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SUBJECT: NONDESTRUCTIVE SENSING OF MAGNETIC CORES

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Abstract: A "Nondestructive" method for sensing the information state of magnetic-memory cores is under development. This new method involves the use of a quadrature magnetic field which, when pulsed, produces an output voltage. The polarity of the output voltage contains the information--a positive output pulse represents a ONE, and a negative pulse a ZERO. Reading in this manner can be repeated indefinitely without destroying the information held by the core. The method has proven to be exceedingly fast, giving output pulses of 0.2 microseconds in duration, and because of the rapid flux change when sensing, the output voltage has been observed as high as two volts per turn.

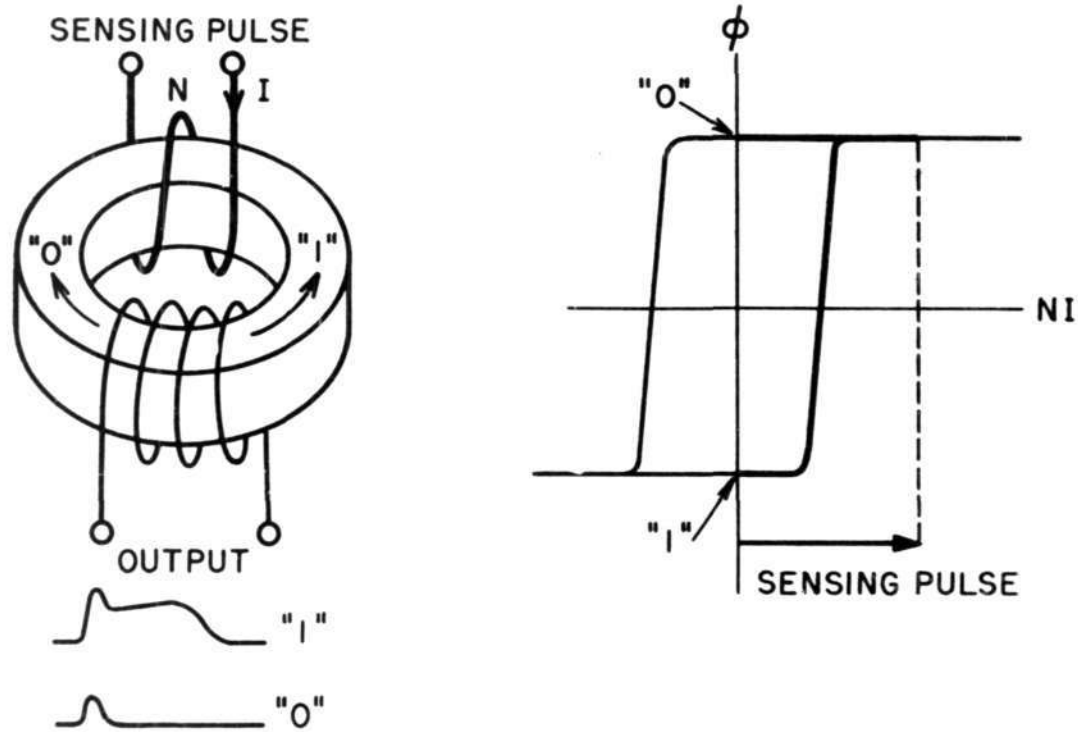
Magnetic cores with rectangular hysteresis loops are of interest to the field of digital computers because of their ability to hold, or "remember", the direction in which they have been magnetized. In digital computer terminology, a magnetic core may be said to contain a binary ZERO if its remanent flux is positive or a ONE if its remanent flux is negative. A group of magnetic cores can therefore hold a pattern of ZEROs and ONES which make up a binary number.

#### HOW INFORMATION IS STORED IN AND READ OUT OF A MAGNETIC MEMORY CORE

Figure 1 shows a single magnetic memory core together with a somewhat idealized plot of its rectangular hysteresis loop, i.e., a graph of the amount of magnetic flux ( $\Phi$ ) present in the core as a function of the magnetizing force (NI) impressed on that core.

To write a ZERO in the core, a pulse of current is made to flow in the magnetizing winding in a positive direction, setting up magnetic flux in a clockwise direction. This corresponds to a movement to the right (positive direction) on the  $\Phi$  vs NI graph. It can be seen that if we move far enough to the right, following the curve, we will eventually end up on the upper horizontal slope of the hysteresis loop. We will have saturated the core, and regardless of how much the magnetizing force is increased, the flux in the core remains the same. When the magnetizing force is removed corresponding to a displacement to the left in the  $\Phi$ -NI plane, we move along the upper horizontal slope until we come to rest at its intersection with the center line (no magnetizing force) marked "0". The graph indicates that

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DESTRUCTIVE SENSING

FIG. 1

almost the entire saturation flux is retained even after the magnetizing force has been removed. The core now holds a ZERO.

Conversely, in order to write a ONE, negative current sets up negative flux, i.e. counter-clockwise. In terms of the  $\phi$ -NI plane this means that the core is moving to the left along the curve until it hits the bottom horizontal slope. When the magnetizing current is stopped, the core comes to rest at the intersection of the bottom horizontal and the vertical centerline. The core then holds a ONE.

The read process makes use of the fact that when a magnetic flux change occurs inside a coil, a voltage is generated in that coil. An output winding is placed on the memory core (bottom of sketch in Figure 1), and a sensing pulse is applied to the input winding. The sensing pulse, also called "read" pulse, indeed, is nothing but a "write-ZERO" pulse. When it is applied, two possibilities exist: either the core holds a ONE or it holds a ZERO.

If the core holds a ONE, it starts out at the bottom, center, of the hysteresis loop marked "1" and begins to move to the right. The extent of this motion is indicated by the arrow marked Sensing Pulse. As the core gets around the knee of this curve, a large change of flux occurs while we move from the bottom to the top of the rectangular hysteresis loop. This large change of flux generates a large voltage in the output winding, thus indicating that the core had held a ONE.

If the core holds a ZERO (i.e. rests at the top, center, of the hysteresis loop), and a sensing pulse is applied, all that happens is that the core moves out to the right on the graph along an essentially horizontal line. Thus very little flux change occurs; therefore no voltage (or only a very small voltage) appears across the output winding, thus indicating that the core had held a ZERO.

A somewhat simpler way of looking at this read process is to imagine that it consists in magnetizing or "switching" the core into the ZERO position. If the core was initially in the ONE state, the flux has to be reversed, and therefore a change of flux occurs which generates an output voltage. If the core was already in the ZERO position, no change of flux is needed and no output signal is generated.

As shown above, this system of reading destroys the stored information: after having been read, a core will always find itself in the ZERO (or "cleared") state regardless of whether it contained a ONE or a ZERO just prior to reading. If information is to be retained for further use, it must be rewritten into the core.

The challenge, quite naturally, arose to devise a system of extracting information which would not destroy that information in the process. This paper describes one such nondestructive read system.

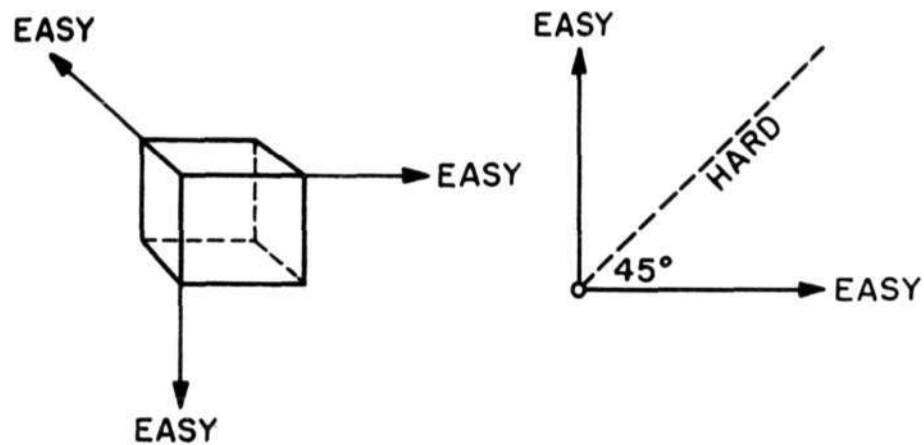
A NONDESTRUCTIVE READ SYSTEM

This particular nondestructive read system is based on the tendency of materials with rectangular hysteresis loops to maintain their remanent flux in certain easy directions of magnetization. These materials behave in many ways like a single ferromagnetic crystal, or cube, with easy directions of magnetization along its edges. In the absence of an external field, the residual magnetization vector of such a cube will lie in one of these easy directions (Figure 2, left). With this diagram reduced to a two-dimensional picture (Figure 2, right), a hard direction of magnetization can be imagined between each of the easy directions, as shown. If a magnetic field were applied at right angles to the remanent-flux vector, the vector would tend to align itself with the field and would thus be rotated away from its preferred direction toward a hard direction of magnetization. If this quadrature field were not strong enough to rotate the remanent-flux vector past the hard direction, this vector would snap back to its original easy direction as soon as the quadrature field was removed. (For easier identification, the usual magnetizing field on a core will henceforth also be referred to as the  $\alpha$  field, while the quadrature field will also be called a  $\beta$  field.)

This same principle may be used in conjunction with larger masses of rectangular-hysteresis-loop materials. These materials may be thought of made up of individual crystals all oriented in such a manner that one of their easy directions of magnetization lies in the direction in which the magnetizing ( $\alpha$ ) field is to be applied. In the case of a ring-shaped core, this means that one of the easy directions would be the tangential.

Figure 3 illustrates what happens when a magnetic field is applied at right angle to the remanent flux of a memory core.

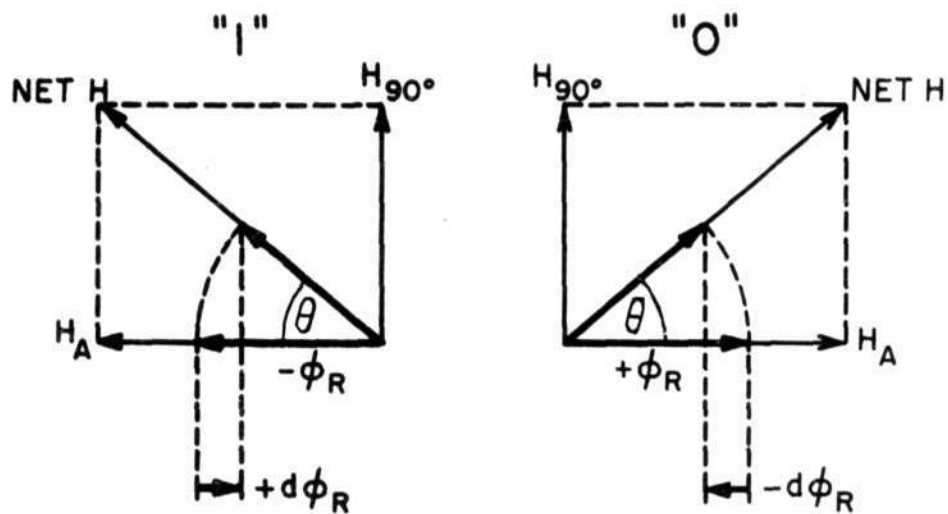
The remanent flux ( $\phi_R$ ) originally lies along the  $\alpha$  direction (in line with  $H_A$ ). If the core contains a ONE, this will be in the negative direction ( $-\phi_R$ ); if it contains a ZERO, in the positive direction ( $+\phi_R$ ). When the quadrature magnetic field ( $H_{900}$ ) is applied at right angle to  $H_A$ , the two will combine, vectorially, to form a resultant field (Net H). The remanent flux,  $\phi_R$ , will then line up with this combined field; i.e., it is rotated away from its easy direction of magnetization (along the dotted arc in Figure 3). The magnitude of the flux, however, will remain essentially unchanged, since in a rectangular-hysteresis-loop material the remanent flux is practically the same as the full saturation flux. Therefore, the output winding on that core effectively will see the flux reduced from  $\phi_R$  to  $\phi_R \cos \Theta$  (where  $\Theta$  is the angle of vector rotation), and a voltage is induced in the output winding. In the case of a ZERO with the remanent flux in the positive direction, the winding will see a negative change of flux ( $-d\phi_r$ ) as the  $\beta$  field is applied, and a positive change of flux as the  $\beta$  field is removed and the remanent flux is allowed to snap back into its preferred direction. Conversely, in the case of a ONE with the remanent flux in the negative direction, a positive voltage will be induced upon application of the  $\beta$  field, and a negative voltage upon removal of the  $\beta$  field. Thus, merely by observation of the polarity of the voltage induced in the winding of the memory core upon application of a  $\beta$  field, the state of magnetization of this core may be ascertained. In other words, the memory core may be read without destroying the information it contains.



