IMA

The International Magnetics Association

Standard Recommendations:

Soft Ferrite Cores, A User's Guide

THIS USER'S GUIDE
This User's Guide is intended to acquaint the new user with the advantages, limitations, and applications of soft ferrites; and also to enhance the knowledge of more experienced users.

CORE STANDARDS
IMA Standards now available:

- IMA-STD 110, Standard Specification for Pot Style Cores
- IMA-STD 120, Standard Specification for Ferrite Threaded Cores
- IMA-STD 130, Standard Specification for Ferrite U, E, & I Cores
- IMA-STD 140, Standard Specification for Ferrite Toroid Cores

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SECTION 1.0, INTRODUCTION TO SOFT FERRITES

In the early days of the electrical industry, the need for magnetic materials was served by iron and its magnetic alloys. However, with the advent of higher frequencies, the standard techniques of reducing eddy current losses, using lamination or iron powder cores, were 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 would result that was particularly
well suited for high frequency operation.

Research to develop such a material was being done 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 1935-45 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 ferrimagnetism provided the theoretical understanding of this type of magnetic material.

Ferrites are ceramic, homogeneous materials composed of various oxides with iron oxide as their main constituent. Ferrites can have several distinct crystal structures. However, for this brochure, we are only concerned with the magnetically soft ferrites, which have a cubic crystal structure.

Based upon the chemical composition, soft ferrites can be divided into two major categories, manganese-zinc ferrite and nickel-zinc ferrite. In each of these categories many different MnZn and NiZn material grades can be manufactured by changing the chemical composition or manufacturing technology. The two families of MnZn and NiZn ferrite
materials complement each other and allow the use of soft ferrites from audio frequencies to several hundred megahertz.

The first practical soft ferrite application was in inductors used in LC filters in frequency division multiplex equipment. The combination of high resistivity and good magnetic properties made these ferrites an excellent core material for these filters operating over the 50-450 kHz frequency range.

The large scale introduction of TV in the 1950's was a major opportunity for the fledgling ferrite industry. In TV sets, ferrite cores were the material of choice for the high voltage transformer and the picture tube deflection system.

For four decades ferrite components have been used in an ever widening range of applications and in steadily increasing quantities. Table 1A is a partial listing of major applications for soft ferrites. Table 1B is a partial listing of soft ferrite design advantages.

Table 1A
Soft Ferrite Applications

MAGNETIC DEVICES:	*USED IN:*
Power transformer and chokes	HF power supplies and lighting ballasts
Inductors and tuned transformers	Frequency selective circuits
Pulse and wideband transformers	Matching devices
Magnetic deflection structures	TV sets and monitors
Recording heads	Storage devices
Rotating transformers	VCRs
Shield beads and chokes	Interference suppression
Transducers	Vending machines and ultrasonic cleaners

Table 1B
Design Advantages

High resistivity	Large material selection
Wide range of operating frequencies	Versatility of core shapes
Low loss combined with high permeability	Low cost
Time and temperature stability	Lightweight

SECTION 2.0, PROCESSING

Ferrites are manufactured by processing a composition of iron oxide mixed with other major constituents such as oxides or carbonates of either manganese and zinc or nickel and zinc. The basic process is common to most ceramic process technologies and can be divided into four major functions:

- Preparation of the powder
- Forming powder into cores
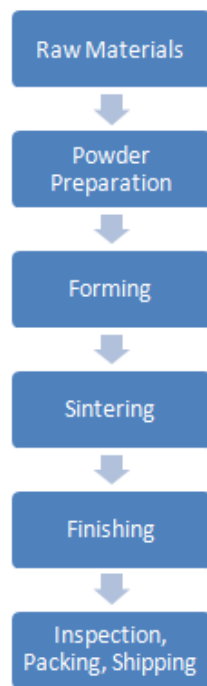- Firing and sintering
- Finishing the ferrite components

Figure 1
Processing Flow Diagram

Please note that quality assurance steps are not shown in order to simplify the diagram. Quality Assurance however, does play an integral part in the manufacturing process and will be discussed in the next section.

Powder Preparation

The first step in the production of powder starts with the chemical analysis of the raw materials, the oxides or carbonates of the major constituents. The purity of these materials contributes directly to the quality of the final product and needs to be controlled to assure a batch-to-batch consistency. The exact amount of the major constituents is weighed and thoroughly mixed into a homogeneous mixture. This mixing can be done in a dry process, or water can be added to form a slurry and then mixed in a ball mill. When wet mixing is **used,** a drying procedure is required to reduce the moisture content prior to calcining. Calcining is a preferring process in which the powder temperature is raised to approximately 1000 "C in an air atmosphere. During the calcining there is a partial

decomposition of the carbonates and oxides, evaporation of volatile impurities and a homogenation of the powder mixture. There is a degree of spine1 conversion during calcinin'g and this pre-firing step also reduces the shrinkage in the final sintering.

After calcining the powder is mixed with water and the slurry is milled to obtain small and uniform particle sizes. At this stage of the process binders and lubricants are added. The type of binder and lubricant is determined by the forming technology.

The last step in the powder preparation is to spray dry the slurry in a spray dryer. Figure 2 illustrates the powder preparation flow.
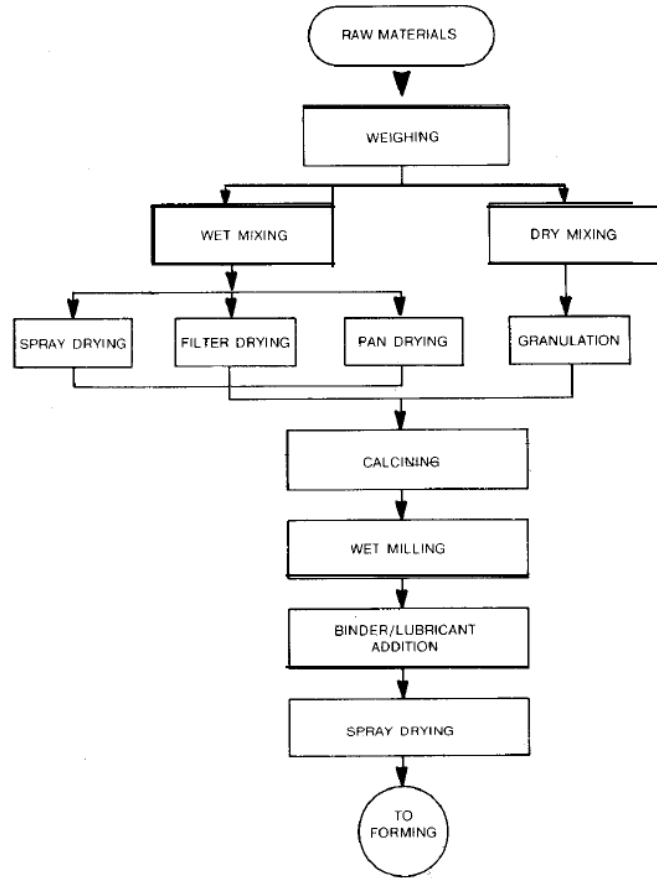

Figure 2
Powder Preparation Flow Chart

Forming

The second step in the ferrite processing technology is the forming of the component. The most often used technique is dry pressing the powder into the core configuration. Other techniques are extruding and isostatic pressing.
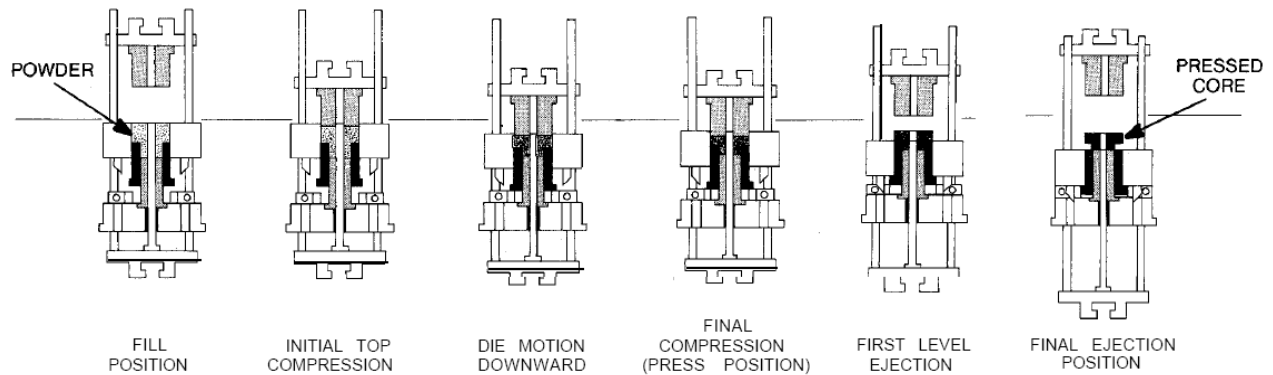
Figure 3
Dry Pressing Techniques

Dry pressing or compacting is done using a combined action of top and bottom punches in a cavity such that a part of uniform density is formed. Today's presses and tooling technology enable the pressing of multiple parts and very complex core shapes. Since compacting is only along the vertical axis, the only size adjustment that can be made is of the press height. See Figure 3 for some aspects of this pressing technique.

Isostatic pressing typically uses flexible containers, such as thick rubber molds, which have very rudimentary shapes (blocks, rods, discs, etc...). The container is filled with non bindered powder, sealed, and placed inside a pressure chamber or vessel (Isostatic press). Pressure is increased to a specific level, commonly 10K psi to 30K psi, and then decreased. The container is then removed from the vessel, unsealed and the pressed form is withdrawn ready for sintering. Organic binder is not used in this process because of the mismatch between the rate at which the binder is burned out during sintering and the shrinkage that is occurring at the same time. This mismatch could cause the product being sintered to literally tear itself apart. Isostatic pressing produces material with high, uniform density suitable for machining into complex geometries. This is valuable for prototype designing in which no dry press molds (tools) exist. This process can also produce geometries that cannot be produced using standard pressing techniques such as large core volume or non-pressable shapes.

Extruding is typically used to form long, small cross section parts such as rods and tubes. The spray dried powder is mixed with a moisturizing plasticizer that allows the powder to be forced through the appropriate extruding die.

In all of the above forming methods the dimensions of the forming tool must be larger than the final product dimensions by a factor that allows for shrinkage during sintering.

Sintering

This is the most critical step in the manufacturing of ferrites. It is during this phase of the process that the product achieves its final magnetic and mechanical characteristics.

Sintering of maganese-zinc ferrites requires an equilibrium between time, temperature and atmosphere along each phase of the sintering cycle. Sintering starts with a gradual ramping up from room temperature to approximately 800" C as impurities, residual moisture, binders, and lubricants are burned out of the product. The atmosphere in this part of the sintering cycle is air.
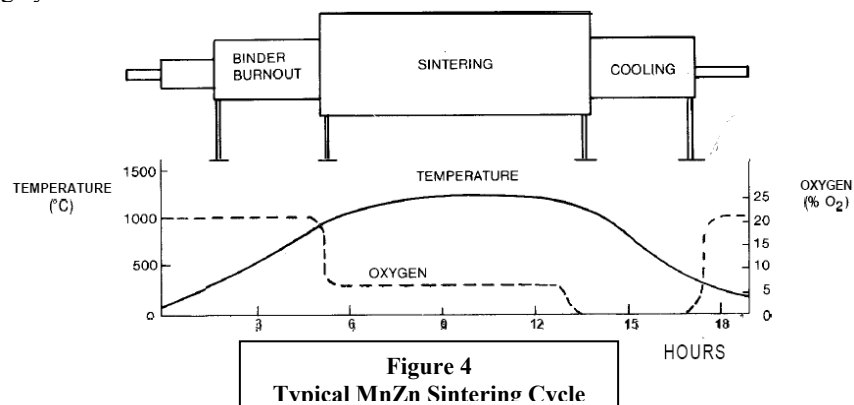

Figure 4
Typical MnZn Sintering Cycle

The temperature is further increased to the final sinter temperature. of IOOO- 1500" C, depending upon the type material. While the temperature is increasing, a non oxidizing gas is introduced into the kiln to reduce the oxygen content of the kiln atmosphere. During the cool-down cycle a reduction of oxygen pressure is very critical in obtaining high quality MnZn ferrites.

The sintering of nickel-zinc ferrites occurs at lower temperatures, in the range of 1000-1200" C. This material can be sintered in an air atmosphere.

During sintering the parts shrink to their final dimensions. Different material and processing techniques result in variance in this shrinkage but typical linear shrinkage ranges from 10 to 20% of the formed dimensions. The final part dimensions can be held to mechanical tolerances of +2% of the nominal part dimensions. Figure 4 shows a typical manganese-zinc sintering cycle in a tunnel kiln.

Finishing

After sintering most ferrite parts will require some form of finishing operation to meet customer requirements. Although the intrinsic magnetic properties have been set during sintering and cannot be altered, proper finishing techniques can optimize the magnetic performance of ferrite cores. The following are common examples:

Gapping

There are two accepted methods for specifying a gap. One is by specifying an AL value, the second is to specify a mechanical gap length. The former allows for tighter A, tolerance but with slightly varying gap lengths from batch to batch. Thus the user must specify one of the two methods, never both.

Typically, ungapped cores have tolerances of *25% on the A,. Standard "gapped A, values" have tolerances from 1.0% to 5%, if gap depth is 0.010 inches or larger. Shown in Figure 5 is an example of A, vs. gap length curves. As you move up the A, scale, it becomes increasingly difficult to hold tight tolerances. This is due to the decreasing size of the gap coupled with limitations of the machine performing the gapping.
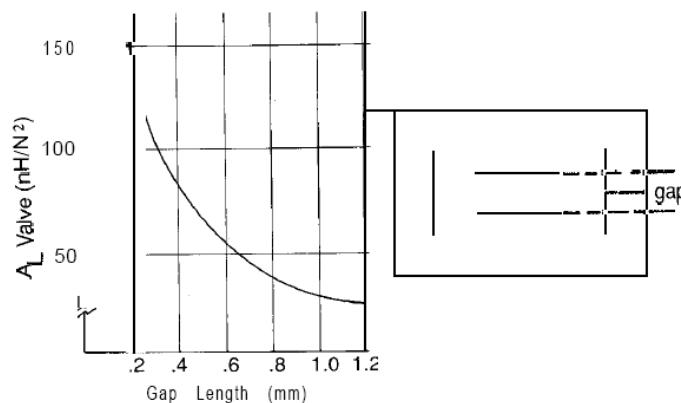

Figure 5
A, vs. Gap Length

Lapping

Lapping is an additional production process used to decrease the effects of an air gap on mated cores, typically done on mated cores with material permeabilities over 5000 in order to achieve the maximum A, value for a given material. The process involves polishing the mating surface of the core, after grinding, using a slurry based media. This produces a "mirror-like" finish that requires careful handling in packaging and in customer assembly. However, cosmetic appearance is secondary to the specified '4,. Since this is a time consuming secondary operation, the cost impact vs. minimum A, should be considered.

