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MULTI-COORDINATE SELECTION SYSTEMS FOR MAGNETIC-CORE STORAGE

R. S. DiNolfo

division 6 · lincoln laboratory massachusetts institute of technology

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Approved

R. R. Everett

Report 6R-235

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Report 6R-235

ABSTRACT AND FOREWORD

For many computational applications there is a need for a high-speed digital computer with a large internal memory capacity. The search for a reliable random-access memory with a fast information-access time brought about the development of the magnetic-core memory system. Systems of this type using a 2-coordinate "read" and 3-coordinate "write" have been operating very successfully for some time.

This thesis report reviews and extends the theory of magnetic-core memories for the generalized n-coordinate selection system. The criteria for obtaining the maximum selection ratio under a variety of conditions and arrangements are derived, and the resultant effects on the noise and sensing problem are discussed.

A particular system which uses a 4-coordinate read and 5-coordinate write in an attempt to reduce the number of required electronic circuits is analyzed. Experimental work with the breadboard of such a system (using a 3-to-2 selection-current ratio) was performed. The results, here indicated, show that a 4096-bit digit plane (8 driving lines in each of the 4 coordinates) is operable, albeit with very narrow margins, with a memory cycle time of approximately 9 microseconds, and with no more than one-fourth the number of driving cathodes required by a comparable system which uses a 2-coordinate read and a 3-coordinate write. The recent development of improved cores and diodes satisfactory for low-level mixing of memory signals could be used to improve the operating margins significantly.

Report 6R-235

Because it presents information of general interest, this thesis report, which has had only very limited distribution, is being issued as a Division 6 R-Series Report.

R. S. Di Nolfo

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS
(continued)

PART I

THE THEORY OF CORE MEMORY SYSTEMS

CHAPTER 1

SELECTION

1.01 The Basic Problems

To illustrate more clearly the basic concepts involved in random access magnetic-core memory systems, this section on the theory of selection will be developed for idealized memory elements. However, all that is derived for this case will apply directly or with slight modifications to the actual case.

The memory element to be considered is a ferromagnetic toroid which has nearly rectangular hysteresis loops. For binary storage* two remanent flux states of the core are used to represent the two digits, ZERO and ONE, as defined for the hysteresis loop of Fig. 1.01a.

In using an array of these elements as a storage medium, it is necessary that the system be able to perform two functions. The first is determining the information state of one or more cores, and the second is putting these cores in a desired information state; both of these being done without affecting the information state of the other cores in the array. An operation of the first type will be referred to as "reading" and that of the second type as "writing."

From a study of Fig. 1.01a, a suitable read operation may be defined as exciting the selected core with a pulse of current of maximum

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*Only binary storage will be considered in this thesis.

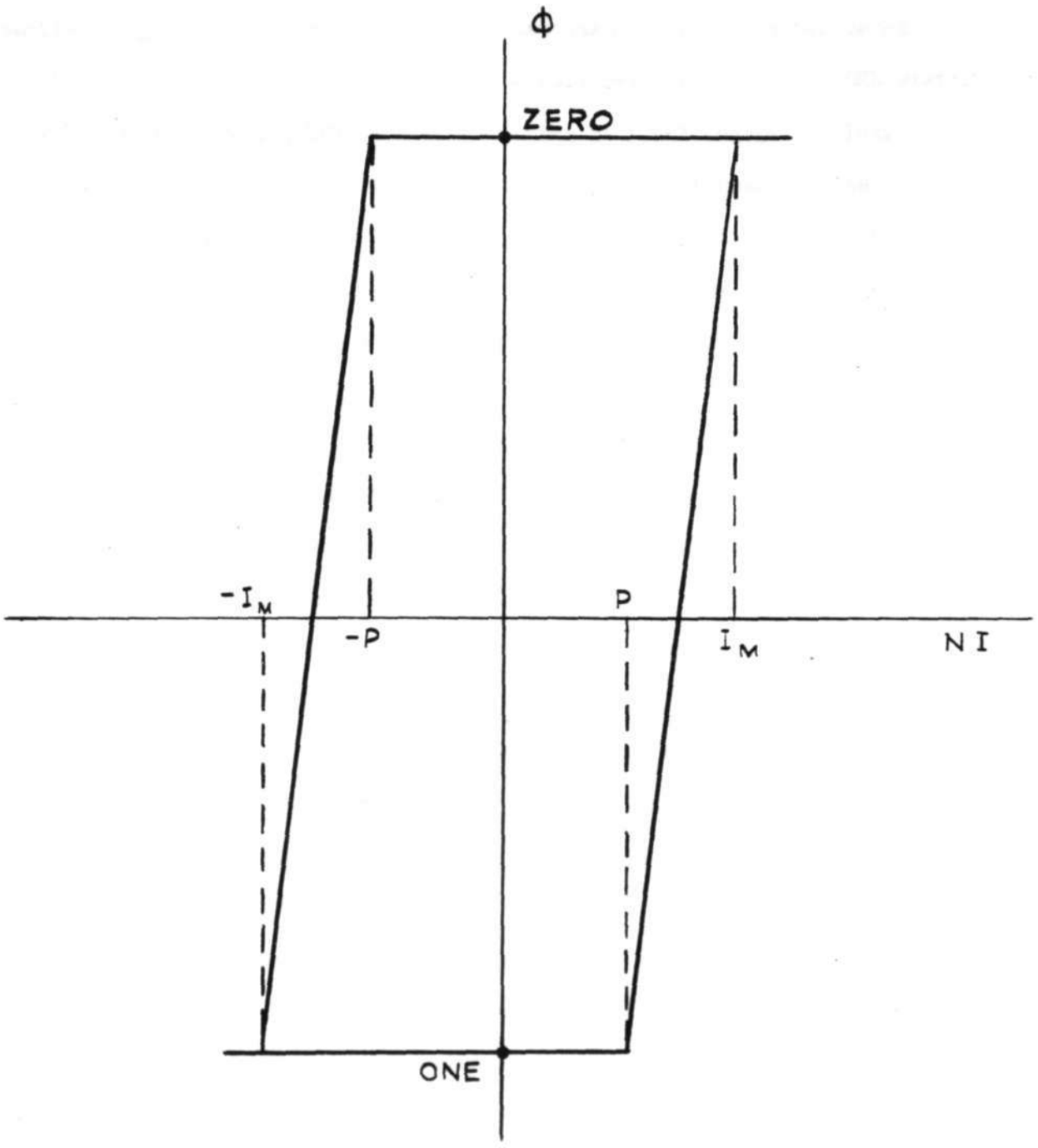

FIG. 1.01 a

HYSTERESIS LOOP OF AN IDEAL MEMORY CORE

A-59648

amplitude I_m, while restricting the excitations of the unselected cores to less than P and greater than -P. If a selected core is in the ONE state, it will "switch" to the ZERO state, resulting in a net change in flux, whereas if it is originally in the ZERO state, it will reassume its original state after the read operation with no change in flux. The flux state of all unselected cores will remain unchanged. If a "sense" winding is passed through a selected core, the reading of a ONE will induce a voltage in the winding, whereas the reading of a ZERO will induce no voltage in the winding. Voltage or flux amplitude discrimination can be used to distinguish a ONE from a ZERO, the first technique being a measure of the time derivative of flux. These two methods of detection will be discussed and compared more fully in the next chapter.*

Since after reading, a core in the ONE state will be left in the ZERO state, the read operation is destructive.** Consequently, if a core is to be left in the ONE state, the read must be followed by a write consisting of exciting the core with a pulse of current of maximum amplitude $-I_m$. Again the excitations of all unselected cores must be restricted to less than P and greater than -P.

1.02 Necessary and Redundant[3] Coordinates

As a basis for further discussion of selection systems, three definitions will be made at this point.

Definition 1: A coordinate of a selection system is a group of driving lines which do not intersect at any core within the array.

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*See Section 2.03.

**Only the destructive read described will be discussed in this thesis. Non-destructive reads have been devised and the reader is referred to References 1 and 2.

Definition 2: A coordinate of a selection system is a necessary coordinate if upon removing it the same selection cannot be accomplished by an adjustment of the excitations in the remaining coordinates.

Definition 3: A coordinate of a selection system is a redundant coordinate if upon removing it the same selection can be accomplished by an adjustment of the excitations in the remaining coordinates.

To illustrate the definitions given above, first consider Fig. 1.02a. If an X, Y, and Z driving line are chosen, it is possible, with the proper choice of excitations, to select the one core lying at the intersection of the three selected lines without destroying the information states of the other cores. However, if any one of the three coordinates is removed (Fig. 1.02b), it is impossible to select only a single core for each choice of driving lines in the remaining coordinates since any line of one coordinate intersects those of another more than once. Therefore, the three coordinates of this system are nonredundant.

Fig. 1.02c shows a redundant system. Any one of the three coordinates is redundant since it may be removed (Fig. 1.02d) and the same selection accomplished, i.e., any core can be selected singly by an adjustment of excitations in the remaining coordinates.

The remainder of this thesis will be confined to the analysis of nonredundant systems, and the word coordinate without further qualification implies necessary coordinate.

1.03 p_{min} as a Function of the Number of Coordinates[3]

Consider an n-coordinate system which is capable of selecting a single core from an array of cores. Each core is at the intersection of n driving lines, one in each coordinate, and a core is selected by exciting one line in each coordinate such that the sum of the excitations

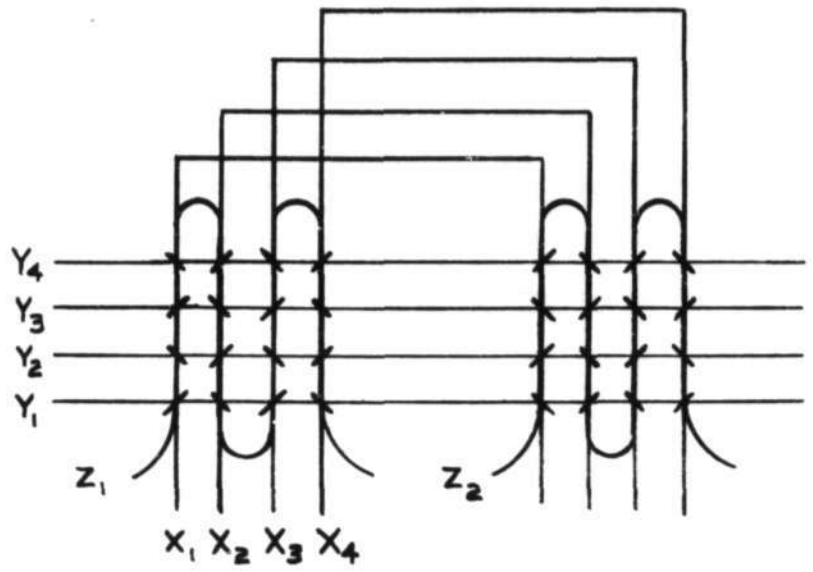

FIG. I. 02 a

A NONREDUNDANT SELECTION SYSTEM

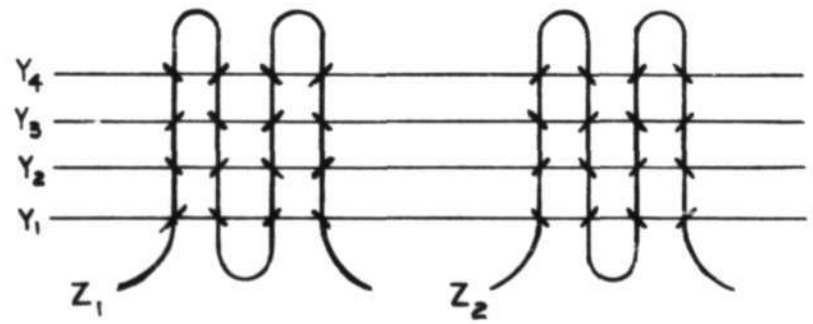

FIG. I.02 b

THE SYSTEM OF FIG. I.02 a WITH THE X COORDINATE REMOVED

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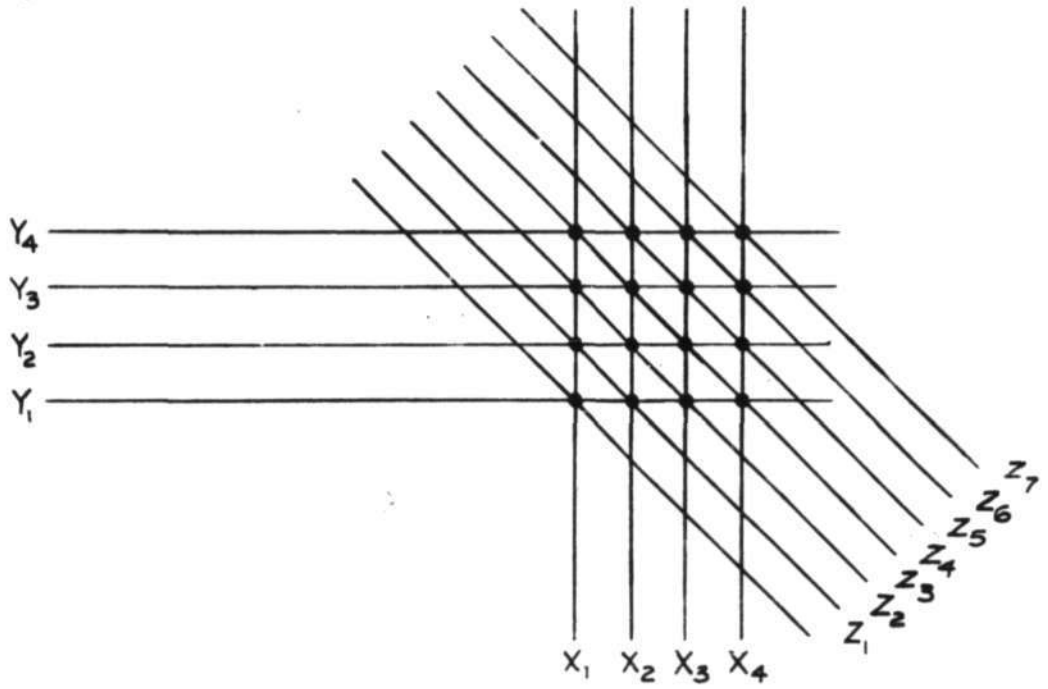


FIG. 1.02 c

A REDUNDANT SELECTION SYSTEM

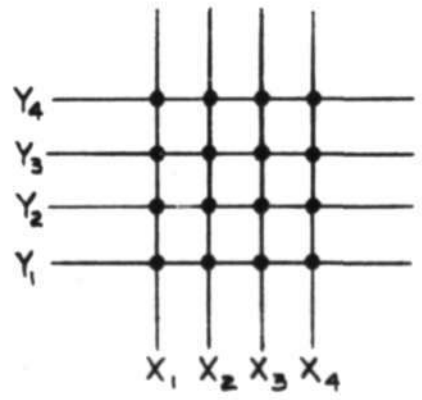


FIG. 1.02 d

THE SYSTEM OF FIG. 1.02 c
WITH THE Z COORDINATE REMOVED

A-59644

is one unit. (See the hysteresis loop of Fig. 1.03a.) All other driving lines are excited so that at any other core the total excitation is less than p and greater than -p. The lines passing through the selected core will be termed selecting lines, and all other lines unselecting lines. For this system the minimum required value of p (p_{min}) is of interest since it places the least requirement on the rectangularity of the hysteresis loop, and this can be easily found in the following manner:

Since one and only one driving line from each coordinate passes through a core, if an equal amount is added to all the driving lines, selecting and unselecting, of any one coordinate, the excitation of all the cores will be changed by this amount. Let s_j be defined as the value of the excitation of the selecting line in the jth coordinate, and let u_j be defined as the value of the excitations of the unselecting lines in the same coordinate. By adding $-s_j$ to the excitations of all the driving lines in the jth coordinate, the excitation on all the cores will change by $-s_j$. If this process is repeated for all n coordinates, i.e., $-s_k$ is added to the driving lines of the kth coordinate, etc., the excitation on all the cores will diminish by one unit since as previously stated the sum of the selecting excitations is unity, $\sum_{j=1}^{n} s_j \triangleq 1$.

Passing through any unselected core there can be a minimum of one and a maximum of n unselecting lines, and if the above procedure were to be carried out, the maximum excitation on an unselected core would be $-U_j$ and the minimum excitation would be $-\sum_{j=1}^{n} U_j$, where

$$U_j \triangleq -(u_j - s_j) \cong s_j - u_j;\ j \cong 1,2,\cdots,n \qquad (1)$$

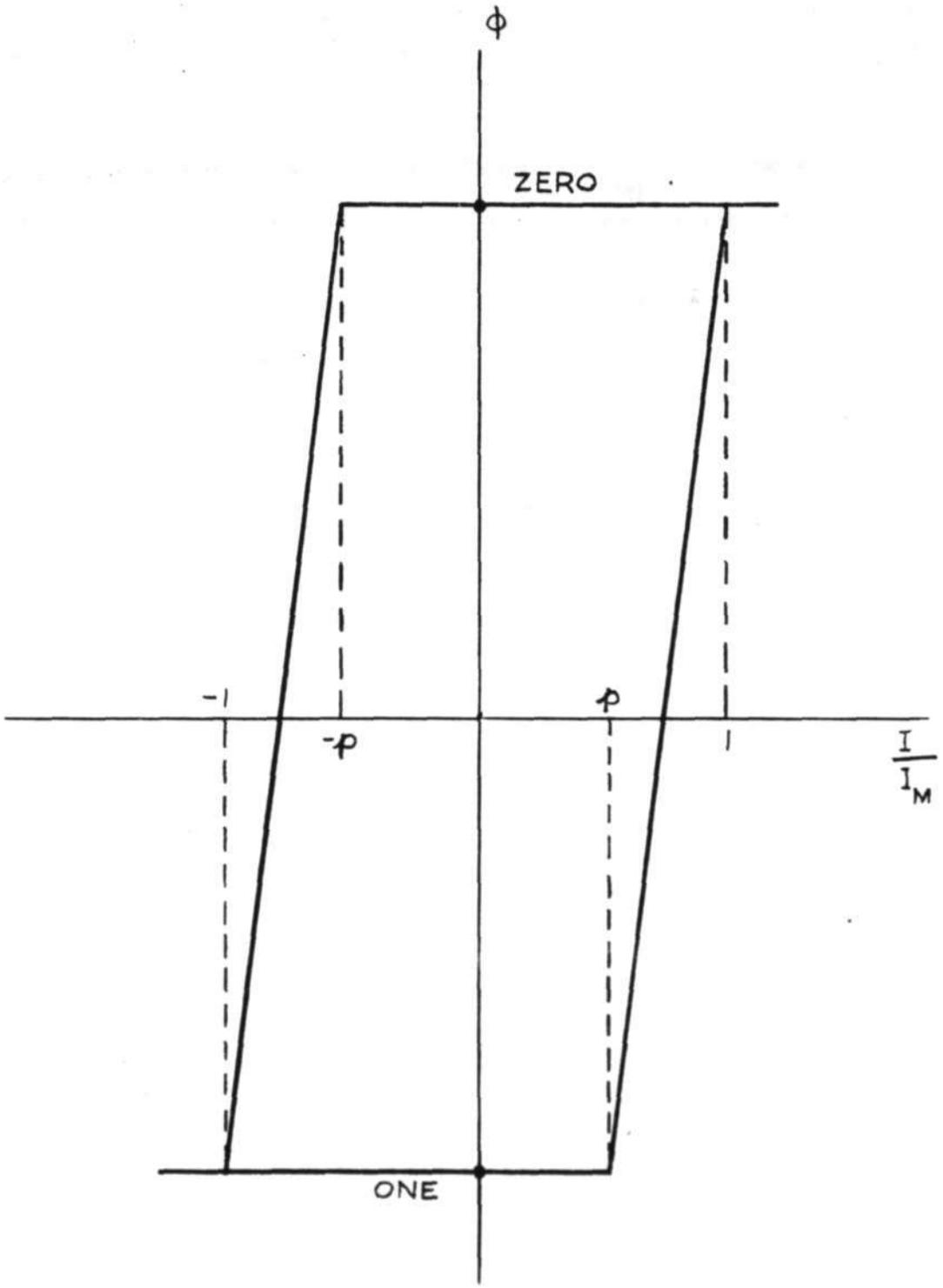


FIG. 1.03a

HYSTERESIS LOOP OF AN IDEAL MEMORY CORE

A-59645

Therefore, for the original system, the maximum excitation on an unselected core is $1-U_j$ and the minimum excitation is $1-\sum_{j=1}^{n} U_j$. From a consideration of the hysteresis loop (Fig. 1.03a), the restrictions on the system are

$$1-U_j \geq 0 \tag{2}$$

and

$$1-\sum_{j=1}^{n} U_j \geq -p \tag{3}$$

or subtracting one from both sides of inequality 1.03-(2) and summing from j=1 to j=n,

$$-\sum_{j=1}^{n} U_j \leq -n(1-p) \tag{4}$$

and subtracting one from both sides of inequality 1.03-(3),

$$-\sum_{j=1}^{n} U_j \geq -(1+p) \tag{5}$$

Combining inequalities 1.03-(4) and 1.03-(5)

$$-n(1-p) \geq -(1+p) \tag{6}$$

$$p \geq \frac{n-1}{n+1} \tag{7}$$

and therefore,

$$p_{min} = \frac{n-1}{n+1} \tag{8}$$

When the selection ratio (R) is defined as the excitation applied to the selected core divided by the maximum excitation applied to any unselected cores,

$$R_{max} = \frac{1}{p_{min}} = \frac{n+1}{n-1} \tag{9}$$

1.04 Necessary Condition for R_{max}

Continuing the discussion of the previous section, the next step is to obtain the necessary condition for R_{max}. This is easily obtained from the inequalities 1.03-(4) and 1.03-(5) by a substitution of equation 1.03-(8).

$$-(1+p) \leq -\sum_{j=1}^{n} U_j \leq -n(1-p) \tag{1}$$

and

$$p_{min} = \frac{n-1}{n+1} \tag{2}$$

therefore

$$\frac{-2n}{n+1} \leq -\sum_{j=1}^{n} U_j \leq \frac{-2n}{n+1} \tag{3}$$

$$\sum_{j=1}^{n} U_j = \frac{2n}{n+1} \tag{4}$$

But from inequality 1.03-(2)

$$U_j \geq (1-p) = \frac{2}{n+1} \tag{5}$$

and therefore

$$U_j = \frac{2}{n+1} \tag{6}$$

To determine what restriction this imposes on the original n-coordinate selection system, equation 1.03-(1) is recalled and the final result is that

$$s_j - u_j = \frac{2}{n+1} \; ; \quad j = 1,2,\cdots n \tag{7}$$

is a necessary condition for a maximum selection ratio, and this constraint with the original constraint that

$$\sum_{j=1}^{n} s_j = 1 \tag{8}$$

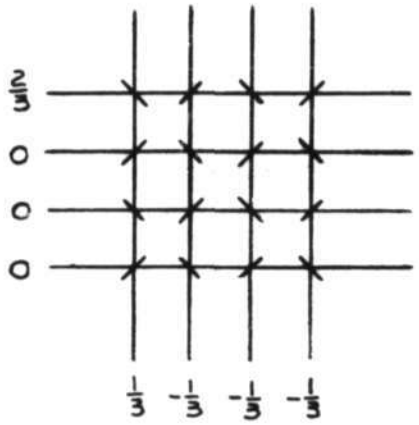
define the system. In a practical system the further restriction that

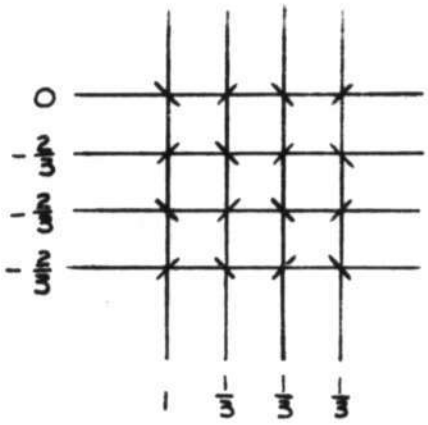
$$|u_j| \; ; \; |s_j| \leq \frac{2}{n+1} \tag{9}$$

is required to allow for variations in the times that the drivers take to reach maximum amplitude.

