FLUX CHARACTERISTICS OF LOGIC CORES

By

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1960

Submitted to the Faculty of the Graduate School of
the Oklahoma State University
in partial fulfillment of the requirements
for the degree of
MASTER OF SCIENCE
May, 1961

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PREFACE

In the last few years, major advances have been made in computer technology through the use of newly-developed magnetic devices. These devices have made possible computers with larger storage capacities, faster operating speeds and increased reliability.

The magnetic core has been extensively used as a storage element since the interrogation can be accomplished in a few microseconds with moderate currents supplied by relatively simple selection systems. Also, the cores are extremely reliable in that there are no moving parts nor are there any aging effects. And, lastly, the cores can be made fairly economically and are amenable to simple wiring techniques. As a result, an assembly of a million cores can be fabricated at a moderate cost.

The refined development of these elements has been enhanced mainly through the theoretical work of Curie, Weiss, Van Vleck, Neel, Frankel, Heisenberg, Landau, and Kittel.

Some of the first articles published of an engineering nature using these elements were by W. N. Papian (See Master of Science Thesis, M. I. T. Electrical Engineering

Department, 1950), An Wang and Way Dong Woo (See J. Appl. Phys., V 21, 1950), and J. W. Forrester (See J. Appl. Phys., V 22, 1951). Since then, articles of this nature have been published by J. Rajchman, R. Stuart-Williams, M. Rosenberg, K. Olsen, J. Karnaugh, E. A. Sands, and J. R. Freeman, to mention a few. J. W. Forrester holds a patent (2-28-56) on a multicoordinate digital information storage device.

The development of workable circuits or systems using these components has been a laborious task to the engineer. Even though the engineer may be familiar with such terms as domain growth, domain rotation, Bloch wall, domains of closure, anisotropy energy, magnetostriction, preferred axis, spin relaxation, nucleation, Barkhausen effect, remanence, coercivity, saturation, etc., there is still much to be desired as far as the simplification of the design of either the components or the systems is involved.

The author wishes to gratefully acknowledge the instruction, encouragement and advice of his adviser, Professor Paul A. McCollum. It was through his interest in the subject that I initially became engaged in the study of magnetic cores.

To Magnetics, Inc. and the International Business Machines Corporation, I would like to express my appreciation for the selection of cores supplied. Also, I would like to thank Dr. H. T. Fristoe and Texas Instruments for obtaining and supplying, respectively, the transistor used in the test setup.

Lastly, I wish to thank my wife, Sue, for her constant encouragement throughout my post-graduate work, expecially during the preparation of this thesis.

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CHAPTER I

INTRODUCTION

In recent years, the use of magnetic materials in engineering applications has increased considerably, so that, today, the magnetic storage device is considered commonplace in electronic design. While many magnetic circuits have been developed to the level of being standard, the engineer attempting new designs is often limited by (1) his lack of understanding concerning the fundamental nature of the magnetic material, and (2) not having available the characteristics necessary for design.

In order to obtain suitable magnetic core characteristics for design purposes, measurements of flux (ϕ), flux density (B), and magnetic intensity (H) are necessary. The magnetic flux is the integral with respect to time of the induced voltage, thus presenting the necessity of an operational amplifier. The d-c amplifier as well as a wideband Miller integrating amplifier could be used. Because of the extremely small parameters involved, some amplification is necessary.

While there are several different types of measurements that would express the parameters involved, this thesis considers a few which are pertinent to the design of magnetic cores and the design of circuits involving these cores. The resulting data are then used to show various characteristic curves which could be used in design work.

CHAPTER II

MAGNETISM

Magnetic Materials

In order to solve problems involving magnetic theory, it is essential to have a relationship between B and H, or, equivalently, a relationship between M (magnetic dipole moment per unit volume) and one of the magnetic field vectors. These relationships depend on the nature of the magnetic material and are usually obtained experimentally.

In a large class of materials, there exists an approximately linear relationship between M and H. If the material is isotropic as well as linear, M is equal to $X_m H$, where the dimensionless scalar quantity X_m is called the magnetic susceptibility. If X_m is positive, the material is called paramagnetic, and the magnetic induction (B) is strengthened by the presence of the material. If X_m is negative, the material is diamagnetic, and the magnetic induction is weakened by the presence of the material. Although X_m is a function of the temperature, and sometimes varies quite drastically with temperature, it is generally safe to say that X_m for paramagnetic and diamagnetic materials is quite small; i.e., $|X_m| \ll 1$.

A linear relationship between M and H also implies a linear relationship between B and H:

$$B = uH \qquad (2.1)$$

$$= u_oH(1 + X_m) \qquad (2.2)$$

where B = magnetic flux density in webers per square meter

H = magnetic intensity in ampere-turns per meter

u = permeability

$u_o = 4\pi \times 10^{-7}$ Weber/ampere-meter in rationalized MKS units

X_m = magnetic susceptibility

The ferromagnetics form another class of magnetic material. Such a material is characterized by a possible permanent magnetization and by the fact that its presence usually has a profound effect on the magnetic induction. Ferromagnetic materials are not linear, so that the above equations with constant X and u do not apply. If the u of a ferromagnetic material is defined by Eq. (2.2), then, depending on the value of H, u goes through an entire range of values from infinity to zero and may be either positive or negative. The maximum permeability occurs at the "knee" of the curve. The explanation for the knee in the curve is that the magnetization, M, reaches a maximum value in the material, and

$$B = u_o(H + M) \qquad (2.3)$$

continues to increase at large H only because of the u_oH term. The maximum value of M is called the saturation magnetization of the material.

B-H Relationships

If the magnetic intensity, initially zero, is increased monotonically, then the B-H relationship will trace out the virgin magnetization curve of the material. (See dashed curve of Figure 1). Now consider a ferromagnetic

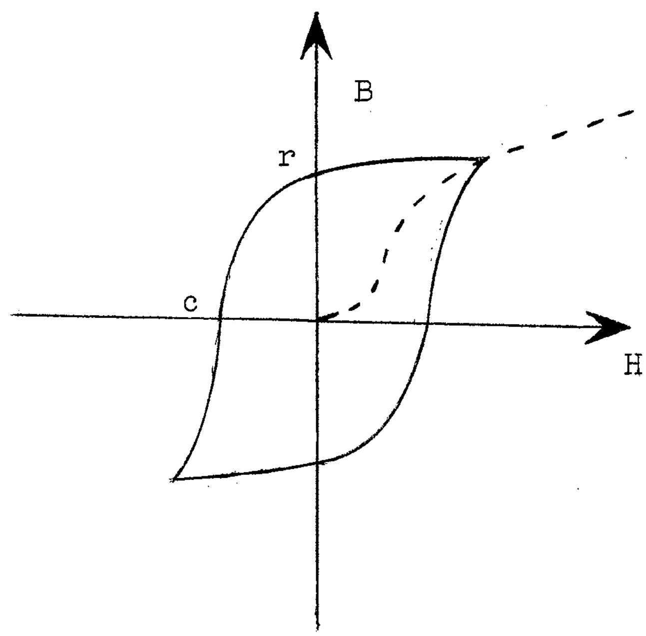


Figure 1. Hysteresis Loop

specimen magnetized by the above procedure. If the magnetic intensity is decreased, the B-H relationship does not follow back down the original curve, but instead, moves along the new curve of Figure 1 to point r. The magnetization, once established, does not disappear with the removal of H; in fact, it takes a reversed magnetic intensity to reduce the magnetization to zero, which occurs at point c.

The solid curve of Figure 1 is called the hysteresis loop of the material. The value of B at point r is known as the retentivity or remanence; the magnitude of H at point c is called the coercive force or coercivity of the material.[1]

When calculations are to be made with ferromagnetic materials, it is essential to have experimentally determined B versus H curves available. The curves should be ones that have been determined under essentially the same conditions as will be experienced in the work being calculated. While there are many different B versus H curves that can be determined for a given ferromagnetic material, there are only three or four types that are of general importance: (1) the virgin curve, (2) the normal magnetization curve, (3) the hysteresis loop approaching saturation on each half-cycle, and (4) some ΔB versus ΔH curves at different fixed-field biases. The virgin curve (1) is obtained when the material is first magnetized after having been cooled from above its Curie temperature in a zero magnetic field. This is not nearly as important as the normal magnetization curve (2) that is obtained by a cycling process. In the cycling process, the material is first demagnetized by cyclically reversing the applied magnetic field and slowly reducing it. After demagnetization, a small field H is applied and reversed several times. One-half the change in magnetic induction produced by reversing H is taken as the value of B to be plotted versus H. When B versus H curves are given without specifying the experimental procedure, they are nearly always "normal magnetization" curves.[2]

Domain Theory

The magnetization M has a value very closely approximating, but not exactly equal to, $B/4\pi$. A French physicist, named Weiss, first explained this phenomenon by suggesting that the net magnetic moments of each of the particles within a ferromagnetic material interacted with adjacent particles so as to align the magnetic moments of each in the same direction. (A net magnetic moment exists when more electrons favor one magnetic spin than the other. An excess of either one, positive or negative, creates a "magnetic moment".) However, all of the moments align themselves perfectly only at 0° Kelvin. Above this temperature, the alignment decreases until, at a certain temperature known as the Curie point, the magnetic materials do not align themselves and the material no longer exhibits the high magnetization property described above.

