The Magnetic Applications Choice Among Ferrite Ceramics, Metallic Strips, or Metal Powder Cores

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Iron-based metallic strip materials such as iron, silicon-iron, and amorphous metal are used for low frequency (50-60 Hz. line) power applications. Low-loss Nickel-based alloys as high permeability strip or insulated powder cores are the choices for stable, low-level higher frequency applications. Iron-based powder cores offer low cost as power supply filter chokes. Ceramic ferrites combine highest frequency operation with low cost and reduced component size as transformers and chokes in telecommunication and high frequency power supply applications.

Keywords

magnetic ferrites, magnetic powder core, switching power supplies, magnetic saturation, eddy currents, magnetic ferrous alloys, nickel-based alloys

1. Magnetization and Induction

THE SOURCE of ferromagnetism in magnetic materials originates with the unpaired electrons in the 3d or 4f electron subshells. We limit our discussion to the 3d electrons in which only the spin magnetic moments are operative in a crystal structure.

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In Fig. 1, the iron atom is shown with its 4 unpaired 3d electrons, which in the free atom, hold a potential of 4 μ_B. (Bohr magneton, μ_B, is the quantized magnetic moment per unpaired spin.) In the metal itself, the 3d electrons along with the 4s are the outermost electrons and, therefore, are partially responsible for the interatomic bonding and conduction. The result is that the 4 potential μ_B in the case of iron is reduced to a nonintegral 2.2. In the cases of cobalt and nickel, which have potential 3 and 2 μ_B, respectively, they are similarly reduced to 1.7 and 0.6 μ_B, respectively. In the case of the ferric ion, Fe^{3+} (such as found in ferrites), the 3d electrons are localized and do not take part in conduction. Therefore, they yield a true 5 μ_B (Table 1).

In the case of iron, if the 3d electrons could be localized in a ferromagnetic manner, the magnetic moment would have the potential of exceeding that of iron. Such cases have indeed been reported. At the Joint Intermag-MMM Conference in Al-