Fig. 1.04a shows two systems with a maximum selection ratio. Since in both cases n=2,

$$R_{max} = \frac{n+1}{n-1} = \frac{3}{1} \tag{10}$$





1	1/3	1/3	1/3
1/3	-1/3	-1/3	-1/3
1/3	-1/3	-1/3	-1/3
1/3	-1/3	-1/3	-1/3

1	1/3	1/3	1/3
1/3	-1/3	-1/3	-1/3
1/3	-1/3	-1/3	-1/3
1/3	-1/3	-1/3	-1/3

EACH NUMBER IN THE TABLES CORRESPONDS TO THE EXCITATIONS RECEIVED BY THE CORES IN THE SIMILAR POSITIONS IN THE ARRAY.

FIG. 1.04a

EXAMPLES OF 2-COORDINATE SYSTEMS

A-59643

and

$$s_j - u_j = \frac{2}{n+1} = \frac{2}{3} \tag{11}$$

By comparing the tables it should be noted that the distributions of excitations are identical. For any two nonredundant systems of the same n, this is always the case when the conditions for a maximum selection ratio are adhered to. This is implied in equation 1.04-(4), and is more readily seen in equation 1.04-(6).

1.05 The Choice of u_j and s_j

In the previous section it was shown that the only restrictions on s_j and u_j are:

$$-(1+p) \leq \sum_{j}^{n} u_j - s_j \leq -n(1-p) \tag{1}$$

and

$$\sum_{j=1}^{n} s_j = 1 \tag{2}$$

However, it is desirable to make either the unselecting or the selecting excitations zero in as many coordinates as possible since this system will require the smallest number of drivers. The following is a derivation of the best possible selection ratio that can be obtained when this is done, and it will be shown that this ratio cannot always be made equal to R_{max}.

Let N_u be the number of coordinates in which the excitations of the unselecting lines are zero, and let N_s be the number of coordinates

in which the excitation of the selecting line is zero. Then,

$$N_u \pm N_s = n \tag{3}$$

A study of Section 1.03 shows that for the best possible selection ratio

$$U_1 = U_2 = \cdots = U_n \triangleq U \tag{4}$$

since

$$R \triangleq \frac{1}{1-U_j} \tag{5}$$

Therefore,

$$s_j - u_j \triangleq U \; ; \; j = 1, 2, \cdots n \tag{6}$$

But in each coordinate either u or s is zero, and therefore, either

$$u \triangleq -U \tag{7}$$

or

$$s = U \tag{8}$$

with the least allowable value of p being correspondingly

$$p = 1+u \triangleq 1-s \tag{9}$$

Substituting the previous expressions into inequality 1.05-(1) and equation 1.05-(2), the conditions become

$$-(1+1-s) \leq n\,U \leq -n(1-1+s) \tag{10}$$

$$-(2-s) \leq n\,U \leq -ns \tag{11}$$

$$-(2-s) \leq -ns \leq -ns \tag{12}$$

$$-(2-s) + ns \leq o \tag{13}$$

$$-2 + (n+1)\, s \leq o \tag{14}$$

and

$$N_s\, s = 1 \text{ or } s = \frac{1}{N_s} \tag{15}$$

Substituting for s in 1.05-(14)

$$-2 + (n+1)\, \frac{1}{N_s} \leq o \tag{16}$$

$$N_s \geq \frac{n+1}{2} \tag{17}$$

and since

$$N_s = n - N_u \tag{18}$$

$$N_u \leq \frac{n-1}{2} \tag{19}$$

By combining equation 1.05-(5), (9) and (15), the best possible selection ratio can be expressed as

$$R = \frac{N_s}{N_s - 1} \tag{20}$$

where N_s is as small an integer as possible. When n is an even integer, the smallest integral value N_s can take on is

$$N_s = \frac{n+2}{2} \tag{21}$$

and correspondingly,

$$N_u = \frac{n-2}{2} \tag{22}$$

The best possible selection ratio is then

$$R(n) = \frac{n+2}{n} = R_{max}\,(n+1) \tag{23}$$

However, if n is an odd integer,

$$N_s = \frac{n+1}{2} \tag{24}$$

and

$$N_u = \frac{n-1}{2} \tag{25}$$

giving a best possible selection ratio of

$$R(n) = \frac{n+1}{n-1} = R_{max}(n) \tag{26}$$

Considering the case when n is an even integer, the value of U_j can be obtained from substituting equation 1.05-(23) into equation 1.05-(5).

$$U_j = 1 - \frac{n}{n+2} = \frac{2}{n+2} \tag{27}$$

For the case of n equal to an odd integer U_j is as given in equation 1.04-(6)

$$U_j = \frac{2}{n+1} \tag{28}$$

Therefore,

$$s_j - u_j = \begin{cases} \frac{2}{n+2} & \text{for even } n \\ \frac{2}{n+1} & \text{for odd } n \end{cases} \qquad (29)$$

1.06 Parallel-Digit Storage

Magnetic-core memories of the type described are ideal for parallel-type computers. In this case, a binary word of D digits is stored in the memory, all digits being stored simultaneously. The group of D cores in which the digits of a single word are stored is called a register, and the read operation consists of selecting all the cores of the selected register, whereas the write, which follows the read, consists of selecting only those cores of the register which are to be switched to the ONE state. The important point to note is that, in general, the write utilizes at least one more coordinate than the read, i.e., the read selects all the cores of the register whereas the write must discriminate between the different digits comprising a register.

Since only one register is selected at a time a single sense winding can pass through a given digit of all the registers. Generally, these cores on the same sense winding are placed in the same plane, and hence, the term "digit plane" is often used in reference to them.

All the derivations of the previous sections apply to systems of this type. The read selection and write selection are considered separately, the formulas being evaluated for the particular values of n, and in general, a system using an n-coordinate read will use an $(n+1)$-coordinate write.

1.07 An Economical Means of Doubling Memory Capacity for Even n*

Consider the special case discussed in Section 1.05 where either the selecting excitation or unselecting excitations in each coordinate are zero. For this case it will be shown that whenever n is even it is possible to double the selection capacity without doubling the number of drivers in a coordinate, but first the case for n=2 will be illustrated.

Referring to Fig. I.07a, any core to the left of the dotted line can be selected by exciting the selected driving line in each coordinate with $I_j = \frac{1}{2}$, and any core to the right of the dotted line can be selected by exciting the selected line in one coordinate with $I_1 = \frac{1}{2}$ and the selected line in the other coordinate with $I_2 = -\frac{1}{2}$. Tabulated below the figure are the excitations for each case, and it is seen that the 2 to 1 selection ratio which would otherwise be obtained (equation 1.03-(9)) has not been affected.

At a first glance it would seem that nothing is gained since it is now necessary to have drivers of the opposite polarity, and the same effect could be obtained by just doubling the number of driving lines in a coordinate. However, when it is recalled that in a system, both read and write drivers are need, and that a write excitation can be made equal in magnitude but opposite in polarity to a read excitation, the benefits of the system are seen. To obtain the desired effect, it is only necessary to use the write drivers of one coordinate during the read cycle when the cores to the right of the dotted line are to be selected.

Consider again the case of Section 1.05, but now for any n.

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*This was first pointed out to the author for the case when n=2 by D. A. Buck.

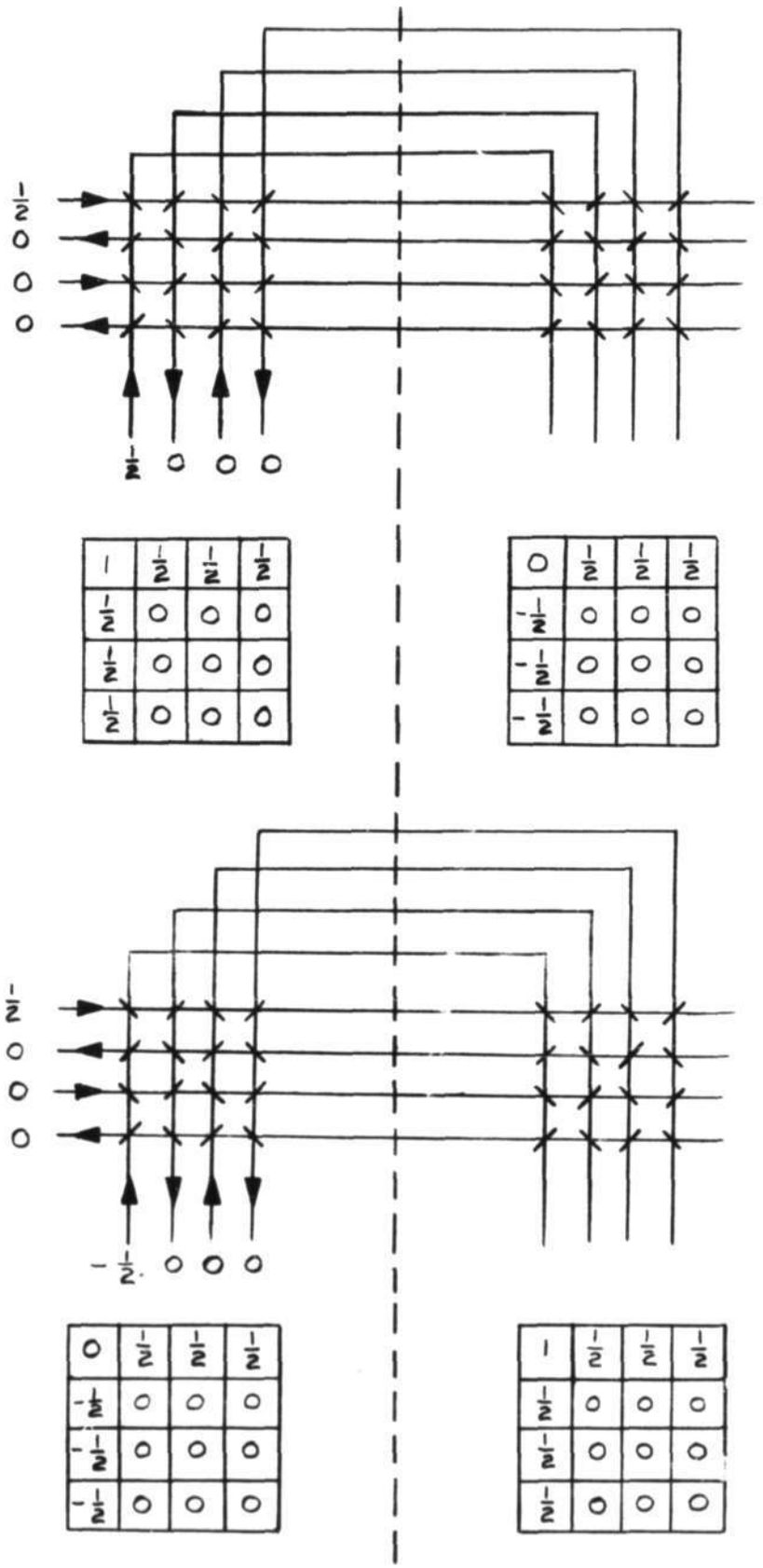

FIG. 1.07a

DOUBLING MEMORY CAPACITY FOR EVEN n

The maximum excitation is received by the selected core, and the value of this excitation is unity for both odd and even n. However, the minimum excitation any core receives is a function of n, and this function is not the same for odd and even n. The minimum excitation is

$$N_u\left[\frac{-2}{n+2}\right] \cong \frac{n-2}{2} \cdot \frac{-2}{n+2} \cong -\frac{n-2}{n+2} \text{ for even n} \qquad (1)$$

and

$$N_u\left[\frac{-2}{n+1}\right] \cong \frac{n-1}{2} \cdot \frac{-2}{n+1} \cong -\frac{n-1}{n+1} \text{ for odd n} \qquad (2)$$

Also, the best possible selection ratios are

$$R(n) \cong \frac{n+2}{n} \text{ for even n} \qquad (3)$$

and

$$R(n) \cong \frac{n+1}{n-1} \text{ for odd n} \qquad (4)$$

Now, consider reversing the polarity of just one of the selecting lines. Then the maximum excitation any core receives is now also a function of n and is

$$\left[N_s-1\right]\left[\frac{2}{n+2}\right] \cong \frac{n}{2} \cdot \frac{2}{n+2} = \frac{n}{n+2} \text{ for even n} \qquad (5)$$

and

$$\left[N_s-1\right]\left[\frac{2}{n+1}\right] \cong \frac{n-1}{2} \cdot \frac{2}{n+1} = \frac{n-1}{n+1} \text{ for odd n} \qquad (6)$$

and the minimum excitation is now

$$N_u \left[\frac{-2}{n+2}\right] + 1 \left[\frac{-2}{n+2}\right] = \left[\frac{n-2}{2}\right]\left[\frac{-2}{n+2}\right] - \frac{2}{n+2} = \frac{-n}{n+2} \text{ for even } n \quad (7)$$

and

$$N_u \left[\frac{-2}{n-1}\right] + 1 \left[\frac{-2}{n+1}\right] = \left[\frac{n-1}{2}\right]\left[\frac{-2}{n+1}\right] - \frac{2}{n+1} = -1 \text{ for odd } n \quad (8)$$

The best possible selection ratio for even n is still

$$R(n) = \frac{n+2}{n} \quad (9)$$

However, a system of odd n is no longer possible because of the possibility of the -1 excitation destroying the information stored in the array. Therefore, only when n is even is it possible to reverse the polarity of one selecting line without affecting the information state of the array. This fact plus the fact that two driving lines can be passed through a core such that the total excitation is either the sum or difference of the two separate excitations makes it possible, when n is even, to double the selection capacity without doubling the number of drivers in a coordinate.

The read selection is done by an even coordinate system and no additional drivers are necessary to read the information in the additional registers. However, since the write is one coordinate more than the read, the write selection will be done by an odd coordinate system, and, therefore, the number of drivers in one write coordinate must be doubled to write in the additional registers. Consequently, the total memory capacity can be doubled by doubling the number of drivers in just a write coordinate.

1.08 External Selection

No mention has been made yet of the means of selecting the driving lines within a memory coordinate. Generally, the initial selection in each coordinate is done by f_j bi-stable elements, where f_j is an integer related to d_j, the number of driving lines in the jth coordinate, by the equation

$$2^{f_j} = d_j \; ; \quad j = 1,2, \cdots n \tag{1}$$

Therefore, the external selection problem is that of going from an f_j coordinate system of two driving lines per coordinate to a one coordinate system of d_j driving lines. Except for the trivial case when d_j is equal to two, an intermediate system is necessary for performing this conversion. Usually it consists of a diode matrix switch [4,5], and its associated buffer amplifiers selecting gated drivers which excite either the memory coordinate line(s) or the coordinate line(s) of a magnetic core matrix switch[6,7,8,9] which excites a memory coordinate line*.

A. Diode Matrix Switch

Figure 1.08a shows a schematic of a diode matrix where for each setting of the bi-stable elements one output will be positive with respect to all other outputs which are at approximately the same potential, and Fig. 1.08b shows a matrix where the opposite is true. By properly biasing the gated drivers and using the correct type of diode matrix, either one or all but one of the drivers can be made to conduct when they are gated on.

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*The core switch cannot be used when several memory coordinate lines are to be excited simultaneously. Also, the diode matrix is unnecessary when the number of switch coordinates equals f_j.

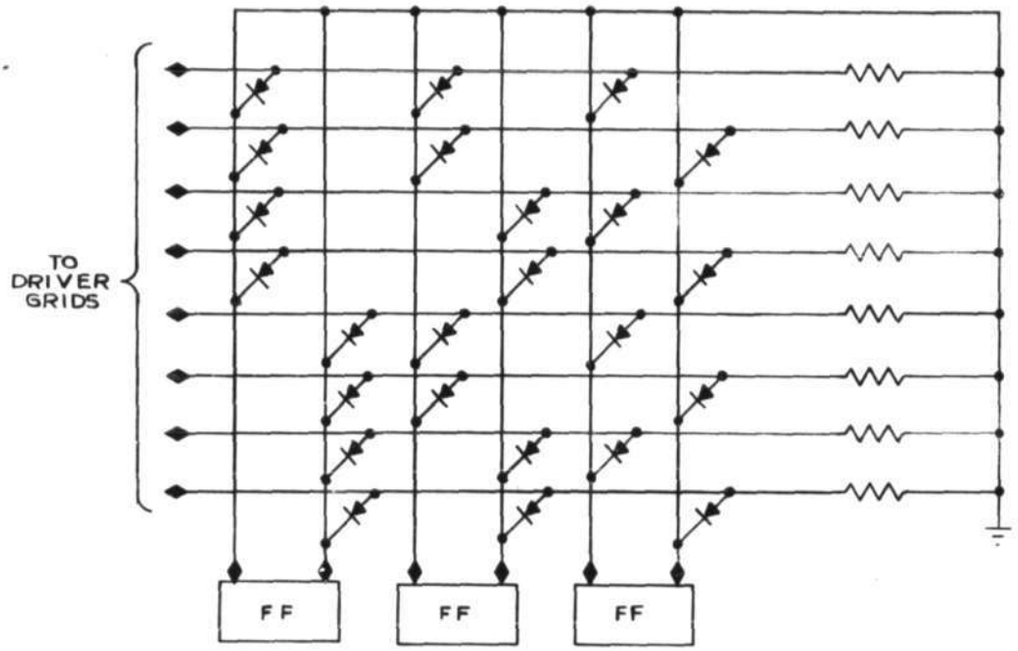


FIG. 1.08 a

CRYSTAL MATRIX FOR SELECTING A SINGLE DRIVER

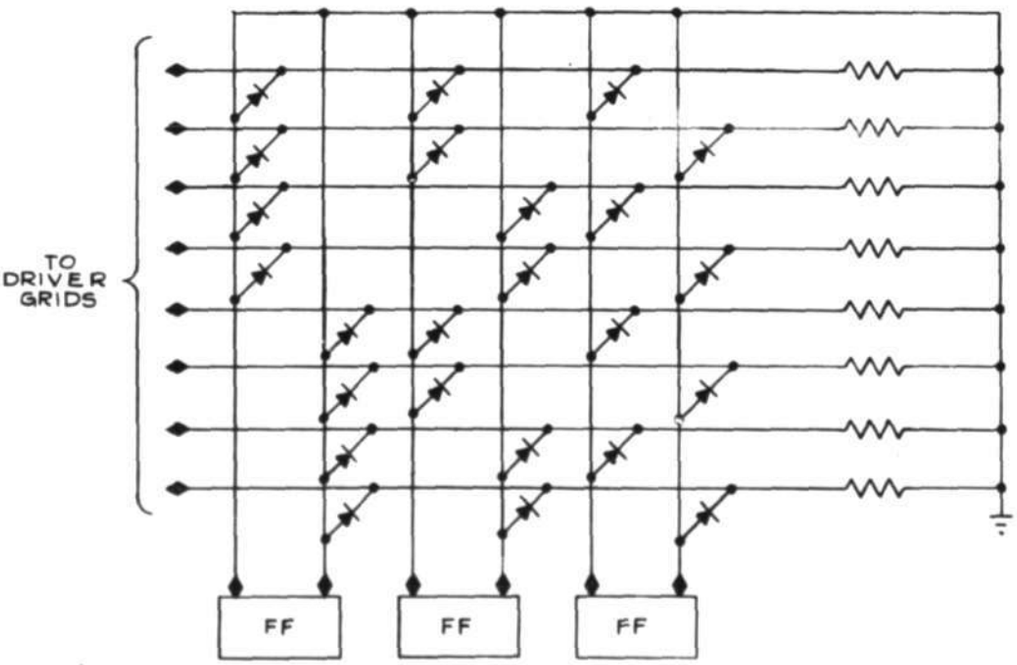


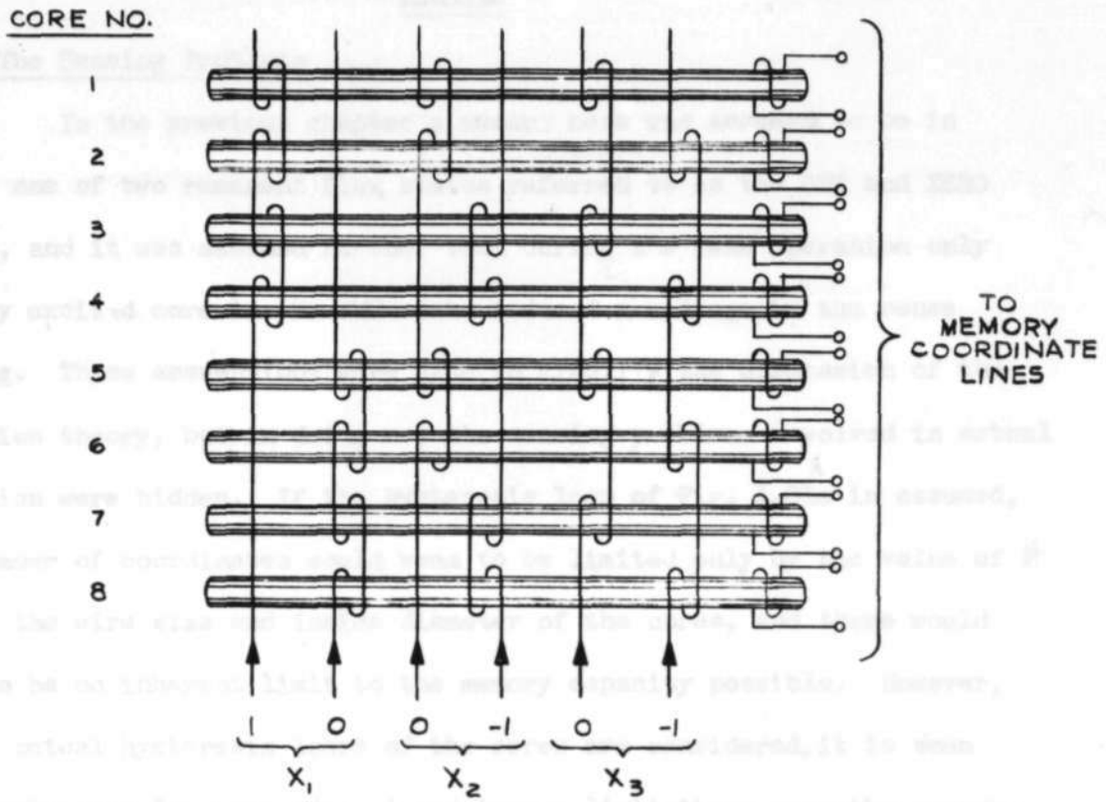
FIG. 1.08 b

CRYSTAL MATRIX FOR SELECTING ALL BUT ONE DRIVER

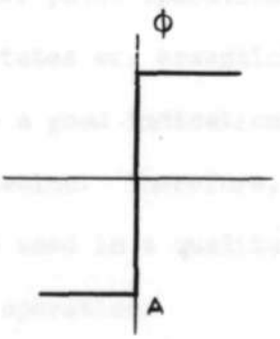
If the drivers are gated, this is another degree of selection in addition to that obtained from the diode matrix, and, therefore, each matrix output can be used to control the grid potential of more than one driver, each of these being selected by a different gate generator which is in turn selected by a bi-stable element.