Weiss Domain

Weiss's alignment theory showed how the incremental moments became aligned after an external field was applied. However, it did not account for the fact that more ferromagnetic materials are usually first found in an unaligned state with a magnetization of zero. In order to explain this situation, Weiss introduced a second theory: all ferromagnetic material is divided into very small regions, called "domains", which are often about 0.01 mm in size. Further information on domains may be found in references 3 and 4.

Becker has explained the increase of magnetization within a ferromagnetic material through two methods: first, one domain having its total magnetic moment in the direction of the external field could increase greatly in size at the expense of the domain of different magnetic directions; or second, all of the domains could rotate in such a direction as to favor that of the external field.

In order to produce a permanent condition of magnetization, a large enough external magnetic field, H, must be supplied to bring the total net magnetic moment at each point in the material above a certain magnetization called "intrinsic magnetization". (It is sometimes referred to as "pulse threshold"). It should be realized that the point of intrinsic magnetization must be reached before a magnetic sample can be brought to a permanent condition of magnetization.

Through experimentation, it has been discovered that, in external magnetic fields of low intensity, domain growth is most likely to occur. However, in fields of high intensity, domain rotation occurs more frequently. Figure 2 illustrates this situation. Note that at the point of intrinsic magnetization, a permanent condition of magnetization is reached.[3]

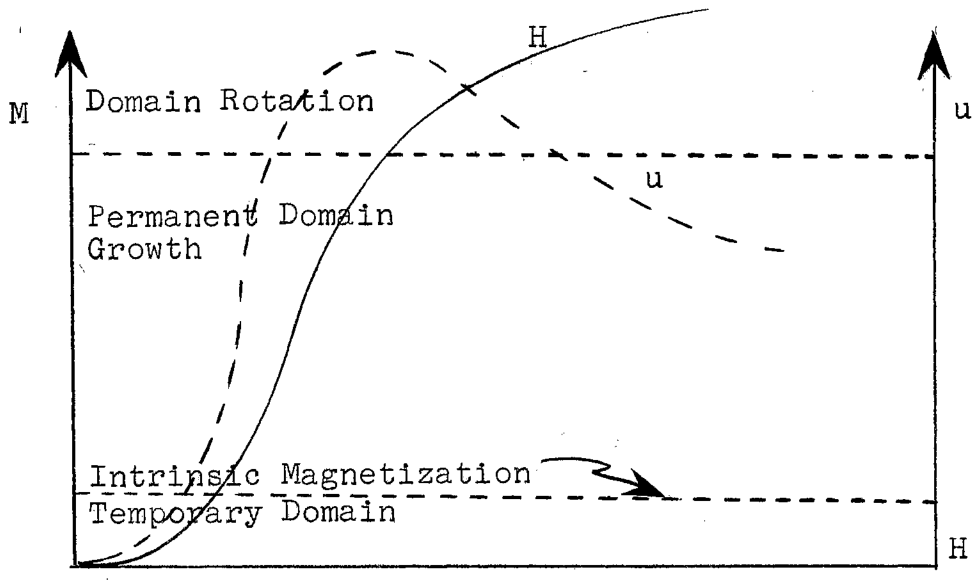


Figure 2. Magnetization and Permeability Change Due to the Application of a Field, H.

CHAPTER III

CORE CHARACTERISTICS

General

The magnetic core is now used extensively as the storage element in high-speed digital data processing systems. The core must be made of material having a rectangular hysteresis loop. A typical hysteresis curve is shown in Figure 3.

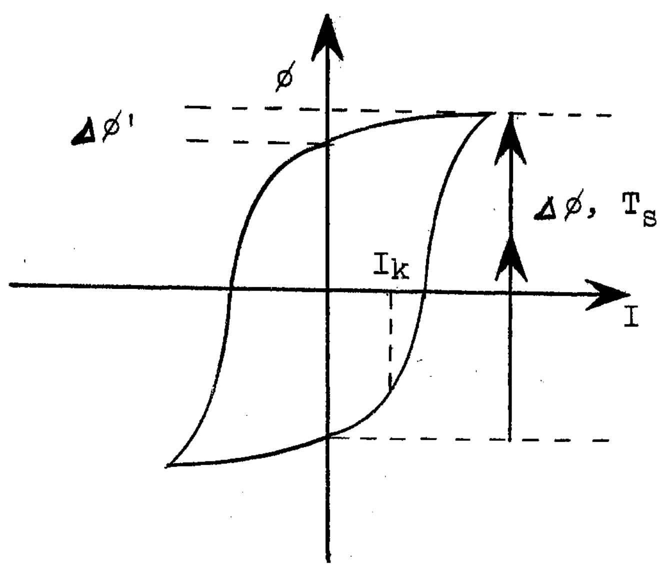


Figure 3.- A Typical Hysteresis Loop of a Core. As the current exceeds the knee value, I_k, the flux reversal process beings. The total flux reversed, $\Delta\phi$, is large compared to the shuttle flux, $\Delta\phi'$. The flux, $\Delta\phi$, is reversed in a time T_s by a current $2I_k$.

Information is stored by the sense in which the magnetization is directed, i.e., counter-clockwise or clockwise within the core. The material can be magnetized to either state by passing a current through a wire which is threaded through the core. When the current is removed, the material will remain in the magnetized or remanent state. If the core is magnetized in the lower remanent state and a positive current is applied, very little magnetic flux changes direction until the current reaches the value indicated as I_k. The existence of the knee is important in that it permits the selection of one core out of an assembly of cores since a current of $2I_k$ will reverse most of the flux. When the current pulse is removed, the material relaxes back to the upper remanent state. Now, if a current pulse in the positive direction is applied, the core will shuttle outward and, on the removal of the pulse, will return back to the upper remanent state. The flux change during the shuttle is very small compared to the flux change between the lower and upper states. The fact that a current of $2I_k$ produces a large flux change when the core is switched, but only a small flux change when the core is shuttled means that a ratio of flux changes may be used to detect the remanent state of the core. Such an interrogation will destroy the stored information.[5]

Switching Time

The data in Figure 4 represents the output voltage response after the core had been reset to saturation with a very large current pulse. The value of T_s is taken as the time interval between the 10 per cent points of the output voltage waveform. Sometimes the switching time is taken as the interval between the 10-to-90 per cent points on the integrated output voltage waveform. (See Figure 5). These two values are quite different, since in the latter case the time depends on the magnitude of the flux change, whereas the former is a measure of the rate of change of flux. The cores have large regions in which the switching time obeys the relationship $S_W = T_S(H - H_o)$, where S_W is the slope of the curve, H versus $1/T_S$, and H_o is the projected intercept and is not necessarily equal to the d-c coercive force.[6]

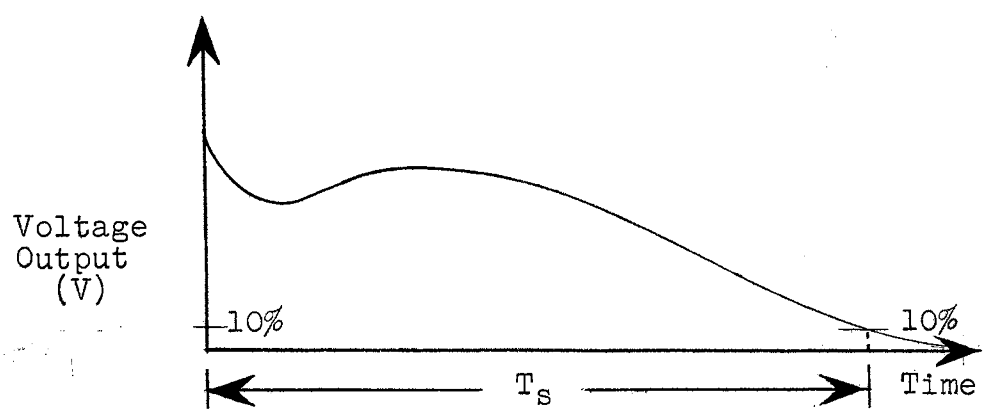


Figure 4. Switching Time as Measured Between 10% Points on the Voltage Output Curve.

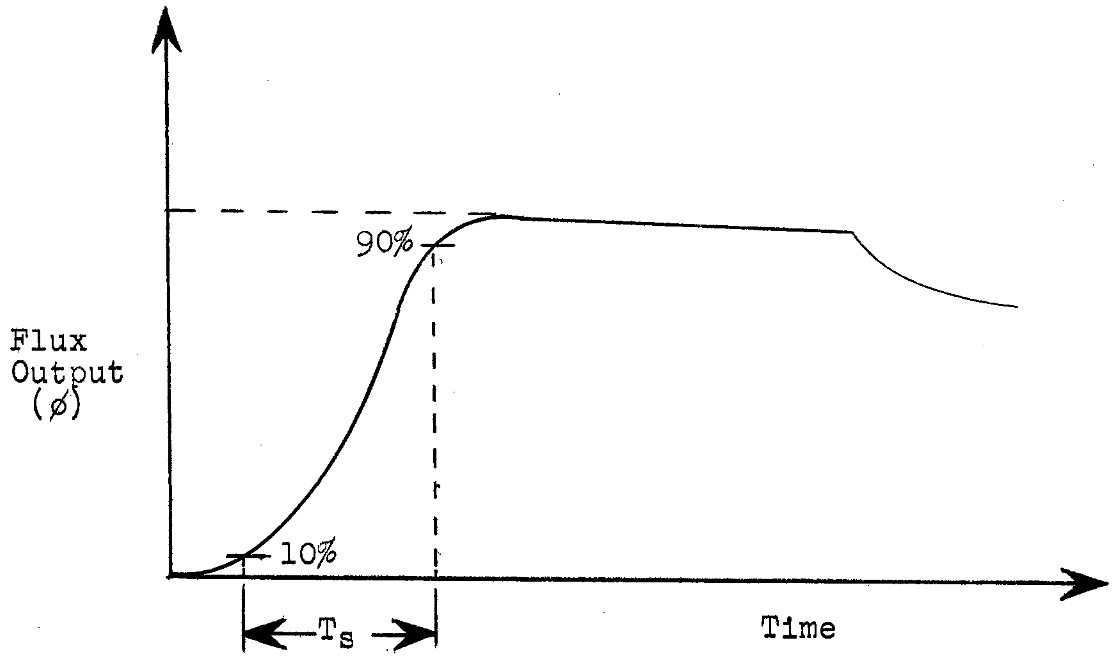


Figure 5. Switching Time as Measured Between the 10 and 90% Points on the Output Flux Curve.

