Digital Computer Laboratory
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SUBJECT: MAGNETIC MATERIALS FOR HIGH-SPEED PULSE CIRCUITS
(Presented at A.I.E.E. Winter General Meeting, New York, January, 1953.)

To: Jay W. Forrester

From: David R. Brown

Date: February 27, 1953

Abstract: Magnetic materials are attractive for digital computer systems and other large pulse-circuit systems because they promise to be stable and trouble free. Ultra-thin molybdenum-permalloy cores and ferrite cores possessing rectangular hysteresis loops have short switching times suitable for high-speed circuits. An important application is a large-capacity coincident-current memory in which the applied field cannot exceed the coercivity by more than 100 percent. Under these conditions, ferrites with large coercivity (1.5 oersteds) switch in one microsecond but metal cores or ferrite cores with small coercivity (0.1 oersted) switch in ten microseconds. The same basic factors are believed to be important in determining the switching time in either material.

This paper is intended as a progress report on the development of ferromagnetic materials for use in high-speed digital computers.

For digital-computer application, or pulse-circuit applications in general, we are interested in components which display a marked non-linearity. This has lead to an effort to develop magnetic materials possessing rectangular hysteresis loops.

The reason magnetic materials are so attractive for digital-computer applications, is that they promise to be very stable and trouble free in operation.

Some of the magnetic cores now being investigated at the Digital Computer Laboratory of M.I.T. are illustrated in Figure 1. The top row illustrates ferrite cores, the smallest being 3/32 of an inch in diameter and the largest approximately 2 inches in diameter. These ferrite cores are polycrystalline ceramics and have a resistivity of the order of 10^7 ohm-centimeters. The saturation flux density is approximately 1800 gauss, the coercivity 1.5 oersteds, and the B_r/B_s ratio is approximately 0.9. The bottom row illustrates some magnetic cores made of 4-79 molybdenum permalloy, cold rolled to thicknesses of 1/4 mil and 1/8 mil. The ribbon is 1/8 of an inch wide and is wrapped on a nonmagnetic ceramic bobbin before it is annealed. This material has a resistivity of approximately 5×10^{-5} ohm-centimeters, a saturation flux density of 8700 gauss, a coercivity of 0.1 oersteds, and a B_r/B_s ratio of 0.9.

One very important application makes use of magnetic cores for the storage of binary information in a large-capacity arbitrary-access high-speed memory. The storage of binary information in a magnetic core having a rectangular hysteresis loop is illustrated in Figure 2. The positive remanence point, corresponding to flux in the clockwise direction, is defined as the ONE state and the negative remanence point, flux in the counter-clockwise direction, is defined as the ZERO state. Notice that if the current I_m is applied in the proper direction, the state of the core can be changed. Note also, however, that if the current $I_m/2$ is applied in either direction, the state of the core will remain unchanged, whether ZERO or ONE initially.

Figure 3 shows how cores having the above characteristics are used in the coincident-current memory. The illustration shows an array having only two vertical elements and two horizontal elements. An array useful for a digital computer would have many such elements, possibly 32 or 64. Notice that the number of storage cells is equal to the square of the number of vertical or horizontal selection elements. (The selection system is extremely important for digital computer memories for the number of storage cells in an array must measure in the thousands. An important advantage of the coincident-current memory is the simplification of the selection system.) Suppose that all the cores in the array were in the ZERO state. Simultaneous current pulses applied to one of the vertical elements and one of the horizontal elements as shown would change the state of the selected core at the intersection of these elements from the ZERO to the ONE state, no other cores in the array would be effected. In this manner, a selected core may have a ONE "written" into it.

Figure 4 shows a photograph of an actual array illustrating the extreme simplicity of the construction. The fine wire shown in this slide threads through every core in the array and has induced on it the voltage of the selected core during the read operation. Reading is accomplished by pulsing the selected elements of the array in the opposite direction from that used for writing. If the selected core holds a ONE, there is a large change in flux in the selected core. If it holds a ZERO, the flux change is very small.

Figure 5 shows the voltages on the output winding, depending upon whether the selected core holds a ONE or a ZERO. The waveforms shown are for ferrite cores. Notice that the total switching time is approximately 1 microsecond.