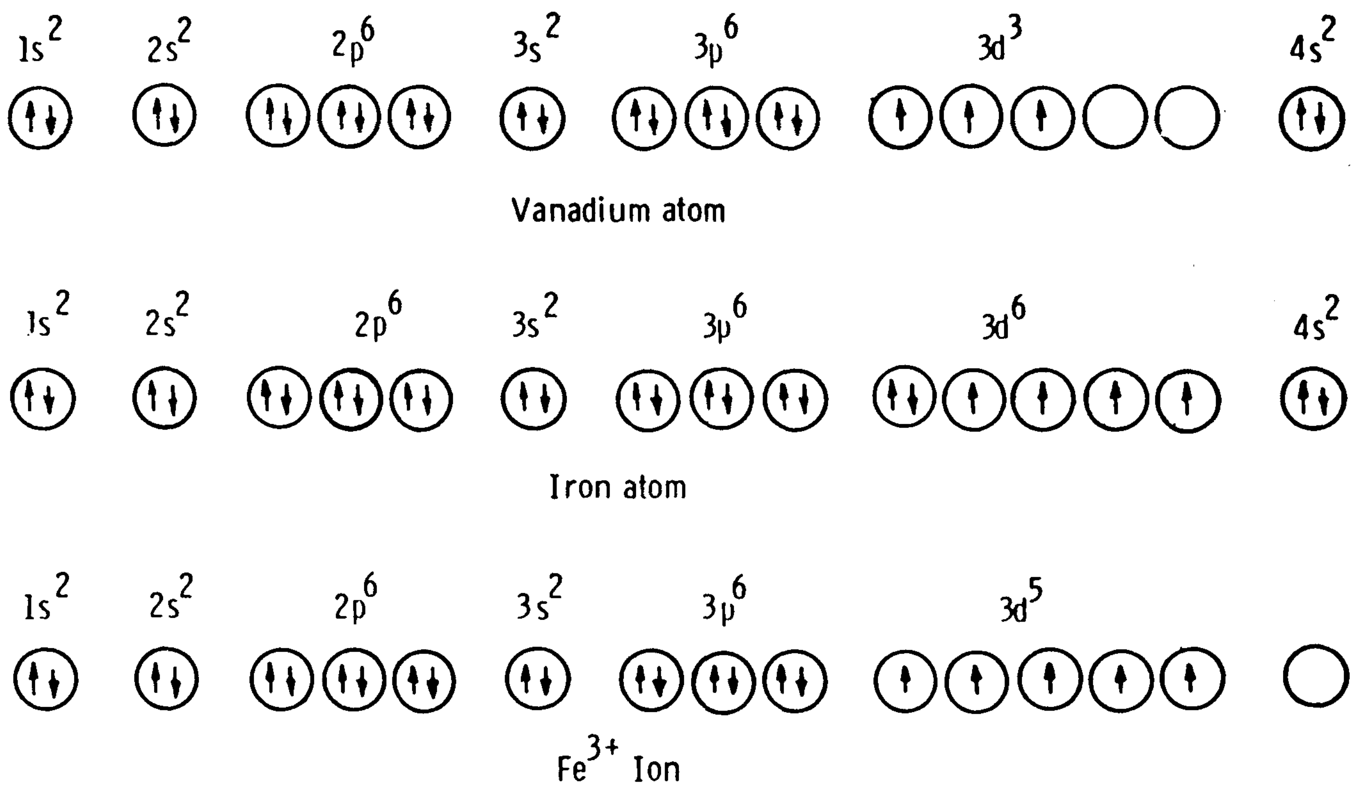

Fig. 1 Electronic configuration of vanadium atoms, iron atoms, and ferric ion

buquerque held last year, a session on giant magnetic moments reported nominal values of 2.6 μ_B for some iron nitrides and somewhat controversial values up to 3.2 μ_B. The applications thus far are for hard magnetic materials.

The magnetic moments for iron discussed above are measured at very low temperatures and extrapolated to 0 K. These are reduced at higher temperatures, such as room temperature, but still are quite high for known materials. When these moments are combined to give bulk magnetic values known as saturation magnetizations, M_S, these represent the highest achievable magnetizations at a specific temperature. M_S is only dependent on the chemistry and thus is an intrinsic property of a material. A derived property is the saturation induction, B_S, which in soft materials is practically equal to $4\pi M_S$. An operational parameter is the maximum induction, B_M, which is the highest induction encountered during the traversal of the hysteresis loop, B_M is obviously limited by B_S. In fact, in some cases, the electrical designer must be careful not to specify a B_M too close to B_S because the differential permeability approaches zero, the current rises precipitously, and catastrophic failure may occur. This limitation on going into saturation is discussed later in other aspects.

Table 1 Comparison of magnetic moments in free atoms and bulk

Material	Free atom, Bohr magnetons	Magnetic moment bulk metal, Bohr magnetons
Iron	4	2.2
Cobalt	3	1.7
Nickel	2	0.6
Magnetic moments of free ions and in ferrites		
Fe^{3+}	5	...
Fe^{2+}	4	...
Mn^{2+}	4	...
Co^{2+}	3	...
Ni^{2+}	2	...
Cu^{+}	1	...
Zn^{2+}	0	...

2. Low-Frequency Saturation-Driven Power Applications

In a power application, the induced voltage is given by the Faraday induction equation (using cgs units):

