The Utilization of Domain-Wall Viscosity in Data-Handling Devices

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THE MAGNETIC INERTIA EFFECTS

Experimental Account

DURING the investigation of the high-speed switching of ¼-mil grain oriented 4-79 Molybdenum Permalloy tape a group of effects were discovered which do not seem to have been previously described in the literature. These effects will be referred to as the magnetic inertia effects. They appear to be associated with the viscosity of the magnetic domain boundaries and can be demonstrated in ferrites as well as in Molybdenum Permalloy. This paper will be concerned with the description and utilization of the effects in 4-79 Molybdenum Permalloy as it is this material which has been chiefly investigated to date. The Magnetic inertia effects can be described under the three following headings.

Nondestructive Read-Out: This effect has been demonstrated in ¼-mil as well as ¾-mil grain oriented tape made of 4-79 Molybdenum Permalloy. It was found that the application of magnetizing pulses much larger than the coercive force did not give rise to permanent changes of magnetization provided that the duration of the pulses was sufficiently short. This effect is demonstrated in Fig. 1 (next page) which shows the waveforms resulting from the application of a continuous train of 0.1 microsecond half sine-wave current pulses through suitable magnetizing windings to a toroid consisting of 5 wraps of ¼-mil material. The coercivity of this material was approximately 0.08 oersted. The peak height of the magnetizing pulses shown in Fig. 1 is 0.63 oersted. This is close to the maximum amplitude of 0.1-microsecond half sine-wave pulses which can be applied to this material without significantly affecting the permanent state of magnetization.

Size Anomaly of Nondestructive Read-Out Signal: The minimum amplitude of 0.1-microsecond pulses required to switch completely the core under discussion was 2.8 oersteds. Waveforms accompanying complete switching are shown in Fig. 2. Comparison with Fig. 1 shows that the reversible magnetization changes occurring during nondestructive read-out consist of a relatively large fraction of the total magnetization change obtainable on completely switching the core. The nondestructive read-out signals are approximately symmetrical about the base line in ¼-mil material and their amplitude is strongly dependent on the state of remanence. In a representative case such as that shown in Fig. 1, the ratio between the peak amplitudes of the “one” and “zero” output signal is of the order of 3:1, and the peak of the voltage pulse associated with the nondestructive read-out in the “one” state is as high as 17 per cent of the voltage pulse associated with complete flux reversal.

A High Field Threshold: In the type of core described above having a coercivity of approximately 0.08 oersted, the maximum amplitude of 0.1-microsecond pulses which do not cause a permanent change of flux is of the order of 0.63 oersted. This is less than ¼ of the pulse height required for complete switching. To use the inertia effects for writing into a random-access memory it would be useful to find some way of applying pulses of at least ¼ the height required for complete switching without destroying the information content of the core. A means of doing this exists. It is found that pulses of more than half the amplitude required for complete switching can be applied without causing a permanent change of state, provided that each pulse is followed by an opposite polarity pulse of similar amplitude. Alternatively a pair of positive pulses can be followed by a pair of negative pulses. The time interval between the pulses can be of arbitrary length. The permissible difference in amplitude is of the order of 7 per cent at 1.8 oersteds, and becomes larger as the pulses become smaller. Output signals resulting from nondestructive read-out of this type are shown in Fig. 3.

The technique of current amplitude coincidence for core selection in conventional memories employs the core coercivity as a threshold mechanism. The switching speed of cores selected in this fashion is limited because the total switching field applied cannot be made greater than twice the coercivity. The results described above indicate the existence of a threshold field much higher than the coercivity.

This makes it possible to use amplitude coincidence for core selection using much larger fields than the coercivity and consequently attaining much higher switching speeds.

Some numerical results which have been abstracted from Figs. 1 to 3 are summarized in Table I, p. 75. It is interesting to compare the flux change associated with complete switching—19-volt millimicroseconds/turn with the complete reversible 2.4 volt millimicroseconds/turn which occurs during nondestructive read-out with pulses in one direction.

The flux change which occurs during the application of a sensing pulse of 1.8 oersteds is shown to be 9.1-volt millimicroseconds/turn. Integration of the waveforms of Fig. 3 shows that approximately 43 per cent of this flux change is elastic, i.e., reversible, and exists only during

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the application of the sensing pulse. The other 57 per cent is inelastic and remains after the termination of the sense pulse. This inelastic flux change can be cancelled out by a pulse which is within 7 per cent of the initial pulse in peak amplitude but in the opposite direction. The fact that the net flux excursion over a whole cycle is zero is proved by the fact that the nondestructive read-out effect is maintained even when positive and negative pulses are applied indefinitely.