B. Core Switch

Fig. 1.08c is a schematic of a magnetic core switch. The switch consists of an array of cores similar to the memory array, but unlike the memory, every core is in the same state at the beginning of each cycle (State A as shown in the figure). Therefore, the problem of selecting a single core from the switch core array is less severe than for the memory array. The only requirements are that the sum of the selecting excitations is equal to the switching current and that the unselecting excitations are of sufficient magnitude to bias all other cores so that they cannot switch. The outputs from the switch cores excite the memory lines directly, and the switch must be designed to give the proper outputs.



CORE NO.	EXCITATION
1	1
2	0
3	0
4	-1
5	0
6	-1
7	-1
8	-2



A HYSTERESIS LOOP OF AN IDEAL SWITCH CORE

FIG. 1.08 c

A 3 — COORDINATE MAGNETIC CORE SWITCH

A-59647

CHAPTER 2

SENSING

2.01 The Sensing Problems

In the previous chapter a memory core was assumed to be in either one of two remanent-flux states referred to as the ONE and ZERO states, and it was assumed further that during the read operation only a fully excited core in the ONE state induced a voltage in the sense winding. These assumptions were made to simplify the discussion of the selection theory, but in doing so, the sensing problems involved in actual operation were hidden. If the hysteresis loop of Fig. 1.01a is assumed, the number of coordinates would seem to be limited only by the value of F and by the wire size and inside diameter of the cores, and there would seem to be no inherent limit to the memory capacity possible. However, if the actual hysteresis loops of the cores are considered, it is seen that deviations from the ideal loops impose limitations upon the memory.

Although the hysteresis loop traversed under pulse operation and the D.C. hysteresis loop differ, the remanent flux states are essentially the same,[10] and the shape of the D.C. loop does give a good indication of the suitability of a core material for memory application. Therefore, this more familiar and easily obtainable loop can be used in a qualitative discussion of sensing problems that arise in actual operation.

As can be seen in Fig. 2.01a, the hysteresis loop is not perfectly flat out to the knee, and therefore, $\frac{d\phi}{dt}$ is not zero in this region. Consequently, the partially excited cores will induce voltages in the sense winding during the read, and these voltages will add to that induced by the selected core. Also, as a result of the various disturb excitations, there exist not just a single ONE state and single ZERO state,

CORE MATERIAL : GENERAL CERAMICS TYPE BODY MF 1326-B,
F-394 DIE SIZE

MAXIMUM CURRENT: I_M = 840 ma.

FIG. 2.01a

A HYSTERESIS LOOP OF A TYPICAL MEMORY CORE MATERIAL

A-59720

but several ONE states and several ZERO states.* If the voltage from the disturbed cores were a constant, the magnitude of a ONE output as seen across the sense winding (i.e., the voltage output from a selected core in a ONE state plus the disturb voltages) would always be larger than the ZERO output, and it would always be possible to discriminate between the two. However, the disturb outputs are not constant, but are a function of the information state of the core,and, therefore, one requirement must be that a fully selected ZERO output plus the maximum possible sum of disturb outputs never exceeds in magnitude a fully selected ONE output plus the minimum sum of disturb outputs.**

2.02 The ONE and ZERO States

To determine qualitatively the different possible information states of a core in a particular system, it is convenient to think of the magnetization process as consisting of both reversible and irreversible processes;[11,12] that is, either a very small fraction or a very large fraction of the potential energy is dissipated as heat, or in terms of the path traversed in the ϕ-NI plane, the path closes for a reversible process whereas it does not close for an irreversible process (Figs. 2.02a and 2.02b).

For example, consider a core which is in the state represented by point A on the major hysteresis loop of Fig. 2.02a. If this core is excited with a current I_B, the path in the ϕ-NI plane will be along the major loop to point B. Since the large change in flux was due mainly to an irreversible process, upon removal of the excitation, the core will not return to state A but will move along path ℓ to state C. However,

*See Section 2.02

**See Section 2.03

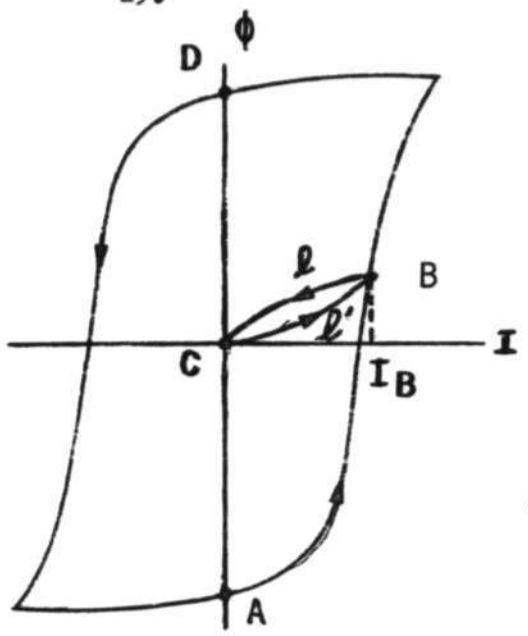


FIG. 2.02 a

CORE STATE AS A FUNCTION OF HISTORY

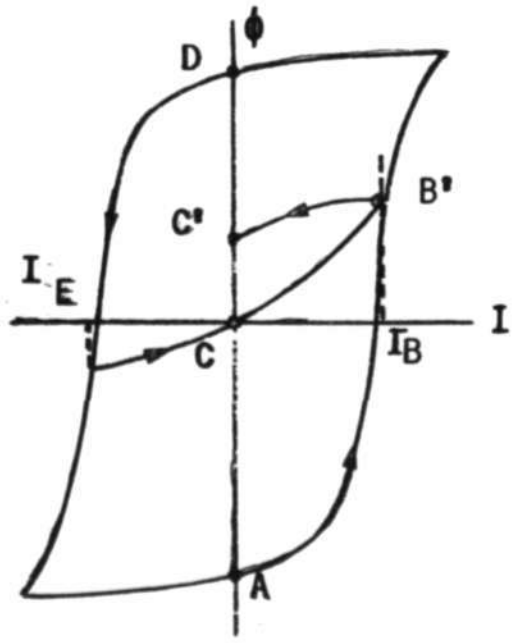


FIG. 2.02 b

CORE STATE AS A FUNCTION OF HISTORY

if the core is excited with I_B once more, it will move along ℓ' to approximately point B, and upon removal of the excitation it will follow approximately path ℓ back to state C. In this case the process was essentially reversible.

Figure 2.02b shows the path traversed in the Ø-NI plane when the core was placed in state C, starting originally in state D and exciting with I_E and then removing the excitation. If the core is now excited with I_B it will not assume state B, but a new state, B', and upon removal of the excitation, the final state will be C', the process being mainly irreversible. Although in both cases the core passed through state C, the final state was dependent upon previous history.

From the results of Chapter 1, , the different possible disturbing modes for a particular system can be determined, and by reapplying the examples shown, the various information states can be determined.* It should be realized that the assumption is made that the loops close on the first traversal, while the actual process is an asymptotic one, and, therefore, the number of possible states is infinite. However, this assumption is a good first approximation, and the results are useful in the system analysis.

2.03 Sensing Schemes

Assuming temporarily that the polarity of all the cores on the sense winding is the same, the condition for reliable memory operation can be summarized symbolically as follows:

$$\left[\min V_1^{ONE} + \min \sum V_d\right] - \left[\max V_1^{ZERO} + \max \sum V_d\right] \geq \epsilon$$

or

$$\left[\min V_1^{ONE} - \max V_1^{ZERO}\right] - \left[\max \sum V_d - \min \sum V_d\right] \geq \epsilon \qquad (1)$$

*See Section 4.02

where

V_1^{ONE} = the voltage output from a fully selected core in a ONE state

V_1^{ZERO} = the voltage output from a fully selected core in a ZERO state

$\sum V_d$ = the sum of the outputs from the partially selected cores

and ϵ is the required working margin to allow for system variations. For simplicity the symbol V and not $V(t_1)$ was used; however, it should be remembered that the voltages are functions of time evaluated at a particular instant in time.

From the inequality above, it is easily seen that to maximize the left-hand side, it is desirable to maximize the difference in the first bracket and to minimize the difference in the second bracket. The first is accomplished mainly through the choice of core material and careful single core testing, whereas the second is accomplished both through the choice of core material and the use of various sensing techniques.

A. Direct Amplitude Discrimination

Of the various sensing schemes to be discussed, the simplest is amplitude discrimination in time. This scheme involves sensing at the same time in each cycle which gives the best over-all working margin for all addresses and patterns. Aside from its simplicity, this scheme gives a very fast information access time and a short memory cycle. With some ferrite cores, these times are of the order of 1 and 5 microseconds, respectively. However, since the effect of the

partially selected cores has not been appreciably minimized, the cores must be carefully selected and the memory size is seriously limited by the selection of cores. This assumes that there is a single sense winding per digit. Any number of sense windings could be used to reduce the effect of disturbed cores at the expense of additional sense amplifiers, and this is a factor to be considered in the choice of a sensing scheme for a particular system.

B. Post-Write Disturb

Several means have been used in trying to reduce the effect of the partially selected cores, one of the first methods being the "post-write disturb."[12,13] The assumption is that at the sensing time the outputs from partially excited cores will be more nearly equal if the cores are previously disturbed so as to make the outputs reversible. (When this method was first presented, it was not thought of in these terms, but this is what is actually being done.) In the general n-coordinate system a series of pre-read disturbs must be used to get the cores into these reversible states.*

C. Staggered Read

A more effective way of reducing the voltage outputs from partially selected cores at sensing time is to use staggering in the selection. The excitations can be chosen such that either the selecting or unselecting excitations in each coordinate are zero and the selection done in the following manner. All but one of the coordinates are excited, the remaining coordinate being one in which the unselecting lines are zero, and after sufficient time has been allowed to let the voltages

*See Section 2.03D

induced in the sense winding decay to zero, the remaining coordinate is excited. If there are d_j driving lines in this remaining coordinate, when it is selected only $\frac{1}{d_j}$ of the total number of cores will induce voltages, one of these being the selected core, and thus the number of disturb outputs at sensing time has been greatly reduced.

When considering staggering, some thought should be given to the number of driving lines in each coordinate. Generally, the number of driving lines per coordinate is made equal to minimize the number of drivers required for a specified memory capacity. However, the staggering technique can be used to a greater advantage if the final coordinate excited is larger than the others since then a smaller fraction of the total number of memory cores will induce voltages at the sensing time.

By referring to the results of Chapter 1, it can be shown that the staggering technique does not destroy the information states of the unselected cores. When either the selecting or unselecting excitations in each coordinate are made zero, the values of the non-zero excitations will be $\pm \frac{2}{n+1}$ if n is odd and $\pm \frac{2}{n+2}$ if n is even. Also, the corresponding values of N_u and N_s are $N_s = \frac{n+1}{2}$ and $N_u = \frac{n-1}{2}$ for odd n, and $N_s = \frac{n+2}{2}$ and $N_u = \frac{n-2}{2}$ for even n. Therefore, when all but the last coordinate are excited, the minimum excitation any core receives is

$$\left(\frac{-2}{n+1}\right)\left(\frac{n-1}{2}\right) = -\frac{n-1}{n+1} \quad \text{for odd n} \tag{2}$$

and

$$\left(\frac{-2}{n+2}\right)\left(\frac{n-2}{2}\right) = -\frac{n-2}{n+2} \quad \text{for even n} \tag{3}$$

and the value of the maximum excitation any core receives is

$$\left(\frac{2}{n+1}\right)\left(\frac{n-1}{2}\right) = \frac{n-1}{n+1} \quad \text{for odd n} \tag{4}$$

and

$$\left(\frac{2}{n+2}\right)\left(\frac{n}{2}\right) = \frac{n}{n+2} \quad \text{for even } n \tag{5}$$

Recalling that the cores must be capable of withstanding excitations of $\pm \frac{n-1}{n+1}$ for odd n and $\pm \frac{n}{n+2}$ for even n, it is seen that the above procedure has not switched any of the cores in the array.

D. Amplitude Discrimination after Integration

Through the use of a pre-read disturb sequence it is possible to get all but the selected core into states that will give essentially reversible outputs when partially excited during the read, and since by definition there is no net flux change for a reversible output, the effect of the disturbed cores can be eliminated by integration. However, in actual operation the outputs are not completely reversible and these cores still have some effect although it has been reduced by a large factor.

The need for selective disturbing can be explained best by observing that if the partially excited cores receiving a positive read excitation are previously disturbed with the maximum partial excitation and those receiving a negative excitation are previously disturbed with the minimum partial excitation, they will be in states which give reversible outputs during the read. If none of the cores receive a negative excitation during the read, a disturb similar to the post-write disturb is sufficient. However, for most cases, the disturbing must be selective, being done by exciting the different coordinates in various sequences just before the read. (See Section 4.04.)

E. Sensing Schemes Using Difference Amplifiers

Several schemes which make use of a difference amplifier are outlined in Reference 13. One of these uses a double read pulse

after having disturbed the array so that there is only a single ONE state and a single ZERO state, all of the cores being in either one or the other. If the first read output is delayed and compared with the second read output in a difference amplifier, the outputs from the partially excited cores will be the same for each cycle and cancel.

A second proposal postulates a read current with the rise and fall times equal. If the outputs from the partially selected cores are the same in magnitude but the opposite in polarity at the beginning and end of the read pulse, by properly delaying and comparing in a difference amplifier, these outputs can be made to cancel. Actually cancellation here is only partial at best.

2.04 The Number of (1-kU) - Excited Cores

To quantitatively analyze the sensing problems involved with a particular memory system, it is always necessary to determine the number of cores receiving a specific excitation. A means of doing this is to use the same technique used in deriving the theory of selection where the excitation on all the core was diminished by one unit.* Then the problem becomes that of determining the number of cores having k unselecting lines through them where k = 1,2,···n and the value of the unselecting excitation is generally either $\frac{-2}{n+1}$ or $\frac{-2}{n+2}$ depending on whether n is either odd or even.

Consider the system with coordinates X_1, X_2··· X_n and let d_1, d_2, ···d_n equal the number of drivers in the respective coordinates.

---

*See Section 1.03.

The total number of cores in the array will be $\prod_{j=1}^{n} d_j$, and any line in the mth coordinate will excite $\frac{1}{d_m}$ of the total number of cores. Therefore, when the mth coordinate is unselected $\frac{d_m-1}{d_m} \prod_{j=1}^{n} d_j$ cores will receive U units of unselecting excitation. By using this fact a general formula can be deduced. Consider first unselecting only coordinate X_1; then

$\frac{d_1-1}{d_1} \prod_{j=1}^{n} d_j$ cores will receive 1 - U units

$\frac{1}{d_1} \prod_{j=1}^{n} d_j$ cores will receive 1 unit

If X_1 and X_2 are unselected, then

$\frac{d_1-1}{d_1} \prod_{j=1}^{n} d_j \frac{d_2-1}{d_2}$ cores will receive 1 - 2 U units

$\frac{1}{d_1} \prod_{j=1}^{n} d_j \frac{d_2-1}{d_2}$ cores will receive 1 - U units

$\frac{d_1-1}{d_1} \prod_{j=1}^{n} d_j \frac{1}{d_2}$ cores will receive 1 - U units

$\frac{1}{d_1} \prod_{j=1}^{n} d_j \frac{1}{d_2}$ cores will receive 1 unit

Summing the terms, the results become

$\frac{d_1-1}{d_1} \cdot \frac{d_2-1}{d_2} \prod_{j=1}^{n} d_j$ cores will receive 1 - 2 U units

$\frac{(d_1-1)-(d_2-1)}{d_1 d_2} \prod_{j=1}^{n} d_j$ cores will receive 1 - U units

$\frac{1}{d_1 d_2} \prod_{j=1}^{n} d_j$ cores will receive 1 unit

Carrying this procedure further the general form can be obtained for the case when all n coordinates are unselected. In doing so it is seen that each expression for the number of cores receiving 1-(k-1)U units of excitation can be obtained from that for 1-kU units, except for a constant factor, by adding the partial derivatives. Also $\prod_{j=1}^{n} d_j$ will be cancelled by the factors in the denominator when all n coordinates are selected.

Let C_k = the number of cores receiving 1-kU units of excitation.

Then $$C_n = \prod_{j=1}^{n} (d_j - 1) \tag{1}$$

$$C_k = \frac{1}{(n-k)!} \sum_{j=1}^{n} \frac{\partial C_{k+1}}{\partial d_j} \qquad k = 1,2, \cdots (n-1) \tag{2}$$

$$C_o = 1 \tag{3}$$

Since the maximum number of cores can be selected with a given number of drivers when the number of drivers in each coordinate is the same, it is of interest to determine the form that these expressions take for this case.

Let $d_1 = d_2 = \cdots = d_n$

Then

$$C_n = (d-1)^n \tag{4}$$

$$C_{n-1} = \frac{1}{1!} n(d-1)^{n-1} \tag{5}$$

$$C_{n-2} = \frac{1}{2!} n(n-1)\,(d-1)^{n-2} \tag{6}$$

.

.

.

$$C_k = \frac{1}{(n-k)!} n(n-1)\cdots(k+1)\,(d-1)^k \tag{7}$$

or

$$C_k = \frac{n(n-1)\cdots(n-k+1)}{k!}(d-1)^k, \quad k = 1,2\cdots n \tag{8}$$

$$C_o = 1 \tag{9}$$

2.05 $ONE_{min} - ZERO_{max}$

The next step in this analysis is to determine the difference between ONE_{min} and $ZERO_{max}$ where

$$ONE_{min} = \min V_1^{ONE} + \min \sum V_d \tag{1}$$

and

$$ZERO_{max} = \max V_1^{ZERO} + \max \sum V_d \tag{2}$$

Since there are generally several ONE and several ZERO states possible and the disturb outputs from these states are different, it is difficult to derive a general expression for this difference. However, a general expression can be derived which can be used to obtain a lower limit, or modified to fit a particular case.

Assume that the sense winding goes through all the cores such that the voltage output induced by each core is positive when it is excited with a positive read current. The output voltage induced in the sense winding will be then the voltage from the selected core plus the sum of the voltages from all the partially excited cores. From the hysteresis loops, the indication is that the largest positive disturb voltages will come from cores in a particular ONE state and the minimum positive voltages will come from cores in a particular ZERO state.*

Let $V_{1\text{-}kU}^{ONE}$ = the voltage from a core in the ONE state giving the largest positive voltage output and receiving 1-kU units of excitation.

and

$V_{1\text{-}kU}^{ZERO}$ = the voltage from a core in the ZERO state giving the smallest positive voltage output and receiving 1-kU units of excitation.

---

*See Section 4.02

If it is assumed that these states also give the smallest and largest negative outputs respectively, then

$$ONE_{min} = V_1^{ONE} + \sum_{k=1}^{n} C_k \, V_{1-kU}^{ZERO} \tag{3}$$

and

$$ZERO_{max} = V_1^{ZERO} + \sum_{k=1}^{n} C_k \, V_{1-kU}^{ONE} \tag{4}$$

Let

$$\delta_{1-kU} = V_{1-kU}^{ONE} - V_{1-kU}^{ZERO} \tag{5}$$

Then

$$ONE_{min} - ZERO_{max} = V_1^{ONE} - V_1^{ZERO} - \sum_{k=1}^{n} C_k \, \delta_{1-kU} \tag{6}$$

This expression gives a lower limit which is usually not obtainable in actual operation. The actual worst difference is somewhat better than this since the mode of operation does not permit all of the cores to be in these worst states at the same time. A closer approach to this figure can be obtained by analysing the particular system to determine the different possible δ_{1-kU}'s and the worst possible combination of these obtainable; however, this becomes very involved because of the effect of previous history on the state of the cores.

