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SUBJECT: SWITCH-CORE DESIGN AND POWER LOSS

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Abstract: Criteria for the design of switch cores to be used in a magnetic-matrix switch are established. Core loss is shown to depend only on the average value of net ampere-turns excitation if certain assumptions are made about memory requirements and switch construction. Temperature effects on core output are discussed, and the problem of heat dissipation is considered. Comparison of 2 ferrite and 1 metallic core materials show the latter superior, and specifications are given for a metallic core which should be capable of driving a magnetic memory without cooling although such operation would probably be marginal under the worst possible operating conditions.

Introduction

The principal problem in the design of a magnetic-matrix switch has been essentially that of designing a saturable core transformer to provide a current pulse specified in shape and amplitude into a specified load. The latest 32-position switches represent the results of efforts in this direction.

Of late it has become necessary to recall that the core in the matrix switch is really a device for distributing blocks of energy, often at very high repetition rates; that the losses in the core are considerable; and that heating is a problem of great importance, since magnetic cores are in general temperature-sensitive components.

I. Excitation and Core Output

The voltage output from a core is a function of the flux in the core and the net ampere-turns linking it. Two voltage waveforms of interest are shown in Figures 1 and 2 with the corresponding excitations which produce them. The first corresponds to driving with a current source (the case of a memory core, for instance). The second corresponds to a voltage-source drive which might be used to produce a flat-topped pulse from a switch core. (This assumes perfect coupling which is approached in most square-looped materials.)

The total energy loss in a core being switched is expressed by:

$$W = \int_0^t Ni_{net} \cdot \nu \, dt \qquad (1)$$

where $\nu = \frac{d\phi}{dt}$ is the rate of change of flux in the core and T is the switching time.

For constant i or constant v, the two cases considered above, this reduces to

$$W = NI_{net} \cdot \Delta \Phi \qquad (2)$$

where $\Delta\Phi$ is the total flux change of the core switching and NI_{net} is the time-average value of Ni_{net}. The d-c hysteresis loop for a square-loop material is shown in Figure 3. We recall that the change in flux is given by the area of the voltage pulse on a single turn linking the core. It is immediately apparent from an examination of Figures 1 and 2 that the d-c loop does not give an accurate account of the operating point of the core under pulsed conditions. If it did, the time response could, of course, be predicted from the shape of the input current pulse and the d-c loop alone.

It is also clear that the energy loss of a core switching under pulsed conditions is not given by the area of the d-c loop, but rather by the area of the appropriate pulsed loops drawn roughly in Figures 5 and 6 for constant current and constant voltage drives, respectively. (In drawing these it was assumed that there was no flux change on the rising edge of the current pulse.) The added energy may be thought of as going into relaxation and eddy-current losses.

For rise times used in the magnetic-matrix switch the assumptions made above are well justified; at worst they give a slightly exaggerated estimate of the energy loss in the core.

II. Switch as Used with Memory

The requirements for a memory of the coincident-current type using MF-1326, F-291, cores are:

1) $I_2 \cong 1/2$ amp;
2) $R_2 \cong 64$ ohms;
3) Driving-current shape as shown in Figure 4

These conditions are imposed because:

1) The current amplitude must be half that necessary to switch a core;

2) The resistive termination must be such that the back voltage of 32 memory cores switching will be small compared to the total voltage across the secondary of the switch core. The back voltage for 1 memory core is about 0.1 volt; for 32 cores, 3.2 volts. If we assume that a change in secondary current of less than 10% due to back voltage is required, then:

$$I_2R_2 \cong 10 \times 3.2 \text{ volts}$$

$$R_2 \cong \frac{32}{1/2} = 64 \text{ ohms}$$

It is possible that this estimate of I_2R_2 may be too low since it would allow for a 10% dip in the current pulse from the switch core. For a 2% change, for instance, the switch-core ouput would require 150 volts or a terminating resistance of 300 ohms.

Two switch cores must be pulsed each time a memory address is to be selected. Since one core must supply pulses to all memory cores with the same x (or y) address, it is possible that a single switch core may be required to produce outputs many times in succession for certain programs. If we assume a total read-write cycle of 10 microseconds, a single switch core may be operating at a prf of 100 kc for a considerable period of time. In any case, conservative design demands that such a contingency be provided for.

