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Comparative Wide Temperature Core Loss Characteristics of Two Candidate Ferrites for the NASA/TRW 1500 W PEBB Converter

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COMPARATIVE WIDE TEMPERATURE CORE LOSS CHARACTERISTICS OF TWO CANDIDATE FERRITES FOR THE NASA/TRW 1500 W PEBB CONVERTER

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ABSTRACT

High frequency core loss and magnetization properties of commercial type MN8CX and PC40, high resistivity, MnZn based, power ferrites are presented over the temperature range of −150 C to 150 C, at selected values of peak flux density (B_p). Most of the data is at 100 kHz, with some data extended to 200 and 300 kHz for the MN8CX. Plots of the specific core loss against temperature exhibit the minimal characteristic of such ferrites. These plots show that the MN8CX is optimized for minimum loss at about 25 C, whereas the PC40 is optimized at about 80 C. At the points of minimum loss and for the same B_p, the MN8CX has roughly half the losses of the PC40 at the lower flux densities. This loss ratio continues down to cryogenic temperatures. However, above about 80 C the losses are practically equal. The lowest 100 kHz loss recorded, 50 mW/cm^3 for the MN8CX at a B_p of 0.1T, equals that of a very low loss, Co based, transverse magnetically annealed, amorphous ribbon material. Except possibly at lower B_p or much higher frequencies, these ferrites are not competitive for low losses over a wide temperature range with certain specialty amorphous materials. Permeability is computed from a linear model, plots against temperature are presented and again compared to the specialty amorphous materials.

INTRODUCTION

The NASA/TRW Power Electronics Building Block (PEBB) dc-to-dc converter is designed to provide a 28 V output from a 120 V input and is rated 1.5 kW maximum. It is a zero voltage switched, full bridge topology that has achieved a maximum efficiency just over 92% at about half of its rated power. Its clock frequency is 100 kHz, which thus requires a high frequency magnetic material for the core of its main output transformer.

The present, development prototype converter uses the TDK, Inc. type PC40, MnZn power ferrite, size EC70-Z, in the core of the output transformer. The input voltage to this transformer is a fixed amplitude, slightly drooping square wave, with variable dead zones between the half-cycles, such as to provide for load regulation. At high power, the B-field in the core reaches 0.1 T. The 100 kHz, sinusoidal excitation, specific core loss at $B_{peak} = 0.1T$ is about 0.1 W/cm^3, giving 5.33 W for the total core loss (core volume is 53.3 cm^3).

The above magnetics loss estimate clearly shows that the main transformer core loss amounts to less than 1/2% of the total power, thus being far below the solid state switch and diode losses. However, there are reasons for searching out further core loss reductions even at this already low level. For one, in most power converter circuits that utilize magnetic components, the inductors and transformers are a major contributor to mass and bulk. And a core of a better magnetic material can be smaller without increasing losses. Also, in a chain of n power processors supplying a fixed power P_{load}, the losses of an upstream power converter can be considerably amplified by downstream inefficiencies. Indeed, the ith processor from the start of the chain contributes

$$P_{loss,i} = P_{load}\,\delta_i \,/\,(\varepsilon_i \cdot \varepsilon_{i+1} \cdot \ldots \cdot \varepsilon_n) \qquad (1)$$

to the losses, or input power, where $\varepsilon_i = 1 - \delta_i$ is the efficiency of the ith processor. Even a small savings in losses is valuable, because the loss power usually amounts to waste heat that must be radiated to space.

Specific core loss data is reported below for the commercial type PC40 (TDK, Inc.) and type MN8CX (Ceramic Magnetics, Inc.) MnZn power ferrites. The MN8CX was selected as being unique among MnZn power ferrites for its very low losses up to about a MHz, due in part to its high, 10 Ωm dc resistivity. The purpose is to provide wide temperature baseline data for comparison of these high frequency power ferrites to certain amorphous and nanocrystalline ribbon materials based on Co and/or Fe. There exists an extensive literature describing the physics and characteristics of the amorphous magnetic materials. Also, wide temperature data for a few selected, flat B-H loop types has been reported [1] to NASA. The ferrites selected here are representative of commercially available, competitive types (e.g., the 3C85) and are not intended to be a specific endorsement.

SAMPLE CORES AND MEASUREMENT SETUP

Bare toroidal cores of the MN8CX and PC40 ferrites were equipped with primary exciting and secondary sense windings to provide exciting current and induced voltage data. This data was then recorded digitally in a standard setup described before [1, 2, 3] and processed for core loss and magnetization properties, again as before.

