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SUBJECT: THE NOISE PROBLEM IN THE COINCIDENT-CURRENT MEMORY MATRIX

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THE NOISE PROBLEM IN THE COINCIDENT-CURRENT MEMORY MATRIX †

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Magnetic ferrites which have square hysteresis loops are being used as memory elements in high-speed digital computers. The limiting factor in memory reliability is the noise generated by the magnetic cores which are subjected to field excitations of amplitude insufficient to cause a reversal of magnetization. The occurrence of such excitations (half-amplitude pulses) at any given core in almost any possible sequence is inherent in the two-to-one coincident-current method of register selection. The noise voltage induced by a magnetic core when excited by a half-amplitude pulse $|H_m/2|$ can be expressed as

$$e(t) \propto \mu_\Delta \frac{dH}{dt} + Q$$

where μ_Δ is the incremental permeability for $\Delta H = H_m/2$ from remanence and Q is an irreversible contribution which is shown to be negligible in all cases of interest. The region of validity of the above equation is discussed with reference to particular ferrite materials. The incremental permeability is shown to depend both on the direction (relative to the remanent state) of the applied pulse and on the sequence of excitation since the most recent magnetization reversal. Of particular importance to the matrix-noise problem is the difference between $\mu_{\Delta-}$, the incremental permeability for an excitation in the demagnetizing direction, and $\mu_{\Delta+}$, for an excitation in the magnetizing direction. The contributions to μ_Δ from rotation, domain-wall motion, and reverse-domain nucleation and the mechanism responsible for the permeability difference, $(\mu_{\Delta-} - \mu_{\Delta+})$ are discussed. Also data are presented on the dependence of the various noise voltages on the amplitude and waveform of the pulse excitations. The meaning of these data with regard to the noise problem is discussed.

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I. INTRODUCTION

Magnetic ferrites which have square hysteresis loops are being used as memory elements in high-speed digital computers.[1] Information coded in binary numbers is stored one digit per core; the direction of remanent magnetization of the core determines whether the digit stored is a binary ONE or ZERO, Fig. 2. In the two-to-one selection coincident-current memory,[2] the non-linearity or squareness of the hysteresis loop is utilized in the register-selection operation of the memory. The cores are arranged as elements of a matrix; each core has a row- and a column-coordinate wire passing through its center. A particular core is selected by the simultaneous application of equal current pulses, called half-amplitude pulses, on its row and column wires; the coincident magnetic field at the selected core is sufficient to cause a complete induction reversal. The cores which have the same row or column coordinate as the selected core receive half-amplitude excitations and are called "half-selected". Because of the squareness of the hysteresis loop of the core material, the half-amplitude pulses cause relatively little change of induction in the half-selected cores; but in a large matrix, the total of these half-select induction changes can be appreciable with respect to the induction change of the selected core.

The induction changes of all the cores in the matrix induce voltages on the sense winding, a wire which links all the cores in the matrix. The original remanent state of the selected core is determined from the sense signal; the half-select signals, which tend to obscure the signal from the selected core, may be characterized as noise.

The total noise in the system limits the over-all reliability of the memory. Although other types of noise are important in practical design, the noise from the half-select signals is material dependent and, therefore, of fundamental interest in the evaluation of magnetic materials for memory applications.

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1. W.N. Papian, Proc. Eastern Joint Computer Conference, pp. 37-42, December, 1953
2. J.W. Forrester, J. Appl. Phys., 22, 44 (1951)

The object of this paper is to show the dependence of the half-select signals upon the magnetic-field excitations and to relate this dependence to the parameters of the magnetic material.

II. THEORY

As will be shown from experiment, a half-select voltage e(t) can be expressed as

$$(1) \qquad e(t) \propto \mu_{\Delta} \frac{dH}{dt} + Q$$

where Q is an irreversible contribution and μ_{Δ} is the incremental permeability for a half-amplitude field $|H_m/2|$ applied from remanence. The field H_m is the maximum field amplitude for the hysteresis loop of maximum squareness. For a field pulse defined as positive in the magnetizing direction, the incremental permeability is $\mu_{\Delta+}$; for a pulse in the negative or demagnetizing direction, $\mu_{\Delta-}$. The difference, $\delta = |\mu_{\Delta-} - \mu_{\Delta+}|$, is important to the memory-noise problem because the sense winding links all the cores in the matrix such that the half-select voltages tend to cancel. For perfect uniformity of the memory cores, the maximum error of cancellation per pair of cores depends on δ. The incremental permeability is considered experimentally to have both a reversible and an irreversible part such that μ_{Δ} depends upon the amplitude of the field pulse and the excitation sequence since the most recent magnetization reversal. The factor Q is introduced to account for the deviation from the dH/dt relation.

A model, essentially the same as that used by Goodenough,[3] is the basis for calculating the incremental permeability at remanence. Consider a unit volume τ of a domain whose direction of magnetization is at an angle θ with respect to the direction of net magnetization. Assume that the unit volume contains fractional volumes v and v' (averaged for the total sample at the square-loop remanence) of reverse and closure domains, respectively. The induction per unit volume in the direction of net magnetization is thus

3. J. B. Goodenough, Phys. Rev. 95, 917 (1954)

(2) $$B_\tau = B_s\,(1-v'-2v)\cos\theta$$

where B_s is the saturation induction of the material. For an axially symmetric material with uniform angular distribution from $\theta = 0$ to $\theta = \theta_m$, the net induction at remanence on the hysteresis loop of maximum squareness is

(3) $$B_r = B_s\,(1-v'-2v)\,(1+\cos\theta_m)/2\,.$$

Goodenough[3] has shown that the magnetic field necessary to cause closure domains to grow is large with respect to the coercive force of the material. Since the fields here are less than the coercive force, v' is assumed to be constant.

Induction changes occur by (1) the rotation of domain directions of magnetization, (2) the growth of existent reverse domains, and (3) the nucleation and growth of reverse domains. With reference to Eq. 3, the first mechanism causes a variation of θ_m and the second and third mechanisms cause a variation of v.

The incremental permeability per unit volume for a field increment ΔH from remanence is

(4) $$(\mu_\Delta)_\tau \approx -\frac{B_s}{\Delta H}\sin\theta\,\Delta\theta - \frac{B_s}{\Delta H}\,6v\left[\left(\frac{\Delta r}{r_o}\right) + \left(\frac{\Delta r}{r_o}\right)^2\right]\cos\theta$$

where the fractional volume v is assumed to consist of a number of ellipsoidal reverse domains of average radius r_o and an eccentricity $\sqrt{1-\lambda^2}$. The first term on the right is the incremental permeability due to the rotation of the domain directions of magnetization through an angle $\Delta\theta$; the second term is due to the growth of the reverse domains by an average radial increment Δr, λ assumed constant. Both these processes are considered as completely reversible. The irreversible part of the incremental permeability can be explained by variations in the number of reverse domains (nucleation) and in r_o. Such variations would cause corresponding changes in v and μ_Δ. However, for field amplitudes smaller than the field value at the knee of the square hysteresis loop, there should be little nucleation or irreversible growth of reverse domains.[3]

It is observed experimentally that the first field pulse in a direction opposite to the previous pulses causes a measurable irreversible change; succeeding pulses in the same direction cause only reversible changes. Because of the difficulty in calculating the irreversible part, only the theory of the reversible part of the incremental permeability is considered.

A. Incremental Permeability Due to Rotation

The angle of rotation $\Delta\theta$ is determined by the variation of the magnetic and anisotropy energy density. For small values of $\Delta\theta$,

$$\Delta E \approx K_{eff}(\Delta\theta)^2 - (\Delta H)I_s\cos(\theta + \Delta\theta),$$

where K_{eff} is the effective anisotropy and θ is the original angle between the magnetization direction and the direction of the applied field. The minimization of ΔE with respect to $\Delta\theta$ gives

$$(5) \qquad \Delta\theta = -\alpha\sin\theta/(1 + \alpha\cos\theta),$$

where $\alpha = (\Delta H)B_s/8\pi K_{eff}$.

