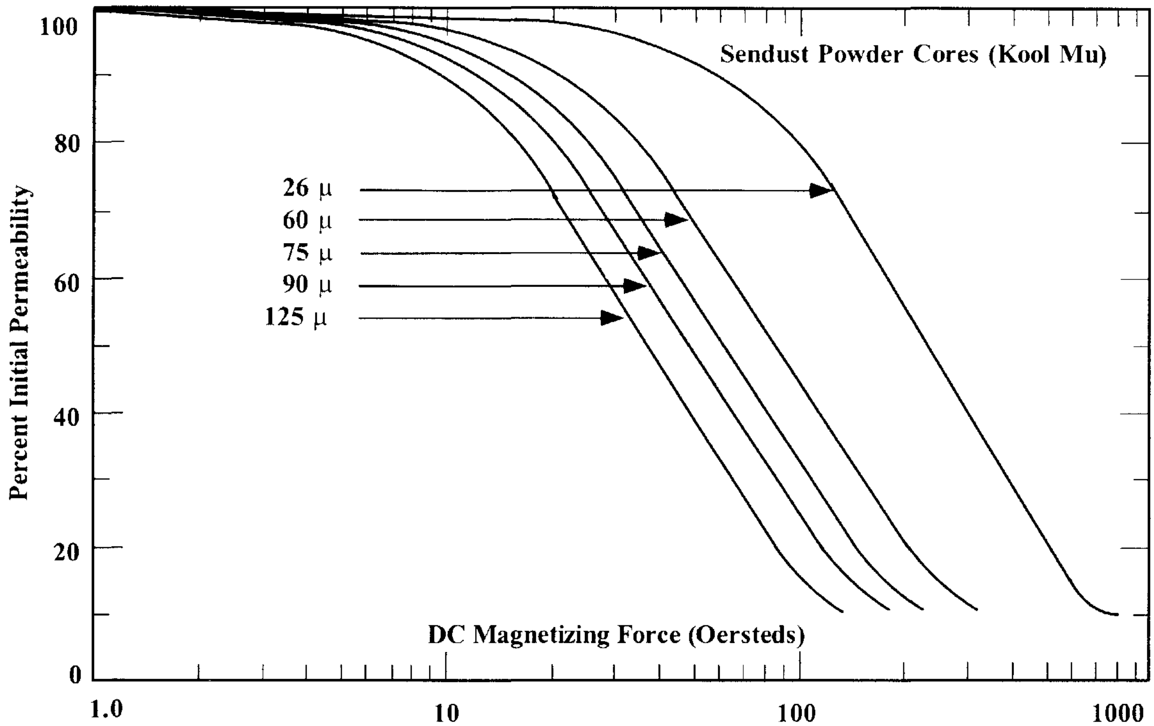

Figure 2-22. Permeability Versus dc Bias for Sendust Powder Cores.

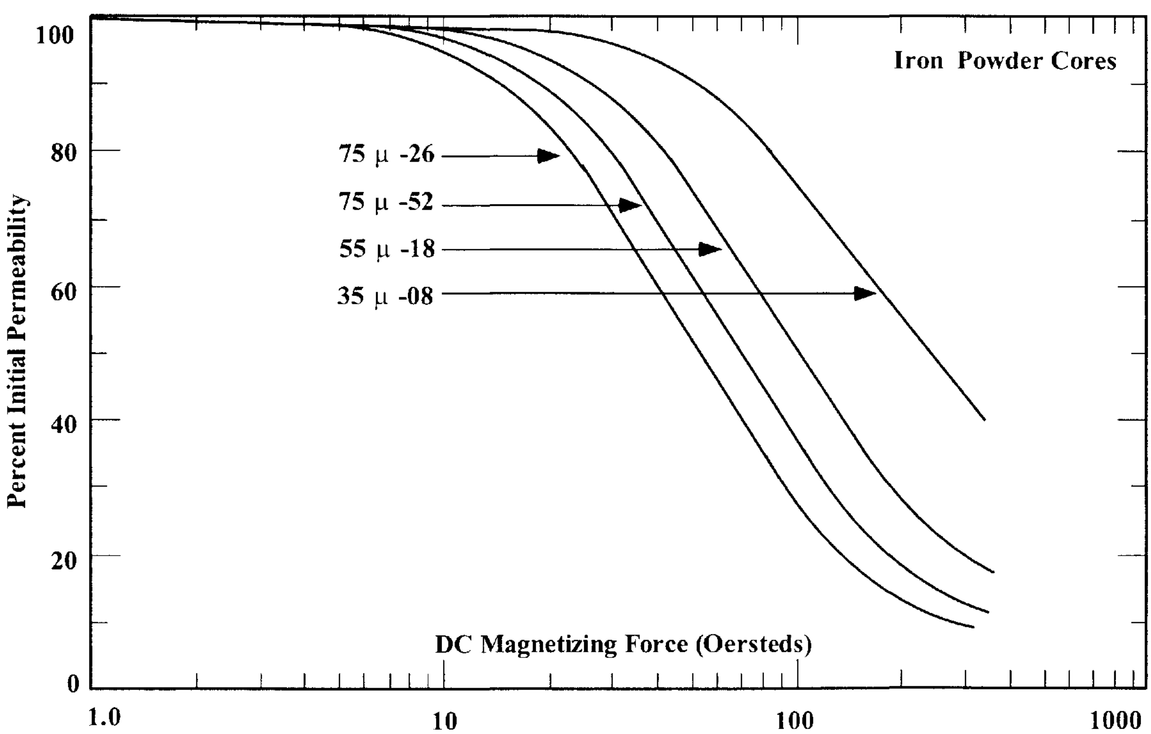

Figure 2-23. Permeability Versus dc Bias for Iron Powder Cores.

