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SUBJECT: EFFECTS OF TAPE THICKNESS AND TEMPERATURE ON FLUX REVERSAL OF 4-79 MOLYBDENUM-PERMALLOY

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Abstract: Measurements of the flux reversal time τ have been made for 1/8-mil, 1/4-mil, 1/2-mil, and 1-mil 4-79 Molybdenum-Permalloy tape cores as a function of the applied field. These measurements were taken at seven different temperatures, ranging from -196°C. to 270°C. From these measurements, the switching coefficient $S_w = (H - H_o)\tau$ is found. Determination of the switching coefficient as a function of tape thickness is shown to permit a separation of the spin-relaxation and eddy-current contributions to switching delay. These contributions are studied individually as functions of temperature. Upon increasing the temperature over the range considered, the eddy-current contribution and the threshold field value H_o are approximately halved while the spin-relaxation contribution is reduced by 20%. All these factors lead to a faster flux reversal at higher temperatures. This behavior is shown to be in agreement with theoretical predictions.

I. INTRODUCTION

Interest in ultra-thin metallic tapes in this laboratory has been increased by considerations which indicate that metallic tapes are superior to ferrites in switching circuits and stepping registers.[1] Among the factors favoring metallic tapes are: better thermal properties, higher flux-density, and faster flux-reversal characteristics.

In this paper the flux-reversal characteristics of ultra-thin 4-79 Molybdenum-Permalloy tape cores are investigated as a function of tape thickness and temperature. A theoretical study has been made which relates these characteristics to eddy-current and spin-relaxation damping in metals and ferrites,[2] and which predicts the changes to be expected upon varying tape thickness and temperature. These predictions are compared with the experimentally observed results.

II. THEORETICAL CONSIDERATIONS

The switching time τ of ferromagnetic materials is inversely proportional to the applied magnetic field. This is expressed by the equation

$$(H - H_o)\tau = S_w \tag{1}$$

where H is the applied magnetic field, H_o is the threshold field value for domain-wall motion, and S_w is a constant defined as the switching coefficient of the material.

The observed value of the switching coefficient is the sum of two independent effects. Thus

$$S_w = S_w^e + S_w^r \tag{2}$$

where S_w^e is the eddy-current contribution to the switching coefficient and S_w^r is the spin-relaxation contribution. For ultra-thin metallic tapes, these contributions are related to the fundamental parameters of the material by the equations[2]

$$S_w^r = \frac{4\pi\Lambda B_s d}{(\gamma^2 B_s^2 + 16\pi^2\Lambda^2)\langle\cos\theta\rangle}\left(\frac{K}{A}\right)^{1/2} \approx \frac{4\pi\Lambda d}{\gamma^2 B_s\langle\cos\theta\rangle}\left(\frac{K}{A}\right)^{1/2} \tag{3a}$$

$$S_w^e = \frac{\pi B_s L^2}{2\rho c^2\langle\cos\theta\rangle^3} \tag{3b}$$

In eqn. 3a, B_s is the flux density, d is the maximum distance a domain wall moves during a flux-reversal, Λ is the relaxation frequency, γ is the magneto-mechanical ratio, $\langle\cos\theta\rangle$ is the mean value of the cosine of the angle between the applied field and the direction of easy magnetization, K is the anisotropy constant, and A is the exchange constant. In eqn. 3b, L is the tape thickness, ρ is the resistivity in statohm-cm, and c is the velocity of light.

Since S_w^r is independent of the tape thickness, and S_w^e is proportional to the square of the thickness, any variation in S_w between metal-tape cores of different thickness is entirely due to the change in the eddy-current contribution. This affords a simple experimental means of separating S_w^e and S_w^r in order to study their properties independently.

III. EXPERIMENTAL RESULTS

This experiment was performed with 4-79 Molybdenum-Permalloy tape cores with thicknesses of 1/8-mil (.000125 inches), 1/4-mil (.00025 inches), 1/2-mil (.0005 inches), and 1-mil (.001 inches), supplied by Magnetics Inc. In order that the cores be as uniform as possible, the 1/8-mil, 1/4-mil, and 1/2-mil tapes were all prepared from the same melt. The 1-mil tapes are not manufactured by the same company, so they could not be prepared from this melt. Two tape-cores of each thickness were used in this experiment and, unless otherwise stated, all values given below represent the average value for both cores.

A. EXPERIMENTAL PROCEDURE

The input current used to reverse the magnetization of the cores is of the form shown in Fig. 1. It is effectively a constant-current signal with a rise time $t_r \approx 0.2$ microseconds. The pulse length is long enough to permit a complete magnetization reversal of the core. The input current amplitude was varied, and the switching time of each core was determined as a function of the applied magnetic field. A typical set of data, based on results obtained at room temperature (26°C) from a single core of each thickness, is shown in Fig. 2. The applied field value used is based upon an average core diameter of 0.345 cm. For a single turn input, this leads to the relationship $H = 1.16\ I$, where H is the applied field in oersteds and I is the input current in amperes. This procedure was repeated for all cores at temperatures of -196°C, -60°C, 26°C, 76°C, 155°C, 225°C, and 270°C.

The assumption of a constant-applied-magnetic field is not valid during the rise time of the pulse. This effect was minimized by limiting all measurements to field values at which the switching time is greater than or equal to 0.7 microseconds. The applied field is then constant during most of the switching cycle.