The temperature control fixture used below room temperature was a small, electrically heated ceramic-walled oven, suspended in a liquid nitrogen dewar. Temperatures above room were controlled by heating tapes in another compact oven. These fixtures were suitable for high frequency data, from −150 C to 150 C. Most of the data was taken at 100 kHz (sinusoidal) over this temperature range, but a few data runs were done at 200 kHz and 300 kHz for the MN8CX only.

Dimensions of the present test cores and their selected material properties, as given by the manufacturers [4, 5], are provided in Table I.

CORE LOSS CHARACTERISTICS

Temperature resolved specific core loss data at 100 kHz and three selected values of peak flux density (B_{peak} or B_p) is presented in Figure 1. These curves show two of the well known and notable characteristics of many ferrites. First, the specific core loss is very temperature sensitive - much more so than the losses observed for some magnetic tapes of crystalline nickel-iron [6], or amorphous Co or Fe based alloys [1]. Second, these ferrites have a very pronounced minimum in the specific loss at a temperature which depends on the material, but is not sensitive to B_p. Also, the sharpness of this minimum increases with increasing B_p for the MN8CX and PC40.

Quantitatively, the minimum specific loss at 100 kHz and 0.1 T is seen to be 50 mW/cm^3, at about 25 C, for the MN8CX and 95 mW/cm^3, at about 100 C, for the PC40. However, at about 80 C or above (to the limits plotted), these materials exhibit comparable core loss. But when going to cryogenic temperatures, the MN8CX is seen to have roughly half the losses of the PC40. Comparing losses at the minimum points for the same B_p in Figure 1, the MN8CX is generally seen to have roughly half the losses of the PC40.

Due to the limited resources available for this experimental study, core loss dependence on frequency and B_p was measured for the MN8CX only. And this data was restricted to 100, 200 and 300 kHz, and to 25 and 100 C. Figures 2 and 3 summarize these results. The data obtained for these ferrites falls on the roughly straight lines usually seen for such log-log plots.

A word about tolerable core loss is appropriate here. In previous NASA reports, a steady core loss exceeding about 1.7 W/cm^3 in metallic tape wound cores has been considered impractical, from the standpoint of heat removal. A number of points presented in the data above are far in excess of this value, having been taken by a low duty cycle, signal burst method. Such high loss operating points in ferrites would likely be applicable to pulse power only.

MAGNETIZATION PROPERTIES

A previous report [1] to NASA reviews the use of a parallel L-R circuit to model core loss and magnetization properties in the linear region of the dynamic B-H characteristic of a core. This R accounts for the core loss, but not the winding loss. Such linear modeling is of course best for low hysteresis, essentially flat B-H loop core materials, which the ferrites are not. However, at low flux densities and high frequencies, the dynamic loop of a ferrite is close to elliptical and linear modeling is then useful. This parallel L-R model assigns a relative permeability μ_r according to

$$\mu_r \mu_0 = \omega B_p^2 / [(V_p I_p / V_c)^2 - 4\overline{p}_c^2]^{1/2} \qquad (2)$$

and a 'quality factor'

$$Q = \left[\left(\frac{V_p I_p}{2\overline{P}_c} \right)^2 - 1 \right]^{1/2} \qquad (3)$$

to the core material. Here V_c is the core volume, $\overline{p}_c$ is the volume-specific average core loss, $\overline{P}_c = V_c \overline{p}_c$ is the total average core loss, V_p is the peak induced voltage and I_p is the peak current. The parameters needed in the above formulas are all part of the experimental data.

μ_r values derived from Equation 2 are plotted against temperature in Figures 4 (MN8CX) and 5 (PC40) for 3 selected values of B_p. The generally strong dependence of μ_r on B_p shows that neither of the two materials are flat loop. The rapid μ_r drop off at the high temperature end, seen for the B_p=0.2, 0.3 T curves, can be attributed to the onset of magnetic saturation. This was evidenced by the appearance of saturation effects in the corresponding dynamic B-H loops (not presented here).

Although the magnitude of the μ_r is comparable for the two ferrites, its variation with temperature has an obvious qualitative difference. The μ_r curve of the MN8CX for B_p=0.1 T has an interval where it decreases with increasing temperature, exhibiting a local maximum and a minimum. This property is also evident for the 0.2 T curve, but is presumably obscured by magnetic saturation effects for the 0.3 T curve. The μ_r curves for the PC40 show no such behavior. This difference in temperature dependence of the μ_r could preferentially select one of these materials in a resonant circuit application that must operate over a temperature range.