EASY DIRECTIONS OF  
MAGNETIZATION

FIG. 2

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VECTOR REPRESENTATION OF  
NON-DESTRUCTIVE SENSING

FIG. 3

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It might be well to note here that this sensing operation does not "switch" the magnetic flux in the core, and that therefore it does not involve the destruction and formation of domain boundaries. This means that no hysteresis loss is incurred and that the system is, potentially, very fast.

#### EXPERIMENTAL SETUPS AND TECHNIQUES

As soon as it was attempted to try the proposed nondestructive read scheme, the question arose how to generate the  $\beta$  field. Two possibilities were envisaged:

- (1) An externally generated  $\beta$  field
- (2) An internally generated  $\beta$  field

#### The Externally Generated $\beta$ Field

A magnetic path, made of iron or some other material without a rectangular hysteresis loop, is so constructed that it contains a gap into which a memory core may be inserted (Figure 4). Through a winding on the iron path, a short current pulse is driven which induces magnetic flux at right angles to the remanent flux of the memory core. The remanent-flux vector is rotated for as long as the quadrature-field current flows, and the sensing winding (or output winding) sees the change of flux in the tangential direction. This change of flux, ideally, occurs just as rapidly as the current in the  $\beta$ -field winding can build up. Now the voltage induced in the sensing winding is proportional to the time rate of change in flux which this winding sees; so that, although the flux change is relatively small, the voltage output might be quite large if the change can be made to take place in a very short time.

#### The Internally Generated $\beta$ Field

Consider a hollow, toroidal magnetic-memory core (Figure 5) with a conductor placed circumferentially inside the hollow. The magnetizing winding occupies its usual place, and, after current has been allowed to flow through it, residual flux will exist along the large circumference. When a current pulse is sent through the conductor inside this hollow toroid, a field will temporarily exist around the conductor, deflecting the circumferential remanent flux in either a clockwise or counterclockwise direction. The effect may be compared to that obtained by twisting a handful of "Chinese Sticks" (Figure 6). Again, in the case of a ZERO we will first see a negative change of flux as the  $90^\circ$  field is turned on, followed by a positive change as the field is removed and the vectors revert to their original positions; conversely, in the case of a ONE we will see a positive change followed by a negative one.

K. H. Olsen suggested, and first tried, a different way of generating internal  $\beta$  fields in ribbon-wound cores. With leads attached directly to the two ends of the metallic tape (Figure 7), the core itself forms the path for the quadrature-field current.

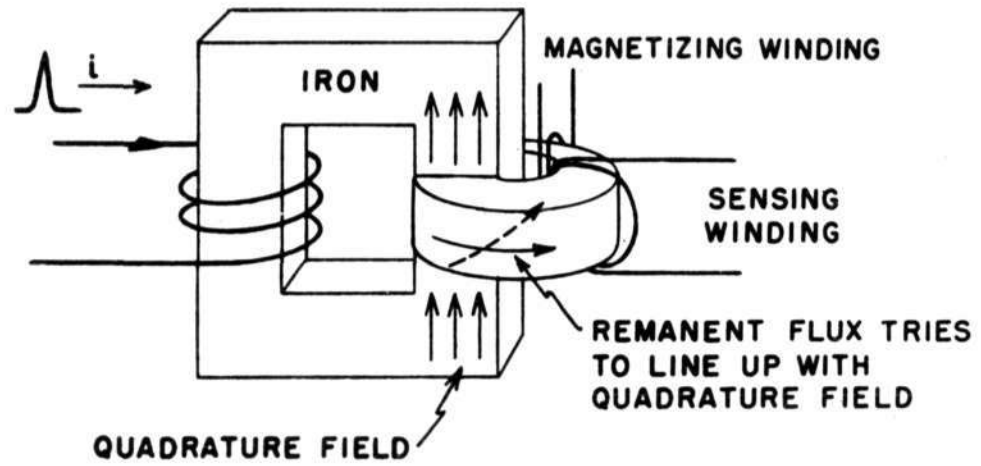
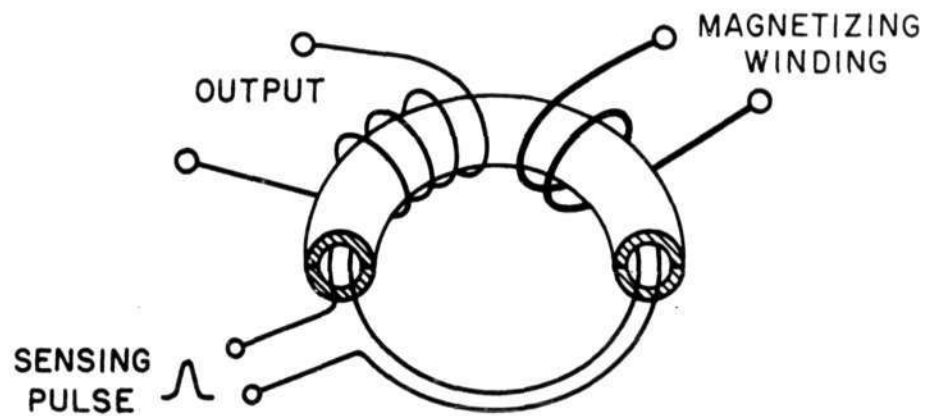


FIG. 4

EXTERNALLY GENERATED  $\beta$  FIELD

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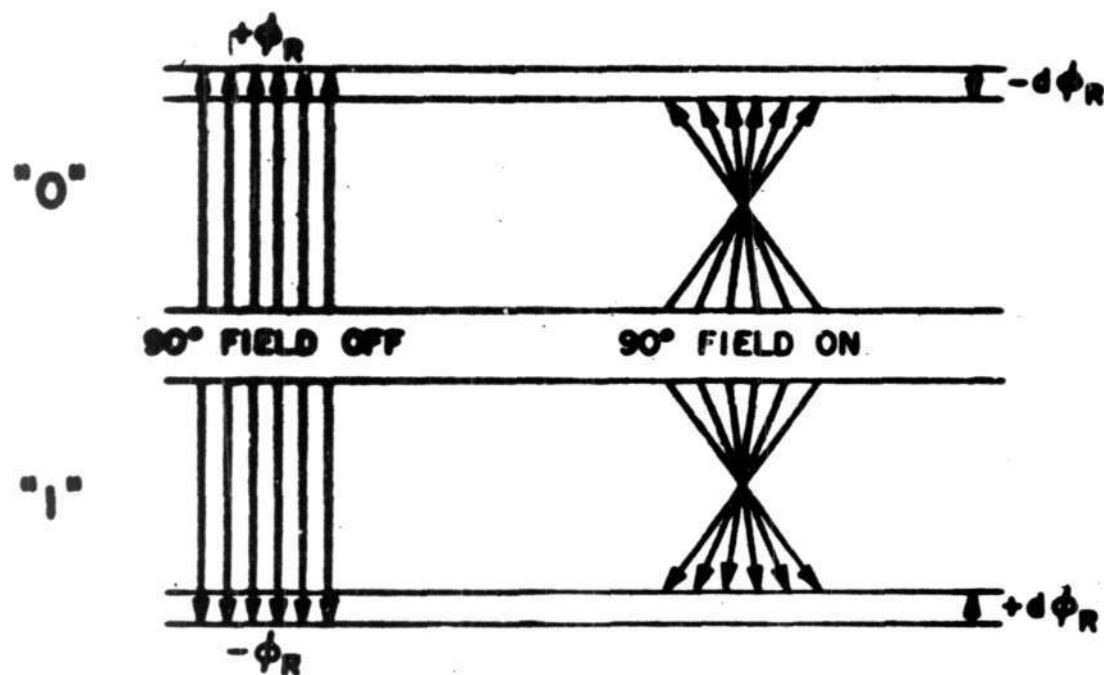


HOLLOW TOROID GEOMETRY

FIG. 5

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VECTOR REPRESENTATION OF  
HOLLOW TOROID SENSING

FIG. 6

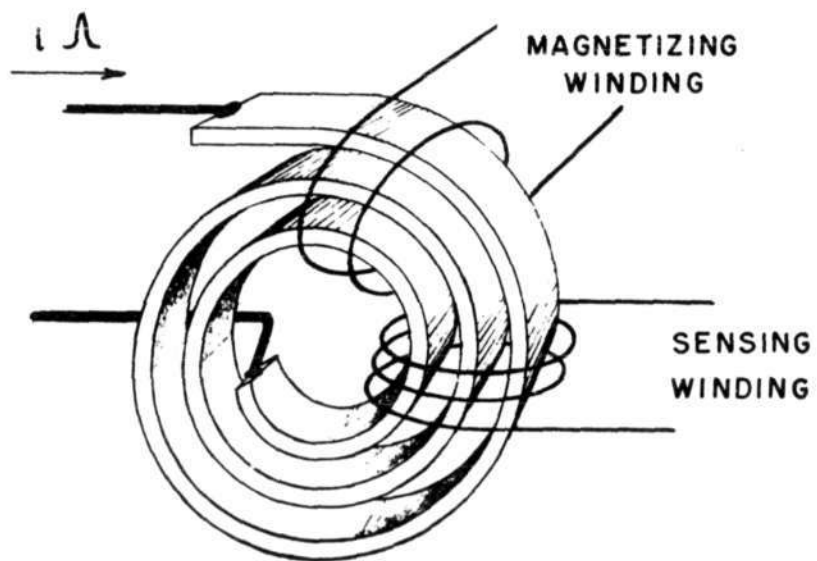


FIG. 7

METALLIC RIBBON TYPE MEMORY CORE CONNECTED  
TO GENERATE  $\beta$  FIELD INTERNALLY

In Figure 8 is shown a perpendicular cross section of the metallic tape. The large arrow protruding from the face of the section represents a quadrature-field-current vector surrounded by its associated magnetic field (counterclockwise). Since the entire tape conducts current, the total resultant quadrature field will be strongest around the outside edges of the section (represented by the six thin arrows in the plane of the section). The remanent-flux vectors perpendicular to the plane of the section are deviated by this field as shown; again a sensing winding will detect the change of flux.

#### Other Quadrature Fields

The possibility was also envisaged of using a third field at right angles to both the initial remanent flux ( $\alpha$  field) and the  $90^\circ$  field ( $\beta$  field); it might be called the  $\gamma$  field. This might be useful for some sort of "coincident field" selection scheme, in which, for instance, the  $\beta$  field is pulsed along the rows and the  $\gamma$  field along the columns of a matrix. A ONE, say, would be indicated by coincidence of pulses on two output windings, one sensitive to  $\beta$  excitation and the other to  $\gamma$  excitation.