Substituting Eq. (5) into the first term of Eq.(4) and averaging over the angular distribution, we obtain the incremental permeability at remanence due to rotation

$$(6) \qquad (\mu_\Delta)_{rot} = \frac{B_s}{\Delta H}\,\alpha\left\{\frac{1}{3}(2-\cos\theta_m-\cos^2\theta_m) - \frac{\alpha}{4}\,\frac{\sin^4\theta_m}{(1-\cos\theta_m)}\right\},$$

where higher-order terms in α and the harmonic value of $\theta < \pi/2$ in θ_m are neglected. The difference $(\mu_{\Delta-} - \mu_{\Delta+})$ is given from Eq. (6) as

$$(7) \qquad (\delta)_{rot} = \frac{B_s}{|\Delta H|}\,\frac{\alpha^2}{2}\,\frac{\sin^4\theta_m}{(1-\cos\theta_m)}.$$

The substitution into Eq. (7) of the reasonable values -- $B_s = 3 \times 10^3$ gauss, $K_{eff} = 10^4$ ergs-cm^{-3}, $\theta_m = 45^\circ$, and $\Delta H = 0.5$ oersted -- gives $(\mu_\Delta)_{rot} \approx 1$, $(\delta)_{rot} \approx 10^{-2}$. These values are two orders of magnitude smaller than the values obtained from the d-c hysteresis loop and from pulse experiments. Therefore, we conclude that the rotation of domain directions of magnetization cannot account for the magnitude of the incremental permeability at remanence.

According to Eq. (6), a decrease in K_{eff} tends to increase μ_Δ; however, a lower value of K_{eff} results in better alignment (by the internal field) of the directions of magnetization. The resultant decrease in θ_m would cause a decrease in μ_Δ. It is expected that the rotation mechanism could yield a large value of μ_Δ only for materials with very low effective anisotropy.

To justify the assumption that θ_m is constant, we substitute the numerical values into Eq. (5) and find the maximum $\Delta\theta$ as $\Delta\theta_{max} < 0.1^\circ$. Since this value is negligible, the maximum angle θ_m of the angular distribution is not changed appreciably by fields smaller than the coercive force.

B. Incremental Permeability Due to Domain Growth

Ellipsoidal domains of reverse magnetization are assumed to exist at crystal imperfections in the material. Possible sites for the nucleation of such domains are grain boundaries, inclusions, etc. These domains are assumed to have an average radius r_o in zero external field and an eccentricity $\sqrt{1 - \lambda^2}$ where $\lambda \ll 1$ and is assumed constant. Only the reversible part of the incremental permeability will be calculated; hence r_o is assumed to be constant.

The total energy associated with a reverse domain in an external field H is

$$E = E_m + E_w + E_d + E_p, \tag{8}$$

where the magnetic energy is $E_m = 2\,\vec{H}\cdot\vec{I}_s\,V$, the domain-wall energy is $E_w = \sigma_w A_w$, and the demagnetization energy is $E_d = 2NI_s^2V$. In the above energy terms, σ_w is the domain-wall energy per unit area; the demagnetization constant for an ellipsoid is $N = 4\pi\,\lambda^2\left[\ln(2/\lambda) - 1\right]$; and $V = 4\pi r^3/3\lambda$ is the volume of the ellipsoid with surface area $A_w = \pi^2 r^2/\lambda$. The saturation magnetization I_s may be expressed in terms of saturation induction B_s as $B_s/4\pi$.

The energy term E_p represents the magnetic-pole-distribution energy gained by the introduction of reverse domains. Assuming E_p to depend on the cross-sectional area of the reverse domain, we take $E_p = -pr^2$ where p is independent of r. A more exact calculation† shows E_p to have a term in r^4 with a coefficient small compared to p. However, the expression used here for E_p is sufficiently accurate for an order of magnitude calculation.

By minimizing the total domain energy with respect to r, we obtain the equilibrium value of r for an applied field H,

$$(9) \qquad r = \frac{\lambda p - \pi^2\sigma_w}{4\pi(\vec{H}\cdot\vec{I}_s + NI_s^2)} .$$

Equation (9) shows clearly the importance of E_p; reverse domains exist at remanence only if $p > \pi^2\sigma_w/\lambda$. This means that the energy gain from the reduction of the surface-pole-distribution energy must be greater than the energy required to form the walls of the reverse domain.

For H = 0, $r = r_o$ and p may be expressed in terms of r_o; then,

$$(10) \qquad r = r_o \frac{1}{1 + \vec{H}\cdot\vec{I}_s/NI_s^2}$$

† To be published.

For the domain lying at an angle θ with respect to the external field and for ΔH applied from remanence, the resultant change in radius is

$$\text{(11)} \qquad \Delta r = - r_o \beta \frac{\cos\theta}{1 + \beta\cos\theta} ,$$

$$\beta = \frac{4\pi(\Delta H)}{NB_s}$$

Substitution of Eq. (11) into the second term of Eq. (4) and averaging over the angular distribution gives the incremental permeability at remanence due to domain growth,

$$\text{(12)} \qquad (\mu_\Delta)_{d.g} = \frac{B_s}{\Delta H} \cdot 2v \cdot \beta \left\{ \frac{(1-\cos^3\theta_m)}{(1-\cos\theta_m)} - \frac{3\beta}{2} \frac{(1-\cos^4\theta_m)}{(1-\cos\theta_m)} \right\} ,$$

where higher order terms in β are neglected.

From Eq. (12),

$$\text{(13)} \qquad (\delta)_{d.g} = \frac{B_s}{|\Delta H|} \cdot 6v \cdot \beta^2 (1+\cos\theta_m+\cos^2\theta_m+\cos^3\theta_m).$$

Taking $v \approx (B_s-B_r)/2B_s \approx 1/6$, $\Delta H = 1$ oersted, $B_s = 2 \times 10^3$ gauss, $\theta_m = 45°$, and $\lambda = 1/30$, we find $(\mu_\Delta)_{d.g} \approx 200$ and $(\delta)_{d.g} \approx 100$. Experimental values are $\mu_\Delta = 50 - 500$ and $\delta = 10$-100. In view of the simplifying assumptions made, the order-of-magnitude agreement is good. Therefore, it appears that the incremental permeability at remanence is primarily due to the growth of reverse domains.

IV. EXPERIMENTS AND DISCUSSIONS

Pulse measurements have been made of the incremental permeability at remanence as a function of (1) the magnetic-field-pulse waveform and (2) the sequence of excitations.

A. Definitions

Definitions of the parameters of the pulse measurements are given in Fig. 1. Fig. 2 shows the method of information storage (discussed in Section I) and defines the terms used in this application.

Fig. 1 goes here

Fig. 1. Definitions of Pulse Measurements

Fig. 2. goes here

Fig. 2. Storage of Binary Information in a Magnetic Core

During the READ operation, a field pulse $+H_m$ is applied to the selected core. If the core were in the ONE state, the resultant change of induction is relatively large and induces a large voltage on the sense winding; if the core were in the ZERO state, the induction change and induced voltage are small. The half-selected cores are excited by a field pulse $+H_m/2$, and the sum of their induction changes induces a noise voltage N(t) on the sense winding. This noise voltage has been expressed by Freeman[4] in terms of the peak signal voltages. His expression can be written in the form of Eq. (1) as

$$N(t) \propto \mu_{\Delta eff}\, dH/dt, \qquad (14)$$

where, as will be shown later, the irreversible term Q may be neglected in a practical memory, and the effective incremental permeability may be defined in terms of the parameters μ_Δ, δ, and γ as

$$\mu_{\Delta eff} = 2\mu_\Delta + (\gamma - 2)\,\delta\ . \qquad (15)$$

The parameter γ is the dimension, or number of rows, in the square memory matrix. It is assumed that there is perfect uniformity of the

4. J. R. Freeman, Proc. I.R.E. Wescon Computer Sessions, pp. 50-61, August, 1954.

cores in the matrix and that the sense winding links the cores diagonally through the matrix so as to achieve noise-signal cancellation between the diagonal rows. For $\mu_\Delta = 100$, $\delta = 50$, and $n = 64$, $\mu_{\Delta eff} = 3300$, an appreciable value. It can be seen from these values and Eq. (15) that the material-dependent contributions to the matrix noise is of great importance in large matrices.

Information is extracted from the memory only during the READ operation; therefore only the half-select signals caused by half-amplitude READ pulses contribute to the noise. Experimentally it is found that these signals depend upon the remanent state of the core as determined only by (1) the digit stored and (2) the nature of the previous pulse. If Freeman's nomenclature for voltage signals is used, the letters Vh indicate that the voltage signal is caused by the application of a half-READ ($+H_m/2$) pulse. A lower-case letter preceding the Vh indicates whether the previous pulse was the full pulse which determines the digit stored, a half-amplitude WRITE pulse ($-H_m/2$), or a half-amplitude READ pulse ($+H_m/2$); these are indicated by u, w, and r, respectively. Finally the letter z or the number 1 following Vh indicate whether the digit stored is a ZERO or a ONE.