2.06 Sense Winding Geometry

The effect of sense winding geometry on the difference between ONE_{min} and $ZERO_{max}$ is the next point to consider, and for all but a very small array, this difference can be shown to be independent of the winding geometry if air flux pickup is neglected.

Consider just two cores of an array, the selected core and a core receiving 1-kU units of excitation. Pass a sense winding through the two cores such that the voltage outputs add. Then,

$$ONE_{min} = V_1^{ONE} + V_{1-kU}^{ZERO} \quad (1)$$

$$ZERO_{max} = V_1^{ZERO} + V_{1-kU}^{ONE} \quad (2)$$

and

$$ONE_{min} - ZERO_{max} = V_1^{ONE} - V_1^{ZERO} - \delta_{1-kU} \quad (3)$$

Now pass the sense winding through the two cores such that the voltage output of the disturbed core is of opposite polarity.

Then,

$$ONE_{min} = V_1^{ONE} - V_{1-kU}^{ONE} \quad (4)$$

$$ZERO_{max} = V_1^{ZERO} - V_{1-kU}^{ZERO}$$

and

$$ONE_{min} - ZERO_{max} = V_1^{ONE} - V_1^{ZERO} - \delta_{1-kU} \quad (5)$$

Therefore, changing the polarity of the disturbed core did not affect the magnitude of ONE_{min} minus $ZERO_{max}$ for the selected core, and since the disturbed core was any one in the array, this will be true for the case when the winding goes through all the cores of the digit plane. Since, except for very small arrays, the magnitude of ONE_{min} and $ZERO_{max}$ will be the same for every address, ONE_{min} minus $ZERO_{max}$ is independent of the sense winding geometry.

Although ONE_{min} minus $ZERO_{max}$ is independent of geometry, it should be realized that the individual quantities are affected and, consequently, the ratio of ONE_{min} to $ZERO_{max}$ is a function of geometry. Air flux pickup varies with geometry too, and these factors must be considered in designing a system.

PART II

A 4-COORDINATE READ — 5-COORDINATE WRITE CORE MEMORY SYSTEM

CHAPTER 3

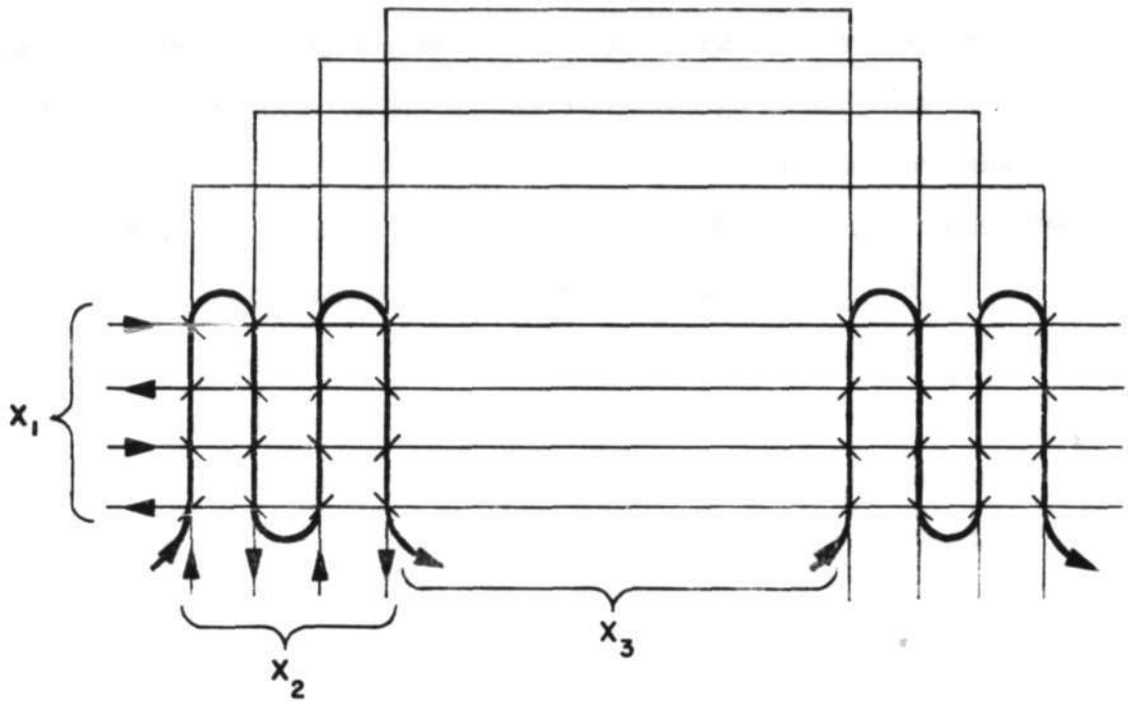
INTRODUCTION

3.01 History of the M.I.T. Core Memory

The most successful work in magnetic-core memories has evolved from a proposal made in 1949 by Jay W. Forrester.[14] It suggested the use of magnetic cores as memory elements and illustrated a 2-coordinate read, 3-coordinate write scheme of the general type discussed in Part I. (See Fig. 3.01a.) In 1950, W. N. Papian investigated this proposal, and found that metallic-ribbon cores with hysteresis loops of sufficient rectangularity for memory application were available.[15] From the results of this investigation, a one digit memory of 4 bits was built, and eventually this was expanded to 256 bits.[16] However, during this period, powdered ferrite cores were being developed which were faster switching and cheaper to manufacture than the metallic-ribbon cores, and, therefore, further experimentation was concentrated mainly on the use and development of ferrite cores. By 1953 the two banks of electrostatic storage of Whirlwind I (2048 17-digit registers) had been replaced by ferrite core storage, and by the spring of 1954 a memory of twice this capacity was operating reliably. At present, serious consideration is being given to the possibility of constructing memories of even larger capacity, and one of the problems to be dealt with is the increased number of vacuum tubes which would be required for the larger system.

3.02 Memory Systems with More than 3 Coordinates

By using magnetic-core switches and by increasing the number of memory coordinates, the number of vacuum tube drivers necessary



READ:

	X_1	X_2	X_3
S_j	$\frac{1}{2}$	$\frac{1}{2}$	0
u_j	0	0	0

WRITE:

	X_1	X_2	X_3
S_j	$-\frac{1}{2}$	$-\frac{1}{2}$	0
u_j	0	0	$\frac{1}{2}$

FIG. 3.01 a

A 2-COORDINATE READ-3-COORDINATE WRITE CORE MEMORY

A-59699

for a given memory capacity can be reduced by a large factor. A great deal of work has been done on the analysis and design of the core switch,[6,7,8,9] but no work has been done previously to investigate the possibility of memory systems with $n > 3$. It is only due to the improvement of core materials that such an investigation is now worthwhile.

As n increases the number of drivers is reduced and better core materials are required. This is true because:

1. For a given memory capacity the number of coordinate lines decrease as n increases and a larger fraction of the memory is excited by each coordinate line.

2. Since $p_{min} = \frac{n-1}{n+1}$, the cores must have more rectangular hysteresis loops as n increases.

3. With a given core material, $ONE_{min} - ZERO_{max}$ will decrease because of the fact that more cores are partially excited and the value of the maximum partial excitation increases with increasing n.

The third point mentioned is the most important disadvantage of increasing n since it affects the working margins of the system.

In many computer applications, a memory system is designed primarily with reliability in mind. If the term is defined as the ratio of the number of memory cycles to the number of errors, it is essentially the reciprocal of the probability of the operating point drifting from its optimum setting into a region of error.[17] This probability is dependent upon many things including the probability of tube failure and the size of the working margins. Therefore, any evaluation of a system design in terms of reliability must not only consider the tube count, but also the effect this design has on margins.

3.03 The Proposed Investigation

The remainder of this thesis will be concentrated on determining whether a large capacity memory using a 4-coordinate read — 5-coordinate write is practical from the standpoints of reliability, speed and cost. In Chapter 4 the general theory of Part I will be applied to this specific case, in Chapter 5 the data obtained from single cores will be analyzed, and in Chapter 6 the experimental analysis of a 8 x 8 x 8 x 8 memory plane will be given along with the final conclusions.

CHAPTER 4

SELECTION AND SENSING

4.01 The Selection System

The following specifications will be placed on the system to be analyzed.

1. The read will use a 4-coordinate selection system and the write will use a 5-coordinate selection system.

2. Either the selecting line or unselecting lines in each coordinate will use a zero excitation, and the excitations will be chosen to obtain the best possible selection ratio.

With these specifications in mind, the results of Part I can be evaluated to determine the necessary excitations. For the read,

$$u_j - s_j = \frac{-2}{n+2} = -\frac{1}{3} \tag{1}$$

with

$$N_s = \frac{n+2}{2} = 3 \tag{2}$$

and

$$N_u = \frac{n-2}{2} = 1 \tag{3}$$

and for the write,

$$u_j - s_j = \frac{2}{n+1} = \frac{1}{3} \tag{4}$$

with

$$N_s = \frac{n+1}{2} = 3 \tag{5}$$

and

$$N_u = \frac{n-1}{2} = 2 \qquad (6)$$

These results are tabulated below, and Fig. 4.01a shows the read wiring schematic for a 4x4x4x4 digit plane. The wiring for the write is the same except for an additional winding in each digit plane, this winding passing through all the cores of the plane.

TABLE 4.01a

READ EXCITATIONS

	X_1	X_2	X_3	X_4
s_j	1/3	1/3	1/3	0
u_j	0	0	0	-1/3

TABLE 4.01b

WRITE EXCITATIONS

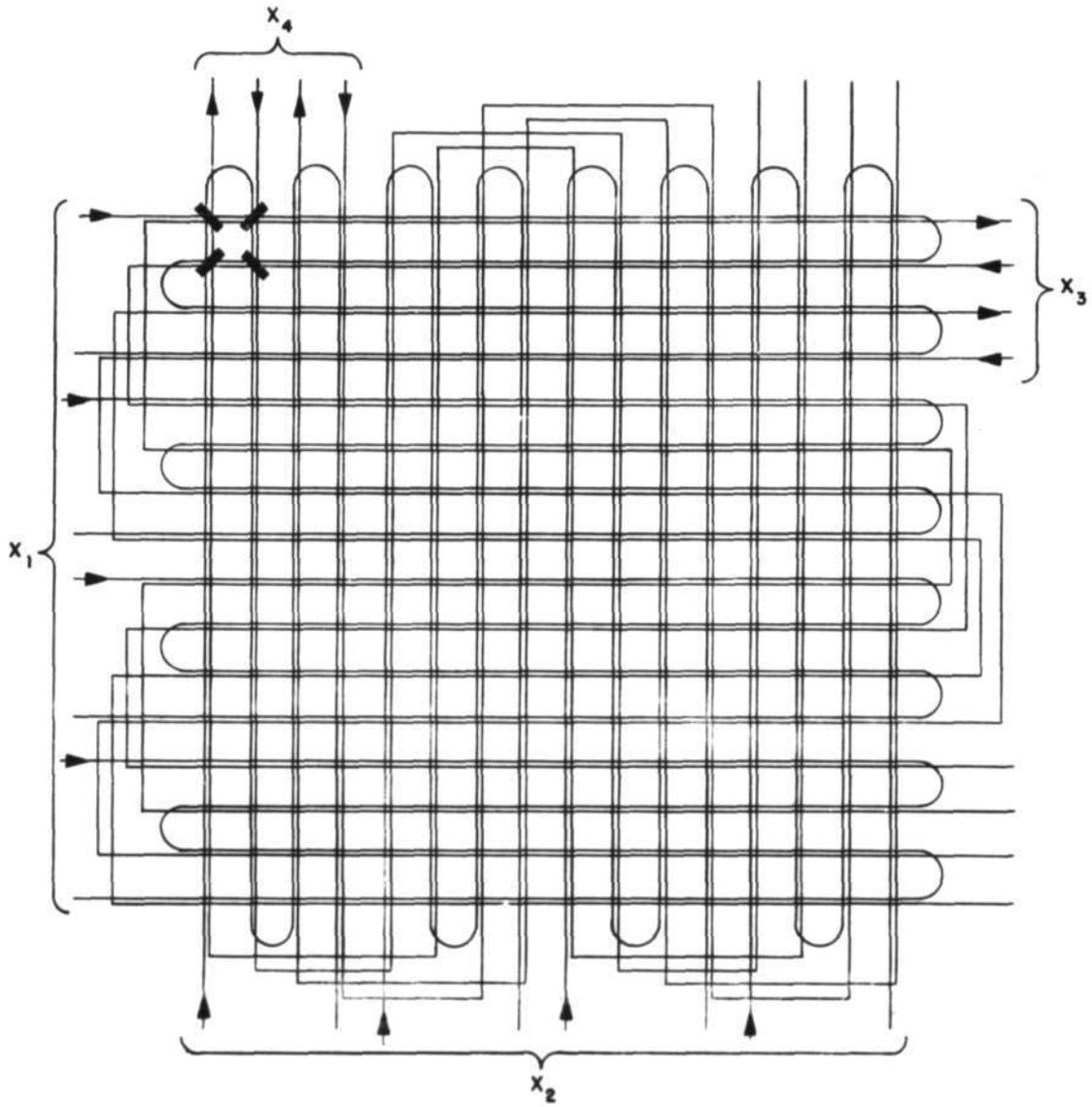
	X_1	X_2	X_3	X_4	X_5
s_j	-1/3	-1/3	-1/3	0	0
u_j	0	0	0	1/3	1/3

The selection ratios obtained with these excitations are:

$$R = \frac{n+2}{n} = \frac{3}{2} \qquad (7)$$

for the read selection, and

$$R = \frac{n+1}{n-1} = \frac{3}{2} \qquad (8)$$



	X_1	X_2	X_3	X_4
S_j	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	0
u_j	0	0	0	$-\frac{1}{3}$

NOTE: ONLY FOUR CORES ARE SHOWN

FIG. 4.01 a

A 4-COORDINATE READ SYSTEM

B-59696

for the write selection.

4.02 The ONE and ZERO States

Assuming that the hysteresis loops close upon the first traversal, there will be a finite number of ONE and ZERO states, and these may be determined from the different possible read-write sequences tabulated below.*

TABLE 4.02a

POSSIBLE READ-WRITE SEQUENCES OF PULSES RECEIVED BY CORES IN THE PLANE

	If the information written in the selected core is ONE		If the information written in the selected core is ZERO	
	Read	Write	Read	Write
If core in question is selected	1	-1	1	-2/3
If core in question is unselected	2/3	-2/3	2/3	-1/3
	1/3	-1/3	1/3	0
	0	0	0	1/3
	-1/3	1/3	-1/3	2/3

*See Section 2.02.

These states and the associated hysteresis loops are depicted in the sketch of Fig. 4.02a, and combinations of read-write sequences that will place a core in each of these states are given in Table 4.02b.

To determine the accuracy of the qualitative picture given in Fig. 4.02a, D.C. hysteresis loops were obtained for a typical memory core material (Fig. 4.02b). From these loops it can be seen that for the smaller excitations the assumption that the loops close on the first traversal is quite good whereas for the larger excitations this assumption is less accurate. However, since the results of this section can be used in obtaining only a rough indication of the working margin, any more accurate assumptions would only add to the complexity of the problem without increasing the accuracy of the results.

4.03 The Memory Plane Output

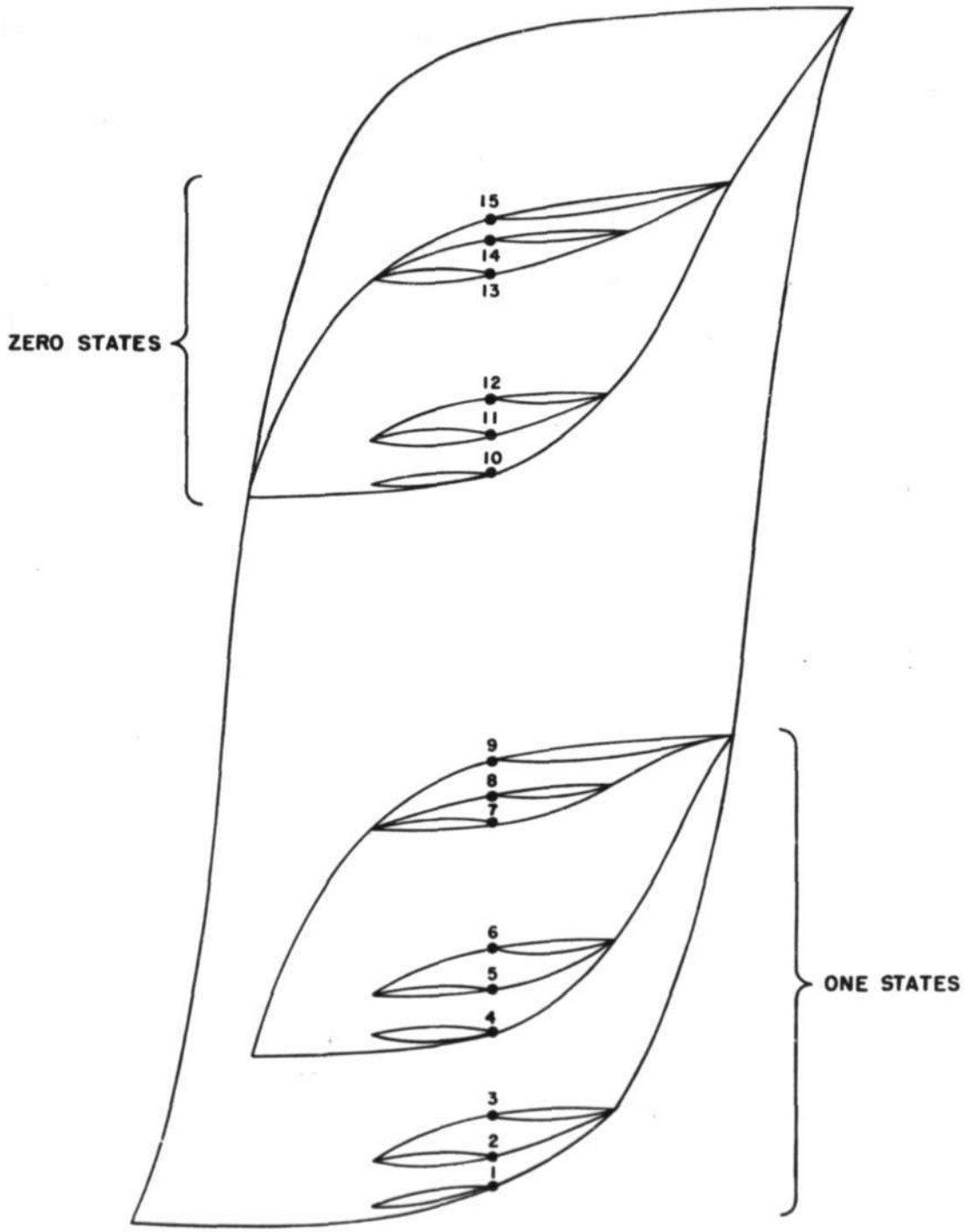
As was stated in Section 2.05, because of the many information states that exist, it becomes nearly impossible to predict the memory plane output since it will be a function of both the pattern stored and the sequence of register selections. A very pessimistic estimate of the worst difference that will exist between a ONE and ZERO output can be obtained for this system by evaluating equation 2.05(6) for n=4*

$$ONE_{min} - ZERO_{max} = V_1^{ONE} - V_1^{ZERO} - \sum_{k=1}^{4} C_k(n)\,\delta_{1-k/3} \qquad (1)$$

and if $d_1 = d_2 = \cdots = d_n$

$$ONE_{min} - ZERO_{max} = V_1^{ONE} - V_1^{ZERO} - 4(d-1)\delta_{2/3} - 6(d-1)^2\delta_{1/3} - 4(d-1)^3\delta_0 - (d-1)^4\delta_{-1/3}$$

*One sense winding per digit plane is assumed.



B-59697

FIG. 4.02 a

THE ONE AND ZERO STATES

TABLE 4.02b

SEQUENCES FOR OBTAINING A GIVEN STATE

State*	Cycle 1		Cycle 2		Cycle 3	
	Read	Write	Read	Write	Read	Write
1	1	-1				
2	1	-1	1/3	-1/3		
3	1	-1	1/3	0		
4	1	-1	2/3	-2/3		
5	1	-1	2/3	-2/3	1/3	-1/3
6	1	-1	2/3	-2/3	1/3	0
7	1	-1	2/3	-1/3		
8	1	-1	2/3	-1/3	1/3	0
9	1	-1	-1/3	2/3		
10	1	-2/3				
11	1	-2/3	1/3	-1/3		
12	1	-2/3	1/3	0		
13	1	-2/3	2/3	-1/3		
14	1	-2/3	2/3	-1/3	1/3	0
15	1	-2/3	-1/3	2/3		

*The numbers refer to Fig. 4.02a.

A-59698

SAMPLE: MF1326B
MOLD: F262

SCALE: ϕ - 25 MAXWELLS / INCH
NI-.625 AMP TURNS / INCH

FIG. 4.02 b

D.C. HYSTERESIS LOOPS FOR A TYPICAL MEMORY CORE MATERIAL

$$= V_1^{ONE} - V_1^{ZERO} - 4(d-1)\delta_{2/3} - 6(d-1)^2\delta_{1/3}$$

$$-(d-1)^4\delta_{-1/3} \qquad (2)$$

where the δ's are the worst possible. However, in actual operation it is impossible to get all the cores into the worst states simultaneously, and therefore, the results given by 4.03-(2) can be overly pessimistic by an order of magnitude.

If staggering is used in the selection, this margin (between ONE_{min} and $ZERO_{max}$) can be improved greatly since then only 1/d of the total array will give outputs at the sensing time. Also, a pre-read disturb sequence and integration can be used, and for this case equation 4.02-(2) still applies, being evaluated for the new values of δ_{1-kU}.

4.04 Selective Disturbing

It was pointed out in Section 2.03 that for some sensing schemes, it is necessary to have cores in states that will give reversible outputs when selected, and that this could be done by a selective pre-read disturb sequence. For the case under consideration this sequence can be determined by observing the following points.

