THE DEVELOPMENT OF A
MULTIAPERTURE RELUCTANCE SWITCH

by

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This paper describes the development of a substantially improved transfluxor type device called the Multiple Apertured Reluctance Switch (MARS). The MARS is similar to the classic transfluxor in that it comprises square loop magnetic material embodying two apertures. However, in deducing the details of a subtle switching phenomena, a powerful electrical control parameter was discovered, permitting geomechanic design of MARS devices mechanically characterized by two apertures having substantially the same inner perimeter (figure 1). Eliminating the necessity for the large aperture, a mechanical characteristic of the classic transfluxor, was necessary before a practical three-dimensional coincident current, non-destructive readout memory could be developed.

The address conductor (B) passes through the control aperture. Current pulses applied to this conductor determine by means of flux distributions whether the "one" or "zero" information state occurs.

To qualitatively describe the operation of the MARS, a timing diagram is shown in figure 3. This diagram describes the time relationship between the read and control pulses applied to conductors A and B respectively. These pulses have been numbered to provide a simple method of distinguishing one pulse from another during the following discussion.

Figures 4a through 4d describe the saturated flux distribution that encircles the read aperture resulting from driving the current pulses (figure 4e) through it. Figure 4f describes the output signal present at the sense winding terminals during the application of corresponding current pulses No.1 through No.4.

In all flux distributions drawings shown, the current pulses applied to line A switch only the direction of flux encircling the read aperture, i.e., from a clockwise to a counterclockwise direction. A voltage pulse developed at the sense winding terminals corresponds to the time rate-of-change of this flux reversal. The magnitude of this voltage is proportional to:

\[ e = - \frac{\Delta \psi}{\Delta T} = - \frac{(Br + Bm)}{\Delta T} \]  

(1)
where

\[ As = \text{equivalent cross-sectional area of saturated flux encircling the read aperture} \]

\[ \Delta T = \text{time increment} \]

Equation (1) describes the output voltage for the case where the flux encircling the read aperture is switched from \( 4B_r \) (the remnant flux density) to \( 4B_m \) (maximum flux density).

Figure 5 shows an effective hysteresis curve that defines the flux density and magnetizing force relationship while the MARS is storing a binary "one", as viewed from the read aperture.

The amplitude of read current pulses No. 1 through No. 10 (figure 3), excluding control pulses No. 5 and No. 10, are of sufficient amplitude to saturate flux around the read aperture to a radius slightly less than its diameter.

Pulses No. 5 and No. 10 (figure 3), which interrogate the control aperture, are called the write "zero" and write "one" pulses respectively. The polarity of pulse No. 5 is not arbitrary. Its polarity must be in a direction that will produce remnant flux around the control aperture in the same direction last developed around the read aperture. For example, figure 4d shows flux in a clockwise direction established around the read aperture owing to the application of pulse No. 4 to line A. To establish the binary "zero" saturation flux distribution, current pulse No. 5 must be in a direction that establishes saturation flux in a clockwise direction around the control aperture.

Figure 6 shows the remnant flux distribution for the binary "zero" condition. Because of the shape, it is called the "pulley" flux pattern. This situation is analogous to the block condition of the transfluxor.1 The belt of saturation flux encircling both read and control apertures formerly encircled only the read aperture. Specifically, this flux is near the control aperture, riding on the outer boundary of saturated flux encircling the control aperture. In essence, the application of the write "zero" control pulse switched the reluctance of the MARS to a higher value.

In figure 7 the solid base line passing through \(-B_R\) is the higher reluctance or binary "zero" response excitation characteristic, as viewed from the read aperture. Current pulses that interrogate conductor A, formerly sufficient to switch flux encircling the read aperture, are now insufficient to switch the flux belt encircling both read and control apertures. When the pulley pattern exists, the sense winding signal at the read aperture is substantially zero. Bi-polar read pulses may be applied indefinitely to the A conductor with no effect upon the pulley pattern, if the pulses are below a critical amplitude (\(I_{RD}\) in figure 7). This critical amplitude (read destructivity threshold) and the switching mechanism is discussed later. The amplitude of the write "zero" current pulses (pulse No. 5) should be of sufficient magnitude to extend the flux in a radial direction from the center of the control aperture until the flux is tangent to the inside diameter of the read aperture. This is the situation shown in figure 6.

