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SUBJECT: A COMPARISON BETWEEN SQUARE-LOOP METALS AND FERRITES FOR HIGH-SPEED PULSED OPERATION

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Abstract: Metals and ferrites with rectangular hysteresis loops are used in magnetic amplifiers, switching networks, and data-storage systems. In these applications, the large-signal pulse response is most important. To reduce the effect of eddy currents, metals have been rolled to ultra-thin gage and high-resistivity ferrites have been used. By these techniques, eddy currents have been reduced to the point where relaxation effects limit the response time in both cases.

I. Introduction

This comparison is based on magnetic materials which are currently available and which have been investigated in this laboratory. In view of the rapid strides made in the development of new magnetic materials in the last few years, future advances in this field may alter the conclusions contained in this report.

This laboratory is primarily concerned with rectangular-loop materials for use in high speed memory and switching circuits. These applications employ constant magnetic fields applied as step functions (rise time $< 0.2\ \mu$sec) with signal levels exceeding the coercive force of the materials. Theoretical and experimental results indicate that metals are better for stepping registers and switching circuits, while ferrites are better for use in a coincident-current memory.

II. Energy Loss Factors

The three major sources of energy dissipation upon reversing the magnetization of a ferromagnetic core are: hysteresis losses, eddy-current losses, and relaxation losses. The first two factors mentioned above are familiar; the relaxation loss is essentially a damping loss representing the delay of the individual electron spin vectors in aligning themselves in the direction of the applied field. This phenomenon has been discussed extensively in the literature by Landau and Lifschitz,[1] Kittel,[2] Galt,[3] and others.

III. Comparison

A. Physical Description and Fabrication Technique

Square-loop metallic cores are prepared by a process of cold-rolling and annealing. Eddy-current effects are reduced by rolling the magnetic metal into ultra-thin tapes from which ring-shaped cores are made by wrapping the thin ribbon around a spool. Since the material is strain-sensitive, this wrapping operation usually precedes the anneal. Metallic cores, therefore, are often wrapped on ceramic spools (Fig. 1) which are able to withstand the annealing temperature. A typical core might have 40 wraps of 1/8-mil molybdenum-Permalloy on a 1/8-inch wide and 3/16-inch diameter spool.

Ferrites are metallic oxides which are prepared by pressing into the desired shape and sintering at high temperature. Since the magnesium-manganese ferrites presently employed in coincident-current memory devices have d-c resistivities of the order of 10^{12} as great as metals, eddy-current effects are negligible and there is no need for laminations with the sizes used in these tests. A number of different-sized ferrites prepared in this way is also shown in Fig. 1. The smallest core size shown, with an outside diameter 0.090-inch and inside diameter 0.050-inch is currently employed in the coincident-current memory.

B. Eddy Current

The reduction of eddy-current losses through the use of thinner metal tapes permitted higher repetition rates until ultra-thin tapes below 1 mil thickness were obtained. However, further reduction to 1/4-mil and 1/8-mil tapes did not permit the higher repetition rate expected. This indicated that losses other than eddy-current losses were predominant. It will be shown below that reducing the thickness of molybdenum-Permalloy to 1/8-mil reduces eddy-current losses to approximately 5 percent of the relaxation losses.

In view of the high resistivities involved, the eddy-current losses in ferrites are negligibly small.

C. Relaxation Effects

In both the ultra-thin tapes and ferrites the repetition rate is limited primarily by the relaxation loss. The order of magnitude of the relaxation loss per unit volume is the same for both metals and ferrites.

D. Hysteresis Effects

The hysteresis loss per unit volume per cycle of square-loop ferrites is approximately equal to $4I_sH_c$, where I_s is the saturation magnetization and H_c is the coercive force. In magnesium-manganese ferrites, $I_s \sim 10^2$ and $H_c \sim 1$ oersted; in molybdenum-Permalloy cores, $I_s \sim 10^3$ and $H_c \sim 0.1$ oersteds. Therefore, the hysteresis loss ~ 400 ergs/cm^3/cycle in both cases.