Physical Mechanisms

The magnetic inertia effects can be explained at least qualitatively in terms of existing domain theory. Following a discussion of each of the three inertia effects, the ideas presented will be examined in the light of recent results obtained by other workers from the study of thin films. It will be seen that several of the mechanisms used to account for the magnetic inertia effects in grain oriented tape have been shown to be of importance in the switching behavior of thin films.

Nondestructive Read-Out: The fact that it is possible to apply an indefinitely large number of very short mag...

Fig. 1—Nondestructive read-out in 1⁄4-mil 4-79 Molybdenum Permalloy.
Core construction: 5 wraps of 1⁄4-mil tape, 1⁄2 inch wide, ceramic bobbin, 1⁄2 inch od.
(a) Voltage across 5-turn sense winding: core at negative remanence.
(b) Voltage across 5-turn sense winding: core at positive remanence.
(c) Negative magnetizing pulse through 5-turn drive winding. Rep. rate: 2 kc.

Fig. 2—Complete switching of 1⁄4-mil 4-79 Molybdenum Permalloy.
Core construction: As in Fig. 1.
(a) Voltage signal across 5-turn sense winding.
(b) Set pulse through 5-turn winding. (Minimum amplitude required for complete switching.)
(c) Reset pulse through 5-turn winding.

Fig. 3—Nondestructive read-out in 1⁄4-mil 4-79 Molybdenum Permalloy using symmetrical 0.1-microsecond half sine wave pulses of 1.8-oersteds peak amplitude.
Core construction: as in Fig. 1.
(a) Voltage signal across 5-turn sense winding. Core at positive remanence.
(b) Voltage signal across 5-turn sense winding. Core at negative remanence.
Netzuring pulses considerably exceeding the coercive force of 1/4-mil or 1/2-mil grain oriented Molybdenum Permalloy tape without causing a cumulative change of the state of magnetization can be explained in terms of the domain-wall viscosity and surface tension.

It seems likely that the existing domain walls are moved over such a relatively small distance during the application of the nondestructive read-out pulse that they fall back to their original position after the cessation of the pulse. The assumption that the movement of domain walls over small enough distances is not accompanied by irreversible magnetization changes is supported by the well known fact that the application of sufficiently weak fields of arbitrary duration to conventional magnetic materials will not result in irreversible magnetization changes. This is true even in portions of the hysteresis loop where most of the magnetization change takes place by domain-wall motion.

It can be calculated that the distance moved by a domain wall under the influence of the maximum 0.1-microsecond pulse of 0.63 oersted which gives nondestructive read-out in the case of 1/4-mil permalloy is approximately five times its own thickness. This result indicates that the mechanism assumed for the nondestructive read-out effect is plausible, since studies of the Barkhausen effect in related materials indicate that irreversible changes only become important as a domain wall moves through a distance which is between one and ten times its own thickness.1

The nondestructive read-out signal from 1/4-mil material shown in Fig. 1(a) shows a slight exponential "tail." This feature is accentuated in 1/2-mil material and is probably associated with eddy currents. The calculated decay time constant of the eddy current field agrees to within an order of magnitude with the experimentally observed values. The value of permeability used in this calculation is 4000 cgs units, a value which corresponds to the flux changes observed during nondestructive read-out.

It has been pointed out that nondestructive read-out is possible with pulses as large as half the amplitude required to switch the core completely, provided that each positive pulse or pair of pulses is followed at an arbitrarily long time interval by an equal number of negative ones. In this case the application of the first pulse tending to switch the material results in a degree of irreversible wall movement. It is clear that the reabsorption pulse moves the domain walls to a position sufficiently close to their remanence location for no cumulative changes to occur under the influence of repeated pairs of pulses.

Size Anomaly of Nondestructive Read-Out Signal: Having shown that nondestructive read-out using short pulses is possible because the domain walls move over a relatively short distance, it is necessary to explain why the reversible changes accompanying nondestructive read-out with pulses in one direction are as large as 12 per cent of the major loop magnetization change. Moreover, the reversible component of the flux change associated with nondestructive read-out using symmetrical excitation is as high as 19 per cent of the flux change associated with complete switching. These results cannot be accounted for on the basis of domain wall movement alone.