The Q of these materials was generally quite low, hardly ever exceeding 10 for the range of operating parameters studied here. For the same $\bar{p}_c$, B_p and frequency f, a high μ_r reduces the Q, as is clear from the relation

$$\mu_r Q = \pi f B_p^2 / (\mu_0 \bar{p}_c) \, . \qquad (4)$$

Being of lesser interest, no plots are presented here of these low values of Q.

The reader should recall again that the above Q applies only to the core material and represents the high frequency region of the total Q of an inductor. At low frequencies, the winding losses start to dominate and cause the total Q to fall off.

SUMMARY AND CONCLUSIONS

100 kHz core loss and magnetization data was obtained over the temperature range of −150 C to 150 C for two MnZn type power ferrites, suitable for frequencies above 100 kHz. These were manufacturers' type MN8CX and PC40. Additional wide temperature data was taken for the MN8CX at 200 and 300 kHz, at selected values of the peak flux density B_p. These materials are representative of a class of relatively high resistivity MnZn power ferrites that are candidates for high frequency magnetics in aerospace inverters/converters, such as the NASA/TRW 1500 W power electronics building block prototype.

As expected for ferrites, the specific core loss was found to be much more temperature sensitive than the losses observed for some very low loss magnetic tapes of crystalline nickel-iron, or amorphous Co or Fe based alloys. Also as expected, these ferrites have a pronounced minimum in the specific loss at a temperature which depends on the material, but is not sensitive to B_p. However, the sharpness of this minimum increases noticeably with increasing B_p. Figure 1 shows that the MN8CX is optimized at about 25 C, whereas the PC40 is optimized at about 80 C, as concerns minimum core loss. At the respective temperatures of minimum loss and at cryogenic temperatures, the PC40 was observed to have roughly twice the core loss of the MN8CX. However, at about 80 C or above (to the limits plotted), these materials exhibit comparable core loss. The lowest 100 kHz core loss plotted in Figure 1 is about 50 mW/cm^3, attained by the MN8CX at 25 C and B_p=0.1 T. Core loss data for the MN8CX at higher frequencies is presented in Figures 2 and 3 at 25 C and 100 C, respectively, showing the usual quasi straight line characteristics on the log-log scales.

Certain relatively low saturation (~ 0.5 T), high permeability (~ 10^5 at low frequency), cobalt based, transverse magnetically annealed amorphous tapes, such as the manufacturers' types 6025F and 2714AF, are among the lowest loss commercially available core materials [1, 7]. And, unless driven to saturation, their specific loss has only a slight temperature sensitivity. The 100 kHz loss of these materials (18 to 23 μm thick tapes) at B_p=0.1 T is about 50 mW/cm^3. Thus the MN8CX can do as well at 0.1 T and 100 kHz, but only at 25 C. Moreover, even at 25 C and 100 kHz, the MN8CX becomes losswise noncompetitive to the amorphous tapes, as the B_p is raised to say 0.2 T. The MN8CX then dissipates 354 mW/cm^3, while the 6025F dissipates 198 mW/cm^3. Only when going to lower B_p and/or higher frequencies can the MN8CX gain an advantage.

A parallel inductor-resistor circuit was used to assign linear magnetization properties, such as the relative permeability μ_r and 'quality factor' Q, to the core material, from the original exciting current and induced voltage data. Such linear modeling provides useful estimates for some linear applications, even though the low B part of the magnetization curve of the above ferrites is quite nonlinear and there is also intrinsic hysteresis. This nonlinearity was seen as a strong B_p dependence of the thus derived μ_r.

Both ferrites exhibited a temperature sensitive μ_r, of the order of several thousands and with a generally positive temperature coefficient, over the range of −150 C to 150 C. However, temperature regions of decreasing μ_r were seen. For values of B_p above 0.1 T, a rapid drop of the

μ_r at the high temperature end was attributed to the onset of magnetic saturation. Also, each of the MN8CX μ_r curves for B_p=0.1, 0.2 T has an interval of decrease, before resuming to increase with increasing temperature. The μ_r curves for the PC40 show no such behavior. Hence one of these ferrites may be preferred in some resonant circuits subject to temperature swings. In comparison to the amorphous tapes [1], a less temperature and B_p sensitive μ_r of about the same magnitude is available in the Co based, transverse magnetically annealed, type 6030F or similar material.