According to eqn. 1,

$$H = S_w/\tau + H_o \qquad (4)$$

which is the equation of a straight line of slope S_w and intercept H_o. The values of S_w and H_o for each core is therefore directly obtainable from curves similar to those shown in Fig. 2. The average values of S_w and H_o obtained as functions of thickness and temperature, are listed in Table I.

Temperature (Degrees Cent.)	1/8-mil		1/4-mil		1/2-mil		1-mil	
	$S_w x10^6$ (0_e-Sec)	H_o (0_e)	$S_w x10^6$ (0_e-Sec)	H_o (0_e)	$S_w x10^6$ (0_e-Sec)	H_o (0_e)	$S_w x10^6$ (0_e-Sec)	H_o (0_e)
-196°	0.425	0.236	0.592	0.207	1.11	0.15	3.06	0.194
-60°	0.409	0.197	0.52	0.157	1.00	0.124	2.75	0.152
26°	0.394	0.18	0.497	0.142	0.921	0.111	2.49	0.142
76°	0.389	0.167	0.482	0.128	0.873	0.097	2.29	0.128
155°	0.360	0.15	0.461	0.10	0.815	0.08	2.05	0.10
225°	0.355	0.125	0.424	0.09	0.693	0.067	1.81	0.09
270°	0.346	0.12	0.395	0.086	0.628	0.063	1.5	0.089

TABLE I: Switching Characteristics of 4-79 Molybdenum-Permalloy as Functions of Temperature and Thickness

B. CORRELATION OF THEORY AND EXPERIMENT

1. Effect of Tape Thickness

Equations 2 and 3 lead to the relationship

$$S_w = S_w^r + DL^2 \qquad (5)$$

where

$$D = \frac{\pi B_s}{2 \rho c^2 \langle \cos \theta \rangle^3} \qquad (5a)$$

is the eddy-current contribution to the switching coefficient per unit thickness, in units of oersted-seconds per centimeter squared. Since D is a constant at constant temperature, a plot of the switching coefficient versus tape thickness squared should yield a straight line of slope D and intercept S_w^r. A series of such curves, taken at different temperatures, are shown in Fig. 3. In all cases, the linear relationship holds well within the 10% thickness tolerance set by the manufacturer.

Since the intercept of the curves on the S_w axis in Fig. 3 represents the spin-relaxation contribution to the switching coefficient, it is apparent that the eddy-current contribution has been reduced to almost negligible proportions in the 1/8-mil tape and is still small in the 1/4-mil tape. In the 1/2-mil tape the eddy-current contribution is comparable to the spin-relaxation contribution, and in the 1-mil core the switching delay is predominantly an eddy-current effect.

A corroboration of these conclusion can be obtained from the shape of the output-voltage of these cores, as seen on an oscilloscope. Fig. 4 shows the output-voltage signals obtained at room temperature upon reversing the magnetization of an 1/8-mil, 1/4-mil, 1/2-mil, and 1-mil 4-79 Molybdenum-Permalloy core with a magnetic field of 1.75 oersteds. Fig. 5a shows a typical output-voltage signal obtained upon reversing the magnetization of a high-resistivity ferrite core in which eddy-current effects are negligible. Fig. 5b represents the theoretical voltage output of a metal-tape core due to eddy-current effects.[3]

Comparison of Figures 4 and 5 shows that the voltage-output curves of the 1/8-mil and 1/4-mil cores closely approximate that of the ferrite, where damping is almost entirely due to spin-relaxation effects. On the other hand, the 1-mil core output approaches the shape Fig. 5b, which indicates that eddy-current damping predominates. The 1/2-mil core output is somewhere between these extremes. Thus Figures 4 and 5 quatitatively corroborate the quantitative results shown in Fig. 3.

2. Effect of Temperature Variation

a. Effect upon Eddy-Current Contribution

Since the flux density B_s and the electrical resistivity are the only temperature dependent variables on the right hand side of eqn. 3b, S_w^e varies with temperature as B_s/ρ. The electrical resistivity of 4-79 Molybdenum-Permalloy is given by Littman[4] as 55 microohm-cm. at room temperature (6.1×10^{-17} statohm-cm.), and the temperature coefficient of electrical resistivity α is given by the Magnetic Metals Company as .0011 per degree Centigrade in the range 20°C to 500°C*. Within this temperature range, all the terms on the right hand side of eqn. 5a are known except B_s and $\langle \cos \theta \rangle$. The experimentally determined value of D can therefore be used to find $B_s / \langle \cos \theta \rangle^3$ as a function of temperature. The results of this calculation are given in Table II. The units given for D in this table introduces a conversion factor of 6.45×10^{-6}.

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* The figure is given for Hymu "80", which is the trade name of the Carpenter Steel Company for a material with the same composition as 4-79 Molybdenum-Permalloy.