The basic factors determining rectangularity of the hysteresis loop are not thoroughly understood. Rectangular hysteresis loops have been observed by H. J. Williams and others in closed frames cut from single crystals so that the axes of the frames are parallel to the principal crystal axes. In these cases, very simple domain patterns are observed. Rectangular hysteresis loops have also been observed in certain crystal-oriented or grain-oriented magnetic alloys and magnetic metals under tension. More recently, rectangular hysteresis loops have been observed in polycrystalline ferrite rings when the rings were placed under compression by means of an inward radial pressure on the outside diameter of the ring. In this case, the internal forces are believed to set up an easy direction of magnetization which accounts for the rectangular hysteresis loop. In the case of ferrites which possess rectangular hysteresis loops, even with no externally applied pressure, the rectangularity may be due to residual mechanical stresses which have been fired into the piece.

Figure 6 shows a family of hysteresis loops of the General Ceramics' body MF-1118. These characteristics are observed after the piece has been fired with no further treatment necessary. Notice that for coincident-current memory application the outside or saturation loop cannot be used. One of the inside loops will be that traversed during operation of the memory. The reason for this is that the current I_m must be sufficient to switch the core, but the current $I_m/2$ must not switch.

The voltage observed on an output winding of a core switched in this manner, that is, by a current which produces a field of the same order of magnitude as the coercivity of the material, is very interesting. Figure 7 shows several switching waveforms. These represent the $d\Phi/dt$ or voltage response as a function of time, when a step function of current is applied to the core. As the amplitude of the current increases, the switching time decreases. The peculiar "double peak" is observed for both molybdenum-permalloy and ferrite cores. In the case of molybdenum-permalloy cores, for satisfactory coincident-current memory application, the minimum switching time is approximately ten microseconds. In the case of ferrite cores, the minimum switching time is the order of 1 microsecond. This is not the relationship one would expect if eddy currents were limiting the switching time, since the resistivities of the two materials differ by a factor of 10^{12}. Recent experiments indicate that when rectangular-loop ferrites are made with coercivities of less than one and a half oersteds, the switching time goes up as the coercivity goes down. In the case of one material, prepared by Dr. E. Albers-Schoenberg of the General Ceramics and Steatite Corp., having a coercivity half that of MF-1118, the switching time was found to be twice as long. In the case of the stressed nickel-zinc ferrite prepared by Mr. H. J. Williams of the Bell Telephone Laboratories, the coercivity of the material was approximately the same as that obtained in the molybdenum permalloy and the switching waveforms were observed to be practically the same as that observed in the molybdenum permalloy. This suggests that the same factors are important in the switching mechanism of both molybdenum permalloy and ferrites.

