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WADC TECHNICAL REPORT 52-287

SURVEY, CHARACTERISTICS, AND EVALUATION OF HIGH-PERFORMANCE MAGNETIC CORE MATERIALS

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NOVEMBER 1952

WRIGHT AIR DEVELOPMENT CENTER

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SURVEY, CHARACTERISTICS, AND EVALUATION OF HIGH-PERFORMANCE MAGNETIC CORE MATERIALS

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Components and Systems Laboratory

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Wright Air Development Center
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Wright-Patterson Air Force Base, Ohio

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FOREWORD

This report was initiated by the Components and Systems Laboratory of the Directorate of Laboratories at Wright Air Development Center, Wright-Patterson Air Force Base, Ohio. The report was prepared as part of the work essential to RDO No. 112-157, "Magnelectric Materials." The author of the report was the project engineer.

A major portion of the information contained herein was first presented by the author as a technical paper at The National Conference on Airborne Electronics, 12 May through 14 May 1952. The manuscript of this report was presented on 16 June 1952 for publication as a Wright Air Development Center Technical Report.

Acknowledgment is made of the cooperation of the following companies and organizations in supplying information: Allegheny-Ludlum Steel Corporation of Brackenridge, Pennsylvania; Armco Steel Corporation of Middletown, Ohio; Arnold Engineering Company, Marengo, Illinois; Bell Telephone Laboratories, Murray Hill, New Jersey; D. M. Steward Manufacturing Company, Chattanooga, Tennessee; Ferroxcube Corporation of America, Saugerties, New York; General Ceramics and Steatite Corporation, Keasby, New Jersey; Stackpole Carbon Company, St. Marys, Pennsylvania; and Westinghouse Electric Corporation, East Pittsburgh, Pennsylvania.

Particular appreciation for special communications is extended to Messrs. G. H. Cole, D. C. Dieterly, and M. F. Littman of the Armco Research Laboratories and to Mr. W. Stifler of the Ferroxcube Corporation of America.

ABSTRACT

The great number of high performance magnetic core materials is surveyed and various direct current and alternating current characteristics of such materials are presented in table and chart formats. Figures of merit are derived and their suitability for a characterization of materials is discussed. These figures of merit are used to compare and evaluate such different types of core materials as laminated materials, powdered materials, and ferrites.

Universal charts covering characteristics of high performance core materials over wide frequency and flux density ranges are presented herein. A portion of this report is devoted to the review and consolidation of various permeability concepts which are used to describe material characteristics at high frequencies.

PUBLICATION REVIEW

The publication of this report does not constitute approval by the Air Force of the findings or the conclusions contained therein. It is published only for the exchange of ideas.

FOR THE COMMANDING GENERAL:

for C. C. Eckert
RICHARD S. CARTER
Colonel, USAF
Chief, Components and
Systems Laboratory
Directorate of Laboratories

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INTRODUCTION

The comparison and evaluation of magnetic core materials present problems because of the wide variety of both materials and characteristics. This is particularly true in the field above power frequencies where different kinds of materials such as thin laminations, powdered irons, and non-metallic ferrites are competing. Except for early compilations of data on direct current (dc) characteristics (see references 1, 6, and 11), the available information on magnetic materials, which would aid in selection, is scattered throughout numerous publications and frequently does not lend itself to the making of comparisons and evaluations.

The purpose of this report is to present a brief survey of magnetic materials and to derive and present characteristics in a form which is suitable for comparison and evaluation. Data are compiled from various publications and from manufacturers' information. (See references.)

No attempt has been made to cover as many materials as are available. Emphasis has been placed on presenting data on high performance magnetic materials which are commercially obtainable in the United States. A few experimental and foreign materials which exhibit interesting or outstanding characteristics have been included.

Designers who are not too familiar with magnetic materials are cautioned about the wide variations which may be encountered in the characteristics of magnetic materials. All figures presented herein are to be understood as approximate. Deviations between material samples can exceed 100%, particularly in such characteristics as permeability, coercive force, and others.

DIRECT CURRENT CHARACTERISTICS OF MAGNETIC MATERIALS

The large number of metallic core materials is arranged according to composition in Table I. This arrangement automatically shows identical or similar materials even though they may have entirely different trade names.

Since iron is the most important component of magnetic alloys, the dc characteristics of a pure iron sample are presented as the first item in Table I. Iron, if carefully purified and prepared, has very good magnetic properties. However, a shortcoming of pure iron is its low resistivity which is detrimental in all alternating current (ac) applications. The resistivity of pure iron can be increased by the addition of small quantities of silicon.

METAL OR ALLOY	MATERIAL OR TRADE NAME	COMPANY	COMPOSITION IN PERCENT (REST IRON)	CHARACTERISTIC PROPERTY OR APPLICATION	PERMEABILITY		SATURATION [K GAUSS]	RESIDUAL IND. [KG.]	COERCIVE F. [OERST.]	RESISTIVITY [MICROHM cm]	CURIE TEMP. [°C]
					INITIAL	MAXIM.					
	Purified Iron		0.02 Imp.	Low Resist.	25,000	275,000	21.5	13.6	0.05	10	770
SILICON-IRON	Silicon-Iron	see ref. 4	4 Si	Transformer	400	7,000	20	12	0.5	60	690
	Hypersil	Westinghouse		Grain					0.1		
	Trancor 3X	Armco	3.5 Si	Oriented	1,500	35,000	20	13.7	÷0.3	50	750
	Silectron	Allegheny-Ludlum									
	Sendust	Japanese	9.5 Si 5.5 Al	HF Powder	30,000	120,000	10	5	0.05	80	
COBALT-IRON	Hyperco	Westinghouse	35 Co 0.5 Cr	High	650	10,000	24	>13	>1	28	970
	2V Permendur	Western Electric	49 Co 2V	Saturation	800	4,500		14	2	25	980
NICKEL-IRON	45-25 Perminvar	Bell Telephone Laboratories	45 Ni 25 Co	"Constant"	400	2,000	15.5	3.3	1.2	20	715
	7-70 Perminvar		70 Ni 7 Co	Permeability	850	4,000	12.5	2.4	0.6	15	650
	Conpernik	Westinghouse	50 Ni		1,500	2,000	16			45	
	36 Isoperm	German	36 Ni 9 Cu	High	60	65				70	300
	50 Isoperm		50 Ni	Frequency	90	100	16			40	500

METAL OR ALLOY	MATERIAL OR TRADE NAME	COMPANY	COMPOSITION IN PERCENT (REST IRON)	CHARACTERISTIC PROPERTY OR APPLICATION	PERMEABILITY		SATURATION [K GAUSS]	RESIDUAL IND. [KG.]	COERCIVE F. [OERST.]	RESISTIVITY [MICROHM cm]	CURIE TEMP. [°C.]
					INITIAL	MAXIM.					
NICKEL-IRON	45 Permalloy	Western Electric	45 Ni	Combine Good Permeab. and Flux D.	2,700	23,000	16.5	8	0.3	45	440
	"4750"	Allégheny-Ludlum	47 - 50 Ni		9,000	50,000	16	6.2*	0.08*	52	430
	Armco 48	Armco	48 Ni								
	Nicaloi	General Electric	49 Ni								
	High Perm 49	Carpenter	49 Ni		5,000	50,000		6.5	0.03	43	475
	Hipernik	Westinghouse	50 Ni, Si, Mn		4,000	100,000		8*	0.03*	45	500
	Monimax	Allegheny-Ludlum	47 Ni 3 Mo	High Resist.	2,000	38,000	15		0.06	80	390
	Sinimax		42 Ni 3 Si		3,500	30,000	11		0.1	90	290
	Permenorm 5000Z	German	45 to 50 Ni	Rect. Hyst. Loop	400 ÷1,700						
	Permenite	I.T.E. Circ. Br. Co.									
	Deltamax	Arnold Engr. Co.				40,000	15.5	13	0.2	40	450
	Hypernik V	Westinghouse				÷100,000	÷16	÷15	÷0.4	÷50	÷500
	Orthonik	Armco									
	Orthonol	Navy Ordn Lab.									
	65 Permalloy	Bell Tel. Lab.	65 - 68 Ni		1,500	250,000 ÷600,000	13	13	0.03	20	600

*Bmax = 10,000 Gauss

TABLE I (continued)

METAL OR ALLOY	MATERIAL OR TRADE NAME	COMPANY	COMPOSITION IN PERCENT (REST IRON)	CHARACTERISTIC PROPERTY OR APPLICATION	PERMEABILITY		SATURATION [K GAUSS]	RESIDUAL IND. [KG.]	COERCIVE F. [OERST.]	RESISTIVITY [MICROHM cm]	CURIE TEMP. [C°]
					INITIAL	MAXIM.					
NICKEL-IRON	1040 Alloy	German	72 Ni 14 Cu 3 Mo		40,000		6	2.5	0.02	55	290
	Mumetal	Allegheny-Ludlum	77 Ni 5 Cu 2 Cr		20,000	100,000	8	6	0.05	60	400
	78 Permalloy	Western Electric	78 Ni 0.6 Mn	Highest	9,000		10.7	6	0.05	16	580
	4-79 Mo-Permalloy		79 Ni 4 Mo	Perm.	20,000	75,00	8	5.5	0.05	55	
	Supermalloy	Arnold Engr. Co.	79 Ni 5 Mo	Low	55,000	500,000	6.8		0.002	65	400
				Sat.	÷150,000	÷10^6	÷7.8		÷0.05		
	Hymu 80	Carpenter	80 Ni		10,000	100,000	8		0.06	58	460

Silicon-iron was the first special alloy developed specifically for use as a magnetic core material. Because of its relatively low cost and its satisfactory performance in a wide field of applications, silicon-iron has dominated the field in the electrical industry.