#### Typical Setups

Figure 9 shows a typical arrangement for an externally generated  $\beta$  field: The memory core is a rectangular-loop ferrite (MF-1118,\* die size F-259) with a 1-turn magnetizing winding and a 20-turn sensing (output) winding. The quadrature field is developed across a slot cut in a larger core, also a ferrite (MF-666,\* die size F-262, outside diameter about 3/8 inch), with a 20-turn exciting winding. The Lucite board measures 3 x 3 inches. Figure 10 shows a metallic-ribbon type of core set up for an internally generated  $\beta$  field. The core is wound of 15 wraps of a rectangular-loop nickel-iron alloy (Deltamax\*\*) 0.0007 inch thick and 1/4 inch wide, with an inside diameter of about 2 inches, and a 20-turn sensing (output) winding. Figure 11, another internal  $\beta$ -field setup, shows a core made up of 10 wraps of a nickel-iron-molybdenum alloy ribbon (Mo-Permalloy 216\*\*\*), 1/4 mil thick and 1/8 inch wide, with a 2-turn magnetizing winding and a 20-turn sensing winding.

#### Equipment Used

Most of the data were obtained using the core-testing setup shown in Figure 12. This arrangement is made up largely of M.I.T. Digital Computer Laboratory standard test-equipment building blocks. It furnishes, for magnetizing and sensing circuits, three pulses, one of maximum amplitude 750 ma ( $H_m$ ) and two each with a maximum of about 400 ma ( $1/2H_m$ ), which may be combined to form one pulse of 800 ma.

The #3 pulse will always follow a #1 pulse (unless, of course, the switches 1 or 2 are opened), after which from 0 to well over 100 #2 pulses may be inserted. The length of these pulses may be varied by adjusting the time delay between the input to and the output from the Gate and Delay Unit

\* Made by General Ceramics and Steatite Corp., Keasbey, N. J.

\*\* Made by Allegheny-Ludlum Steel Corp., Brackenridge, Pennsylvania

\*\*\* Made by Magnetics, Inc., Butler, Pennsylvania

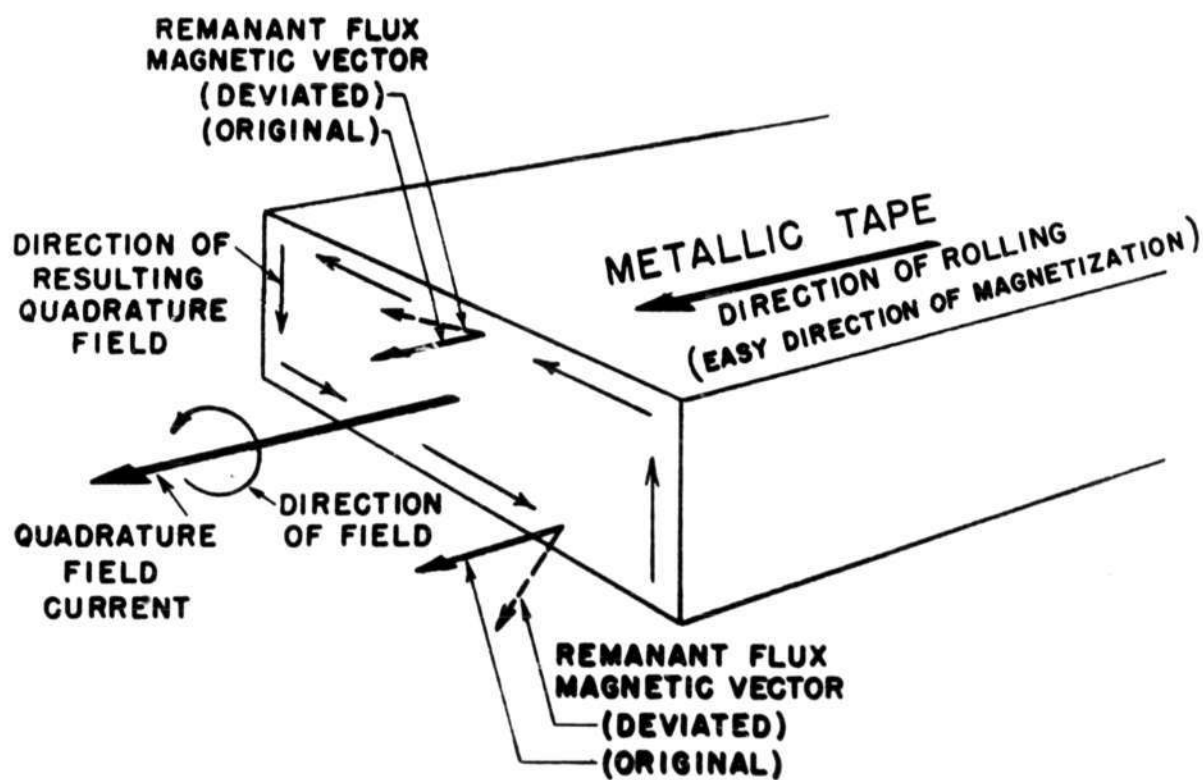


FIG. 8

INTERNALLY GENERATED QUADRATURE FIELD

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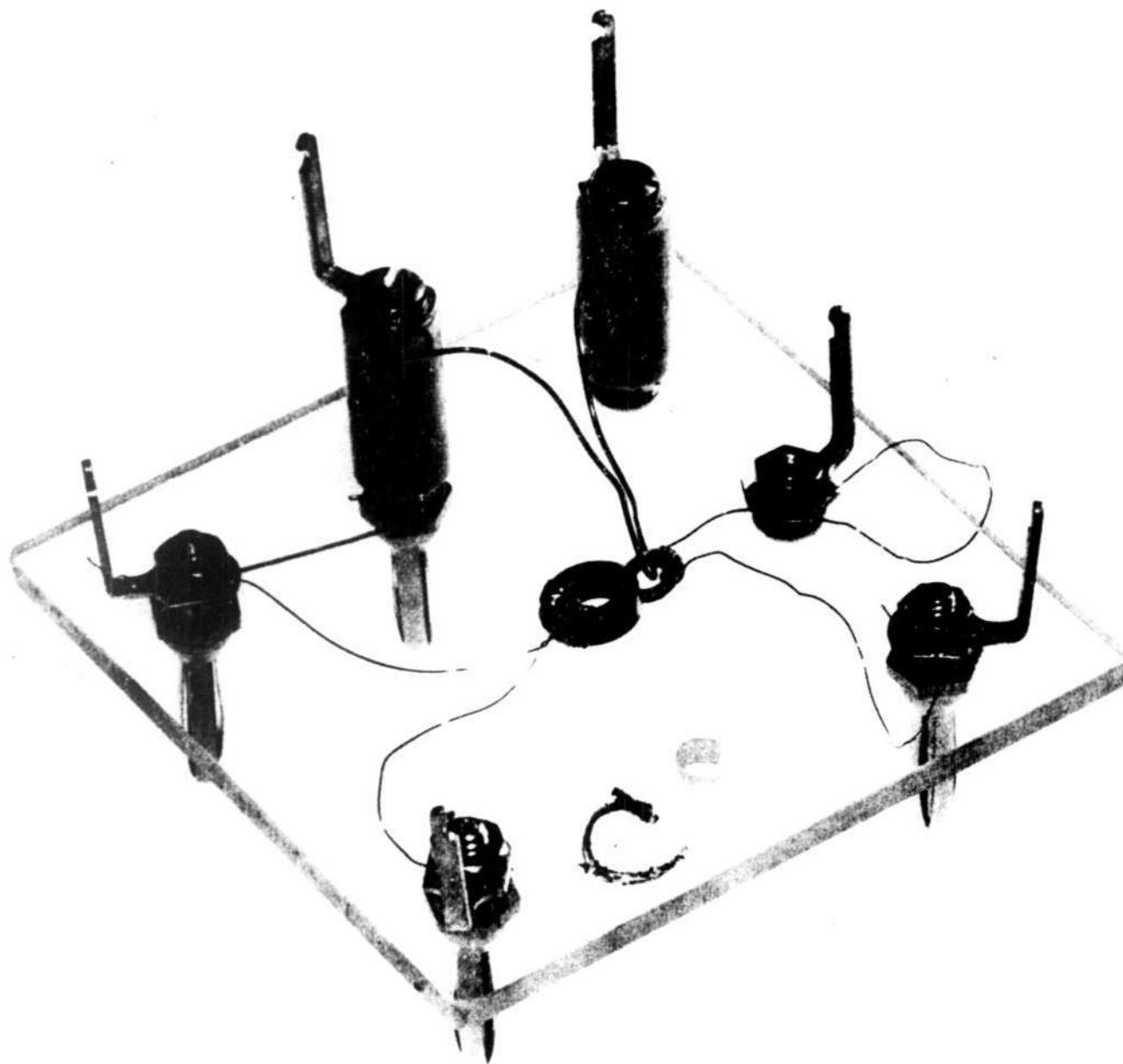


FIG. 3

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ARRANGEMENT FOR AN EXTERNALLY GENERATED  $\beta$  FIELD

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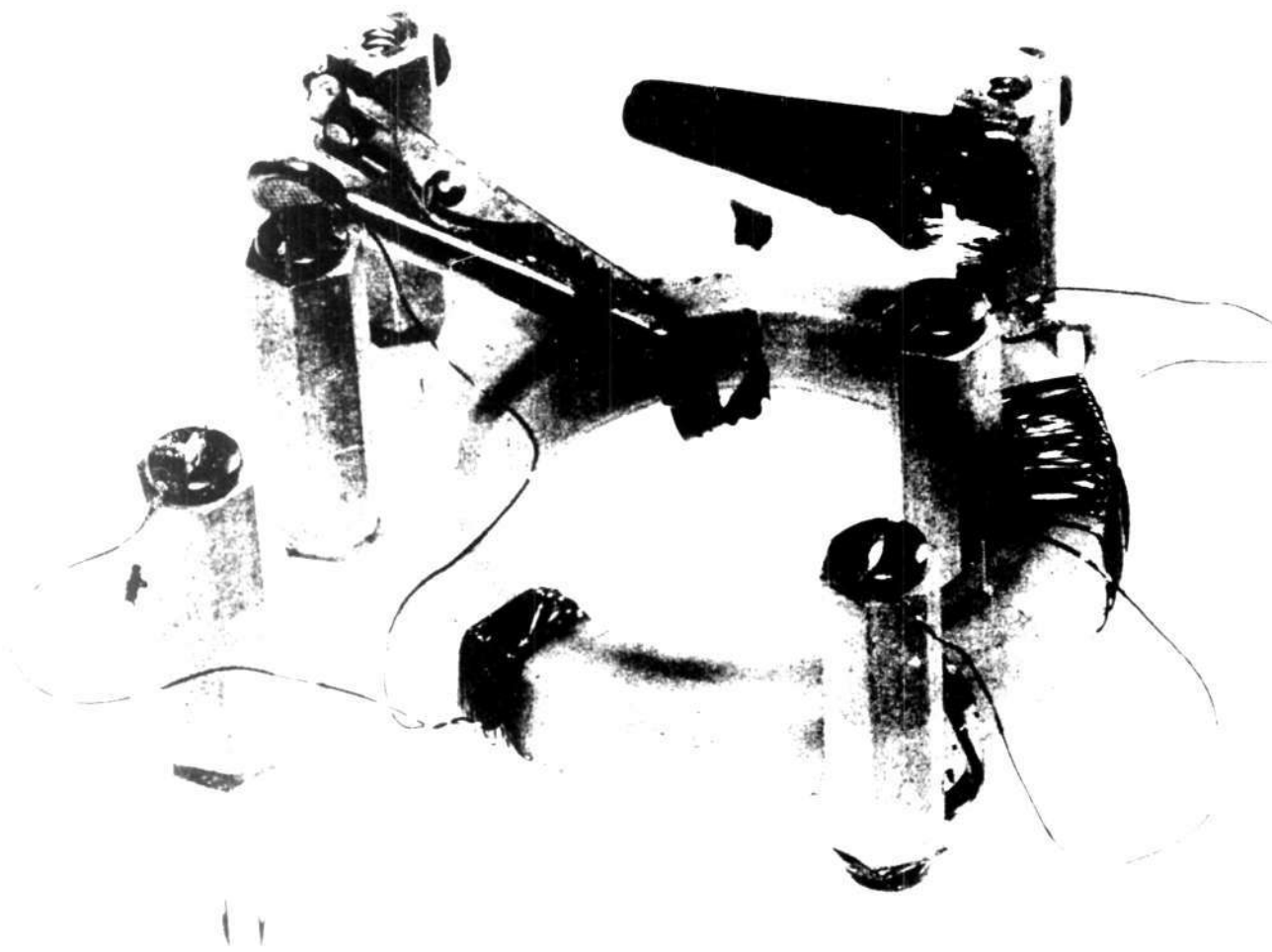