The computed Q of these ferrites was quite low, hardly ever exceeding 10 for the range of operating parameters studied here. This was shown to be due to the rather high μ_r – in the thousands, as compared to the tens or hundreds of the higher Q, moly permalloy powder cores. However, ferrite cores easily can be, and often are, gapped to linearize the magnetization curve, decrease the μ_r and thus increase the Q.

Both of the ferrites characterized here are equally suitable for low loss, 100 kHz power transformers when operating not below about 70 C. Sufficiently below this temperature, the core loss can be reduced by as much as 50% of the PC40 loss by picking the MN8CX, partly because the MN8CX has been optimized for low loss at about 25 C and the PC40 at about 80 C. Although at 25 C, 100 kHz and 0.1 T the MN8CX can equal the core loss (50 mW/cm^3) of certain very low loss, amorphous tape cores, this ferrite can not compete for low loss with these amorphous cores over a wide temperature range. To obtain a competitive edge in losses, at least over some temperature range, operation has to be below 0.1 T or much above 100 kHz.

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Table I. Physical Properties of the MN8CX and PC40 Ferrites.

Type	B_s (T)	T_c (C)	H_c (A/m)	B_r (T)	ρ (Ωm)	δ (g/cm^3)
MN8CX	0.47	185	14.3	0.070	10.0	4.8
PC40	0.51	215	14.3	0.095	6.5	4.8

B_s - saturation magnetic induction, at 25 C
T_c - Curie temperature
H_c - Coercivity, at 25 C
ρ - electrical resistivity
δ - density

<u>Toroidal test core dimensions</u>:

	MN8CX	PC40
OD :	23.3 mm	20.1 mm
ID :	14.9	14.5
Ht :	7.69	7.46

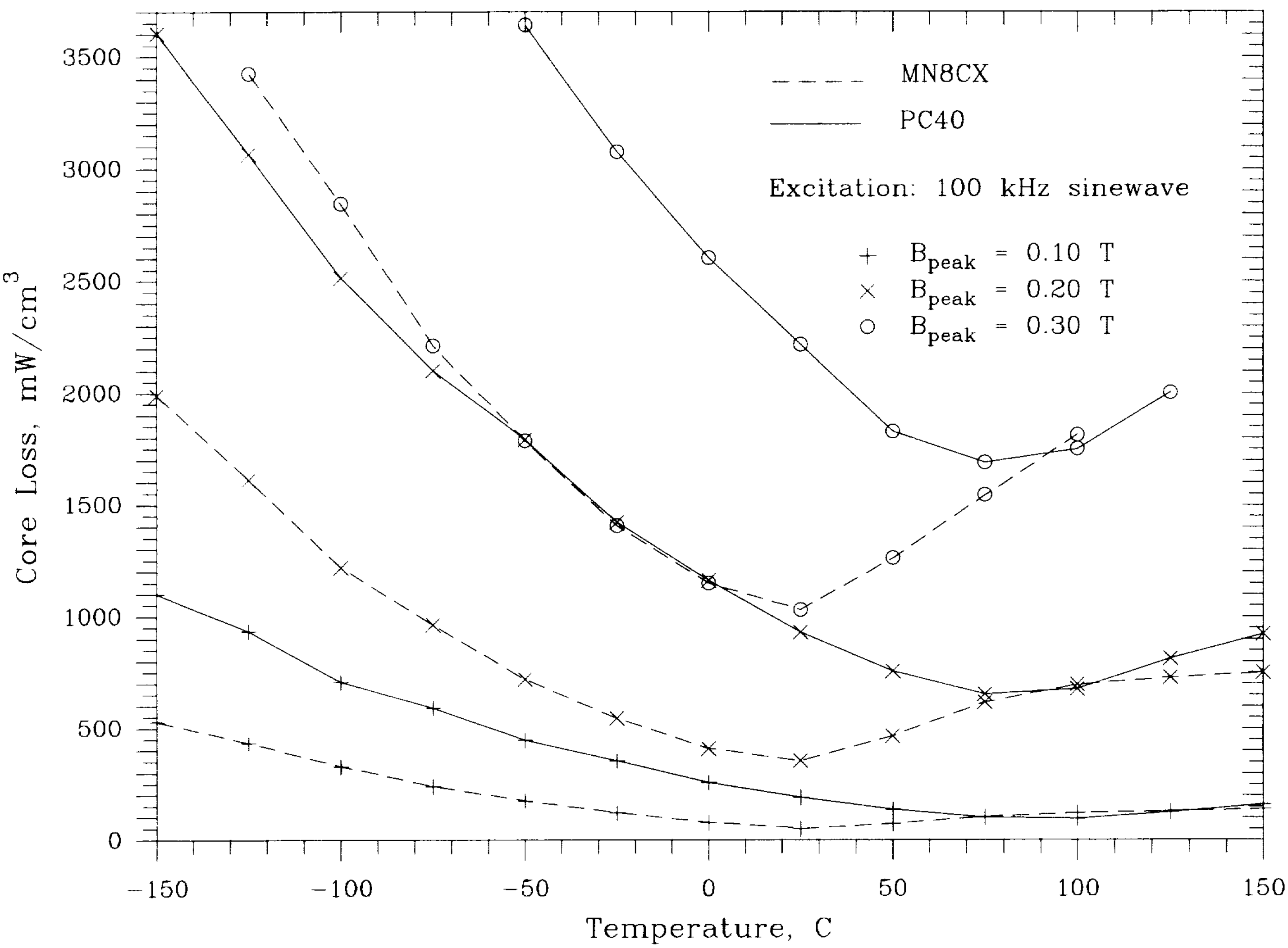

Figure 1. 100 kHz core loss in MN8CX and PC40 ferrites at selected peak flux densities.