E. The Switching Coefficient

1. Definition

It has been observed that the switching time τ of a square-loop material is inversely proportional to the applied field, according to the relationship

$$(H - H_o)\tau = S_w \qquad (1)$$

where H is the applied field, H_o is the threshold field for domain wall motion, and S_w is a constant defined as the switching coefficient. The switching time τ is defined as the time required for the output voltage of a magnetic core to go from 10 percent of its maximum value through the maximum and down to 10 percent. This is shown in Figure 2.

The linear relationship expressed by equation 1 is limited to field values sufficiently high to permit complete magnetization reversal of the ferromagnetic material. In practice, this limits the applied field to values $H \gtrsim 2H_c$. As the field is increased, the switching time decreases until the rise time of the applied field (0.2 μsec) becomes a sizable portion of τ. This sets an upper limit to the linear relationship. However, it should be borne in mind that this upper limit is due to the limits of the measuring technique rather than a property of the material.

Equation 1 can be expressed in the form

$$H = \frac{S_w}{\tau} + H_o \qquad (2)$$

which is the equation of a straight line of slope S_w and intercept H_o.

2. Experimental Results

Curves of the inverse switching time as a function of the applied field have been taken for 1/8-mil and 1/4-mil 4-79 molybdenum-Permalloy cores and for a General Ceramics MF-1312-B magnesium-manganese ferrite core. The curves are shown in Figure 3, and the results obtained therefrom are listed in Table I.

Material	S_w (oe.-sec)	H_o (oe)
4-79 mo-Permalloy 1/8-mil	0.55×10^{-6}	0.14
4-79 mo-Permalloy 1/4-mil	0.63×10^{-6}	0.14
MF-1312-B Ferrite	1.02×10^{-6}	0.52

Table I. Slope and Intercept of $1/\tau$ vs. H Switching Characteristics

It is of interest to note that the value of S_w is about the same for materials as different as mo-Permalloy and magnesium-manganese ferrite. This is even more striking in view of additional experiments conducted in this laboratory with other ferrite bodies. These experiments were conducted with magnesium-manganese ferrites of various compositions and with several nickel-zinc ferrites. In every case the resultant S_w was found to lie within a factor of 2 of the value given above for the MF-1312-B.

It can be noted in Figure 3 that the combination of a lower threshold field value and lower S_w permits the 4-79 mo-Permalloy to switch approximately twice as fact as the ferrite at a given applied field value.

3. Theoretical Considerations

The experimental value of the switching coefficient is the sum of two effects, as may be expressed by the equation

$$S_w = S_w^{(r)} + S_w^{(e)} \tag{3}$$

where $S_w^{(r)}$ is the contribution to the switching coefficient due to relaxation effects, and $S_w^{(e)}$ is the eddy current contribution.

These contributions to the switching coefficient can be related to the physical constants of the material by the equations[4]

$$S_w^{(r)} = \frac{\Lambda I_s d}{(\gamma^2 I_s^2 + \Lambda^2)\langle\cos\Theta\rangle} \sqrt{\frac{K}{A}} \approx \frac{\Lambda d}{\gamma^2 I_s \langle\cos\Theta\rangle} \sqrt{\frac{K}{A}} \tag{4a}$$

$$S_w^{(e)} = \frac{8\pi^2 I_s r_m^2}{\rho c^2 \langle\cos\Theta\rangle^3} \tag{4b}$$

Equation 4b is limited to ultra-thin tapes of thickness 1 mil or less.

In equation 4a, Λ represents the relaxation frequency of the material, I_s the saturation magnetization, d the maximum distance a domain wall moves during a magnetization reversal, K the effective anisotropy constant, γ the magneto-mechanical ratio, $\langle\cos\Theta\rangle$ the mean value of the cosine of the angle between the applied field and the direction of easy magnetization, and A is the exchange parameter.