There are more than ten manufacturers producing more than one hundred brands of magnetic silicon-irons in the United States, alone (Ref. 15). Many of these brands are identical in silicon content and performance. This class of material, which ranges in silicon content from less than .25% up to approximately 5%, is not covered in detail in this report. The differences in performances are small in comparison with the differences encountered in this survey. Data on a 4% silicon transformer iron are given in Table I as an example and as an aid in making comparisons.

Single crystals of magnetic materials are, generally, anisotropic. This means that the characteristics depend upon crystal orientation. Single crystals of magnetic materials have not yet been used beyond the laboratory, but grain-orientated materials, which have a preferred orientation of the crystals in a suitable direction, already play an important role in commercial materials. Proper grain-orientation results in a more rectangular hysteresis loop and in a higher operating flux density. Half hysteresis loops of various materials, including those with grain-orientation, are compared in figure 1.

Cobalt and nickel, the other two important ferromagnetic elements, have no significance as magnetic materials in pure form; however, they are the most important alloying elements. The addition of cobalt to iron substantially increases the saturation of iron, as in the case of Permendur and Hyperco. The advantage of higher saturation of these materials is partly overcome by higher losses. Reductions in size and weight can be obtained only in some power applications. Furthermore, cobalt is a "critical" material.

Other alloys, designated by the trade name, Perminvar, (Ref. 9) have a smaller cobalt content than does Permendur and Hyperco and also display unique magnetization curves. The Perminvar alloys have constant permeability and almost no hysteresis up to flux densities of 1,000 Gauss. Even at still higher flux densities, residual magnetization and coercive force remain practically zero. The permeability of Perminar, however, remains constant only as long as high magnetization is avoided. Other materials which have constant permeability are Conpernik, Isoperm, and powdered irons.

Nickel is of great significance as an alloying component in high performance core materials. Iron-nickel alloys are characterized by high permeability if properly processed. The saturation flux density, however, is reduced by nickel. Commercial iron-nickel alloys can, for the purposes of this report, be divided into two groups. This rough division groups together those alloys which contain 45% to 50% nickel and places in the other group those alloys which have a nickel content of from 65% to 80%.

The 45-50% nickel alloys display a higher saturation and generally a higher resistivity than do the alloys with higher nickel content. Small quantities of other alloying elements and special processing can produce desirable variations in characteristics. Examples in this group are Sinimax in which the resistivity has been increased to 90 microhm/cm and Isoperm from which low ac distortion and low high-frequency losses have been obtained. Alloys in the 45-50% nickel group

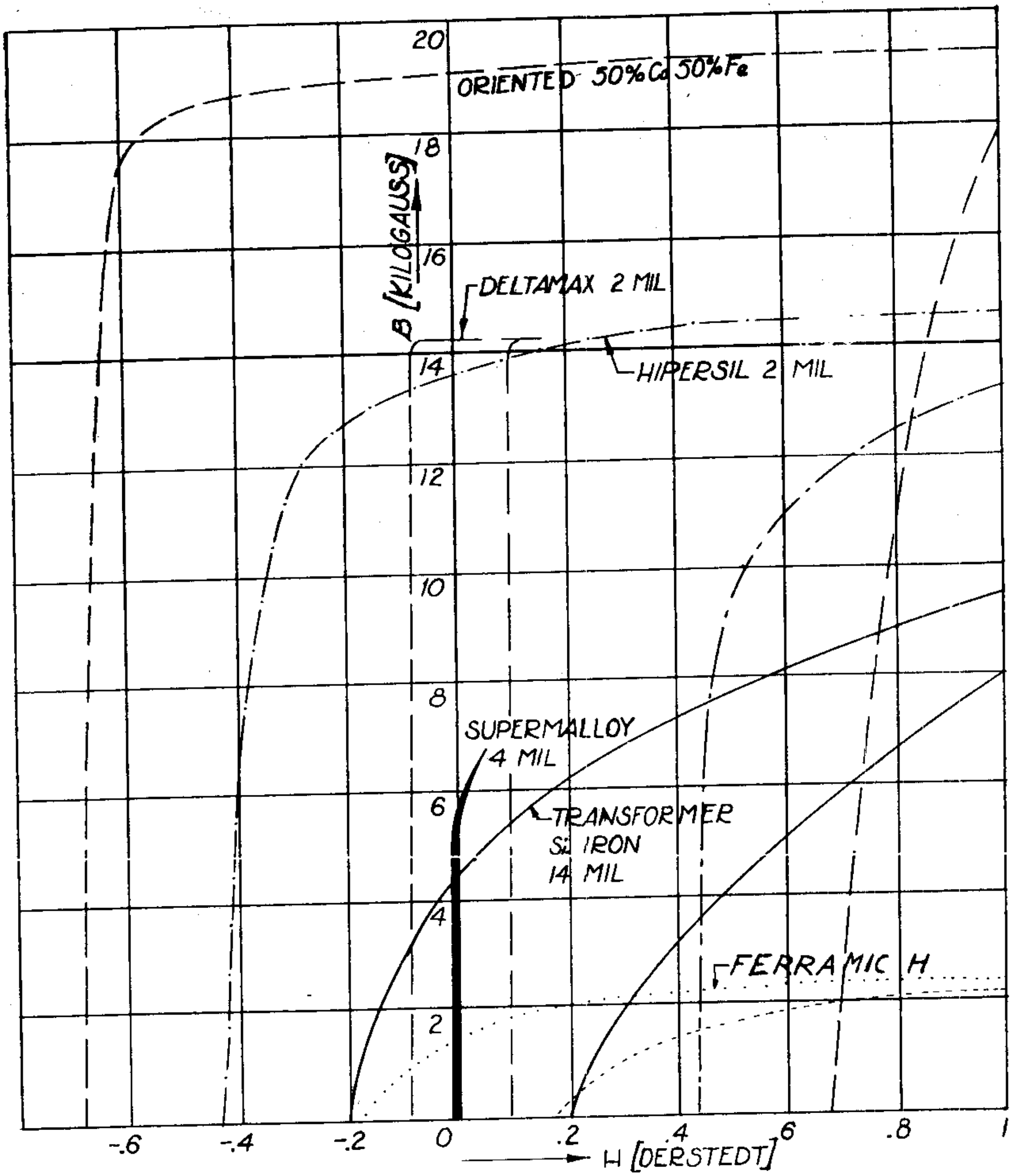


Fig. 1 Half DC Hysteresis Loops of Various Core Materials

have a great significance in the grain-orientated form in which they display rectangular hysteresis loops (see Deltamax: Fig. 1 and Ref. 7) which are desirable in magnetic amplifiers, magnetic pulse generators, computers, mechanical rectifiers, harmonic generators, etc.

As compared to the 45-50% group, the materials with higher nickel content have higher permeabilities, lower coercive forces, but much lower saturation. Unique characteristics of the alloys in this group are low magnetostriction and low anisotropy. Supermalloy (Ref. 4) is the latest development in this group and can be rated as the most advanced among the iron-nickel alloys. The hysteresis loop of Supermalloy condenses into one line if plotted for comparison with other materials. (See figure 1.)

The interesting characteristics of 65% Permalloy are obtained by an anneal in a magnetic field which has an effect on the hysteresis loop similar to that which results from grain-orientation. With magnetically annealed 65% Permalloy, almost perfectly rectangular hysteresis loops have been obtained. (See Ref. 8.)

The ferromagnetic ferrites, listed in Table II, represent a different class of materials. Their fundamental differences, as compared to the materials which have been discussed so far, are their non-metallic properties such as high resistivity and low weight. Ferrites are ceramic materials composed of certain divalent metal oxides among which is Fe_2O_3. Unfortunately, the term "ferrite" also denotes a particular (α) crystal phase of pure iron with which the ferrites under discussion herein should not be confused. Though known for a long time (German patents in 1909), practical ferrites did not become available until after World War II.

Low saturation and low permeability of ferrites exclude them from most low frequency applications but their high resistivity makes them superior at medium and high frequencies as is shown in the section entitled, "Alternating Current Characterization and Evaluation." The Curie temperatures of ferrites are, generally, lower than those of metallic materials. At present, high permeability can only be obtained at low Curie temperatures. Maximum permeabilities up to 9,000 coupled with Curie temperatures of approximately 80°C have been reported. Manufacturers can supply far more ferrite materials with desired combinations of characteristics than are listed in this report. Also, compounds with highly rectangular hysteresis loops have been announced. For more information on ferrites see references 3, 5, 17, 18, and 19.