Metal-tape Versus Ferrite Core Losses

The magnetic losses of ferromagnetic permalloy (metal-tape) and ferrimagnetic (ferrite) cores will be discussed by pointing out how certain properties of the cores contribute to these losses.

A. Ferromagnetic metal-tape cores

The eddy currents induced in tape cores due to the rapid changes of flux play a dominant role in the operation of an information storing matrix. The dissipation of power is not as significant as the fact that these currents oppose the effects of externally applied current and slow down the rate of change of flux. As a result, a certain time elapses between the application of a current step and the completion of the change of flux corresponding to that current. This delay in switching time of the core is in part detrimental, because it limits the speed at which the memory system can be operated, and is, in part, beneficial because it provides a means of time discrimination, in addition to amplitude discrimination, between wanted and unwanted reading signals.

In materials with a very rectangular loop, there are two distinct ranges of permeability values with an abrupt transition between these values being a thousand to one, or more. For a low magnetizing force, only the low permeability region is traversed by the core, the consequent damping of eddy currents is small, and a sharp voltage pulse is produced. For higher magnetizing forces, the high permeability region is encountered (See Figure 2), and the greater damping causes the voltage pulse to have half of a long, bell-shaped waveform. Thus, the voltage pulse is the composite of these two pulses and has two distinct maxima. For still higher magnetizing forces, the delays due to the damping of the eddy currents become shorter because these opposing currents become relatively smaller with respect to the drive. The waveforms of Figures 16a and 16b taken with increasing magnetizing force illustrates the last two effects.

Some properties of ferromagnetic metal-tape cores are listed below.

1. Resistivity low, resulting in possibly a large eddy current loss.

2. Eddy current losses are reduced by reducing the tape thickness to a minimum.
3. Tape thickness varies inversely with H_c, therefore, there is an optimum thickness whereby both eddy current loss and minimum drive requirements depend.
4. Rajchman[10], 1952, contributes the major loss of a 1/8-mil 4-79 Mo-Permalloy tape wound core to eddy currents. The change of flux being delayed by an amount increasing with electrical conductivity and magnetic permeability of the material.
5. Owen[9], 1953, contributes the major loss of a 1-mil sheet of 4-79 Mo-Permalloy to eddy currents with a slight loss due to hysteresis.
6. A spin relaxation contribution arises from the delayed response of the atomic spins to a force which would change their direction. The viscous-damping parameter $\beta = \beta_e + \beta_r$. Whereas, β_r is an inherent quality of the magnetic material, β_e is strongly dependent upon the macroscopic dimensions of the sample. Menyuk and Goodenough[11], 1955, found for the 1/8-mil 4-79 Mo-Permalloy cores that the eddy current damping was only 5 per cent of the relaxation damping.

B. Ferrite Cores

A brief history of the origin of the term "Ferrimagnetism" would be in order at this point. A good introduction is given by reference 12, pages 3 to 5, a portion of which is related below.

It has recently been shown (Neel, 1948) that spontaneous magnetization may arise not only through positive interactions, i.e., ones tending to make neighboring elementary moments parallel to each other, but also through negative interactions, tending to make neighboring moments antiparallel. In a simple cubic lattice, such interactions would, of course, lead to an uncompensated residue of moments all pointing in the same direction and so producing a spontaneous magnetization. It appears that the magnetism of many oxides and, in particular, of the ferrites (Fe_2O_3.MO, where M is a bivalent metallic ion) is of this type, to which Neel gives the name "ferrimagnetism". Although the source of the spontaneous magnetization may be different, the considerations affecting the occurence and behavior of domains in these materials must be the same as those in ordinary ferromagnetic metals and alloys.[12]

Although ferromagnetism is an uncommon phenomenon among elements, it is quite common among compounds, particularly among complex oxides of the so-called transition group of elements. The outstanding advantage which these materials offer, in addition to their ferromagnetism, is the fact that they are insulators, or sometimes semiconductors; consequently, there is little eddy current loss.[13] The term ferrites, as used by Smit and Wijn, is used to refer to all magnetic oxides containing iron as the major metallic component.[8]

Some properties of ferrimagnetic ferrites are listed below.

1. High dc resistivity (corresponding to those of semiconductors) prevents the formation of eddy currents.[9]
2. Loss per cycle increases rapidly with ascending frequencies. (Eddy current calculations based on dc resistivities no longer hold.)[9]
3. The rapid rise in core loss is associated with a rapid decline in permeability.[9]
4. The decreased switching time of the ferrites in memory core applications is the result of high coercivities.[11]
5. The type and size of the sample can have a marked effect on permeability and core loss, unpredicted from usual eddy current computations.[9]
6. In ferrites, wall motion may be restricted severly by impurities, voids, and crystal imperfections including grain boundaries. However, where wall motion exists, it may "relax" above a certain frequency, producing a decrease in permeability and an increase in core loss.[9]
7. The magnetic losses in ferrites are contributed to[9]

   a. Eddy currents (negligible)

   b. Hysteresis

   c. Domain wall relaxation

d. Domain wall resonance

e. Dimensional resonance

f. Ferromagnetic resonance

In summary, the eddy current loss is made small by using ferrites or metal tapes with thickness in the order of 1/8-mil.

CHAPTER IV

INTEGRATORS

Integrating Amplifiers

First, operational amplifiers in general are to be considered. The amplifier may be represented by the system shown in Figure 6.

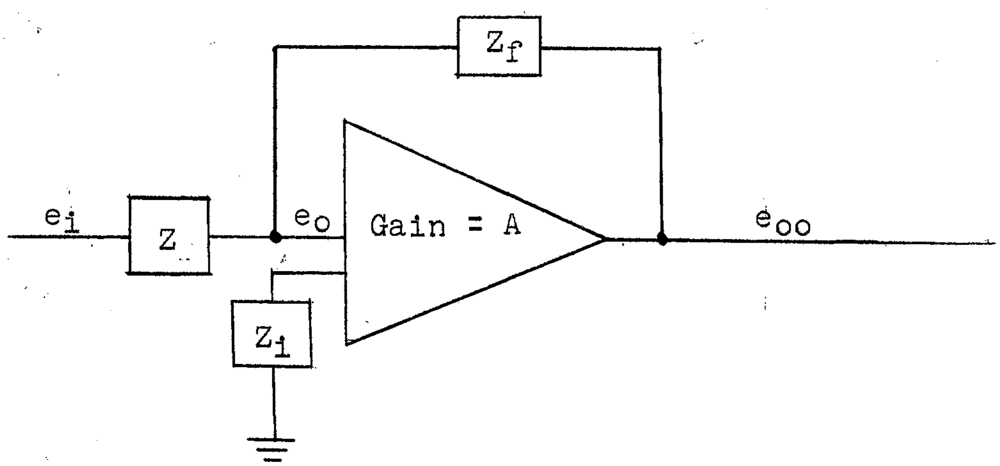


Figure 6. Amplifier Block Diagram.

Writing the node equations,

$$\frac{e_o - e_i}{Z} + \frac{e_o - e_{oo}}{Z_f} + \frac{e_o}{Z_i} = 0 \qquad (4.1)$$

Since e_o equals e_{oo}/A,

$$\frac{e_{oo}}{AZ} - \frac{e_i}{Z} + \frac{e_{oo}}{AZ_f} - \frac{e_{oo}}{Z_f} + \frac{e_{oo}}{AZ_i} = 0 \qquad (4.2)$$

$$\frac{e_{oo}}{A}\left[\frac{1}{Z} + \frac{1}{Z_f} + \frac{1}{Z_i} - \frac{A}{Z_f}\right] = \frac{e_i}{Z} \tag{4.3}$$

$$\frac{e_{oo}}{e_i} = \frac{A}{1 + \frac{Z}{Z_f} + \frac{Z}{Z_i} - \frac{AZ}{Z_f}} \tag{4.4}$$

$$= \frac{AZ_iZ_f}{Z_iZ(1 - A) + Z_f(Z + Z_i)} \tag{4.5}$$

$$= \frac{AZ_f}{Z(1 - A) + Z_f(1 + Z/Z_i)} \tag{4.6}$$

With $Z_i \gg Z$

$$\frac{e_{oo}}{e_i} = \frac{AZ_f}{Z(1 - A) + Z_f} \tag{4.7}$$

If the amplifier is to be used as an integrator, Z_f must be a capacitor. In that case, the Laplace transform of Z_f is $1/pC$. If Z is a resistor, Equation (4.7) for the amplifer becomes

$$\frac{e_{oo}}{e_i} = \frac{A/pC}{R(1 - A) + 1/pC} \tag{4.8}$$

$$= \frac{A}{pRC(1 - A) + 1} \tag{4.9}$$

It can be seen that the time constant of the circuit is $(1 - A)RC$. If $pRC(1 - A) \gg 1$

$$\frac{e_{oo}}{e_i} = \frac{A}{pRC(1 - A)} \approx -\frac{1}{pRC} \tag{4.10}$$

providing the gain (A) is very high.