For example, wVhz means the output signal from a half-select READ pulse applied to a core which contains a ZERO and was last subject to a half-amplitude WRITE pulse, or from Fig. 2, the signal from a core previously driven by a half-amplitude pulse in the demagnetizing direction but now driven by a half-amplitude pulse in the magnetizing direction.

B. Experimental Materials

The pulse measurements have been taken on two ferrite materials: Ferramic S-1 made by General Ceramics and a material (identified as the DCL ferrite) prepared at Lincoln Laboratory. These two were chosen because they are being used in the coincident-current memory application; they compare as shown in Table I.

Table I: Comparative Properties of Two Memory-Core Ferrites

	S-1(I-83)*	DCL(2-853HR-1)*
Composition as fired (mole percent),		
Fe_2O_3		40
MgO		38
MnO		22
Saturation induction, B_s(gauss)	~2000	~2200
Remanent induction on the loop of maximum squareness, B_r(gauss)	~1300	~1800
Squareness ratio, R_s +	0.82	0.86
H_c(oersted)	~ 1.4	~1.4
H_m(oersted)	~ 2	~ 2

*Identification numbers of the lots from which samples were taken.

+The squareness ratio is defined with reference to Fig. 1 as $R_s = B'/B_m$.

The two materials are found to similar; this is not surprising since the two have approximately the same composition. However, the DCL ferrite has a significantly higher remanent induction on the hysteresis loop of maximum squareness. On the basis of the theory developed in Section II, this difference is expected to give a similar difference in the fractional volume of reverse domains and to predict the relative properties in Table II. The experimental values are $\mu_{\Delta -} = 25$ and $\delta < 10$ for the DCL ferrite and $\mu_{\Delta -} = 55$ and $\delta = 22$ for Ferramic S-1. These results are in agreement with the theoretical predictions.

Table II: Predicted Relative Properties of Two Memory-Core Ferrites

	DCL	S-1
Functional volume of reverse domains, v		larger
Incremental permeability at remanence, μ_Δ		larger
$\delta = \lvert \mu_{\Delta -} - \mu_{\Delta +} \rvert$		larger
Squareness ratio, R_s	larger	

Fig. 3 goes here

Fig. 3. Reversible Voltage Signal
(a) Field Pulse
(b) Voltage Signal

C. The Time Dependence of the Half-Select Signals

Figure 3 shows a half-select signal which is taken for a large number of pulses in the magnetizing direction and thus is completely reversible. The applied-field pulses have a rise time less than 7×10^{-9} second and a peak amplitude approximately one oersted. The rise time of the oscilloscope used is about 7×10^{-9} second.

The voltage signal (b) is shown superimposed on the field pulse waveform (a). Both are seen to rise as rapidly as the oscilloscope could follow; when $dH/dt \approx 0$, the voltage signal falls with the same rapidity. There is no long "tail" corresponding to a relatively slow induction change. On the actual photograph, the "ring" following the initial pulse is seen to be related to the ripple on the field pulse.

Fig. 4 goes here

Fig. 4. Reversible Half-Select Signal Peak Amplitude vs Field Pulse Rise Time

From Eq. (1), the peak amplitude of the half-select signal can be expressed in volts as

$$(1') \qquad e(t)_p = \mu_\Delta (A \times 10^{-8})\, H_p/\tau_r$$

where Q is neglected, A is the cross-sectional area of the core in square centimeters, and H_p and τ_r are the peak amplitude in oersteds and rise time in seconds, respectively, of the field pulse. Fig. 4, which is a plot of $e(t)_p$ vs $1/\tau_r$, shows that Eq. (1') is valid for reversible half-select signals where $\tau_r < 0.1$ microsecond and $|H_p| < |(H_d)_{max.}|$. $|(H_d)_{max.}|$ is defined in Fig. 2 as the field value at the knee of the square hysteresis loop. For $|H_p| < |(H_d)_{max.}|$, each field pulse in the demagnetizing direction causes an irreversible induction change; a long series of such pulses causes an almost complete induction reversal and thus destroys the information stored by the core.

Fig. 5. goes here

Fig. 5. Half-select Signals (a) ZERO (b) ONE (Freeman)

Figure 5 shows the half-select signals important to the study of memory-core pulse response[4]. The pulse sequences by which these signals are obtained are shown in the insets of Figs. 6 and 7. In the insets, the large pulses are full amplitude; the small, half-amplitude; the READ direction is up; WRITE, down. The arrow indicates the pulse at which the signal is observed. The amplitude and rise time of the half-amplitude field pulse are approximately one oersted and 0.2 microsecond, respectively; the rise time of the oscilloscope is about 0.03 microsecond.

The rVhl signal is completely reversible; the small tail is caused by the shape (dH/dt) of the field pulse. By comparing the other signals to rVhl, we see that only the uVhl has an appreciable tail. However, the uVhl is relatively unimportant to the matrix noise problem. In the memory, a WRITE operation always follows the READ operation so that only the core being selected can be in the virgin ONE state. Therefore, only one uVhl signal at most can occur during any READ operation.

Fig. 6 goes here

Fig. 6. Incremental Permeability at Remanence vs Field-Pulse Duration (from ONE signals)

Fig. 7 goes here

Fig. 7 Incremental Permeability at Remanence vs Field-Pulse Duration (from ZERO signals)

D. Experimental Study of the Incremental Permeability at Remanence

The incremental permeabilities corresponding to the half-select signals from which they are calculated are shown in Figs. 6 and 7 as functions of $\tau_d - \tau_r - \tau_f$, the time interval during which the field amplitude is equal to or greater than ninety percent of the peak value, see Fig. 1. The data are averaged from measurements taken at $|H_m| = 1.8$ oersted and $|H_m/2| = 0.9$ oersted and for three values of rise time, $\tau_r = 0.2$, 0.5, and 0.8 microsecond.

The incremental permeabilities at remanence increase as $\tau_d - \tau_r - \tau_f$ decrease. The switch time τ_s and peak time τ_p (defined in Fig. 2) are found to decrease as $\tau_d - \tau_r - \tau_f$ decreases, see Fig. 8. These variations are explained as follows: As $\tau_d - \tau_r - \tau_f$ becomes less than the switch time (asymptotic value), the duration of the peak amplitude of the driving field is less than the time necessary for the magnetization to traverse the hysteresis loop of maximum squareness. Therefore, the magnetization follows smaller and less square hysteresis loops as the peak-field duration decreases.

Fig. 8 goes here

Fig. 8. Switch Time and Peak Time vs Field Pulse Duration (Ferramic S-1 Material)

For these hysteresis loops of decreasing squareness, the incremental permeabilities at remanence are expected to increase; hence, the dependence on $\tau_d - \tau_r - \tau_f$ shown in Fig. 6 and 7.

Since Eqs. (12) and (13) show μ_Δ and δ to have approximately the same dependence on parameters of the magnetic material, δ is expected to vary with $\tau_d - \tau_r - \tau_f$ as does μ_Δ. Figure 9 shows the predicted dependency of δ on $\tau_d - \tau_r - \tau_f$.

Fig. 9 goes here

Fig. 9. Delta vs Field-Pulse Duration

In Figs. 6 and 7, μ_Δ[rhl] and μ_Δ[rhz] correspond approximately to $\mu_{\Delta -}$ and $\mu_{\Delta +}$, respectively. Because the total pulse sequence is different for μ_Δ[rhl] and μ_Δ[rhz], they are measured at slightly different remanent states which implies a difference in v, the fraction volume of reverse domains in Eq. (12). Since the wVhl signal has a small irreversible part, δ as shown in Fig. 9 is the maximum "delta" occurring in the matrix and should be larger than the theoretical δ obtained in Section II.

Note that the incremental permeabilities at remanence, δ , τ_s, and τ_p all reach their asymptotic values at a field-pulse peak duration $\tau_d - \tau_r - \tau_f$ approximately equal to the asymptotic value of τ_s. This observation is reasonably valid for all $\tau_r < \tau_p$. For slow-rise-time field pulses, the departures of the above parameters from their asymptotic values are less abrupt.