TRADE NAME	COMPANY	RECOMMENDED FREQUENCY RANGE OR APPLICATION	PERMEABILITY		SATURATION [K GAUSS]	RESIDUAL INDUCTION [K GAUSS]	COERCIVE FORCE [OERSTEDT]	RESISTIVITY [OHM cm]	CURIE TEMP. [°c]	TEMP. COEFF. OF IN. PERM. [%PER °C]
			INITIAL	MAXIM.						
Ceramag[4] 5N	Stackpole		560	1,840	2,300	1,400	0.4	10^3	170°	
7	Carbon Co.,	see graph	540	4,600	2,460	1,750	0.2	1.8×10^4	170°	
8	St. Marys,		450	1,700	2,850	2,100	0.6	2.1×10^4	190°	
	Pa.									
(all data referring to 60 cps)										
Ferramic A	General		15 at 1 megacycle	97	0.84	0.61	3.7	10^9	280	0.65
B	Ceramics		95	183	1.9	0.83	3	2×10^5	260	0.04
C	and	see	220	710	3.8	2.7	2.1	2×10^3	330	0.4
D	Steatite	graphs	410	1,030	3.1	1.3	1	3×10^7	165	0.3
E	Corp.,		750	1,710	3.8	1.9	0.65	4×10^5	160	0.25
G	Keasbey,		410	3,300	3.2	1	0.25	1.5×10^8	160	1.3
H	N. J.		850	4,300	3.4	1.4	0.18	10^5	150	0.66
I		Const. Perm.	900	1,000	1.5	0.6	0.4	2×10^5	70	0.3
J			330	750	2.9	1.6	0.8		180	0.22
Ferroxcube 3	Ferroxcube		1,000	1,200	3		0.2	10^3	140	
3C	Corp. of		900	1,100	3.5				160	
For more compounds see figure 7	Am., 50 E. 41st St. New York, N. Y.									

TRADE NAME	COMPANY	RECOMMENDED FREQUENCY RANGE OR APPLICATION	PERMEABILITY		SATURATION [K GAUSS]	RESIDUAL INDUCTION [K GAUSS]	COERCIVE FORCE [OERSTEDT]	RESISTIVITY [OHM cm]	CURIE TEMP. [°c]	TEMP. COEFF. OF IN. PERM. [%PER °c]
			INITIAL	MAXIM.						
Lavite FIS	D. M.		1,000	3,000					250	
FX-6S	Steward	20-200 MC	8-11	100	0.6	0.5	3.7	10^6	200	0.03
FX-22S	Manuf. Co.	1-20 MC	15-20	120	0.9	0.6	3.7	10^6	200	0.03
FX-15S	Chattanooga	High Sat.) to	250	3,000	5	1.9	1	10^6	200	0.45
FX-27S	Tenn.	Transf. } 150 KC	850	4,000	3.5	1.5	0.25	10^6	150	0.5
FX-18S		Ant. Rod 1 MC	300	750	3	1.6	0.8	10^7	200	<3.5
High Perm.		1-150 KC	1,000	5,000	4	1.5	0.15	10^6	150	0.1

TABLE II (continued)

ALTERNATING CURRENT CHARACTERIZATION AND EVALUATION

Since core materials are generally used in alternating fields, their ac characteristics are more conclusive for evaluation purposes than are the dc characteristics. Alternating current characteristics, particularly, have to incorporate the losses which occur in a material. Core losses of various materials, in watts per pound, are presented in figure 2 with flux density as the ordinate. Frequencies, materials, and lamination thicknesses appear as parameters. It should be noted that in this representation, in which losses are given in watts per pound, ferrites are penalized because of their lower specific gravity. A comparison based on the losses per unit volume would make the advantages of ferrite materials at high frequencies more apparent. Even in the comparison on a watts per pound basis shown in figure 2, Ferroxcube III B appears clearly superior at 100 kilocycles. This advantage is particularly great at low flux densities.

Loss figures, alone, do not characterize a material and cannot be used for general evaluation. They have to be supplemented by other data such as exciting volt-amperes per pound. These characteristics are plotted in figure 3 which corresponds in representation with figure 2.

A suitable combination of both the losses expressed in watts per pound and the apparent watts expressed in exciting volt-amperes per pound can provide a figure of merit which may be used for the evaluation of materials. It should be noted that the smallest possible losses and exciting volt-amperes are desired for a given flux density. Hence, a single figure of merit can be derived by adding the losses of in-phase volt-amperes and the exciting volt-amperes. Such data are plotted in figure 4 which corresponds to figures 2 and 3 in representation. Materials with the lowest volt-ampere figures for a given frequency and flux density have to be rated highest in this diagram.

It must be emphasized that no particular physical meaning is attributed to the figure of merit thus derived. For simplification, volt-ampere vectors ("Phasors") are arbitrarily added as scalars. It should be realized that a figure of merit is, in general, more or less arbitrary and that its limitations should be studied in order to avoid misleading results. The meaning and possible limitation of the figure of merit, as proposed in the previous paragraph, can be understood better by noting the presentation in figure 5 where the locus is depicted for all exciting volt-ampere vectors for which the figure of merit is equal. This locus represents the exciting volt-amperes of all materials which would have to be rated as equal. The intersection of the locus with the reactive axis represents a material without any loss but with a rather low permeability. These conditions can be approximated with powdered core materials. The intersection of the locus with the in-phase axis represents a material with rather high losses but with a permeability of infinity because no magnetizing current is required to give rise to a certain assumed flux density. This type of material can be approximated by a perfectly cut single crystal of pure iron.

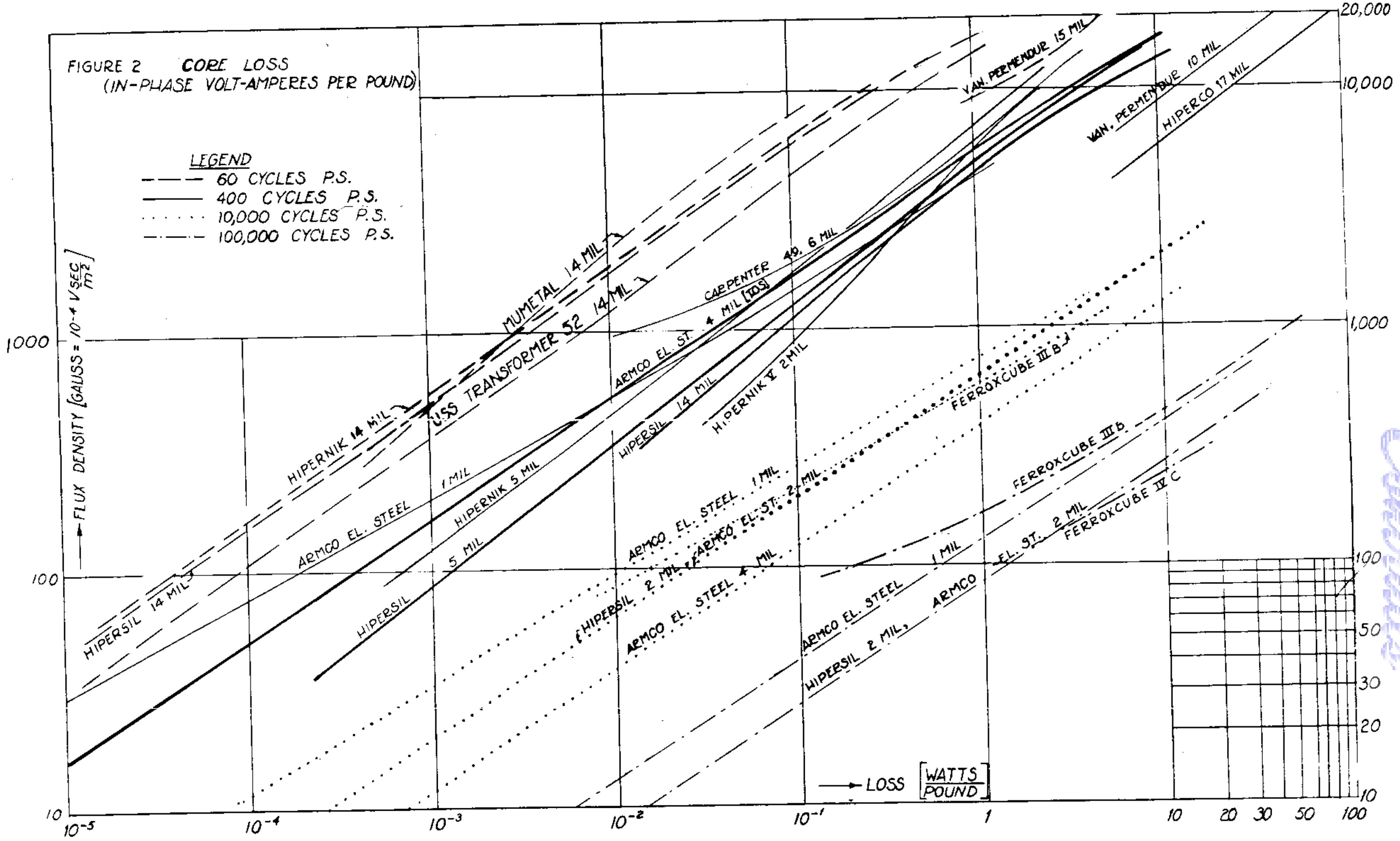


FIGURE 2 **CORE LOSS**
(IN-PHASE VOLT-AMPERES PER POUND)