FIG 10

1 MIL DELTAMAX USED WITH INTERNAL  $\beta$  FIELD

**F-1655**

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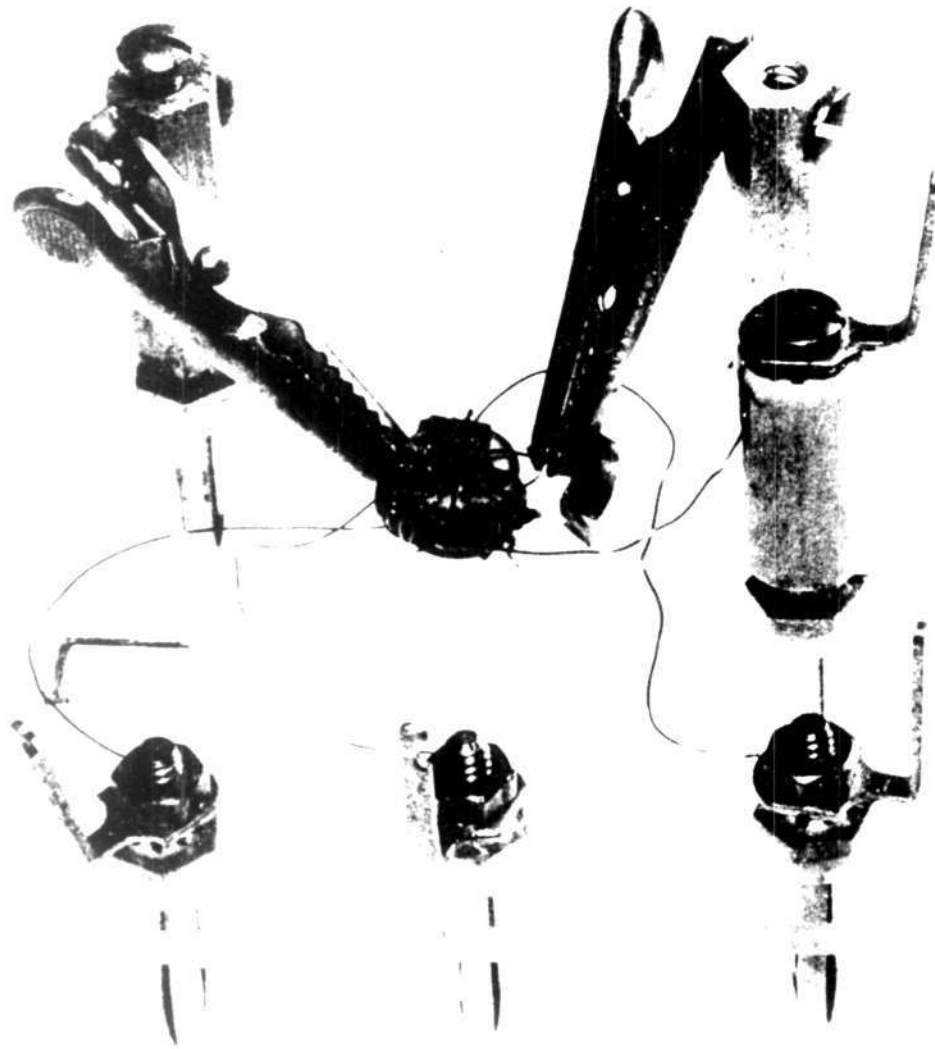


FIG. 1  
 $\frac{1}{4}$  MIL MO-PERMALLOY WITH INTERNAL  $\beta$  FIELD

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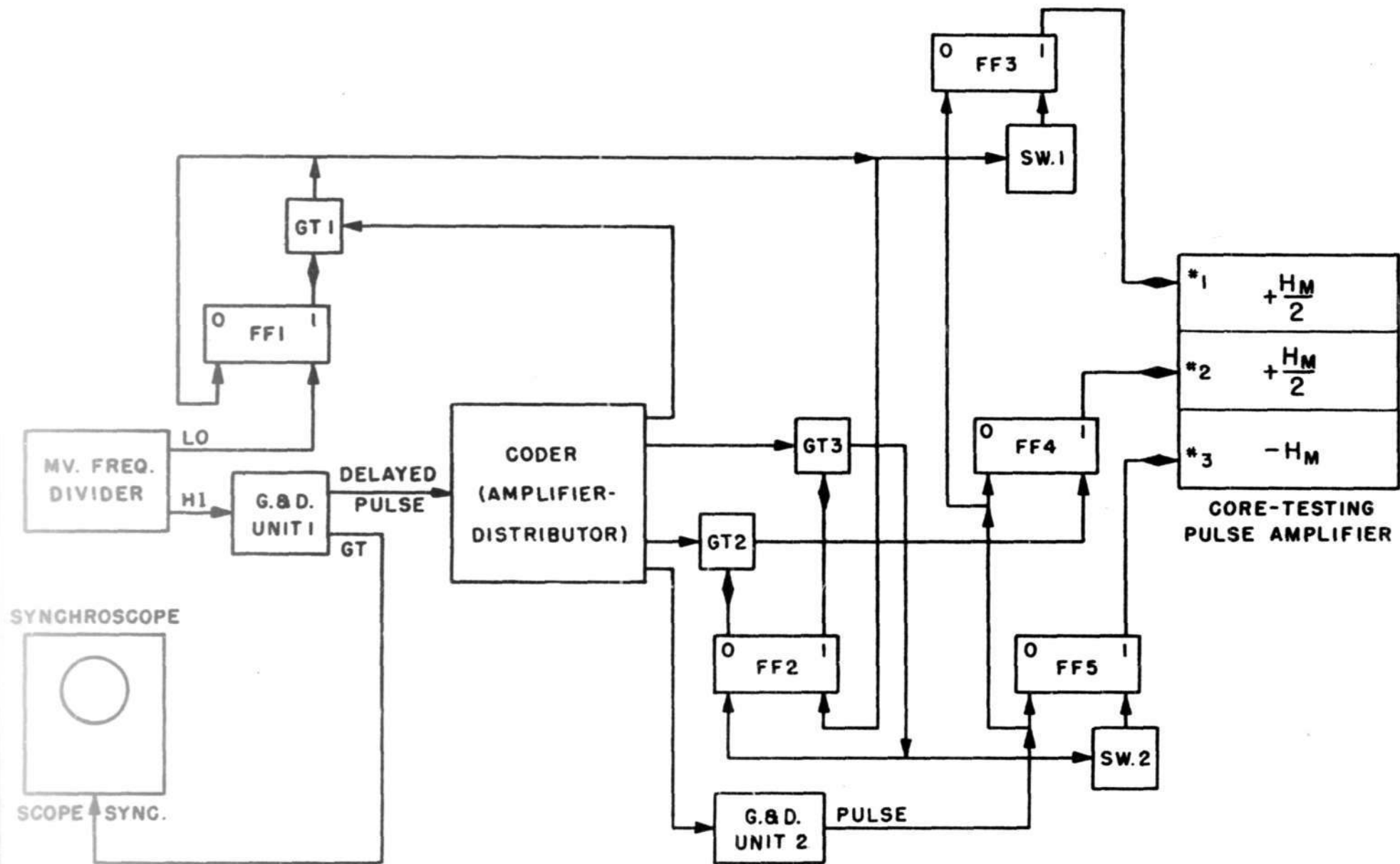


FIG. 12  
BLOCK DIAGRAM CORE-TESTING SETUP

#2 (near the bottom of the block diagram) from about 0.2  $\mu$ sec to well over 100  $\mu$ sec. For every particular setting, all 3 pulses will be of equal width. The repetition rate is varied by changing the free-running frequency of the high-frequency multivibrator in the Multivibrator Frequency Divider from about 2 to about 250 kc.

The amplitude of the current pulses is variable from 0 to about 750 ma. For those tests requiring larger currents, a thyatron pulse generator was used varying from about 0.8 ampere to 3.8 amperes. The number of #2 pulses inserted between #3 and #1 is varied by varying the low frequency of the multivibrator frequency divider.

### Oscilloscopes

All measurements (except d-c resistance measurements), readings, and photographs were taken on either a type 513D or a type 514D TEKTRONIX 'scope, both having a 1-megohm and 40-mmf input impedance.

### Steady-State Measurements

For steady-state measurements, the core was switched into ZERO and ONE position by means of a battery, a key, a variable resistor, and a reversing switch. Once the information had thus been stored, only one pulse was needed: the quadrature-field read-out pulse.

### Transient Measurements

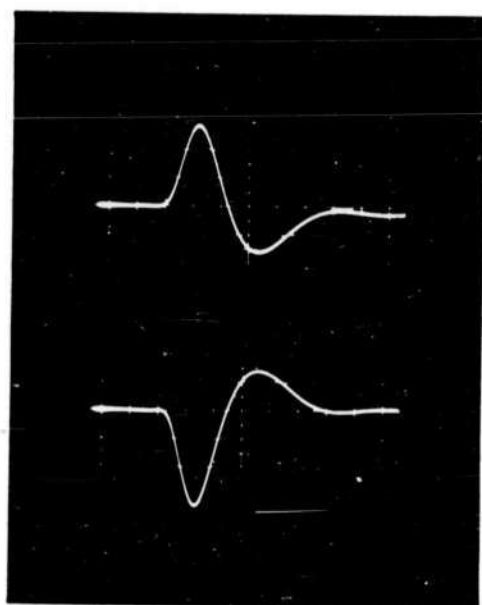
For transient measurements, again, the information was stored, initially, by means of the outside battery. Then, with SW 1 open, the quadrature-field leads were connected to pulse #2 and the magnetizing winding of the core to pulse #3. Thus a variable number of read-out pulses could be set up, followed by a remagnetizing pulse.

## EXPERIMENTAL RESULTS

### Typical Waveforms

Figure 13 shows typical waveforms (voltage vs time) obtained with an open output winding. The top picture shows the output of a memory core holding a ONE. It illustrates the positive change in flux (represented by the positive voltage induced in the sensing winding) as the  $\beta$  field is turned on, followed by a negative change as the  $\beta$  field is removed and the remanent flux returns to its easy direction of magnetization. When the information held by the core is changed to a ZERO (bottom picture), a pattern of opposite polarity is observed.

Figure 14 shows the output of a metallic-ribbon type core into a 20-turn sensing winding terminated in 93 ohms, with both internally and externally generated  $\beta$  field. As may be seen, the loading of the output winding has the effect of slowing down the return of the disturbed remanent flux vector to its easy direction of magnetization, so that the output signal is essentially confined to a single positive pulse for a ONE and a negative pulse for a ZERO.