In equation 4b r_m is one-half the tape thickness, ρ is the resistivity in statohm-cm, and c is the velocity of light.

a) Relaxation Effect--Theoretical

The parameters Δ, K, A, and d are unknown for the materials in question. However, an intelligent estimate can be made of Δ and K by comparison with the known values of these parameters in similar materials. The distance d can be estimated from the grain structure of the material and A can be approximated by $A \sim kT_c/a$ where T_c is the Curie temperature, k is the Boltzmann constant, and a the lattice parameter. Calculations of $S_w^{(r)}$ based on these approximations yield the correct order of magnitude.

b) Eddy Current Effect--Theoretical and Experimental

The eddy current contribution to the switching coefficient can be calculated directly from equation 4b for the 1/8-mil and 1/4-mil mo-Permalloy tapes. The values of the parameters for this material are: $I_s = 700$, $\rho = 6 \times 10^{-17}$ statohm-cm, $\langle \cos \theta \rangle \approx 1$ since this material is grain oriented, and $r_m = 1.6 \times 10^{-4}$ cm for 1/8-mil and $r_m = 3.2 \times 10^{-4}$ cm for the 1/4-mil tape. Substitution of these values into equation 4b yields

$$\left.\begin{aligned} S_w^e \text{ (1/8-mil)} &= 0.3 \times 10^{-7} \text{ Oe-sec} \\ S_w^e \text{ (1/4-mil)} &= 1.2 \times 10^{-7} \text{ Oe-sec} \end{aligned}\right\} \qquad (5)$$

Since S_w^r is independent of the thickness of the material, the variation in S_w between 1/8-mil and 1/4-mil mo-Permalloy, as given in Table I, is entirely due to the change in the eddy-current contribution. S_w^e varies as the square of the thickness, so

$$S_w^e \text{ (1/4-mil)} = 4S_w^e \text{ (1/8-mil)}$$

and

$$S_w \text{ (1/4-mil)} = S_w^r + 4S_w^e \text{ (1/8-mil)} = 6.3 \times 10^{-7}$$

$$S_w \text{ (1/8-mil)} = S_w^r + S_w^e \text{ (1/8-mil)} = 5.5 \times 10^{-7}$$

Therefore

$$\left.\begin{aligned} S_w^e \text{ (1/8-mil)} &\approx 0.27 \times 10^{-7} \\ S_w^e \text{ (1/4-mil)} &\approx 1.07 \times 10^{-7} \end{aligned}\right\} \qquad (6)$$

The theoretical and experimental results, as given in equations 5 and 6, yield essentially the same result. They show that the use of 1/8-mil tapes has succeeded in reducing the eddy-current effect to approximately 5 percent of the relaxation effect.

F. Energy Considerations

The energy loss per cm^3 per cycle is related to the switching coefficient by the equations[4]

$$\text{Eddy current loss/cm}^3\text{/cycle} = \frac{2I_s \langle \cos \theta \rangle}{\tau} S_w^{\,e} \qquad (7)$$

$$\text{Relaxation loss/cm}^3\text{/cycle} = \frac{2I_s}{\tau} S_w^{\,r} \qquad (8)$$

Since $I_s \sim 700$ for 4-79 mo-Permalloy, and $I_s \sim 200$ for MF-1312-B ferrite, the total relaxation and eddy current loss for these materials, when switching in 1 μsec, is approximately 770 ergs per cm^3 per cycle for the metal and 400 ergs per cm^3 per cycle for the ferrite.

Equations 7 and 8 show that the eddy current loss for 1/8-mil mo-Permalloy is only 5 percent of the relaxation loss. Thus further reduction of the thickness will have a negligible effect in reducing the eddy current loss. This further explains why the reduction to 1/4-mil and 1/8-mil did not produce the expected increase in permissible repetition rate.

G. Heating Effects

For a step-function input, the above considerations show that the power dissipation is directly proportional to the frequency. In addition, a complete magnetization reversal per half cycle requires that $1/\tau > 2f$ where f is the frequency. At high frequencies, this faster switching requirement further serves to increase the power loss.

Although the power dissipation per cm^3 per cycle of the metals and ferrites are comparable at room temperature, operation at high frequencies gives rise to heating effects which limit the operation of the magnetic core as a switching device. It is therefore necessary to compare the thermal behavior of ferrites and metals under these conditions.

1. Output Signal

The higher flux density of the metallic tape permits the use of a smaller cross section, and hence smaller volume, of metal than ferrite to achieve the same flux change. Thus the power dissipation per core is somewhat smaller in the metals. Because of the lower S_w value, the metals require less magnetomotive force to obtain the same time rate-of-change of flux.