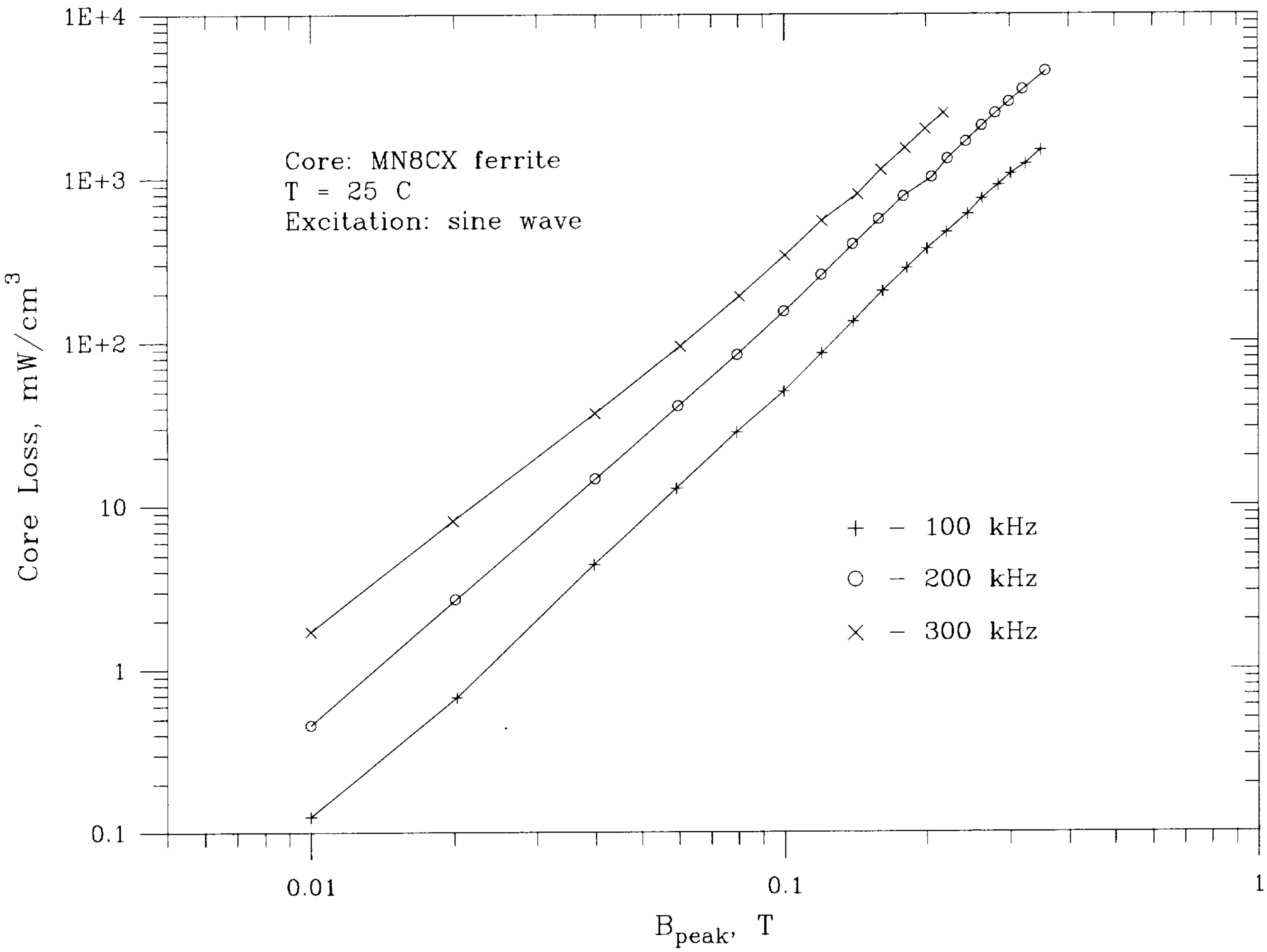

Figure 2. Variation of the specific core loss in the MN8CX ferrite with B_{peak} at 25 C for three selected frequencies.