III. Switch-Core Design

In switch-core design, three relations governing core operation must be kept clearly in mind. We can formulate them as follows:

$$N_2 \Delta\Phi = I_2R_2T \qquad (3)$$

$$\Delta\Phi = f(N_1I_1) \qquad (4)$$

$$T = g(NI_{net}) \qquad (5)$$

where

T is the output-pulse length;

R_2 is the secondary resistance;

$NI_{net} = N_1I_1 - N_2I_2$ (capitals indicate time-average values).

Equation 3 is merely a particular example (for a square pulse) of the general equation which states that the area of the secondary voltage pulse equals the number of secondary flux linkages.

It is important to note that I_2R_2, and T are usually specified beforehand in switch design; therefore the product $N_2\Delta\Phi$ is fixed and represents a prime design criterion.

Equation 4 states that the total flux change depends only on the input ampere-turns. This is true only if the secondary pulse is allowed to go to completion before the input current pulse has ended. The functional relationship is best expressed graphically. The curve is much the same in shape as the familiar magnetization curve for iron except that the entire curve is shifted by a constant amount along the NI axis. This shift is an indication of the square-loop characteristic of the material. Its shape of course depends on the particular square-loop material being used. Curves for MF-1312, F-262, for MF-1131, F-262, and for mo-Permalloy 4-79 1/4 mil, 1/4-inch wrap are shown in Figure 7. In order to eliminate inequalities in output due to pulse-sequence sensitivity arising from unequal biases on different cores, the switch is generally designed to operate in the saturated region of the $\Delta\Phi$ vs N_1I_1 curve.

Equation 5 says that the switching time T depends on the net ampere-turns linking the core. This expression, unfortunately, is the one most difficult to evaluate explicitly. In order to obtain this data, the core with its secondary open-circuited is excited with a low-impedance source. This yields a flat-top voltage pulse on the secondary and the driving current gives a direct measure of Ni_{net}.

We can use the three equations above (with their corresponding graphs) and certain constraints imposed by memory-driving requirements to outline the steps to be followed in designing a switch from any given core material. If it is assumed that N_1I_1 is limited by tube and construction restraints to some maximum value and that I_2, R_2, and T are constants fixed by the memory, the design procedure is as follows:

1. Determine NI_{net} for the value of T required;

2. Find N_2 from the equation $N_2 = \frac{N_1I_1 - NI_{net}}{I_2}$ where all of the quantities on the right side of the equation are now fixed;

3. Determine the $\Delta\Phi$ required from $\Delta\Phi = \frac{I_2R_2T}{N_2}$;

4. Calculate the height of the core needed to supply the necessary $\Delta\Phi$ from the magnetization curve for the material.

For these assumptions, then, switch-core design and the consequent power loss are fixed. Core loss may now be expressed as a function of NI_{net} alone using the results obtained above.

$$W = NI_{net} \cdot \Delta\Phi$$

$$= NI_{net} \frac{I_2^2R_2T}{N_1I_1 - NI_{net}} \qquad (6)$$

This last equation shows that core loss depends only on NI_{net} and that its variation with NI_{net} is more than linear since NI_{net} appears with a minus sign in the denominator of the second factor.

It was stated above that the design was completely fixed once we assumed a fixed value of N_1I_1 which was the largest physically obtainable. This was done, since increasing N_1I_1 to its maximum tends to decrease core loss as shown by Equation 6, above. It may be desirable to reduce N_1I_1 in order to place less of a load on the driver tubes. Such reduction will cause the losses to increase, and some kind of compromise between high driving current and high core loss will have to be made. At present, heating seems to be the predominant difficulty so that maximum driving ampere-turns will be used in subsequent calculations in this memorandum.

IV. Core Loss

Temperature effects on core output

Tests on different materials show the same general effects of temperature on output waveform as shown in Figure 8. It is important to note that variation in output with changes in temperature is not a discontinuous phenomenon but occurs throughout a large range of temperatures. In the range from -20 C to 100 C, pulse amplitude increases and switching time decreases fairly linearly with incremental increases in temperature. It seems reasonable to define workable temperature limits in terms of the greatest difference in core temperature which can be tolerated in a switch. We will call this temperature ΔU and note that it should be no less than the difference between the maximum core temperature (core being pulsed at 100 kc) and the ambient temperature. The allowable ΔU will be determined by how much variation in output waveshape we can tolerate and will depend on the core material used. We arbitrarily limit variations in core output to switching-time change no greater than 0.2 microsecond (out of total length of 2.5) and amplitude change less than 3%.