Temperature (Degrees Cent.)	D O_e-Sec/(mil)^2	ρ Statohm-cm.	$B_s/\cos\theta^3$ Gauss
-196°C.	2.68×10^{-6}		
-60°C.	2.38×10^{-6}		
26°C.	2.12×10^{-6}	6.11×10^{-17}	11500
76°C.	1.94×10^{-6}	6.45×10^{-17}	11080
155°C.	1.72×10^{-6}	7.00×10^{-17}	10570
225°C.	1.42×10^{-6}	7.39×10^{-17}	9330
270°C.	1.17×10^{-6}	7.75×10^{-17}	8120

TABLE II: Variation of S_w^e, Electrical Resistivity and Flux Density with Temperature

There are no directly determined experimental values of B_s vs. temperature available for comparison with these calculated values. However, since the angle θ is temperature independent within the range considered, the variation of $B_s/\langle\cos\theta\rangle^3$ with temperature is the same as that of the flux density. Therefore, the experimental variation of B_s with temperature can be compared with the variation predicted by the magnetization curves based on the Brillouin function

$$\frac{I_s}{I_o} = \frac{2J+1}{2J} \operatorname{ctnh} \frac{(2J+1)a}{2J} - \frac{1}{2J} \operatorname{ctnh} \frac{a}{2J}$$

where $a = \frac{Jg\beta(H+NI_s)}{kT}$,

J is the angular momentum quantum number, NI_s is the molecular field, β is a Bohr magneton, g is the Landé factor, k is the Boltzmann constant, I_s is the temperature dependent saturation magnetization, and I_o is the saturation magnetization at zero degrees absolute. For the small field values involved in these experiments, $B_s = 4\pi I_s$.

The normalized magnetization curve is shown in Fig. 6 for $J = 1/2$ and $J = 1$. The normalized experimental points are also shown for comparison. These points are based on the assumed value $B_o/\langle\cos\theta\rangle^3 =$ 11750 gauss, and the Curie temperature T_c is given by Littman[4] as 420°C. The close agreement of the theoretical and calculated experimental values strongly corroborates the prediction that S_w^e varies as B_s/ρ.

The value of B_s at room temperature is given as 8700 gauss. The value of $B_s / \langle \cos \theta \rangle^3$ as determined in this experiment is 11500 gauss. This leads to a mean value of θ of 24°, which seems slightly high for a grain-oriented material.

b. Effect upon Spin-Relaxation Contribution

The spin-relaxation contribution to the switching coefficient S_w^r is obtained from the intercept of the S_w vs. thickness curve shown in Fig. 3. The results obtained are shown in Fig. 7. Despite the uncertainty in the individual readings, the results show that S_w^r decreases slowly with increasing temperature, changing from 0.4×10^{-6} at $T = -196°C.$ to 0.32×10^{-6} at $T = 270°C.$ No anomolous effects occur within this temperature range.

According to eqn. 3a

$$S_w^r \propto \frac{\Lambda(K)^{1/2}}{B_s}$$

where all the other terms on the right hand are temperature independent. Actually, there should be a variation in d, but this variation is assumed to be small. The relative change of B_s with temperature is obtainable from Fig. 6. The temperature dependence of the relaxation frequency is not known for 4-79 Molybdenum-Permalloy. However, Bloembergen[5] has investigated the relaxation frequency of supermalloy, a material of similar composition, as a function of temperature. Bloembergen's results indicate that Λ increases by approximately 40% from room temperature to 270°C. Thus the variation of Λ and B_s are in the direction tending to increase S_w^r with temperature.

In order to overcome this tendency and yield the decrease in S_w^r actually observed, there must be a five-fold decrease in the anisotropy constant K over this temperature range. Data given by McKeehan[6] shows that the anisotropy constant of an iron-nickel alloy containing 30% iron and 70% nickel increases by a factor of 3.5 on going from 20°C. to 200°C. Thus the figures obtained appear reasonable. Furthermore, the sharp decrease that must occur in S_w^r above 270° to obtain $S_w^r = 0$ at $T = T_c$ is also reasonable since, according to Van Vleck,[7] the anisotropy constant at high temperature varies approximately as B_s^{10}. Thus, in the region in which B_s is varying rapidly, S_w^r is proportional to B_s^4.

The above evidence indicates experimental agreement with the predicted behavior. However, conclusive proof must await measurement of the values of Λ and K for 4-79 Molybdenum-Permalloy as function of temperature.

3. Threshold Field

The threshold field H_o represents the effective zero level which must be overcome for domain wall motion. It is closely related to, but not identical with, the coercive force H_c. The coercive force of ultra-thin metal tapes decreases with increasing thickness.[4] This is also true of the threshold field values of the 1/8-mil, 1/4-mil, and 1/2-mil tapes investigated in this experiment. These tapes were all obtained from the same original melt. The 1-mil tape has a threshold field value which is approximately equal to that of the 1/4-mil tape. However, since the 1-mil tape was manufactured by a different company, variations in processing techniques could explain this apparent discrepancy.

In general, the coercive force of a ferromagnetic material decreases with increasing temperature. The variation of the threshold field with temperature is shown in Fig. 8 for all core thicknesses. Like the coercive force, the threshold field decreases with increasing temperature.

IV. CONCLUSIONS

The use of ultra-thin metallic tapes below 1/2-mil thickness successfully reduces the eddy-current damping to a small proportion of the total damping. For 1/8-mil tapes the eddy current effect is less than 10% of the spin-relaxation damping at room temperature. Further reduction of tape thickness will therefore have a negligible effect upon the switching coefficient S_w. However, in metallic tapes of 1/2-mil thickness or greater, the eddy-current damping factor is predominant and the switching coefficient increases sharply with increasing thickness. This limits the use of 4-79 Molybdenum-Permalloy to tapes of 1/4-mil and 1/8-mil for high-speed-digital-computer applications.