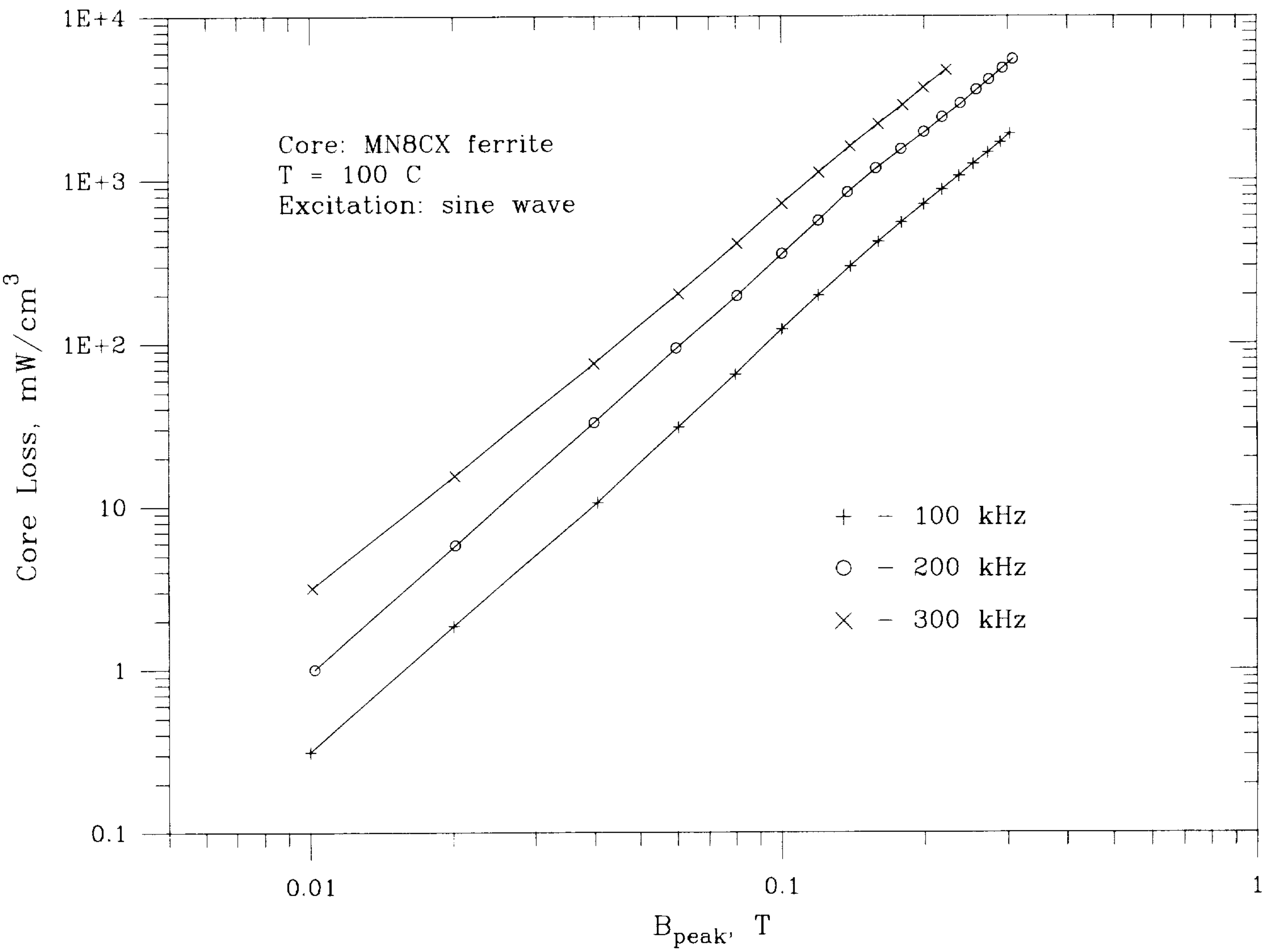

Figure 3. Variation of the specific core loss in the MN8CX ferrite with B_{peak} at 100 C for three selected frequencies.

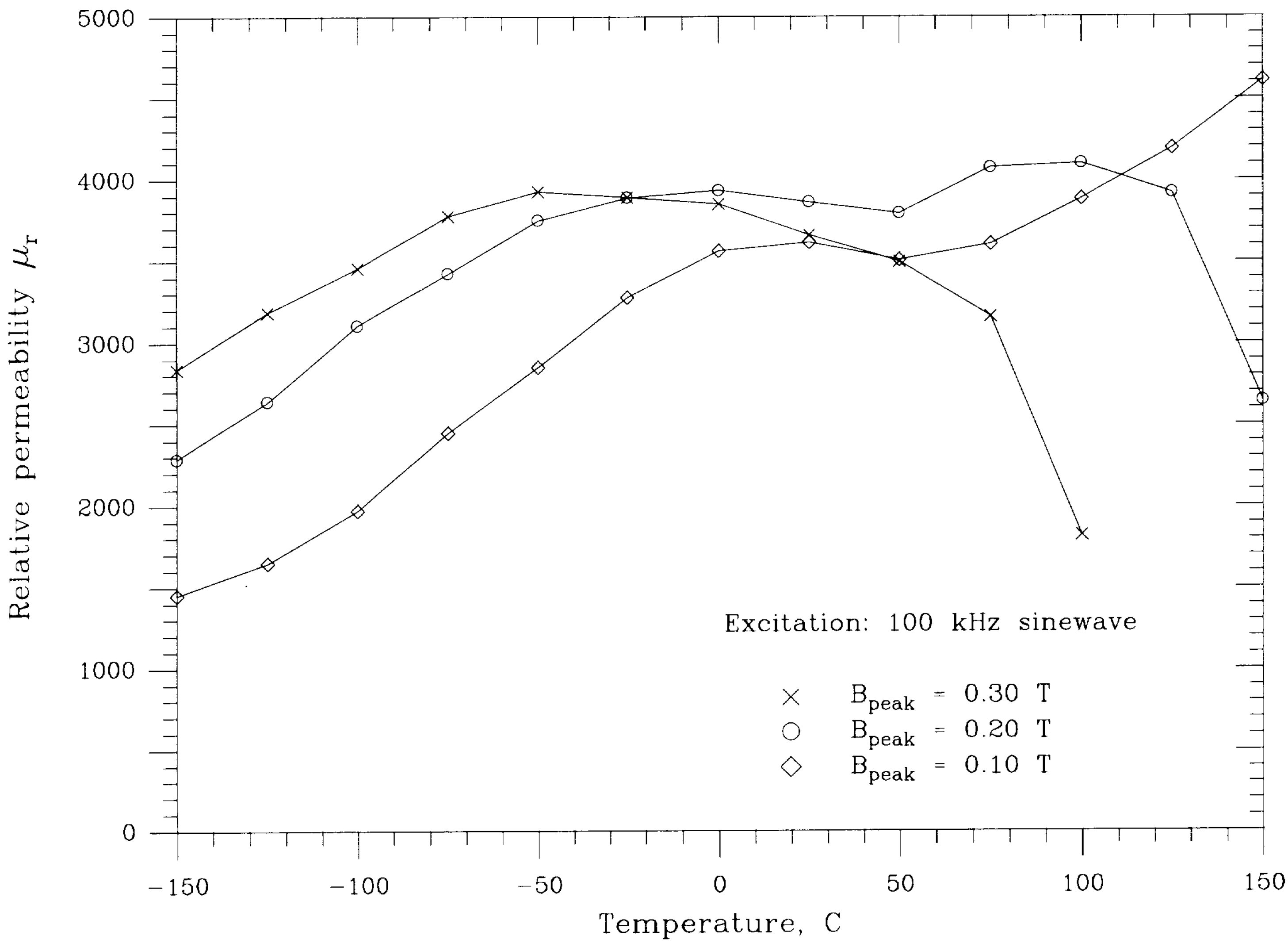

Figure 4. Temperature dependence of the relative permeability of type MN8CX ferrite at selected B_{peak} and f=100 kHz