Heat dissipation in core

Once the maximum power loss in the core has been determined as well as the allowable temperature rise and the area of the core, it is convenient to formulate a measure of the required amount of heat to be dissipated per degree centigrade per unit surface area of material. We denote this required coefficient of heat transfer by h; the defining equation is:

$$h = \frac{Q}{A\Delta U}$$

where Q is the maximum power (at 100 kc);
A is the free surface area; and
ΔU is the allowable temperature rise.

The results of cooling tests in still air and with small-fan cooling are shown in the curves of Figure 8. They indicate that maximum values of h obtainable with still air are about 0.025 watts per in^2 per degree centigrade; with a concentrated blast of air from a small fan, an h of 0.14 watts per in^2 per degree centigrade.

It is apparent from the above analysis that the problem of heat dissipation is a direct function of the material used. The two most important factors are NI_{net} (which alone determines core loss) and ΔU (the allowable temperature rise in a core), both of which vary greatly for different materials. A third factor whose effect is not quite so easy to estimate is the flux per unit volume of material. In order to make a reasonable comparison between different core materials it is necessary to assume that any core material could be redistributed so that the over-all dimensions would be comparable for different materials. It is also necessary to assume some maximum fixed height of core material (imposed probably by wiring restrictions). Otherwise the material could always be stretched out to give enough area to provide the necessary dissipation. If all the materials then are of the same height, the flux per unit volume for each will determine the required outside diameters for each, assuming the inside diameters are unchanged. This outside diameter will then give a measure of the free surface area for cooling for each material. The assumption is made that cooling in the switch only takes place at the surface lying on the outside diameter.

When considering heat dissipation from a core the tacit assumption has been made that there was no temperature gradient within the core and that cooling was merely governed by the equation:

$$Q = hA\Delta T$$

However, it is clear that the larger the difference between inside and outside diameters the less valid this assumption of uniform core temperature. It would therefore seem desirable to include in any comparison of materials a measure of the difference between inside and outside diameters which will be denoted by "L". For this comparison, L is not measured on the original core but rather on the "redistributed" core obtained by making cores of equal height and required total flux with inside diameter unchanged. The results of this comparison between three materials on the basis of h and L appear in Figure 10 in tabulated form. A maximum core height of 2 inches is assumed. Maximum N_1I_1 is assumed to be about 4.0 ampere-turns.

The table indicates clearly the advantage of metallic cores over ferrites from the point of view of power-dissipation problems. Other properties which make it particularly desirable for switch-core applications are squareness of loop and saturability of the $\Delta\Phi$ vs NI curve which lead to reduced noise and greater uniformity of output, respectively. The results tabulated in Figure 10 show that the metallic core will require about 1/10 the cooling of the ferrite core. It also shows that with simple fan cooling a mo-Perm core having the following specifications should be capable of driving a memory without significant change in output due to core heating:

Tape width	2 inches
Inside radius	3/32 inch
Outside radius	0.128 inch
Material	4-79, 1/4 mil

With natural convection (still-air cooling) such a core would still produce outputs with less than 0.3 microsecond variation in pulse length and less than 3% change in amplitude.

V. Conclusions

A search for new materials should follow along the lines suggested by the analysis given above, the main criteria being fast switching time (low net ampere-turns for a given switching time), insensitivity of output to temperature change, and high flux per unit volume of core material.

The mo-Perm 4-79 had values equal to or better than any other cores tested for these three factors. These values are .75 ampere-turns for 2.5 microseconds switching time (from open-circuit test), 90 C allowable temperature rise, and about 30,000 maxwells per cubic inch.

It is important to realize that the energy dissipated in the core is directly proportional to the output power (Equation 6) and that as a result the losses go up directly with the terminating resistance on the secondary. The heat-dissipation problem will become more and more serious, therefore, as the current regulation is improved through higher secondary resistance. Recent tests with linear transformers indicate that extremely good regulation may be required in which case the core loss could be increased by a significant factor.