$$E = -N\, d\phi/dt \qquad \text{(Eq 1)}$$

Table 2 Properties of soft magnetic materials

Materials	Saturation flux density		Curie point, °C	Density, g/cm³	Resistivity, μΩ · cm	Initial Permeability, μ0	Maximum Permeability	Core loss, W/kg	At frequency	At induction, kG
	G	T								
Iron	21,500	21.5	770	7.85	9.6	300	6,000	...	...	...
Cobalt	19,000	1.9	1,121	8.84	9	70	250	...	...	...
Nickel	6,080	0.6	358	8.89	8.7	250	2,500	...	...	...
Low-frequency power material										
Cold-rolled low-carbon steel	21,500	2.15	770	7.85	9.6	200	5,000	7.3	60 Hz	15
Nonoriented 3% Se-Fe	20,000	2.0	750	7.65	47	280	8,000	3.2	60 Hz	15
Oriented 3% Si-Fe	20,000	2.0	750	7.65	50	1,400	50,000	1.17	60 Hz	15
Hi B 3% Si-F3	20,000	2.0	750	7.65	50	1,920	...	1.46	60 Hz	17
Metglas(a) 2605 S2	15,600	1.56	415	7.18	130	...	...	0.25	60 Hz	14
Metglas(a) 2605 SC	16,100	1.6	370	7.32	125	...	...	0.3	60 Hz	14
Permendur	24,500	2.45	950	8.3	7	1,000	11,000	25	400 Hz	20
2-V Permendur	24,000	2.4	980	8.15	26	800	5,000	8.8	50 Hz	
Supermendur	24,000	2.4	940	8.15	26	800	70,000	12.1	400 Hz	
27% Co-Fe	24,200	2.42	970	8.02	19	650	2,800	6	60 Hz	15
Inductor and shielding materials										
50% Ni-Fe	15,500	1.55	500	8.2	45	3,500	100,000	6.6	1 kHz	10
Oriented 50% Ni-Fe	16,000	1.6	500	8.2	45	...	200,000	8.8	1 kHz	10
Mumetal	6,500	0.65	460	8.25	55	20,000	100,000	5.5	5 kHz	5
Metglas(a) 2826 MB	8,800	0.88	353	8.02	160	...	750,000	96	50 kHz	2
4-79 Permalloy	7,500	0.75	460	8.74	55	50,000	300,000	12.2	10 kHz	4
Supermalloy	7,000	0.7	460	8.77	65	60,000	800,000	17.5	10 kHz	4

(a) Metglas is a proprietary trademark of Allied Corporation.

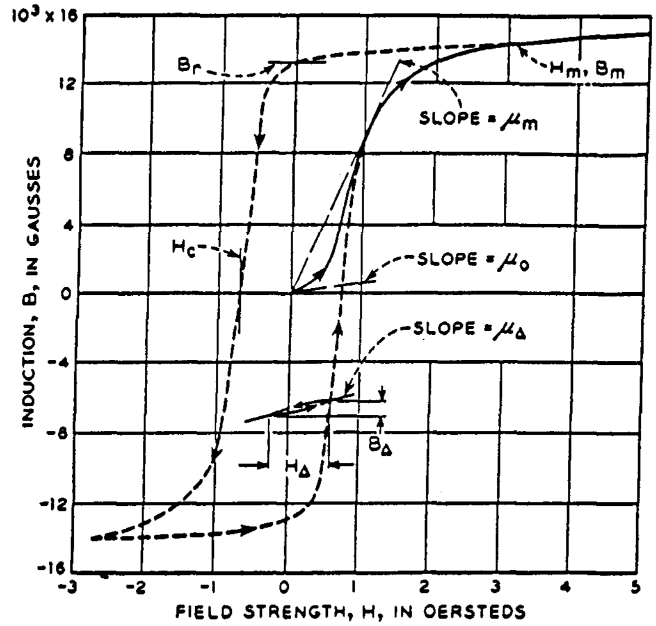

Fig. 2 Various types of magnetic permeabilities: μ_0 is initial permeability, μ_m is maximum permeability, and μ_Δ is differential permeability.

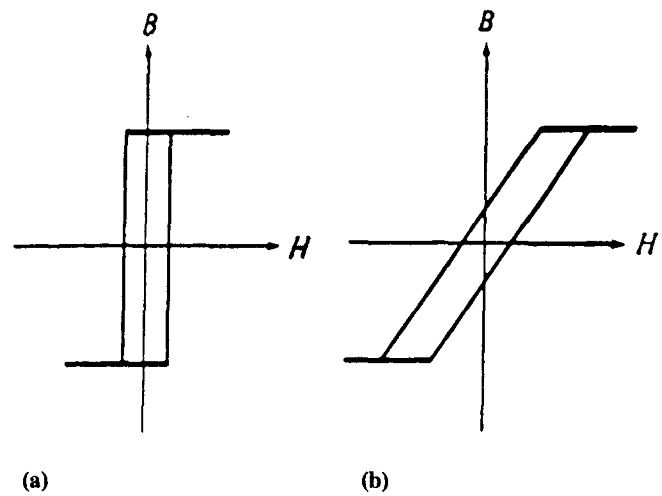

Fig. 3 Shearing of a hysteresis loop by application of an air gap in a magnetic circuit

where E is induced voltage (volts), N is number of turns, t is time (seconds), and ϕ is magnetic flux (maxwells).