Coating

Coating of toroids is done after tumbling to enhance dielectric resistance, reduce edge chips, and provide a smooth winding surface. Among the choices of coatings are nylon, epoxy paint and parylene.

The nylons and epoxy paints typically need a minimum coating thickness of .005" to ensure uniform protection. Because of this restriction, they are used mainly on toroids with outer diameters of .500" or greater. One advantage of these coatings is that the color can be varied for core material identification without stamping. Breakdown voltages are between 500 to 1000 volts per .003" of coating. Parylene is a colorless coating used on toroids with outer diameters less than .500" due to the high cost of the raw material.

Parylene offers the advantage of higher voltage breakdown, at approximately 1000 volts per .OOl". The coating thickness can be controlled down to .0005" and still maintain uniform protection. Table 2 lists additional finishing operations.

Surface grinding to obtaining tight mechanical tolerances
Slicing rods and tubes of beads on wire
Profile grinding of threaded cores
Cementing wires for identifcation
Marking for identification
Packaging for automated assembly
Installing tuner nuts in pot cores and RM cores
Gapping to Control A_L, and bias capability

Table 2
Ferrite Finishing Operations

SECTION 3.0, PROCESS CONTROL / QUALITY ASSURANCE

As is the case in most technologies, ever increasing demands are being placed on soft ferrite manufacturers to further improve their performance in terms of both product quality and adherence to specified delivery schedules. Successful worldwide competitiveness, in all areas of commercial endeavor, requires that the highest levels of quality and reliability be maintained. The member companies of the IMA Working Group have recognized the needs of the industries they serve, and have instituted measures to insure that they are able to meet their customers' quality requirements. The implementation of statistical process control, SPC, and the attendant emphasis on controlling quality at each process step rather than inspection of the final product, has led to significant improvements in overall performance.

Implicit in every manufacturing step indicated in Figure 1 of Section 2, is a process control function. The capability of each step of the process is first determined, and the performance of the operation is then constantly measured against the established standard. By insuring that each discreet process is functioning within predetermined acceptable limits, a high probability exists that the properties of the final product will conform to expected values. Each step of the process generally has several critical parameters, which if permitted to vary from the established allowable limits, will result in the final product not attaining its required properties. One cannot deem any of the processing steps as being the most important, since failure to properly control any one of them will result in an unpredictable final result. Listed below are examples of some of the processing parameters which must be controlled in the manufacture of soft ferrites, along with indications of the effects of the variations beyond acceptable limits. The list is not meant to be all inclusive.

Raw Materials
- Impurities must be present below specified upper limits.
  For example, excessive silica in manganese zinc
  ferrite material will severely limit the attainable permeability.

- Specific surface area must be within allowable limits.
  Variations will produce adverse effects on magnetic
  properties and changes in sintering shrinkage

Powder Preparation

- Chemical composition must be kept within allowable limits in order to achieve desired magnetic properties. This control is achieved using advanced analytical instrumentation.

Physical Aspects of Powder

- Moisture content, flowability, and particle size distribution must be controlled to insure that a structurally sound part is formed.

Pressing

- Pressed density must be controlled in order to achieve desired sintering dimensions, as sintering shrinkage is a function of the density of the green (unsintered) part.

- Green density uniformity must be controlled over the entire volume of a pressed part in order to prevent distortion upon sintering, such as the warpage of E core legs, or cracked cores.

- Press height must be controlled to achieve desired sintered height. As noted earlier, the sintering shrinkage is a function of the green density as well as the inherent material shrinkage, at a given pressed density. Figure 6 is a representation of the typical change in core volume from the green to the sintered state, which is typically 40 to 50%.
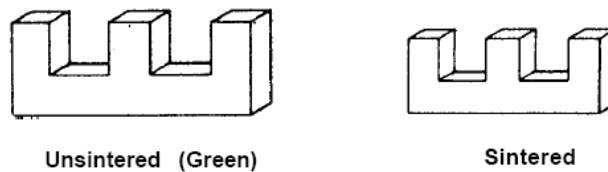

Unsintered (Green)　　　Sintered

Figure 6
Typical change in core volume from the green to the sintered state

Sintering

- Temperature Profile - temperatures constituting the sintering process must be maintained within tight limits in order that correct physical and magnetic properties are attained. Improper control during the initial stages of sintering can result in physical problems due to overly rapid binder removal. Poorly controlled initial stages of heating, or later stages of cooling, can result in stress induced fracture. A difference of as little as 3" out of 1400" C in peak temperature can have a profound effect on final properties.

- Atmosphere Profile - proper control of atmosphere during sintering is necessary to achieve desired magnetic properties. Inadequate control, to the extent of 0.1% oxygen during the cooling stages of sintering a manganese zinc ferrite, or even 0.01% oxygen at the very end of the process, can have extremely deleterious effects.

Finishing

- Grinding of Mating Surfaces - proper control of the flatness and degree of finish of the mating surface is essential to achieving the desired A, value of parts such as E, EC, RM, ETD, and Pot Cores.

- Development of Edge Radius - tight control of the tumbling operation for toroids, beads and baluns, is necessary in order that a sufficient radius is developed along with chip and crack free cores.

In addition to extensive process control measures, the member companies of the MMPA utilize other means to achieve improved quality and reliability. These include the implementation of quality manuals and quality audits, the use of quality circles and the establishment of continuing training programs. Maintaining good supplier/user communications is also a key factor in providing a quality product meeting customer requirements. The user's contribution is critical to this process. All these measures insure a highly controlled final product which in theory does not require final inspection. Achievement of this state is a fundamental necessity for predictable cost effective manufacturing. It provides the user with consistent quality, lot-to-lot, shipment-to-shipment.

SECTION 4.0, MATERIALS & GEOMETRICS

As mentioned earlier, soft ferrites are a class of ferrite materials based on the spine1 or cubic crystal structure. They are produced in two material categories, manganese-zinc and nickel-zinc.

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 MnZn category a large variety of materials is possible. The material selection is mainly a function of the application that needs to be accommodated. The application dictates the desirable material characteristics, which in turn determines the chemical composition of the ferrite material. Manganesezinc ferrite is primarily used for frequencies less than 2 MHz. Figure 7 shows the composition diagram for MnZn ferrites in mol % for Fe,O,, MnO and ZnO. It identifies the composition which gives optimum performance for saturation flux density (Bs), low losses (Q) and high initial permeability (pi). It also identifies the Curie temperature (T,) lines for 100 and 250°C. From this composition chart, it is clear that not one composition, not one MnZn ferrite, can fulfill all design objectives.
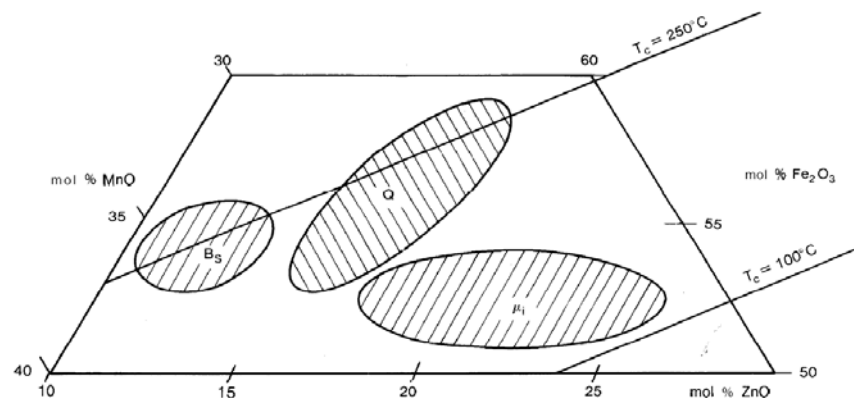

lure 7. Composition Diagram for MnZn Ferrites

B_s - Compositions of Higher Saturation
Q - Compositions of Higher Q
μ_i - Compositions of Higher Initial Permeability

Figure 7
Composition Diagram for MnZn Ferrites

Nickel-Zinc Ferrites.

This class of soft ferrites is characterized by its high material resistivity, several orders of magnitude higher than MnZn ferrites. Because of its high resistivity NiZn ferrite is the material of choice for operating from l-2 MHz to several hundred megahertz. To cover such a wide frequency range and different applications, a large number of nickel-zinc materials have been developed over the years.

It should be noted that certain nickel chemistries, especially those containing cobalt, can be adversely changed by some types of stress. Mechanical shocks from dropping or from some grinding operations are one possibility. Strong magnetic fields from holding devices and fixtures or magnetic chucks used in machining operations may also provide this stress.

These resulting changes can include increasing of permeability and core loss (lowering of Q). These changes cannot be reversed by degaussing or other electric/magnetic processes. In some cases, a thermal anneal at high temperature can restore some of the initial properties. The core manufacturer can provide details for treatment appropriate to core and process.

A summary of typical MnZn and NiZn materials, indicating the major material parameters and the operating frequency ranges, is shown in Table 3.

TABLE 3

PARAMETER	MANGANESE-ZINC				NICKEL-ZINC		
TYPICAL FERRITE MATERIALS							
Initial permeability range	"1400 to 3500	750 to 3500	3500 to 4500	4500 to 15,000	10 to 75	75 to 200	200 to 1000
Curie temperature range ("C)	180 to 280	150 to 250	130 to 150	120	250 to 500	200 to 500	90 to 200
Flux density range (gauss)	3500 to 5200	2400 to 4750	3000 to 5000	3000 to 5000	1000 to 2500	2500 to 3500	2800 to 3500
at H (oersted)	12.5	12.5	12.5	12.5	100	50	25
Power loss density (mW/cm³) at 100 kHz - 1000 G	< 100						
Loss factor tan δ/μ_i x10^{-6} at f- 30 kHz				30			
100 kHz	10	5	20				
300 kHz							10-50
1 MHz		25				20-40	20-70
3 MHz						25-60	50-200
10 MHz					50-200	100	
30 MHz					1 oo-1500		
100 MHz					400-2000		
**Typical frequency range kHz	10 to 500	10 to 2000	10 to 200	10 to 100			
MHz					10-150	2-30	1.5-5

*Materials for power applications
**This frequency range does not apply for ferrite materials used in EMI suppression applications.

Ferrite versus other Magnetic Materials.

After comparing the two types of soft ferrites, it might be of interest to see how soft ferrites compare with other magnetic materials such as magnetic alloys and iron powder. See Table 4.

TABLE 4

MAGNETIC MATERIALS				
	FERRITES	ALLOYS	IRON POWDER	AMORPHOUS
Initial permeability range	5 to 15,000	5000 to 300,000	5 to 150	3000 to 150,000
Curie temperature range (°C)	100 to 500	500	750	210 to 485
Saturation flux density range (k gauss)	3 to 5	8 to 24	10 to 12	5.5 to 10
Coercive force (oersted)	.05	.003 to 3		.003 to 3
Loss factor tan δ/μ_i x10^{-6}				
at f = 10 kHz	5	8	25	
100 kHz	10	80	30	
1 MHz	25	4000	100	
Resistivity (Q-cm)	10' to 10^8	10^{-5}	10^4	1.4 x 10^{-4}

At high frequencies, ferrites have substantial advantages over conventional metallic materials, either in lamination or powder forming technology. Ferrites offer additional mechanical features as well. Ferrites can be shaped in a variety of different core geometries optimized for specific applications. For example, cores can be designed for ease of assembly, or made self shielding where required. Table 5 highlights the differences between soft ferrites and other magnetic materials.

TABLE 5

FERRITES VERSUS OTHER MATERIALS	
ADVANTAGES	DISADVANTAGES
High resistivity	Low saturation flux density
Wide range of operating frequencies	Poor thermal conductivity
Low loss combined with high permeability	Low tensile strength
Time and temperature stability	Brittle material
Large material selection	± 2% tolerances on unfinished dimensions
Versatility of core shapes	
Low cost	

Core Geometries

As in the case with ferrite materials, where specific applications require materials developed for that application, core geometries can be tailored to meet specific magnetic and mechanical requirements. A tunable high Q inductor dictates a different core shape than one used in TV line output transformers. Figures 8-1, 8-2, and 8-3 on the next pages show an evaluation of the most popular core geometries for a number of design parameters and cost considerations.

Future Trends

The various material chemistries and their respective properties and trade-offs are well known to the core manufacturers. Specific application trends will drive future material development. High frequency power and noise reduction are major areas of user interest.

Development costs and manufacturing economics limit the number of materials manufacturers can produce. Each offering is a compromise designed to best meet ongoing customer needs. New material developments can take two to three years. Manufacturing logistics and economics also limit the combinations of core size/material, as do applications.

New shapes evolve more rapidly. Tooling made from carbide is expensive. Producing a die for low volume application is not economical or efficient. For special shapes, prototypes, and low volume applications, cores can frequently be machined or partly machined more economically than building a die. Discussions with suppliers regarding realistic quantity needs define the most cost effective manufacturing method.

Major current shape development trends relate to low profile and surface mount applications. Low profile designs are simple shapes (See Figure 8-3) in which the core is inserted through a circuit board containing the "windings". Other designs use longer, lower winding windows along with more sophisticated core designs to meet low height needs. "Integrated. Magnetics" attempts to optimize a total conductor/ core structure performing multiple magnetic functions for maximum density and efficiency.

Surface mount designs offer simple as well as complex approaches. Small beads can be connected with a simple formed conductor. Conventional through-hole bobbins for mated cores can be tooled with surface mount terminations. With this approach, the magnetic (transformer) design need not be redone. Other adaptations combine low profile designs with surface mount configurations to minimize space requirements.