1. Since during the read part of the array will receive positive disturbs and part will receive negative disturbs, the disturb sequence cannot consist of a single excitation on a winding common to all the cores of the digit plane, as was true of the post-write disturb of the system when n=2, for states which give reversible outputs for positive excitations will give irreversible outputs for negative excitations and vice versa. The pre-read disturb must be such that all cores receive an excitation equal in sign and at least equal in magnitude to the excitation received during the read (See Fig. 4.02a).

2. The only negative read disturb is a -1/3 disturb, and since driving lines in only one coordinate are negatively excited, and this excitation is -1/3, the previous selection of this coordinate alone will put the cores negatively excited during the read in states which will give reversible outputs. These cores will be unaffected by any pre-read selection of the remaining coordinates.

3. If the remaining coordinates are selected two at a time using the three possible combinations, all the cores receiving a 2/3 excitation during the read will be pre-disturbed by this amount, and all those receiving a 1/3 excitation will be pre-disturbed by at least 1/3 and at most 2/3.

Therefore, the disturb cycle consists of pulsing coordinate X_4 (Fig. 4.01a) and then pulsing the remaining coordinates two at a time, i.e., X_1 and X_2, followed by X_2 and X_3, followed by X_3 and X_1.

CHAPTER V

SINGLE CORE DATA

5.01 The Core Material

In order to make a preliminary selection from the large number of core materials available, use was made of the wealth of data taken at M.I.T. for 2 to 1 selection operation. The available data consisted of two types; that obtained from 60 cycle hysteresis loops* and that obtained from pulse tests. A quantitative index of hysteresis-loop squareness, the "squareness ratio" (see Figure 5.01a), had been defined and for each material data had been taken for the loop with the highest squareness ratio. This ratio then had been used as one means of comparing cores for memory application, the assumption being that the 60 cycle loop gives some indication of pulse operation, and that to a certain degree, the higher the squareness ratio the better the core. The cores with the higher squareness ratios and lower driving currents then had been pulse tested to determine the voltage outputs from the possible states and on the basis of these outputs, a final choice was made.

In selecting a material for the system under analysis, the same techniques could have been used. A new squareness ratio could have been defined (Figure 5.01b) and materials chosen on this basis with a final decision having been made from pulse tests. However, to economize on the time allowed for this study, the initial selection was done from

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* For this application the 60 cycle loop can be considered equivalent to the D.C. loop.

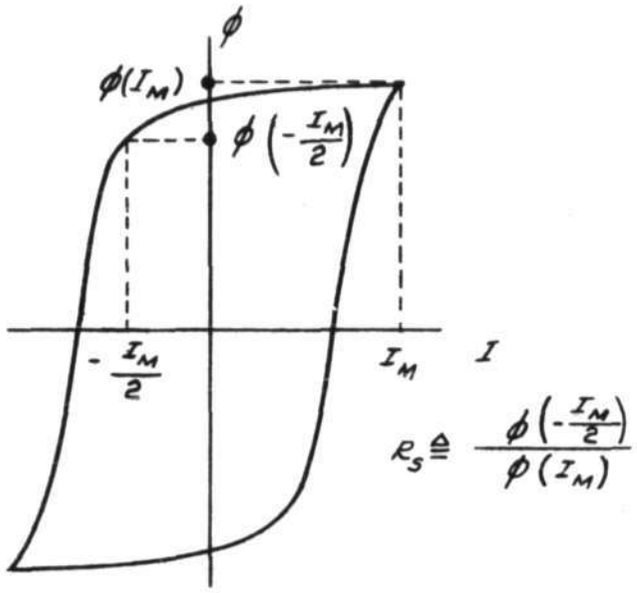


FIG. 5.01 a

SQUARENESS RATIO DEFINED FOR 2 TO 1 SELECTION

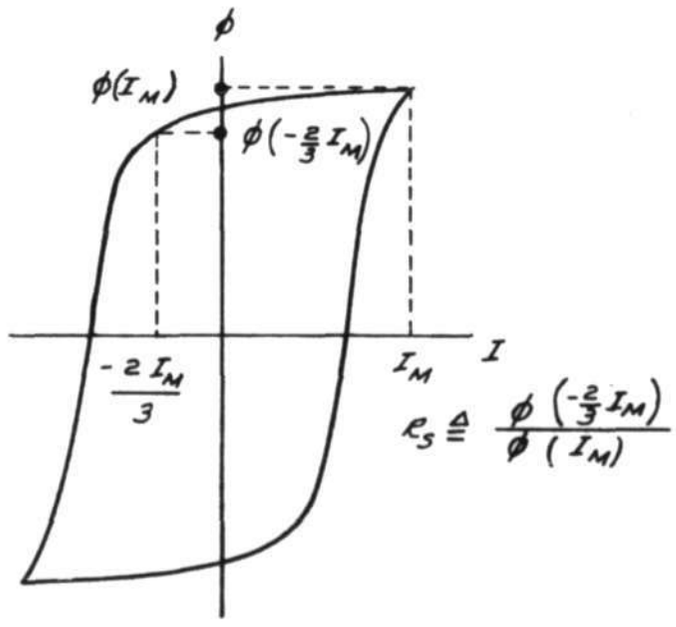


FIG. 5.01 b

SQUARENESS RATIO DEFINED FOR 3 TO 2 SELECTION

A-59745

a study of the hysteresis loop data that had been obtained for the 2 to 1 selection system. The assumption made was that the squareness on the 2 to 1 basis gives an indication of the relative squareness on the 3 to 2 basis. Using this assumption and adding the restriction that the maximum driving force required be less than 1 ampere, several core materials were chosen for an initial pulse test and from these the core material chosen for extensive analysis was General Ceramics type body MF 1326-B, F-394 die size. There were several core materials that might have been used and the final choice was based mainly on the facts that it was a faster switching material and that a sufficient number of cores were readily available for building an 8 x 8 x 8 x 8 digit plane.

5.02 The Pulse Tester

The pulse tester was made up using Burroughs test equipment and Model V core drivers,[20] and core outputs were observed with a Tektronix 514D, series A oscilloscope, a Tektronix 121 preamplifier being used when necessary. The tester was capable of placing cores in any one of the possible states of Figure 4.02a and then exciting them with any one of the six possible excitations. Binary counters were also included in the logic so that any read-write cycle could be repeated up to 4096 times. Figure 5.02a shows a block diagram of this set up.

5.03 Pulse Test Data for MF 1326B

Fifty MF 1326B cores were chosen at random from Lot G92 and used in obtaining the pulse characteristics for a 3 to 2 selection ratio. (The cores had been previously sorted for 2 to 1 operation and at the optimum selecting current of 820 m.a., the fully selected outputs ranged from

D-47144

105 to 120 mv.) These cores were driven simultaneously and the sum of the individual outputs was observed on a winding common to all the cores. Preliminary experimentation showed that for a 3 to 2 selection system the optimum current lay somewhere between 550 and 650 ma. and that even in this range, the various disturb voltage outputs were such that it would be impossible to operate an 8 x 8 x 8 x 8 digit plane with a single sense winding, using only amplitude discrimination. Pictures of these voltage outputs were taken for selecting currents of 600, 650 and 700 ma. with rise times of approximately .5 μsec and those for $I_m = 650$ are shown in Figures 5.03a through 5.03d. Taking measurements from the pictures an average value for each output was calculated on a single core basis for the time when the fully selected ONE output was maximum and these values are tabulated in Table 5.03a.

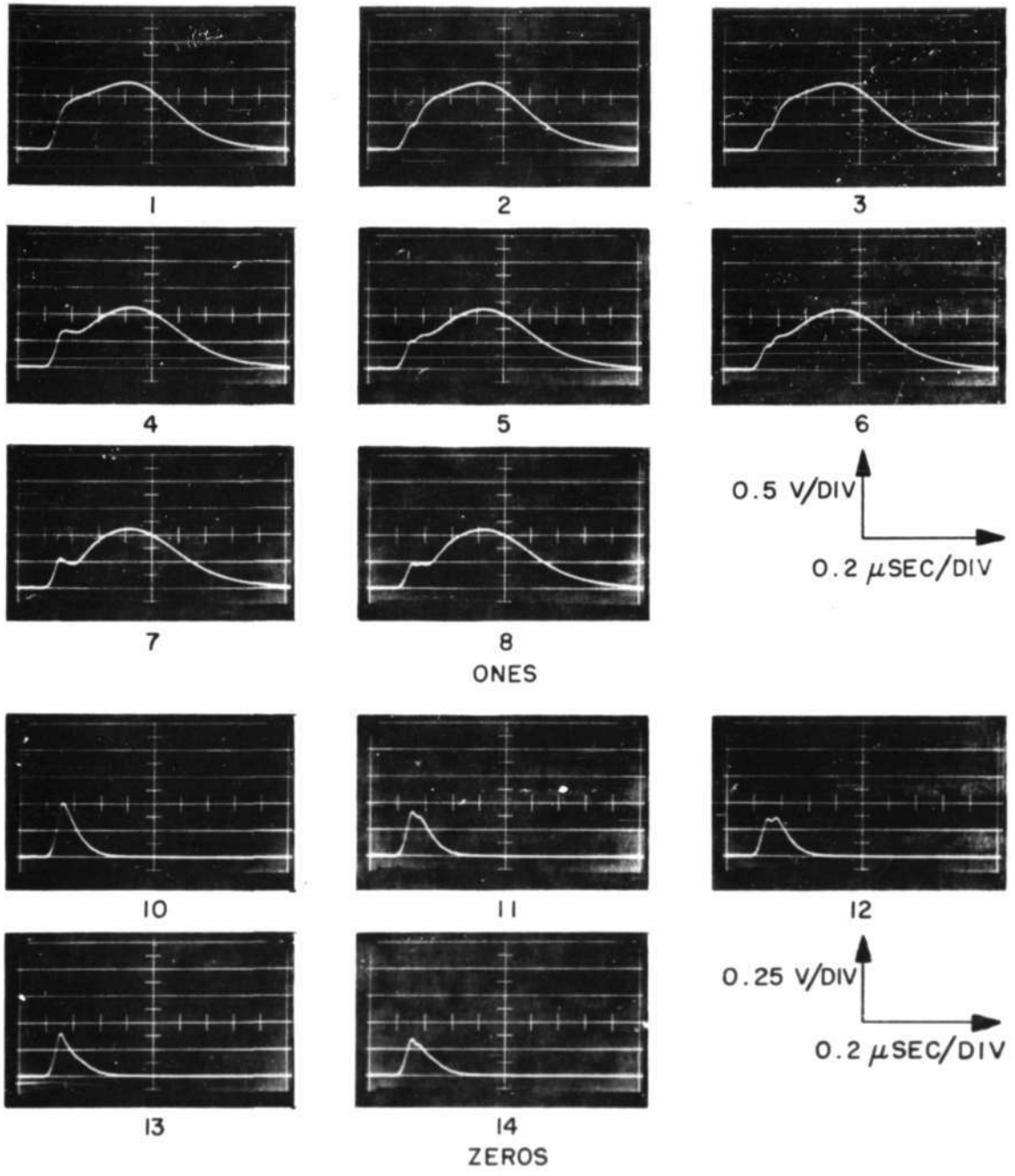
Equation 4.03-(2) can be evaluated using this data and for $I_m = 650$ ma. and $d_1 = d_2 = d_3 = d_4 = 8$.

$$|ONE|_{min} - |ZERO|_{max} = V_1^{ONE} - V_1^{ZERO} - 4(d-1)\,\delta_{\frac{2}{3}} - 6(d-1)^2\,\delta_{\frac{1}{3}} - (d-1)^4\,\delta_{-\frac{1}{3}}$$

$$= .044 - .001 - 28(.0053) - 294(.0008) - 2401(.0007)$$

$$= .044 - .001 - 2.16 < 0$$

Clearly, the magnitude of the disturb voltages is such that it would be impossible for the system to operate. The fact that the difference is negative indicates that the magnitude of the ZERO can exceed the magnitude of the ONE. Even if the results are in error by a factor of ten, this would still be true. The situation could be improved some if the sensing were done a little later in time since although the fully selected ONE



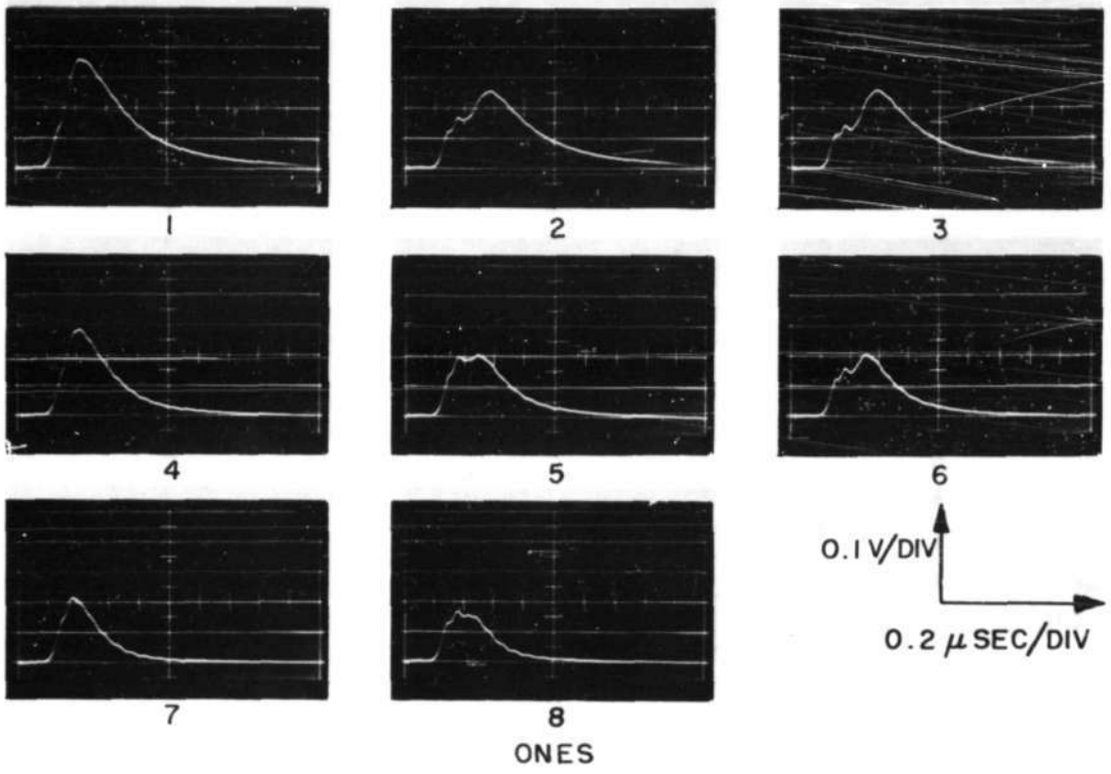
NOTES:

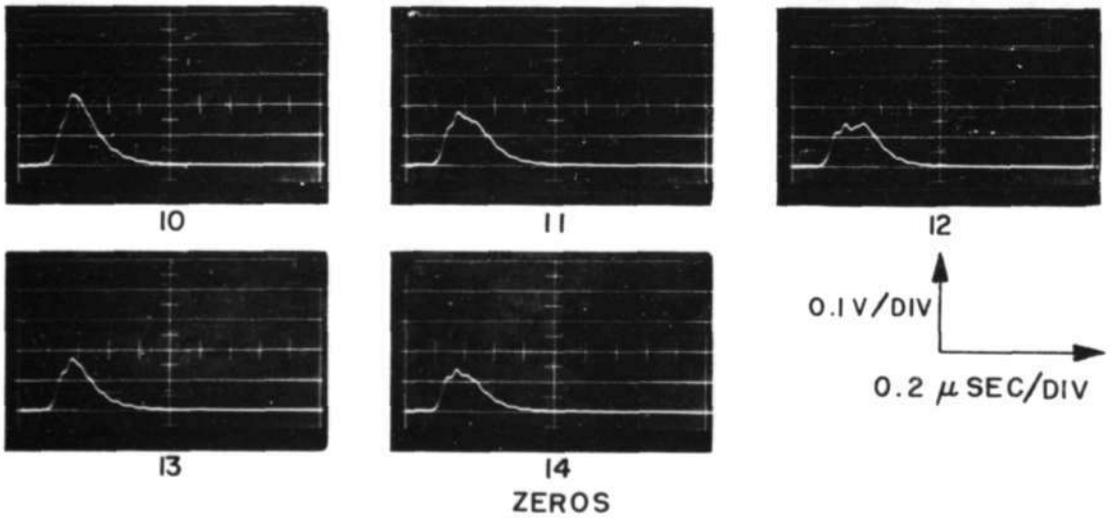
1. NUMBERS UNDER PICTURES REFER TO STATES OF FIG. 4.02 a
2. THESE OUTPUTS ARE FOR 50 CORES MF 1326-B, DIE SIZE 394, LOT G92

FIG. 5.03 a

V_1's AT I_M = 650 ma

A-59692





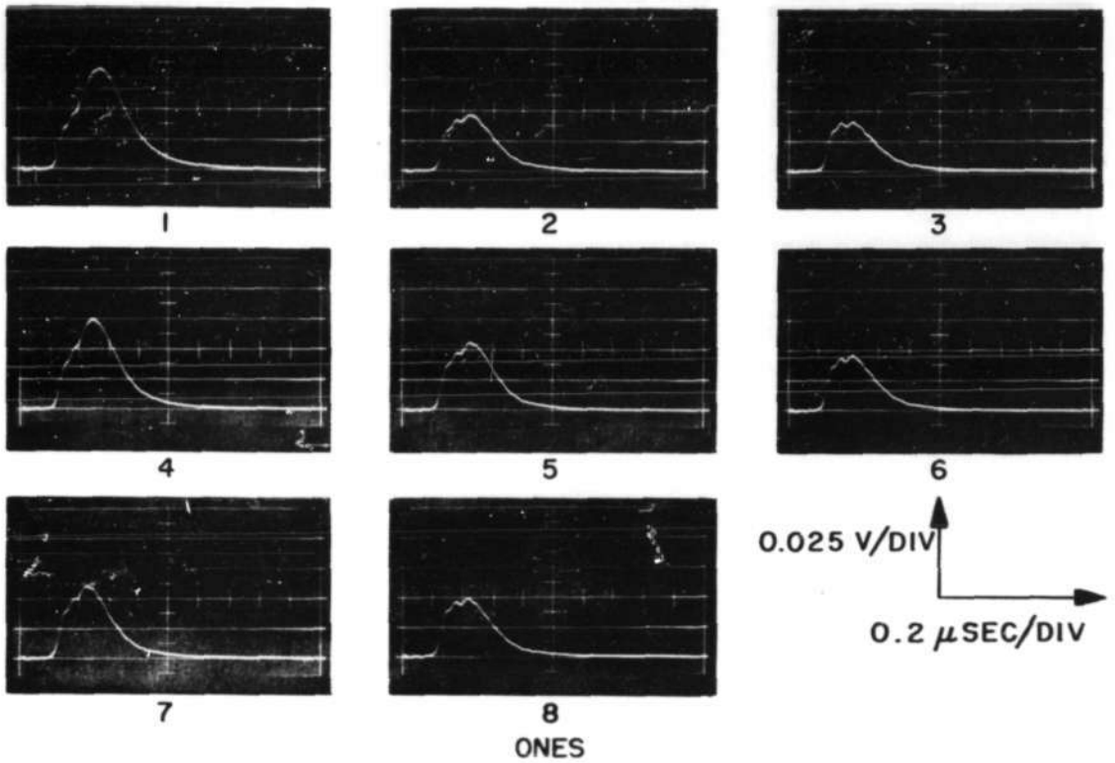
NOTES:

1. NUMBERS UNDER PICTURES REFERS TO STATES OF FIG. 4.02 a
2. THESE OUTPUTS ARE FOR 50 CORES MF 1326-B, DIE SIZE 394, LOT G92

FIG. 5.03 b

$V_{\frac{2}{3}}$'s AT I_M = 650 ma

A-59693



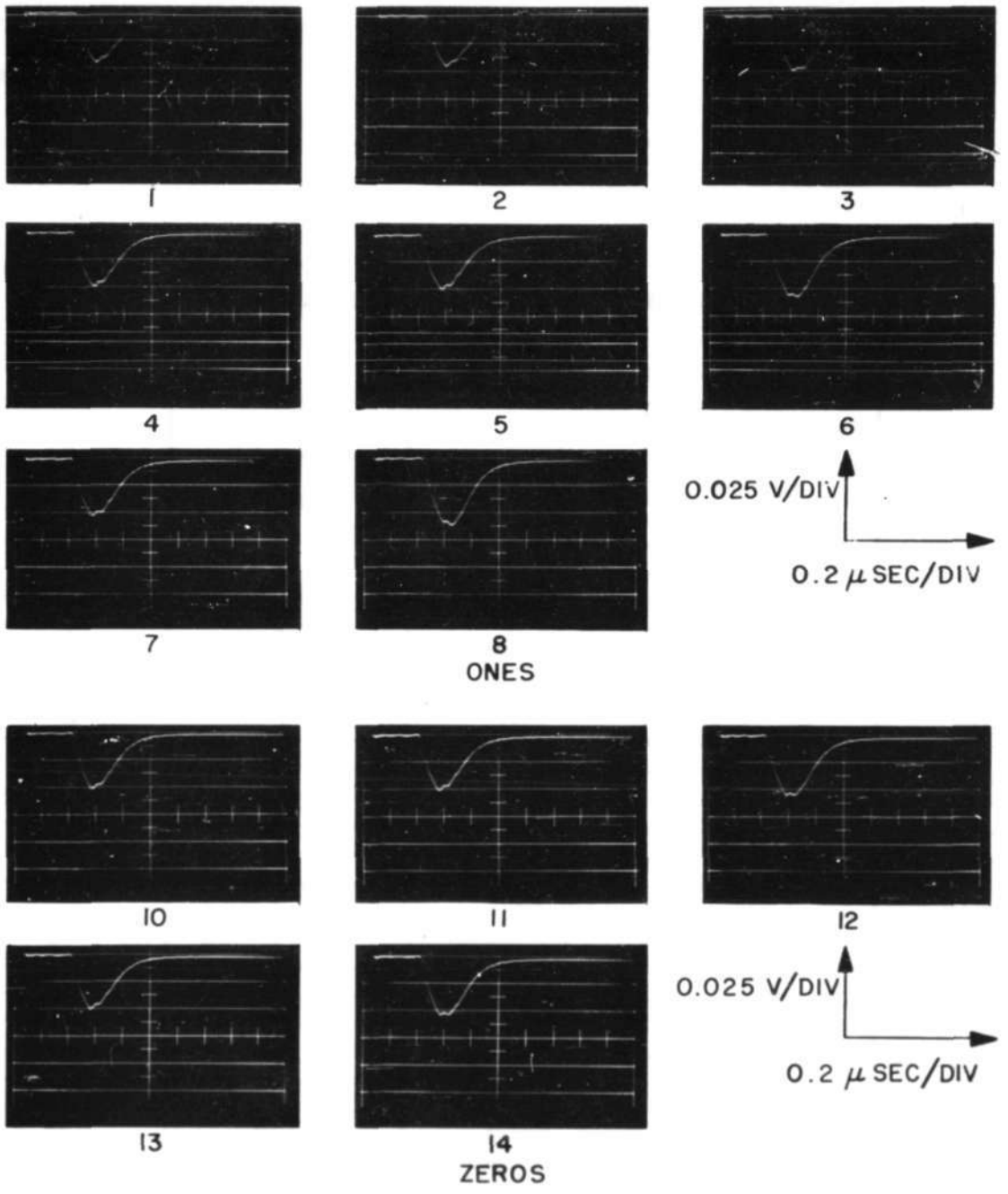
NOTES:

1. NUMBERS UNDER PICTURES REFER TO STATES OF FIG. 4.02 a
2. THESE OUTPUTS ARE FOR 50 CORES MF 1326-B, DIE SIZE 394, LOT G92

FIG. 5.03 c

$V_{\frac{1}{3}}$'s AT I_M = 650 ma

A-59694



NOTES:

1. NUMBERS UNDER PICTURES REFER TO STATES OF FIG. 4.02a
2. THESE OUTPUTS ARE FOR 50 CORES MF 1326-B, DIE SIZE 394, LOT G92

FIG. 5.03d

$V_{-\frac{1}{3}}$'s AT $I_M = 650$ ma

A-59695

TABLE 5.03a

VOLTAGE OUTPUTS AT A GIVEN SENSING TIME

STATE	EXCITATION I_m	VOLTAGE OUTPUT (Volts) I_m=600 ma.	I_m=650 ma.	I_m=700 ma.
1	1	.036	.050	.070
2	1	.035	.049	.069
3	1	.035	.050	.068
4	1	.032	.045	.061
5	1	.032	.045	.060
6.	1	.032	.045	.060
7	1	.032	.045	.057
8	1	.032	.044	.057
9	1			
10	1	.001	.001	.001
11	1	.001	.001	.001
12	1	.001	.001	.001
13	1	.001	.001	.001
14	1	.001	.001	.001
15	1			
1	2/3	.0052	.0050	.0060
2	2/3	.0054	.0054	.0060
3	2/3	.0056	.0056	.0068
4	2/3	.0026	.0024	.0048
5	2/3	.0024	.0024	.0048
6	2/3	.0024	.0024	.0048
7	2/3	.0012	.0008	.0014
8	2/3	.0010	.0008	.0014
9	2/3			
10	2/3	.0008	.0003	.0006
11	2/3	.0006	.0004	.0004
12	2/3	.0007	.0004	.0003
13	2/3	.0006	.0004	.0002
14	2/3	.0004	.0004	.0002
15	2/3			

TABLE 5.03a (Continued)

STATE	EXCITATION I_m	VOLTAGE OUTPUT (Volts) I_m=600 ma.	I_m=650 ma.	I_m=700 ma.
1	1/3	.0015	.0010	.0009
2	1/3	.0003	.0003	.0002
3	1/3	.0003	.0002	.0002
4	1/3	.0009	.0005	.0005
5	1/3	.0005	.0003	.0003
6	1/3	.0004	.0002	.0002
7	1/3	.0005	.0003	.0004
8	1/3	.0003	.0003	.0003
9	1/3			
10	1/3	.0005	.0003	.0005
11	1/3	.0003	.0002	.0002
12	1/3	.0003	.0002	.0002
13	1/3	.0003	.0003	.0002
14	1/3	.0003	.0002	.0002
15	1/3			
1	-1/3	-.0005	-.0005	-.0003
2	-1/3	-.0005	-.0005	-.0003
3	-1/3	-.0008	-.0006	-.0005
4	-1/3	-.0007	-.0005	-.0009
5	-1/3	-.0007	-.0005	-.0005
6	-1/3	-.0009	-.0007	-.0006
7	-1/3	-.0005	-.0005	-.0004
8	-1/3	-.0008	-.0009	-.0006
9	-1/3			
10	-1/3	-.0005	-.0004	-.0003
11	-1/3	-.0005	-.0004	-.0003
12	-1/3	-.0006	-.0006	-.0004
13	-1/3	-.0003	-.0002	-.0003
14	-1/3	-.0005	-.0004	-.0004
15	-1/3			

NOTE: 1. The sensing time for I_m=600 ma. was .80 μsec after the time marker shown in each of the photographs, and for I_m=650 ma. and I_m=700 ma., it was .85 μsec.

2. At the time the data was taken, the mistaken impression was held that states 9 and 15 were impossible in system operation and consequently no data was taken for these states; other results indicate that they do not differ greatly from states 8 and 14 respectively.

will be smaller in amplitude, the difference between the disturb voltages, which are much more numerous, would also be less. However, data from the 8 x 8 x 8 x 8 digit plane shows that there is not sufficient improvement, and therefore, other schemes, such as staggering in selection or disturbing and integrating, must be considered.*

Since the data indicates that if the system is to operate at all, a more sophisticated technique of sensing must be used, possibly involving integration, a set of pictures were taken showing the integrated outputs for $I_m = 650$. A simple RC integrator with R = 100k and C = 220 μμf was used, and the integration was done from the start to the end of the read, the theory being that the integral of the reversible outputs is zero. These pictures are shown in Figures 5.03e through 5.03h and a comparison of this data and that already presented is given in Table 5.03b. The important point to note is that to a first approximation, those outputs that were predicted to be reversible are so.**

One final test was made to determine whether the cores were disturb sensitive, i.e., whether information was destroyed by repeatedly disturbing a core without rewriting. To determine this the cores were put in State 9 with $I_m = 700$ and then disturbed repeatedly from 1 to 4096 times with a 2/3 disturb pulse. The results of this test indicate that after an initial small change in the peak amplitude of the ONE output, no further change was noted. Figure 5.03i shows the outputs after 1, 64 and 4096 disturbs.

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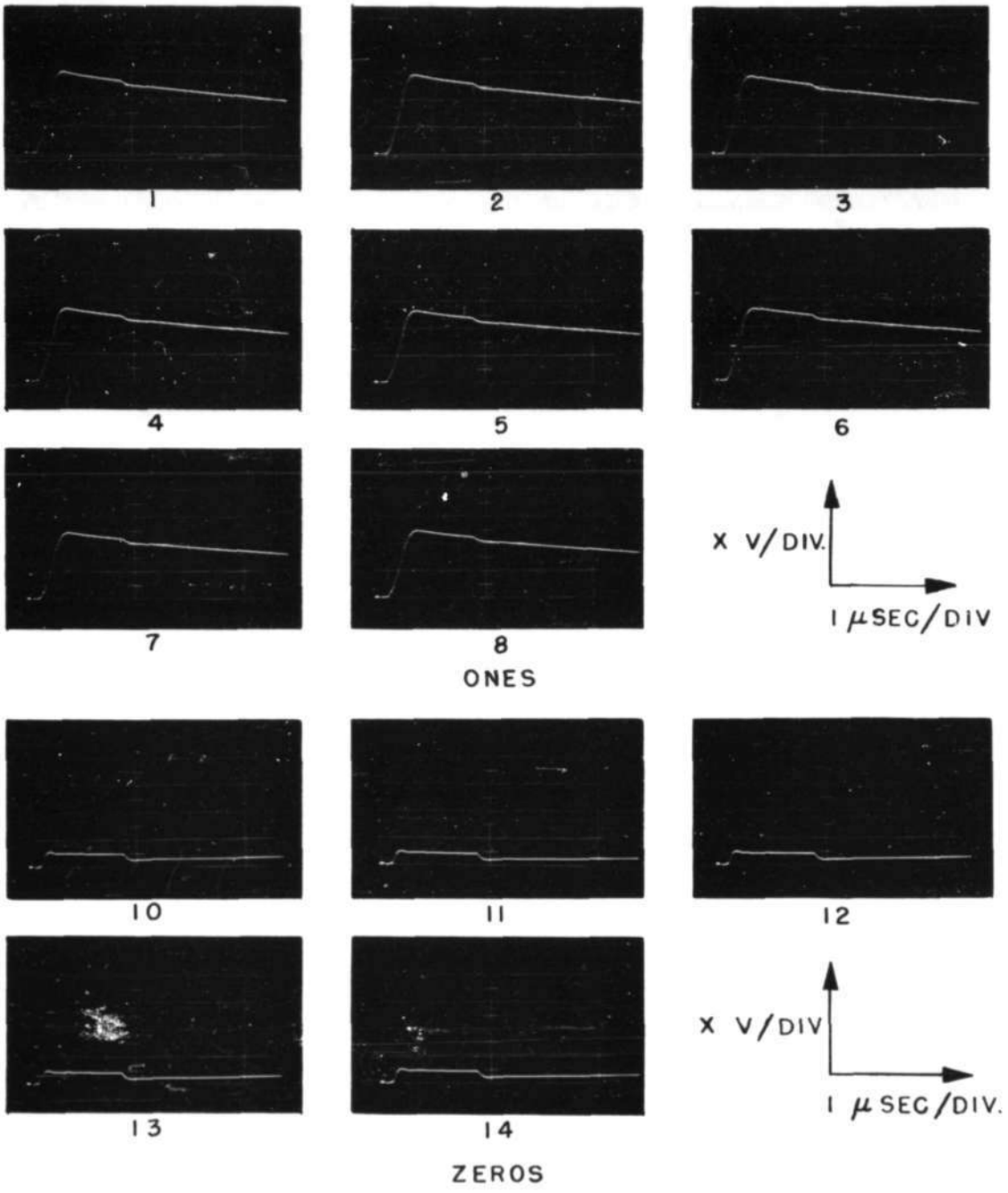
*See Section 2.03

**See Figure 4.02a



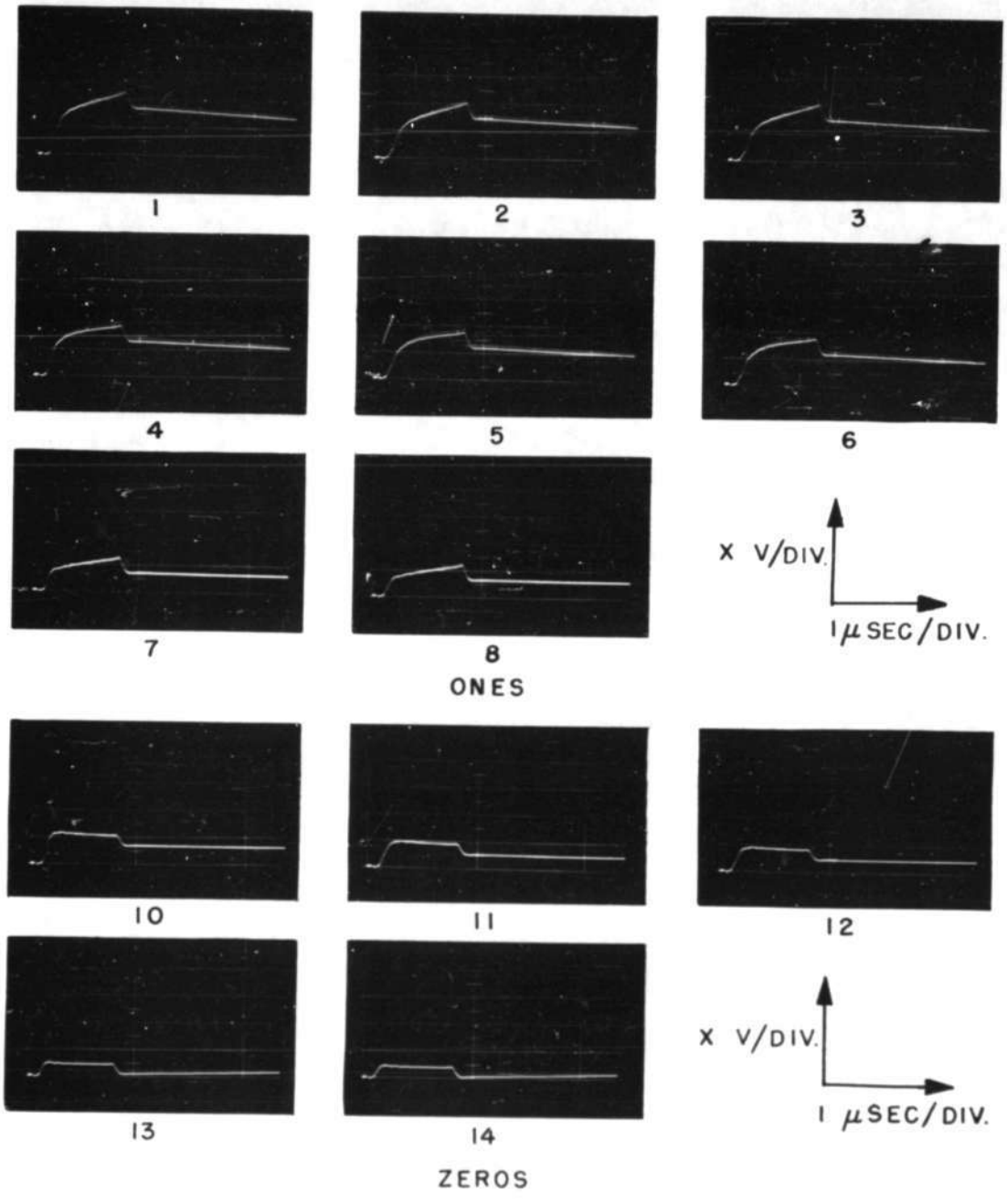
NOTES:

1. NUMBERS UNDER PICTURES REFER TO STATES OF FIG. 4.02a
2. THESE OUTPUTS ARE FOR 50 CORES MF 1326-B, DIE SIZE 394, LOT G92.

FIG. 5.03e

INTEGRATED V_I'S AT I_M = 650 ma.

A-59713



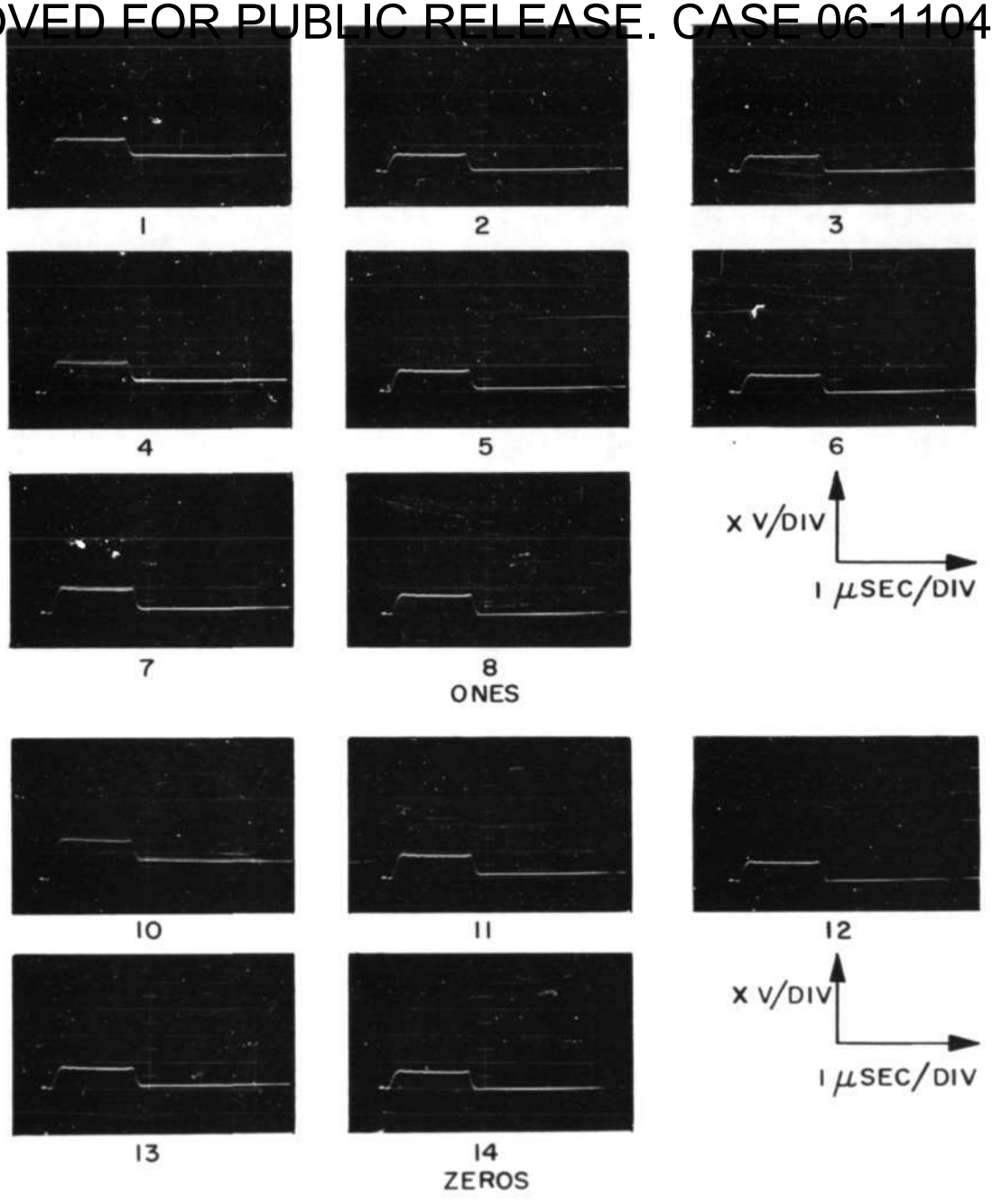
NOTES:

1. NUMBERS UNDER PICTURES REFER TO STATES OF FIG. 4.02 a
2. THESE OUTPUTS ARE FOR 50 CORES MF 1326-B, DIE SIZE 394, LOT G 92.

FIG. 5.03 f

INTEGRATED $V_{\frac{2}{3}}$'S AT I_M = 650 ma.

A-59714



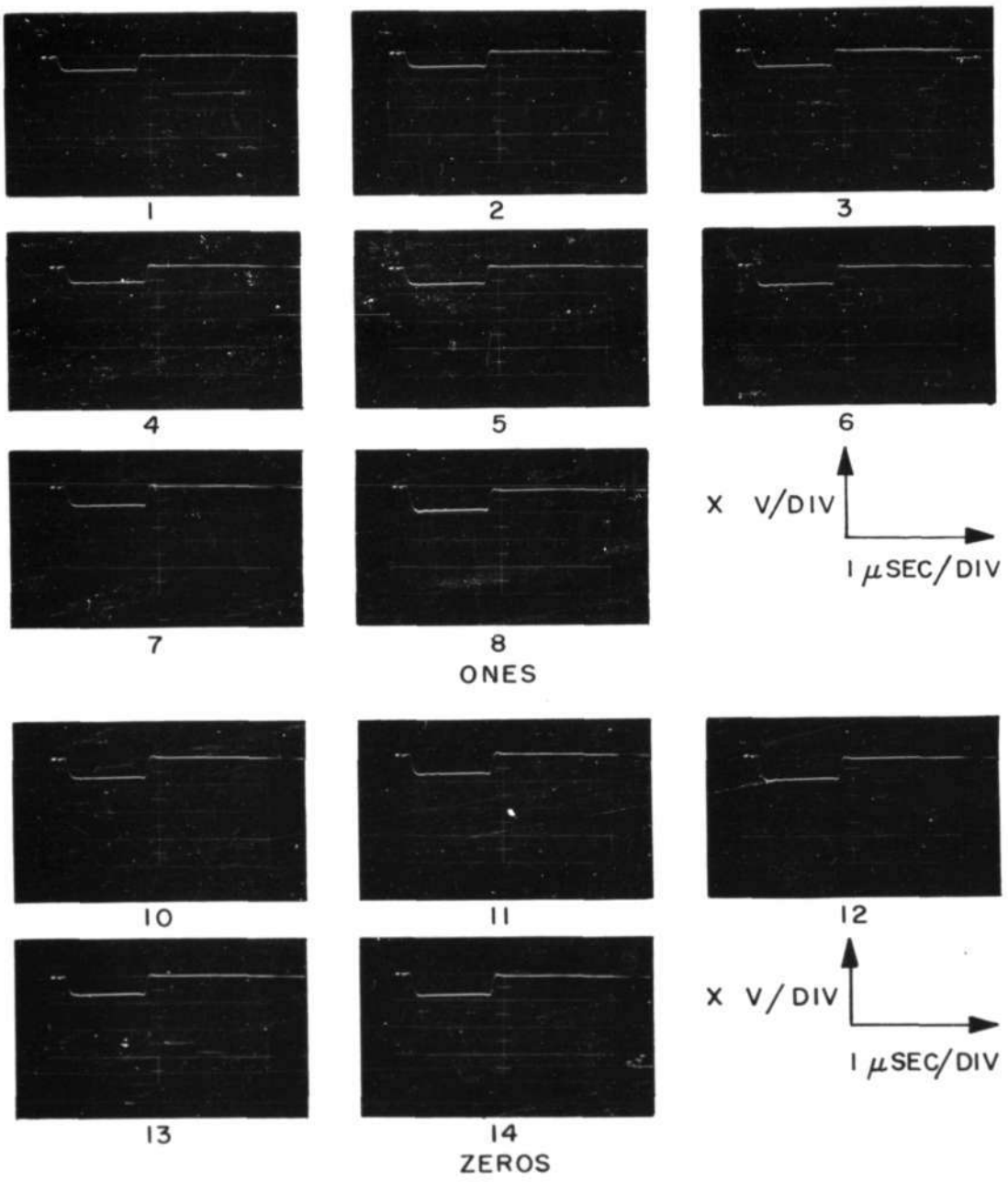
NOTES:

1. NUMBERS UNDER PICTURES REFER TO STATES OF FIG. 4.02 a
2. THESE OUTPUTS ARE FOR 50 CORES MF 1326-B, DIE SIZE 394, LOT G92

FIG. 5.03 g

INTEGRATED $V_{\frac{1}{3}}$'s AT I_M = 650 m.a.