It has been shown that shunt feedback in an operational amplifier reduces the input impedance.[15] When the shunt feedback impedance takes the form of a capacitor, the lowered input impedance is manifested as an apparent increase in the size of this capacitor. Thus, the Miller integrator effectively places a large capacitor between the right-hand terminal of R and ground. With sufficient gain in the amplifier, a feedback capacitor of a few microfarads may be made to look like an appreciable part of a farad, and results in an integrator with a very long time constant. (See Equation 4.9)

Conventional Integrators

Figure 7 shows the circuit of a basic R-C integrator.

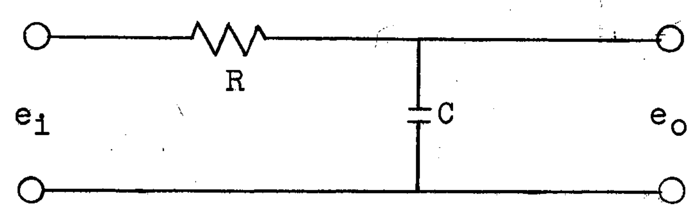


Figure 7. Basic R-C Integrator.

The transfer function is easily found to be

$$\frac{e_o}{e_i} = \frac{1}{pRC + 1} \qquad (4.11)$$

and if $pRC \gg 1$ then

$$\frac{e_o}{e_i} = \frac{1}{pRC} \qquad (4.12)$$

The time constant is equal to the product RC. If the time constant is increased by increasing R, C, or both, the value of the voltage e_o is decreased, which implies a loss in sensitivity. Therefore, the conventional integrator is good only for short integration times unless some amplification is used.

Comparing Equations (4.11) and (4.9) shows that the Miller integrator has an output approximately A times that of a conventional integrator.

Circuit Description

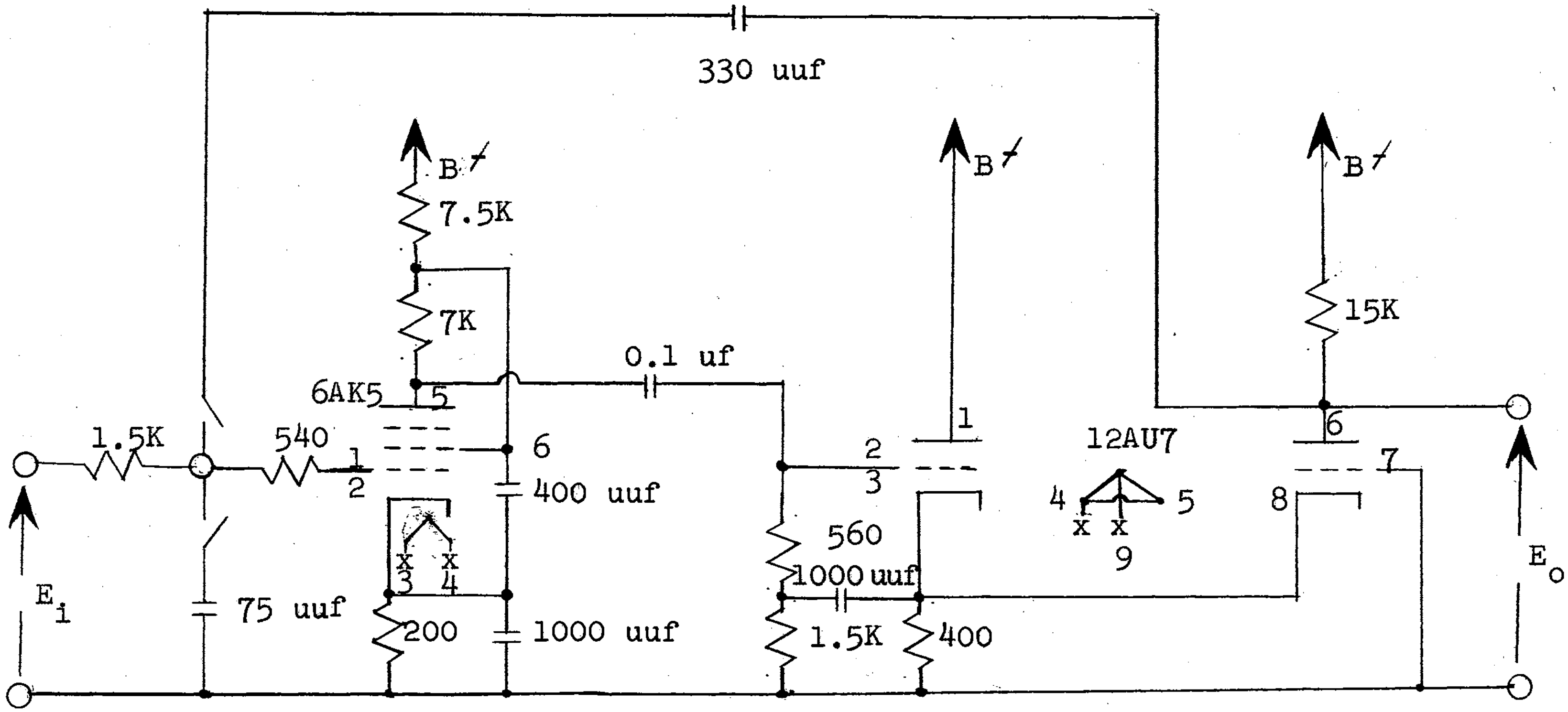
A d-c amplifier is usually used for electronic integration. However, as the minimum frequency response required to successfully reproduce the waveform (a 2 microsecond pulse) is 500 Kcps, typical commercial units such as the Philbrick K2 were found to have insufficient bandwidth for this application and some distortion resulted.[4]

Because the low frequency requirements are not critical, an a-c amplifier can be used. Some of the advantages of using an a-c amplifier rather than a d-c amplifier are:

1. There are less problems with drift.
2. High-frequency response and gain are easier obtained.
3. D-c stabilization is unnecessary as it is with high gain d-c amplifiers.

A diagram of the a-c amplifier which was designed specifically to integrate dϕ/dt of the core and obtain the total flux reversal in the core is shown in Figure 8.

The amplifier has an open loop gain of approximately 100, with a bandwidth of 0.8 Mcps. It is a three-stage amplifier with a 180 degree phase reversal. The first stage is a pentriode amplifier which provides wide



1 - 180VDC
2 - GND
3 - 6.3VAC
4 - 6.3VAC

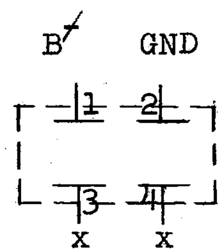


Figure 8. Integrator

bandwidths without the use of compensating circuits.[15] The second stage is a cathode-follower type amplifier with a gain approaching unity. Its low output impedance permits the use of a grounded-grid amplifier, which has a low input impedance, in the third stage. A grounded-grid amplifier was used because shunt capacity effects do not adversely effect its high-frequency response such as it does in the grounded-cathode amplifier. Since the cathode-follower as well as the grounded-grid contain no phase reversal, the only phase reversal is in the first stage, giving an over-all phase reversal of 180 degrees.

Forcing the amplifier to possess a capacitive input impedance was found to be necessary in order to obtain some degree of stability at the frequencies involved. The gain in stability greatly offset the slight reduction in integrator output which resulted.

Calibration

Since

$$E_o = \frac{1}{RC_{eq}} \int E_i \, dt \qquad (4.13)$$

then

$$\int E_i \, dt = RC_{eq} E_o. \qquad (4.14)$$

Calibration of the integrator involves determining the multiplying factor (RC_{eq}.) of the amplifier. By injecting a voltage pulse of known amplitude (V) and time (T), the integral of Vdt is just the product VT. Then, with the above voltage pulse applied to the integrator, E_o may be determined by reading its value on an oscilloscope. The only unknown is RC_{eq} which can be determined as

$$RC_{eq} = \frac{VT}{E_o} \qquad (4.15)$$

the unit of which is time.

Since the product $RC_{eq}E_o$ has the units of volt-seconds, the amount of flux in maxwells can be determined from

$$1 \text{ maxwell } (\phi) = 1 \text{ volt-second } X\ 10^{-8}.$$

Errors

The errors involved in using an integrating amplifier with finite gain are those associated with gain as well as the time constant of integration. The time constant of integration should, of course, be much greater than the period of the input signal. By using a high gain amplifier and a long time constant of integration, these errors can be held to a minimum. The time constant of integration used could possibly be improved upon, but was considered to be in the same order of accuracy as the other measurements taken.

CHAPTER V

DRIVING FIELD

Drivers

The ideal driving function for pulse testing of cores is a current step with a rise time much shorter than the peaking time of the core switching voltage response. The input drive to the core under test was at first obtained from a General Radio Co., Type 1217A Unit Pulser, and amplified by a Type 1219A Pulse Amplifier. These two units in tandem are capable of generating square pulses of current (up to 600 MA) with a maximum rise time of 0.18 microseconds.