FIGURE8-1. Evaluation of Core Geometries

POT CORE   RM CORE   SOLID CENTER POST RM CORE

	POT CORES	RM CORES	SOLID CENTER POST RM CORES
APPLICATION	High Q Inductors & tuned transformers		Power and wideband transformer
MAGNETIC SHIELDING	Very good	Good	Good
CAN BE SUPPLIED GAPPED	Yes	Yes	Yes
WITH TUNER	Yes	Yes	No
CORE STANDARDIZATION	Yes(IEC)	Yes (IEC)	Yes(IEC)
COST OF CORE	High	High	High
COST OF WINDING & ASSEMBLY	High	Average	Average
HEAT DISSIPATION	NA	NA	Poor
UNIFORM CROSS SECTION	No	No	No(but better than regular RM cores)

EC CORE   U CORE   E CORE   ETD CORE   PQ CORE   U CORE
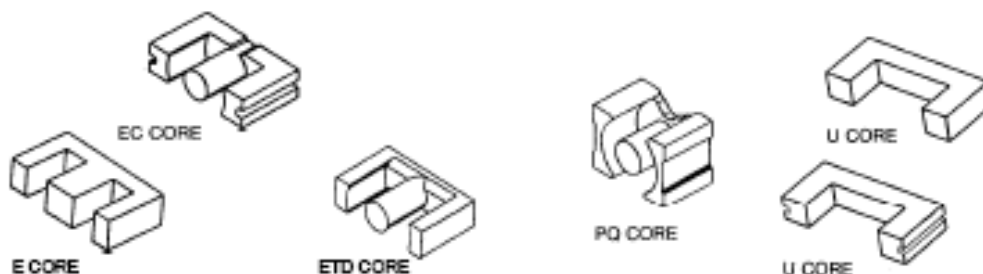
	E CORES				U CORES
	E	EC	ETD	PQ	
APPLICATION	Power transformers and inductors				
MAGNETIC SHIELDING	External magnetic field generated close to the exposed winding				
CAN BE SUPPLIED GAPPED	Yes	Yes	Yes	Yes	No
CORE STANDARDIZATION	De facto	Yes (IEC)	Yes (IEC)	De facto	No
COST OF CORE	Low	Low	Low	Average	Low
COST OF WINDING & ASSEMBLY	Low	Low	Very Low	Average	Low
HEAT DISSIPATION	Very good	Very good	Very good	Very good	Very good
UNIFOM CROSS SECTION	Yes	No	Yes	No	Yes

**Figure 8-2. Evaluation of Core Geometries**

EP CORE   TOROID   BALUN CORE   SIX HOLE CORE
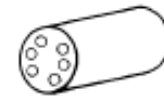
MULTI-APERTURE CORES

	EP CORES	TOROIDS	MULTI-APERTURE CORES
APPLICATION	Power	Wideband and pulse transformers Common mode chokes	
MAGNETIC SHIELDING	Very good	Excellent	Excellent
CAN BE SUPPLIED GAPPED	Yes	Rarely	No
CORE STANDARDIZATION	De facto	De facto	No
COST OF CORE	High	Low	Low
COST OF WINDING & ASSEMBLY	Average	Very High	Very High
HEAT DISSIPATION	Poor	Good	NA
UNIFORM CROSS SECTION	No	Yes	No
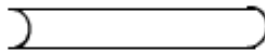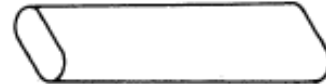
RODS   TUBES   STRIPS

	RODS, TUBES & STRIPS
APPLICATION	Antennas, HF welding
MAGNETIC SHIELDING	Very poor
CAN BE SUPPLIED GAPPED	NA
CORE STANDARDIZATION	No
COST OF CORE	Very low
COST OF WINDING & ASSEMBLY	Average
HEAT DISSIPATION	Good
UNIFORM CROSS SECTION	Yes

Figure 8-3. Evaluation of Core Geometries

CABLE SUPPRESSION CORE

PLANAR

LOW PROFILE CORE

RIBBON CABLE SUPPRESSION CORE

EFD CORE
EPC CORE
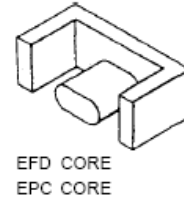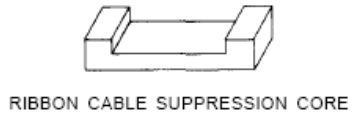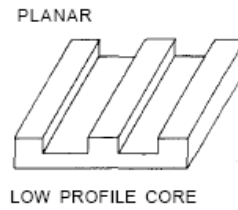
EMI CORE SHAPES

LATEST CORE SHAPES

	EMI CORES	LATEST CORE SHAPES
APPLICATION	EMI Suppression	Low profile & surface mount power transformers
MAGNETIC SHIELDING	Good	Good
CAN BE SUPPLIED GAPPED	N A	Yes
CORE STANDARDIZATION	No	No
COST OF CORE	Average	Average
COST OF WINDING & ASSEMBLY	Low	Low
HEAT DISSIPATION	N A	Very good
UNIFORM CROSS SECTION	Yes	————

SECTION 5.0, DEMINSION NOMENCLATURE FOR SOFT FERRITE CORES

Scope

This standard presents a method for defining the designation nomenclature for the major physical attributes of soft ferrite core shapes. The purpose of this standard is to facilitate uniform usage of dimensional characters by manufacturers, specifiers, and users when describing core dimensions on drawing, in tables, and on catalog specification sheets.

General Assignment Guidelines

- Only upper case alphabetic characteristics are used.
- Only one character per dimension per ferrite piece.
- Character 2B and 2D may be used for core sets

Dimension Descriptions

Table 6 and Table 7 describe the alphabetic character assignments for the major dimensions of ferrite shapes. All other minor core dimensions designations are left to the discretion of the specifier.

Letter	Dimension Description
A	Toroid outside diameter
B	Toroid inside diameter
C	Toroid height

Table 6
Torodial Core Dimension Designations

| Letter	Dimension Description
A	Overall length of the core back or diameter
B	Outside leg length of height of core
C	Core width or floor width at wire aperture
D	Inside leg length or bobbin depth
E	Bobbin width or hole spacing
F	Center post thickness of diameter
G	Wire aperture or slot width
H	Center post hole diameter
J	RM core side-to-side parallel width
K	Center post offset dimension

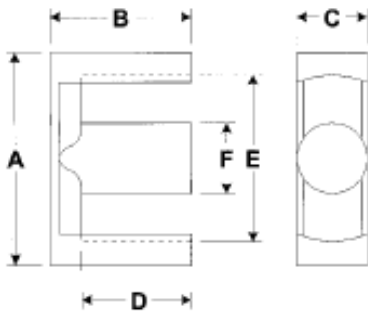**Table 7**
Ferrite Shapes Dimensions Designations

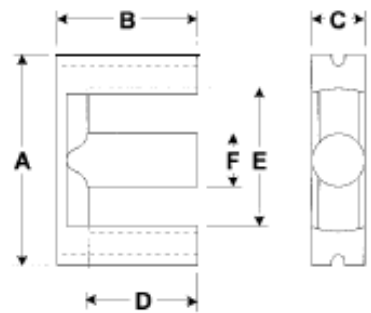The following illustrations represent typical core geometries with the standard dimension nomenclature applied.
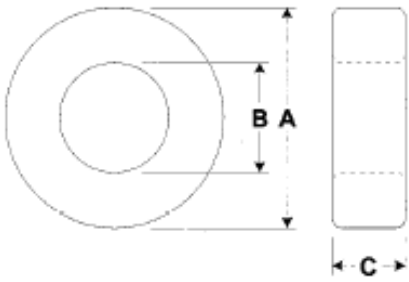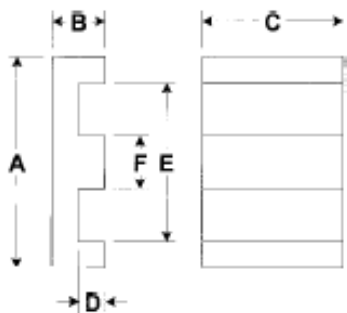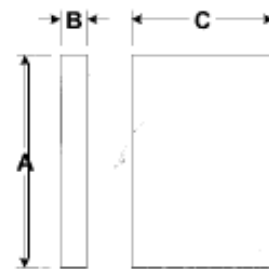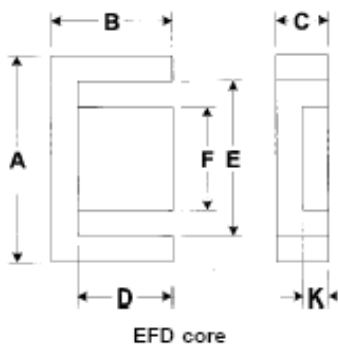

Toroid core
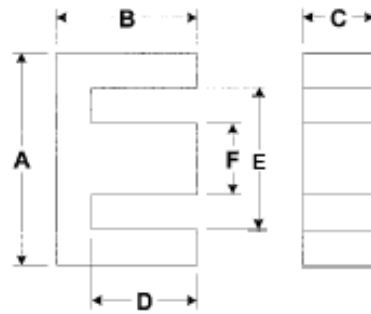
E-core

ETD or ER core

EC core

Planar E-core

I-core

EFD core
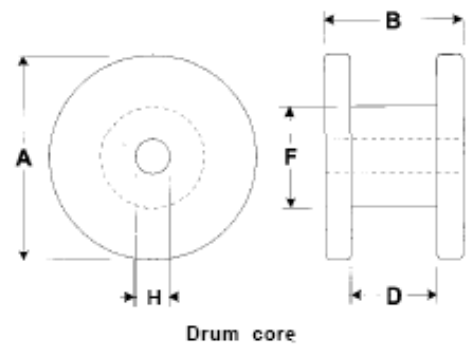
Drum core
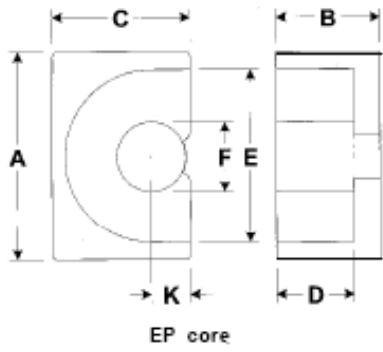
EP core

PQ core

Pot core

RM core

U-core

UR core

Balun

Multi-hole bead
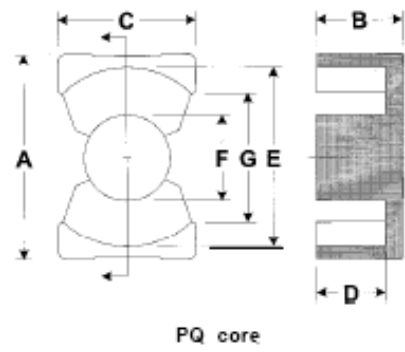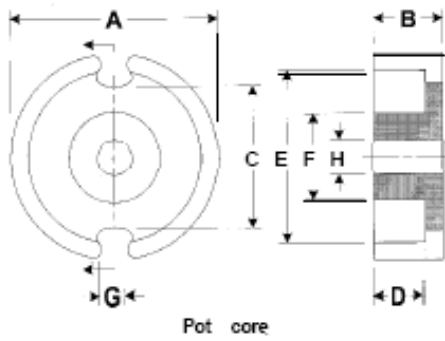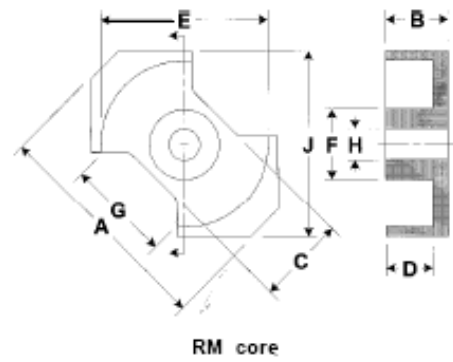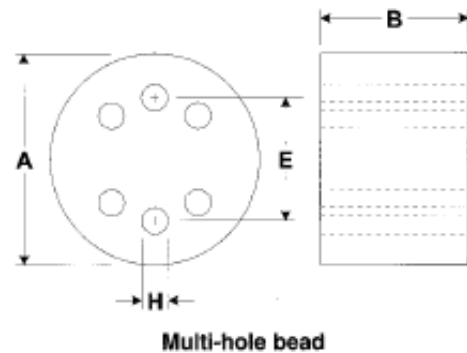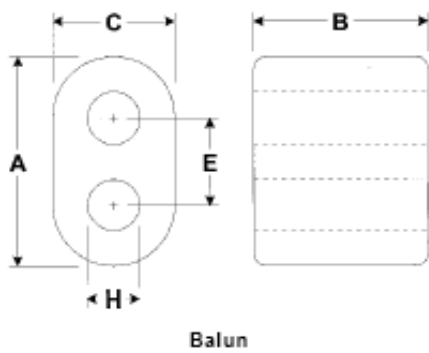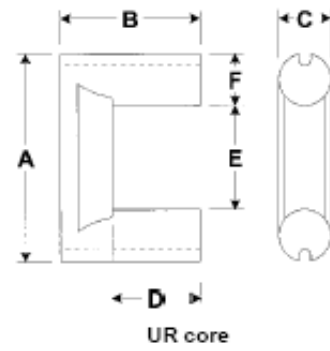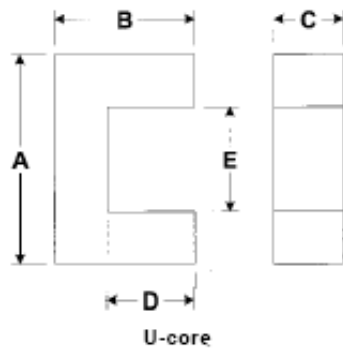
Specific Core Characteristics

Dimension tolerances, calculation of core parameters, chip and crack acceptability, and general test conditions can be obtained from the following IMA Working Group publications:

- IMA-STD 110, Standard Specification for Pot Style Cores
- IMA-STD 120, Standard Specification for Ferrite Threaded Cores
- IMA-STD 130, Standard Specification for Ferrite U, E, & I Cores
- IMA-STD 140, Standard Specification for Ferrite Toroid Cores

SECTION 6.0, CALCULATION OF CORE CONSTANTS

Calculating Core Constants & Parameters

In calculating core parameters, we are defining a hypothetical toroid that will have the same properties as the non-uniform core, In these calculations we follow the rules as defined in IEC Publication 205. (See Appendix 3.) The results of these calculations are approximate because of assumptions made about the mean magnetic path and the effective area of each section of the core.