A-59742



NOTES:

1. NUMBERS UNDER PICTURES REFER TO STATES OF FIG. 4.02a
2. THESE OUTPUTS ARE FOR 50 CORES MF 1326-B, DIE SIZE 394, LOT G92

FIG. 5.03h

INTEGRATED $V_{-\frac{1}{3}}$'s AT I_M = 650 ma

A-59743

TABLE 5.03b

A COMPARISON OF UNINTEGRATED AND INTEGRATED OUTPUTS

I_m=650 maa

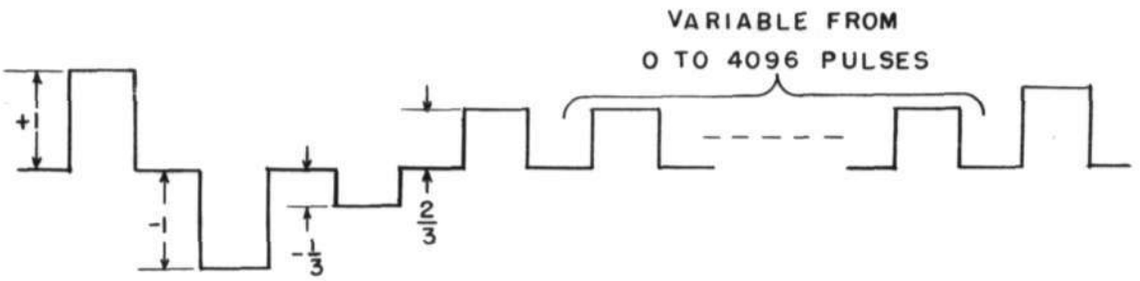
STATE	EXCITATION I_m	UNINTEGRATED OUTPUTS (Normalized)	INTEGRATED OUTPUTS (Normalized)
1	1	1.00	1.00
2	1	.98	.98
3	1	1.00	.97
4	1	.90	.89
5	1	.90	.89
6	1	.90	.89
7	1	.90	.82
8	1	.88	.80
9	1		
10	1	.02	.06
11	1	.02	.04
12	1	.02	.04
13	1	.02	.04
14	1	.02	.04
15	1		
1	2/3	.100	.136
2	2/3	.108	.116
3	2/3	.112	.121
4	2/3	.048	.109
5	2/3	.048	.092
6	2/3	.048	.096
7	2/3	.016	.052
8	2/3	.016	.052
9	2/3		
10	2/3	.006	.056
11	2/3	.008	.090
12	2/3	.008	.036
13	2/3	.008	.010
14	2/3	.008	.004
15	2/3		

TABLE 5.03b (Continued)

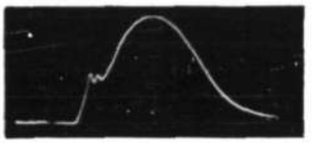
STATE	EXCITATION I_m	UNINTEGRATED OUTPUTS	INTEGRATED OUTPUTS
1	1/3	.020	.013
2	1/3	.005	.001
3	1/3	.004	.000
4	1/3	.010	.010
5	1/3	.005	.003
6	1/3	.004	.000
7	1/3	.006	.004
8	1/3	.005	.000
9	1/3		
10	1/3	.006	.014
11	1/3	.004	.009
12	1/3	.003	.000
13	1/3	.005	.003
14	1/3	.004	.000
15	1/3		
1	-1/3	-.010	-.000
2	-1/3	-.010	-.000
3	-1/3	-.012	-.001
4	-1/3	-.009	-.000
5	-1/3	-.010	-.000
6	-1/3	-.014	-.002
7	-1/3	-.010	-.000
8	-1/3	-.017	-.004
9	-1/3		
10	-1/3	-.007	-.000
11	-1/3	-.007	-.000
12	-1/3	-.011	-.003
13	-1/3	-.004	-.000
14	-1/3	-.007	-.001
15	-1/3		

NOTE: 1. The sensing time for the unintegrated data is .85 μsec. after the time marker, and for the integrated data 3.5 μsec.

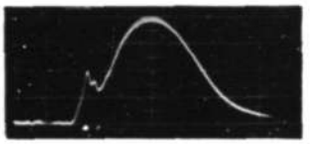
2. In both cases the data has been normalized with respect to the maximum output.



PULSE SEQUENCE



1 DISTURB



64 DISTURBS

4096 DISTURBS

FIG. 5.03 i

DISTURB SENSITIVITY AT I_M = 700 ma

A-5971S

CHAPTER 6

OPERATION OF AN 8x8x8x8 DIGIT PLANE

6.01 The Digit Plane

The data of Chapter 5 gave some insight into the sensing problem, but more experimentation was needed before any final decisions could be made as to the practicability of the system. Although the data indicated that with a single sense winding amplitude discrimination alone was not a satisfactory detection technique, the possibilities of either staggered selection or a pre-read disturb sequence followed by integration still remained to be investigated. Instead of predicting the results from single core data, more accurate information was obtained by testing the different schemes on an 8x8x8x8 digit plane, selecting different cores by manually switching the drivers from one coordinate line to the next.

The plane constructed for testing the different sensing schemes was made of MF1326B cores which had been tested for normal 2 to 1 operation, but had not been tested on the 3 to 2 basis. It was realized that the allowable variations in the fully selected ONE outputs were probably greater than could be allowed on the 3 to 2 basis, but it was felt that at sensing time, the different types of disturb voltages, which are of most concern in this study, would be uniform enough to give sufficiently accurate results. The plane was wired following a pattern similar to that shown in the schematic for a 4x4x4x4 plane (Fig. 4.01a). A cancelling sense winding was used i.e., if all the lines in any coordinate were similarly excited, half the cores would induce positive voltages in the winding and the remainder negative voltages. Fig. 6.01a is a photograph of the plane. In all there were ten #38 wires passing through each core, and the actual

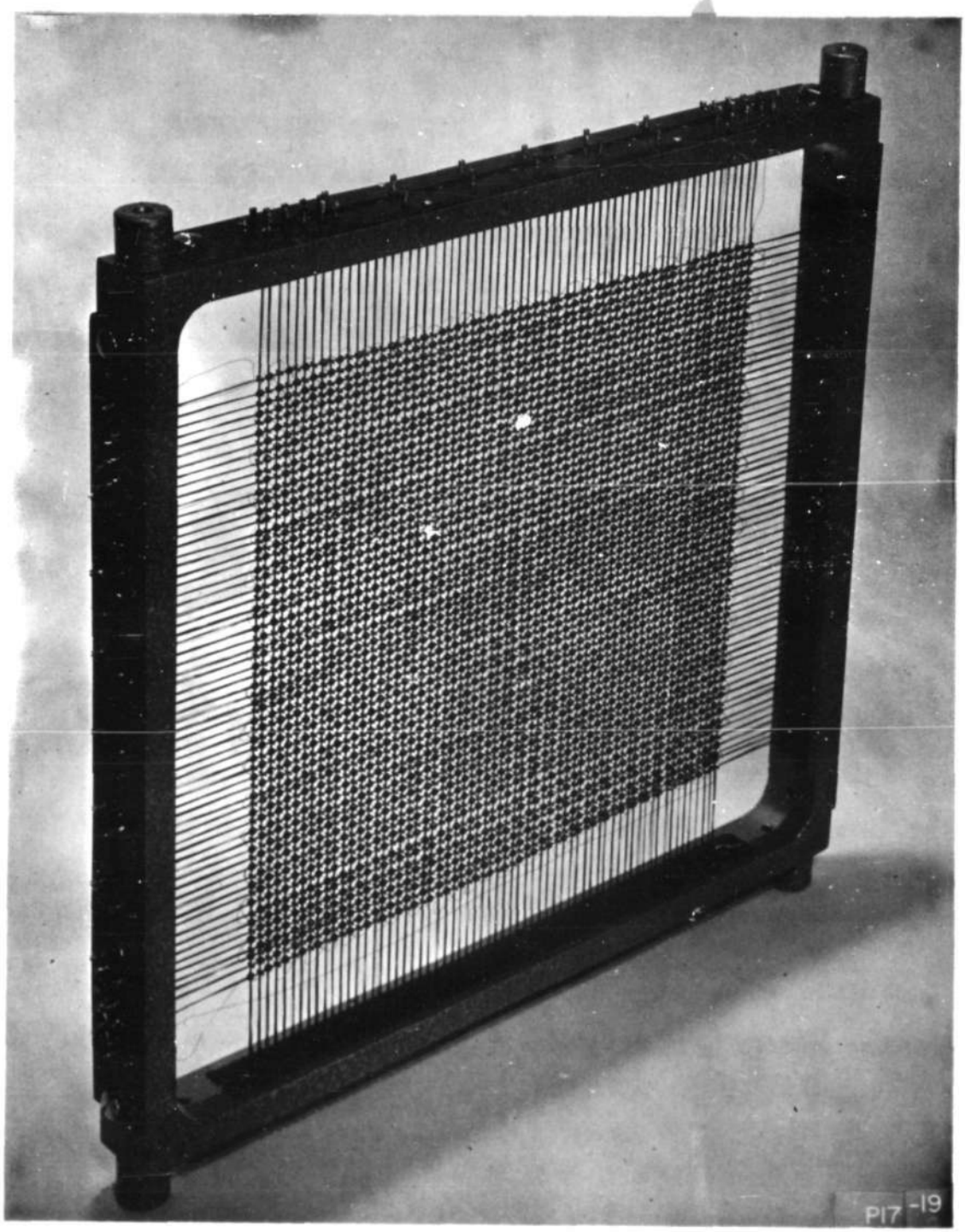


FIG. 6.01a
AN 8×8×8×8 MEMORY DIGIT PLANE

A-59702

wiring time was approximately 50 hours, the wiring being done by a technician experienced in building 64x64 planes of the same physical dimensions.

6.02 The Memory-Plane Tester

Fig. 6.02a is a photograph of the memory-plane tester, and Fig. 6.02b is the block diagram. The equipment used was the same as that for the core tester with the addition of a balanced-input sense amplifier (Fig. 6.02c).

The tester was capable of doing the following:

1. Any one of four addresses could be selected manually through the use of toggle switches, and the four driving lines that comprised this group could be changed by resoldering.

2. At any of these addresses a simple read-write cycle, or a pre-read disturb sequence followed by a read-write cycle, or a staggered read-write cycle could be used.

3. All ONEs or all ZEROs (states 1 and 15, respectively) could be written by fully exciting the digit-plane winding.

4. Patterns that gave approximately the minimun ONE and maximum ZERO could be written by exciting the sense winding with $\pm I_m$. This would leave the cores of one polarity in a ONE state and those of the opposite polarity in a ZERO state, and would tend to maximize the magnitude of the net output from the disturbed cores.

6.03 Experimental Results

After making preliminary experiments at different current settings to determine the best operating range, the data were taken in the form of photographs, and those which seemed most significant are

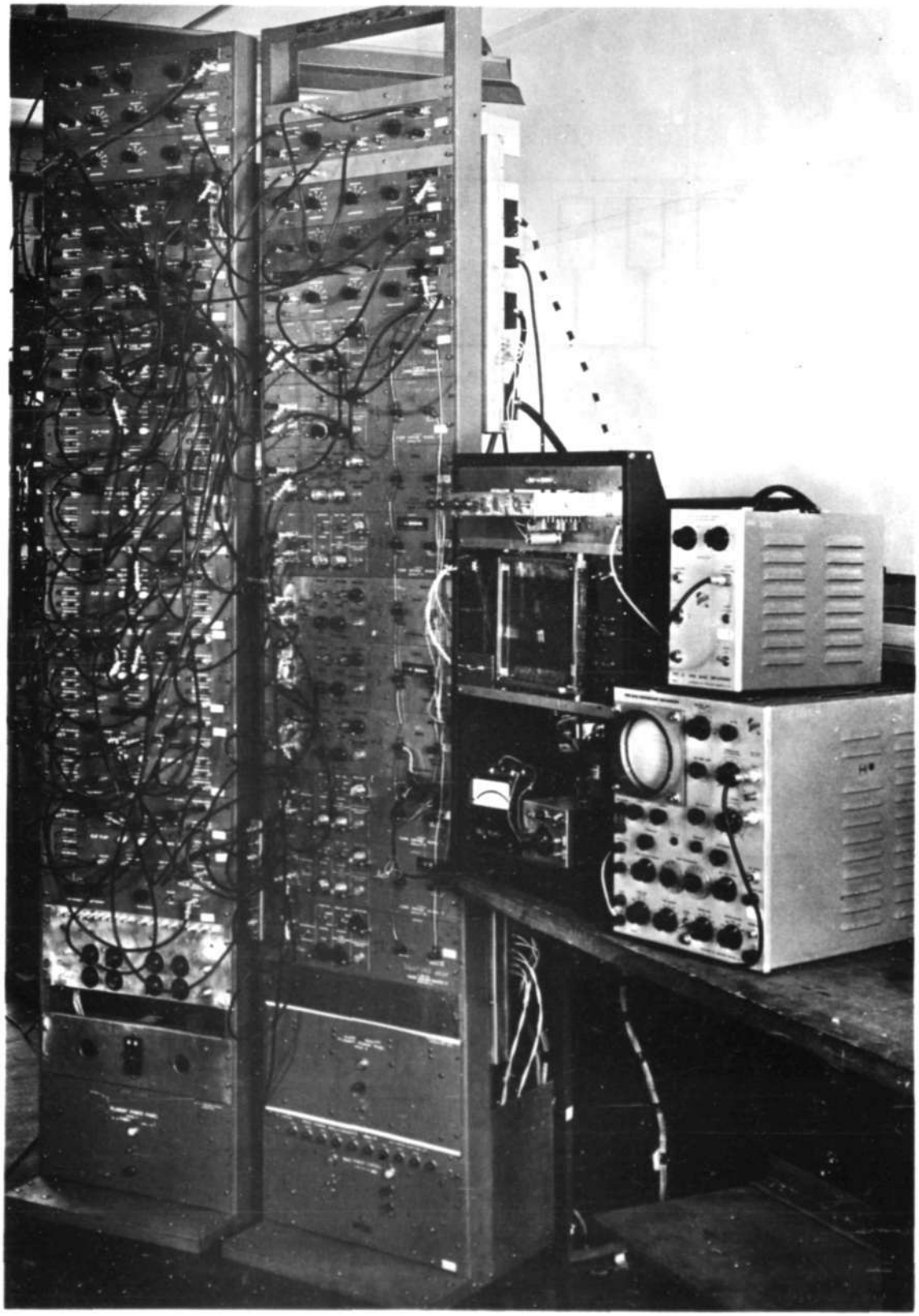


FIG. 6.02 a

MEMORY PLANE TESTER

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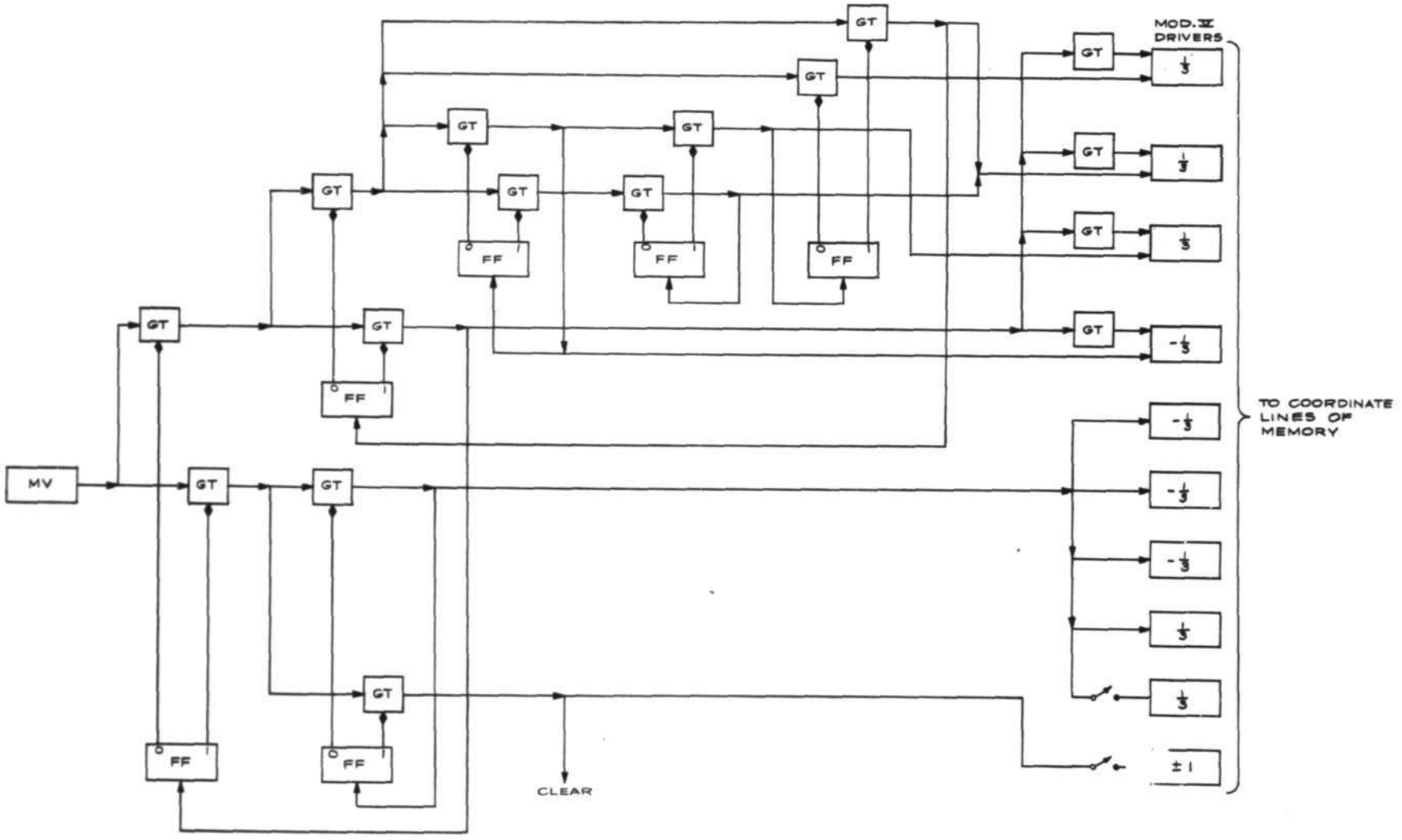
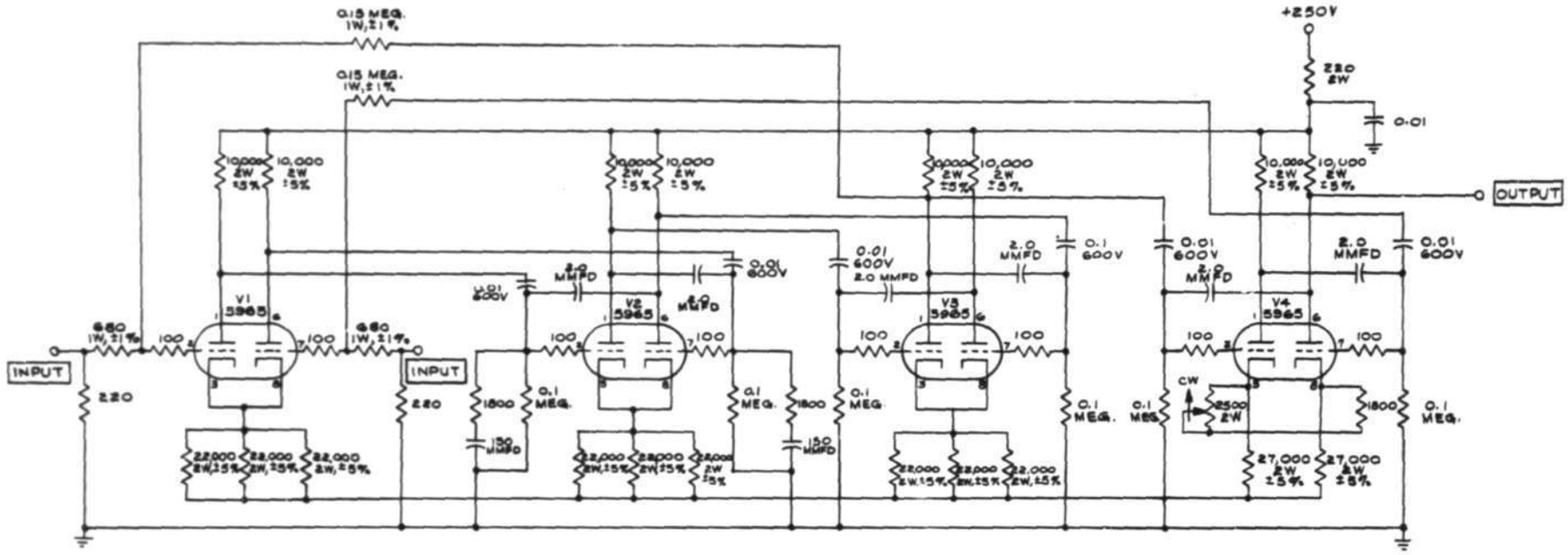
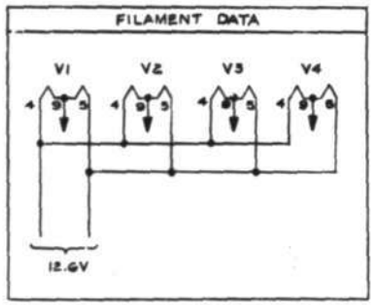


FIG. 6.02b
BLOCK DIAGRAM OF MEMORY PLANE TESTER

C-59747





NOTES:
1. UNLESS OTHERWISE SPECIFIED:
   A. RESISTORS ARE IN OHMS, ½ WATT, ±10%.
   B. CAPACITORS ARE IN MICROFARADS.