In order to have continuously variable control of the output current from the current driver, a medium power switching transistor circuit was designed for this purpose. By using the General Radio Co., Type 1217A Unit Pulser to drive the transistor, current values ranging from zero to 200 MA were available with a rise time of approximately 0.110 microseconds. The transistor was a 2N730 and was supplied by Texas Instruments, Inc., Dallas, Texas. The collector current of the transistor was used as the driving current. By varying the base current drive, the above mentioned variation in collector current was available.

The circuit diagram of the transistor is shown in Figure 9.

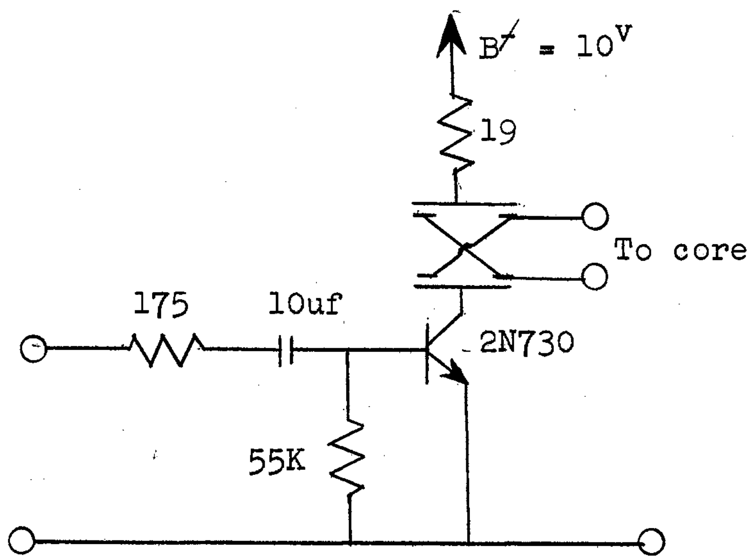


Figure 9. Current Driver.

The large value of series input capacitance was necessary because of the decrease of transistor input resistance when it was driven near the region of saturation. Without this large value of capacitance, the collector waveform contained considerable droop.

In order to have I_c equal to zero with no input, it is usually necessary to reverse bias the base circuit. The type 2N730 had a value of I_{cbo} equal to 1 microampere maximum so was considered to have negligible effect upon the switching characteristics of the cores.

The amount of current available from the collector of the transistor at a particular setting of the input to the base was determined with the aid of a Hewlett Packard 456A current probe. The current waveform, which is calibrated at 1 millivolt equals 1 milliampere, was viewed on an oscilloscope (Tektronix 545) and the magnitude thereby determined. An oscillogram showing the current waveform is shown in Figure 10. The waveform had a slight overshoot which was less than 0.2 of a microsecond in duration.

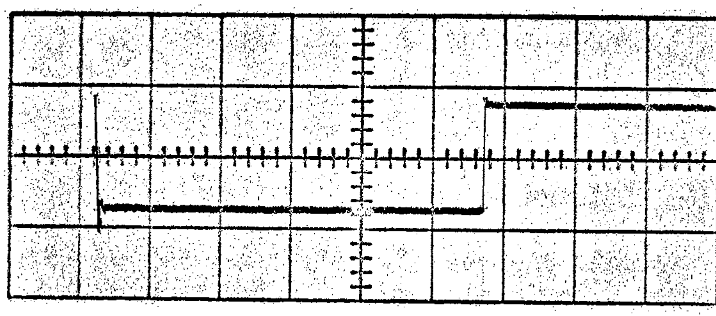


Figure 10. Oscillogram of Driving Current Waveform. Time scale: 5 microsecond/cm. Voltage scale: 0.1 volt/cm.

The collector of the 2N730 is in electrical contact with its case, and, in order to mount it on the same chassis as the integrating amplifier, it was necessary to use an insulated heat sink. The transistor was mounted as close to the core as possible in order to keep all leads short, thereby keeping high-frequency ringing effects to a minimum.

In order to switch the core from one state to the other, it was necessary to be able to reverse the direction of current through the core. A DPDT switch was connected as shown in Figure 11 in the collector circuit of the transistor. A similar setting of the core could have been arrived at by biasing the core in one state.

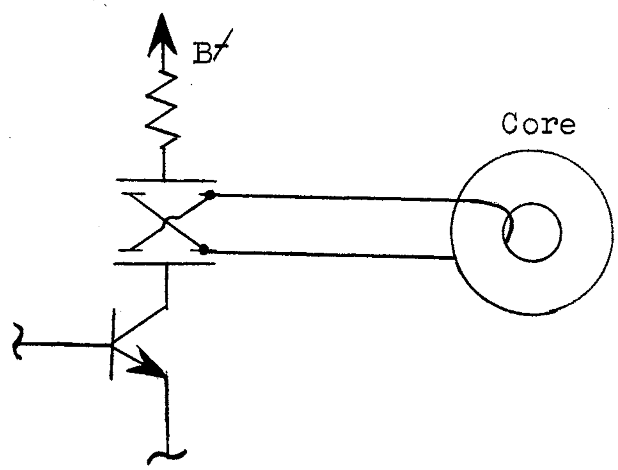


Figure 11. Drive Current Reversing Switch

Magnetic Intensity

If a solenoid is wound around a toroid of homogeneous and isotropic ferromagnetic material, then

$$\oint H dl = NI \qquad (5.1)$$

for every circular path about the axis of symmetry that threads through the N turns of wire each carrying the current I. Symmetry requires that H be tangential to the path and that its magnitude be the same at all points. Therefore, $H 2\pi r = NI$ and

$$H = \frac{NI}{2\pi r} \qquad (5.2)$$

which is independent of the properties of the ferromagnetic material. The assumption was made that the effective radius was much greater than the thickness (height) or width of the tape. In calculating the driving field for the smaller radii cores, some inaccuracy might result.

CHAPTER VI

TESTING AND EVALUATION

Test Setup

In order to obtain data from the cores necessary to relate them to various drive conditions, the test setup shown in Figure 12 was constructed. The input drive to the core consisted of a single positive pulse generated by a General Radio Co., Type 1217A Unit Pulser and amplified by the 2N730 transistor.

The Tektronix oscilloscope, Type 545, with a 53/54L plug-in vertical preamplifier, was used to display the core characteristics. When this scope is adjusted for a single trace upon the application of an external trigger, it also makes available for use a step voltage, which is synchronized with the sweep, of approximately 30 volts and lasts for the duration of the trace. This voltage pulse was then used to trigger the Unit Pulser. This made available a single drive pulse which was delayed approximately 0.5 microseconds from the start of the sweep on the scope. However, in the process of injecting the voltage pulse from the scope into the Unit Pulser, and coupling the