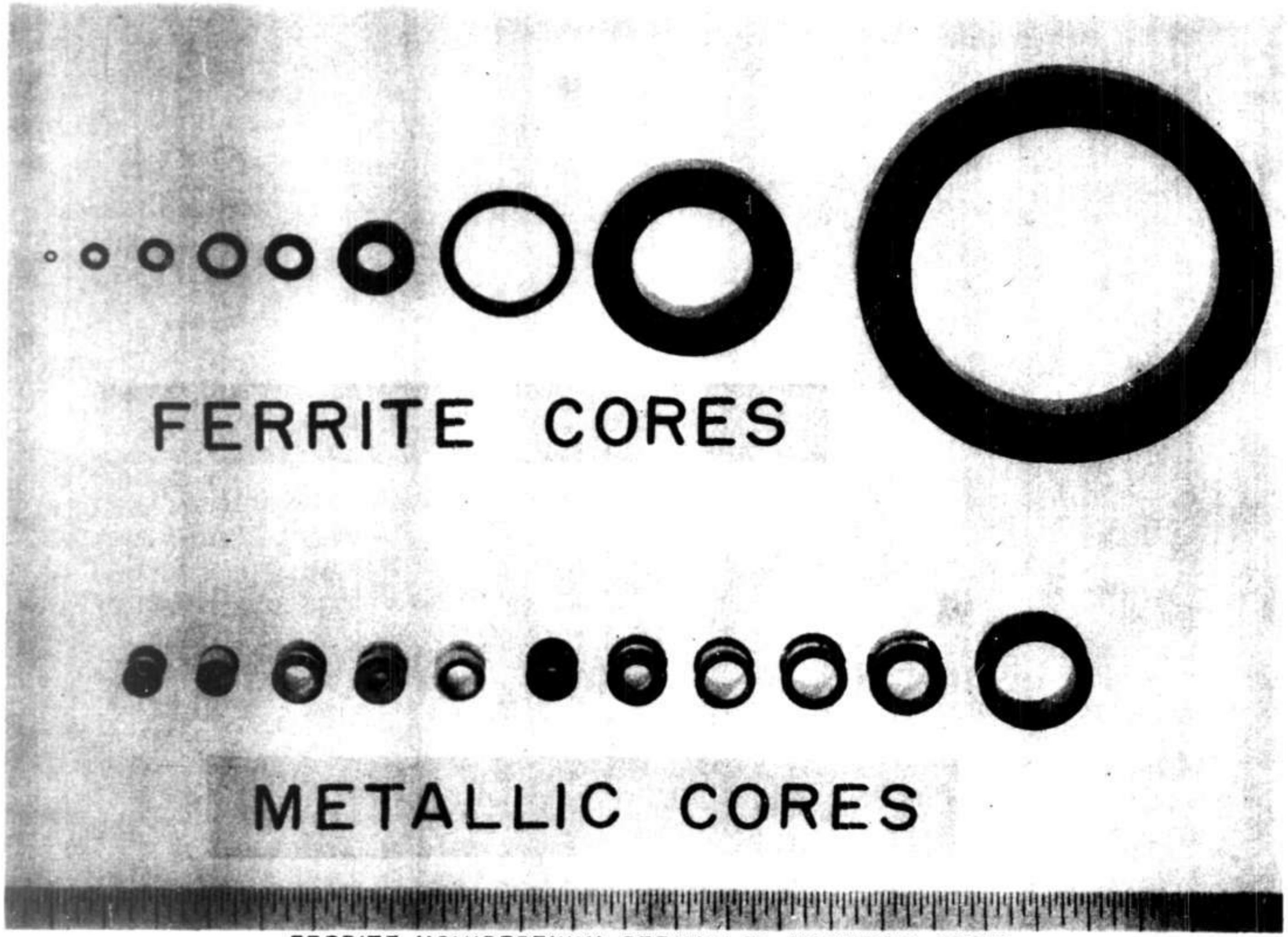
A detailed explanation of the peculiar "double peak" waveform observed when these cores are switched will have to wait for further investigations. The first peak, however, is probably associated with the nucleation of the domains of reverse magnetization. The second peak may then be associated with the motion of the domain walls sweeping out the volume of the material. Since the switching time is found to be independent of the geometry of the core, the domains of reverse magnetization must nucleate at many points throughout the volume of the material, probably at the grain boundaries.