2. Thermal Conductivity

The thermal conductivity of mo-Permalloy is high. Therefore, any cooling device applied to the surface of the metal core will be effective in cooling the entire volume. The thermal conductivity of ferrites is low, so surface cooling will only succeed in setting up a thermal gradient within the sample.

3. Temperature Sensitivity

Since mo-Permalloy has a higher Curie temperature (460° C) than the ferrites (300° C), the metallic core should be less sensitive to small temperature changes in the vicinity of room temperature. Work by J. Raffel[5] of this laboratory indicates that on a specific multi-position magnetic-core switch a temperature rise of 90° C is permissible in 4-79 mo-Permalloy as compared to a 20° C rise for MF-1312-B.

H. Uniformity and Cost

Uniformity considerations remain a major problem in ferrite production. However, the past year has seen a marked improvement in ferrite uniformity and this improvement is continuing.

Ferrite cores can be produced on a large scale at a much lower cost than ultra-thin metallic tapes. On equipment requiring large numbers of magnetic units, this can be a decisive factor.

IV. Conclusions

The factors noted in Section G all favor the use of ultra-thin metallic tapes for stepping registers and switching circuits. Stepping registers using these tapes have been operated up to 0.5 Mcps. No comparable repetition rates are attainable using ferrite cores.

For high-speed coincident-current memory applications of the type introduced by J. W. Forrester,[6] ferrite cores are better. In this application, the applied field is limited to twice the coercive force. Because of the low coercive force of mo-Permalloy cores, its use in this application is limited to the region of slow switching (~10-20 μsec). The higher coercive force of the ferrites permits switching times in the order of 1 μsec. A large coincident-current memory array requires tens of thousands of uniform cores. The poor uniformity of metallic cores makes the selection of this many metal cores difficult.

As mentioned in the introduction, future developments may alter the above conclusions. Ultra-thin metals with a coercive force comparable to that of the ferrites can apparently be manufactured without much difficulty, and improved fabrication techniques may overcome the uniformity problem.

On the other hand, ferrites with a coercive force of 0.2 oersteds have recently been produced, and progress is being made in obtaining ferrites of higher flux density than that of the MF-1312-B discussed above. However, the nature of ferritic materials limits the improvement that can be made in this direction.

Developmental work involving the use of deposited and evaporated films is now going on in various laboratories throughout the country. This work may lead to improvements in the near future.

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Drawings attached:

Figure 1 - A-57781
Figure 2 - A-57782
Figure 3 - B-57487

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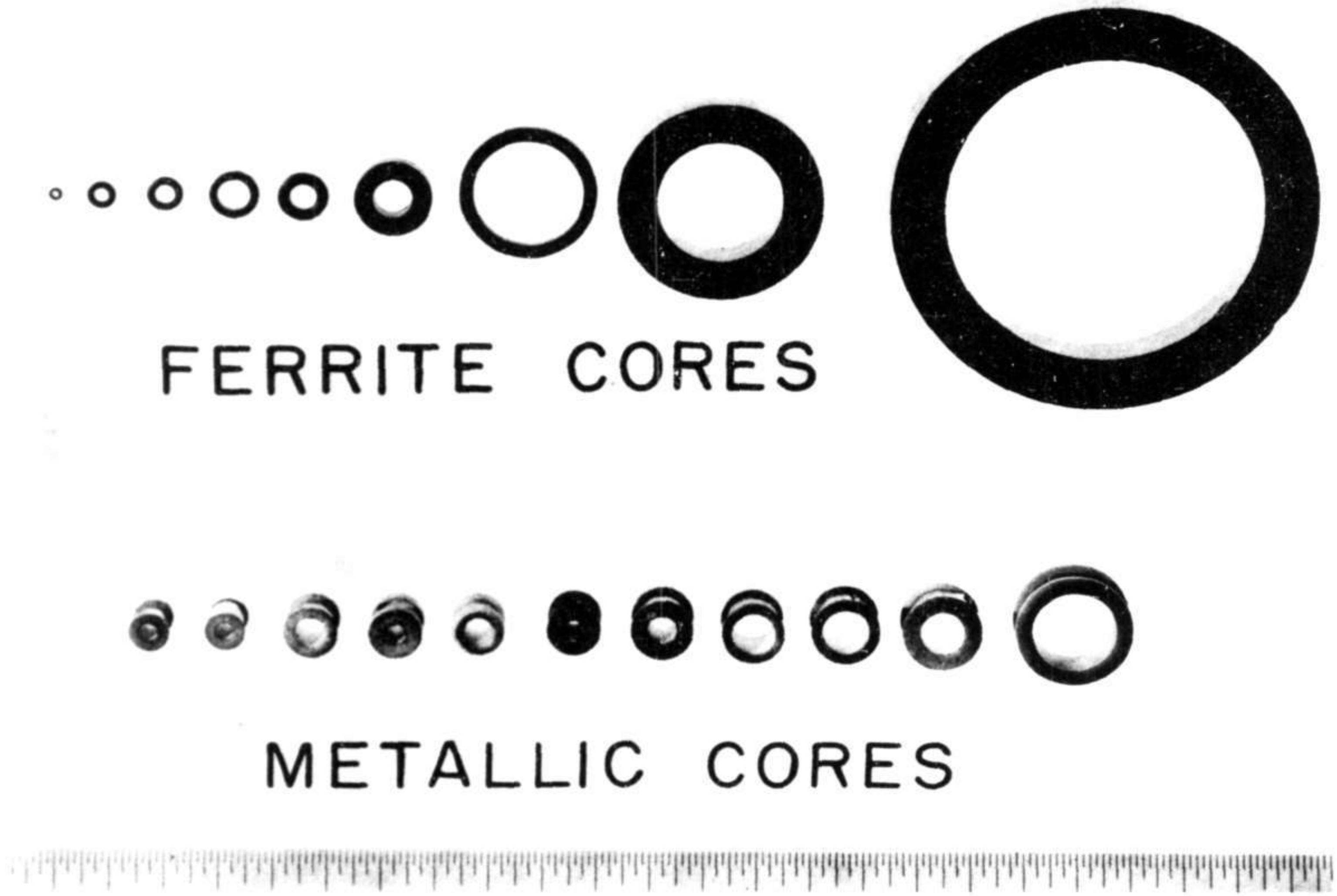