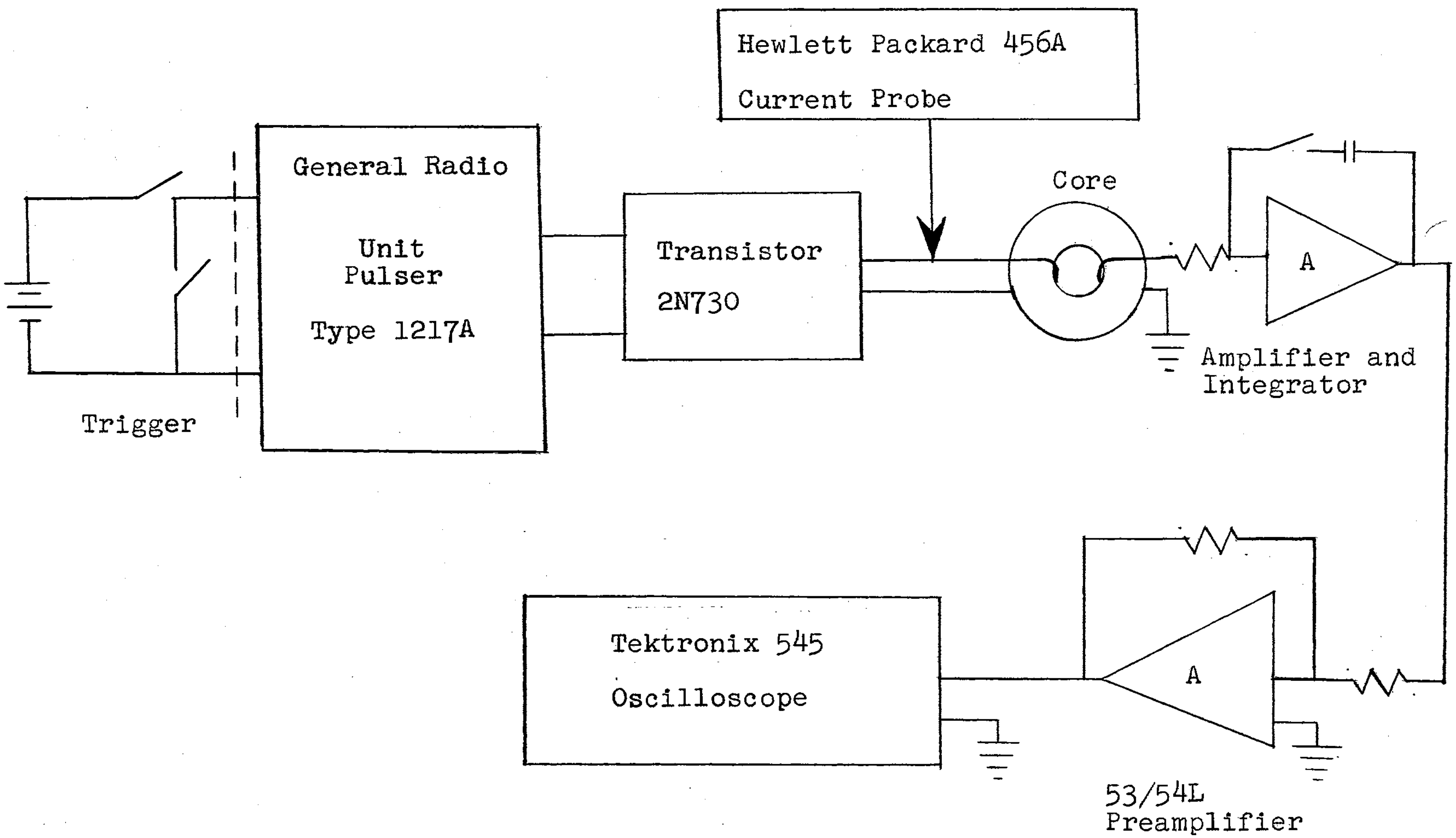


Figure 12. Test Circuit Diagram

output from the core to the integrating amplifier, the previously-mentioned high-frequency ringing which lasted slightly longer than the 0.5 microsecond delay was encountered. Although the ringing did not appear to affect the data involved, another method of triggering the Unit Pulser was desirable. Therefore, the Unit Pulser was triggered with a power supply which removed the undesired ringing effects. By setting the triggering level as low as possible, the incoming signal was used to trigger the scope. This provided a single trace upon the application of the trigger from the power supply to the Unit Pulser. The triggering setup is shown in Figure 13.

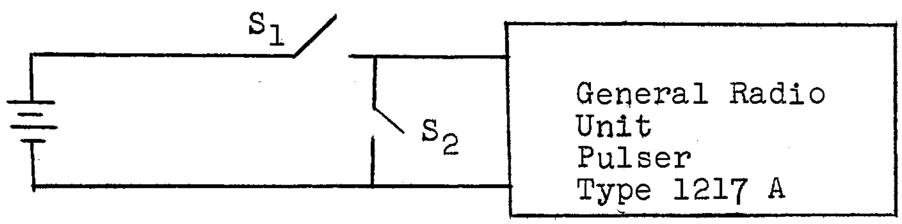


Figure 13. Manual Trigger

Switch S_2 was found necessary in order to discharge the input circuit of the Unit Pulser after each input trigger signal.

OT_s Versus IT_s

With the set of cores used, it was possible to compare switching times and voltage outputs under varied drive conditions with the effective diameter of the cores.

Also, with the integrated output available, it was possible to compare the switching time (OT_s), which is defined as the time interval between the 10 per cent points of the open circuit response, with the switching time (IT_s), which is defined as the interval between the 10-to-90 per cent points on the integrated output voltage waveform. As previously mentioned in Chapter III, these two values are quite different. By comparing the data of Figures 14a and 15a, it can be seen that the switching time (IT_s) is considerably shorter than the switching time (OT_s).

Measurements of switching times were made on a core with 29 wraps of 1/8-mil 4-79 Mo-Permalloy and an ID equal to 0.125 inches. All measurements were made with a single turn drive winding and a single turn sense winding. Also, the cores were set and reset with the same amount of ampere-turns.

Magnetics, Inc., of Butler, Pennsylvania, furnished the tape wound bobbin cores for this study. The cores supplied were of various diameters, ranging from 0.050 to 0.125 inches ID, and were rated at 20 maxwells output flux.

The graphs of $1/OT_s$ and $1/IT_s$ versus driving ampere-turns are shown in Figures 22 and 23. From a plot of $1/OT_s$ versus NI, by extrapolation, it is possible to determine a value, which might be designated as H_o, keeping in mind that H equals $NI/2\pi r$. This is the value of magnetic intensity below which no switching will take place and occurs at the value of $1/OT_s$ equals zero. This value corresponds closely, but is not equal to H_c, and is designated as "pulse threshold". A value for H_o could also be obtained from a plot of $1/IT_s$ versus NI. By comparing Figures 22 and 23, it can be seen that essentially the same value for H_o is obtained. At the same time, it can be seen that the slope of the line (S_w) and the switching times (OT_s and IT_s) differ.

Flux Response Versus Varied Drive Conditions

To analyze the flux response characteristics of a core for various drive conditions, measurements of flux and switching time (IT_s) were made on a core with 29 wraps of 1/8-mil 4-79 Mo-Permalloy and an ID equal to 0.125 inches. Measurements were made as mentioned before. The switching time (IT_s) was decreased from 7.5 microseconds to 2.8 microseconds by increasing the drive from 0.15 ampere-turns to 0.20 ampere-turns. (See Figures 15a, 15b, and 15c.) With the same increase in ampere-turns, the total flux changed from 15.15 to 16.5 maxwells. The flux response is seen to act similarly to the voltage response in that the amplitude increases and the switching time decreases as the drive is increased. The curve of Figure 24 was drawn to show the variation of maxwells/wrap as the driving conditions were varied.

Total Flux Versus Drive Conditions

A curve of total flux versus drive conditions was easily obtained. The amount of total flux switched could be read directly as the amplitude of the flux response waveform. The units are volt-seconds, and when multiplied by 10^{-8}, the total flux in maxwells is found. The curve of flux versus drive ampere-turns is shown in Figure 25. The measurements were made as mentioned previously on a core with 29 wraps of 1/8-mil 4-79 Mo-Permalloy and an ID equal to 0.086 inches.

A normal magnetization curve for this particular core could be obtained by using only half the total flux switched. The values of flux density (B) and magnetic intensity (H) can be determined by knowing the area and radius of the core.

Flux and Switching Time in Relation to Diameter

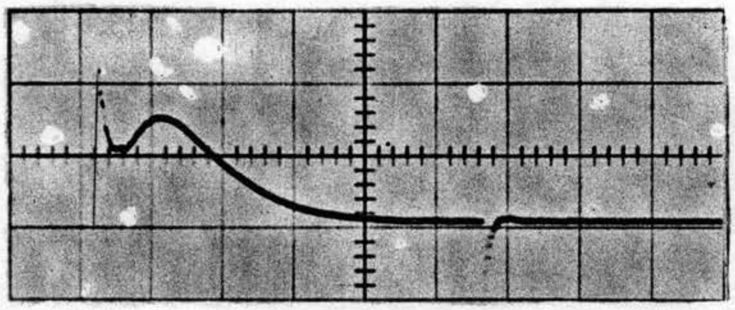
Ebertshauser[4] has shown that the diameter of the cores has little effect upon the switching time and voltage response. However, in his study, he chose to hold the magnetic intensity (H) constant. In this thesis, the value of NI was held constant. The amount of current available, or necessary for a particular application, was considered to be of prime importance.

As the diameter of the core was varied, and the amount of ampere-turns were held constant, both the switching time and output response changed. As the diameter decreased, the output response increased while the switching time decreased. This can readily be noticed by comparing Figures 14a, 16a, 18a, and 20a.

Output Voltage Nonlinearity

The voltage spike at the beginning of the output waveform is not completely understood, but is thought to be connected with the fact that the domain wall spikes associated with imperfections do not pull back on the domain wall until it has moved a little distance. (See Figure 14a.) After the pressure on the wall due to the magnetic field stops (note the length of the driving pulse in Figure 10), the domain spikes associated with imperfections pull the wall back slightly, giving rise to the voltage spike in the opposite direction.[14]

A similar explanation is given by Smit and Wijn[8], page 339, in that both consider the voltage spikes to be caused by some reversible process. A relatively small change of the magnetization occurs fairly rapidly, and the major part of the magnetization reverses only slowly. It seems possible to associate these changes of magnetization with reversible rotation processes and with irreversible domain-wall displacements respectively.

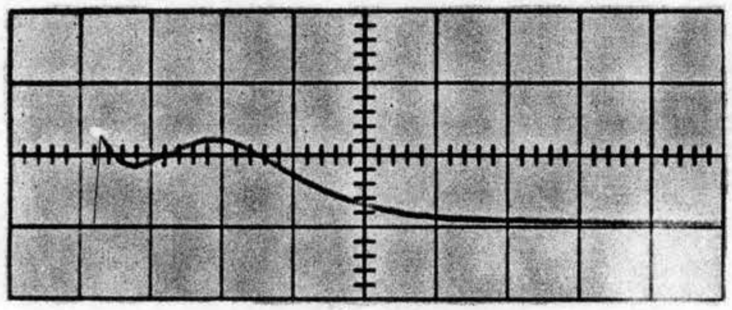


Drive: 0.150 amp-turns

Time scale: 5 u sec./cm.

Voltage scale: 1 volt/cm.

(a)

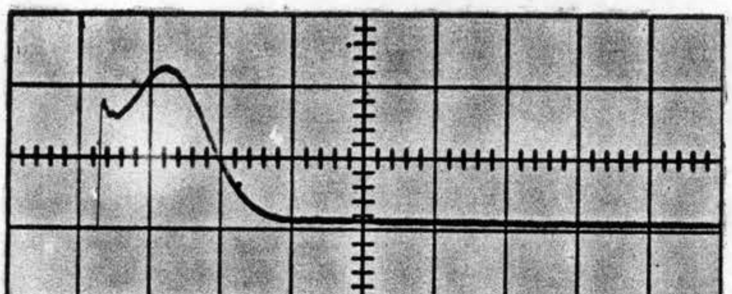


Drive: 0.175 amp-turns

Time scale: 2 u sec./cm.