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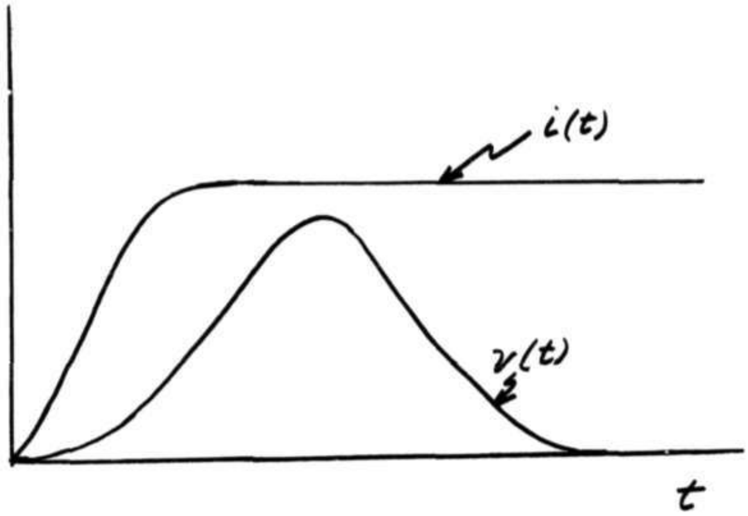