The dependence of the incremental permeability upon the sequence of excitations has been discussed with reference to Figs. 5, 6, and 7. In Fig. 10, the incremental permeabilities $\mu_{\Delta -}$ and $\mu_{\Delta +}$ are plotted versus n, the number of field pulses applied in the demagnetizing direction previous to the measurement. The field amplitudes were $|H_m| = 1.9$ oersteds and $|H_m/2| = 0.96$ oersteds. $\mu_{\Delta -}$ is the completely reversible (for $n > 1$) incremental permeability

Fig. 10 goes here

Fig. 10. Incremental Permeability at Remanence vs Number of Half-Amplitude Demagnetization Field Pulses

for pulses applied in the demagnetizing direction; $\mu^*_{\Delta+}$, which corresponds to μ_Δ[whz], is measured on the first pulse applied in the magnetizing direction after n pulses in the demagnetizing direction and thus has an irreversible part. The incremental permeability for the second pulse in the magnetizing direction is completely reversible and corresponds to $\mu_{\Delta+}$. Note that for n greater than one, $\mu_{\Delta-}$ and $\mu^*_{\Delta+}$ reach equilibrium values.

Figure 11 shows the dependence of $\mu_{\Delta-}$ and $\mu^*_{\Delta+}$ upon the field-pulse amplitude. Only the amplitude of the field pulse for which the measurement is made is varied; thus all measurements are taken on the same square hysteresis loop. The data show that as ΔH increases, the incremental permeability increases. The rate of increase is less than linear and indicates the existence of the second-order term in Eq.(12).

Fig. 11 goes here

Fig. 11. Incremental Permeability at Remanence vs Field-Pulse Amplitude

IV CONCLUSION

The theory of the incremental permeability at remanence as developed in Section II is in reasonable agreement with the experiments reported in Section III. The mechanism of growth of ellipsoidal reverse domains seems to be primarily responsible for the incremental permeability of materials which have large effective anisotropies.

The half-select voltages are shown in Section III to be proportional to $\mu_\Delta dH/dt$; hence, the material-dependent contribution to memory-matrix noise can be reduced by decreasing μ_Δ and δ. According to the theory of Section II, such a decrease can be achieved by a reduction of the fractional volume of reverse domains; this results in an increase in the B_r/B_s ratio, where B_r is the remanence of the maximum squareness loop.

Acknowledgement

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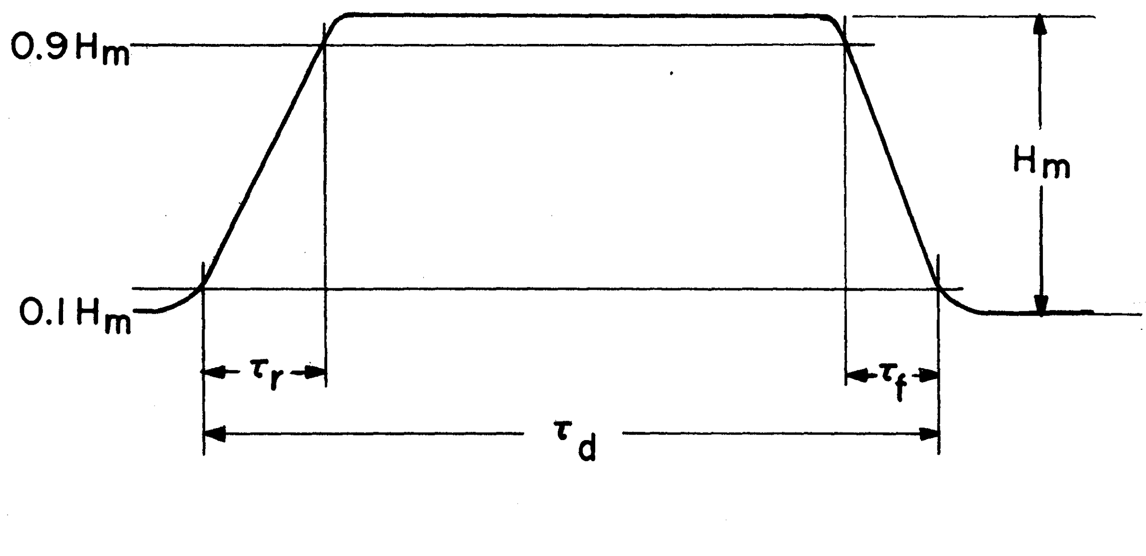
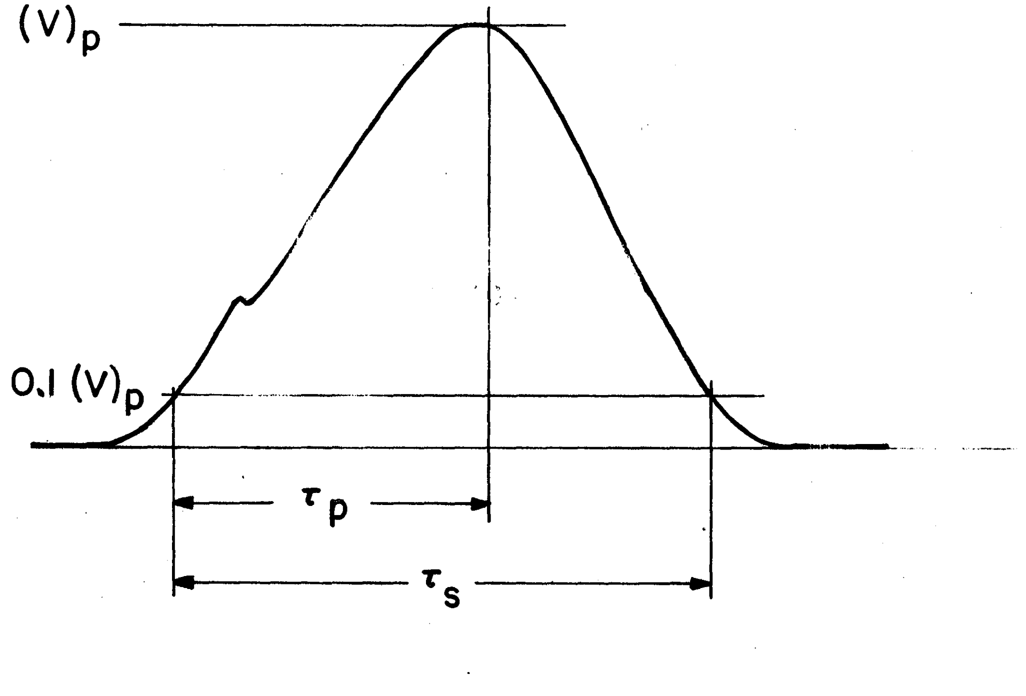
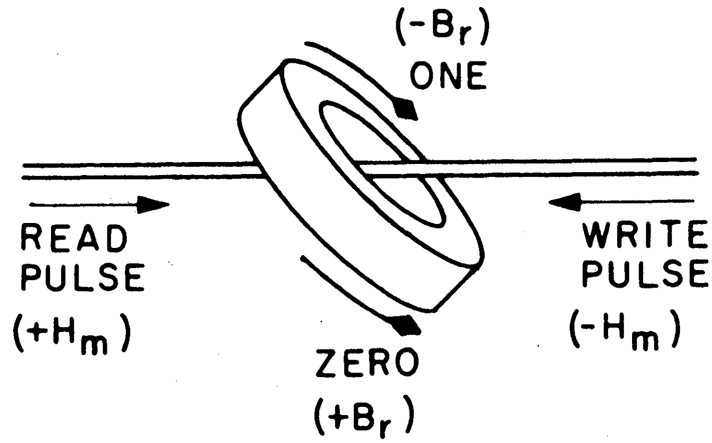