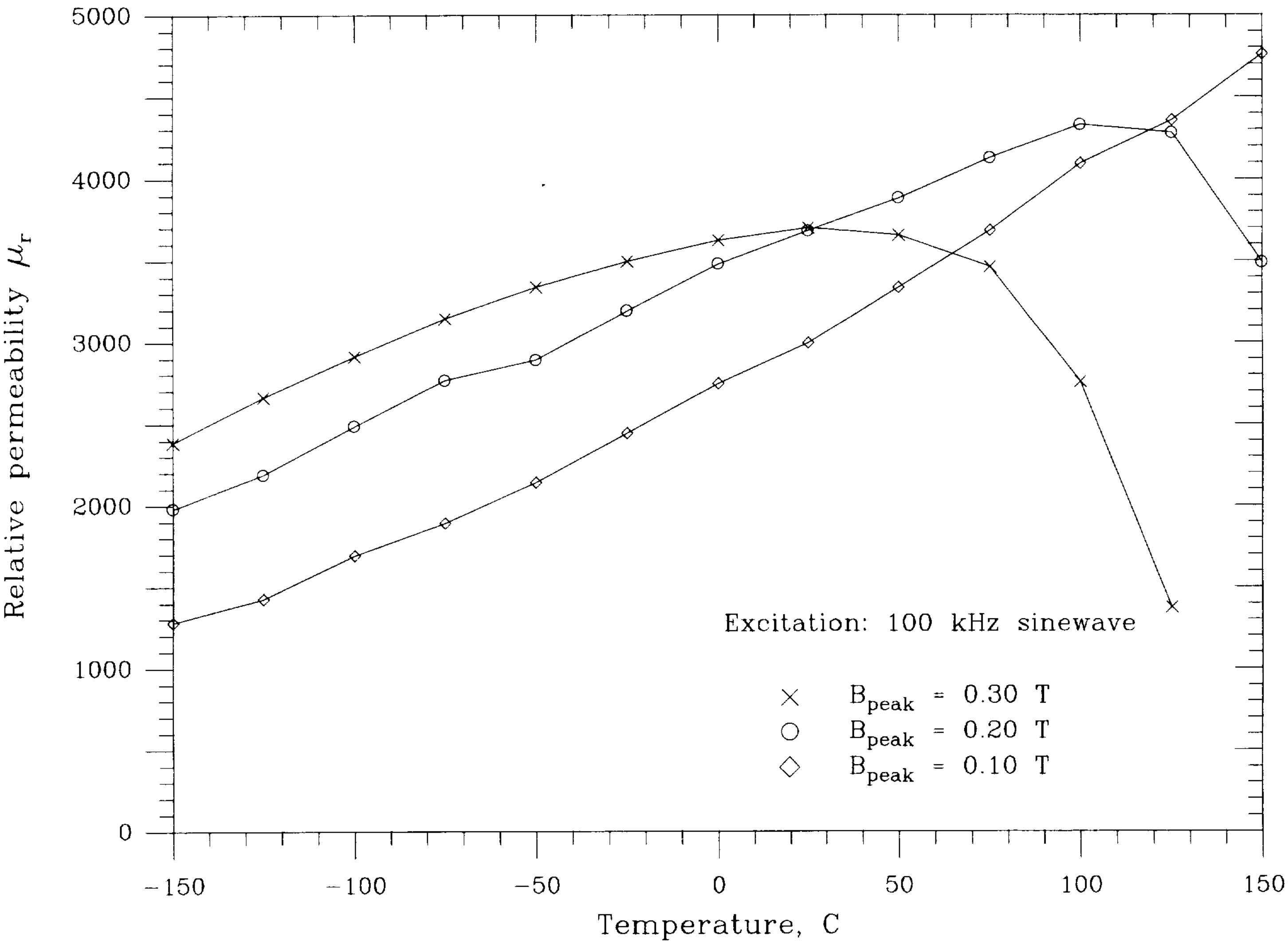

Figure 5. Temperature dependence of the relative permeability of type PC40 ferrite at selected B_{peak} and f=100 kHz.

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13. ABSTRACT *(Maximum 200 words)*

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