Unlike transfluxor operation, the power and energy required to operate the MARS during the control phase is a minimum. This minimum energy requirement, in part, is accomplished by referencing the polarity of the write "zero" control pulse to that of the last read pulse. This technique eliminates the necessity for the control pulse to resaturate leg 1 of figure 8 since this leg was previously saturated during read time. (Leg 1 is the outer leg adjacent to the read aperture.) Re-saturating leg 1 during the writing of a binary "zero" is, therefore, useless and power consuming. However, this referencing technique requires the polarity of the write "zero" control pulse to be in a direction that will develop flux about the control aperture in the same direction as that last established around the read aperture. For example, in figure 6 the last read pulse No. 4, applied prior to writing a zero, establishes clockwise remnant flux about the read aperture. Similarly, control current pulse No. 5 (figure 3) applied to conductor B establishes clockwise saturation flux around the control aperture. This flux links leg No. 2 (figure 8) and opposes that portion of the flux encircling the read aperture. The action of the interference in leg 2 during the control pulse produces the "pulley" flux pattern shown in figure 6.

Figure 9 shows the flux distribution corresponding to the low reluctance state. This state is analogous to the unblocked condition of the transfluxor.1 The flux belt previously encompassing both apertures (figure 6) is now encircling only the read aperture. This process by which the MARS is switched to this low reluctance state starts with the application of the write "one" control pulse No. 10 (figure 3).
This unblocked or binary "one" information state allows read current pulses to switch the direction of the saturation flux encircling the read aperture in the same manner described previously in reference to figure 4. This flux, may be alternately reversed in direction indefinitely. The only restriction is that the correct polarity be established around the read aperture prior to writing a "zero".

Topography Investigation

Discs of ferrite material prepared for experimental evaluation possessed magnetic properties exhibiting the rectangular B-H characteristics shown in figure 10. Each disc, pressed and appropriately sintered, was cylindrical, with diameter and thickness of 0.25 inches and 0.025 inches respectively. Two apertures were then ultrasonically drilled in each disc. The relative position and diameter of these apertures are listed in Table I. These freshly cut samples were re-sintered for a period of 10 minutes to relieve any abnormal strains that might have resulted from the drilling process. Mechanical characteristics and dimensions of these test samples are shown in figure 11.

Table I

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<tr>
<th>Sample No.</th>
<th>Ds</th>
<th>a</th>
<th>L</th>
<th>R₁</th>
<th>R₂</th>
<th>D</th>
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Five basic experiment measurements were performed on each sample. The sequence of these experiments, listed below, was essential to the success of this development effort:

1) Test Sample - material homogeneity measurements.

2) Read destructivity threshold measurements.

3) Write "one" control properties

4) Write "zero" control properties

5) Write "one" - write "zero" switch time measurements.

The meaning of these experimental measurements relative to device operation are discussed later with the results of each experiment along with graphic plots of the appropriate test data. All experiments employed pulse techniques primarily because the mechanisms sought were switching phenomenon. If control of any of these mechanisms were to be developed, the transient nature of coherent energy (flux) interactions during external excitation would be the principal objectives of the experimental work.

Figure 12 shows the current pulse program used throughout the experiments. Each pulse in the sequence is numbered to simplify identification of individual pulses discussed.

Each test sample was wired with No. 35 Formvar insulated wire to conform with the arrangement shown in figure 13.

In figure 13 sense winding S1 and S2 linking leg 1 and leg 3 were provided to measure the change in the effective vector magnitude of the flux density occurring within the magnetic material...
comprising leg 1 and leg 3 respectively. (The nature of the flux reversals occurring within these boundaries is discussed later.)

The following paragraphs describe the experimental procedure for obtaining the read and control response excitation characteristics of each test sample in order to determine the influence of aperture topography.

**Uniformity Measurements**

The first experiment determined electrical uniformity of the magnetic material comprising the test devices, both individually and as a group.