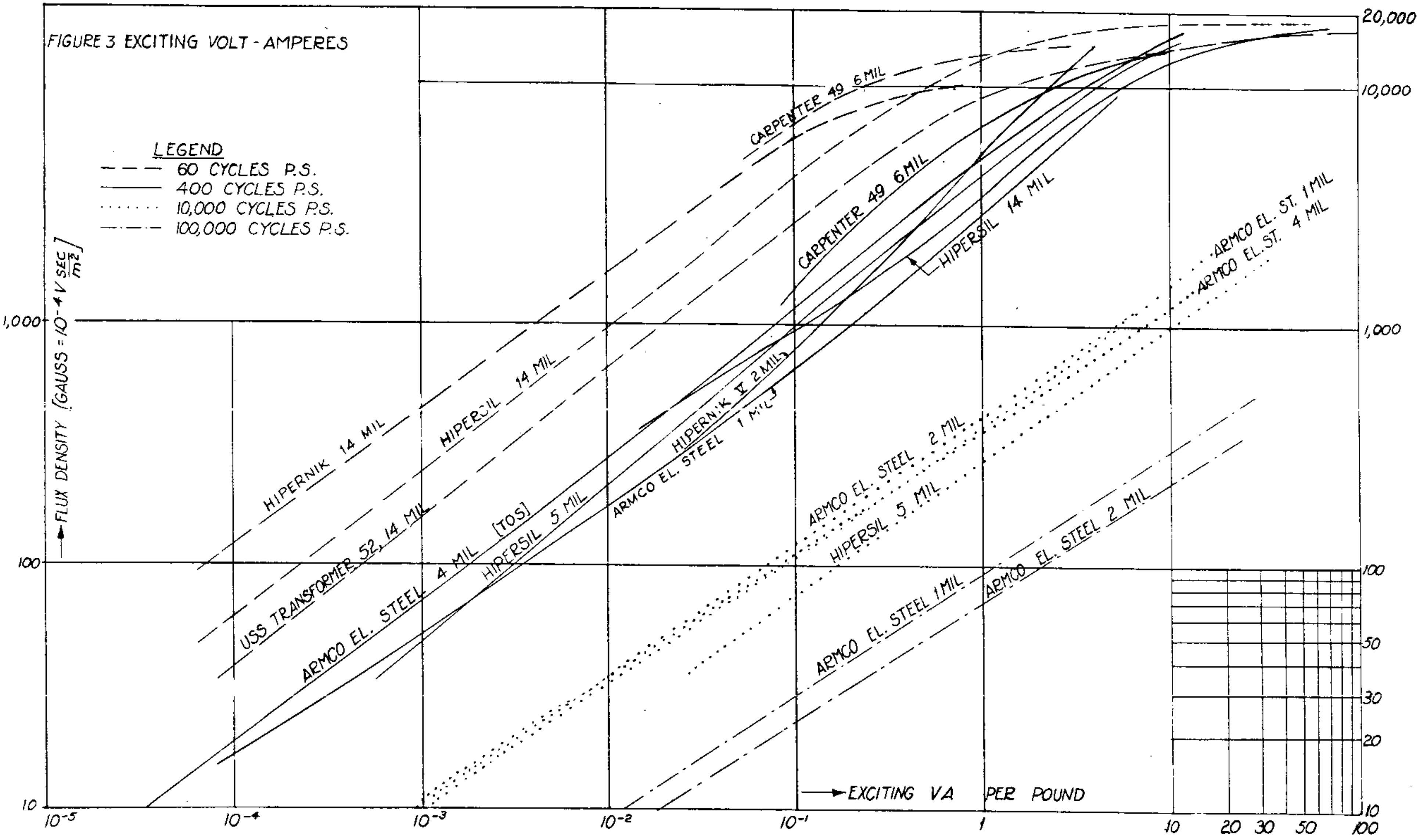


FIGURE 3 EXCITING VOLT - AMPERES

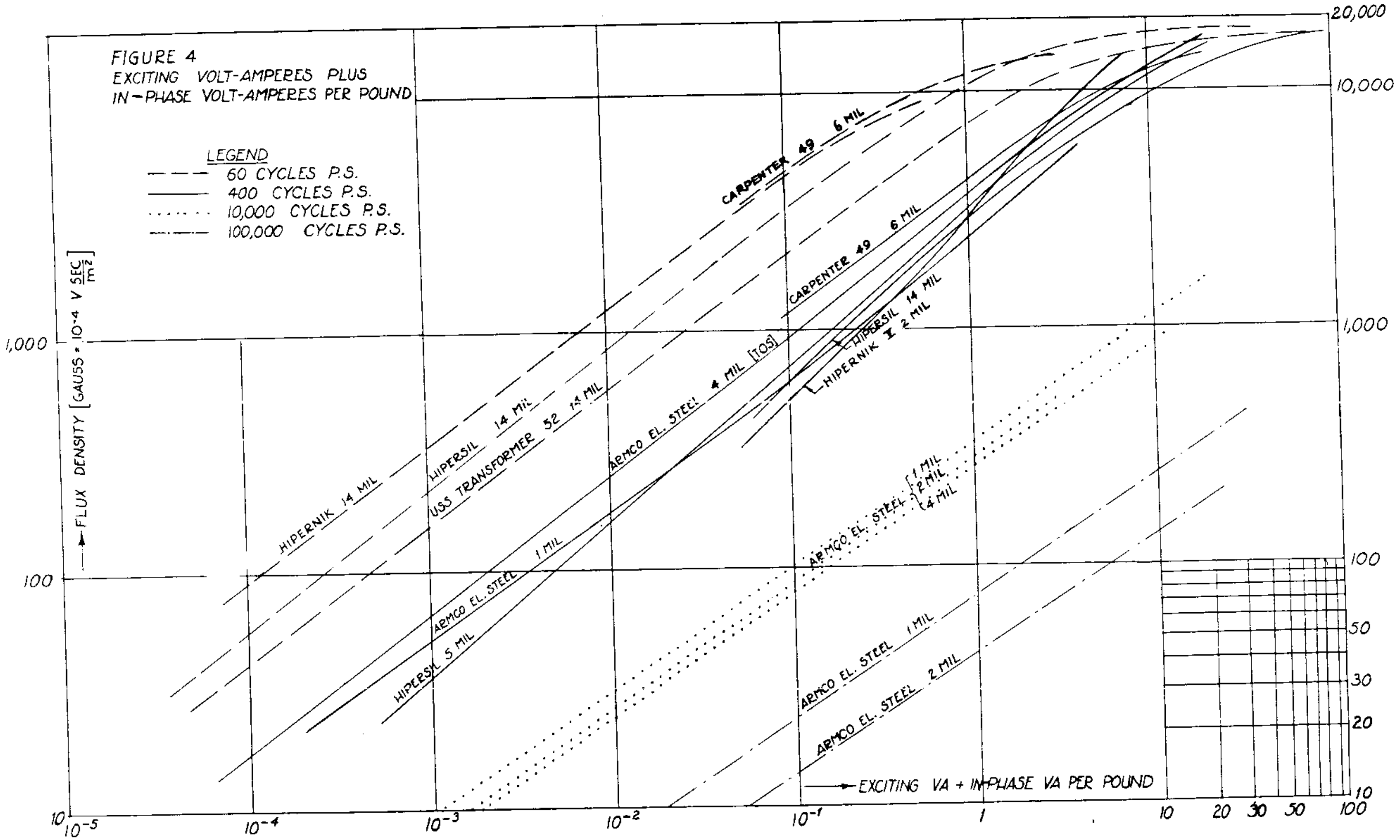


FIGURE 4
EXCITING VOLT-AMPERES PLUS
IN-PHASE VOLT-AMPERES PER POUND

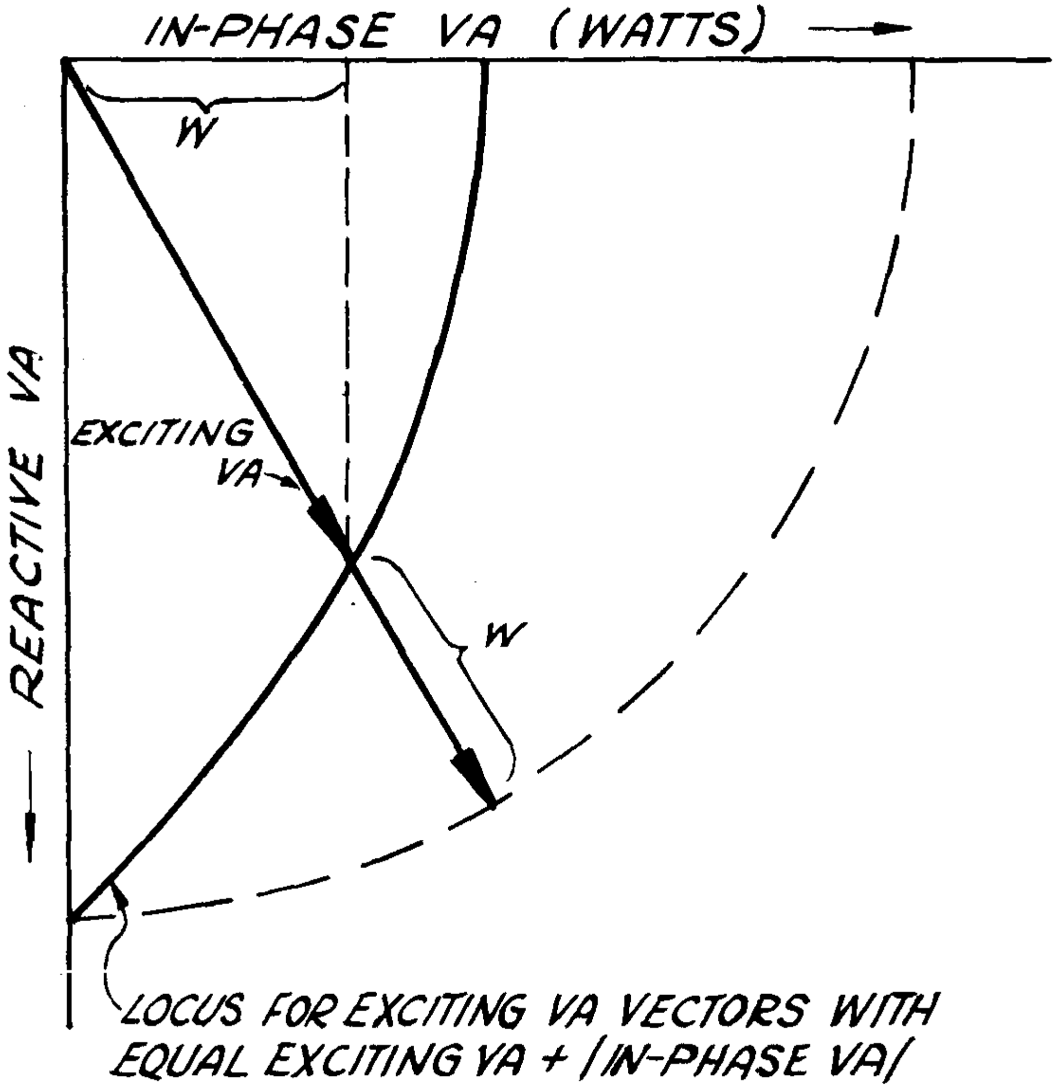


Fig. 5 Exciting Volt-ampere Vector Locus Resulting in Equal Figure of Merit for Given Flux Density and Frequency

Characteristics of those materials which have extremely small or great phase angles are not available and hence could not be incorporated in figure 4. Even sufficient data on ferrites are not yet available. The materials which are represented in figure 4 differ only slightly in characteristics and the figures of merit plotted there should provide a suitable base for evaluation of laminated core materials.

At very low flux densities, such characteristics as are presented in figures 2 through 4 are not very practical. Instead of exciting volt-amperes and power losses, reactive and resistive components of impedance are used to characterize inductors and core materials. Expressing the total loss component of an inductor by an equivalent series resistance R_s, the loss tangent $\tan \delta = \frac{R_s}{\omega L_s}$ relates the resistive component R_s to the reactive component ωL_s. The expression for $\tan \delta$ is also denoted as "dissipation factor" D or the reciprocal of the "quality" or "storage" factor Q. At high Q values, the power factor $\cos \varphi = \frac{1}{\sqrt{Q^2+1}}$ becomes equal to the dissipation factor, hence, it can be written

$$\tan \delta = \frac{R_s}{\omega L_s} \approx D = \frac{1}{Q} \longrightarrow \cos \varphi \qquad (1)$$

The total series resistance R_s is composed of a component R_c which represents the effective series resistance originating in the coil and of a component R_m which represents an effective series resistance that is caused by the losses in the magnetic core. This can be written