Core constants C_1 and C_2 can be expressed as:

$$C_1 = \Sigma \frac{\ell}{A} (cm^{-1}) \text{ and } C_2 = \Sigma \frac{\ell}{A^2} (cm^{-3})$$

The effective core parameters can be calculated from C_1 and C_2:

Effective area $\quad A_e = \dfrac{C_1}{C_2} (cm^*)$

Effective path length $\ell_e = \dfrac{C_1^2}{C_2} (cm)$

Effective Volume $\quad V_e = \dfrac{C_1^3}{C_2^2} (cm^3)$

The core constant C_1 is also used to determine the air core inductance of a core configuration:

$$L_0 = \frac{4\pi N^2 10^{-9}}{C_1} (H)$$

Toroidal Core

(See Figure 10). The summation is performed using a small slice of the core, " dr" over the cross sectional area resulting/ in:
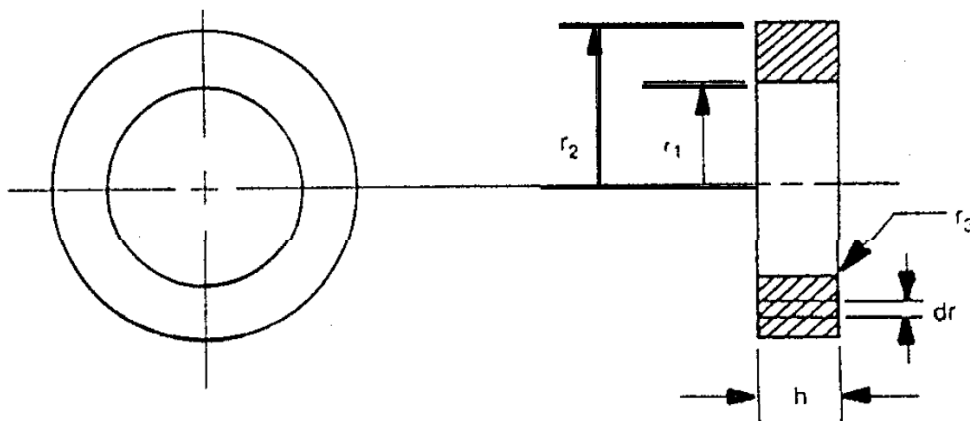
Figure 10
Toroid

$$C_1 = \frac{2\pi}{h \log_e (r_2/r_1)}$$

$$C_2 = \frac{2\pi (1/r_1 - 1/r_2)}{h^2 \log_e^3 (r_2/r_1)}$$

To correct for rounded corners r_3, multiply " h" by:

$$1 - \frac{.8584 r_3^2}{h (r_2 - r_1)}$$

E Core Set

(See Figure 11). This core set is divided into five sections. The e/A and the e /ti for each section is shown below
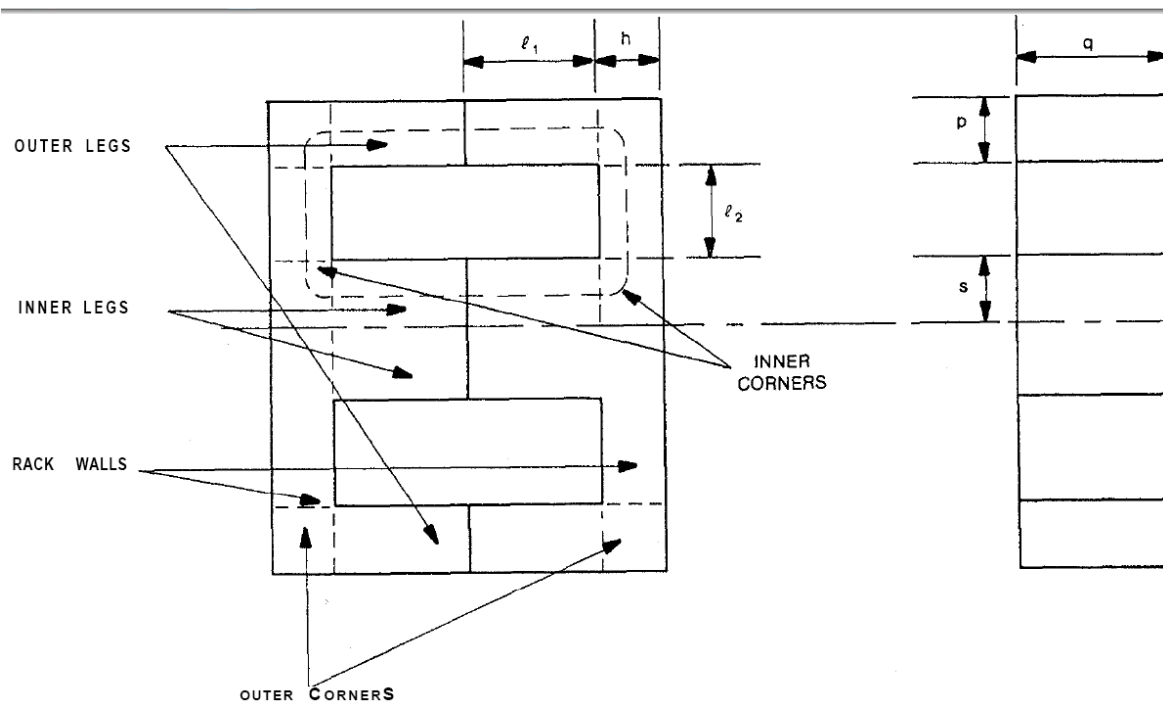
Figure 11
E Core Set

$$C_1 = \sum_1^5 \frac{\ell}{A} \qquad\qquad C_2 = \sum_1^5 \frac{\ell}{2A^2}$$

Outer legs (1):	$\dfrac{\ell_1}{pq}$	$\dfrac{\ell_1}{2\,(pq)^2}$
Back walls (2):	$\dfrac{\ell_2}{hq}$	$\dfrac{\ell_2}{2\,(hq)^2}$
Inner legs (3):	$\dfrac{\ell_1}{sq}$	$\dfrac{\ell_1}{2\,(sq)^2}$
Outer comers (4):	$\dfrac{\pi}{4q}$	$\dfrac{\pi}{4q^2\,(h+p)}$
Inner comers (5):	$\dfrac{\pi}{4q}$	$\dfrac{\pi}{4q^2\,(h+s)}$

Pot Core Set

(See Figure 12). The pot core set is divided into five sections:
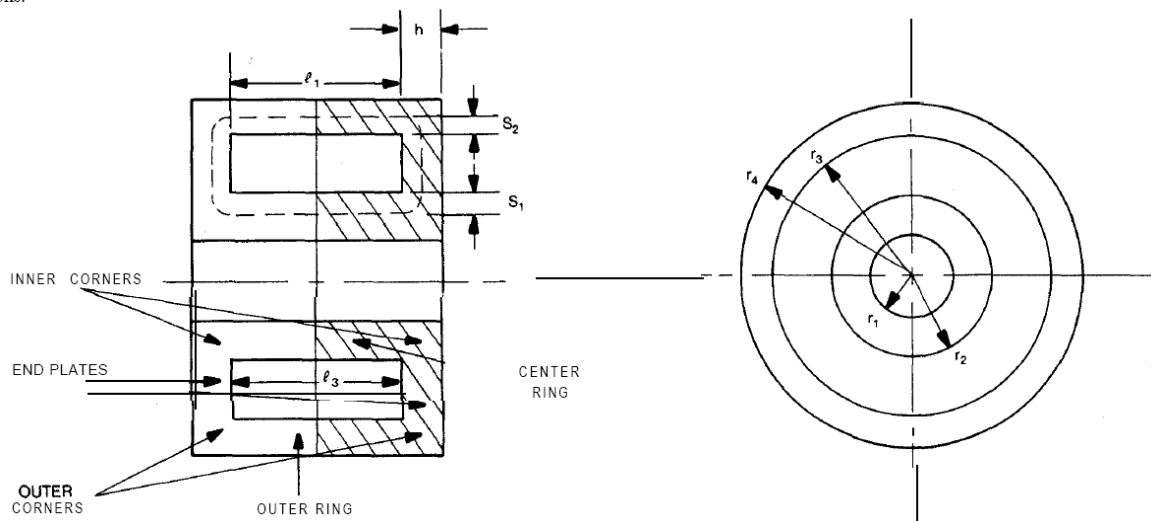
Figure 12
Pot Core Set

$$C_1 = \sum_{1}^{5} \frac{\ell}{A} \qquad C_2 = \sum_{1}^{5} \frac{\ell}{A^2}$$

Outer ring (1): $\qquad \dfrac{\ell_1}{\pi(r_4^2 - r_3^2)} \qquad \dfrac{\ell_1}{\pi^2(r_4^2 - r_3^2)^2}$

End plates (2): $\quad \dfrac{1}{\pi h}\log_e\dfrac{r_3}{r_2} \qquad \dfrac{1}{2\pi^2 h^2}\dfrac{r_3 - r_2}{r_2 r_3}$

Center ring (3): $\qquad \dfrac{\ell_3}{\pi(r_2^2 - r_1^2)} \qquad \dfrac{\ell_3}{\pi^2(r_2^2 - r_1^2)^2}$

Outer comers (4): $\qquad \dfrac{(s_2 + h/2)}{2r_3 h + r_4^2 - r_3^2} \qquad \dfrac{2(s_2 + h/2)}{\pi(2r_3 h + r_4^2 - r_3^2)^2}$

Inner comers (5): $\qquad \dfrac{(s_1 + h/2)}{2r_2 h + r_2^2 - r_1^2} \qquad \dfrac{2(s_1 + h/2)}{\pi(2r_2 h + r_2^2 - r_1^2)^2}$

Where:

$$s_1 = r_2 - \sqrt{\frac{r_1^2 + r_2^2}{2}} \qquad s_2 = \sqrt{\frac{r_3^2 + r_4^2}{2}} - r_3$$

For pot core sets with slots, the following corrections can be made:

$\qquad$ n = number of slots

g = width of slots

Subtract from outer ring area (At);

$$ng(r_4 - r_3)$$

Correct end plates by multiplying:

$$\frac{\ell_2}{A_2} \text{ by } \frac{1}{1 - \dfrac{ng}{2\pi r_3}}$$

and

$$\frac{\ell_2}{A_2{}^2} \text{ by } \frac{1}{\left(1 - \dfrac{ng}{2\pi r_3}\right)^2}$$

Correct outer corner areas (A_4) by multiplying:

$$1 - \frac{ng}{\pi(r_3 + r_4)}$$

SECTION 7.0, APPLICATIONS

The early development of soft ferrites was directed towards materials of high permeability and low loss for use in the entertainment and telecommunications industries. From this modest beginning, soft ferrite's usage mushroomed into a broad range of applications that cover a wide operating frequency range.

The shape of the hysteresis loop for any soft ferrite is interrelated with its application. How the ferrite reacts to its excitation frequency and amplitude is very important in measuring its effectiveness to meet user needs. Figure 9 illustrates a typical loop and describes several of the significant magnetic parameters. Soft ferrite features are described in the section titled "Materials and Geometries". Selection of both core material and geometry is clearly application oriented. Optimal performance is achieved through correct material and geometry choices.

Classifications

Soft ferrite applications fall into three major areas:
- Low signal ferrites
- Power handling ferrites
- Interference suppression ferrites

There are other uses for ferrites, such as memory storage systems, microwave gyrorotational devices, and thermal switching devices, but most of the materials produced today focus on these three classifications.

Low Signal Level

Low signal level ferrites may be grouped into four sub-classifications:

- High Q inductors
- Common mode inductors

- Wideband and matching transformers
- Pulse transformers

In all of these, the core windings excite the core to low levels of operating flux density. Each of the subclasses requires unique features in the ferrite core. Some of these are common, but there are preferred shapes and material types for each.

High Q Inductors

The majority of High Q Inductors are used in analog devices, particularly in telecommunications applications. A component must resonate at the desired frequency, be stable over time and temperature range, and have high permeability combined with negligible energy loss. Finally, the inductor should occupy the smallest possible volume and be cost effective.

Although telecommunications is the largest and most critical segment, High Q Inductors are also used in many other electronic areas. These include communications, entertainment, controls. and other industries. The objectives and the features that ferrite vendors supply to facilitate the design of High Q Inductors are found in Table 6. As reflected in this table, device specifications mandate the ferrite material and core geometry requirements.
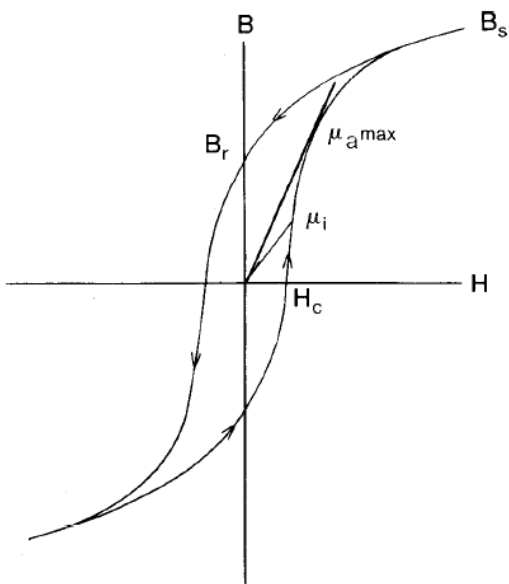
Figure 13
Typical B vs. H Loop

$B =$	Magnetic Flux Density
$B_S =$	Saturation Flux Density
$B_r =$	Remanence
$H =$	Magnetic Field Strength
$H_C =$	Coercive Force
$\mu_i =$	Initial Permeability
$\mu_{a(max)} =$	Maximum Amplitude Permeability

The area enclosed by the hysteresis loop is a measure of hysteresis loss per cycle.

Application Objectives	Ferrite Core Features
High quality factor	Material with low core loss; gapped structure
Adjustable inductance	Mechanically tunable
Precise inductance	Closely controlled material permeability; closely controlled physical characteristics; gapped structure
Long term stability	Material with loc disaccommodation factor; gapped structure

Low cost	Standardized core sizes
Smaller size device	Further improvements in material characteristics

Table 8
Features of High Q Inductors

Ferrite manufacturers provide standard inductor geometries, influenced by IEC standards. These are in the configurations of pot cores, RM cores, and in some cases, toroids. Manufacturers' literature describes the magnetic and physical parameters of the cores.

Common Mode Inductors

The most frequent use of common mode inductors is in power conditioning or power supply components. Although this is a relatively narrow application segment of the soft ferrite market, large quantities of cores are utilized. Their function is to insure that the power being supplied to an electronic device is "clean". Additionally, they prevent common mode noise generated by the equipment from escaping into other circuitry. The common mode inductor forms the heart of the low pass power filter.

The core may operate at moderate flux densities, but is generally designed to function at low amplitudes. Many of the characteristics desired in materials for High Q Inductors are also needed for these filters Demands on temperature stability, high quality factor, and precision inductance are not as stringent.

Most common mode inductors utilize toroids, but in some cases ungapped pot cores or PQ cores may be employed. When using toroids, the core must be insulated from the winding with high resistance barrier. The section of the guide on "User Assembly Considerations" should be noted when applying these coatings. The device requirements of common mode inductors and the corresponding ferrite features are shown in Table 9.