The amplitudes of positive and negative current pulses, such as pulses 1 and 2 in figure 12, applied to the read aperture of each test sample via conductor A, were gradually increased and maintained equal in magnitudes. The corresponding peak amplitude, switch, and peak time of the electrical signal sensed by winding S1 were recorded. Similar procedures were employed for each sample by sensing, with winding S2, irreversible flux switched about the control aperture owing to the bi-polar pulses passed through conductor B. This data was plotted for each sample, as exemplified by figure 14. The inner wall irreversible switching threshold for each sample was obtained by projecting the linear portion of the output pulse amplitude until it intersected the abcissa or current axis. It was important for subsequent tests to know that the switching threshold (Io) for each sample had substantially the same value.

**Write "One" Control Properties**

The write one control properties for each test sample were obtained by using the following experimental techniques:

In figure 12 the magnitude of pulse No. 10, the write "one" control pulse interrogating the control aperture, was adjusted from an initial value of zero in increments of increasing amplitude. For each increment, the magnitude of current pulse No. 10 was recorded along with the corresponding peak amplitude, peak, and switch time of the read signal sensed by winding S1 during the application of read pulse No. 1. This response data could also have been taken during the first positive read pulse (pulse No. 11) occurring immediately after the application of the write "one" control pulse. However, there was a slight difference in the shape of the first readout signal obtained during pulse No. 11 compared to that measured at any other appropriate read time. But the area under each output response was the same. The difference in the observed response is believed to be associated with a slight disturbance in the distribution of flux encircling the read aperture caused by the application of the first positive read pulse following control pulse No. 10.

The measured response excitation (write "one" and "zero") characteristics for samples No. 2, No. 6, and No. 8 have been plotted collectively in figure 15. Two critical points (Irds and Irdf) in the write "one" control property have been indicated for each sample.

Irds corresponds to the control current amplitude where the reluctance of the MARS, viewed from the read aperture, begins to switch from the high to the low reluctance state. Irdf corresponds to the control current amplitude which is sufficient to completely switch the MARS into the low reluctance state. Flux distributions within the MARS device for the low and high reluctance states are shown in figures 9 and 6 respectively.

Before describing the significance of the write "one" control properties through an interpretation of the data, the procedure for obtaining the write "zero" control properties will be described.

**Write "Zero" Control Characteristics**

The order of the following control properties is essential for proper evaluation of the MARS device. The write "one" control properties must be established first because there is a third break current associated with this control process. It is called the reflex break current, Irb.

The write "zero" control functions of the test samples were obtained by using the current pulse program shown in figure 12. For each sample under test, the amplitude of current pulse No. 10, (Write "one" control pulse) was adjusted to be in excess of the break current (Irdf), but less than the reflex break current (IrB). Once this condition was satisfied, current pulse No. 3, (figure 12) was adjusted from an initial value of zero in equal increasing increments. By recording the magnitude of current pulse No. 3 at each increment and the associated peak amplitude, peak, and switch time of the signal appearing at the terminals of winding S1 during read current pulse No. 5, figure 12, we obtained the write "zero" response excitation characteristics plotted in figure 15.
Unlike the write "one" control function, there are only two current break points indicated in the figures, IRIS and IRIF. IRIS corresponds to the current magnitude where the reluctance of the MARS starts to increase (RIS - Reluctance Increase Start). IRIF corresponds to the current amplitude of the write "zero" control pulse where the reluctance of the MARS is completely switched to the high reluctance state, (IRIF - Reluctance Increase Finish).

An interesting phenomenon, shown in figure 15; is associated with the write "one" control response excitation characteristics. For each sample tested, break point (IRDS) was substantially identical. The results of this experiment indicated that:

\[
\text{IRDS} \text{ is independent of the separation distance between the read and control apertures, and it is directly proportional to the inner perimeter of the control aperture and the switching coercivity of the magnetic material comprising the device.}
\]

Break points IRIS, IRIF, and IRDF, however, are substantially affected by aperture separation.

For a MARS device to be conveniently operated in a three dimensional, coincident current system, the following are critical design criteria:

\[
\begin{align*}
\text{IRDS} &= \text{IRIS} \\
\text{IRDS} &= 66\% \text{IRDF} \\
\text{IRIS} &= 66\% \text{IRF}
\end{align*}
\]

Figure 15 shows that an increase in aperture separation increases the current amplitude at which thresholds IRIS, IRIF, and IRDF occur. For wide aperture separation distances, exemplified by samples 6 and 8, two criteria specified by equations (1) and (3) are violated. If this situation were tolerated, considerable power would be required to operate the device. Fortunately, equation (1) and equation (3) are compatible with low-power operation since they require close aperture proximity. However, a later section describes a phenomenon, the read destructivity threshold, which if uncontrolled prohibits close aperture proximity. The solution to this dilemma is discussed later and a unique method for electrically controlling this destructivity threshold is described.