For a sine wave, this equation is then given by:

$E = 4.44BNAf \times 10^{-8}$ volts

where B is maximum induction (gausses), A is cross-sectional area (cm^2), and f is frequency (hertz). For a given voltage and frequency, to minimize the cross-sectional area and number of turns (reduce the size of the core), the B_M must be maximized.

3. Low-Frequency Core-Loss-Limited Applications

If saturation induction were the only characteristic needed for power applications, iron would be the material of choice because of its low cost and high induction. In addition to high induction, the losses in the magnetic core must be controlled to reduce the amount of heat generated in the process. Aside from the loss of efficiency, the excess heat also lowers the saturation, possibly leading to a chain reaction effect.

The metallurgical community has done an outstanding job in lowering the core losses of low-frequency power materials. Texture is used to increase the orientation of the magnetization in line with the easy axis. The early (Goss) texture was followed by the Hi-B material (Nippon Steel) and, more recently, by mechanical or laser scribing methods. Another technique used to lower the core losses is by lowering eddy current losses. The equation for core losses due to eddy currents is:

$$P_E = KB_M^2 f^2 d^2/\rho \qquad \text{(Eq 2)}$$

where K is a constant depending on the shape of the sample, B_M is maximum induction (gausses), f is frequency (hertz), d is shortest dimension perpendicular to the flux path, and ρ is resistivity ($\Omega \cdot$ cm).

Lowering B_M is not desirable because it increases the size of the magnetic core as shown in the previous equation. In metallic strip, the d dimension is the tape thickness. Reducing the gage has been one of the methods of reducing core losses especially at somewhat higher frequencies. There are limitations of reducing strip thickness. One is cost, and the other is technical limitation. One of the advantages of the amorphous metal strip is the thin gage that can be produced rather easily. Another method of eddy-current loss reduction involves the increase in resistivity by the addition of silicon. The further increase in resistivity in the amorphous material is another advantage for that material. A listing of core losses as well as saturations and other properties of these materials is given in Table 2. The saturations for iron and cobalt are both high, but a 50-50 alloy of the two has a higher value than either. This alloy, therefore, has been a material of choice in applications involving highest saturation, such as needed in aircraft and space applications.

4. Permeability-Driven Materials-NiFe Alloys

Leaving the area of low-frequency power materials, we encounter the telecommunications application. Here, the frequencies are much higher, and the power levels are much lower. In fact, we are dealing primarily with the Rayleigh, or initial permeability region, as shown in Fig. 2. In addition to the chemistry needed to achieve high permeability and lower high frequency losses, appropriate heat treating and processing are also required. The materials in this category, which are mostly nickel iron alloys, are listed in Table 2.

5. Saturation and Stability-Limited Magnetic Materials

Another group of metallic magnetic materials also involves the telecommunications or high-frequency low level applica-

Table 3(a) High-frequency inductor materials

Materials	Saturation flux density G	T	Curie point, °C	Resistivity, $\Omega \cdot cm$	Initial Permeability μ_0	Frequency range	Loss factor, $1/\mu Q$
Permalloy powder	8,000	0.8	460	500	14-300	1-300 kHz	300×10^{-6}
Sendust powder	10,000	1.0	500	10	80	1-100 kHz	300×10^{-6}
Carbonyl iron powder	12,000	1.2	700	100	3-40	0.1-100 MHz	20×10^{-6}
Mn-Zn ferrite	3,800	0.38	145	100	2,000	1-200 kHz	2×10^{-6}
Ni-Zn ferrite	1,500	0.15	350		80		
	3,500	0.35	400	10^7	1,500	1-20 MHz	100×10^{-6}

Table 3(b) High-frequency power materials

Materials	Saturation Flux density G	T	Curie point, C	Resistivity	Initial permeability, μ_0	Maximum permeability	Core loss, W/kg	At frequency	At flux level
Metglas(a) 2605 S3	15,800	1.5	405	$125\ \mu\Omega \cdot cm$	...	20,000	10	20 kHz	2 kG
Mn-Zn ferrite	4,700	0.47	250	$100\ \Omega \cdot cm$	2700	4,500	14	20 kHz	2 kG
Powder core 50-50 Ni-Fe	15,000	1.5	500	$10\ \Omega \cdot cm$	125	150	88	20 kHz	2 kG (0.2 T)
Iron powder core	19,000	1.9	770	$5\ \Omega \cdot cm$	90	250	360	20 kHz	2 kG

(a)Metglas is a proprietary trademark of Allied Corporation.