Signed *David R. Brown*
David R. Brown

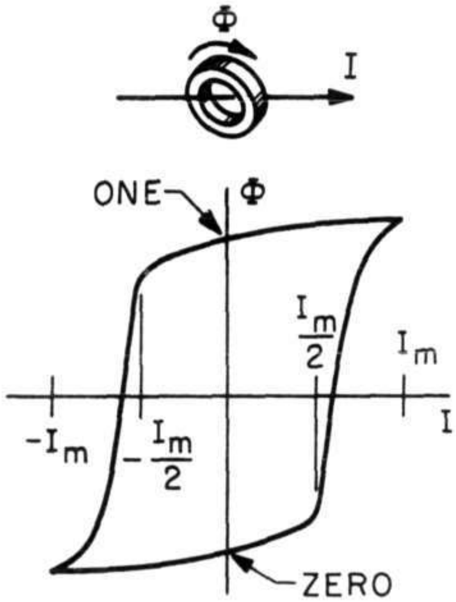
DRB/jk

Drawings Attached:
A-53928, A-53567, A-36611, A-53927, A-53565, A-53566, A-53659

A-53928
F-1612



FERRITE MOLYBEDENUM PERMALLOY MAGNETIC CORES
USED FOR HIGH-SPEED CIRCUITS

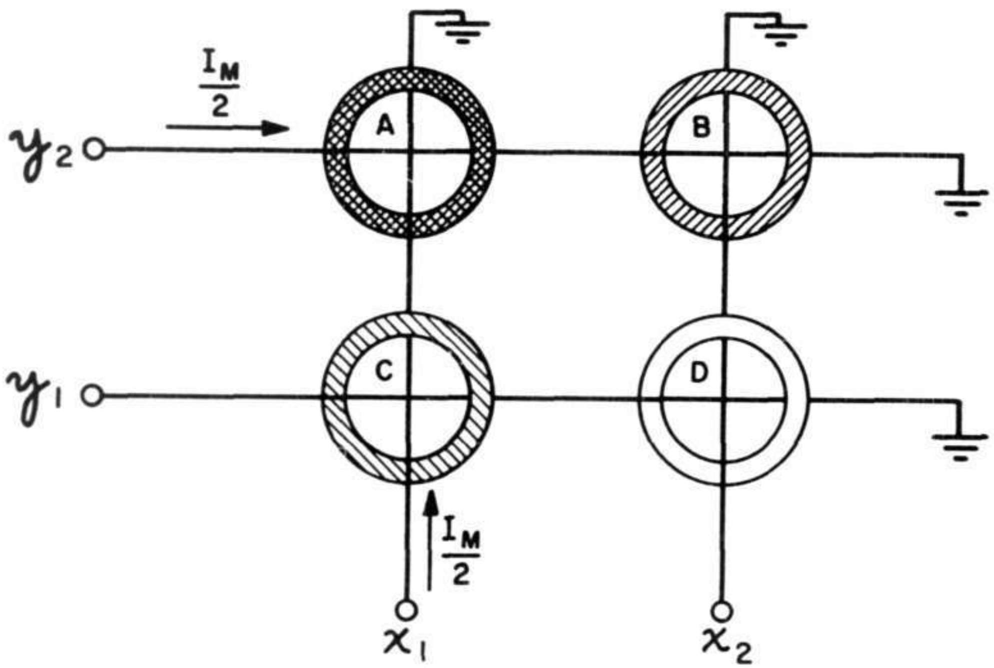