**Read Destructivity Threshold**

The read destructivity threshold is the amplitude at which read current pulses start to reduce the reluctance of the MARS device, viewed from the read aperture. This phenomenon was referred to as spurious unblocking in reference 1. High and low reluctance states define the binary "zero" and "one" information states respectively. (Reluctance as used in this paper defines the relative degree of impedance encountered at the read aperture by the energizing means to switching irreversibly the flux in leg 1 (figure 13) of the MARS).

It is essential to understand the destructivity threshold in terms of flux distributions and particularly the switching mechanisms responsible for it. Characteristically, the existence of this phenomena determines to a great extent the limitations of multipath devices for practical applications in random access, non-destructive memory systems. Furthermore, if these subtle switching phenomena are understood, the optimum geomechanics of this and other multipath devices can be determined both experimentally and analytically.

The physical arrangement of the conductors passing through each experimental test sample is shown in figure 13. Conductors A and B permit external energizing means to influence the material energy state in the vicinity of the read and control apertures. Conductors S1 and S2 sense the change occurring within the material bounds comprising leg-1 and leg-3 respectively. Regarding current polarities, the reference direction adopted in this paper corresponds to applying positive current pulses to conductors A and B in the direction indicated by arrows in figure 13 to produce counterclockwise energization around the respective apertures.

Read destructivity thresholds for each test sample were determined experimentally by applying the current pulse program shown in figure 16.

Figure 17 is a plot of the switch time of the "zero" readout signal versus the amplitude of read pulse 6 and 7. This data was obtained by recording the electrical properties of the "zero" readout signal occurring during read pulse No. 9.
The readout signal occurring at pulse time No. 2, called a reference signal, was also observed, but only as a relative measure of the degree-of-destructivity being induced by pulse No. 6. This reference signal displayed the electrical output associated with each test sample after it was fully switched by control pulse No. 10 to the binary "one" information state. Referring to figure 17, note that for the reference polarity established, no destructivity threshold occurred for clockwise flux inducing read current pulses.

It is important to know the amplitude at which positive read current pulses start partial destruction of the binary zero information state, and how the geomechanic properties of the test samples influence this phenomenon.

Figure 16 shows the pulse program used to measure the positive and negative read destructivity threshold by overdriving read pulse No. 6 and 7 respectively.

Figure 18 shows the effect the width of the common leg, separating the read and control apertures, on the current amplitude at which the destructivity threshold occurred.

For all samples tested, the amplitude of the positive read current pulse, corresponding to the destructivity threshold, was in excess of the magnetizing force I₀ required to just irreversibly switch flux in the unblocked wall of the read aperture, but substantially less than twice this magnitude. This situation is shown in figure 17 where the "zero" readout response excitation of sample No. 2 and No. 8 are plotted collectively. Notice that the destructivity threshold I_RD is substantially less than twice I₀. This situation apparently compromises the effective use of multipath devices with similar apertures in a coincident current, three dimensional matrices. The nature of this threshold and its severe compromises provided a motivation to deduce, by experimental techniques, the mechanism responsible for it, and hopefully to evolve a suitable control technique. The material presented subsequently describes experimental techniques which led to the discovery of the switching phenomenon identified as "inner wall reflex switching". These critical experiments, conceived to verify this switching mechanism, provided a powerful control technique and design variable.