Wideband & Matching Transformers

Although some energy is transferred in wideband transformers, they are used primarily to match impedances, provide precise current or voltage ratios and serve as interfaces between balanced and unbalanced circuits. Wideband transformers are designed to operate over a wide frequency range with low insertion loss in the mid-band area. Communications systems employ the largest number of wideband transformers. The materials utilized depend upon the frequency where low and high end cut-offs occur and the width of the pass band. Material requirements are high initial permeability (compatible with the frequency used), low loss, and magnetic stability. Design objectives and ferrite core features are shown in Table 10a. Typical geometries are shown in Table 10b.

Application Objectives	Ferrite Core Features
Very high inductance	Material with high permeability
Good quality factor	Material with low loss characteristics
Minimum stray field	Use of toroid or pot core
Long term stability	Low disaccommodation factor
Performance over temperature	Closely controlled μ_i versus temperature

Table 9
Features of Common Mode Inductors

Application Objectives	Ferrite Core Features
Lowest R_{dc} / L	Use IEC standard core
Sufficient termination room	Use core allowing compatible slots
Proper multi-pin coilform	Consult core supplier
Good magnetic shielding	Use cores that enclose windings

Table 10a
Design Considerations for Wideband Transformers

Ungapped pot cores
Ungapped RM cores
Ungapped EP cores
Multi-aperture cores
Toroids
E type cores

Table 10b
Commonly Used Shapes

Pulse Transformers

While pulse transformers are required to function over a wide frequency band, the fact that their signal wave shape is not sinusoidal makes them unique, both in their function as well as their ferrite requirements. The effect of the ferrite on the generally rectangular pulse shape is an important measure of their performance. The transformer, to function effectively, should transfer the pulse shape without appreciable distortion.

Ferrites are utilized as low-power pulse transformer cores in data circuits involving:
- Impedance matching
- Balanced to unbalanced circuits
- Isolation
- Precise voltage or current transformation
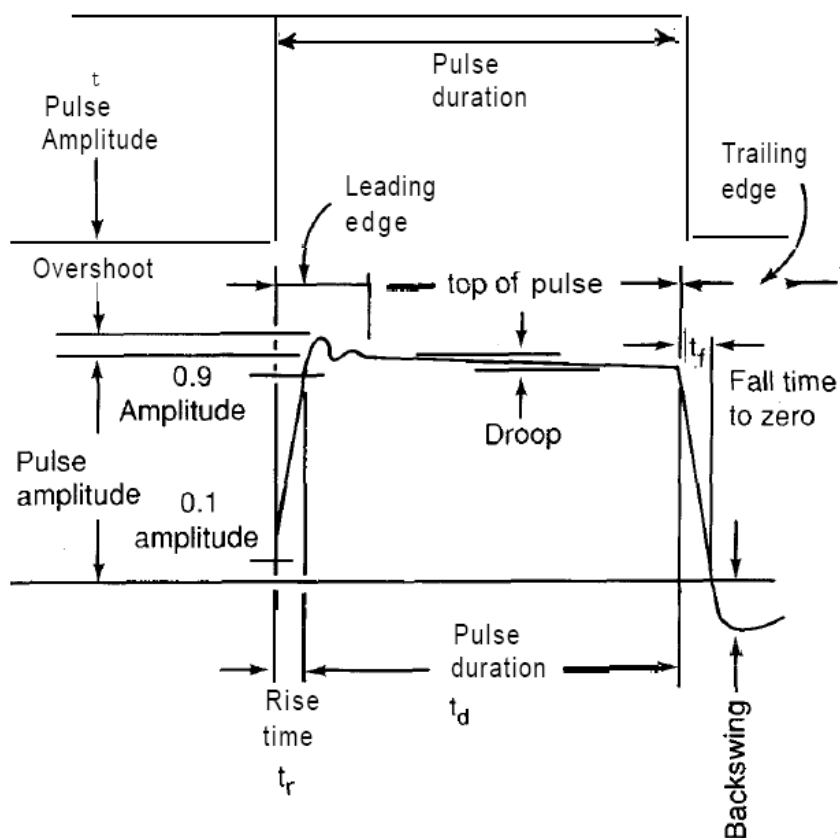
Figure 14
Ideal vs. Typical Tranmitted Pulse

NOTE: Figure 14 provides a description of an ideal pulse shape, and a typical transmitted pulse, showing the effect of the distortion contributed by the transformer. The important effects on the pulse shape are:

Pulse Portion	Effect
Leading Edge	Rise Time
Pulse Peak	Overshoot, Droop
Falling Edge	Fall Time, Backswing

Core properties impact all three areas. The two significant pulse ferrite parameters are the pulse permeability (l.+,) and a measure of the non-linearity of the magnetizing current commonly referred to as the voltage-time product (Et). The ferrite types used in pulse applications exhibit:
- High permeability
- Low core loss
- High saturation flux density
- Good magnetic stability

Geometries most frequently employed are:
- Toroids
- Pot cores - ungapped
- RM cores - ungapped
- EP cores - ungapped

Typical Properties Supplied By Manufacturers of Low Signal Ferrites

Producers of low signal ferrites provide data on their materials. They also provide component related information. Table 11a lists the typical information usually provided on these ferrites. Table 11b provides the component specific information.

Tabular Data	Graphic Data
Initial permeability	Loss factor-frequency

Saturation flux density	Initial permeability-frequency
Coercivity	Diaccommadation-time
Remanence	Permeability flux density
Curie temperature	Permeability temperature
Temperature coefficient of initial permeability	
Recommended frequency range	

Table 11a
Data Supplied By Ferrite Manufacturers For Low Signal Applications

Inductance factor for both ungapped and gapped cores (A)
Effective magnetic length of the core (I)
Effective cross sectional area of the core (A)
Effective volume of the core (V_e)

Table 11b
Component Specific Information Provided

Figures 15-1 through 15-5 represent typical graphic data supplied by the manufacturer. In figure 15-1, note that material A supplies lower loss at frequencies less than 1 MHz but material B becomes the low loss choice above that frequency.
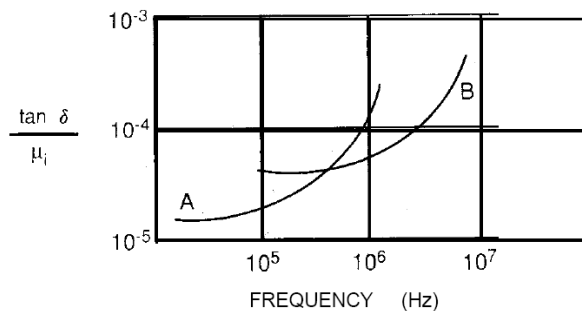
Figure 15-1. Loss Factor vs Frequency for 2 Materials
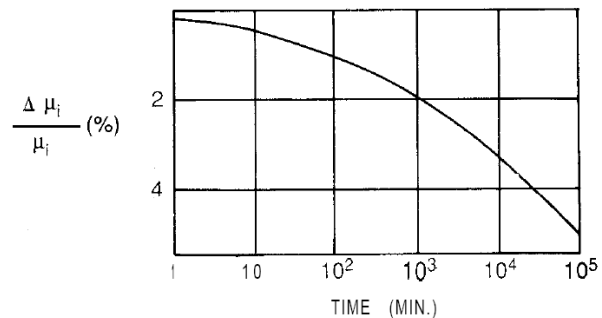
Figure 15-2. Proportional Decrease in Permeability vs Time
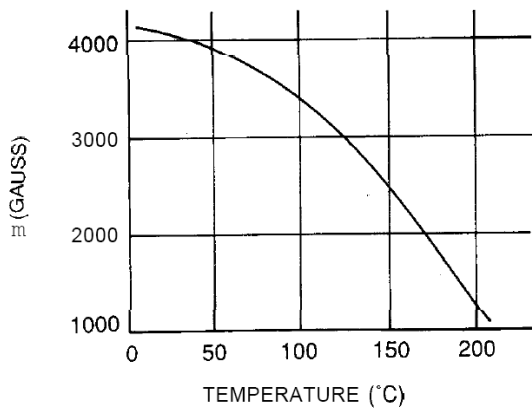
Figure 15-3. **Flux Density vs Temperature**
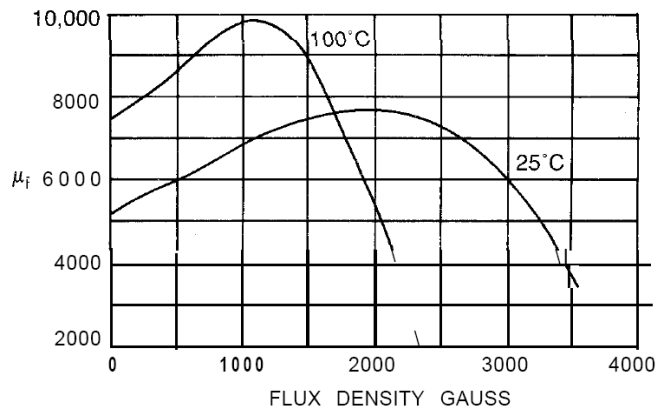
Figure **15-4. Permeability vs Flux Density**

Effects of Providing an Air Gap in a Ferrite Core Component

As noted in Table 8, the introduction of an air gap in the magnetic circuit can have an enhancing effect on the core performance in several ways. The effect of gapping mitigates material variations in permeability and moderates the temperature and disaccomodation factors of the ferrite on the component.

Gapping also reduces the loss factor compared to an ungapped circuit. A detailed discussion of the magnetic circuit theory relating to gapping ferrite cores may be found in Chapter 4 of "Soft Ferrites, Properties and Applications", 2nd edition, by E.C. Snelling (Butterworth and Company, 1988).
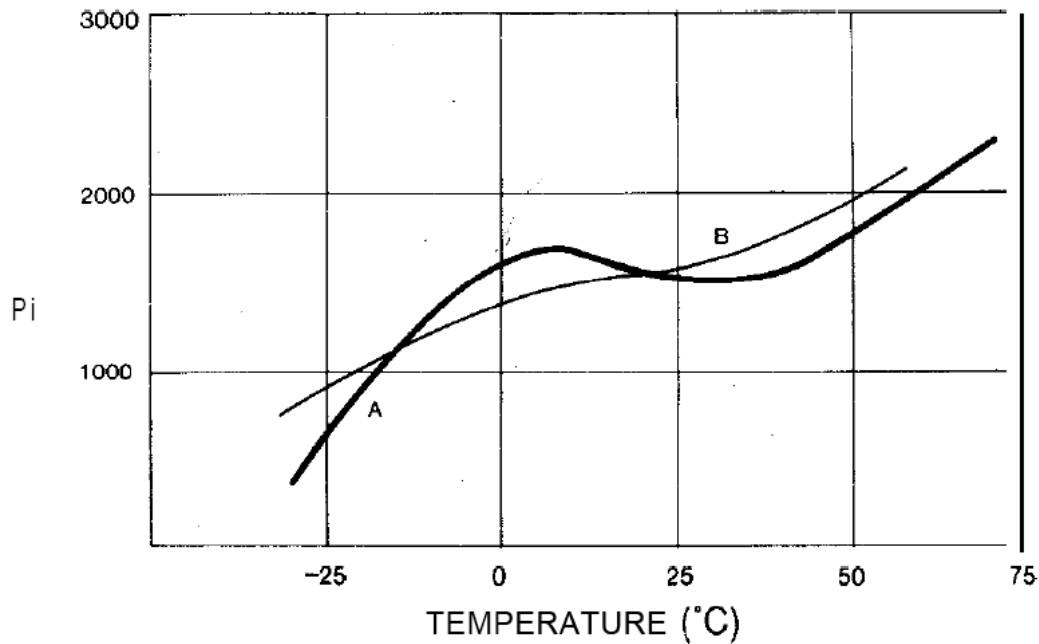
Figure 15-5. **initial Permeability vs Temperature**

Application Areas	Magnetic Function							
	Transformers				Inductors			
	POWER	DRIVE	LINE OUTPUT	CURRENT	CHOKE	MAGAMP	FILTER	STORAGE
Automotive Electronics	·	·		·	·		·	·
Consumer Electronics	·	·	·	·		·	·	·
Electronic Data Processing	·	·	·	·		·	·	·
Electric Tools		·		·	·			
Household Appliances	·	·			·		·	
Lighting		·			·		·	·
Measurement & Control		·	·	·			·	
Power Conversion	·	·		·	·			·
Telecommunication	·	·			·		·	·
EMC							·	

Table 12
Application Areas and Magnetic Functions

Power Applications

Power applications require the transfer of power through the magnetic device. This requires operation of ferrite at high flux density and elevated temperature in the core. Magnetic components are used for various applications throughout the industry. The magnetic function of these components in power applications is normally a transformer or inductor. Main application areas and function for power ferrites are listed in Table 12.

With the advent of switched-mode power supplies, the demand for ferrites in power applications has increased significantly. The trend in high frequency power supplies is to go to higher frequencies, which results in size reduction of the magnetic components. This challenge can only be met with ferrites.

The optimal design of a magnetic device with a ferrite core for power applications is governed by:
- Saturation flux density
- Allowable temperature rise

The first limitation applies to low operating frequency, typically 10 to 50 kHz. The second limitation, based on ferrite core and copper losses, normally applies to high operating frequencies (typically above 50 kHz).

Desirable ferrite material characteristics for power applications are:
- High saturation flux density at elevated temperatures (e.g. 100°C)
- Low loss at the operating frequency at high flux density and elevated temperature
- Minimum losses in the operating temperature range (usually 70-100°C)
- High resistivity to minimize the eddy current core loss

To aid the designer in choosing the most suitable material for a given power application, ferrite manufacturers provide typical material characteristics in a tabular or graphical form. This information is usually generated using a toroidal core of a given size. Guaranteed performance characteristics, such as inductance factor, core loss and amplitude permeability at specified test conditions, are given for a specific core. The most important parameters given in manufacturer's catalogs are:

- Amplitude permeability as a function of peak flux density (see Figure 16-1) normally given at room temperature (25°C) and maximum recommended operating temperature (100°C). The main use of these curves is to check that inductance of a given design stays within requirements over the specified range of flux densities. Power-ferrite cores will often have guaranteed minimum inductance at a specified flux density and temperature.
- One of the most important parameters for power ferrites in the power loss per unit volume as function of peak flux density. Data is provided at an elevated temperature for family of frequencies (see Figure 16-2). These curves show typical power loss characteristics of core materials measured on a medium size toroid (25mm OD) with sinusoidal excitation. This set of graphs is particularly helpful in selecting the operating flux density for magnetic designs that are loss limited. For the chosen frequency, an acceptable power loss density will determine the operating ,flux density. Maximum power loss is normally specified for a power ferrite core at given frequency, flux density, and temperature.