No comparative figures are available for ultra-thin metallic tapes other than 4-79 Molybdenum-Permalloy. However, the switching coefficient of several magnesium-manganese and nickel-zinc ferrites have been determined in this laboratory. The values obtained at room temperature with these ferrites range from 0.9 x 10^{-6} to 2.1 x 10^{-6} oersted-seconds. Thus the lowest value obtained with ferrites is almost double the value obtained with the 1/4-mil tape core. In addition, the threshold field value of the ferrites is uniformly higher than that of the metal-tape cores. This low values of S_w and threshold field indicate that, for a given applied field, ultra-thin 4-79 Molybdenum-Permalloy tape cores undergo flux reversal faster than any ferrite investigated to date.

Upon increasing the temperature from -196°C. to 270°C., spin relaxation damping is decreased by 20% while eddy-current damping and the threshold field values are approximately halved. All these factors tend to produce a faster switching time at higher temperatures for a given applied field. However, since the spin-relaxation damping is less temperature sensitive than eddy-current damping over this range, the relative change in switching time is smallest for the 1/8-mil tape cores and largest for the 1-mil tape cores. Thus, for an applied field of 0.6 oersteds, the switching time of the 1/8-mil tape core over this temperature range varies by a factor of approximately 1.7 as compared to a factor of 2.3 for the 1-mil tape core. The values for the 1/4-mil and 1/2-mil tape cores fall between these extremes.

Although this variation of switching time with temperature is significant, it is too small to warrant the use of higher temperatures to attain faster-switching cores. On the other hand, the results indicate that the switching time is relatively insensitive to small temperature variations. For a 1/8-mil tape core, a change of twenty degrees centigrade in the vicinity of room temperature should produce a switching time variation of about 3%. For thicker tapes, the temperature sensitivity is slightly higher.

The effects of tape thickness and temperature upon the eddy-current contribution to the switching coefficient S_w^e strongly corroborate the theory discussed in section II. The variation of S_w^r with temperature also agrees with the theory within the limits of independent data presently available.

The writer wishes to thank P. Fergus and H. Mogensen for their help in obtaining the experimental data and to J. Childress for his assistance in maintaining the experimental equipment.

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Signed Norman Menyuk
N. Menyuk

Approved JRB
D. R. Brown

NM/djd

cc: Group 63

Drawings Attached:

Figure 1 - A-58597
Figure 2 - A-58782
Figure 3 - A-58783
Figure 4 - A-58784
Figure 5 - A-58785
Figure 6 - A-58786
Figure 7 - A-58787
Figure 8 - A-58788

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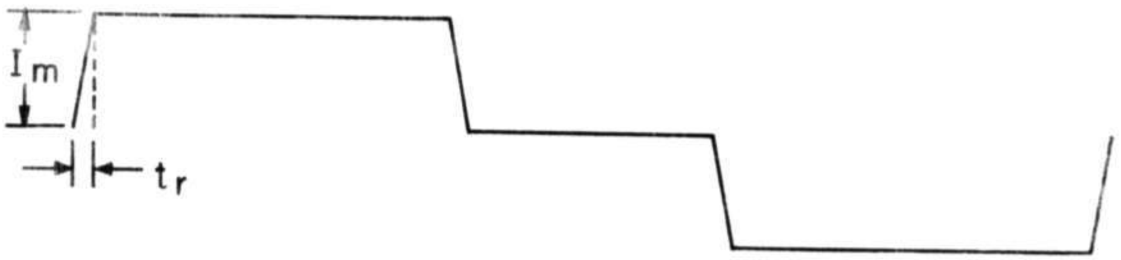