Prior to discovering the actual nature of this switching phenomenon, geomechanical techniques were used for increasing the relative current level at which the destructivity threshold occurs. These techniques are exemplified by the experimental characteristics plotted in figure 18 and by the classic transfluxor where the inner perimeter of the control aperture is substantially larger than that perimeter comprising the read aperture.¹,²

The switching mechanism associated with the read destructivity threshold is shown in figures 19a through 19d. These drawings show the distribution of flux thought to exist in the proximity of the read and control apertures during different stages of deformation. The degree of deformation is proportional to the amplitude of positive current pulses applied to the read aperture. Referring to figure 19a, leg 2 separating the read and control apertures was saturated in the reference direction (up) during the generation of the pulley flux pattern by control pulse No. 3 (figure 16). The flux density (Br) in this leg can be increased, depending on material rectangularity, by externally applying to the read aperture a magnetizing force in only one direction. For the established reference direction, this corresponds to the positive current pulses shown in figure 16. The intensity of the H field propagated from the conductor can be calculated to be proportional to the current and inversely proportional to the radial distance from the conductor. The action of the H field propagated from conductor A increases the flux density in leg 2 in diminishing proportions depending upon the radial distance of leg 2 from the conductor and simultaneously diminishes flux density in leg 3 by the action of the same vortex source, particularly in the vicinity of the wall area of the control aperture.

As the amplitude of the positive read current is increased, the coherent energy (flux) distribution internal to the magnetic material at the wall of the control aperture and tangent to leg 3 reaches a critical level. When this critical level is surpassed, the coherent energy directed clockwise around the wall of the control aperture reflexes back tangent to the remote side of the control aperture. This switching phenomenon, shown in figure 19d, has been called "inner-wall reflex switching".

The necessary conditions believed to be required to perpetrate this reflex switching is summarized by the following hypothesis, which is subsequently confirmed by experimental evidence.

A given region in bounded magnetic material that is suitably influenced by energy generated externally contains adequate internal coherent energy including that produced by the external
influence) to cause a reversal in the direction of coherent energy in another region. This second region undergoing reversal is in the immediate proximity of the first, and it has a lesser mean path length.

When this inner wall reflex switching is allowed to occur, it acts as a gate permitting flux to irreversibly switch in a counterclockwise direction concentrically about the read aperture. This situation is shown in figure 19d. Furthermore, the amount of flux permitted to switch about the read aperture is directly proportional to that amount reflexed about the wall of the control aperture. This, therefore, is the mechanism alluded to earlier as being responsible for the read destructivity threshold. Although the occurrence of this switching mechanism is undesirable in memory device applications, it undoubtedly is useful for others.

To experimentally determine that reflex switching is the mechanism responsible for the read destructivity threshold, and that it obeys the hypothesis outlined, some critical experiments were performed. Specifically, these experiments were designed to determine the following:

1) That reflex switching occurs.
2) That it occurs in the wall of the control aperture.
3) That by occurring first, it acts like a proportional flux gate producing the effect at the read aperture just described.

Does reflex switching occur? Conceptually, the experiment designed to answer this question is simple: By applying the train of current pulses shown in figure 16 to the appropriate apertures, and then increasing the amplitude of current pulse No. 6 in excess of the destructivity threshold, a signal should appear at the terminals of sense winding S2 (figure 13). The anticipated signal was observed. This would indicate that a change in the vector magnitude of the total coherent energy in leg 3 had actually occurred. As expected, the switching characteristics of the electrical signal detected were considerably different from those normally associated with irreversibly switching a similar amount of flux in a path closed about an external vortex source. The principal difference observed was a characteristically long trailing tail on the detected electrical response signals. Figure 20 depicts the electrical signal observed compared to the switching that encloses an external vortex source.

It was more difficult to devise an experiment for determining whether reflex switching instigates the destructivity threshold by occurring first and at the wall of the control aperture.

The experiments conducted show that the results anticipated occurred by using the pulse program shown in figure 21 and proceeding with the destructivity threshold measurements in exactly the same sequence already described to obtain the plot shown in figure 17. The salient results are shown in figure 22 which plots the switch time for the “zero” read out signal as a function of positive read current pulse amplitudes and the amplitude of pulse No. 13. The magnitude of pulse No. 13 is shown as the running parameter in figure 22. We see that bias pulse No. 13 substantially influenced the current amplitude at which positive read current pulses initiate destruction of the binary “zero” information state.

The experiment just described was carried further by determining the relationship of the destructivity threshold (IRD) as a function of the amplitude of pulse No. 13, defined as the “inner wall bias pulse”. The results of this latter experiment are plotted in figure 23.