FIG. 6.02C

CIRCUIT SCHEMATIC, SENSING AMPLIFIER

shown in Figs. 6.03a through 6.03c.

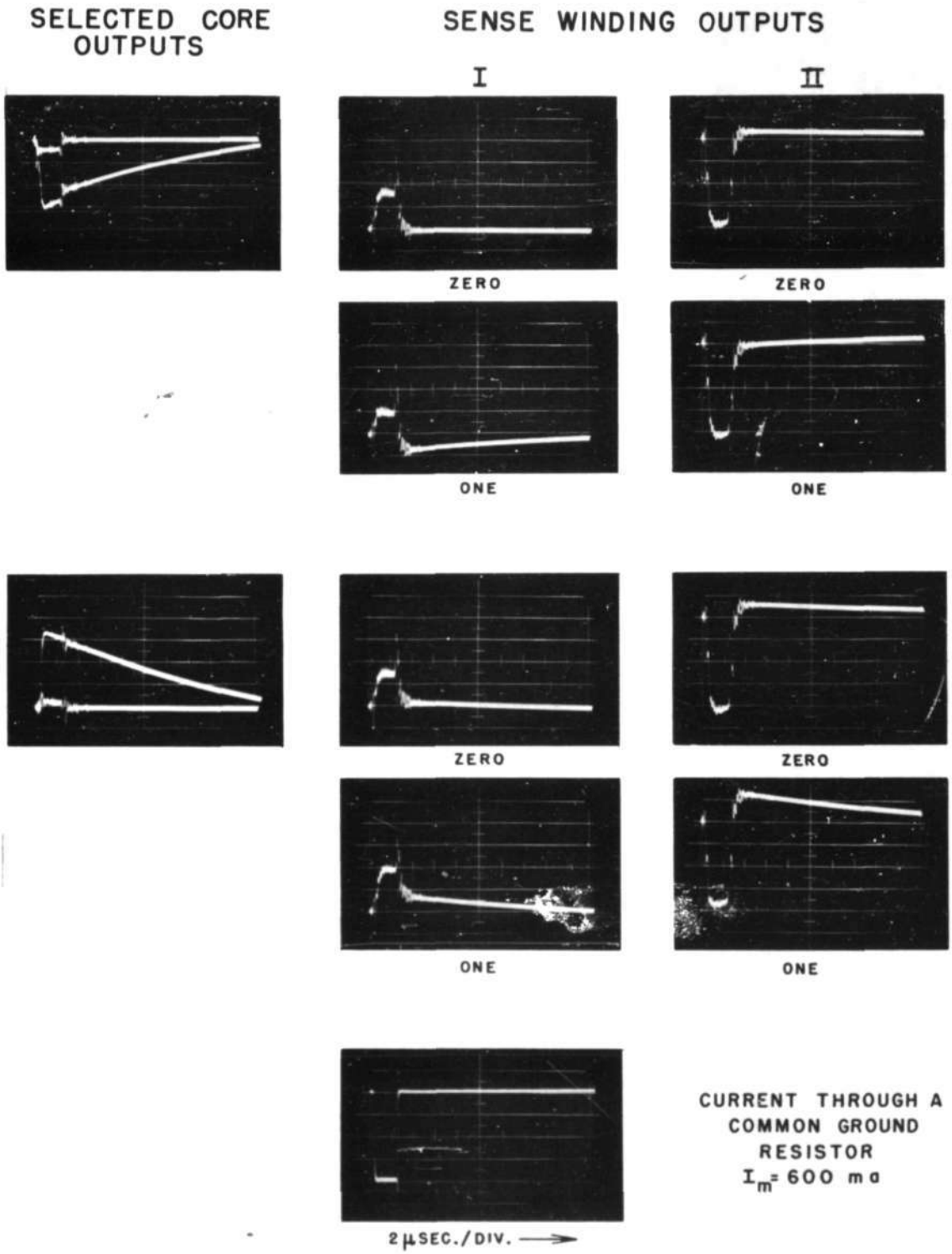
In the first tests that were made only amplitude discrimination was used, and as was predicted in Chapter 5, it was possible for the magnitude of a ZERO plus disturb voltages to exceed the magnitude of a ONE plus disturb voltages. Likewise, when the scheme involving a pre-read disturb and integration was used (Fig. 6.03a), although the results improved by an order of magnitude, there were cases where the magnitude of a ZERO plus disturb voltages was larger than the smallest magnitude of a ONE plus disturb voltages. The last scheme tried was the use of a staggered read, and this seemed to offer a promising solution.

The first data taken with the staggered read* were discarded when it was discovered that the results were in error because of air-flux pick-up. This pick-up was due to the fact that what was assumed to be a non-inductive sense winding was only partially so because of the position of the return lead.** The error was corrected, and Figs. 6.03b and 6.03c show outputs for various pattern sequences. An attempt was made to approximate the worst results that might arise in actual operation, but it should be observed from the photographs shown that, as would be expected, not only were the magnitudes of the outputs influenced by the pattern of information stored in the plane, but they were also influenced by the previous history.

The procedure used to obtain each sequence of photographs was first, the digit plane winding was excited with $\pm I_m$ to establish a pattern with all the cores in the same ONE state, and then a ONE and

* See Reference 20

** For a general discussion of sense winding geometry and its relation to the pick-up problem, see Reference 21.



NOTE: SEE TEXT FOR A DESCRIPTION OF THE DIFFERENT INFORMATION PATTERNS

FIG. 6.03 α

MEMORY PLANE OUTPUTS USING A PRE-READ DISTURB AND INTEGRATION

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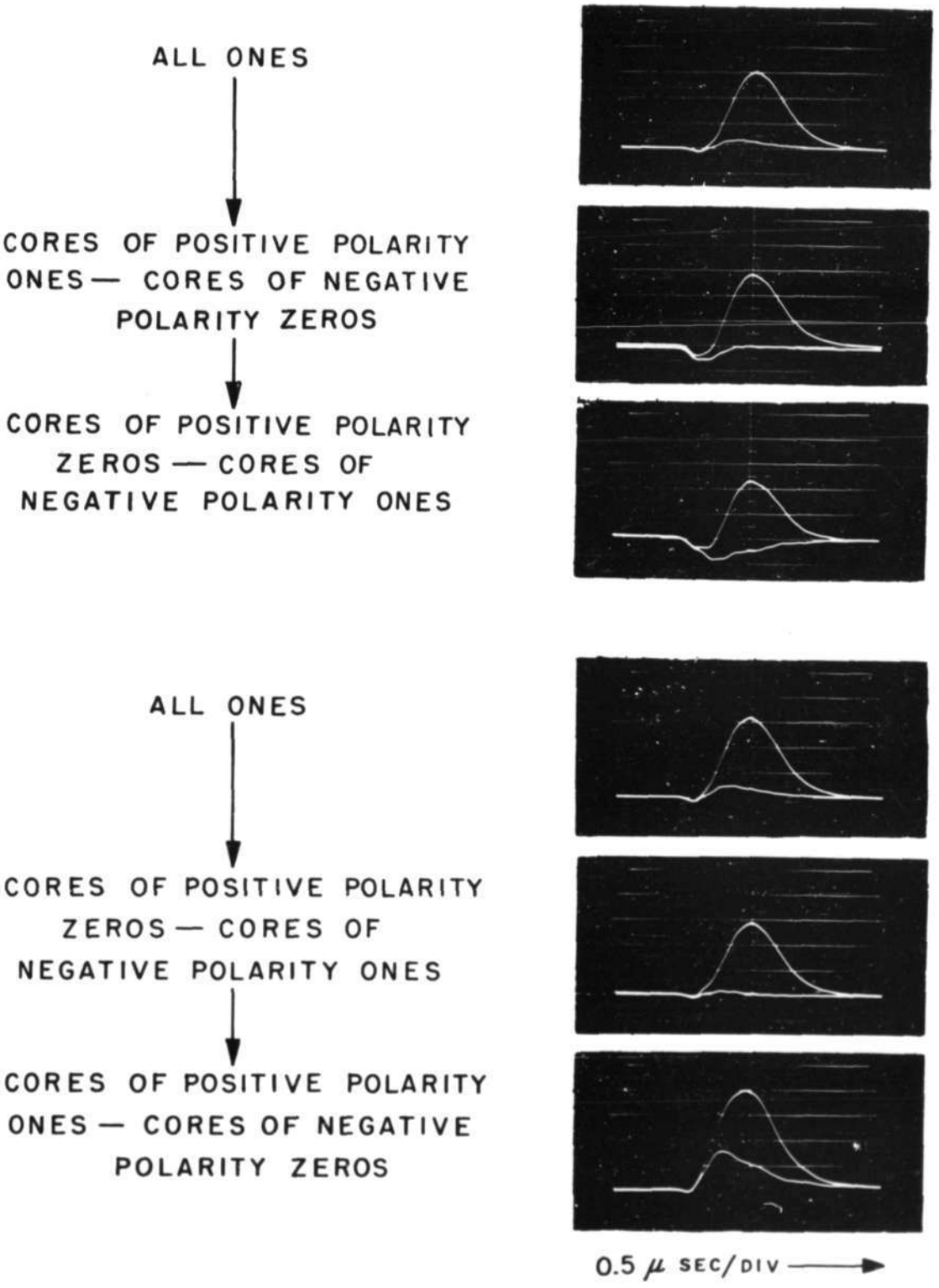


FIG. 6.03b

MEMORY PLANE OUTPUTS FOR A SELECTED CORE OF POSITIVE POLARITY, USING A STAGGERED READ WITH I_m = 630m.a.

A-61733
SHEET 1 OF 2

PATTERN SEQUENCE — SAMPLE ZERO OUTPUTS

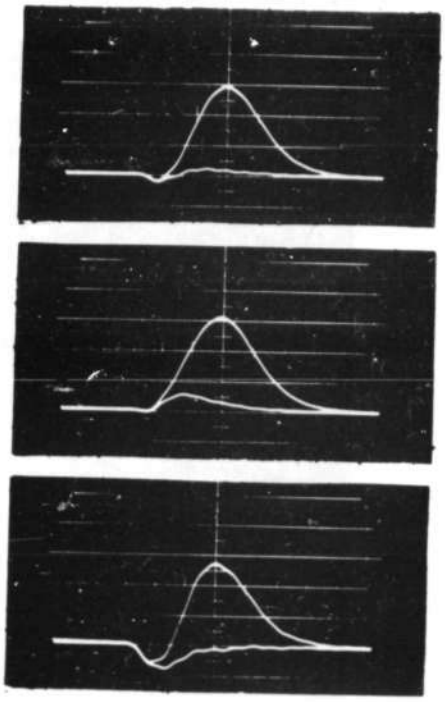
ALL ZEROS

↓

CORES OF POSITIVE POLARITY ZEROS — CORES OF NEGATIVE POLARITY ONES

↓

CORES OF POSITIVE POLARITY ONES — CORES OF NEGATIVE POLARITY ZEROS



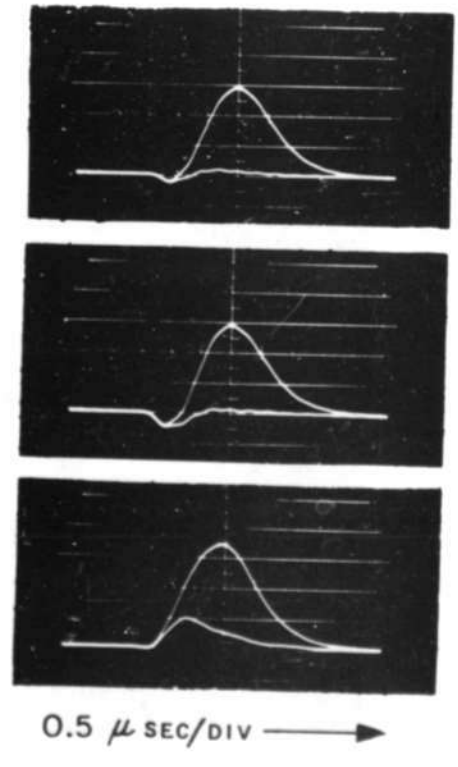
ALL ZEROS

↓

CORES OF POSITIVE POLARITY ONES — CORES OF NEGATIVE POLARITY ZEROS

↓

CORES OF POSITIVE POLARITY ZEROS — CORES OF NEGATIVE POLARITY ONES



0.5 μ SEC/DIV →

FIG. 6.03b

MEMORY PLANE OUTPUTS FOR A SELECTED CORE OF POSITIVE POLARITY, USING A STAGGERED READ WITH $I_m = 630$ m.a.

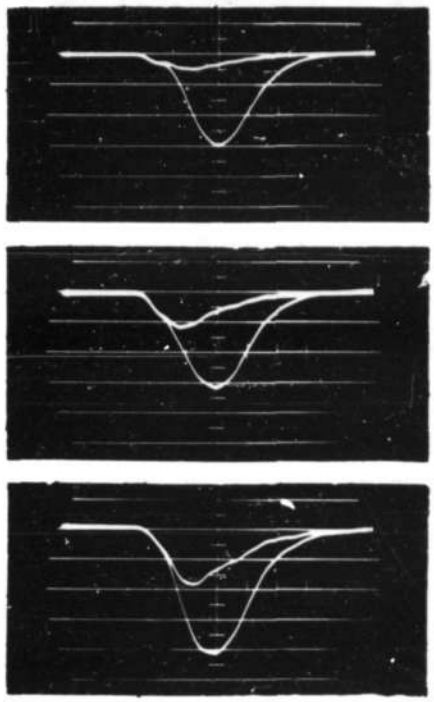
A-61733
SHEET 2 OF 2

PATTERN SEQUENCE — ONE AND ZERO OUTPUTS

ALL ONES

CORES OF POSITIVE POLARITY ONES — CORES OF NEGATIVE POLARITY ZEROS

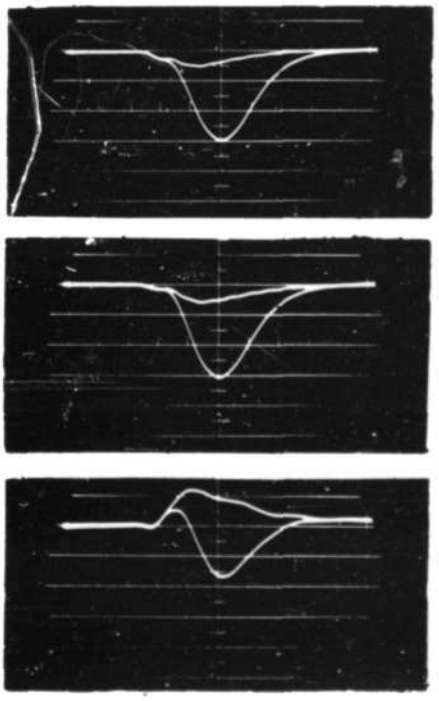
CORES OF POSITIVE POLARITY ZEROS — CORES OF NEGATIVE POLARITY ONES



ALL ONES

CORES OF POSITIVE POLARITY ZEROS — CORES OF NEGATIVE POLARITY ONES

CORES OF POSITIVE POLARITY ONES — CORES OF NEGATIVE POLARITY ZEROS



0.5 μ SEC/DIV ⟶

FIG. 6.03 c

MEMORY PLANE OUTPUTS FOR A SELECTED CORE OF NEGATIVE POLARITY, USING A STAGGERED READ WITH I_m = 630 m.a.

A-61734
SHEET 1 OF 2

PATTERN SEQUENCE — ONE AND ZERO OUTPUTS

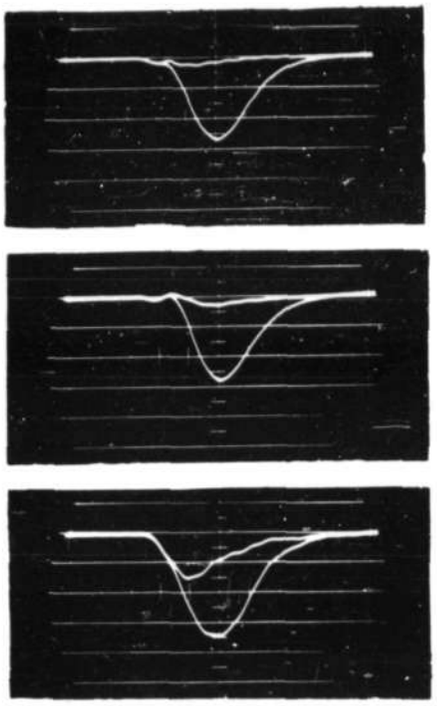
ALL ZEROS

↓

CORES OF POSITIVE POLARITY ZEROS — CORES OF NEGATIVE POLARITY ONES

↓

CORES OF POSITIVE POLARITY ONES — CORES OF NEGATIVE POLARITY ZEROS



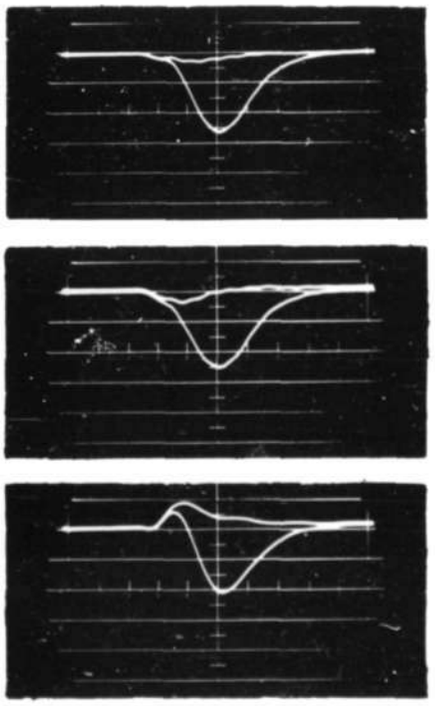
ALL ZEROS

↓

CORES OF POSITIVE POLARITY ONES — CORES OF NEGATIVE POLARITY ZEROS

↓

CORES OF POSITIVE POLARITY ZEROS — CORES OF NEGATIVE POLARITY ONES



0.5 μ SEC/DIV →

FIG. 6.03 c

MEMORY PLANE OUTPUTS FOR A SELECTED CORE OF NEGATIVE POLARITY, USING A STAGGERED READ WITH $I_m = 630$ m.a.

A-61734
SHEET 2 OF 2

ZERO output from a selected core were photographed. Next the sense winding was excited with $\pm I_m$ placing the cores of one polarity in a ZERO state and cores of the other polarity in the ONE state, and again the outputs were photographed. Finally, the sense winding was again excited to store the complement pattern in the plane and the outputs photographed.

A study of the data shows that although the margin is small, the smallest ONE does exceed the largest ZERO, and when it is recalled that the cores were not tested for a 3-to-2 selection scheme, the results are encouraging. It should also be noted that the magnitude of the difference between the smallest ONE and largest ZERO for the positive core chosen is a good deal larger than that for the negative core chosen, and this indicates that there is an appreciable variation in the core outputs, both fully selected and disturb outputs, and that careful core testing at the operating currents would greatly improve the results.

6.04 Conclusions

The data already taken indicate that a more extensive analysis of the proposed system is well worthwhile. It was shown that a core will hold its information even when repeatedly disturbed and that the major problem is due to disturb outputs masking the signal. For the 4096-bit digit plane, the effect of the disturb outputs is reduced by the use of a staggered read to the point where successful operation seems possible.

To further evaluate the proposed system, a comparison can be made with a comparable 4096-register memory using a 2-coordinate read–3-coordinate write. A 64x64 digit plane will require at least 2(64+64)=256 driving cathodes, whereas an 8x8x8x8 digit plane will require 2(8+8+8+8)=64 or 1/4 the former number. The excitation of each driving line in the

2-coordinate system is $I_m'/2$, and in the 4-coordinate system only $I_m''/3$ where the value of I_m is of necessity less for the 4-coordinate case, and experimental results indicate that the current per driving line for this system would be about 1/2 the current for the 2-coordinate system. Although the current is less for the 4-coordinate case, 1/8 of the total array of cores must be excited by each driving line as compared to 1/64 for the 2-coordinate case, and it may be necessary to use a more complicated driving circuit in the former system to obtain a comparable rise time.

In the 2-coordinate system, two 64-position crystal matrices are needed and because of the considerable load this presents, the flip-flops which control the matrices must be followed by cathode followers. With the 4-coordinate system, four 8-position matrices are needed, and the load is reduced to the point where the flip-flops could probably drive the matrices directly.

The magnitudes of the total disturb outputs can be compared roughly by determining the "core-amperes" for each case. That is, the number of excitations received by each core summed over all the cores in the plane. For the 2-coordinate case as operated with no staggering

$$\text{"core-amperes"} = 128 \times \frac{I_m'}{2}$$

and for the 4-coordinate case with staggering

$$\text{"core-amperes"} = \frac{4096}{8} \times \frac{I_m''}{3}$$

Since $\frac{I_m'}{2} = \frac{2I_m''}{3}$ the "core-amperes" increase roughly by a factor of 2 for the 4-coordinate case. If the hysteresis loop were linear in this region and if the loops for each case were the same, then twice the

disturb output could be expected for the 4-coordinate system. However, the hysteresis loop is not linear and therefore, the smaller excitation in the 4-coordinate system produces outputs which are less than would be encountered if the loop were linear. On the other hand, the loop traversed in the 2-coordinate system is larger and has smaller slopes, and this would tend to decrease the size of the outputs as compared to the 4-coordinate loop. These two factors then are seen to work in opposite directions and as a rough approximation might be considered to cancel one another.

Another factor which must be considered is that the ONE output for the 4-coordinate case, which is, after all, the signal to be detected, is about 1/2 as large as the ONE obtained for the 2-coordinate case. The net result, then, is that very roughly the ONE to ZERO ratio for the 4-coordinate system using staggering should be about 1/4 that obtained for a comparable 2-coordinate system not using staggering; the photographs show it is somewhat worse than this.

One final comparison to be made is between the memory cycle times. These times are approximately 6μsec for the 2-coordinate system and 9μsecs. for the 4-coordinate system.

In summarizing the results, it can be said that if a smaller working margin and longer memory cycle are allowable, a considerable reduction in driving cathodes can be made by using a 4-coordinate read—5-coordinate write system.*

* Since the time this work was begun, better cores have been developed and experimental work has also been done on diode mixing at low levels of signals from multiple sense windings. These further developments indicate that a reliable sensing system can be developed.

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