The major contribution to the reversible magnetization changes during nondestructive read-out by short pulses is believed to be that due to spin rotation; i.e., the coherent rotation of the magnetization of a whole domain over a small angle.

This is a process which can be represented by a very simple mathematical model which has been studied rather exhaustively because it is of considerable importance in the operation of small particle permanent magnets.4 Magnetization by rotation is a process which is known to be reversible provided the rotation is over an angle less than a critical value. It is difficult to calculate the value of applied fields at which spin rotation becomes significant, because the magnetic anisotropy constant for Molybdenum Permalloy is rather uncertain. It can however be measured experimentally by applying a field at right angles to the easy direction of magnetization and turns out to be less than 2 oersteds. This is in agreement with the fields of the order of


1 oersted which are found to give nondestructive read-out. Further confirmatory evidence is provided by the work of Conger who has shown that magnetization reversal takes place by rotation rather than wall movement in thin films of 80-20 nickel-iron for applied fields larger than a few oersteds. A further contribution to the reversible magnetization changes occurring during the nondestructive read-out pulse may be due to the creation of reversal domains around imperfections in the material such as grain boundaries. These would be reabsorbed after the termination of the pulse.

The High Field Threshold: It has been stated that the magnetization changes due to 0.1-microsecond pulses have been shown to be mainly reversible below 1.8 oersteds and completely irreversible above 2.8 oersteds. The existence of this second threshold for core switching is a further indication that spin rotation rather than wall movement is taking place since magnetization by wall movement has a threshold at fields of the order of the coercivity which in this case is about 0.1 oersted.

The fact that spontaneous rotation throughout the material occurs when the second threshold field between 1.8 and 2.8 oersteds is exceeded indicates that spin rotation may occur at the lower fields used for nondestructive read-out, in areas surrounding imperfections in the material such as grain boundaries. This type of spin rotation around imperfections could lead to the formation of the transient reversal domains mentioned in connection with the nondestructive read-out effect.

The results of the above section can be summarized as follows.

The phenomenon of nondestructive read-out associated with the application of very short intense magnetizing pulses is attributed to the fact that existing domain walls are moved over distances within their "elastic limit." Any extra domains created during a nondestructive read-out pulse are reabsorbed after its termination.

The reversible magnetization change occurring during nondestructive read-out is ascribed to the reversible movement of existing domain walls and to temporary coherent rotation of the direction of magnetization in areas large compared to the wall thickness. The creation of temporary reversal domains around imperfections in the material may also make a contribution.

The second threshold effect occurs at fields which have been shown to cause magnetization reversal by rotation in films and is therefore identified as corresponding to the onset of irreversible rotation effects.

**Review of Related Work**

Many nondestructive read-out techniques have been described which involve the use of cores with special geometries. A nondestructive read-out technique which uses cores having a conventional geometry has been described by Widrow. This makes use of the sense of the curvature of the hysteresis loop near remanence. The output obtained is relatively small in amplitude.

Haynes showed several years ago that the application of microsecond pulses larger than the coercivity to metal tape cores having a switching time of the order of milliseconds produces a reversible flux change whose duration is dependent on the state of remanence. The switching of the cores investigated was subject to heavy eddy current damping and the nondestructive read-out phenomena observed were interpreted in this light.

Eddy-current damping does not play an important part in the materials reported on in the present paper. This makes it possible to demonstrate and utilize the dynamic properties of the domain walls and spins to a greater extent than would otherwise be possible.

**Applications**

Some of the possible data-handling applications of the two types of nondestructive read-out, and of the second threshold effect will now be briefly described.

**Magnetic Indicator**

The order of magnitude of the nondestructive read-out obtainable with the high excitation possible when symmetrical drive is used is demonstrated by the device shown in Fig. 4. In this deliberately simple circuit the nondestructive read-out signals from a conventional tape core are rectified and used to operate a forward biased neon bulb. The status of the neon indicator shows whether the core being sensed is in a state of positive or negative remanence. In a practical case the discrimination of the output signal could be increased by the use of a bucking core. Alternatively the diode could be replaced with a transistor used as a combined rectifier and amplifier.

**Magnetic Switch**

Nondestructive read-out has been applied to a channel-selecting magnetic switch which embodies the current-steering technique proposed by Karnaugh. The

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Fig. 4—Nondestructive read-out used to operate neon indicator.

principle of the circuit is illustrated in Fig. 5. Each core is provided with set and reset windings which ensure that only one core is set at a time. These are not shown in the figure.