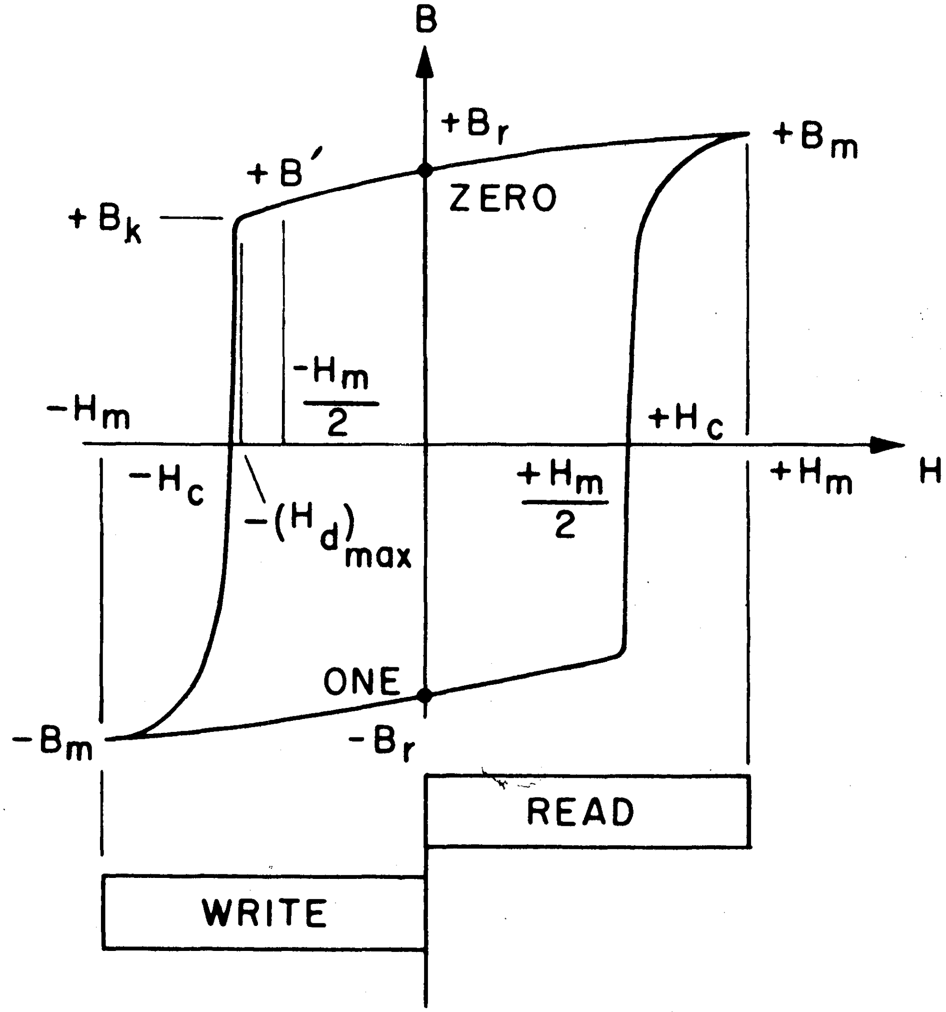
TRAPEZOIDAL FIELD PULSE



CORE OUTPUT VOLTAGE
(FULL SELECTED)