FIG. 1

INPUT CURRENT PULSE

A-58597

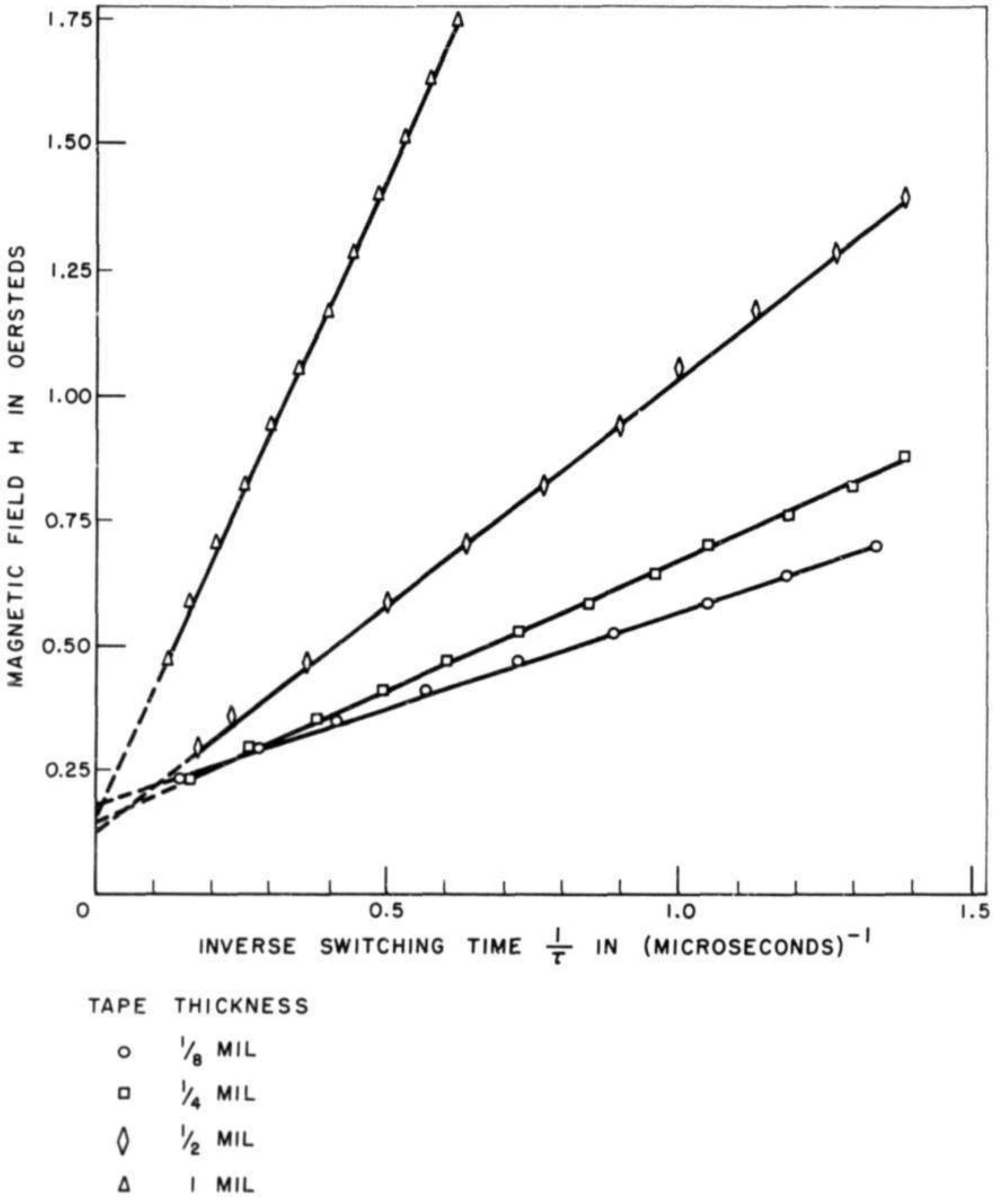


FIG. 2

SWITCHING COEFFICIENT OF TAPE WOUND 4-79 MO-PERMALLOY CORES AT ROOM TEMPERATURE

A-58782

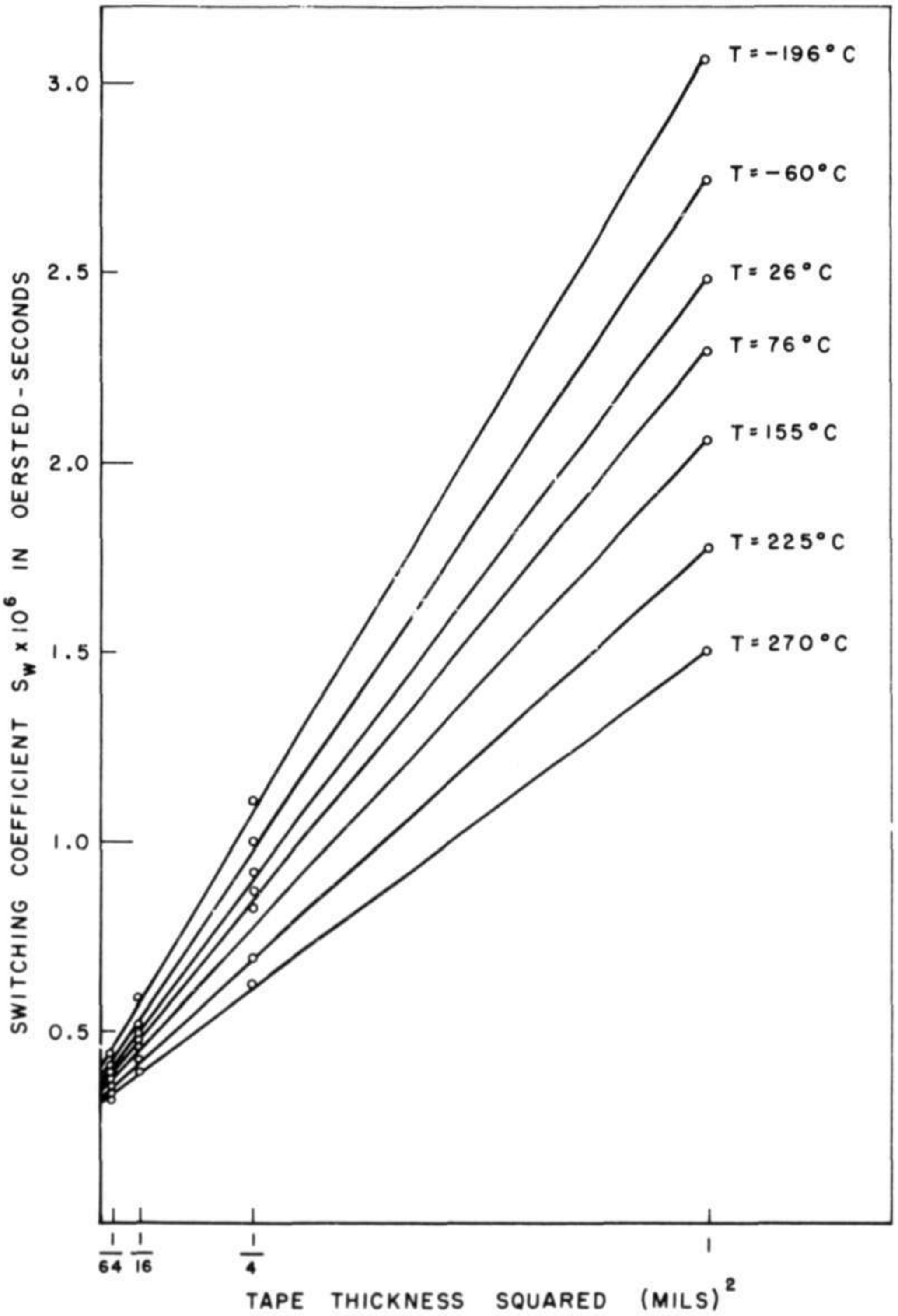


FIG. 3

VARIATION OF SWITCHING COEFFICIENT WITH TAPE THICKNESS AS FUNCTION OF TEMPERATURE

A-58783

(a) $\frac{1}{8}$ - MIL CORE OUTPUT

TIME SCALE: 0.1 μSEC/DIV.

VOLTAGE SCALE: 135 MV/DIV.

(b) $\frac{1}{4}$ - MIL CORE OUTPUT

TIME SCALE: 0.1 μSEC/DIV.

VOLTAGE SCALE: 155 MV/DIV.

(c) $\frac{1}{2}$ - MIL CORE OUTPUT

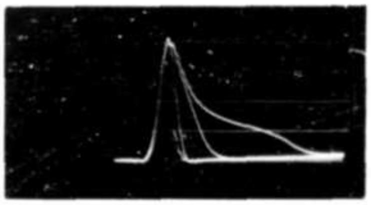
TIME SCALE: 0.2 μSEC/DIV.

VOLTAGE SCALE: 150 MV/DIV.