Table 4 Saturations of various magnetic materials

Material	Saturations, gausses
CoFe (49% Co, 49% Fe, 2% V)	22,000
SiFe (3.25% Si)	18,000
NiFe (50% Ni, 50% Fe)	15,000
NiFe (79% Ni,4% Mo, balance Fe)	7,500
NiFe powder (91% Ni, 2% Mo, balance Fe)	8,000
Fe powder	8,900
Ferrites	4,000-5,000
Amorphous metal alloy (Fe based)	15,000
Amorphous metal alloy (Ni or Co based)	7,000

tions. These consist of the metal powder cores of iron and nickel-iron.

Referring to our previous equation relating eddy current losses to dimensions, reducing the thickness by preparing first wire and finally powder materials would certainly be one method of reducing losses. In addition, the use of insulation between the particles also increases the resistivity of the compacted material, lowering eddy current losses.

With regard to protection against saturation, the presence of a discrete or distributed air gap shears the hysteresis loop. The slope of the loop is reduced and linearized, and the permeability, though lowered, is made very constant (see Fig. 3). In powder cores, the distributed gap avoids the possible fringing flux of a discrete gap. The materials used for this application are listed in Table 3.

6. High-Frequency Power Supplies

The last category of metallic magnetic materials also uses metallic powder cores but instead is involved in generating relatively high power compared to the previous category. Iron, high-flux MPP (molybdenum permalloy powder), and Sendust (Kool-Mu) cores can be used in this application. Most often, these materials are used in either input or output chokes in the power supply. Their use in this application relies on their tolerance to superimposed D.C. and their protection against saturation (See Section 5). Their properties are listed in Table 3.

7. Basic Properties of Ferrite Ceramic Magnetic Materials

As mentioned earlier, the ferric ion, Fe^{3+}, in the free state possesses an integral 5 μ_B. Unfortunately, in oxides of iron including ferrites, the ions do not interact in straight ferromagnetic fashion involving parallel alignment of the magnetic ions. Instead, they interact through the oxygen ion in an antiferromagnetic or antiparallel mechanism. There are two different lattice sites (tetrahedral and octahedral) on which the metal ions are located. The antiferromagnetic exchange occurs mostly between neighboring ions on the two different sites. Thus, the moment on a ferric ion on the A or tetrahedral would cancel the opposing moment on a B site. Fortunately there are twice as many B sites as A sites, and since the extra B sites are also antiparallel aligned to the A sites, there is a net moment. The ions other than the ferric, which can enter the spinel or ferrite lattice, are divalent and can consist of Fe^{2+}, Ni^{2+}, Mn^{2+}, Co^{2+}, Zn^{2+}, Mg^{2+}, and Cu^{2+}. Some of these are not magnetic