FIG. 1

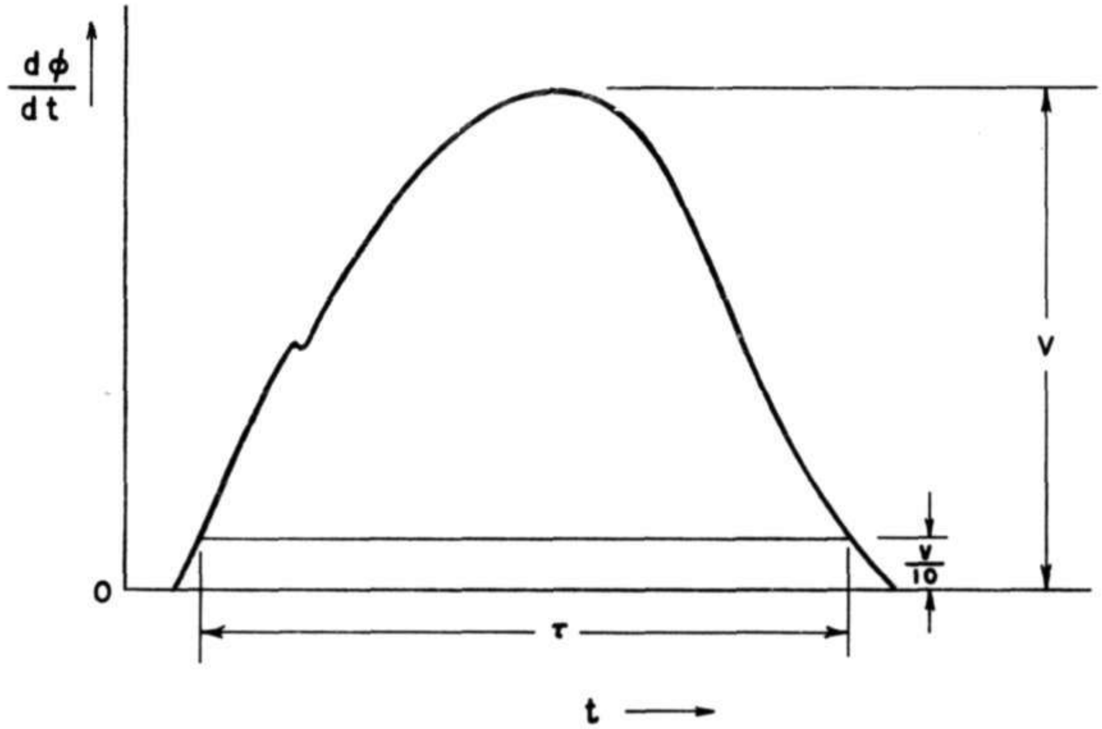

FIG. 2

DEFINITION OF SWITCHING TIME τ

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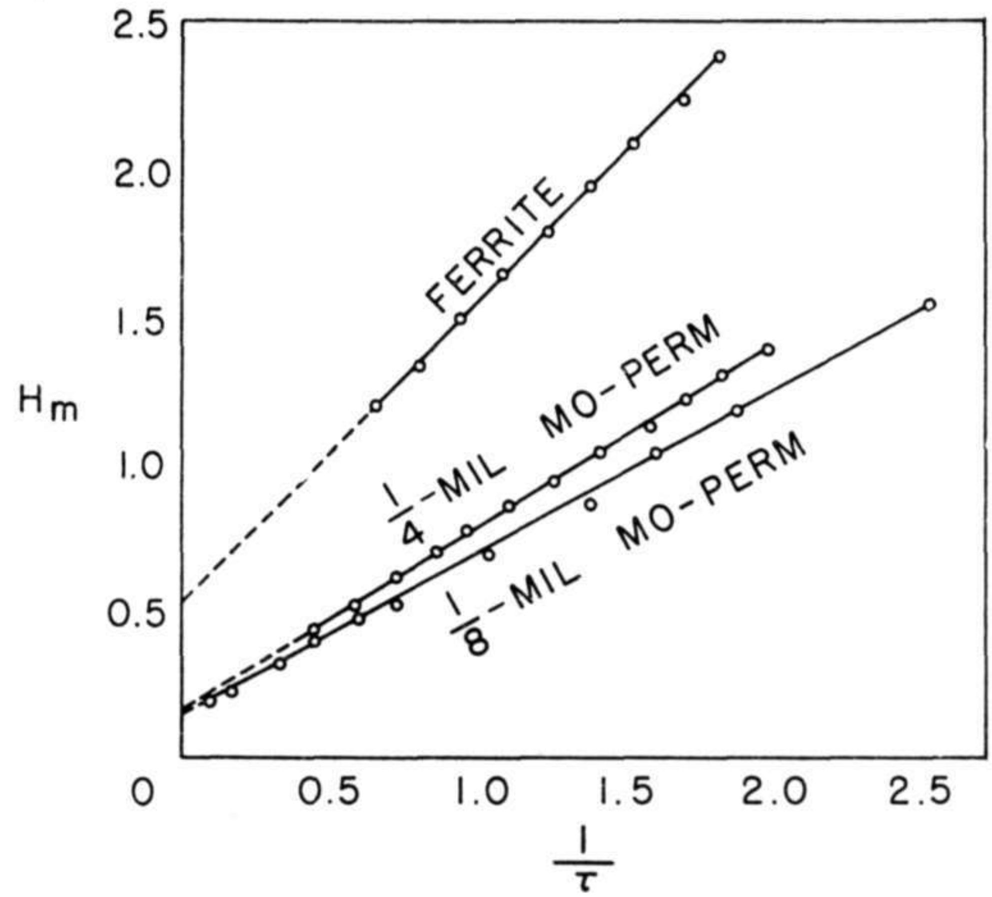

SWITCHING CHARACTERISTICS OF METALS AND FERRITES

FIG. 3

B-57487