FLUX-CURRENT CHARACTERISTIC
OF FERRITE TOROID

A-53567
F-1785
SN-477

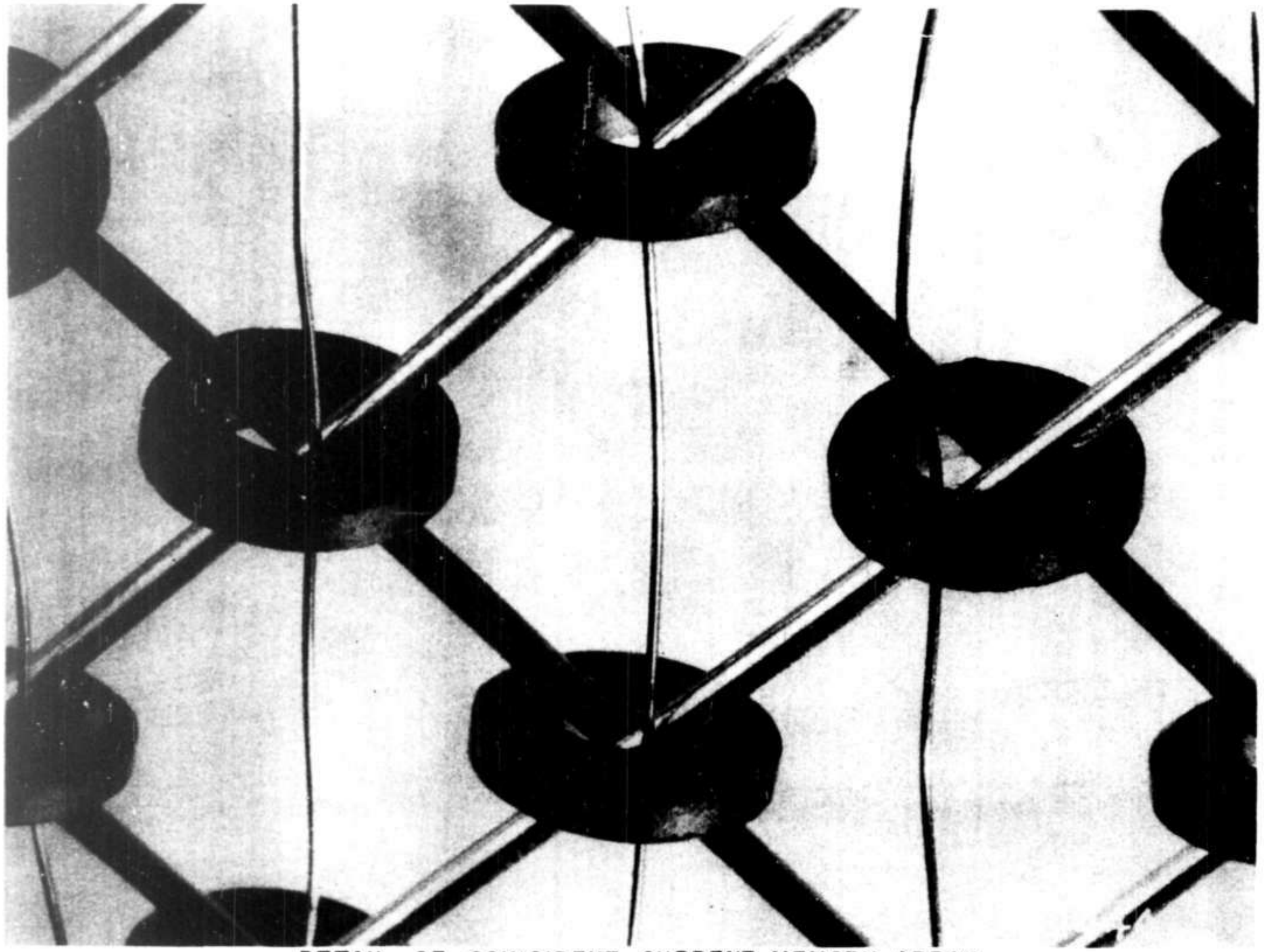
FIG. 2

A-36611
F-1262



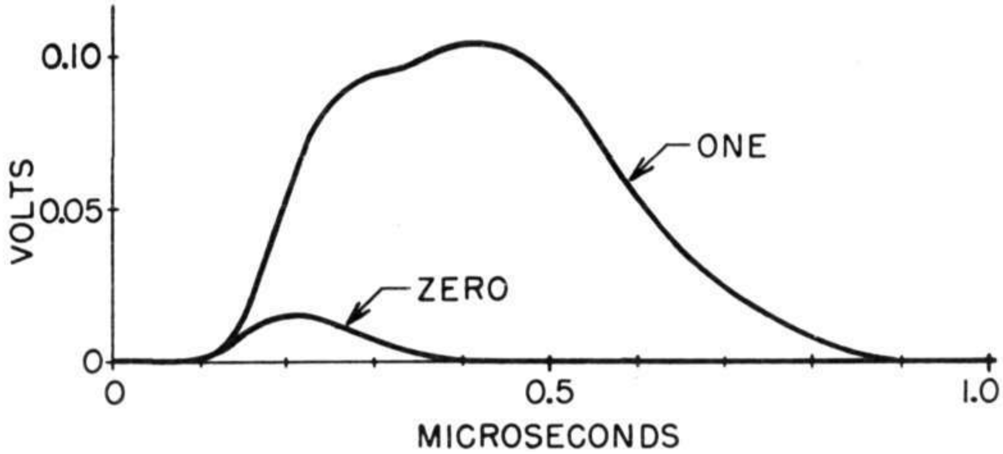
TWO-DIMENSIONAL ARRAY

A-53927
F-1444



DETAIL OF COINCIDENT-CURRENT MEMORY ARRAY
SHOWING OUTPUT WINDING