Voltage scale: 2 volts/cm.

(b)



Drive: 0.200 amp-turns

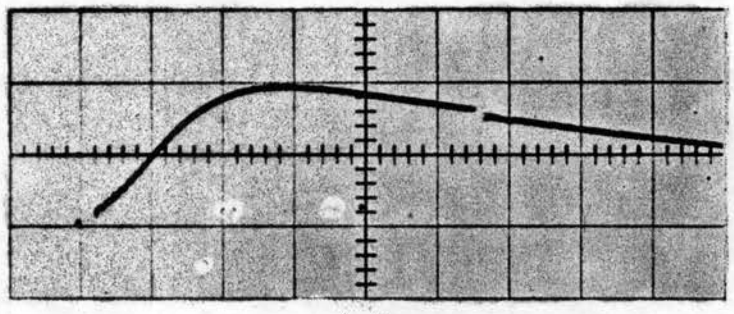
Time scale: 2 u sec./cm.

Voltage scale: 2 volts/cm.

(c)

Figure 14. Voltage Output.

Core: 29 wraps of 1/8-mil 4-79 Mo-Permalloy, 1/16 inches wide. Core ID 0.125 inches. Effective radius 0.0643 inches.

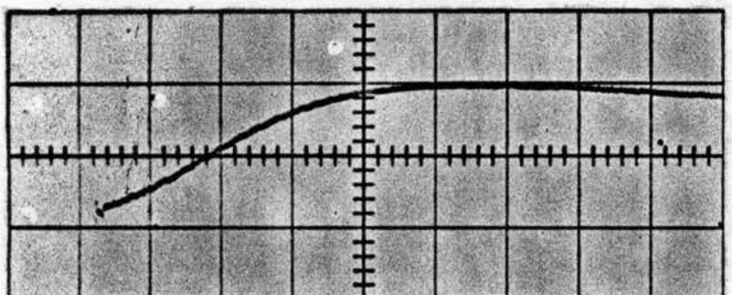


Drive: 0.150 amp-turns

Time scale: 5 u sec./cm.

Voltage scale: 1 volt/cm.

(a)

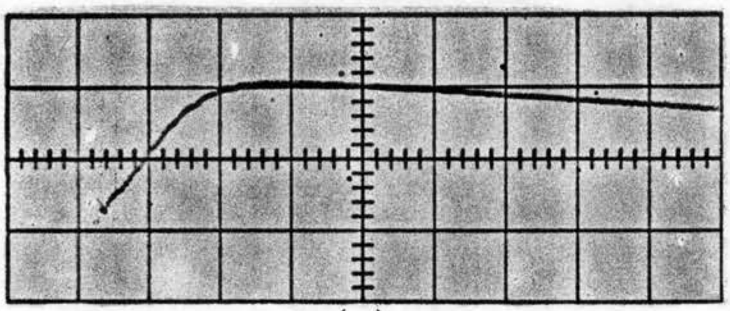


Drive: 0.175 amp-turns

Time scale: 2 u sec./cm.

Voltage scale: 1 volt/cm.

(b)



Drive: 0.200 amp-turns

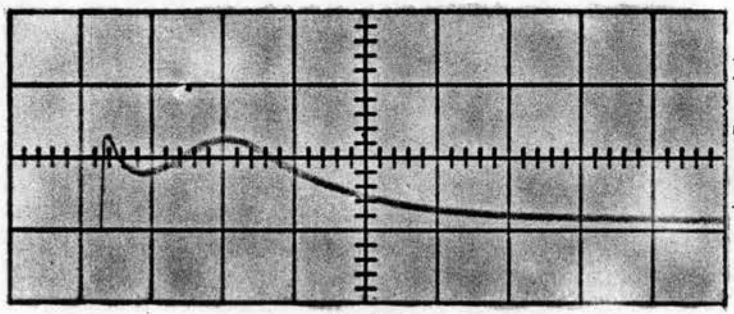
Time scale: 2 u sec./cm.

Voltage scale: 1 volt/cm.

(c)

Figure 15. Flux Output.

Core: 29 wraps of 1/8-mil 4-79 Mo-Permalloy, 1/16 inches wide. Core ID 0.125 inches. Effective radius 0.0643 inches.

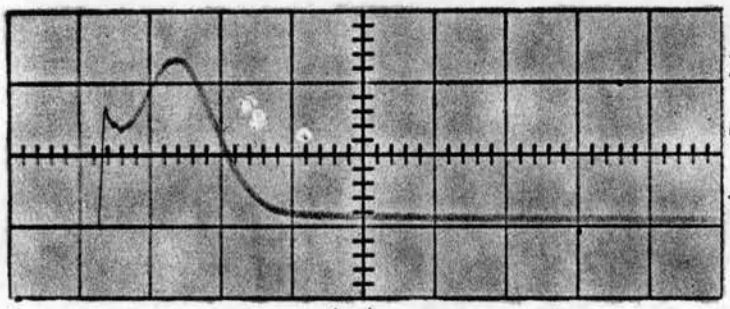


Drive: 0.150 amp-turns

Time scale: 2 u sec./cm.

Voltage scale: 2 volts/cm.

(a)

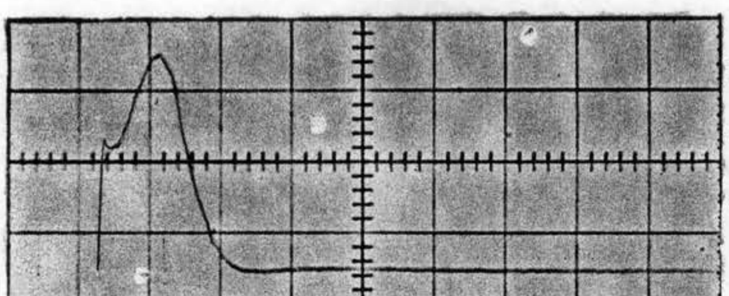


Drive: 0.175 amp-turns

Time scale: 2 u sec./cm.

Voltage scale: 2 volts/cm.

(b)



Drive: 0.200 amp-turns

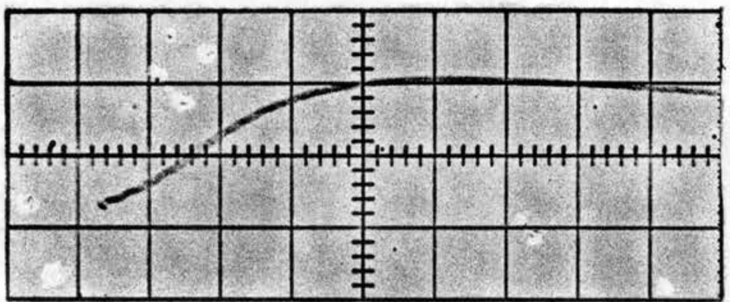
Time scale: 2 u sec./cm.

Voltage scale: 2 volts/cm.

(c)

Figure 16. Voltage Output.

Core: 29 wraps of 1/8-mil 4-79 Mo-Permalloy, 1/16 inches wide. Core ID 0.110 inches. Effective radius 0.0568 inches.

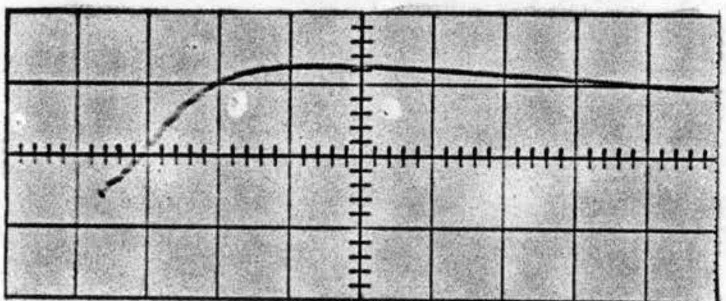


Drive: 0.150 amp-turns

Time scale: 2 u sec./cm.

Voltage scale: 1 volt/cm.

(a)

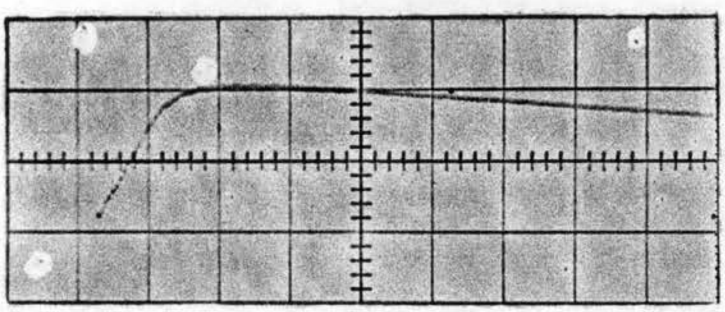


Drive: 0.175 amp-turns

Time scale: 2 u sec./cm.

Voltage scale: 1 volt/cm.

(b)



Drive: 0.200 amp-turns

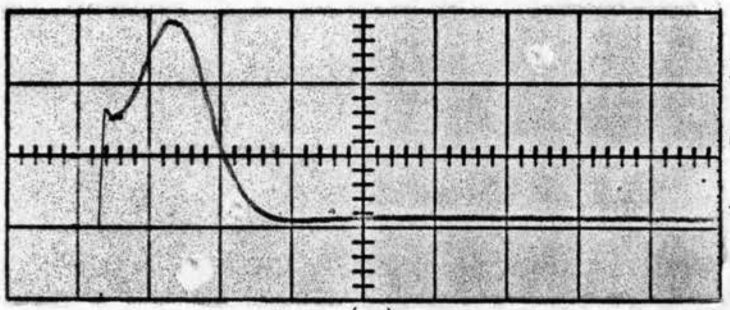
Time scale: 2 u sec./cm.