- Power loss density versus temperature is shown in Figure 16-3. This set of curves shows the power loss density for various flux densities and frequencies as a function of temperature. Modern power ferrites are designed to have a minimum loss at high operating temperatures.

To help the designer in choosing optimal power ferrite material for a given operating frequency, a new parameter for power ferrite classification is proposed. This parameter is called "performance factor", and represents a measure of through-put-power density for power ferrite.
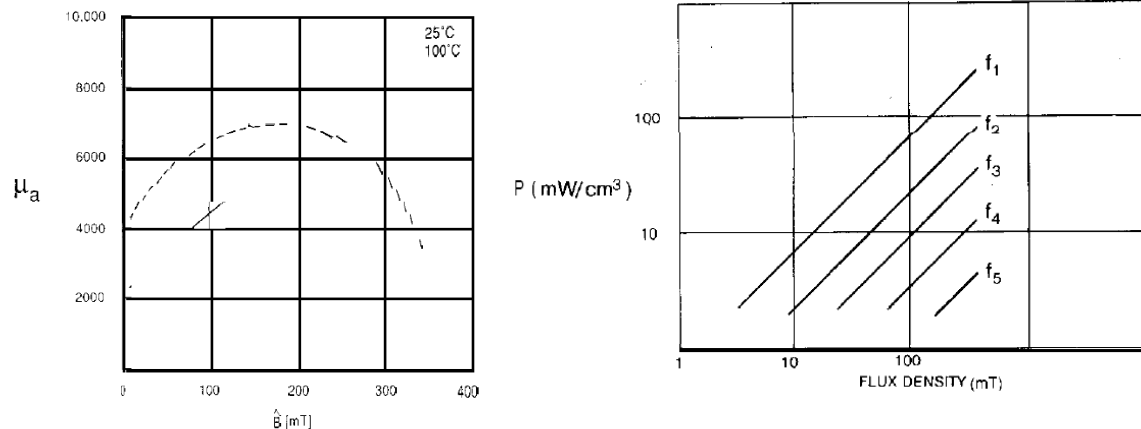
Figure 16-1. **Amplitude Permeability vs Flux density**   16-2. **Power Loss Density vs Flux Density**

Design Requirements	Core Geometry	Advantages	Disadvantages
High power, low cost	EE/EF/EI	Large ratio of core cross-section to winding area. Cores can be staked	Large mean-turn resistance. Insufficient window height for 8mm creep. Poor shielding
Optimal core design & safety isolation	EC/ETD/ER	Low mean-turn resistance & leakage inductance. Sufficient height for creepage	More difficult to manufacture (more expensive) than E-core
Low profile, high operating frequency	EFD/EPC	Easily adaptable for surface-mounting. Easy to assemble	Poor shielding
Very high power, low operating frequency	U-U/U-I	Can be used as building blocks for high power cores	Poor shielding, large mean-turn resistance
High power	PQ/LP	Small footprint on PC board, Easy to wind, terminate and assemble	Difficult to manufacture (high cost)
Efficient PC board utilization	RM/PM	Good magnetic shielding. Standardized range. Good selection of bobbins & clips	Non-uniform core cross-section
The best shielding. Low power, high frequency operation	P	Standardized range. Available with solid-center post	Restricted access for lead-outs. High thermal resistance

Numerous core shapes are available for power applications, some specifically optimized for maximum throughput power. In the selection of a ferrite core shape for high frequency, high power applications, the following core properties are desirable:
- Adequate flux carrying capability
- Minimization of the winding resistance and leakage inductance
- Minimization of thermal resistance (defined below)
- Good magnetic shielding
- Adequate space for safety isolation
- Simple and low cost winding, termination, and assembly
- Lowest cost of power handling
- Capacity per unit core volume

Power handling capability of a magnetic device is a function of Many variables, the most important of them are: circuit topology, ferrite material characteristics, core geometry characteristics, winding(s) configuration, cooling conditions. The throughput power of a ferrite core transformer is directly proportional to both, the operating frequency and the flux density. It can be defined as:

$$P_{th} = W_d \times C_d \times f \times \hat{B}$$

Where: W_d = winding design parameter (a function of coil geometry)
 C_d = core design parameter (a function of core geometry)
 f = operating frequency
 B = peak flux density

Switching frequency and flux density has a major impact on the performance of ferrite core material. For material performance optimization, the above formula can be rewritten as:

$$P_{th} = max = CSP \times (B.f) \, max$$

Where: CSP = core size parameter ($W_d \times C_d$)
 $(B.f)max$ = performance factor of ferrite material

Since it is nearly impossible to give power handling capability of a given core without knowing the above mentioned variables, some ferrite core vendors supply tabular or graphical form of power handling capacity of a given core at a few frequencies and corresponding flux densities for specified circuit topology.

This information is intended for relative comparison only. More work in this area, especially good magnetic design optimization computer programs will be required to provide meaningful information to the user. Some very useful information, especially values of thermal resistance Rth (defined as temperature rise of a magnetic device divided by total dissipated power in the device) for many of the ferrite cores used in power applications, can be found in the book by E.C. Snelling "Soft Ferrites, Properties and Applications" 2nd Edition, 1988 pp. 284-285.

With the great variety of core geometries and sizes manufactured for power applications, one of the most confusing tasks a novice designer is faced with is which core shape to choose. Some guidelines on core shape selection vs. design requirements, as well as advantages and disadvantages of selected core shapes, are summarized in Table 13.

Interference Suppression Ferrites

Government regulation of emission limits from telecommunications and data processing systems has mandated more effective electromagnetic interference control.

As a part of the strategy for controlling EMI, ferrites play an important role as absorptive filters. As their excitation frequency approaches ferromagnetic resonance, loss properties increase dramatically. Hence, it is possible for the ferrite to appear as a low loss inductor to low, data line frequencies but as alossy impedance device to higher interference frequencies (Typically above 25 MHz).

The ferrite core is placed over the conductor on which interference may be impressed. It provides significant series impedance to the EMI, attenuating and absorbing the energy. Because ferrites are cost effective and easy to use, they have become integral components of digital systems. Today, they are designed to fit into circuit boards or system interfaces close to the origin of the EMI. Ferrite geometries for EMI suppressors have changed to provide improved performance.

Nickel zinc ferrites are commonly used for suppression as it is possible to adjust their frequency-loss relationship through changes in their chemistry. Manganese zincs may be employed, but their resonance frequencies are quite low and limit their attenuative range.
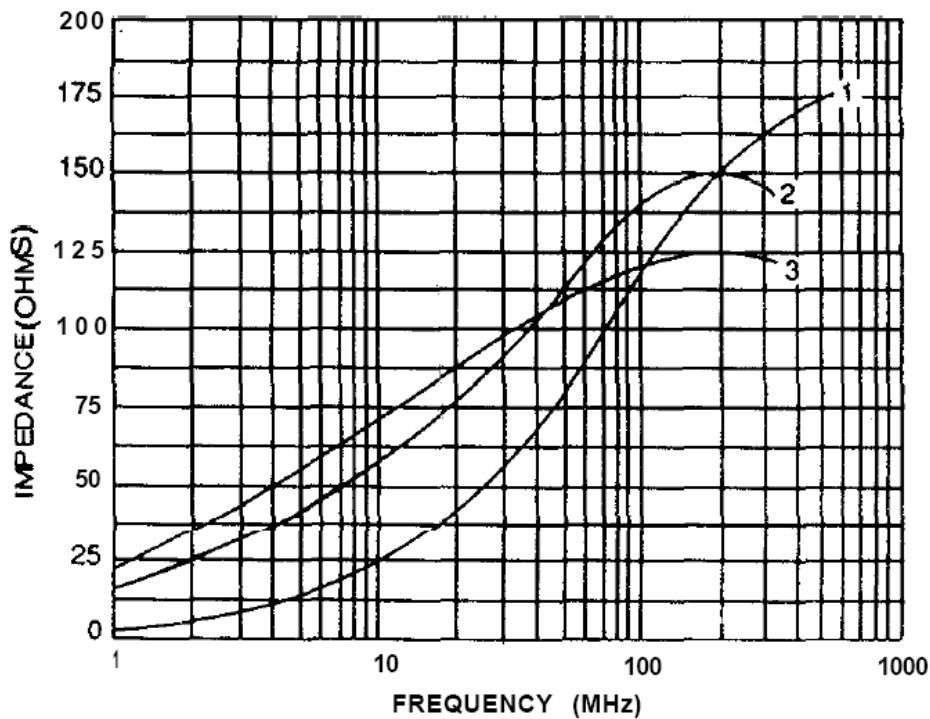
Figure 17
Impedance vs. Frequency for a Series of NiZn Ferrites

End Use	Core Shape
Circuit boards	Multi-hole components
Cables	Conforming sleeves
Connectors	Connector plates
Common-mode chokes	Toroids, pot cores, U-E cores
Differential-mode chokes	Rods, bobbin cores

Table 14
Core Shapes for Interference Suppression

The data ferrite producers supply for this application area is found both in tabular and graphic form. Intrinsic properties, such as initial permeability, saturation flux density, Curie temperature and volume resistivity are typically listed for these materials. Individual parts or components are characterized by graphically showing the impedance-frequency relationship on a single turn component and the pertinent current limiting levels on components with conductors attached. Figure 17 illustrates the impedance-frequency relationship for the same size part for a family of nickel zinc ferrites, with composition 1 containing a higher level of inverse spinel than composition 3.

In a related applications area, suppression ferrites are used as microwave absorbers to attenuate transmitted signals. These may be applied as ferrite tiles or produced as powders and loaded into an elastomer for compliant applications. As anechoic chamber linings, they absorb microwave energy in other application areas.

EM1 suppression geometrics relate directly to their point of application. Table 14 summarizes this information.

User Assembly Considerations

There are several user assembly considerations common to all three application areas. In addition to adding windings, the ferrite user may have to perform any of several operations on ferrite cores when assembling inductors and transformers. Many units require special assembly work such as clamping or bonding, encapsulation, or rarely, ferrite machining.

The following areas require thoughtful consideration if performance degradation in the transformer/inductor design is- to be avoided.

Coatings

The assembly of ferrite toroids consists of winding wire around the core and terminating the ends. Care must be taken in winding toroids as the core surface may scrape the insulation off the wire. MnZn ferrite toroids have a low resistivity and shorting the wire to the core will lower the component's Q value; the high resistivity of NiZn cores can often minimize this loss in Q.

Cores can be supplied coated with paint or other insulating materials to eliminate this problem, and to provide a smooth winding surface. It is also feasible to wrap the core with insulating tape, such as cotton or mylar, before winding.

The coating of cores by the user is NOT recommended. Inappropriate coating processes and materials can degrade core performance.

Clamping and Bonding

Ferrite pot cores and E cores have the winding wound on a plastic bobbin, or a mandrel. The winding is usually placed around the center post of both core halves, which can then be clamped together with hardware available from the core manufacturer. These spring loaded clamps produce a pressure adequate to hold the cores in place and provide performance stability. Clamps should not be disassembled and reused.

Alternatively, cores can be held together with adhesives. If the core contains a large air gap, a thin coat of adhesive is put on the mating surfaces of the cores and the unit clamped until the adhesive hardens. This approach may introduce a small amount of adhesive into the air gap, which normally does not
change the inductance significantly.

With ungapped cores, or cores with a minimal air gap(<lmm), adhesive on the mating surfaces should be avoided. A low viscosity adhesive bead should be applied by straddling the pre-assembled mating surfaces, and the core halves clamped together for curing. A small amount of epoxy seeping into the edges of the mating surfaces will increase the holding power, without increasing the air gap.

In preparing for cementing, the surfaces to be joined should be free of both dirt and moisture. If the finished units are to be used in a damp environment, special adhesives or clamps may be necessary. The adhesive manufacturer's recommendations should be carefully followed.

If you plan to bond, rather than clamp, you may wish to consult your core supplier for his recommendations on adhesive sources.

Encapsulation

Some ferrite components require the finished units to be completely encapsulated so that only the wire terminals are exposed. When selecting the proper encapsulate, it is essential to follow the epoxy manufacturer's recommendations.

The problem associated with encapsulating cores arises from the shrinkage of the resin both during and after curing. During curing, most resins shrink and exert a compressive stress on the core. These stresses can lower the component's inductance and may also cause cracks in the core. Even after the epoxy is cured, it continues to shrink and can add additional stress on the unit. These stresses, and the differences in the thermal coefficient between ferrite and most resins, will cause the potted unit to perform differently than unpotted units; winding and assembly adjustments can sometimes counteract these effects. Dipping the wound components into RTV before potting may minimize these problems, as RTV has a low viscosity and will equalize the pressure during assembly.

Accessories

Accessories, such as clamps, bobbins, and trimmers, are provided by some core suppliers for use with their pot cores, E cores, and other cores used in pairs. These accessories are tailored by each core supplier to provide optimum performance with his core geometries.

Intermixing cores and accessories from different suppliers can degrade unit performance, and is not recommended.

Machining

Machining of ferrite cores should be performed, whenever possible, by the core manufacturer or by firms that specialize in such machining. If it is necessary for the user to modify the core, silicon carbide or diamond-impregnated metal-bonded tools must be used. Adequate coolant is essential to avoid cracks in the cores. Ferrites are ceramic materials, and thus poor heat conductors, and tend to crack rather than expand or contract under mechanical or temperature stresses.

Summary

Your core supplier can be your primary information source in all of the above assembly areas. Consultation, prior to implementation of any processes that may affect core performance, is an excellent investment that can improve your product performance and reduce your costs.

SECTION 8.0, SUPPLIER / USER COMMUNICATION

Core users and suppliers share a common goal:
- A cost effective product that meets user performance requirements.

Increasing demand for high quality cost-effective products mandates close communication between supplier and user. Poor communication costs both user and supplier time and money, and reduces user product quality and performance.

Mutual satisfaction can be attained only if the supplier's and user's engineering, marketing, and purchasing groups communicate early, openly, and effectively to maximize performance and minimize product costs.

Core Selection

For optimal core choice, the user component design engineer, should discuss his needs with the core supplier application engineer. In some cases, the systems design engineer should also participate. Important discussion topics include:
- **Core Material**
  Frequency, power level, temperature range, DC bias, and other parameters germane to special applications influence material choice.

- **Core Geometry**
  Frequency, ease of winding, shielding, assembly costs, bobbin/mounting needs and space availability all affect component performance and cost.