FIG. 1
EXCITATION AND OUTPUT
CURRENT-SOURCE DRIVE

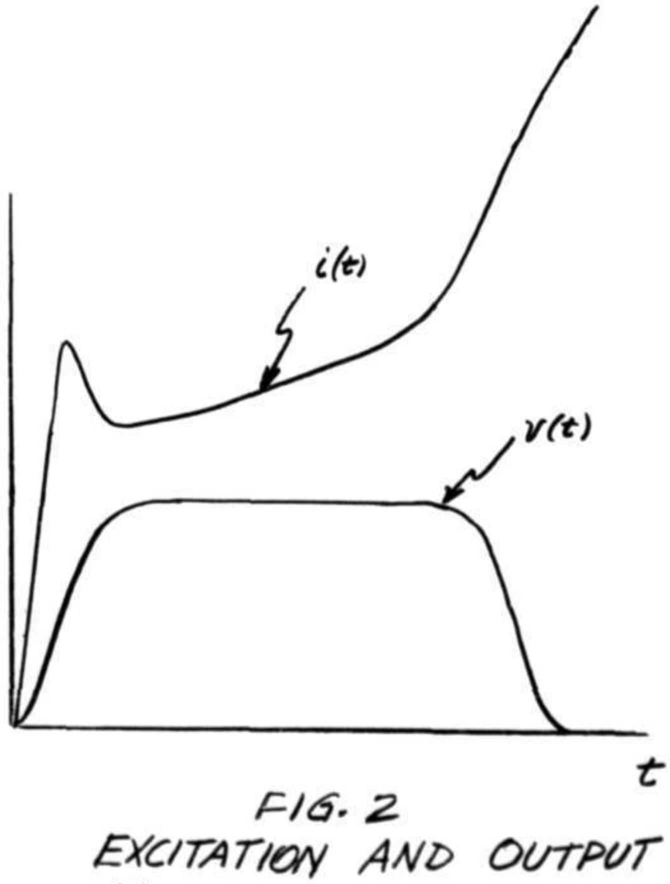

FIG. 2
EXCITATION AND OUTPUT
VOLTAGE-SOURCE DRIVE

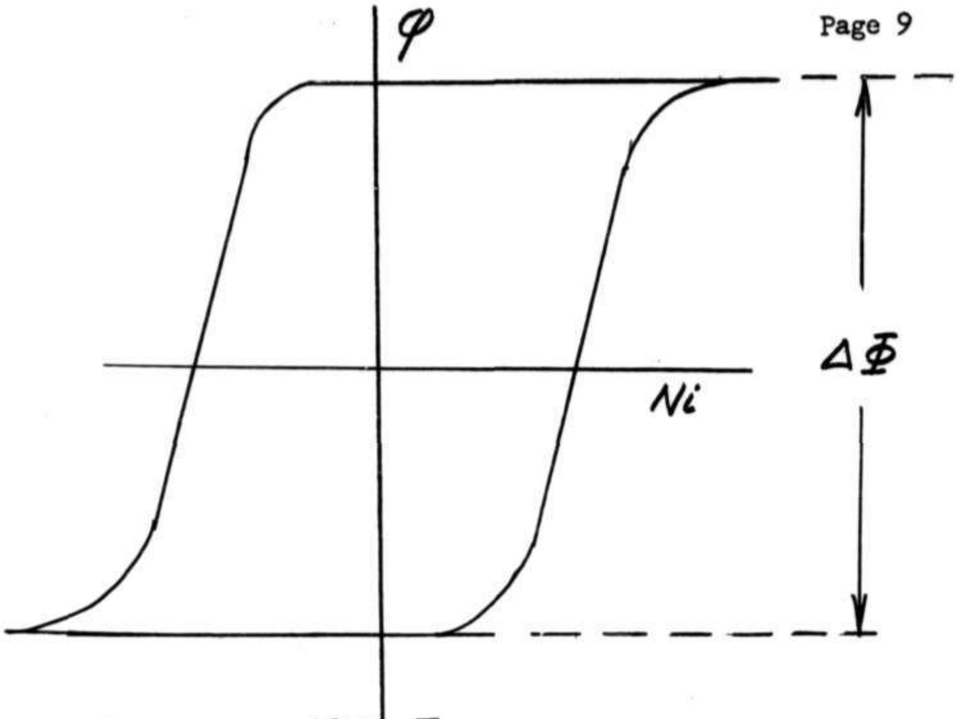

FIG. 3

A "RECTANGULAR" d-c HYSTERESIS LOOP