A-62944
F-2842
SN-1110

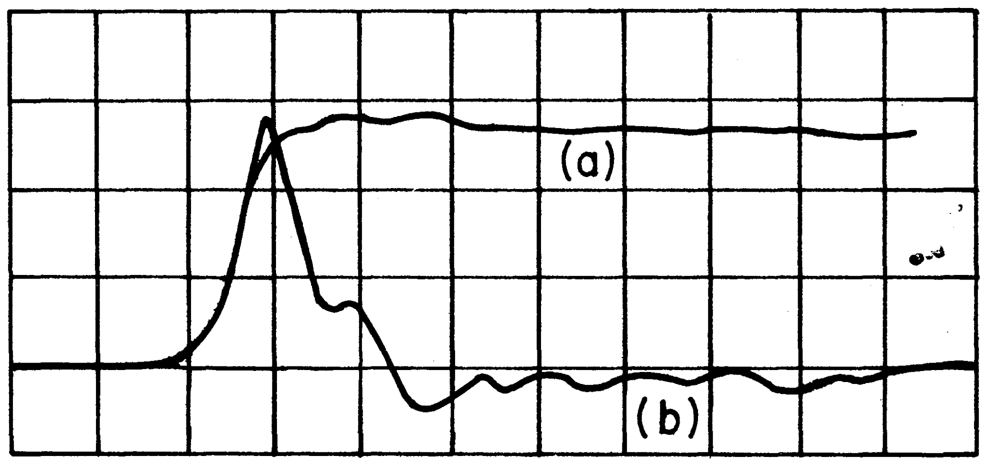




STORAGE OF BINARY INFORMATION IN A MAGNETIC CORE

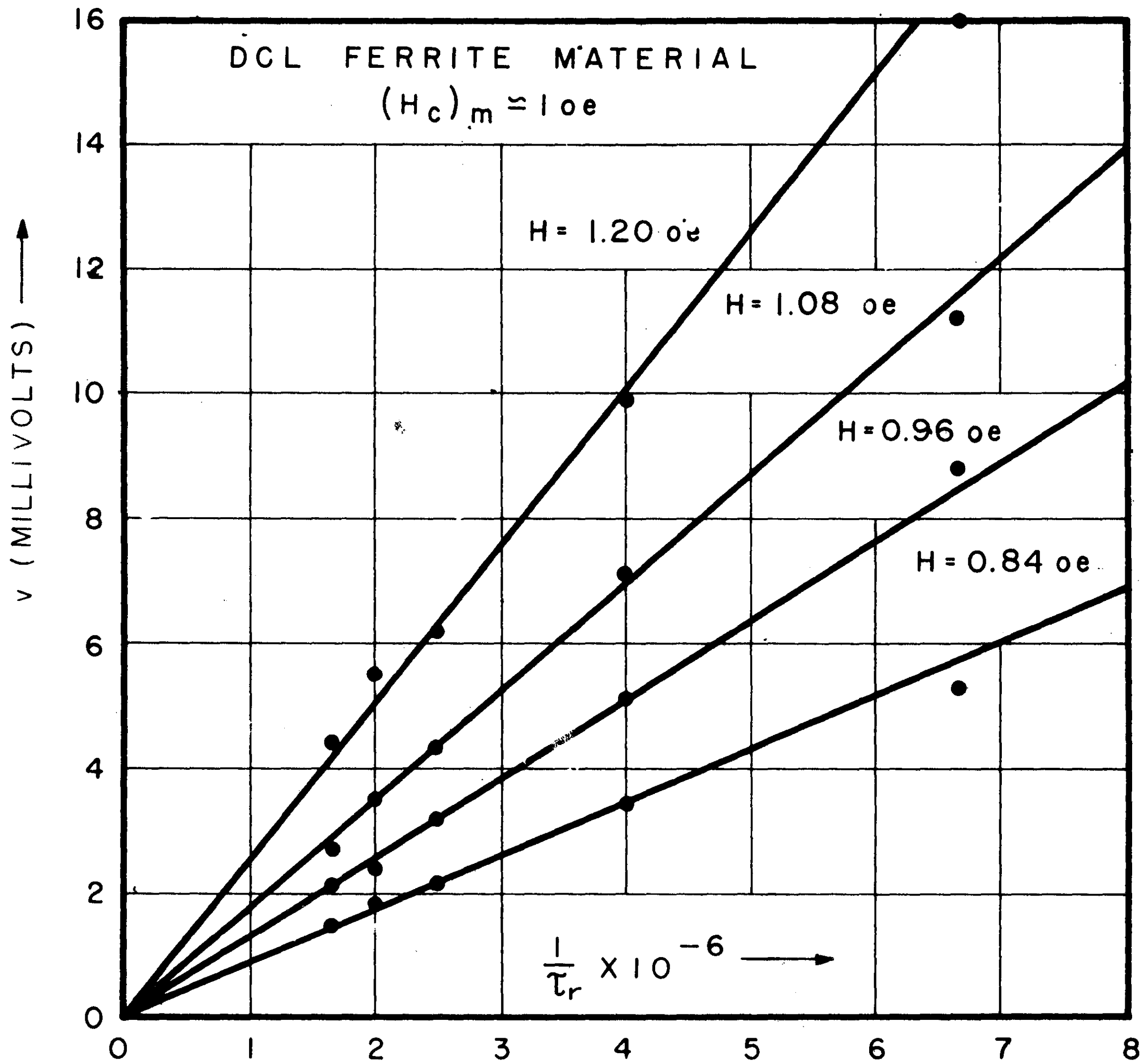
A-63140

A-62828-1
F-2832
SN-1100



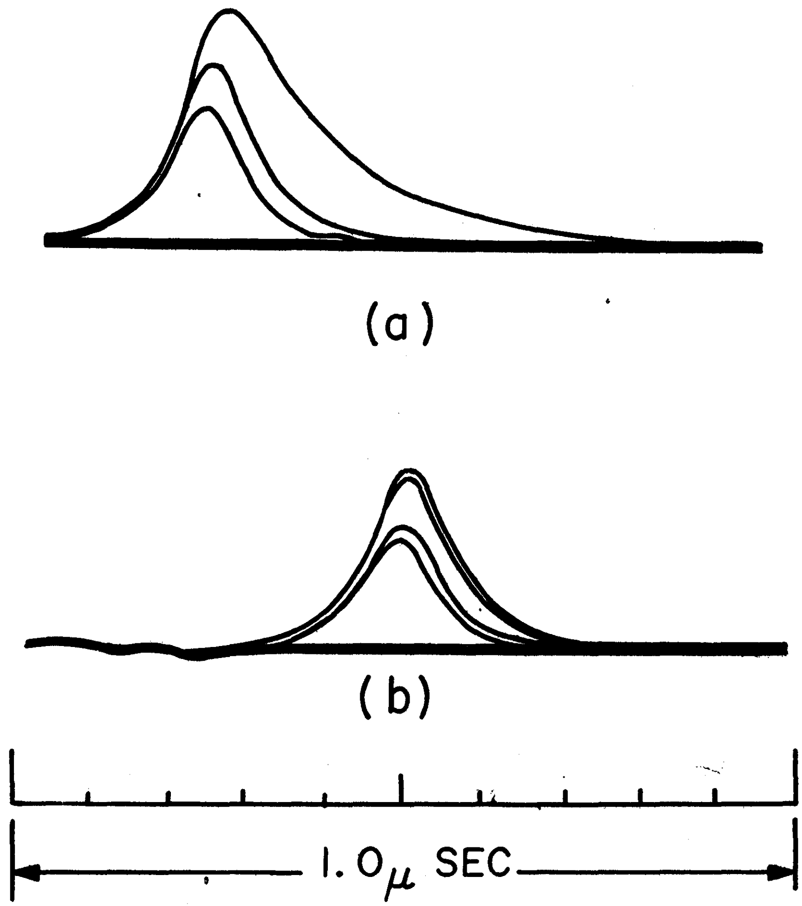
SCALE = 10^{-8} SECOND PER. HOR. DIV.

REVERSIBLE VOLTAGE SIGNAL



REVERSIBLE HALF-SELECT SIGNAL PEAK AMPLITUDE vs FIELD PULSE RISE TIME

FERRAMIC S-1 MATERIAL



FROM SMALLEST TO LARGEST

a) rVhl, wVhl, uVhl

ONE OUTPUTS

b) uVhz, rVhz, wVhz, dVhz

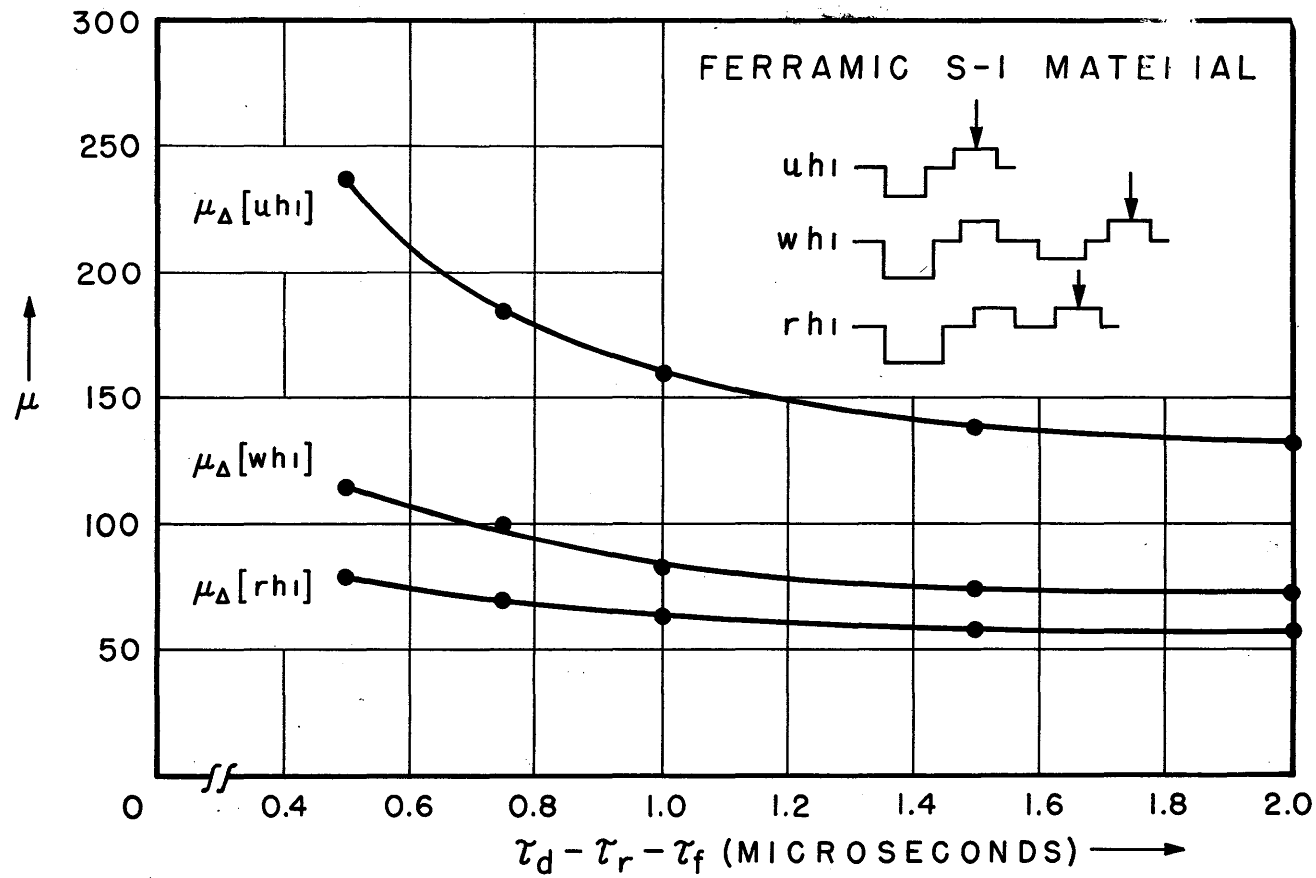
ZERO OUTPUTS

HALF SELECT

(FREEMAN)