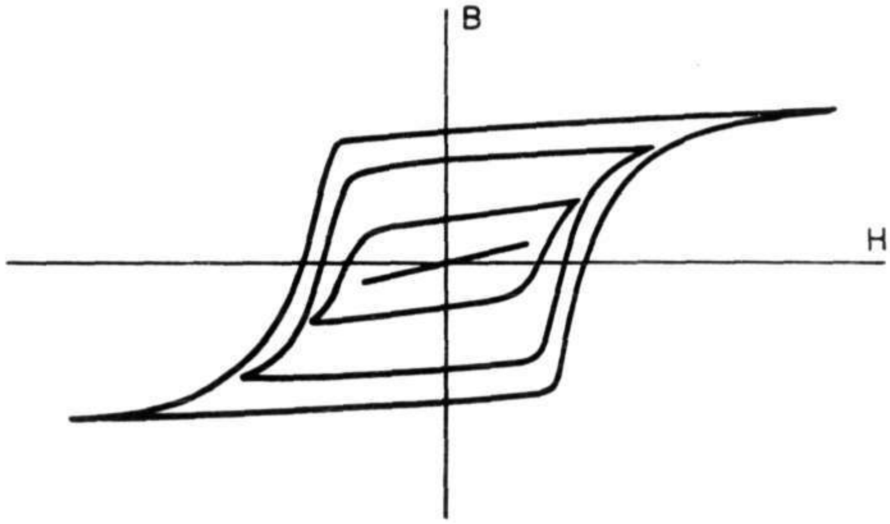
FIG. 4



ONE OR ZERO FROM
SELECTED TOROID

A-53565
F-1783
SN-475

FIG. 5

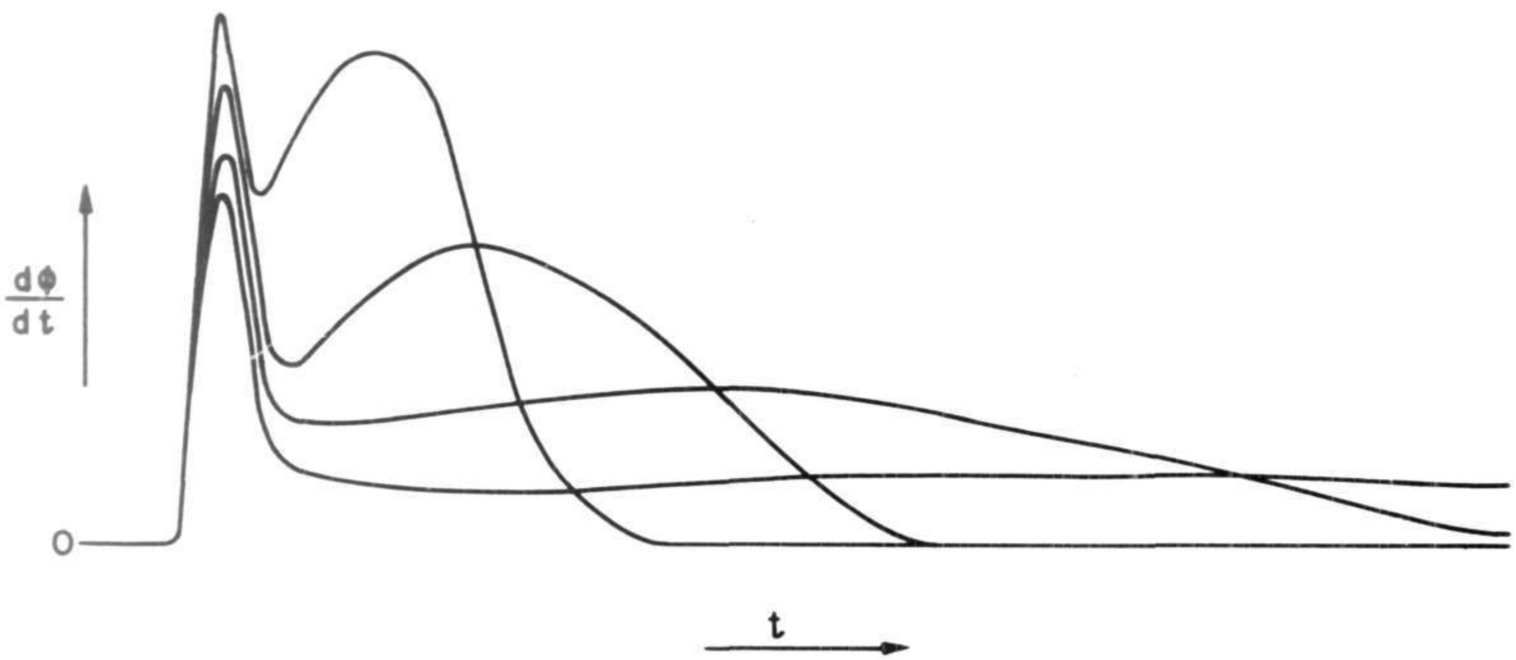


HYSTERESIS LOOPS OF GENERAL CERAMICS BODY MF-1118

A-53566
F-1784
SN-476

FIG. 6

A-53659
SN-313
F-1103



RESPONSE TO CURRENT STEP

FIG. 7