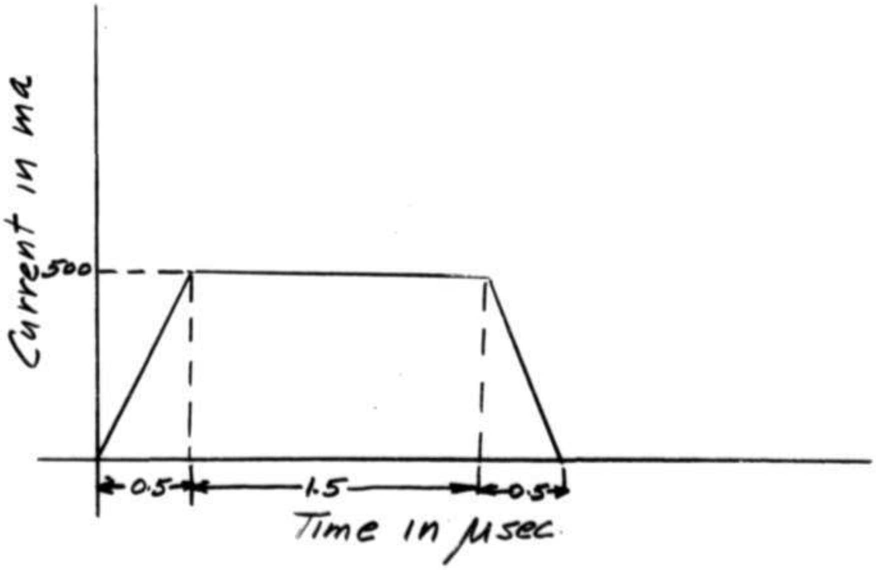

FIG. 4

CURRENT PULSE DESIRED FROM SWITCH CORE

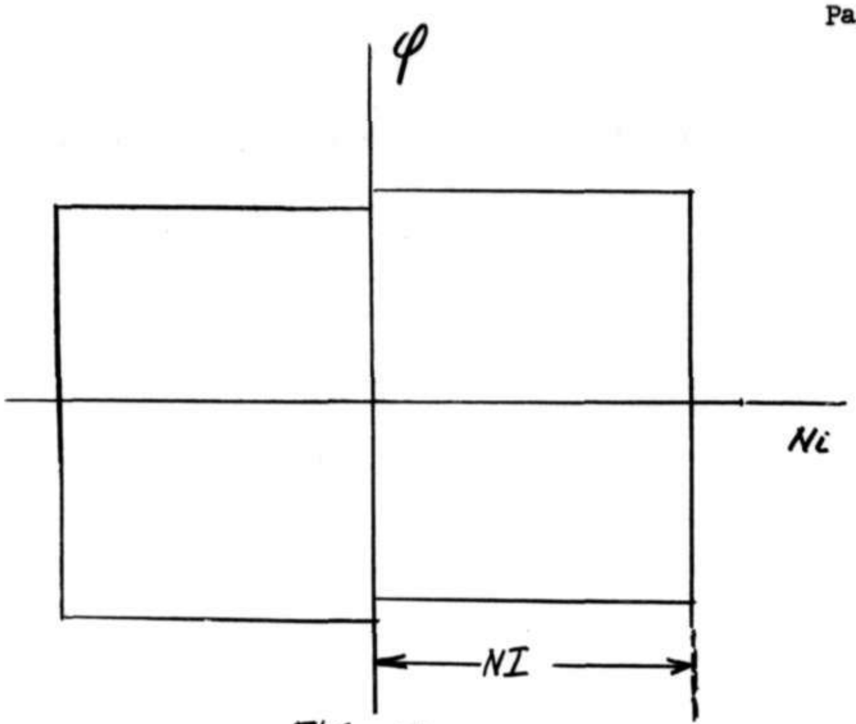

FIG. 5
PULSED LOOP
CONSTANT CURRENT EXCITATION

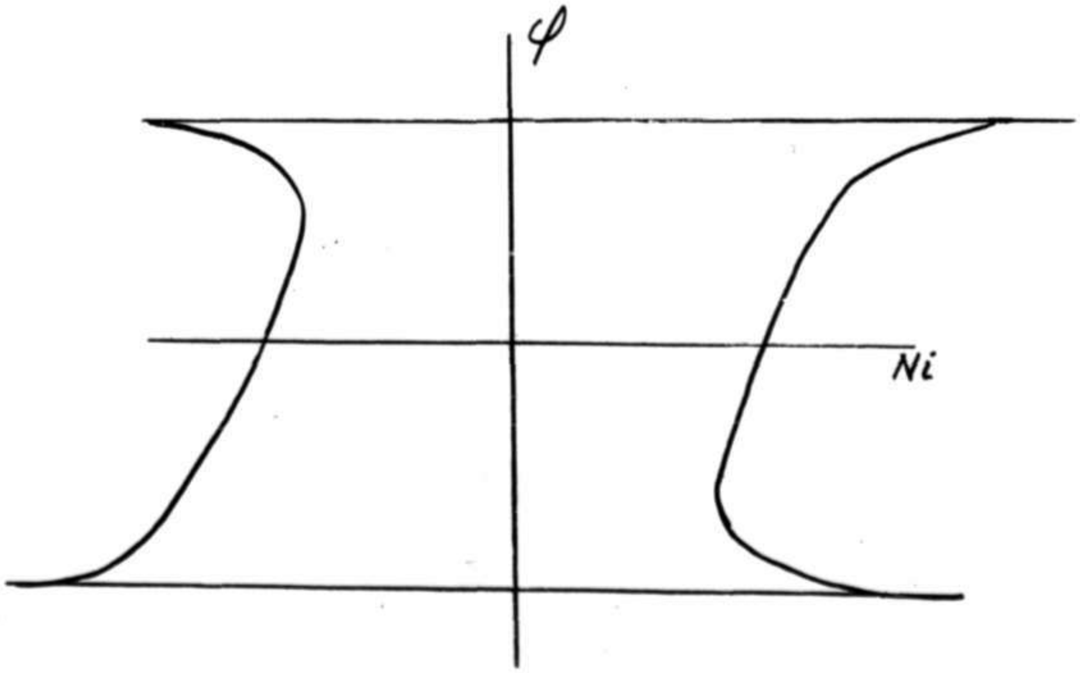

FIG. 6
PULSED LOOP
CONSTANT VOLTAGE EXCITATION