(d) 1 - MIL CORE OUTPUT

TIME SCALE: 0.3 μSEC/DIV.

VOLTAGE SCALE: 150 MV/DIV.



(e) SUPERIMPOSED OUTPUT OF $\frac{1}{8}$-MIL, $\frac{1}{4}$-MIL, $\frac{1}{2}$-MIL, AND 1-MIL CORES

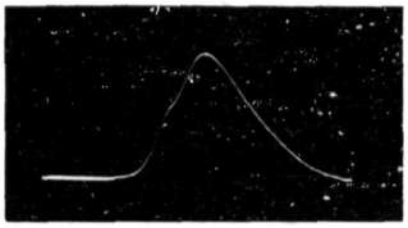
TIME SCALE: 0.3 μSEC/DIV.

VOLTAGE SCALE: 150 MV/DIV.

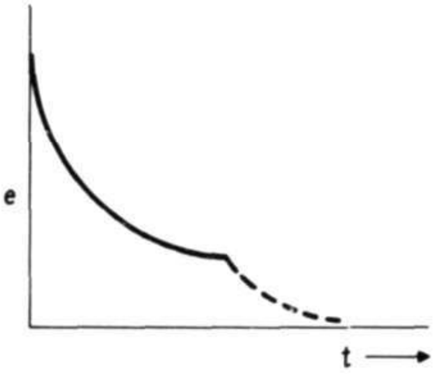
FIG. 4

VOLTAGE OUTPUT CURVES
OF 4-79 MO-PERMALLOY TAPE CORES

A-58784



(a) VOLTAGE OUTPUT OF A HIGH-RESISTANCE FERRITE CORE IN WHICH EDDY-CURRENT EFFECTS ARE NEGLIGIBLE.



(b) PREDICTED VOLTAGE OUTPUT OF A CORE DRIVEN BY A CONSTANT CURRENT GENERATOR, CONSIDERING EDDY-CURRENT EFFECTS. (A. PAPOULIS)