- **Custom Core Geometries**
  Tooling cost, practical core design, availability of machined parts for evaluation, and bobbin/mounting needs must be carefully evaluated. A standard catalog geometry is often the best choice.

- **Quality**
  Customer specifications must be carefully reviewed. Magnetic and mechanical quality requirements must be clearly defined and prioritized. Test procedures and conditions must be specified. Any special documentation or quality audit requirements should be clarified. Requirements should be relevant to the application; over specifying is costly, and should be avoided.

- **Prototype Evaluation**
  Component performance values and tolerances should be based .on published core nominals and tolerances. Small sample lots may not be centered on nominal core value, and may exhibit tighter than normal production tolerances.

- **Assembly**
  Cores can be stress and temperature sensitive. Potting, cementing, or encapsulation needs should be reviewed, and performance degradation minimized. Heat generation in core and windings should be evaluated. Please see Section 5-User Assembly Considerations, for further information.

Core Purchase

Delivery needs must be clearly defined. Any necessary special support systems should be negotiated prior to order entry. Special paperwork requirements must be clearly specified. Conditions of purchase/sale must be understood by both buyer and seller.

For long-term satisfaction, the user should balance factors such as: consistent core quality, inventory support, delivery reliability, application design support, shipping costs, and price.

Industry Support Associations

Core users should take advantage of the many services offered by technical/trade associations such as:
- IEEE Power Electronics Society
- IMA Working Group of the Transformer Association
- IEEE Magnetic Society
- PSMA (Power Source Manufacturers Association)
- IEC (International Electrotechnical Commission)

These groups generate standards, publish guidelines, and present technical seminars; they also can serve as a third party communication link enhancing supplier/user programs.

Partnerships

Effective supplier/user communication extends beyond the choice of a core for a particular application.

The purchase order is only the first link in a chain of cooperation that can lead to profitability and growth for both supplier and user.

Long-term customer support requires constant communication at all levels of supplier/user management to ensure that quality, delivery, and product development needs are consistently met.

Industry leadership mandates high .performance at lowest cost. Effective supplier/user communication can be a major factor in achieving this goal.

SECTION 9.0, SPECIFICATIONS AND TEST CONDITIONS

Ferrite manufacturers produce cores in a number of different materials and in a variety of shapes. All these cores provide specific stated magnetic parameters, which are based upon application related device specifications. These specifications, as measured , are the customer's guarantee that the product will perform as advertised. It is important, therefore, to know the conditions under which the supplier is testing and whether it is relative to the application. It cannot be overemphasized that electromagnetic properties of fenites can be dramatically altered by deviations in temperature, frequency, drive levels, and pressures. In order to assist in improved understanding, the following test methods and test conditions are used and recommended by the members of the soft ferrite division of the MMPA . The conditions of testing should be carefully adhered to. Any variations should be discussed with the manufacturer.

1. **Measurements of inductance factor, losses and initial permeability.**

Equipment: Bridge with variable voltage and frequency, such as HP4275A LCR meter or equivalent.

Test Conditions: Flux density <10 gauss. For loss measurement 1 gauss. Temperature $23 \pm$ ºC. Frequency as specified

Cores have to be properly mounted around the measuring coil, or for toroidal cores, wound with the correct number of turns.**

With frequency set and voltage adjusted for test conditions, the LCR meter will measure Rs and Ls. From these readings, the following parameters can be calculated:

$$\text{Inductance factor } AL = \frac{L}{N^2} \text{ (nH)}$$

$$\text{Initial permeability } \mu_i = \frac{L}{L_0^*}$$

$$\text{Losses } \frac{\tan s}{\mu_i} = \frac{L_0 R}{\omega L^2}$$

$*L_0$ = Air Core Inductance

Measurement of gapped cores for the inductance factor is commonly made at 10kHz. The test winding should fill at least 80% of the available winding area. For gapped pot cores, a fully wound bobbin is recommended.

**LCR meters have a resistor (usually 100 ohm) in series with the oscillator and the Device Under Test. The number of turns should be chosen such that the X, of the core $\geq$ 10 ohms at the frequency of test. This ensures that at least 10% of the test signal is applied to the core.

2. Disaccommodation measurement.

Equipment: Bridge, same as in Procedure 1
                Timing device
                Demagnetizing coil

Test Conditions: Same as in Procedure 2
Temperature stable environment, $< \pm 5$ ºC.

The LCR meter will measure R, and L,.

Wound cores to be tested for disaccommodation need to be demagnetized. This is most easily done with a demagnetizing air coil.

The first inductance reading L, is made at t_1, after demagnetization, the second measurement at time $t_,$. For t and t_2, 10 and 100 minutes are recommended. If other time intervals are used, they need to be identified.

Inductance readings L_1 and L_2 are used to calculate the disaccommodation and the initial permeablilities at t_1 and t.

$$\text{Disaccommodation} \quad D = \frac{L_1 - L_2}{L_1}$$

$$\mu i_1 = \frac{L_1}{L_o} \qquad\qquad \mu i_2 = \frac{L_2}{L_o}$$

$$\text{Disaccommodation} \quad \text{Factor}$$

$$D.F. = \frac{\Delta \mu_i}{\mu_{i1}^2 \; \log_{10} \; t_2/t_1}$$

$$\text{Where:} \; \Delta \mu_i = \mu_{i_1} - \mu_{i_2}$$

Preferred test frequency 10 - 100 kHz. For detailed information on demagnetization see IEC Publication 367- 1, page 25 (See appendix 3).

3. Measurements of changes in inductance versus temperature and curie temperature.

Equipment: Bridge, as in Procedure 2
                    Temperature controlled chamber

Test Conditions: Same as in Procedure 2

The LCR meter will measure R_s and L_s.

Wound cores to be checked for temperature behavior are placed in the temperature chamber and subjected to two stabilizing temperature cycles, e.g. 20 - 70 ºC, with approximately 2 hours at each temperature.

The first inductance measurement L_1 is made at the lowest temperature Θ_1 after a 30 minute soak at that temperature. This procedure is repeated up to the highest specified temperature Θ_2. A measurement made in the 20 - 25 ºC range is considered the reference inductance L_{Ref} the reference temperature $\Theta_{Ref.}$

After measuring at the highest temperature, a final measurement should be made again at the reference temperature. Both measurements of the reference inductance should be the same within the bridge accuracy. If these two readings are not alike, more temperature stabilizing cycles might be needed to eliminate irreversible inductance changes in the test samples.

From the inductance readings at various temperatures, the temperature coefficient of inductance can be calculated.

$$\text{T.C.} = \frac{L_{\theta 2} - L_{Ref.}}{L_{Ref.}\,(\theta_2 - \theta_{Ref.})} \quad \text{or} \quad \frac{L_{\theta 2} - L_{\theta 1}}{L_{Ref.}\,(\theta_2 - \theta_1)}$$

Preferred test frequency $10 - 100$ kHz

For the Curie temperature measurement, the temperature is slowly increased while the inductance is monitored. The temperature where the core inductance decreases to < 10% of its room temperature value is for all practical purposes considered the Curie temperature.

Note: The rate of change in temperature for both tests should not exceed 1°C per minute.

4. Measurement of incremental permeability and inductance factor with a DC bias.

Equipment: Bridge with variable voltage and frequency, capable of accepting a DC bias. Instruments such as GR 1633A bridge or HP4284A LCR meter.

Test Conditions: Flux density < 10 gauss Frequency as specified DC bias as specified

Temperature $23 \pm 3°C$

The bridge will measure R_S and L_S.

Cores should be properly installed around the measuring coils, or for toroidal cores, wound with the correct number of turns.

The bridge frequency and alternating voltage are set and DC bias varied for test conditions. The bridge will read the inductance, with or without a superimposed direct current.

$$\text{Incremental permeability } \mu_\Delta = \frac{L}{L_0}$$

$$\text{Inductance factor } A_L = \frac{L}{N^2}\,(nH)$$

Typical values of incremental permeability and inductance factor are displayed graphically as shown in Figures 18-1 and 18-2:
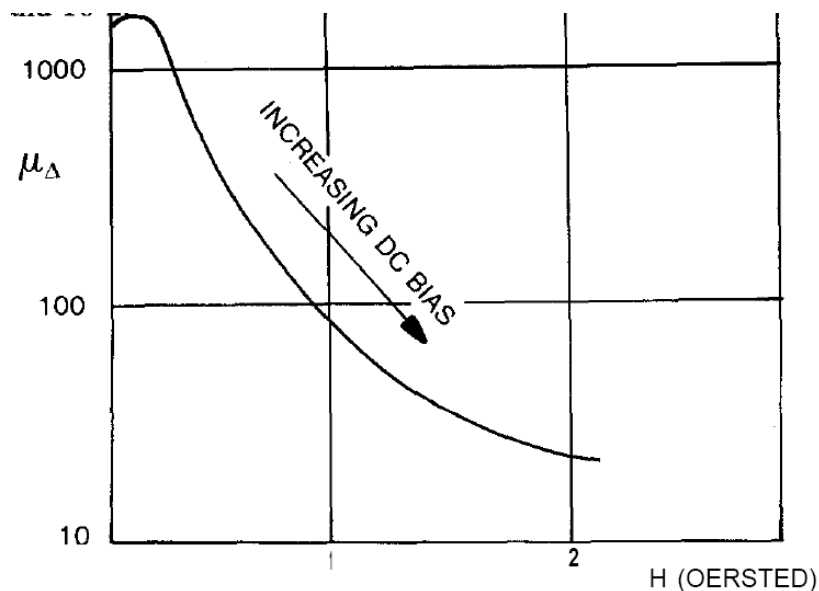
Figure 18-1
Incremental Permeability as a Function of Static Magnetizing Field (oersted)
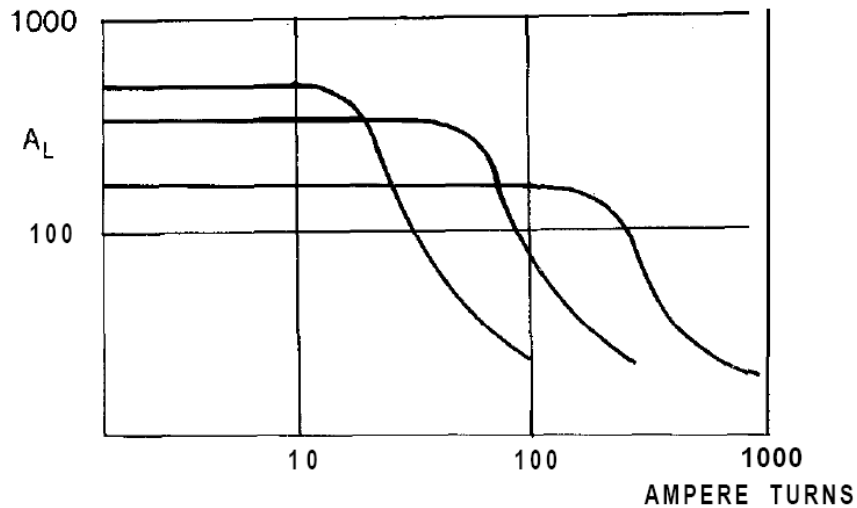
Figure 18-2
Inductance Factor as a Function of Static Magnetizing Field (ampere turns)

5. **Measurements of the flux density, residual flux density, coercive force and amplitude permeability.**

    Equipment: Function generator
                     Amplifier
                     RC network
                     Dual channel oscilloscope

    Test Conditions: Frequency 10 kHz
                     Temperature as specified

The test circuit is shown in Figure 19. The resistor R_1, is kept small in comparison to the inductive reactance of the wound sample. The cores must be properly installed around the primary and secondary windings, or wound with a primary and secondary winding. The field strength H is set by varying the current, which is read as the voltage across resistor R_1.

$$H = \frac{.4\pi NI}{\ell_e} = \frac{.4\pi N_p V_p}{\ell_e R_1} \quad (\text{oersted})$$

The flux density in the core is determined by integrating the secondary voltage using the RC circuit.

$$B = \frac{R_2 C V_p 10^8}{N_s A_e^*} \quad (\text{gauss}) \quad R_2 = \text{ohms}$$
$$C = \text{Farads}$$

From the displayed hysteresis loop, values for coercive force H_C, and residual flux density B_R, can be determined once the dual channel oscilloscope is calibrated for field strength H and flux density.
Amplitude permeability $= \mu_a =$

$$\text{Amplitude permeability} = \mu_a = \frac{\hat{B}}{\hat{H}}$$

*NOTE: For high flux density, high temperature measurements on cores with a non-uniform cross sectional area, use A_{min} instead of A_e.

6. Measurement of power loss.

Equipment:	Signal generator, such as
	HP 33 10 or equivalent
	For frequencies, 50 kHz:
	Power amplifier, Crown M600
	or equivalent
	Clark Hess 256 VAW Meter
	For frequencies 2 50 khz to 1 Mhz**

Test Conditions:	Frequency as specified
	Temperature as specified

Test samples to be measured for power losses should be assembled with a test winding that gives the proper impedance to the power amplifier. For the test circuit, see Figure 20.

The frequency is set and the voltage is adjusted to the desired flux density level. The test voltage can be determined from the formula:

$$E = 4.44fNBA_e10^{-8} \text{ (VRMS)}$$

The Clarke Hess VAW Meter can be used to set the voltage levels. The power losses are indicated by the VAW Meter in watts. Each power loss test should not take more than a few seconds. This will avoid self-heating of the samples, which might affect the test results.

The intrinsic material power loss density can be determined by dividing the measure power losses by the effective volume of the ferrite core. Component core losses are typically expressed in watts/core or watts/set.

The VAW Meter can also be used to measure the magnetizing current I_m. This value can be used to calculate the winding loss $(I_m^2 R_{ac})$, part of the total measure power losses.

** The accuracy at higher frequencies is highly dependent on the phase shift between the voltage and current.

7. Measurement of impedance for suppression applications.

Equipment:	Impedance Analyzer such as HP4 19 1 A with test fixtures 16092A and 16093A.

Test Conditions:	Frequency as specified
	Temperature 23 f 3 "C

This test is most often done on components with a single turn winding. The proper fixture is determined by the test frequency.

Test wires should be kept as short as practical, or the exact length be specified as part of the test procedure. The impedance analyzer will give a direct reading of impedance.