"ONE"

"ZERO"

FIG. 13

TYPICAL WAVEFORMS IN AN  
UNTERMINATED OUTPUT WINDING

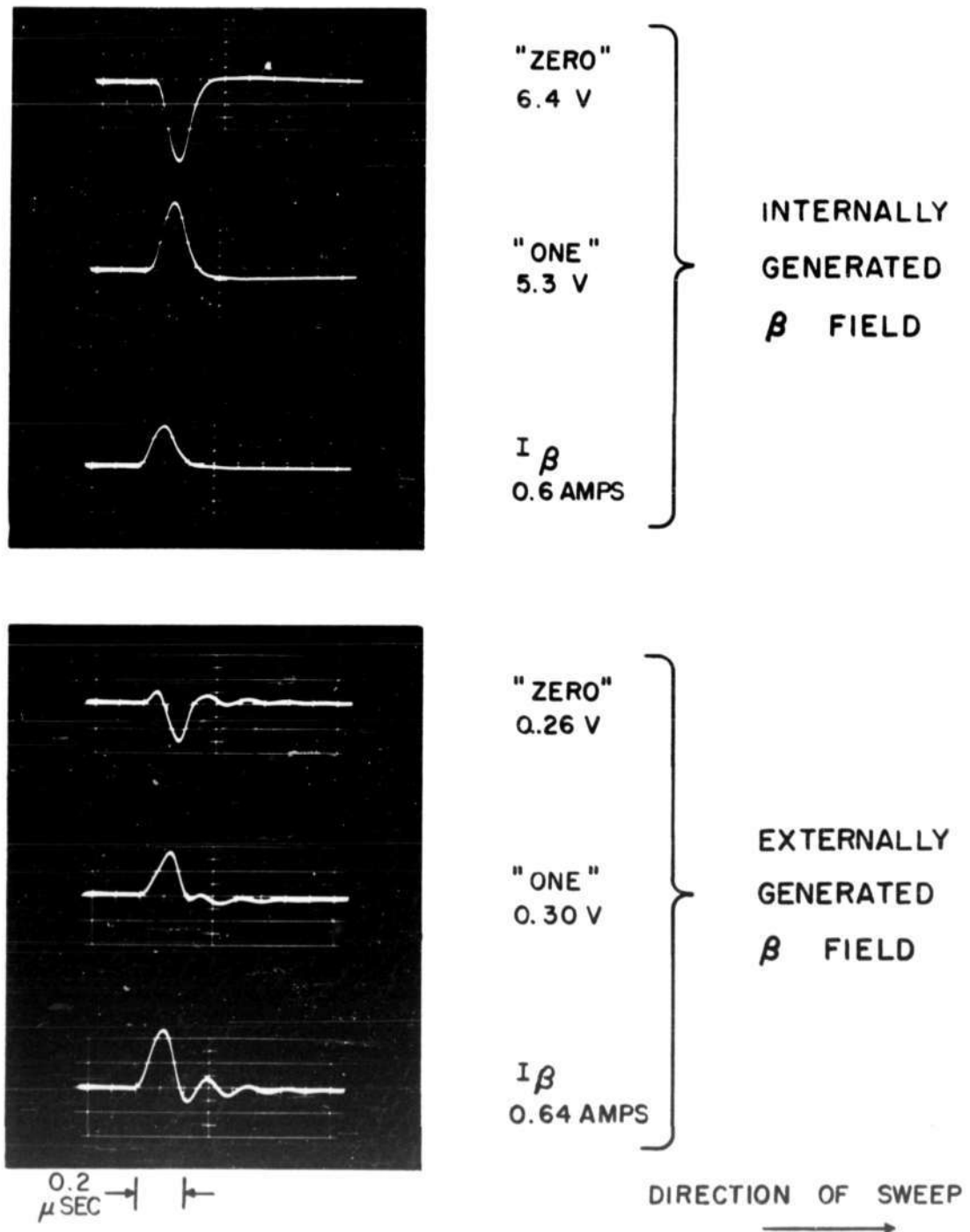


FIG. 14

TYPICAL WAVEFORMS IN AN OUTPUT WINDING  
TERMINATED WITH 93  $\Omega$

There is a striking similarity between results obtained with the two different methods of generating the  $\beta$  field. Except for a scale factor and some oscillation introduced by the external  $\beta$  field, the results may be said to be alike. This is as it should be: the output of the memory core should not depend on the manner in which the quadrature field pulse is generated.

Material used is a 40-wrap 1/8-inch wide 1/4-mil thick Mo-Permalloy 216 core with a 20-turn output winding. The external  $\beta$  field was generated in a Ferramic-D core with a 10-turn exciting winding.

It should also be noted here how closely the output voltage follows the shape of the quadrature-field current pulse. The pictures in each series were taken to the same time scale; all of these pulses are about 0.2  $\mu$ sec long with a 0.1  $\mu$ sec rise time.

#### Output Voltage as a Function of Quadrature-Field Currents

In the relationship between the magnitude of the output voltage and the  $\beta$ -field current, only the internally generated field offers any sensible basis for comparison.

For the case of the external quadrature field, too many variables exist outside the memory core; the size of the quadrature field magnet (relative to that of the memory core), its magnetization curve, the amount of residual flux it retains, and the smoothness of the mechanical fit between it and the memory core are just a few of these variables. With the internally-generated  $\beta$  field, all these parameters are fixed for each core.

Figure 15 shows the output into 93 ohms and open circuit voltages of a 6-wrap Mo-Permalloy core, 1/4 mil thick, 1/8 inch wide, pulsed with a current pulse 0.2  $\mu$ sec long, the amplitude of which was varied from about 0.07 ampere to over 0.6 ampere. The output winding has 20 turns. The curves are typical of many others, obtained both with externally and internally generated  $\beta$  fields.

There is a long, essentially linear (or slightly concave) rise of output voltage as the  $\beta$ -field current is increased, followed by a flattening-out and finally (not shown in this graph) a rapid decrease of output as the nondestructive limit is exceeded. The decrease is probably caused by the quadrature field deflecting the remanent-flux vectors  $\phi_n$  more than  $45^\circ$  from their original position along  $H_A$  (see Figure 3), so that they then line up along  $H_{900}$  instead of dropping back to the  $H_A$  direction. It was found that the point at which the flattening-out of the curve occurs (or where the non-destructive system reaches its limit) could be varied by changing the length of the quadrature-field read pulse. The longer the pulse, the less current was needed to reach the limit of nondestructiveness. Conversely, also, the shorter the duration of the pulse, the greater the amplitude that could be tolerated by the system, and incidentally, the greater the output of the memory core became.

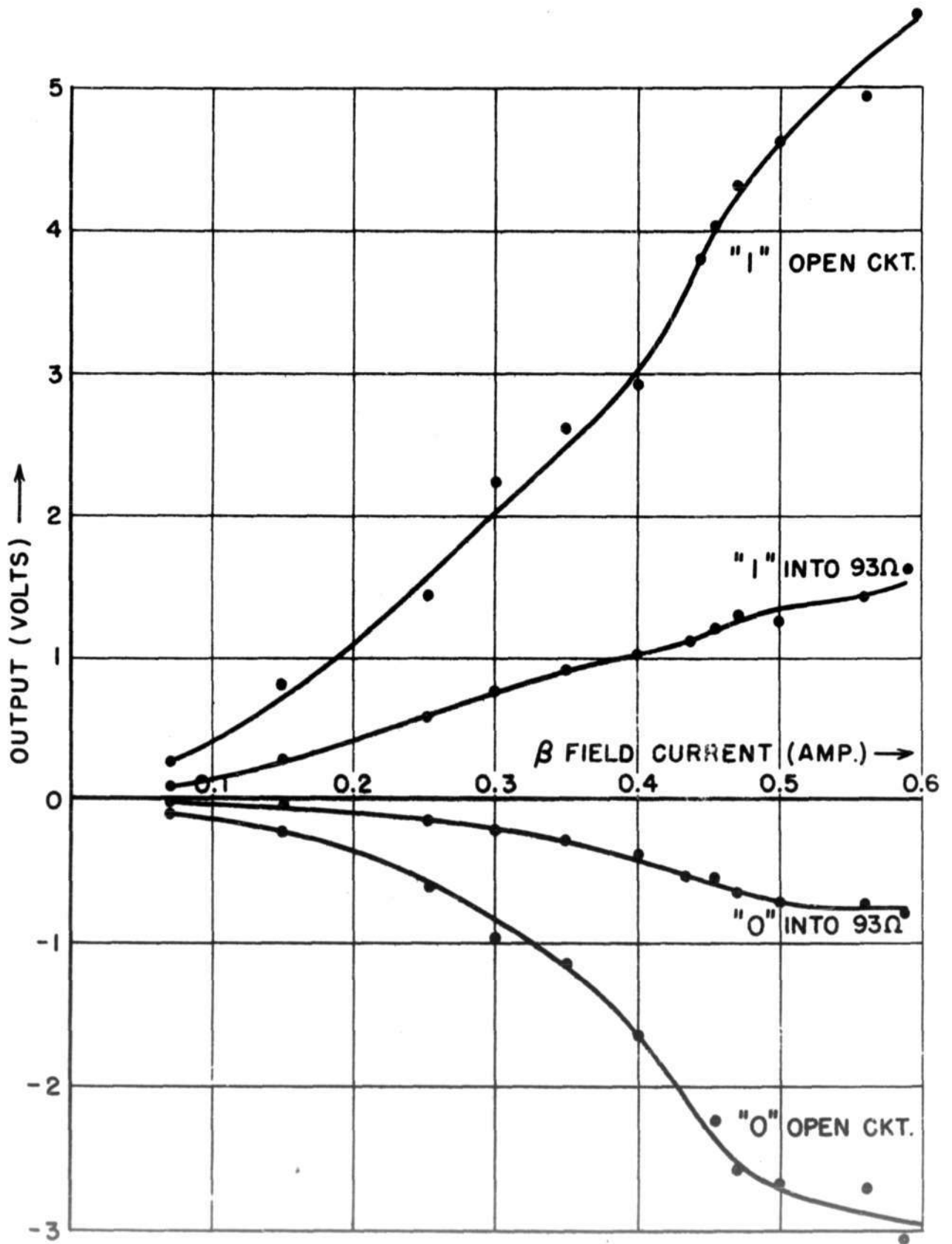


FIG. 15

6 WRAP MO-PERMALLOY

GRAPH OF OUTPUT VOLTAGE Vs.  $\beta$  FIELD CURRENT

A certain asymmetry is noticeable in these curves; the ONE outputs are consistently larger than the ZERO's. This is caused by the  $\beta$ -field-current lead attached to the inside end of the metallic-ribbon memory core; since the current flows in from one side only, the magnetic field surrounding it will boost one direction of magnetization while bucking the other. Subsequently, an experiment was tried where two leads, one from each side, were attached to the inside end of the core. Through a pair of matched resistors, equal current flow through both leads was assured; as expected, most of the asymmetry disappeared.

#### Voltage Output as a Function of Terminating Resistance

Variation of the output voltage of the memory core with changes in the terminating resistance was observed in the same 6-wrap Mo-Permalloy core described above. The plot (Figure 16) on semi-log scale, beginning with very low voltages for small values of terminating resistances, passes through a fairly straight region between 70 and 700 ohms and then, asymptotically, approaches the open-circuit voltage. The halfway point, or point of maximum power transfer, is reached near 200 ohms. A common way of specifying impedance of a winding on a magnetic core is in the unit "ohms per turn squared". For our 20-turn sensing winding, its apparent 200-ohm internal impedance gives, in these units,  $1/2$  ohm per turn squared. The quadrature-current pulse was 0.64 ampere maximum, about 0.25  $\mu$ sec long at the base.

#### Output Voltage as a Function of the Amount of Magnetic Material in the Memory Core

It soon became apparent that the output of a given magnetic core varies a good deal according to its size or the amount of material used. Moreover, the variations seemed to follow different patterns depending on whether externally or internally generated  $\beta$  fields were used for the readout.

a) Externally generated quadrature field: since properly assorted ferrite cores would have been too expensive to obtain, one set of metallic-tape cores was ordered containing 1, 2, 4, 8, 16, 32, and 64 wraps respectively. A Ferramic-D core with a 10-turn exciting winding was prepared by grinding a slot into it just wide enough to receive the metallic memory cores. The latter were Mo-Permalloy 216's,  $1/4$  mil thick and  $1/8$  inch wide, with 20-turn sensing windings. Then, with a constant  $\beta$ -field pulse of 0.72 ampere and 0.2- $\mu$ sec long, maximum output was recorded for each core. Figure 17 shows the maximum output for each core in that series plotted against the number of wraps in each. The result seems odd, at first; one would expect to find an increased output as the amount of material in the core is increased. But it should be realized that there exists an air gap between the edges of the  $\beta$ -field magnet and the memory-core material of at least the thickness of the two flanges of the bobbin on which the metallic tape is wound. The  $\beta$ -field flux is therefore fairly constant no matter how many wraps of material are inserted; however, the flux density will be smaller the more wraps of material are on the memory core. Below 4 wraps, leakage and/or saturation reverses the normal trend.