$$R_s = R_c + R_m$$

$$\text{or} \qquad (2)$$

$$\frac{R_s}{\omega L_s} = \frac{R_c}{\omega L_s} + \frac{R_m}{\omega L_s}$$

It has been shown by various authors that the loss tangent of a ring core is independent of core dimensions and even independent of the inductance L. (For example see reference 12.) For this reason, the loss tangent $\frac{R_m}{\omega L_s}$ which is derived from a closed ring core becomes a practical factor for characterizing material losses.

The loss tangent or its equivalent factors have been depicted in figure 6 for different materials. Several of these curves, particularly those for powdered materials, were computed from loss coefficients (Ref. 12, 13). In these cases, a flux density of 10 Gauss was assumed. Some publications state that the flux densities were very low and the hysteresis losses negligible. It can be assumed that the flux densities involved in figures 6, 7, and 8 are 10 Gauss or less, except the permeability of Supermalloy which is given for Bm = 20 Gauss. At these low flux densities, the hysteresis losses are actually only a small part of the total losses and small differences in flux density do not affect loss data substantially.

Eddy current losses play a more important role. Such losses prevail in metallic materials at higher frequencies because the losses are proportional to the second power of frequency. Eddy current losses are also proportional to the

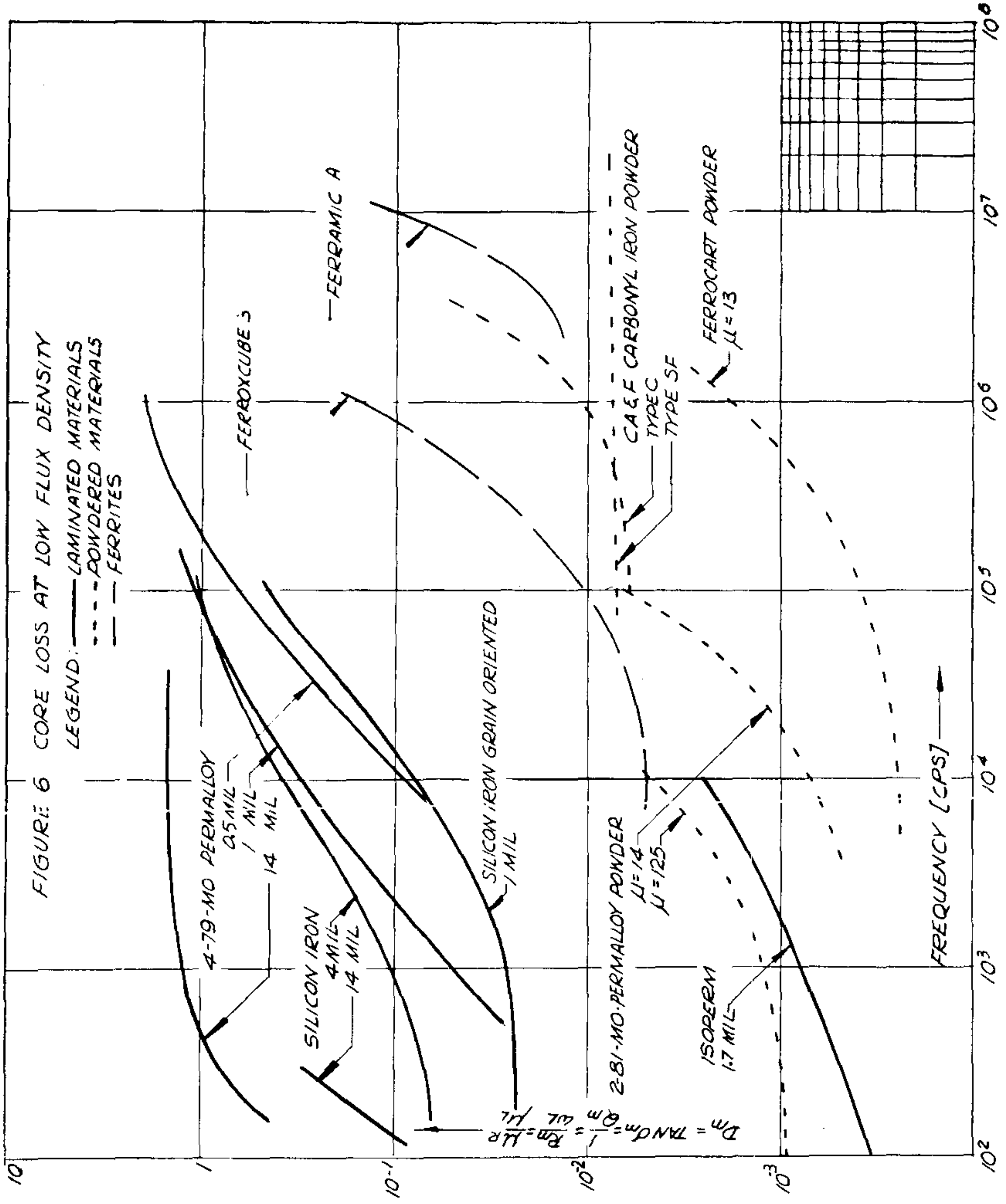


FIGURE 6 CORE LOSS AT LOW FLUX DENSITY

second power of material thickness. This illustrates the importance of subdividing a metallic material into thin laminations or powdered particles. The reduction of losses by the subdivision of the material can be noted in all characteristics. For example, see data on 4-79-Mo Permalloy (Fig. 6) with the lamination thickness being 0.5, 1, and 14 mil. (1 mil. = 0.001 inch).