Fig. 5—Application of nondestructive read-out to current steering switch.

Nondestructive read-out current pulses are applied through R1 in such a direction as to tend to reset the cores. The output windings of the unselected cores produce voltage pulses similar to those shown in Fig. 1(b). The selected core produces a voltage output similar to that shown in Fig. 1(a). The initial output pulse from this core serves to bias off the diodes associated with the unselected cores and "steers" the clock pulse through its own output winding into the selected load. In the circuit shown the clock pulse is produced by delaying and compressing the read-out pulse. Following the termination of the drive pulse the selected core recovers to its "set" state in a fraction of a microsecond. A further read-out pulse can then be applied.

The arrangement of the diodes ensures that no current can flow through any of the loads in the absence of a clock pulse, i.e., during the set and reset of the cores or during their recovery from read-out.

In this circuit the provision of bucking cores in series with each switch core is not required since the operation of the switch ensures that all the sensing current is diverted through the output winding exhibiting the largest voltage pulse. Delay-line effects must however be carefully controlled in the design.

Shift Register with Permanent Output Indication

A one-core-per-bit shift register\textsuperscript{13} which is well suited to nondestructive read-out operation is shown in Fig. 6. Point P is normally held at a positive potential. The application of a current pulse through the advance current winding resets all the cores which were previously set, and in doing so, charges the associated intermediate storage capacitors positive. Immediately after the termination of the advance pulse, point P is pulsed negative, thus discharging any of the intermediate storage capacitors which were charged positive in the previous part of the cycle. In discharging a particular capacitor, the subsequent core is set to a state of positive remanence. In Fig. 6 the shift register has been modified to provide a permanent indication of its contents. A sensing-current source has been attached to the advance winding as shown and each intermediate storage capacitor is connected to a neon indicator through a large resistor R. The other end of the neon indicators is taken to a negative potential so as to minimize the inverse voltage required across the diodes of the circuit.

Between the application of advance pulses the sense pulses which can remain "on" continuously, charge the capacitors which follow cores which are in a "set" state to a positive potential and excite the associated neon. A continuous indication of the contents of the shift register is thereby provided. If the neon indicators are replaced by transistor or vacuum-tube amplifiers as indicated in the diagram, other computing or indicating devices can be driven.

It is noteworthy that the shift register conversion proposed, to provide a continuous indication of its content, is achieved with a minimum of added components—one resistor and neon indicator per stage, one current source of pulses and an extra bias supply for the neon indicators. In particular, no extra windings are required.

\textsuperscript{13} V. L. Newhouse and N. S. Prywes, "High-speed shift registers using one core per bit," IRE Trans., vol. EC-5, pp. 114–120; September, 1956.
Random-Access Memories

Perhaps the most important applications of the magnetic inertia effects lie in the field of data storage.

The use of nondestructive read-out for random access memories of the conventional type is illustrated schematically in Fig. 7. A parallel memory is represented where all the digits of a particular word are read in simultaneously and sensed simultaneously. The read-in process can take place by means of coincident current techniques. A word line corresponding to a particular address is selected by means of the word line selector switch. This switch may utilize vacuum tubes and diodes, transistors, etc. To enter a particular word into the store, the selected word line is pulsed and those digit selection lines corresponding to “ones” in the word are pulsed simultaneously in the well-known manner. To clear a given address the corresponding word line is pulsed with an opposite polarity current in such a way as to reset all the cores in that line.

To sense a given address in a nondestructive manner, the corresponding address line is selected by the word selection switch and is pulsed with a limited amplitude pulse of very short duration. Each of the cores on the pulsed line will emit a voltage pulse on the corresponding digit-selection line whose amplitude will be a function of its remanent state. These pulses are sensed by the amplifiers. It should be noted that this well-known configuration has the constructional advantage that the digit-selection lines are used for sensing also. Furthermore the sensing line passing through each core being sensed does not have other half-activated cores in series with it, producing disturbing signals. The signal-noise ratio of the nondestructive sensing effect does not therefore have to be very high in this application.

The advantages of using nondestructive read-out in a random access memory are as follows:

1) Regeneration is unnecessary. This simplifies the logic circuitry required.