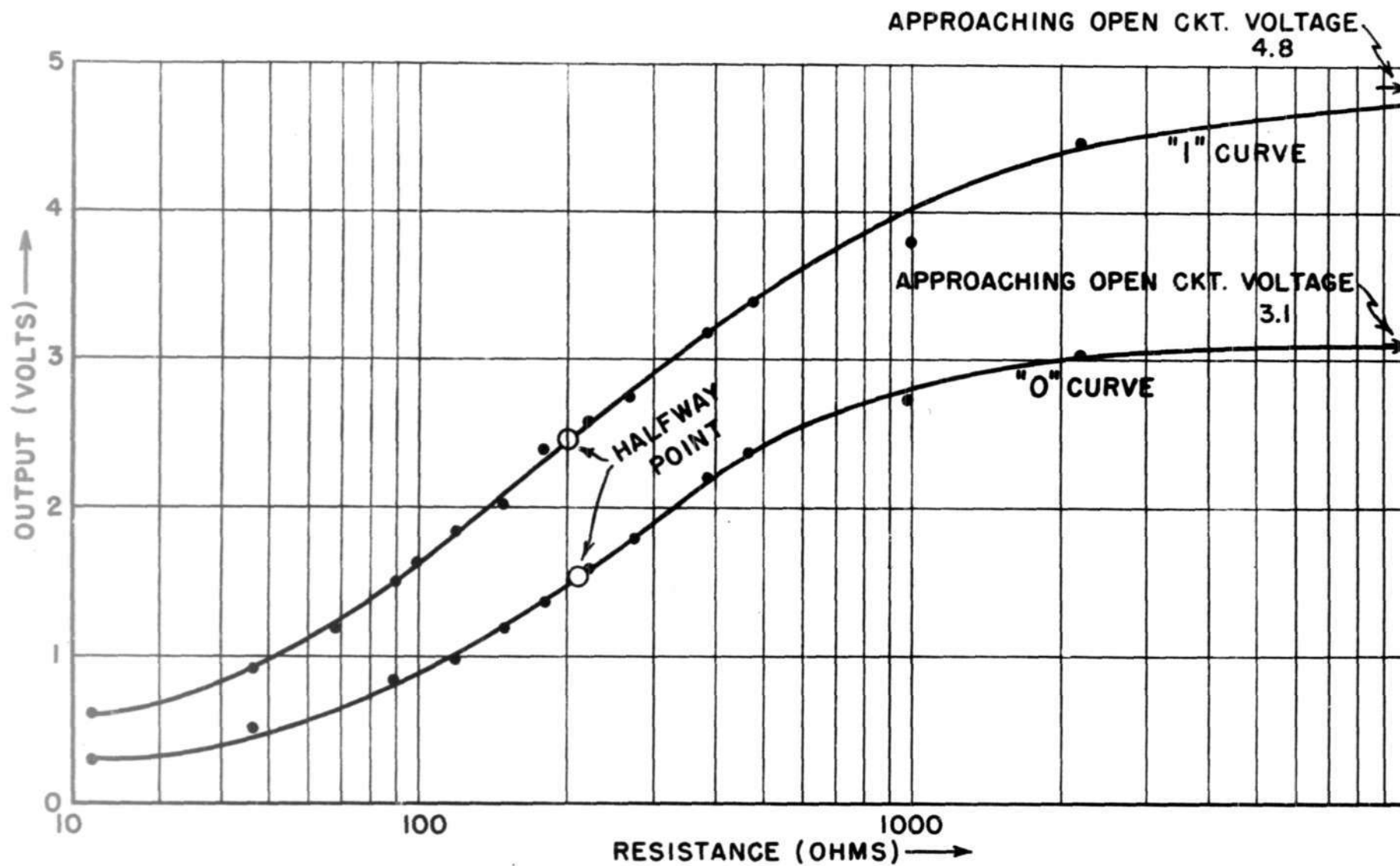


FIG. 16  
6 WRAP MO-PERMALLOY  
 GRAPH OF OUTPUT VOLTAGE vs. TERMINATING RESISTANCE



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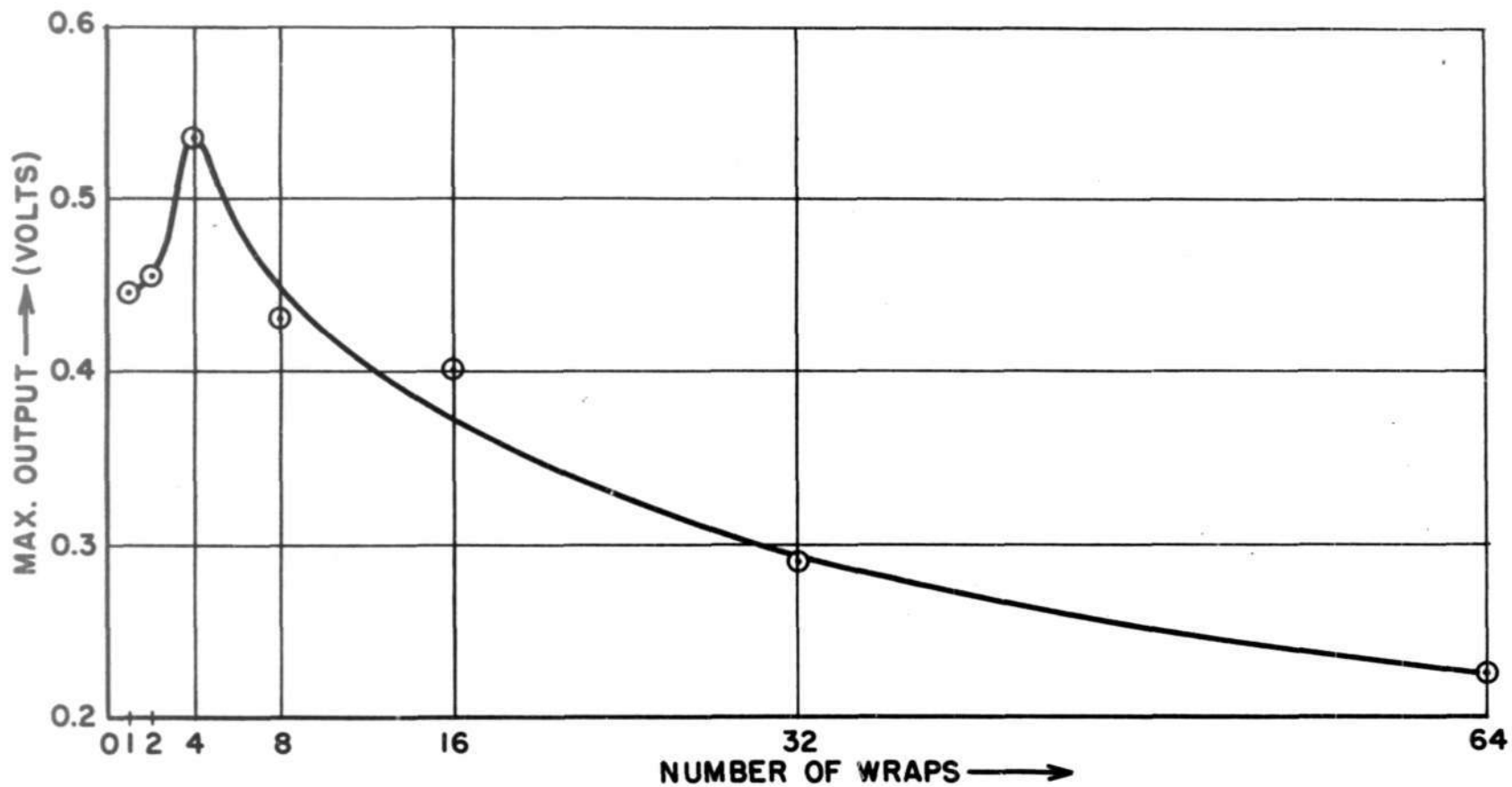


FIG. 17  
 OUTPUT VOLTAGE AS A FUNCTION OF THE NUMBER OF WRAPS  
 (EXTERNAL  $\beta$  FIELD)

b) Internally generated  $\beta$  field: The curve of output vs number of wraps of material for the internal  $\beta$  field (Figure 18, solid line), starts out quite linearly, but soon begins to rise more slowly. Presumably, above a certain large number of wraps no further rise in output would be noticeable as the amount of material is increased.

The back voltage vs number of wraps (broken line) indicates a linear relationship between these two variables, as had been expected. Back voltage in all cases amounted to several times the output voltage.

Back Voltage and Power Consideration

When considering the nondestructive read system from the point of view of power economy, one is immediately aware of its very low efficiency as a power transformer.

An indication of the peak power involved (largely reactive) may be had by multiplying the current peak by the peak of the back voltage. These peaks, from observation, occur simultaneously. Peak power output will then be given by

$$P_{out} = \frac{(E_{out})^2}{R}$$

where  $E_{out}$  is the peak voltage appearing across the sensing winding and R is the terminating resistance. Four typical cores are illustrated in the table below; setups L and  $M_{02}$  used internally generated  $\beta$  fields, setups C and  $M_{04}$  externally generated  $\beta$  fields.

Setup Peak	<u>External <math>\beta</math> Field</u>		<u>Internal <math>\beta</math> Field</u>	
	C	$M_{04}$	L	$M_{02}$
$I_{Beta}$ (amp)	1.0	0.72	0.72	0.168
$V_{Back}$ (volt)	130	39.0	3.5	0.5
$P_{in}$ (VA)	130	28.1	2.52	0.084
$E_{out}$ (volt)	0.55	0.6	0.6	0.1
R (ohm)	93	93	100	93
$P_{out}$ (watt)	0.0033	0.0039	0.0036	0.00011
Ratio: $\frac{P_{in}}{P_{out}}$	39000	7200	700	760