A further reduction of total losses by finer subdivisions of metallic materials is limited. Coercive forces, in particular, will increase as the material thickness is further decreased. Extremely thin laminations cannot be stamped and stacked but have to be wound into toroidal cores. The thickest laminations presently produced are about 0.15 mil. Further substantial reductions cannot be expected because of the difficulties in rolling the materials and because of the decrease in magnetic qualities such as an increase in coercive force. High-frequency applications of thin laminated materials are pulse transformers, magnetic pulse generators, digital computers, and others.

There appears to be a distinct difference in losses (see Fig. 6) by a factor of more than 10 between the laminated materials and the good powdered and ferrite materials. An exception is Isoperm, a German loading coil material which is unique in the field of laminated materials insofar as the dissipation factor is concerned. In Isoperm, losses have been reduced down to those of the best powdered materials. The permeability of Isoperm is, however, substantially lower than that of other laminated materials. High permeability materials such as laminated Mo-Permalloy have the highest losses, while silicon-iron is better as far as losses are concerned. (Compare 1 mil. 4-79-Mo-Permalloy with 1 mil. silicon-iron, Fig. 6.)

From figure 6, it is easy to see that good powdered and ferrite cores have much smaller losses than laminated materials. Powdered core materials, sometimes designated as "Polyirons", have long been known. They consist of powdered pure iron, alloys, and organic binders, or of powdered ferromagnetic oxides.

Problems of powdered iron core development are: (a), to produce uniformly fine powders; (b), to insulate the metal particles from each other; and (c), to make the proportion of metal high in relation to the binder in order to obtain a relatively high permeability. These problems illustrate that compromises have to be made and that there are optimum compositions for individual frequency ranges. Low losses at rising frequency can only be maintained by decreasing the permeability. Because of the many series gaps in powdered material, permeabilities are inherently small and almost constant up to saturation. Permeabilities of commercial powdered core materials range loosely from 3 to 100. The effective permeability is still smaller in applications where the magnetic circuit is not closed.

It should be noted that loss data of commercial powdered cores are usually given as Q values of specific coils with specific cores. Such data are not suitable for material comparison on a universal basis.

Several powdered materials (shown by dotted lines in figures 6 and 7) have the lowest losses according to figure 6. This result is not very significant. The low losses of powdered cores are due mainly to their magnetic "dilution", that is, to the existence of a great number of small gaps between the ferromagnetic particles. These gaps also account for the low permeability of powdered cores. Thus, the low losses of powdered cores are obtained at the expense of permeability. Actually, the best core material, with regard to losses, would be air or free space -- in other words, no magnetic material at all. If size is of no concern, it is known that low inductor losses can be obtained without cores. This illustrates the limited significance of loss data alone and the necessity for including the permeability in a comparison.

The introduction of an air gap in laminated or ferrite cores will also reduce losses and make these materials competitive. Q factors of approximately 600 have been reported on inductors which utilize ferrite pot cores with air gaps (see Ref. 18, p. 262). According to Snoek (Ref. 3), the loss reduction of ferrite cores, because of an air gap, is proportional to the reduction of permeability. This relationship can be expressed by the simple ratio:

$$\frac{D_m}{\mu} = \frac{D_{m'}}{\mu'} \qquad (3)$$

where D_m and μ refer to a closed ring core, while $D_{m'}$ and μ' refer to the same properties of a core with air gap. In addition to reducing losses, an air gap also reduces the effect of temperature on permeability.

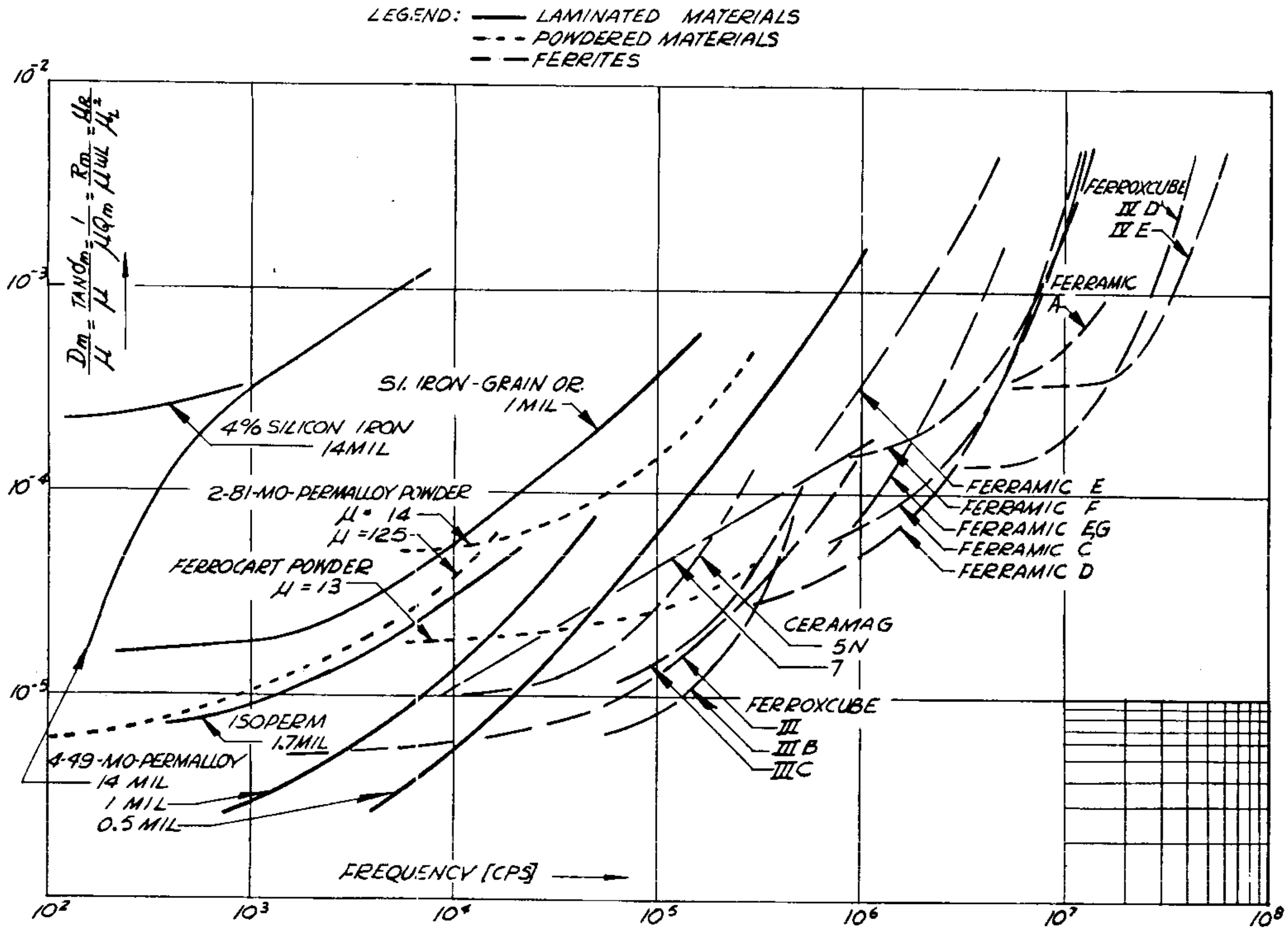
The term $\frac{D_m}{\mu}$ appears suitable for use as a general rating because: (a), it combines the most important core characteristics as D and μ; (b), it extends the applicability of the rating to ferrite cores with air gap; and (c), it can be computed easily from individual loss coefficients as defined by Legg (Ref. 12).

Figure 7 depicts $\frac{D_m}{\mu}$ values versus frequency. Although the number of materials had to be limited, the following conclusions and ratings appear justified: powdered cores, which were superior in figure 6, are surpassed by laminated and ferrite cores; laminated cores rate better up to more than 10,000 cps from which frequency ferrites appear to be better. The unique position of Isoperm in figure 6 has been lost, and, in figure 7, Isoperm rates with other laminated materials. Ferrites which are often considered to fill a gap between laminated and powdered materials are found to be superior over powdered materials. Therefore, it may be expected that ferrites will come into wider use for high frequency applications. At present, the bulk of ferrite applications are in television receivers.

There are various other factors which cannot be incorporated in a universal rating but which may determine the selection of a material. Laminated cores, for example, are strain sensitive and often available as closed toroids only. Ferrites and powdered cores are relatively insensitive, substantially less in weight than laminated materials, and can be formed into a large variety of core shapes. The maximum operating temperatures of ferrite and powdered cores are, as a rule, lower than the maximum operating temperatures of laminated materials.

A less comprehensive but rather interesting diagram is obtained if the permeabilities of materials are plotted versus frequency, as in figure 8.