2) The fact that a memory interrogation does not have to be followed by a regeneration cycle decreases the effective access time of the memory by a factor whose value depends on the proportion of memory interrogation to memory entries. In the extreme case where all the memory references are interrogations the minimum time between interrogations need be no longer than the sum of the length of the interrogation pulse and the time required to refer to a new address in the memory.

To enter information into a memory by means of the magnetic inertia effects, several modes of operation are possible. One of the most interesting has been named the pulse interlace method and operates as follows.

To switch a particular core in a two-dimensional matrix without disturbing any of the others, anticoincident current pulse trains are sent along the appropriate row and column as shown in Fig. 8 (a). The length and amplitude of each pulse and the number of pulses in each train depend on the material used for the storage elements. In the case of the cores described above, the pulse trains shown in Fig. 8 (b) with 1.4 oersted pulses 0.1 microsecond in length are sufficient.

These waveforms are for use in a parallel digit memory of the type shown in Fig. 7. Pulse no. 1 of the row pulse train is used to clear the selected address and is made large enough to perform this purpose even in the absence of column pulse no. 1. Column pulse no. 1 is applied only to those column wires passing through cores which are to be “set” during the read-in portion of the cycle. Its purpose is to prevent column pulse no. 2 from initiating cumulative magnetization changes in cores on unaddressed rows.
The application of row excitation pulses 2 and 3 to a row of reset cores results in a small amount of undesired magnetization change in those cores which have not been switched by the application of a column excitation pulse in the time interval between the two row pulses. This feature is of no consequence in this type of memory structure since every pair of row set pulses is always preceded by a "clear" pulse.

In the pulse interface method the selected core is excited continuously whereas the nonselected cores are excited discontinuously or not at all. The process of magnetization reversal in the selected core must therefore take place by domain-wall movement.

A method of reversing the magnetization by means of spin rotation makes use of the second threshold effect. To switch a core in a two-dimensional matrix in this way, conventional amplitude coincidence techniques may be used provided that each positive pulse on any one line passing through cores which are not to be switched, is followed or preceded by a negative pulse and vice versa. (These pulses are of half the switching amplitude.) Such a cycle is used in the experimental memory described below.

By making use of the second threshold effect relatively high speeds of operation are possible. Using the type of core described above, it is possible to write into any one core of a matrix by means of two time-coincident 1.4 oersteds 0.1-microsecond pulses preceded by two identical coincident "predisturb" pulses of opposite polarity. The total writing time is approximately ten times as short as the switching time required for the same material using conventional coincident current techniques. The nondestructive read-out procedure which can be used in memories of this type take 0.1 microsecond or less, and is thus at least twenty times as short as the conventional destructive read-out procedure if this has to be followed by re-entry of the sensed information.

**Experimental Model of an Inertia Memory**

A very small transistorized random-access memory has been built to investigate the use of the second threshold effect for entry of information and of nondestructive read-out for sensing.

The cores described in connection with Fig. 1 were used as the storage element and were arranged in a twodimensional matrix. The associated control logic is shown in Fig. 9, and enabled the memory locations to be addressed individually for writing, or in sequence for nondestructive read-out.

The core-matrix line-selection circuits use base driven, grounded emitter transistor switches whose collectors are connected in series with the matrix lines through diodes (not shown in the figure). Before pulsing a specific line the emitter base junction of the corresponding switch transistor is forward biased. The application of the matrix-drive pulse thus finds this transistor in a "presaturated" state. This configuration has two advantages.

1) The transistor is not required to undergo a change of state during the application of the drive pulse.
2) The collector base dissipation is a minimum. (Most of the dissipation occurs in the emitter basejunction.)

In this way, conventional rf transistors (2N140) are able to switch millimicrosecond pulses of several hundred milliamps at high repetition rates. In the present instance these pulses were generated from commercial vacuum tube equipment.

Writing a "one" into an individual core was accomplished by passing a 0.1-microsecond pulse corresponding to 1.4 oersteds along one of the pair of vertical lines passing through that core as selected by the corresponding transistor switch. Simultaneously, an identical pulse was passed through one of the pair of horizontal lines intersecting the selected core. These coincident pulses had the effect of entering a "zero" into the selected core and of applying a disturb action in the "zero" direction to the other cores on the selected vertical and horizontal lines. To complete the entry of a "one" into the selected core, current pulses were sent along the two previously excited lines. These switched the selected core into the "one" state and cancelled out the disturbance applied to the other cores on the selected vertical and horizontal lines. To enter a "zero" into an individual location, the order of exciting the selected lines was simply reversed.