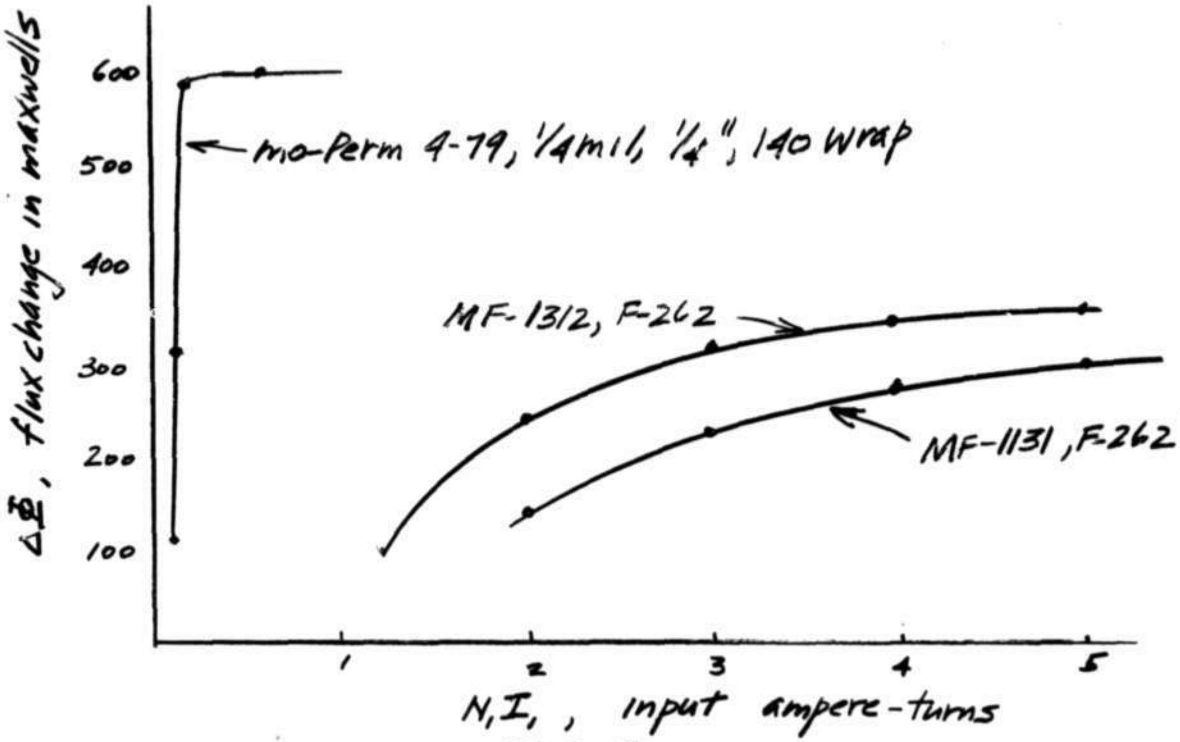

FIG. 7
FLUX CHANGE VS. AMPERE-TURNS
FOR THREE MATERIALS

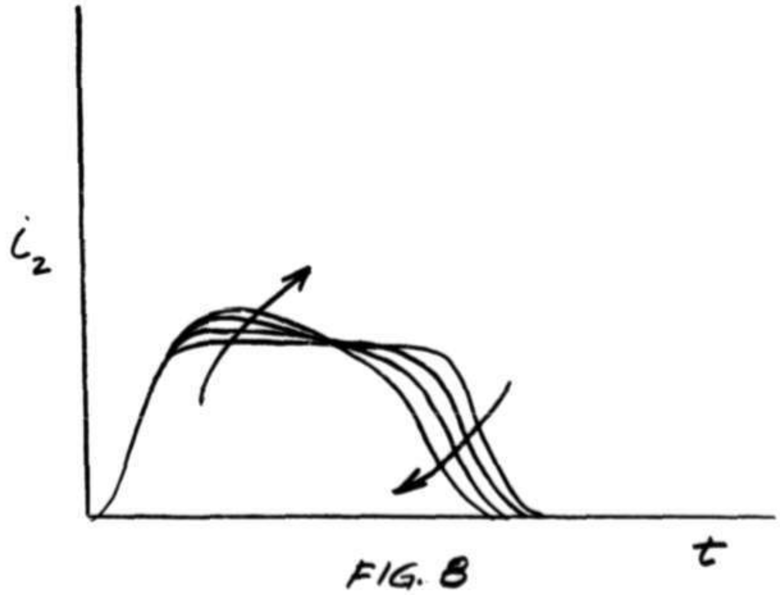

FIG. 8
EFFECT OF TEMPERATURE
ON SWITCH-CORE OUTPUT
(arrow indicates increasing temperature)