FIGURE 7 AC CHARACTERISTICS AT LOW FLUX DENSITY



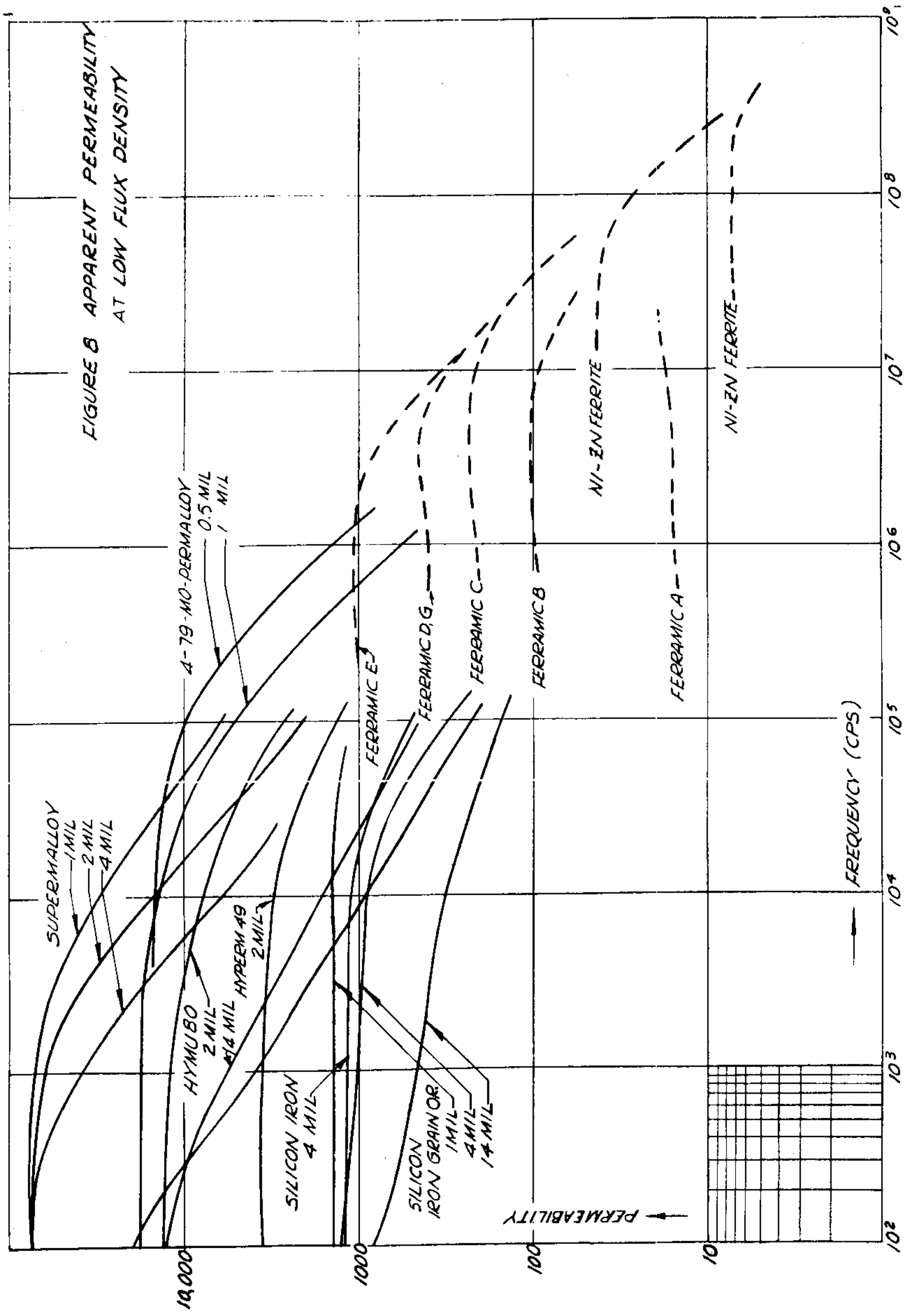
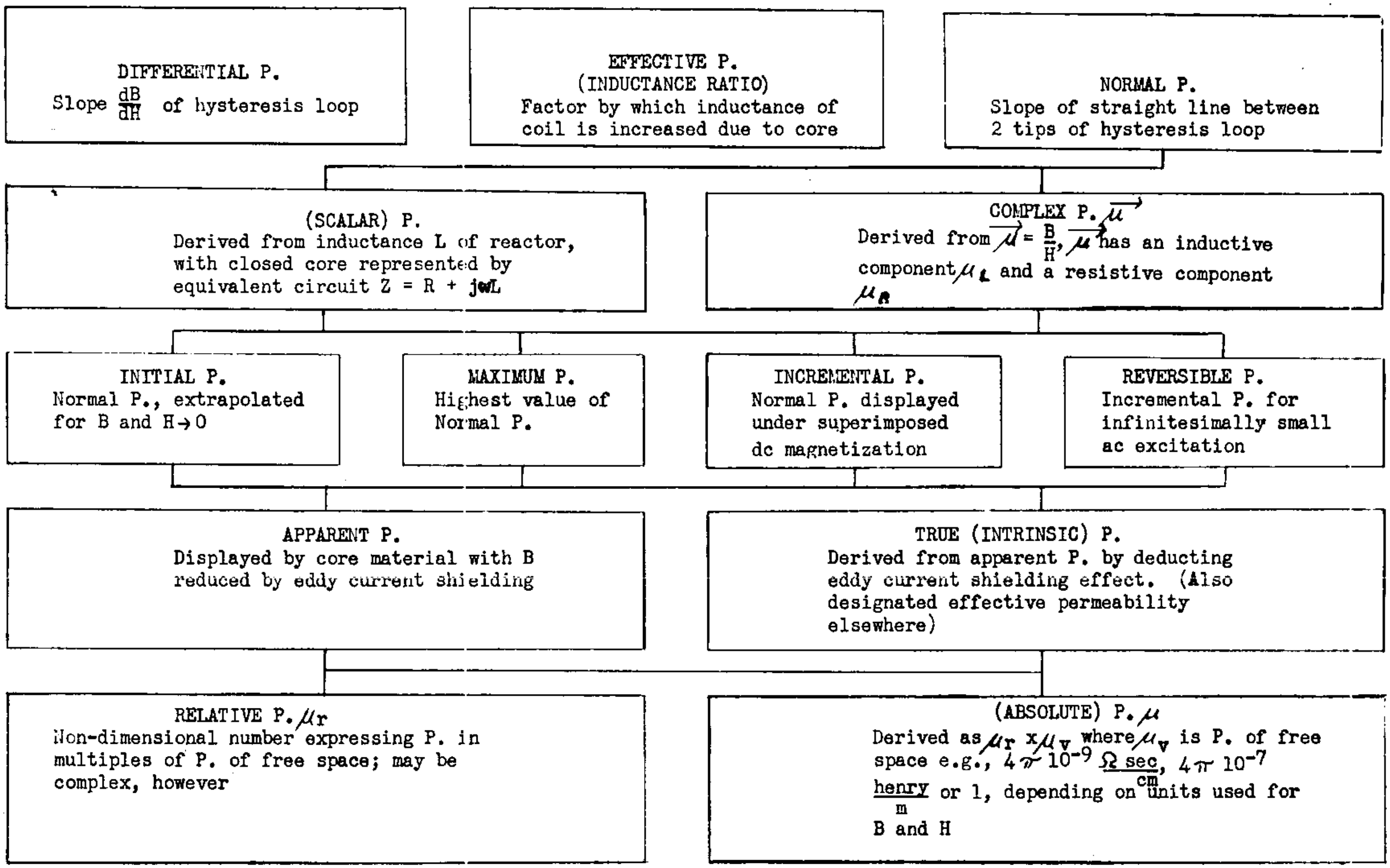


FIGURE 8 APPARENT PERMEABILITY AT LOW FLUX DENSITY



DIFFERENTIAL P.
Slope $\frac{dB}{dH}$ of hysteresis loop

EFFECTIVE P.
(INDUCTANCE RATIO)
Factor by which inductance of coil is increased due to core

NORMAL P.
Slope of straight line between 2 tips of hysteresis loop

(SCALAR) P.
Derived from inductance L of reactor, with closed core represented by equivalent circuit $Z = R + j\omega L$

COMPLEX P. $\vec{\mu}$
Derived from $\vec{\mu} = \frac{B}{H}$, $\vec{\mu}$ has an inductive component μ_L and a resistive component μ_R

INITIAL P.
Normal P., extrapolated for B and $H \to 0$

MAXIMUM P.
Highest value of Normal P.