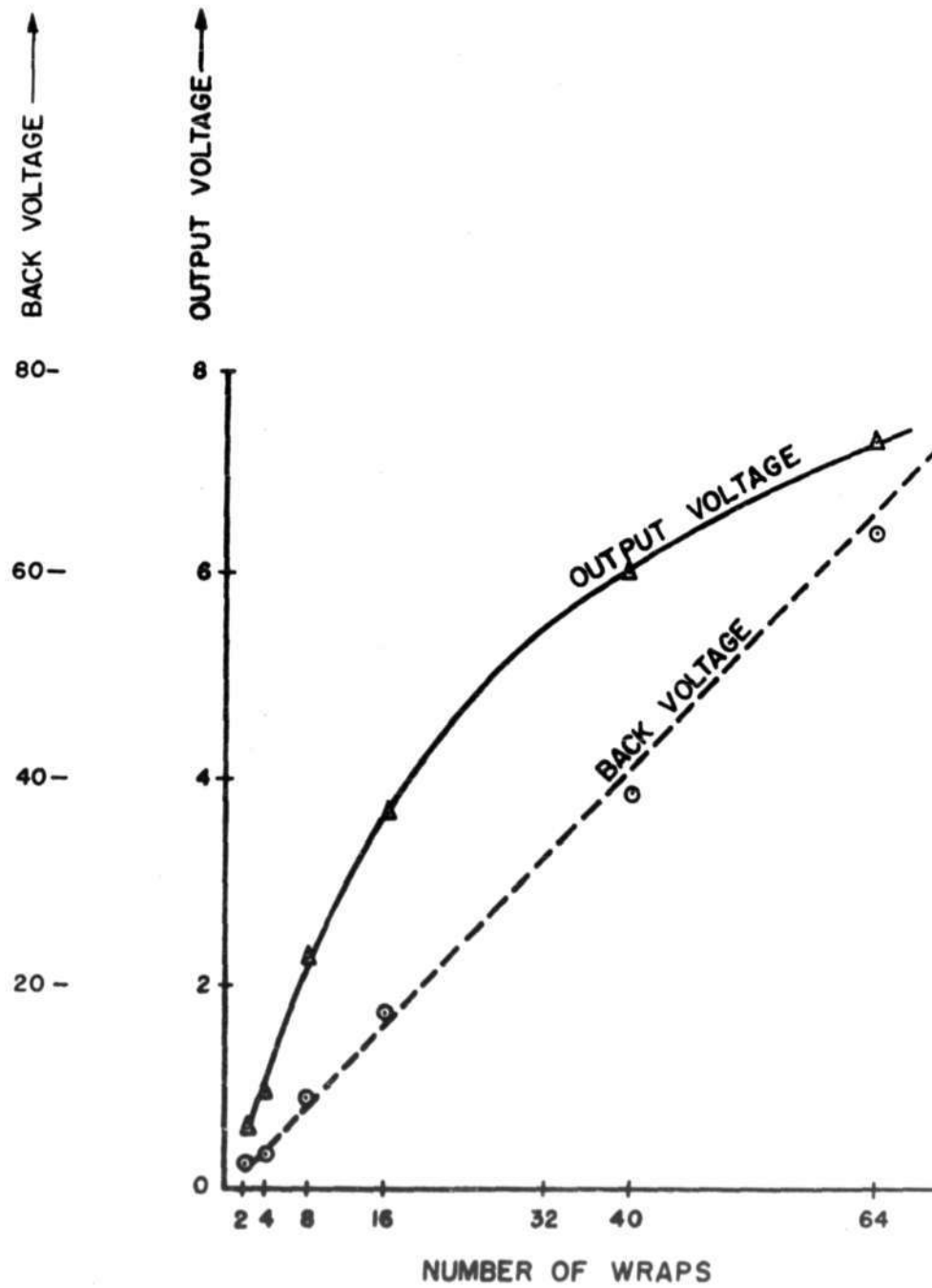


FIG. 18

OUTPUT VOLTAGE AND BACK VOLTAGE  
AS A FUNCTION OF THE NUMBER OF WRAPS  
(INTERNAL  $\beta$  FIELD)

## Materials used:

Setup C (shown in Figure 9)

Memory core: MF-1118 size F-259 ferrite core, with 20-turn sensing winding.

Quadrature-field magnet: MF-666 size F-262 with 20-turn exciting winding.

Setup M<sub>04</sub>

Memory Core: 4-wrap 1/4-mil-thick 1/8-inch-wide Mo-Permalloy 216, 20-turn output winding.

Quadrature-field magnet: Ferramic D 13/16-inch outside diameter with 10-turn exciting winding.

Setup L (shown in Figure 11)

1/4-mil-thick 1/8-inch-wide 10-wrap Mo-Permalloy 216 core with 20-turn sensing winding.

Setup N<sub>02</sub>

1/4-mil-thick 1/8-inch-wide 2-wrap Mo-Permalloy 216 core with 20-turn sensing winding.

As may be seen, back voltages vary a great deal. In the four cases shown, they range from 130 to 1/2 volt.

For applications where outputs of 0.1 volt would be sufficient and where small back voltages are desirable, setup N<sub>02</sub> might be suitable. For applications where large output voltages are needed, a 120-wrap Deltamax core might be useful. Open-circuit outputs of over 50 volts in a 20-turn sensing winding have been obtained with a fast-rising 3.2 ampere  $\beta$ -field-current pulse. This same setup yielded over 20 volts into a 93-ohm terminator.

Transient Behavior

An important question arose early in the investigation: how permanent is this nondestructive read system? It was observed that for a quadrature-field pulse of given magnitude and length, the readout signal did not always remain constant. With relatively short pulses of small amplitude, no change could be detected; but when the quadrature-field pulse approached the limit of the nondestructive system, a definite change could be observed in the magnitude of the readout signal. From a maximum output obtained with a freshly magnetized core, the output would shrink, rapidly at first and then more slowly, until it finally settled at some steady-state value.

Figure 19 shows the traces, as observed on the oscilloscope, of the first fifteen nondestructive readout signals obtained from a freshly magnetized core with internally generated  $\beta$ -field pulses. (The actual photograph is

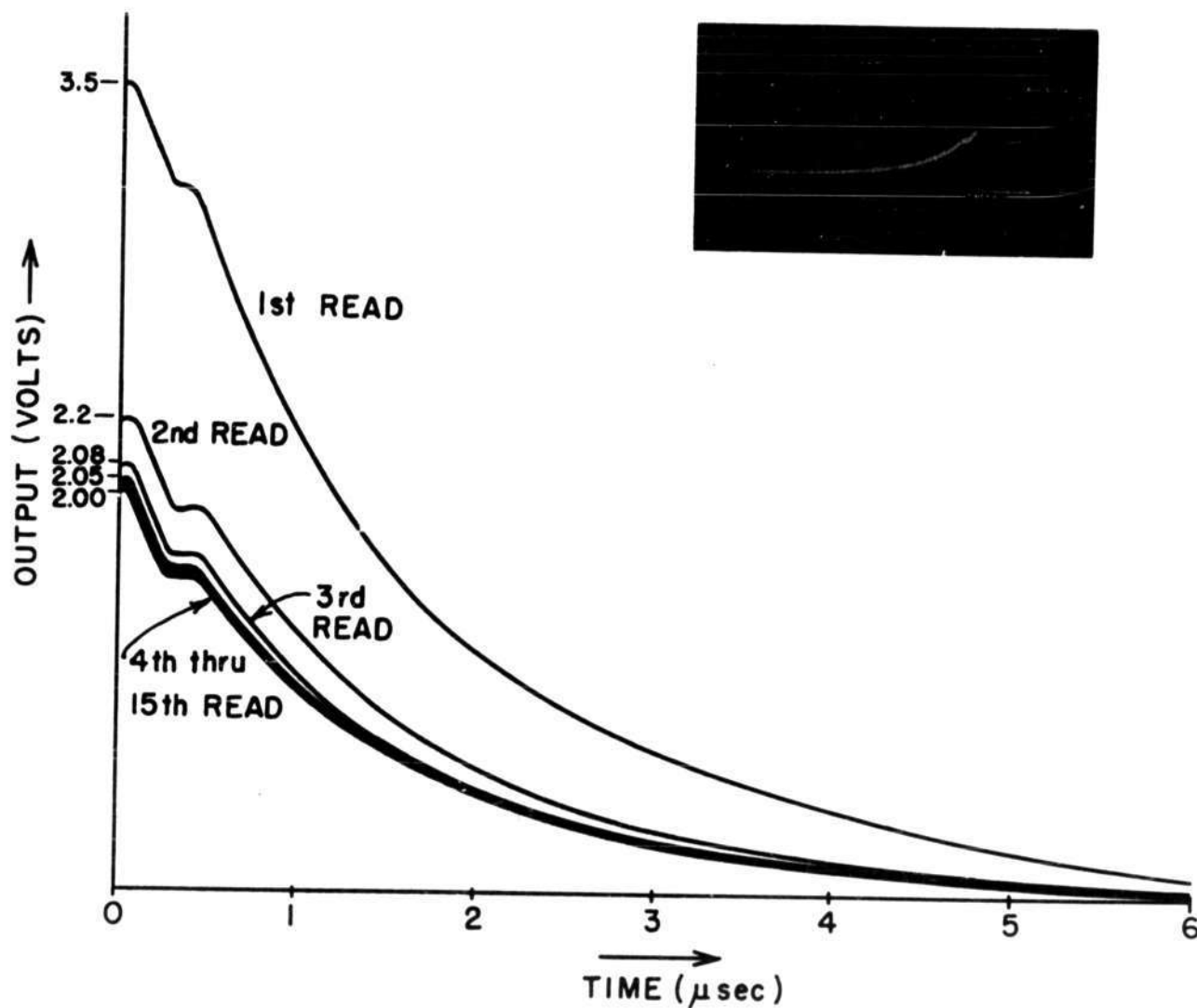


FIG. 19

FIRST 15 READ-OUTS FROM A  
FRESHLY MAGNETIZED CORE

reproduced in the insert; for better visibility the traces were redrawn to a much larger scale.) The pulse was 0.36 ampere high and 6.5  $\mu$ sec long, which, for the type of core used, is very near the destructive limit.

The transient behavior appears to be of an exponential nature. The values obtained are given in the partial table below:

<u>Read Pulse</u>	<u>Output (V)</u>
1 <sup>st</sup>	3.5
2 <sup>nd</sup>	2.2
3 <sup>rd</sup>	(estimated 2.08) 2.0 - 2.1
4 <sup>th</sup>	(estimated 2.05) 2.0 - 2.1
-----	-----
15 <sup>th</sup>	1.9 - 2.0
-----	-----
100 <sup>th</sup>	1.6 - 1.7
-----	-----
10,000 <sup>th</sup>	1.5
-----	-----
15 Millionth	1.5

The core used was a 1/4-mil-thick 1/8-inch-wide 40-wrap Mo-Permalloy 216 core. Repetition rate was 4 kc. At this relatively slow rate, the steady state was reached after about 2-3 seconds; for over an hour thereafter no further changes were observed.

Other endurance tests were run up to 1,200,000,000 readouts, and in all cases no further deterioration of the output signal was noted once it had "settled down."

The number of pulses needed to reach a steady state seems to be inversely related to the magnitude of the quadrature-field pulse. In several cases involving short pulses (0.2  $\mu$ sec), steady state is reached after the second reading.

#### Readout Time

As far as was observed, the lower limit of the readout time seems to depend only on the rise time and length of the B-field-current pulses which the available equipment is able to provide. The fastest pulses so far have been of 0.1- $\mu$ sec rise time and 0.2- $\mu$ sec total length. As illustrated in Figures 13 and 14, the readout signal occurs almost simultaneously with the quadrature-field pulse. There seems to be every reason to expect, if even steeper and narrower quadrature-current pulses could be provided, that the readout signal would also become steeper and narrower, and the voltage correspondingly higher.

SOME FURTHER EXPERIMENTSEffects of Reinforcing Residual Flux

An investigation was made to see what happens when direct current is allowed to flow in the memory-core's magnetizing winding ( $\alpha$ -field winding) while  $\beta$ -field pulses are applied. The effect of the direct current is to increase the  $\alpha$  field. Because of the rectangularity of its hysteresis loop, the magnitude of the residual flux is almost unchanged, but its position is more firmly held in the  $\alpha$  direction: it has been reinforced. Measurements were taken of the core output caused by a given magnitude of the  $\beta$ -field pulse, first without the reinforcing current and then with it.

With a small quadrature-field read pulse the output signal decreased as the residual flux was reinforced. With a relatively large quadrature pulse the output increased when the residual flux was reinforced. W. N. Papian of this Laboratory explained this phenomenon as follows:

As the small  $\beta$  field causes the residual-flux vector to rotate, the sensing winding sees a certain flux change ( $\Delta\phi$  in Figure 20a). When the residual flux is reinforced, the vector is still of the same magnitude but can no longer be rotated as easily as before (Figure 20b), resulting in a smaller flux change and hence in a smaller voltage output.

The large  $\beta$ -field pulses, in the absence of direct current in the magnetizing winding, are powerful enough to switch some of the smaller domains into the  $90^\circ$  direction (Figure 20c), and the residual flux in the  $\alpha$  direction reaches a steady state somewhat below its saturation value. The domains still in the  $\alpha$  direction are deflected as usual; again, the sensing winding effectively sees a change of flux ( $\Delta\phi$ ). When now sufficient direct current is allowed to flow in the magnetizing winding, the small domains are reswitched into the  $\alpha$  direction, and thus the total residual flux in that direction is larger than before. If the rotation caused by the  $\beta$ -field pulses is not too much reduced, the sensing winding will see a larger change of flux than before.