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Core Loss

The designer of power magnetic components, such as transformer and inductors, requires specific knowledge about the electrical and magnetic properties of the magnetic materials used in these components. There are two magnetic properties that are of interest to the design engineer, the dc and the ac. The dc, B-H hysteresis loop is a very useful guide for comparing the different types of magnetic materials. It is the ac, magnetic properties that are of interest to the design engineer. One of the most important ac properties is the core loss. The ac core loss is a function of the magnetic material, magnetic material thickness, magnetic flux density B_{ac}, frequency f, and operating temperature. The choice of the magnetic material is, thus, based upon achieving the best characteristic, using the standard trade-off, such as cost, size, and performance.

All manufacturers do not use the same units when describing their core loss. The user should be aware of the different core loss units when comparing different magnetic materials. A typical core loss graph is shown in Figure 2-24. The vertical scale is core loss and the horizontal scale is flux density. The core loss data is plotted at different frequencies, as shown in Figure 2-24.

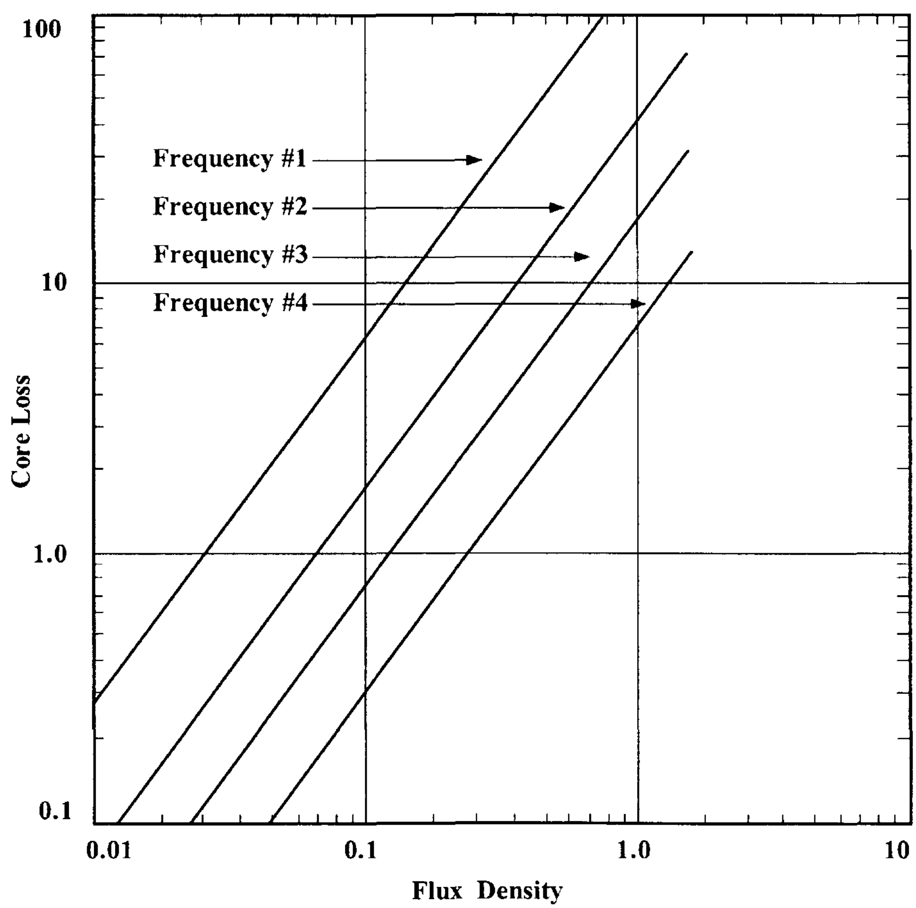

Figure 2-24. Typical Graph for Plotting Core Loss at Different Frequencies.

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Vertical Scale

Here is a list of core loss units used by manufacturers:

1. watts per pound
2. watts per kilogram
3. milliwatts per gram
4. milliwatts per cubic centimeter (cm^3)

Horizontal Scale

Here is a list of flux density units used by manufacturers:

1. gauss
2. kilogauss
3. tesla
4. millitesla

The data can be plotted or presented in either hertz or kilohertz.

Manufacturers are now presenting the core loss in an equation form such as:

$$\text{watts / kilogram} = k\, f^{(m)}\, B^{(n)}$$

Here, again, the units will change from one manufacturer to another.

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