INCREMENTAL P.
Normal P. displayed under superimposed dc magnetization

REVERSIBLE P.
Incremental P. for infinitesimally small ac excitation

APPARENT P.
Displayed by core material with B reduced by eddy current shielding

TRUE (INTRINSIC) P.
Derived from apparent P. by deducting eddy current shielding effect. (Also designated effective permeability elsewhere)

RELATIVE P. μ_r
Non-dimensional number expressing P. in multiples of P. of free space; may be complex, however

(ABSOLUTE) P. μ
Derived as $\mu_r \times \mu_v$ where μ_v is P. of free space e.g., $4\pi\,10^{-9}\,\frac{\Omega\ \mathrm{sec}}{\mathrm{cm}}$, $4\pi\,10^{-7}\,\frac{\mathrm{henry}}{\mathrm{m}}$ or 1, depending on units used for B and H

TABLE III Permeability Definitions Pertinent to Cyclic or Alternating Magnetization

Permeabilities are given for the low flux densities (as discussed in relation to figure 6) and can be termed initial permeabilities unless a more rigid definition (see Table III) excludes several of the data in figure 8.

The apparent permeability (see Table III) of a toroidal metallic core decreases with frequency because the eddy current shielding results in a lower flux density in the inner portions of a ferromagnetic lamination. This well-founded explanation is also substantiated in figure 8 where the permeabilities of thicker laminations decline faster at rising frequency. As in figures 6 and 7, figure 8 shows that the materials with better dc or low-frequency characteristics are surpassed at higher frequencies. Note that 2 mil. Hymu 80 surpasses the initial permeability of 2 mil. Supermalloy at approximately 40,000 cps although the resistivity of Supermalloy is slightly higher.

Lamination thickness and resistivity are the principal factors governing the reduction of the "apparent" permeability of laminated metallic cores over frequency. The "true or intrinsic" permeability of laminated metallic cores can be derived from the apparent permeabilities by calculating and eliminating the eddy current effect in the materials. This means that the true or intrinsic permeability could be realized and measured if the eddy current shielding effect could be avoided as is the case in some ferrites. The true or intrinsic permeability is of great interest for the study of both the ferromagnetic substances at microwave frequencies (see Ref. 2) and the phenomena which reduce the relative permeability to unity. The true permeabilities of metals are rather constant up to approximately 10^8 cps and reduce to unity in the region from 10^{10} to 10^{11} cps.

From the standpoint of core-material utilization, the apparent permeability, as plotted in figure 8, is of main concern because it represents the permeability which can be utilized in a core. Extrapolation of figure 8 indicates that the apparent permeabilities become unity in the region slightly above 10^9 cps.

Another interesting result of figure 8 is the fact that the highest apparent permeabilities of all available materials, as plotted over frequency, can be represented by a rather smooth envelope even though both laminated materials and ferrites are represented. The transition between both types of materials occurs at approximately 2 mc and is actually smoother than shown, taking into consideration that materials which are thinner than 0.5 mil. are available. The practical significance of the envelope in figure 8 can be interpreted as a line which limits the highest initial permeabilities that can be obtained with the best magnetic cores at any given frequency.

Thus far in this report, the term "permeability" is understood to determine the impedance Z_m of a toroidal core which under simplifying assumptions reads:

$$Z_m = R_m + j\omega L = R_m + j\omega \frac{\mu N^2 A}{l} \tag{4}$$

If, however, the permeability is to be derived according to the definition

$$\mu = \frac{B}{H} \tag{5}$$

a discrepancy appears. While B is in quadrature with the applied voltage according to $E_L = \frac{N d(AB)}{dt}$, the magnetizing force is not in quadrature because H, according to definition, is proportional to the current which has a loss or in-phase component. Equation (5) can be applied to ac magnetization only if a phase angle is attributed to the permeability, that is, if the permeability is treated as a complex magnitude. In complex notation, the permeability has been given the form:

$$\vec{\mu} = \mu_L - j\mu_R \tag{6}$$

where μ_L is an inductive component which so far has been referred to simply as permeability, and μ_R is a resistive component. With this complex permeability, $\vec{\mu}$ equation (4) has to be written simply as follows:

$$Z_m = j\omega \frac{\vec{\mu} N^2 A}{\ell} \tag{7}$$

Obviously, the notation of a complex permeability does not describe a new phenomenon in core materials. The usage of this notation is practical, not only because it allows the formal use of equation (5), but because it comprises all of the core characteristics represented in figures 6, 7, and 8. From equations (4) and (7) follows:

$$\vec{\mu} = \frac{R_m + j\omega L_m}{j\omega N^2 \frac{A}{\ell}} = \frac{L_m}{N^2 \frac{A}{\ell}} - j \frac{R_m}{\omega N^2 \frac{A}{\ell}} \tag{8}$$

Equating (8) with equation (6) gives:

$$\vec{\mu} = \mu_L - j\mu_R = \frac{L_m}{N^2 \frac{A}{\ell}} - j \frac{R_m}{\omega N^2 \frac{A}{\ell}} \tag{9}$$

This result serves to illustrate the components μ_L and μ_R which read:

$$\mu_L = \frac{L_m}{N^2 \frac{A}{\ell}} \tag{10}$$

and

$$\mu_R = \frac{R_m}{\omega N^2 \frac{A}{\ell}} \tag{11}$$

In figure 8, μ_L is represented.

The dissipation factor $D = \frac{R_m}{\omega L_m}$ derives from (10) and (11) as:

$$\frac{R_m}{\omega L_m} = \frac{\mu_R}{\mu_L} \qquad (12)$$

The characteristics of figure 7 derive from equation (12) as $\frac{R_m}{\mu \omega L} = \frac{\mu_R}{\mu_L^2}$ because μ, in conventional usage, is identical with μ_L in vector notation.

The complex permeability lends itself well to illustrate the figure of merit $\frac{\mu_R}{\mu_L^2}$ as plotted in figure 7. Again, as in figure 5, loci can be derived representing equal $\frac{\mu_R}{\mu_L^2}$ values. The equation $\frac{\mu_R}{\mu_L^2} = \text{Constant}$ yields parabolas as shown in figure 9. This diagram reveals the limitations of the factor $\frac{\mu_R}{\mu_L^2}$ for material evaluation. Again, as with figure 5, the question, "Which materials are rated equal", can be answered. Materials with loss angles of higher than 45° should be excluded because μ_R increases at a higher rate than μ_L. Loss angles δ of 45° or higher do not occur in practical core materials, and it can be concluded that the factor $\frac{D_m}{\mu} = \frac{\mu_R}{\mu_L^2}$, as plotted in figure 7, gives a satisfactory general rating of core materials.

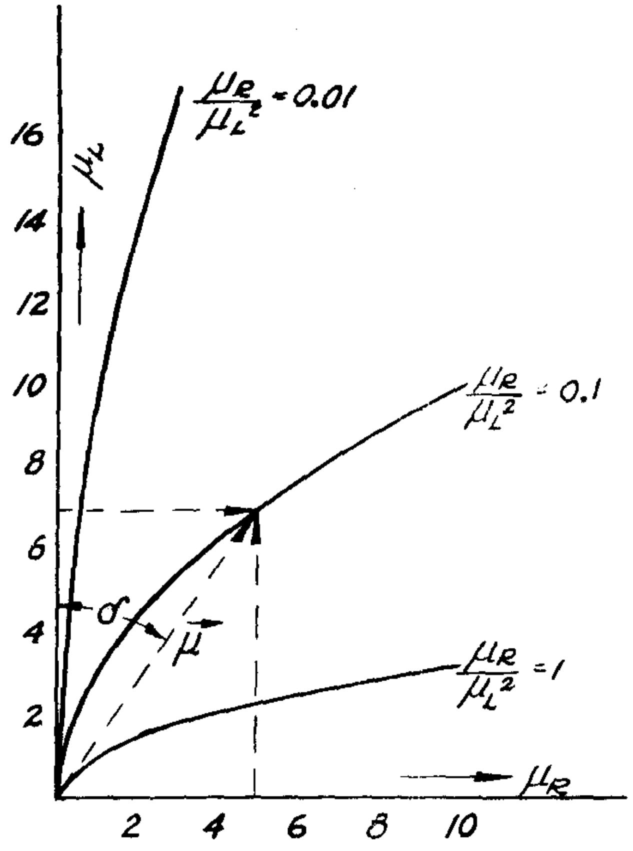


Fig. 9 Loci of Complex Permeability Vectors With Equal Figure of Merit $\frac{\mu_R}{\mu_L^2}$

SUMMARY

The problem of evaluating and selecting magnetic core materials can be partially solved by using suitable figures of merit for characterizing materials. Such figures of merit are exciting plus in-phase volt-amperes and dissipation factor over permeability. Material evaluations, which are based on these characteristics, show the advantages of ferrites over laminated and powdered materials, particularly, at high frequencies. The use of the complex permeability concept for describing the characteristics of materials appears advantageous.

INDEX OF SYMBOLS

A	Sectional area of core
B	Flux density in core
$\cos\varphi$	Power factor
D	Dissipation factor
E	Voltage
δ	Loss angle (see figure 9)
H	Magnetizing force
j	Rotative operator
L	Inductance
l	Mean length of toroidal core
μ	Permeability (see also Table III)
N	Number of turns on core
ω	Circular frequency
Q	Quality or storage factor
R	Resistance
$\tan\delta$	Loss tangent
Z	Impedance

Subscripts

c	Refers to coil
L	Denotes inductive component
m	Refers to magnetic core
R	Denotes resistive component
r	Denotes relative component
s	Denotes equivalent series component
v	Denotes vacuum component

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