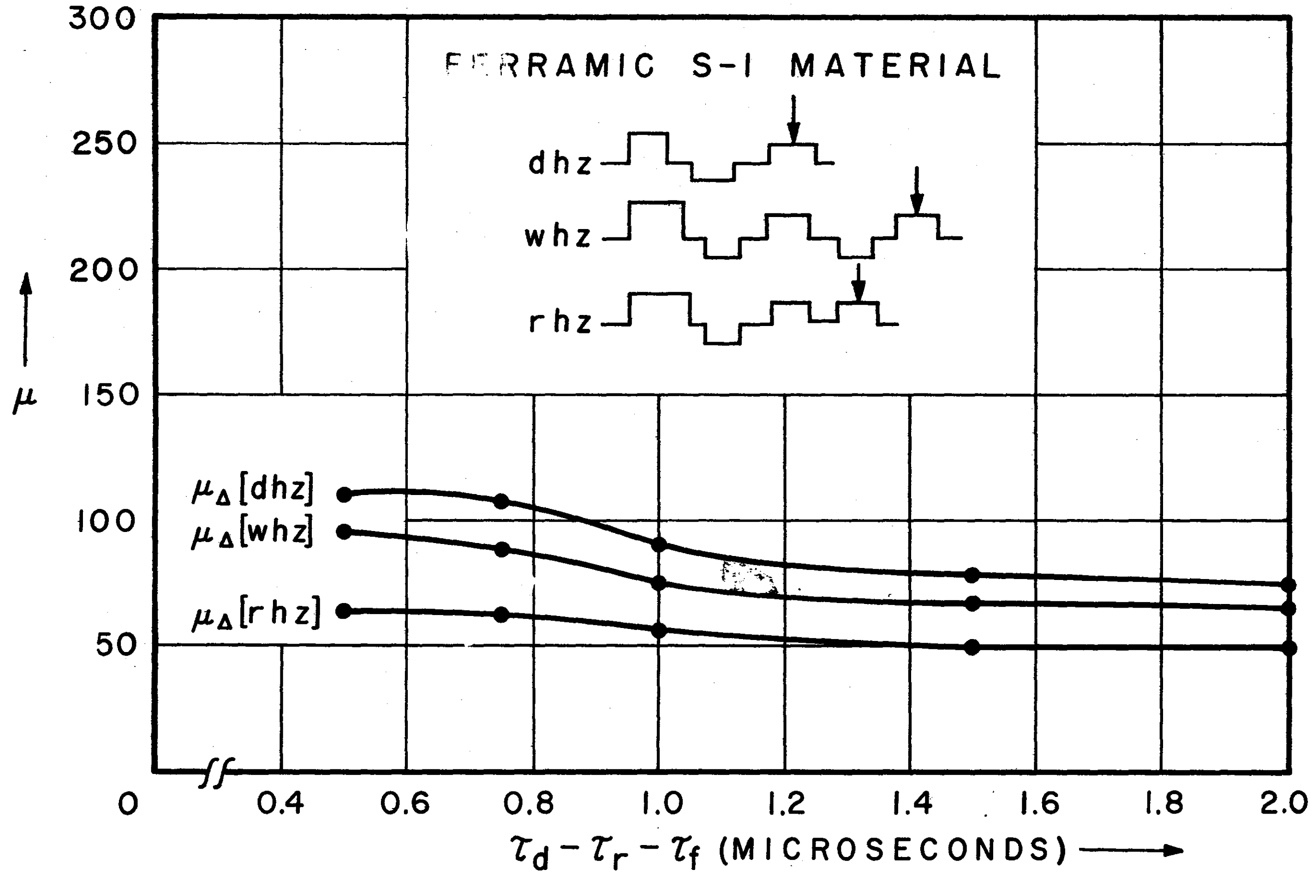
A-63142

B-62938-2
F-2837
SN- 1105
MN



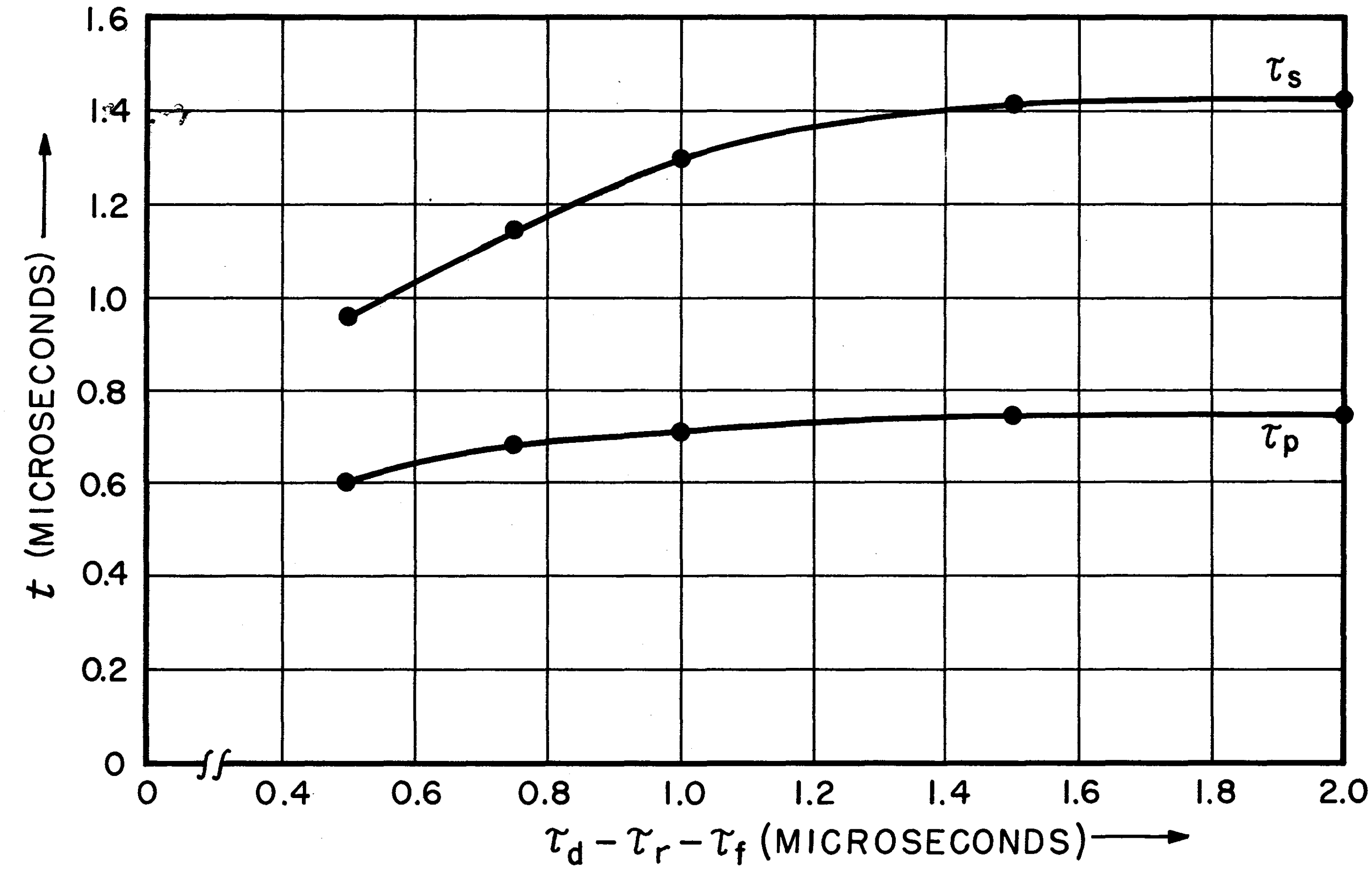
INCREMENTAL PERMEABILITY AT REMANENCE vs FIELD PULSE DURATION

B-62939-2
F-2838
SN-1106
MN



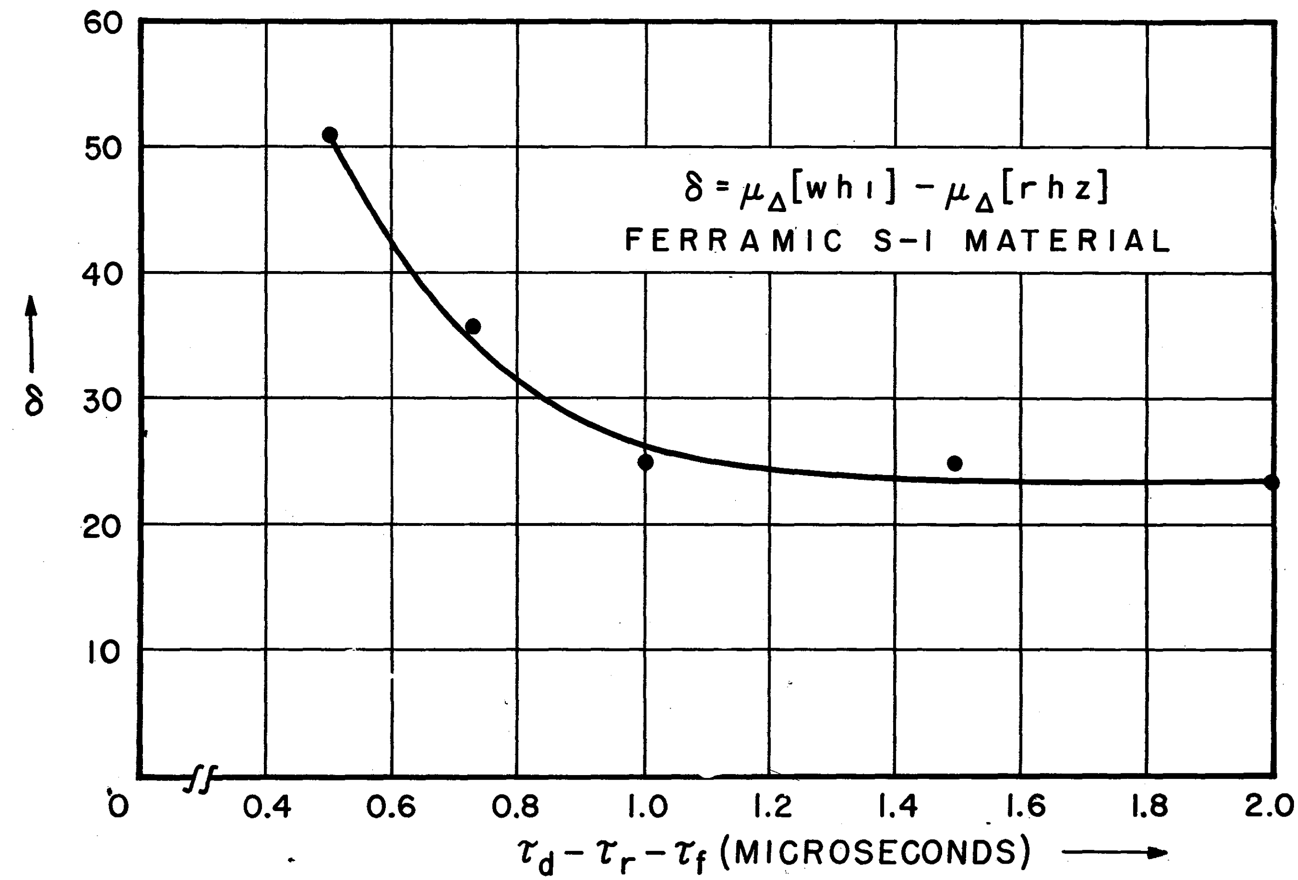
INCREMENTAL PERMEABILITY AT REMANENCE vs FIELD PULSE DURATION