FIG. 5

SHAPE OF VOLTAGE OUTPUTS
DUE TO RELAXATION AND EDDY-CURRENT EFFECTS

A-58785

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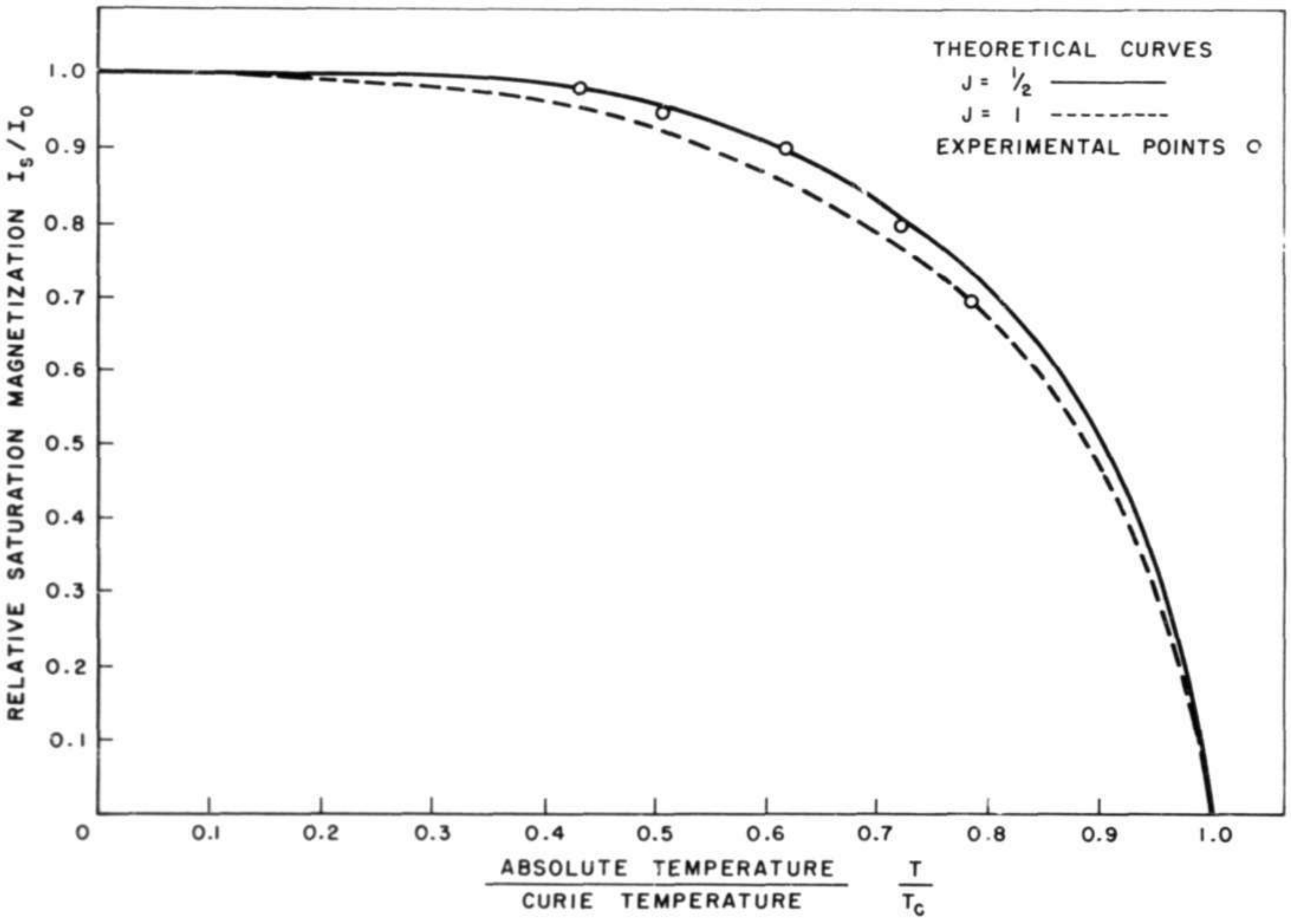