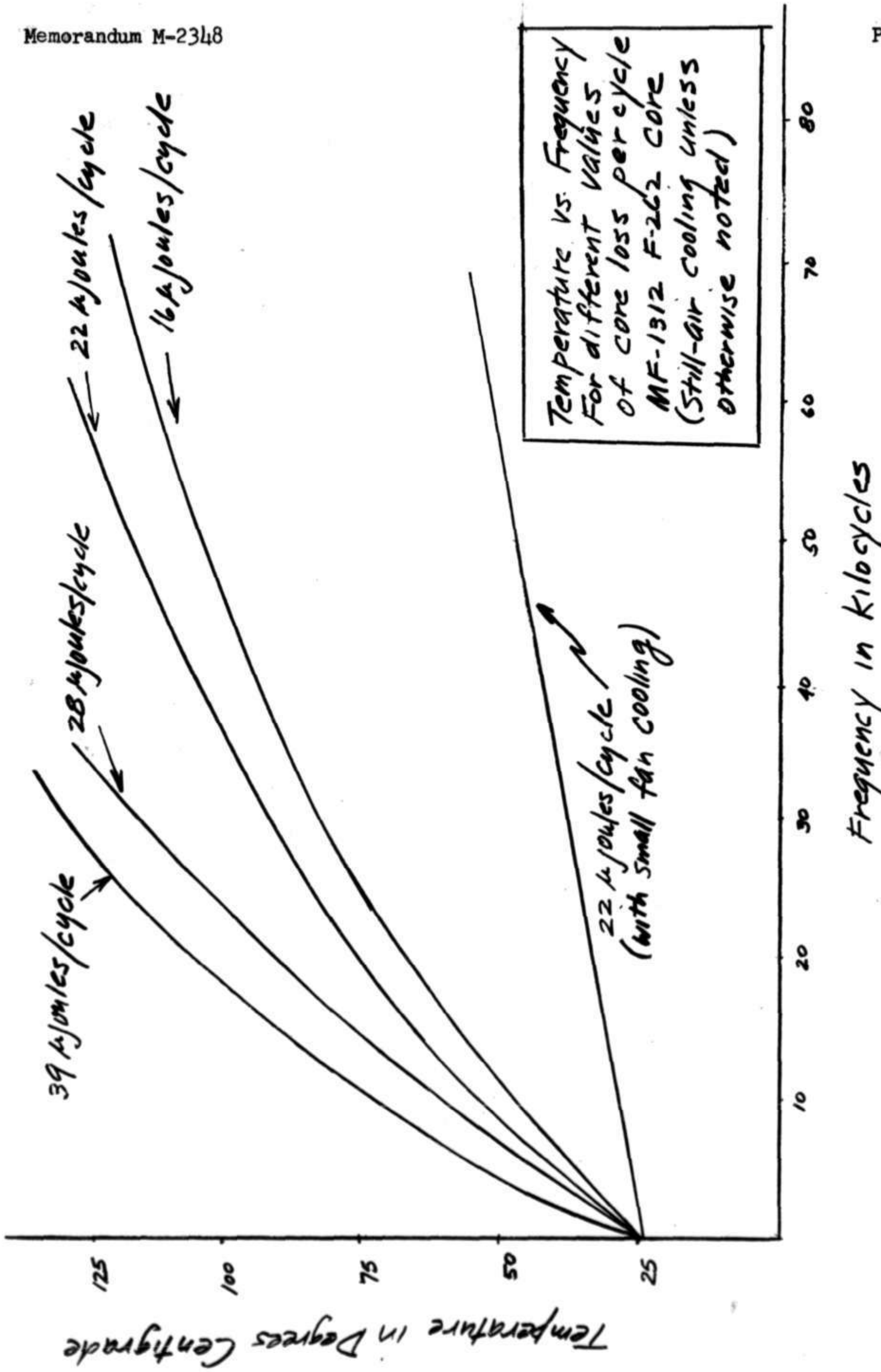

FIG. 9

TEMPERATURE RISE DUE TO CORE LOSS

Core	NI_{NET} amp-turns	N_2 turns	$\Delta\Phi$ maxwells	Flux per Unit Vol. maxwells per cubic inch	r_o Inches	L Inches	ΔU Degrees Centigrade	Surface Area in.^{2}	Loss per cycle μjoules per cycle	h watts per degree C. per in^2
MF-1131 F-262	2.7	3	2,500	26,600	.154	.06	35	1.94	156	.23
MF-1312 F-262	2.3	3	2,500	33,000	.143	.049	20	1.8	145	.40
mo-Perm 4-79 1/4 mil, 1/4" 140 wrap	.75	6	1,250	31,500	.123	.029	90	1.55	22.5	.016

FIG 10

DESIGN CALCULATIONS FOR SWITCH CORES OF THREE MATERIALS, IN TABULAR FORM