Switching Time of a Memory Core While  $\beta$  Field is Applied

The primary function of the  $\beta$  field is to rotate the remanent flux away from its easy direction of magnetization, that is, away from its most stable state. It was thought that the application of a  $\beta$  field while the  $\alpha$  direction was being switched, say, from a ZERO to a ONE would facilitate this switching process and thereby reduce the switching time of the core. Indeed, it was found that switching time could thus be reduced by up to 30% for a given number of ampere-turns.

Regenerative Effect

During the attempt to find the maximum amplitude and length of the quadrature pulse which various memory cores would tolerate and still yield a nondestructive readout signal, an unexpected phenomenon was observed: under certain circumstances, when information retained by a memory core had been largely destroyed by the application of too powerful a quadrature field, this information could be restored merely by shorting the sensing (output) winding of the memory core during the application of a few quadrature field pulses.

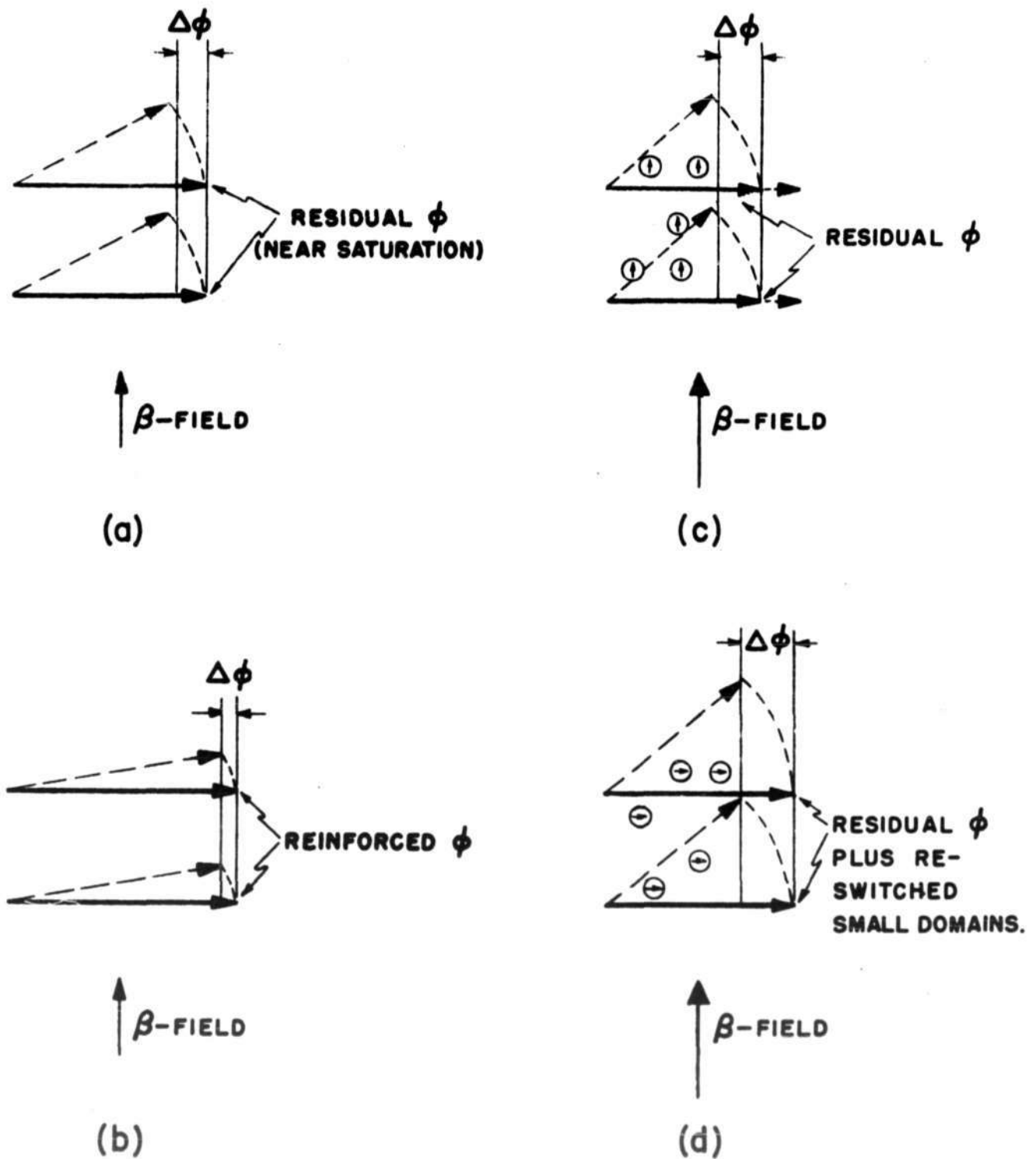


FIG. 20  
EFFECT OF REINFORCED RESIDUAL FLUX



For simplicity's sake, this effect will be referred to as the "regenerative effect."

The effect is by no means found in all cases. So far, it has been observed in only four of the metallic cores (out of over 30 which were used during this investigation) and in none of the ferrite cores.

In a typical case, a 40-wrap 1/4-mil-thick 1/8-inch wide Mo-Permalloy 216 core with a 20-turn unterminated output winding was used. With a 0.5-amp current pulse of 0.1- $\mu$ sec rise time and 0.2- $\mu$ sec length, a ONE output of 13.5 volts was obtained. As the current-pulse length was gradually increased, the output fell, rapidly at first and then more slowly, until at 50- $\mu$ sec pulse length only 1.4 volts was measured. The pulse length was then gradually reduced back to 0.2  $\mu$ sec; the output, however, did not rise above 2 volts, indicating that the information had been largely destroyed, probably because most of the domains had switched into the 90° direction of the  $\beta$  field.

When the output winding was then short-circuited, while the  $\beta$  field pulses continued, regeneration took place; i.e., after the short circuit across the output winding had been removed, the output voltage again stored at 13.5 volts, suggesting the remanent flux had been restored to its original magnitude.

When instead of a short circuit a small resistor was placed across the output winding, the gradual regeneration could actually be observed on the oscilloscope.

Similar results were obtained when the core was magnetized along minor hysteresis loops: application of quadrature field pulses to the core while its output winding was short-circuited brought the remanent flux back to its full saturation value.

No satisfactory explanation of this phenomenon has yet been found. Any thoughts the reader might have about it would be appreciated.

#### Internal $\beta$ Field for Ceramic Cores

A system for generating a  $\beta$  field, and even a  $\gamma$  field, internally was proposed by R. F. Jenney of this Laboratory.

A small cube of ferrite material (Figure 21) is drilled in the three perpendicular directions in such a manner that the three hollows thus obtained pass near one another without actually intersecting. The cube may then be regarded as a core, with the  $\alpha$ -current ( $I_{\alpha}$ ) conductor representing the magnetizing winding and the  $\beta$ -and/or  $\gamma$ -current conductors carrying the quadrature field currents.

Tests with such a drilled-out block of ferrite MF-1326B show that nondestructive reading can be obtained by this scheme.

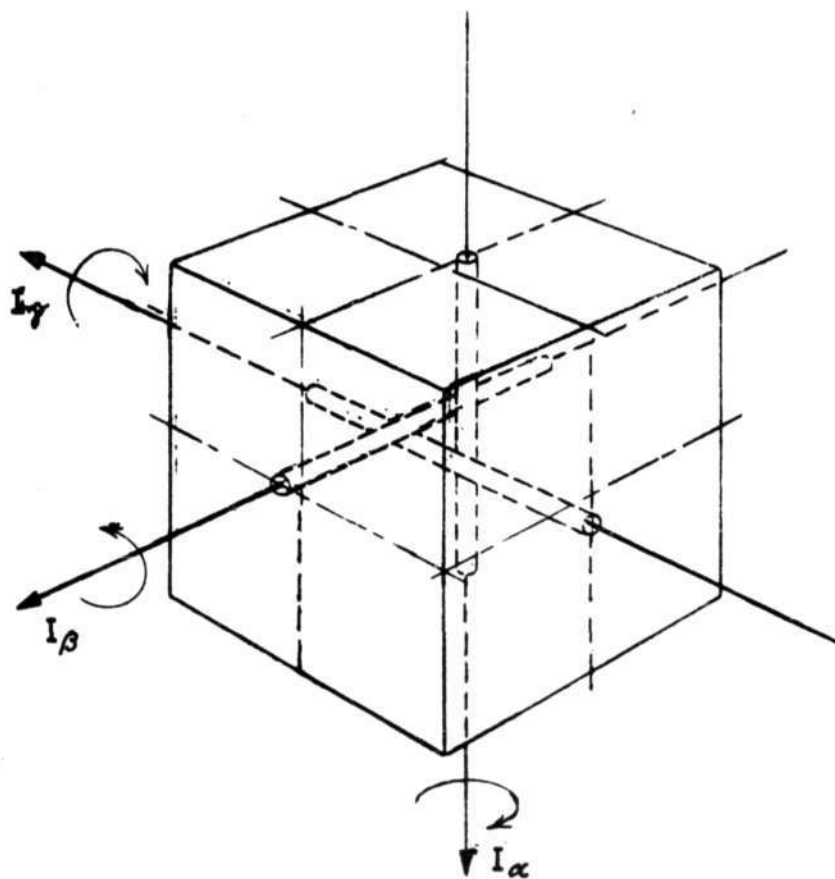


FIG. 21

INTERNALLY GENERATED QUADRATURE FIELDS  
FOR FERRITE MATERIAL

### SOME POSSIBLE APPLICATIONS

Applications for the nondestructive read system could be found wherever permanent or semipermanent memories are used in computers or similar machines.

A magnetic-core binary counter (currently being investigated at this Laboratory) could be equipped with this nondestructive read system, so that the actual count at any one instant could be ascertained without interruption of the process.

A "permanent register" could be built consisting of, say, 16 cores which might be set up by individual toggle switches. If their quadrature fields could be pulsed in series, or possibly if they could all be disturbed by the same quadrature field, all 16 cores could yield their information simultaneously, without the necessity of rewriting the information.

Another possibility might be the use of internally generated  $\beta$  field in a static read system for magnetic-tape recorders or memories using metallic tapes.

Finally, Dr. M. S. Blois suggested the ferromagnetic relaxation oscillator. An oscillator based on the deviation of the magnetic vector under the influence of the quadrature field plus the gyroscopic precession to which this vector would be subject might be stable (since only atomic phenomena are involved) in an ultra-high-frequency region not accessible to quartz resonators. Frequency should be about 5 magacycles per gauss.

### CONCLUSIONS

The principal conclusion to be drawn is that this nondestructive read system works; it furnishes positive information as to the state of magnetization of a memory core without changing that state. The system is fast, and readout times of well below 1  $\mu$ sec are easy to achieve; the lower limits of the system's time response have not yet been found. The system is versatile: several types of material are suitable to be used with it, and two variations of the system have been successfully demonstrated. Furthermore, the effect is not a small one; outputs of over 1 volt per turn have been achieved.

More specifically: the internally-generated  $\beta$  field seems to have several advantages over the external one: it is more compact and more efficient; back voltage can be reduced to reasonably small values (for mass applications); and, above all, output does not depend on position, air gaps, and other variables. External fields, however, would allow the use of a second quadrature field, perpendicular to both the  $\alpha$  and the  $\beta$  field.

Research continues. An explanation will be sought for the regenerative effect. An attempt will be made to reduce back voltages and still retain the present good discrimination between ONE and ZERO.

Signed Dudley A. Buck  
Dudley A. Buck

Werner I. Frank  
Werner I. Frank

Approved DRB  
David R. Brown

DAB/WIF: jk

Drawings attached:

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(100)