FIG. 6

VARIATION OF MAGNETIZATION WITH TEMPERATURE

A-58787

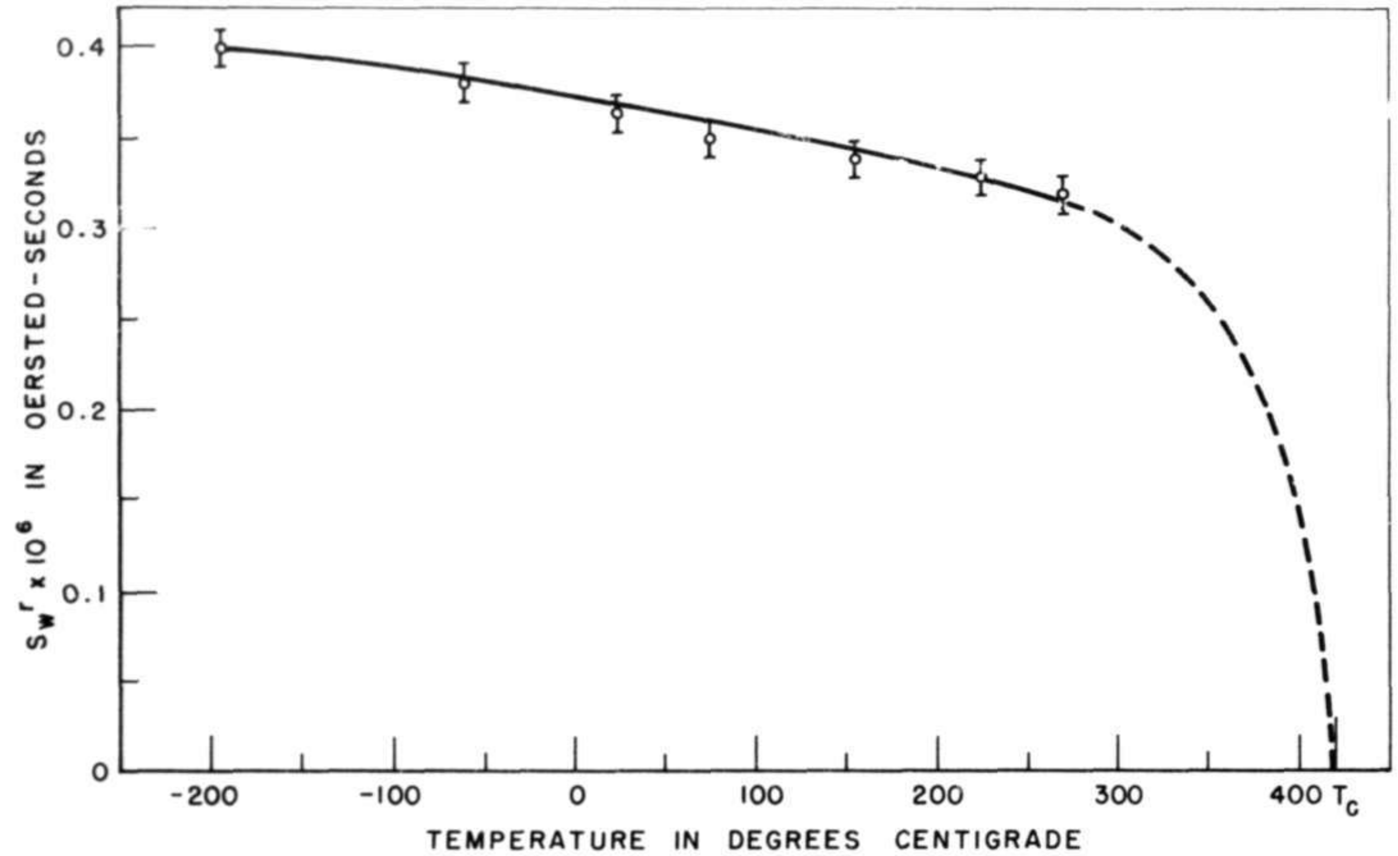

FIG. 7

VARIATION OF S_W^r WITH TEMPERATURE

A-58788

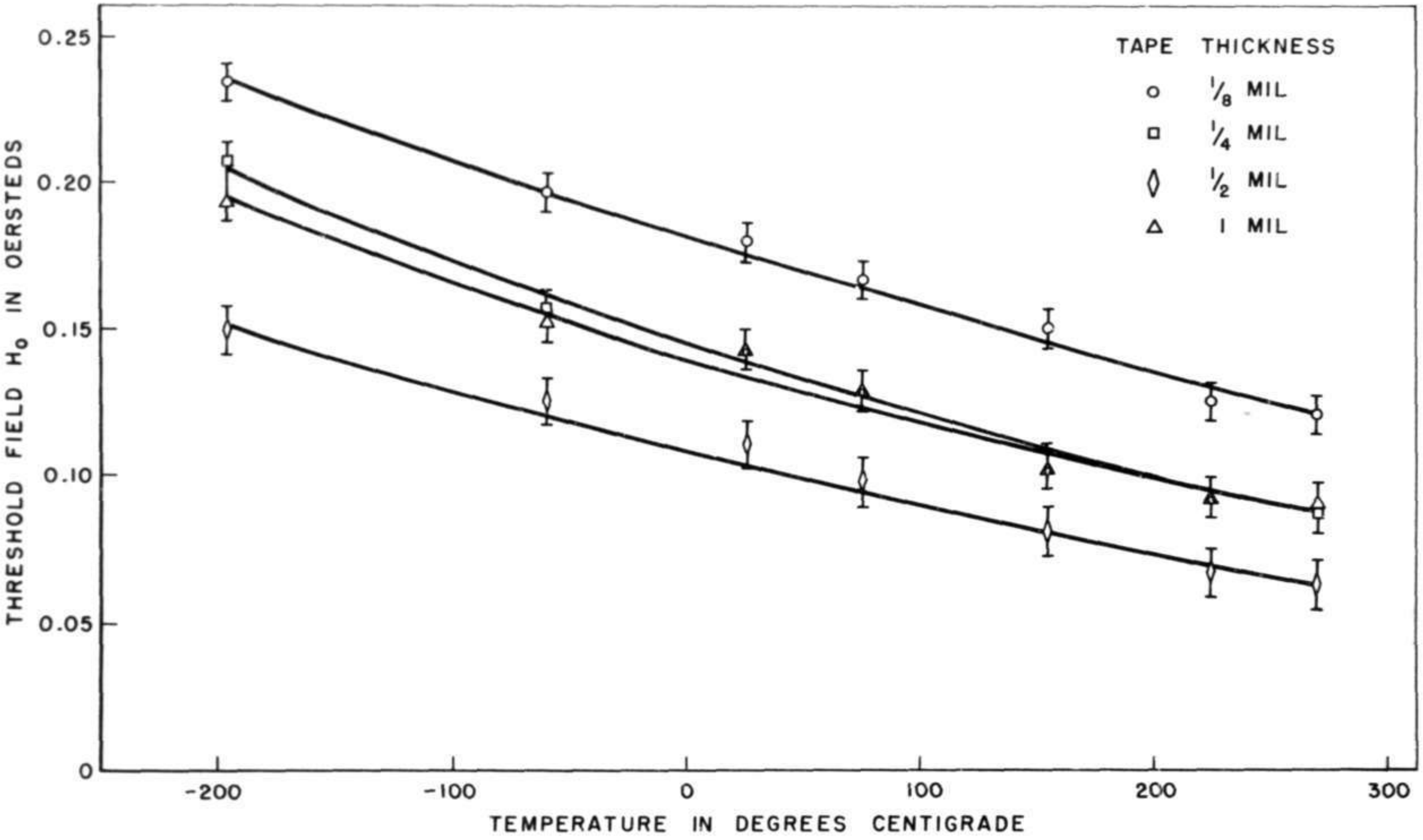

FIG. 8

VARIATION OF THRESHOLD FIELD WITH TEMPERATURE