The data plotted in figure 22 indicates that the energy propagated by the conductor carrying bias pulse No. 13 applied under the conditions specified by the experiment retarded reflex switching. Evidence of this fact is shown in figure 22 where the read destructivity current threshold (IRD) is increased by an amount proportional to the magnitude of bias pulse 13. Figure 23 further exemplifies this condition by showing that the read destructivity threshold is effectively controlled by an amount substantially equal to the magnitude of bias pulse 13, within the limits indicated. The shape of the curve in figure 23 leads one to conclude that reflex switching initially occurs in the wall of the control aperture and not elsewhere.

If reflex switching did not occur in the wall of the control aperture, but in some other more remote position in leg 3 (figure 19d), the control provided by the bias pulse shown in figure 23 would not break down at the current level indicated. Specifically, figure 23 shows that the current level (Io) corresponding to loss of control by the bias pulse is the current amplitude previously determined to be equal to the irreversible switching threshold of the wall of the control aperture.
If reflex switching had started at a position more remote than in the wall of the control aperture, the bias control function shown in figure 23 would have broken at some correspondingly higher amplitude.

Turning to the results of the first experiment, a signal was detected by sense winding No. 2 during an overdriven positive read pulse. Specifically, the electrical characteristics of this reflex signal (figure 21) were different from those normally encountered by irreversible switching of coherent energy about a path enclosing an external vortex source. If reflex switching at the wall of the control aperture acts as a gate, permitting coherent energy to be irreversibly switched around the read aperture enclosing the vortex source, the electrical signal sensed at winding S1 should have identically the same electrical characteristics as that simultaneously sensed by winding S2. Comparing these experimentally measured signals revealed no detectable difference in their response characteristics; also, both signals possessed the response characteristics peculiar to reflex switching. The fact that inner wall reflex switching occurs first (acting as a proportional flux gate) as described permitted controlling the read destructivity threshold by biasing the control aperture.

The effectiveness of this bias technique is illustrated in figures 24a through 24c, using test sample No. 3 for the conditions indicated below. These figures are exact enlarged copies of the actual oscilloscope traces.

Figure 24a shows nondestructive read of "zero" and "one" with read currents of 300 ma full-select, below read destructivity threshold and where no inner wall bias was used.

\[
\begin{align*}
I_{\text{Read}} &= \pm 300 \text{ ma full-select} \\
I_{\text{WR} \, "0"} &= 600 \text{ ma full-select} \\
I_{\text{WR} \, "1"} &= 450 \text{ ma full-select}
\end{align*}
\]

Figure 24b shows nondestructive read of "zero" and "one" with read currents of 400 ma full-select. Note that the positive read current is above read destructivity threshold, hence the increase switching time of the "zero" readout. In figure 24b:

\[
\begin{align*}
I_{\text{Read}} &= \pm 400 \text{ ma full-select} \\
I_{\text{WR} \, "0"} &= 600 \text{ ma full-select}
\end{align*}
\]

Figure 24c shows nondestructive read of "zero" and "one" with drive conditions as shown in figure 24b. Inner wall bias of 100 ma has been used to shift read destructivity threshold. Note the reduction of peak amplitude and switch time of "zero" signal.

The experiments outlined in this section indicate the following:

1) Inner wall reflex switching occurs.
2) Inner wall reflex switching occurs in the wall of the control aperture.
3) By occurring first, inner wall reflex switching acts like a proportional flux gate, allowing switching to occur about the read aperture.
4) Inner wall reflex switching is the mechanism responsible for the read destructivity threshold.

Write "One" Break Point-IRDS

From experimental work outlined earlier IRDS was found to be:

1) Independent of aperture separation
2) Directly proportional to the inner perimeter of the control aperture.
3) Directly proportional to the inner wall switching coercivity of the magnetic material comprising the device.

These experimental results provide useful aperture and topography design parameters. The nature of the IRDS properties and the mechanisms responsible need not be answered to use the experimental findings for engineering purposes.