Typical values:

R1 = 1.0 Ω ± 1% (10 watts)

R_2 = 10.0kΩ ± 1% (2 watts)

c = 1.0uf ± 1%
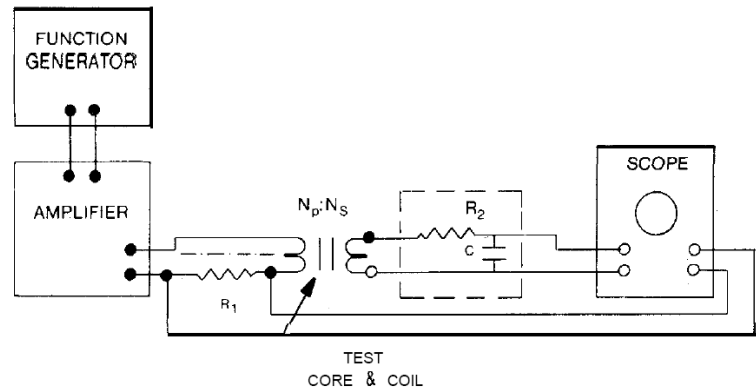
Figure 19
B-H Loop Test Set-Up
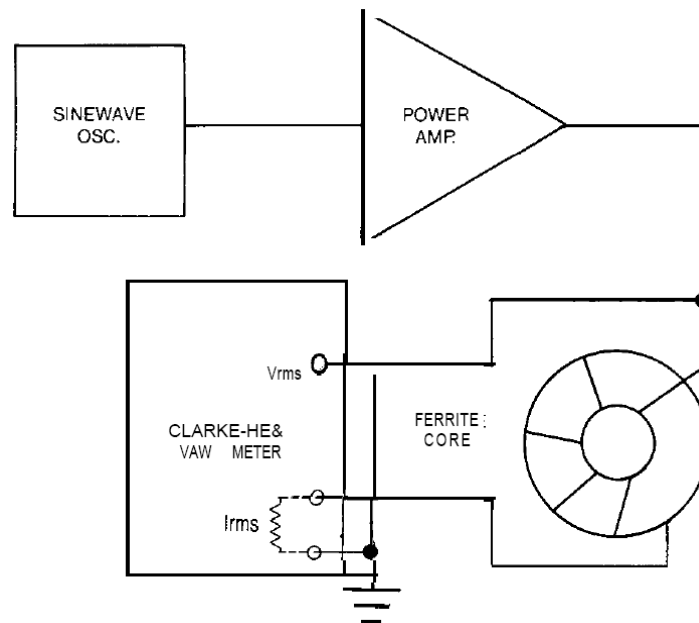
Figure 20
Power Loss Test

GLOSSRY OF TERMS

Air Core Inductance L_o (H). The inductance that would be measured if the core had unity permeability and the flux distribution remained unaltered.

Amplitude Permeability μ_a. The quotient of .the peak value of flux density and peak value of applied field strength at a stated amplitude of either, with no static field present.

Coercive Force H_C, (oersted). The magnetizing field strength required to bring the magnetic flux density of a magnetized material to zero.

Core Constant C_1 (cm^{-1}). The summation of the magnetic path lengths of each section of the magnetic circuit divided by the corresponding magnetic area of the same section.

Core Constant C_2 (cm^{-2}). The summation of the magnetic path lengths of each section of the magnetic circuit divided by the square of the corresponding magnetic area of the same section.

Curie Temperature $T_C(^oC)$. The transition temperature above which a ferrite loses its ferromagnetic properties.

Disaccommodation D. The proportional decrease of permeability after a disturbance of a magnetic material, measured at constant temperature, over a given time interval.

Disaccommodaton Factor D.F. The disaccommodation factor is the disaccommodation after magnetic conditioning divided by the permeability of the first measurement times log, a of the ratio of time intervals.

Effective Dimensions of a Magnetic Circuit Area A_e (cm^2), Path Length l_e (cm>) and Volume V_e (cm^3). For a magnetic core of given geometry, the magnetic path length, the cross sectional area and the volume that a hypothetical toroidal core of the same material properties should possess to be the magnetic equivalent to the given core.

Effective Permeability μ_e. For a magnetic circuit constructed with an air gap or air gaps, the permeability of a hypothetical homogeneous material which would provide the same reluctance.

Field Strength H (oersted). The parameter characterizing the amplitude of alternating field strength.

FIUX Density B (gauss). The corresponding parameter for the induced magnetic field in an area perpendicular to the flux path.

Impedance Z (ohm). The impedance of a ferrite may be expressed in terms of its complex permeability.

$$Z = j \ \Omega L_S + R_S = j \ \Omega L_O(\mu_S - j\mu_S) \ (ohm)$$

Incremental Permeability μ_Δ. Under stated conditions the permeability obtained from the ratio of the flux density and the applied field strength of an alternating field and a super-imposed static field.

Inductance Factor A, (nH). Inductance of a coil on a specified core divided by the square of the number of turns. (Unless otherwise specified the inductance test conditions for inductance factor are at a flux density ~10 gauss).

Initial Permeability μ. The permeability obtained from the ratio of the flux density, kept at <lO gauss, and the required applied field strength. Material initially in a specified neutralized state.

Loss Factor $\tan \delta/\mu_i$. The phase displacement between the fundamental components of the flux density and the field strength divided by the initial permeability.

Magnetic Constant μ_o. The permeability of free space.

Magnetically Soft Material. A magnetic material with a low coercivity.

Magnetic Hysteresis. In a magnetic material, the irreversible variation of the flux density or magnetization which is associated with the change of magnetic field strength and is independent of the rate of change.

Power Loss Density P (mW/cm^3). The power absorbed by a body of ferromagnetic material and dissipated as heat, when the body is subjected to an alternating field which results in a measurable temperature rise. The total loss is divided by the volume of the body.

Pulse Permeability μ_P. Under stated conditions, the permeability obtained from the ratio of the change in flux density and the change in applied field strength of pulse field.

$$\mu_p = \frac{\Delta B}{\Delta H}$$

Remanence B_r (gauss). The flux density remaining in a magnetic material when the applied magnetic field strength is reduced to zero.

Saturation Flux Density B_S (gauss). The maximum intrinsic induction possible in a material.

Temperature Coefficient T.C. The relative change of the quantity considered, divided by the difference in temperatures producing it.

Temperature Factor T.F. The fractional change in initial permeability over a temperature range, divided by the initial permeability. .'

Volume Resistivity p(ohm-cm). The resistance measured by means of direct voltage of a body of ferromagnetic material having a constant cross sectional area.

Note: See Appendix 1 and 2 for formulas and conversion to SI units.

Quantity	Metric Symbol	Metric/ SI Units	Customary Symbol	Customary Units	Multiplication Factor to Convert from Customary to SI Units
Area	m^2	Square meter	cm^2	Square centimeter	1, 10^{-4}
Celsius Temp.	^{o}C	Degree Celsius	^{o}F	Degree Fahreheit	(F-32) *5/9
Density	kg/m^2	Kilogram per cubic meter	g/cm^2	Gram per cubic centimeter	1×10^3
Electric resistance	Ω	Ohm	Ω	Ohm	1
Electric current	A	Ampere	I	Ampere	1
Electrical potential, electromotive force	V	Volt	E	Volt	1
Energy, work	J	Joule	ERG	Centimeter-gram-second	1×10^{-7}
Force	N	Newton	#	Pounds	4.44822
Frequency	Hz	Hertz	KHz	Kilohertz	1×10^3
Inductance, Inductor	H	Henry	L	Henry	1
Length	m	Meter	cm	Centimeter	1×10^{-2}
Magnetic field strength	A/m	Ampere per meter	Oe	Oersteds	79.58
Magnetic flux	Wb	Weber	Mx	Maxwells	1×10^{-8}
Magnetic flu density, Magnetic Induction	T	Tesla	g	Gausses	1×10^{-4}
Mass	kg	Kilogram	g	Gram	1×10^{-3}
Permeability	H/m	Henry per meter	μ	(unit less)	4×10^{-7}
Power	W	Watt	W	mW	1×10^{-3}
Power loss density	kW/m^3	Kilowatt per cubic meter	Pc	mW/cm^3	1
Pressure, stress	Pa	Pascal	PSI	Lbs/in^2	6896.5
Thermal Conductivity	W/(m*K)	Watt per meter Kelvin			
Time	S	Second	S	Second	1
Volume	m^3	Cubic meter	cm^3	Cubic centimeter	1×10^{-6}

APPENDIX 1

Flux Density (Peak)

Magnetizing Force (Peak)

$$\hat{B} = \frac{E\ 10"}{4.44\,f\,NA_e}\quad (\text{gauss})$$

$$\hat{H} = \frac{.4\pi NI_p}{\ell_e}\ (\text{oersted})$$

Note: Use 4.0 for a square wave

Where:

E = RMS sine wave voltage
f = frequency (Hz)
A = Effective area (cm^2)
l_e = Magnetic path length (cm)
I = Peak current (A)
N = Number of turns

Number of Turns

$$N = \sqrt{\frac{L\ 10^9}{AL}}$$

L = Inductance in henries (H)
A$_L$ = Inductance factor in nH/N^2

Inductance

$$L = N^2 A_L\ (nH)$$

$$L = \mu_i \frac{4\pi N^2}{C_1} 10^{-9}\ (H)$$

$$L = \mu_e \frac{4\pi N^2}{C_1} 10^{-9}\ (H)$$

$\Big\}$ C$_1$ in cm^{-}

Air Core Inductance

$$L_o = \frac{4\pi N^2 10^{-9}}{C_1}\ (H)$$

C$_1$ in cm$^{-'}$

For Toroids: (All dimensions in mm)

$$L_o = 4.60 \times \text{Log}_{,,}\ (OD/ID) \times HT \times N^2 \times 10^{-10}\ (H)$$

• or

$$L_0 = 2 \times \ln\ (OD/ID) \times HT \times N^2 \times 10^{-10}\ (H)$$

Effective Permeability

$$\mu_e = \frac{\ell_e}{\ell_e/\mu_i + \ell_g}$$

Where:
ℓ_e = Magnetic path length
ℓ_g = Length of gap

if $\ell_g \ll \ell_e$

Quality   Factor

$$Q = \frac{2\pi f L_S}{R_S} = \frac{R_p}{2\pi f L_p}$$

$$L_S = \frac{L_p Q^2}{1 + Q^2} \qquad R_S = \frac{R_p}{1 + Q^2} \qquad X_S = \frac{X_p Q^2}{1 + Q^2}$$

$$L_p = L_S \left(1 + \frac{1}{Q^2}\right)$$

$$R_p = R_S \left(1 + Q^2\right)$$

$$X_p = X_S \left(1 + \frac{1}{Q^2}\right)$$

Attenuation

$$20 \log_{10} \frac{Z_S + Z_L + Z_{SD}}{Z_S + Z_L} \ (dB)$$

Where:

Z_S = Source impedance

Z_L = Load impedance

Z_{SD} = Shielding device impedance

APPENDIX 2

<table>
<tr><td colspan="2">FERRITE MATERIAL CONSTANTS</td></tr>
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FERRITE MATERIAL CONSTANTS

Specific heat	.25 cal/g/°C
Thermal conductivity	10×10^{-3} cal/sec/cm/°C
Coefficient of Linear expansion	$8 - 10 \times 10^{-6}$/°C
Tensile strength	7×10^{3} lbs/in^2
Compressive strength	60×10^{3} lbs/in^2
Youngs modulus	18×10^{3} lbs/in^2
Hardness (Knoop)	650
Density	-4.8 gm/cm^3 (MnZn)
	-4.6 gm/cm^3 (MnZn)

The above quoted properties are typical values on commercially available MnZn and NiZn ferrites

CONVERSION TABLE

SI Unites	CGS Units
1 T (tesla) = 1 Vs/m^2	$=10^4$ gauss
1 mT	=10 gauss
.1 mT	=1 gauss
1 A/m=10^{-2} A/cm	=.01257 oersted
79.58 A/m	=1 oersted

WIRE TABLE

AWG B & S GAUGE	DIAM. (IN.)	CROSS SECTION (SQ. IN.)	FEET PER OHM (20°C)	OHMS PER 1000 FT. (20°C)	AMPS FOR 1000A/ Sq. In.	TURNS PER SQ. IN. H.F. WIRE	TURNS PER SQ. IN. S.F. WIRE
10	.1019	.00815	1001.	1.00	8.15	89	92
11	.0907	.00647	794.	1.26	6.47	112	118
12	.0808	.00513	630.	1.58	5.13	140	146
13	.0719	.00407	499.	2.00	4.07	176	180
14	.0641	.00322	396.	2.53	3.22	221	231
15	.0571	.00256	314.	3.18	2.56	259	275
16	.0508	.00203	249.	4.02	2.03	327	346
17	.0453	.00161	198.	5.06	1.61	407	432
18	.0403	.00127	157.	6.39	1.27	509	544
19	.0359	.00101	124.	8.05	1.01	634	679
20	.0320	.000804	98.5	10.7	0.804	794	854
21	.0285	.000638	78.1	12.8	0.638	989	1063
22	.0254	.000505	62.0	16.2	0.505	1238	1343
23	.0226	.000400	49.1	20.3	0.400	1532	1677
24	.0201	.000317	39.0	25.1	0.317	1893	2094
25	.0179	.000252	30.9	32.4	0.252	235 1	2632
26	.0159	.000200	24.5	41.0	0.200	2932	3326
27	.0142	.000158	19.4	51.4	0.158	3711	4112
28	.0126	.000126	15.4	65.3	0.126	4581	5213
29	.0113	.000100	12.2	81.2	0.100	5621	6383
30	.0100	.0000785	9.69	104.	.0785	7060	8145
31	.0089	.0000622	7.69	131.	.0622	8455	10,097
32	.0080	.0000503	6.10	162.	.0503	10,526	12,270
33	.0071	.0000396	4.83	206.	.0396	13,148	15,615
34	.0063	.0000312	3.83	261.	.0312	16,889	19,654
35	.0056	.0000248	3.04	331.	.0248	21,163	25,531
36	.0050	.0000196	2.41	415.	.0196	26,389	31,405
37	.0045	.0000159	1.91	512.	.0159	3 1,405	39,570
38	.0040	.0000126	1.52	648.	.0126	39,567	49,070
39	.0035	.00000962	1.20	847.	.0096	53,855	65,790
40	.0031	.00000755	0.953	1080.	.0075	65,790	82,180
41	.0028	.00000616	0.757	1320.	.0062	—	98,856
42	.0025	.00000491	0.598	1660.	.0049		121,174
43	.0022	.00000380	0.476	2140.	.0038		158,246
44	.0020	.00000314	0.375	2590.	.0031		205,317
45	.0018	.00000254	0.299	3200.	.0025		249,855
46	.0016	.00000201	0.238	4050.	.0020		310,205