By setting the address counter and making use of the single cycle facilities of the control equipment, it was verified that a "one" or a "zero" could be entered into
any memory location in a single cycle. It was also established that the continuous entry of "ones" or "zeros" into any position of the memory did not disturb the information in other positions. The contents of the memory could be observed on the column lines by cycling the address counters continuously, while applying nondestructive current pulses corresponding to 0.4 oersted to the rows of the matrix.

It is of interest to compare the inertia memory with the evaporated film memory described by Pohm and Rubens. In this memory the elements are switched by the application of two time-coincident field pulses with the resultant field directed at an angle to the easy direction of magnetization. This produces the effect of a transverse as well as of an antiparallel field on the elements being switched. The switching times reported for the evaporated film memory are of the order of 0.5 microsecond. Destructive read-out is used and the sense signals are of the order of 4 millivolts. Since the magnetization in the partially selected elements undergoes reversible rotation, it would appear that nondestructive read-out techniques can be used in a film memory with a corresponding sacrifice in signal strength.

CONCLUSION

The emphasis in the work done to date has been on the applications of the magnetic inertia effects rather than on a very detailed examination of the effects themselves. An experimental and theoretical study of the wall viscosity should however lead to results of importance to the theory of switching at high fields and may reveal further applications. For example the use of tape-wound toroids where the easy axis of the tape makes an angle with the plane of the toroid should lead to greater speeds of switching for given applied fields at the expense of loss in the effective squareness of the hysteresis loop.

Wall-viscosity effects have been looked for in ferroelectric materials but have not yet been demonstrated in the samples available. Further investigation may reveal their presence.

The construction of memories of large size will necessitate the investigation of techniques for applying the inertia effects to three-dimensional core structures or alternatively to two-dimensional memory arrays driven by magnetic switches.

In the future we hope to be able to present material describing techniques for making use of nondestructive read-out in two-dimensional matrices rather than in one-dimensional matrices as described above.

The work described has been concerned with the use of the magnetic inertia effects in digital devices only. It seems likely however that applications will reveal themselves in allied fields such as that of analog computation.

ACKNOWLEDGMENT

I would like to acknowledge the contributions of W. L. McMillan who played an important part in the work described in this paper and in the design and construction of the two-dimensional memory.

Discussion

G. H. Smith (Autonetics): Would you discuss, briefly, magnetic inertia effects in ferrite cores? Does your research indicate that ferrite cores are practical in the type of memory you described?

Dr. Newhouse: We started work on ferrites after this paper was submitted, and the reason why we concentrated on the metal type cores in the paper is because the switching mechanisms in the metal tapes are similar, and very well known, as compared to the switching mechanisms in ferrites. So it is of more physical interest to concentrate on the metal tape cores. However, it turns out that one can demonstrate all of these effects with pulses on the order of 50 microseconds, particularly the nondestructive read-out effect in conventional square-loop ferrite cores. And the ferrite material in which this has been demonstrated is a material that corresponds closely to the S-1 material, the core material which has been used in most high-speed core memories. The nondestructive read-out effects are, if anything, more pronounced in ferrites than they are in metals. The pulse inhibit effects can also be demonstrated in ferrites, with pulses which are about half the width of the pulses which were used for these metal cores. This, of course, does give a 20 to 1 reduction in cost, from the user's point of view. Also the nondestructive read-out phenomenon can be demonstrated in the aperture ferrite plates.

R. J. Pfaff (IBM): How is a "1" output differentiated from a "0"?

Dr. Newhouse: As shown in Fig. 1 the "1" output is about three times as high as the zero output. With some integration the differences can be made four to one; also these pulses are very constant from one core to the next. As an example, we found that in that experimental memory, we used quarter mil cores by mistake, and we discovered this quite a long time after the memory had been made in the operational.

M. Eisenberg (Thermo Materials, Inc.): How can magnetic domain wall viscosity be defined quantitatively? What would be the effect of temperature on that viscosity?

Dr. Newhouse: It is known that the switching speed of cores varies inversely with the pulse time, so you can draw a straight line by drawing switching times against the applied field. The slope of this line may be expressed in units of centimeters seconds per oersted. And in these practical cases the rough figure of the speed of wall movement is 1000 centimeters per second per oersted. How this has been effected by temperature has been quite carefully investigated by Mena Goodnoff, in a paper, some years ago, in the Journal of Applied Physics.