The switching mechanism associated with the write "one" control process is illustrated by figures 25a through 25e. These drawings show the distribution of coherent energy (flux) in the proximity of the read and control apertures thought to exist during different stages of switching. The degree of switching indicated is proportional to the amplitude of the write "one" control pulse. Referring to figures 25a through 25d we can see that the effects of the write "one" control pulse instigates a complicated redistribution of coherent energy. This redistribution...
involves reflex switching, but not in either aperture wall. Reflex switching is believed to exist in the area shown in the figure because it was observed that part of the electrical signal detected by winding S2 (figure 13) during the write "one" control pulse exhibited the characteristics peculiar to reflex switching described previously.

In addition to the hypothesis cited, this reflex switching is believed to be instigated spontaneously by the action of the innermost band of coherent energy formerly encircling both apertures closing directly about the read aperture as shown in figure 25b. This closure can only be caused by a supplementary component of energy propagated internal to the magnetic material boundaries from conductor B, which carries the write "one" control current. Reflex Break Point IRB

Experimental work reported earlier indicated that a third break point exists in the write "one" response excitation characteristic. This break point, IRB in figure 15, was referred to as the reflex break current. Increasing the amplitude of the write "one" control current beyond the reflex break point affects the readout signal subsequently sensed at the read aperture in essentially the same fashion as when writing a "zero". The mechanism responsible for this phenomenon is defined as inner-wall reflex switching. With the exception of a slight difference in the peripheral flux distribution, the mechanics of the reflex break phenomenon are identical to those described previously as responsible for the read destructivity threshold.

Most of the text regarding inner-wall reflex switching would apply to the reflex break phenomenon if the words "read" and "control" are interchanged.

Figure 25 shows the distribution of coherent energy in the proximity of the read and control apertures for the conditions indicated. A second region of reflex switching is shown in figure 25d, specifically in the wall behind the read aperture. To show that the reflex break phenomena involve inner-wall reflex switching as noted in figure 25e, a pulse bias technique was employed, similar to that disclosed earlier. Figure 26 is a diagram of the current pulse program used. As shown, bias pulse No. 11 and write "one" control pulse No. 8 were applied to their respective apertures simultaneously. The amplitude of the bias pulse was maintained below the inner-wall switching threshold of the read aperture. Experimental data plotted in figure 27 indicates that the reflex break threshold is increased by an amount proportional to the magnitude of bias pulse No. 11, within the limits indicated. The bias current loses control at the magnitude just capable of irreversibly switching the inner perimeter of the read-aperture. The control latitude offered by this bias pulse permits the operation of production MARS devices in a unique three dimensional matrix. In this matrix it is virtually impossible to surpass the reflex break point.

Experimental evaluation showed that IRDS, IRDF, IRIS, and IRIF are unaffected by the presence of bias current of either polarity if magnitude is below that amount required to switch the wall of the aperture through which it is caused to pass.

Verification of the "Pulley" Flux Pattern

Reference has been made to the existence of the "pulley" flux pattern. Verification of its existence was deferred until now because proof is better understood after assimilating some of the concepts developed earlier.

The saturation flux drawn in figure 28a illustrates the coherent energy distribution in the proximity of the read aperture owing to current pulse No. 2 (figure 16). Current pulse No. 3 applied to conductor B is in a direction that establishes clockwise flux around the control aperture, as illustrated in figure 28b. This flux opposes that portion linking leg 2 already established around the read aperture. Under these circumstances, two alternative flux distributions might seem feasible as shown in figures 28c and 28d. Figure 28c is the familiar "pulley" pattern referred to frequently and figure 28d shows the alternate case where a form of reflex switching has occurred.

The purpose of the following experiments is to provide conclusive experimental evidence of the "pulley" pattern of figure 29. It appears from figure 28c that the generation of this flux distribution involves no net change in the flux linking leg 1. On the other hand, figure 29d illustrates a situation in which the total net vector flux linking leg 1 is numerically reduced to zero. If this later condition were the true resultant flux distribution instead of the "pulley" pattern, a substantial signal would be measurable across the terminals of winding S1 (figure 13) during control pulse No. 3. Experimental evidence does not substantiate the flux distribution of figure 29d since there was no switching sig—
Tangible Results

The more immediately tangible results of this study are the following:

1. key-hole MARS
2. three dimensional matrix array

These developments are discussed in the following paragraphs:

The Key Hole MARS

The salient characteristics of the keyhole device are:

1. Non-destructive read-out.
2. Ideally suited for three dimensional, coincident current operation.
3. Half-select currents required for the read and control operations are the same magnitude.
4. Speed capabilities for both read and store modes are at least as fast as a three dimensional toroidal core memory.
5. Device size permits matrix densities of at least 3000 bits per cubic inch.
6. Mechanical characteristics afford relative ease of manufacture and handling.