B-62936-1
F-2835
SN-1103



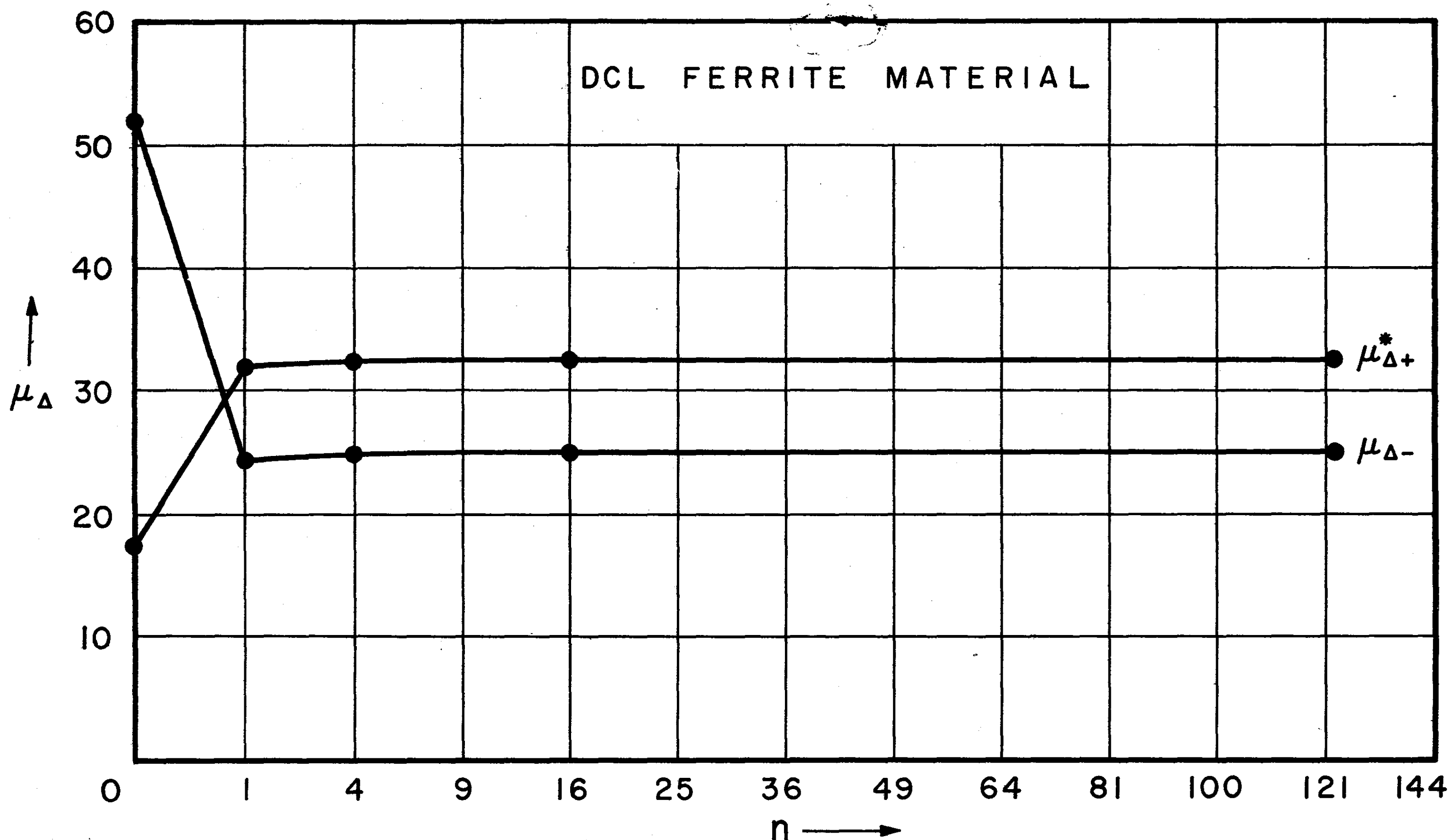
SWITCH TIME AND PEAK TIME vs FIELD PULSE DURATION FERRAMIC S-1 MATERIAL

B-62937-2
F- 2836
SN- 1104
MN



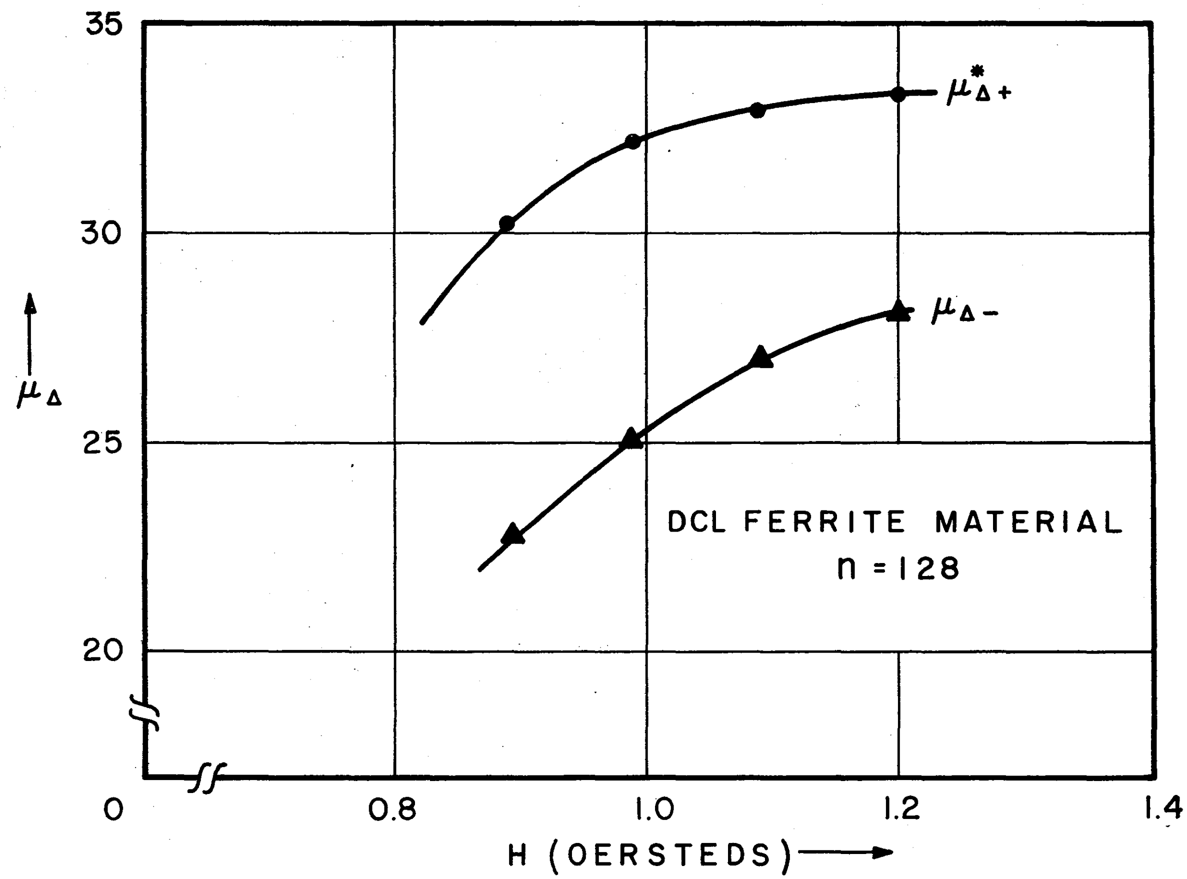
"DELTA" vs FIELD PULSE DURATION

B-62940-2
F-2839
SN-1107
MN



INCREMENTAL PERMEABILITY AT REMANENCE vs NUMBER OF HALF-AMPLITUDE DEMAGNETIZING FIELD PULSES

B-62941-2
F-2840
SN-1108
MN



INCREMENTAL PERMEABILITY AT REMANENCE vs FIELD PULSE AMPLITUDE