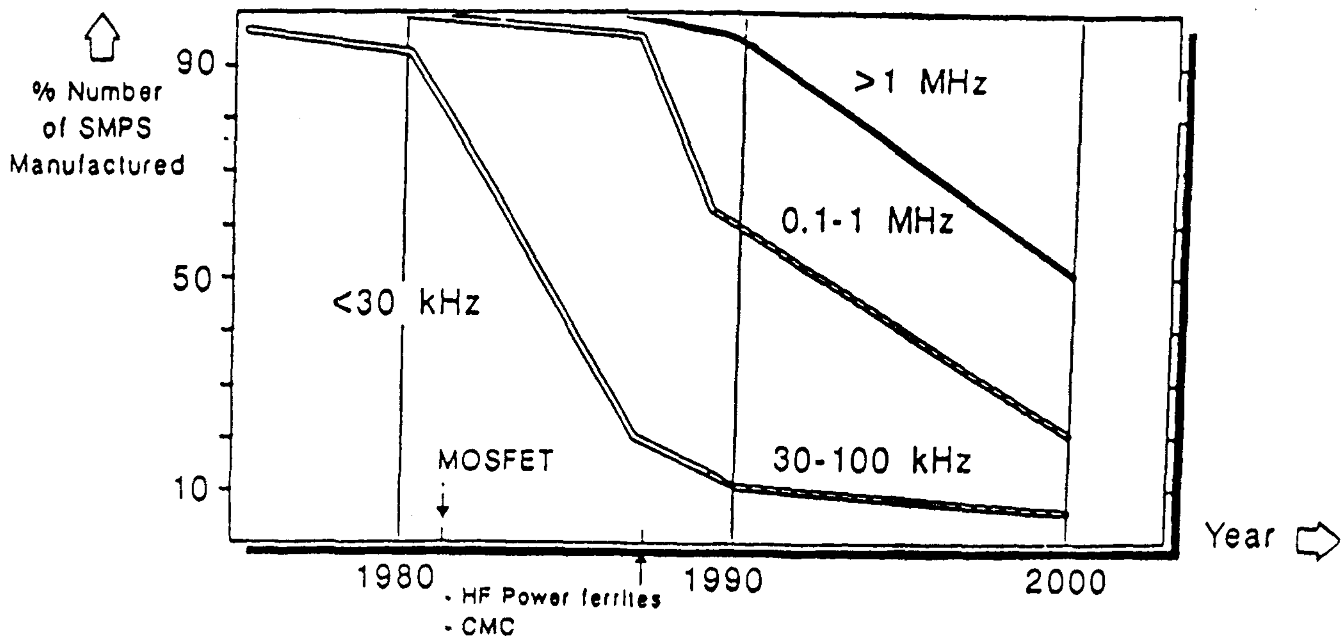

Fig. 4 Modification of operating frequencies of switched-mode power supplies (SMPS) chronologically (Ref 4)

Table 5 Typical resistivities of magnetic materials

Material	Resitivity, Ω · cm
Iron	9×10^{-6}
Silicon iron	50×10^{-6}
Nickel iron	45×10^{-6}
MnZn ferrite	10^2-10^3
Ni-Zn ferrite	10^6-10^8
Yttrium iron garnet	10^{12}

ions, but because of favorable site preferences, they can disproportionate the moments between the two lattices so there is a larger net moment. The range of saturations (in cgs units) in ferrites is given in Table 4 compared to other metallic materials. Note that the saturations for the ferrites are significantly lower than the metallic materials. This is due to the presence of the large oxygen ions and the less efficient moment generation mechanism.

8. High-Frequency Applications of Ferrites

Aside from the dc applications as permanent magnets, the rest of the applications for ferrites involve high-frequency operation. According to Eq 1, if the frequency is changed from 60 Hz to 60,000 Hz, it is theoretically possible to reduce the NA, or size of the core, by a factor of 1000. The saturation of ferrites is lower than some of the metal power materials by a factor of 4 to 5, but there still is quite an overall advantage. The metallic materials could not do this because of the tremendous losses at those frequencies. Losses at these frequencies contain a much larger percentage of eddy current losses. From Eq 2 for eddy current losses, we can reduce the eddy currents at high frequencies by greatly increasing the resistivities. The resistivities for several magnetic materials including ferrites are given in Table 5. There is a difference of almost 10^6 in resistivity between the metallic strip materials and even the lowest resistivity ferrite. Operation at a lower flux level also favors the lower losses in ferrites. Though the frequency dependence is squared and the resistivity dependence is only the first power, there is still about a 1000 to 1 reduction in eddy current losses. While the reduction of size in going to ferrites does not include all the other factors operating, it strongly indicates the trend.

9. Telecommunications or Low-Level Use of Ferrites

Ferrites did not develop much with the telephone because there were magnetic materials available at the time. However, the advent of radio and particularly television really spurred the growth of ferrites after World War II. Eventually some of the telephone applications were switched to ferrites.

10. High-Frequency Switched-Mode Power Supplies

The fastest growing segment in the ferrite applications area is in the new switched-mode power supplies. Because of the advantages of high frequency operation, the efficiency of the usual linear power supply with 60 Hz magnetics can be increased from about 50% to about 70 to 80% efficiency at a frequency of 50,000 to 100,000 Hz. Because of this, the size of the dc power supply can be reduced dramatically and, in many cases, fit on the printed circuit board.