Figure 30 is a schematic of the production key-hole MARS. The specific design criteria dominating the aperture topography were as follows:

\[ \text{IRDS} = \text{IRIS} \]  \hspace{1cm} (1)
\[ 92\% \text{ IOR} < \text{IRDS} \leq \text{IOR} \]  \hspace{1cm} (2)
\[ \text{IRIS} = 68\% \text{IRIF} \]  \hspace{1cm} (3)
\[ \text{IRDS} = 68\% \text{IRDF} \]  \hspace{1cm} (4)

The name "key-hole" was chosen because of the suggestive shape, which was selected to simplify automatic testing, handling, and array assembly. The response excitation characteristics electrically defining the "key-hole" MARS are shown in figures 31a through 31c. The break points \text{IRIS}, \text{IRDS}, and \text{IOR} were controlled through design of the aperture topography. Break points \text{IRD} and \text{IRB} are controlled by uniquely employing inner-wall bias as an integral part of the three dimensional MARS matrix array.

3-D MARS Matrix Address Configuration

Figures 32a through 32c show three coincident current selection schemes. The technique shown in figure 32a is the conventional method for instrumenting transfluxor type devices. Figure 32b illustrates the effective 5-wire system (sense and inhibit not shown) conceived and designed as an integral part of the "key-hole" MARS. The vertical (X) coordinate address selection means "link both apertures (read and control) of each and every element comprising that selected column coordinate". This selection technique automatically provides the inner-wall bias necessary for proper operation of the "key-hole" MARS. Without inner-wall bias, the break points \text{IRD} and \text{IRB} occur at substantially lower excitation levels, as shown in figures 31a and 31c respectively. The ability to employ this matrix technique involves solving the geomechanic design criteria indicated in equation (1) and equation (2). Advantages of this technique are as follows:

1. Only one driving and selection means is required for column selection instead of two.
2. Transmission characteristics resemble those of an ideal transmission line.

The selection scheme shown in figure 33c is called the effective 4-wire, 3-D MARS array. As shown, the X coordinate selection technique is identical to that described for figure 33b. However, the Y coordinate selection means is connected to half-select the read apertures of all devices comprising one row and the control apertures of all devices comprising an adjacent row.
Figure 34 is a photograph showing a section of a 4-wire MARS matrix. This technique, similar to that described for X coordinate selection, eliminates the need for two different selection and driving means. Similarly it provides ideal address transmission line characteristics. The 4-wire MARS matrix array permits a three dimensional Random Non-Destructive Advanced Memory (RANDAM) to be instrumented with no more selection or driving means required than those required to instrument a three dimensional, toroidal core matrix.

Summary

The results of this study provided useful understanding of subtle switching mechanisms peculiar to multi-aperture ferro magnetic devices. The experimental techniques employed to study these switching phenomenon provided a new and powerful control technique called inner wall pulse bias. This bias technique provided the supplementary control variable which, when combined with geomechanic techniques, permitted the development of the Key Hole MARS and embodiment on a unique 3-D coincident current matrix array.

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References


Bibliography


Figure 2. SCHEMATIC OF BASIC MARS DEVICE

Figure 3. TIMING DIAGRAM

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(c) Nearly $I_{PP}$
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Figure 27. PLOT OF BREAK POINT WITH INNER WALL BIAS
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Figure 30. SCHEMATIC OF PRODUCTION "KEY-HOLE" MARS DEVICE
Figure 31.
RESPONSE EXCITATION CHARACTERISTICS OF "KEY-HOLE" MARS DEVICE
Figure 32. **COINCIDENT CURRENT SELECTION SCHEMES**
(a) Classic Three-Wire System
(b) MARS Five-Wire System (Sense and Inhibit Windings Not Depicted)
(c) MARS Effective Four-Wire System (Sense and Inhibit Windings not Depicted)

Figure 33. **SECTION OF MARS FOUR-WIRE MATRIX (PHOTO)**