Frequencies for this type of power supply have risen over the past few years. Figure 4 shows the change in frequencies as

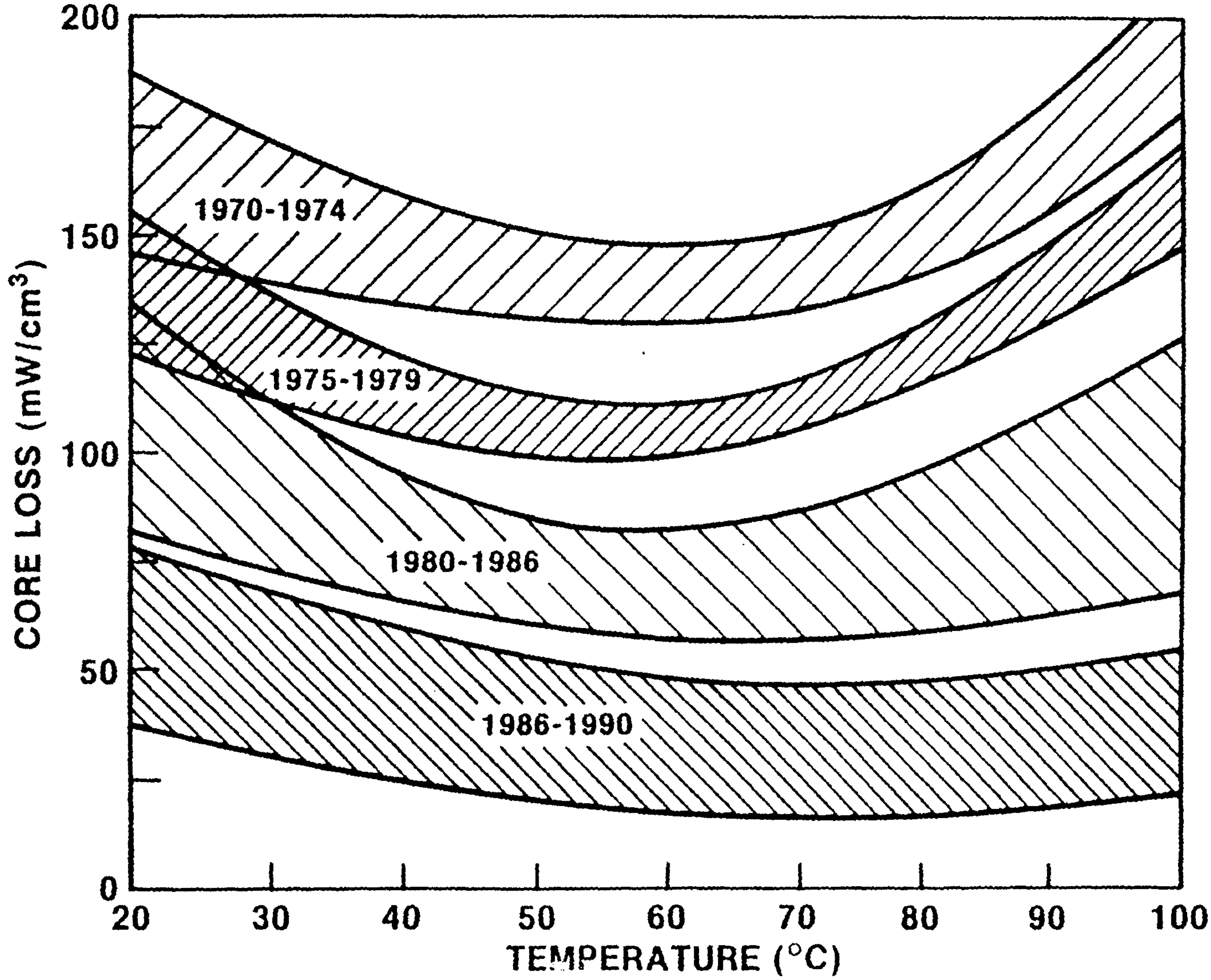

Fig. 5 Reduction in core losses in switched-mode power supplies (1970 to 1990) (Ref 5)

a function of time. The improvement in the core losses from 1970 to 1990 is shown in Fig. 5.

11. Advantages and Disadvantages of Ferrite Materials

The disadvantages of ferrite materials are:

1. Low saturation inductions
2. Low Curie points
3. Low-to-medium permeabilities
4. Low tolerance to high dc
5. Medium temperature stability
6. Low thermal conductivity

The advantages of ferrite materials are:

1. High resistivity
2. Low high frequency losses
3. Increased efficiency in switched-mode power supplies (SMPS)
4. Smaller size and weight in SMPS
5. Low-cost raw materials
6. Low-cost production techniques
7. Versatility in shapes

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