Voltage scale: 1 volt/cm .

(c)

Figure 17. Flux Output.

Core: 29 wraps of 1/8-mil 4-79 Mo-Permalloy, 1/16 inches wide. Core ID 0.110 inches. Effective radius 0.0568 inches.

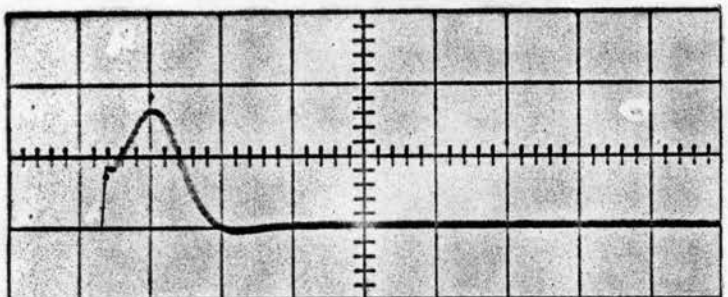


Drive: 0.150 amp-turns

Time scale: 2 u sec./cm.

Voltage scale: 2 volts/cm.

(a)

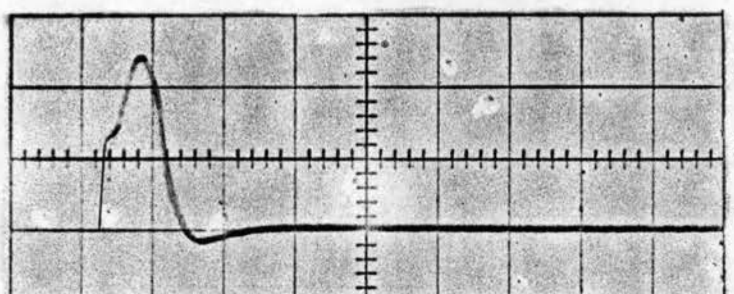


Drive: 0.175 amp-turns

Time scale: 2 u sec./cm.

Voltage scale: 5 volts/cm.

(b)



Drive: 0.200 amp-turns

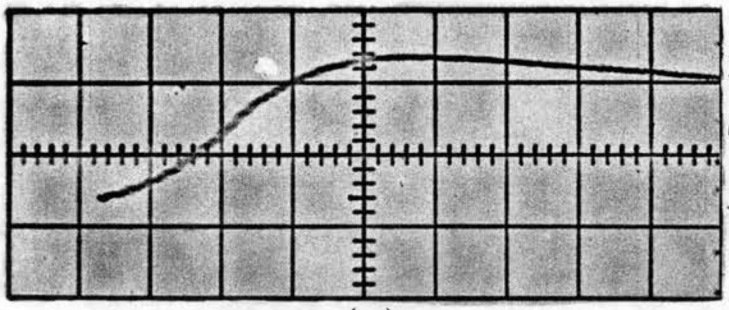
Time scale: 2 u sec./cm.

Voltage scale: 5 volts/cm.

(c)

Figure 18. Voltage Output.

Core: 29 wraps of 1/8-mil 4-79 Mo-Permalloy, 1/16 inches wide. Core ID 0.086 inches. Effective radius 0.0448 inches.

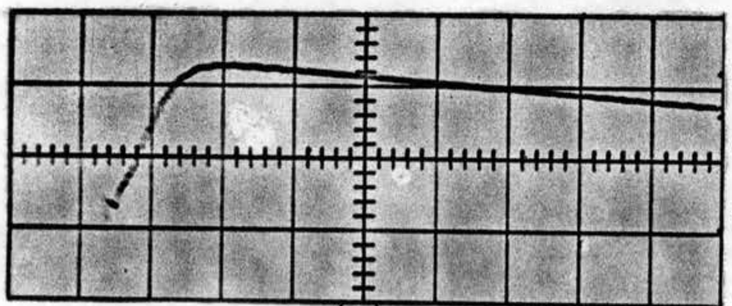


Drive: 0.150 amp-turns

Time scale: 2 u sec./cm.

Voltage scale: 1 volt/cm.

(a)

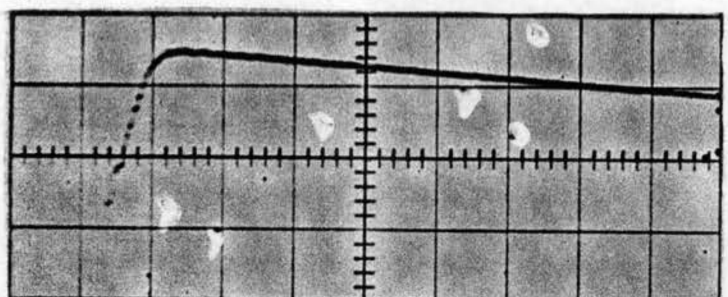


Drive: 0.175 amp-turns

Time scale: 2 u sec./cm.

Voltage scale: 1 volt/cm.

(b)



Drive: 0.200 amp-turns

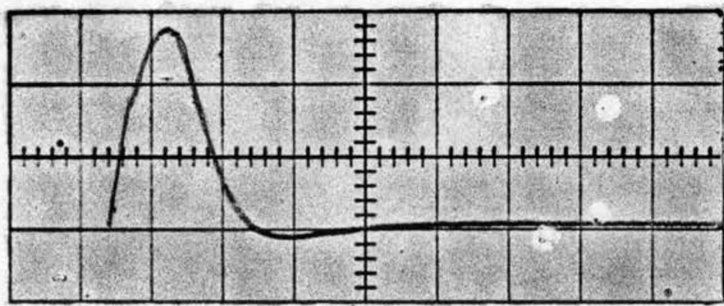
Time scale: 2 u sec./cm.

Voltage scale: 1 volt/cm.

(c)

Figure 19. Flux Output.

Core: 29 wraps of 1/8-mil 4-79 Mo-Permalloy, 1/16 inches wide. Core ID 0.086 inches. Effective radius 0.0448 inches.

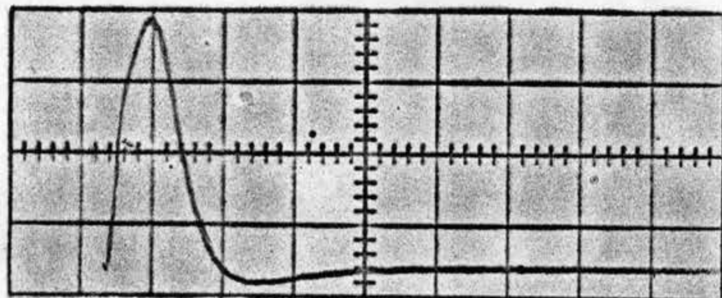


Drive: 0.150 amp-turns

Time scale: 1 u sec./cm.

Voltage scale: 5 volts/cm.

(a)



Drive: 0.175 amp-turns

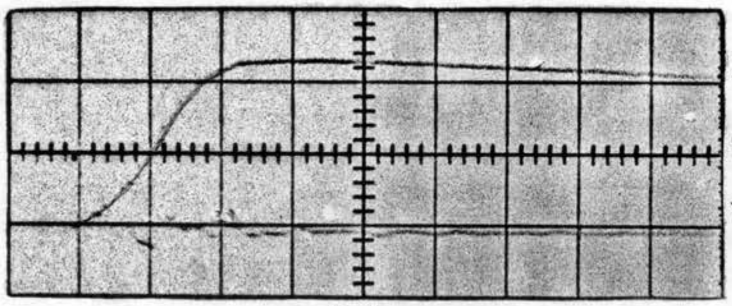
Time scale: 1 u sec./cm.

Voltage scale: 5 volts/cm.

(b)

Figure 20. Voltage Output.

Core: 29 wraps of 1/8-mil 4-79 Mo-Permalloy, 1/16 inches wide. Core ID 0.050 inches. Effective radius 0.0286 inches.

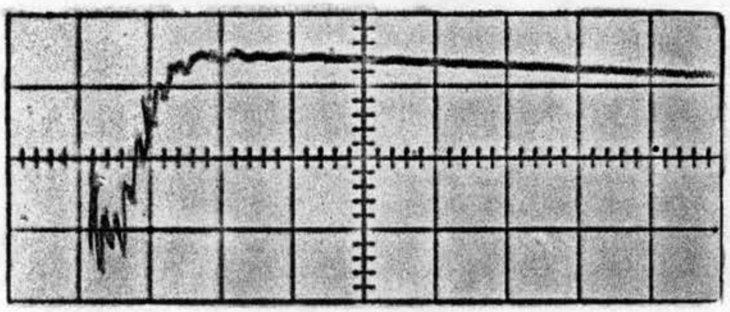


Drive: 0.150 amp-turns

Time scale: 1 u sec./cm.

Voltage scale: 1 volt/cm.

(a)



Drive: 0.175 amp-turns

Time scale: 1 u sec./cm.

Voltage scale: 1 volt/cm.

(b)

Figure 21. Flux Output.

Core: 29 wraps of 1/8-mil 4-79 Mo-Permalloy, 1/16 inches wide. Core ID 0.050 inches. Effective radius 0.0286 inches.

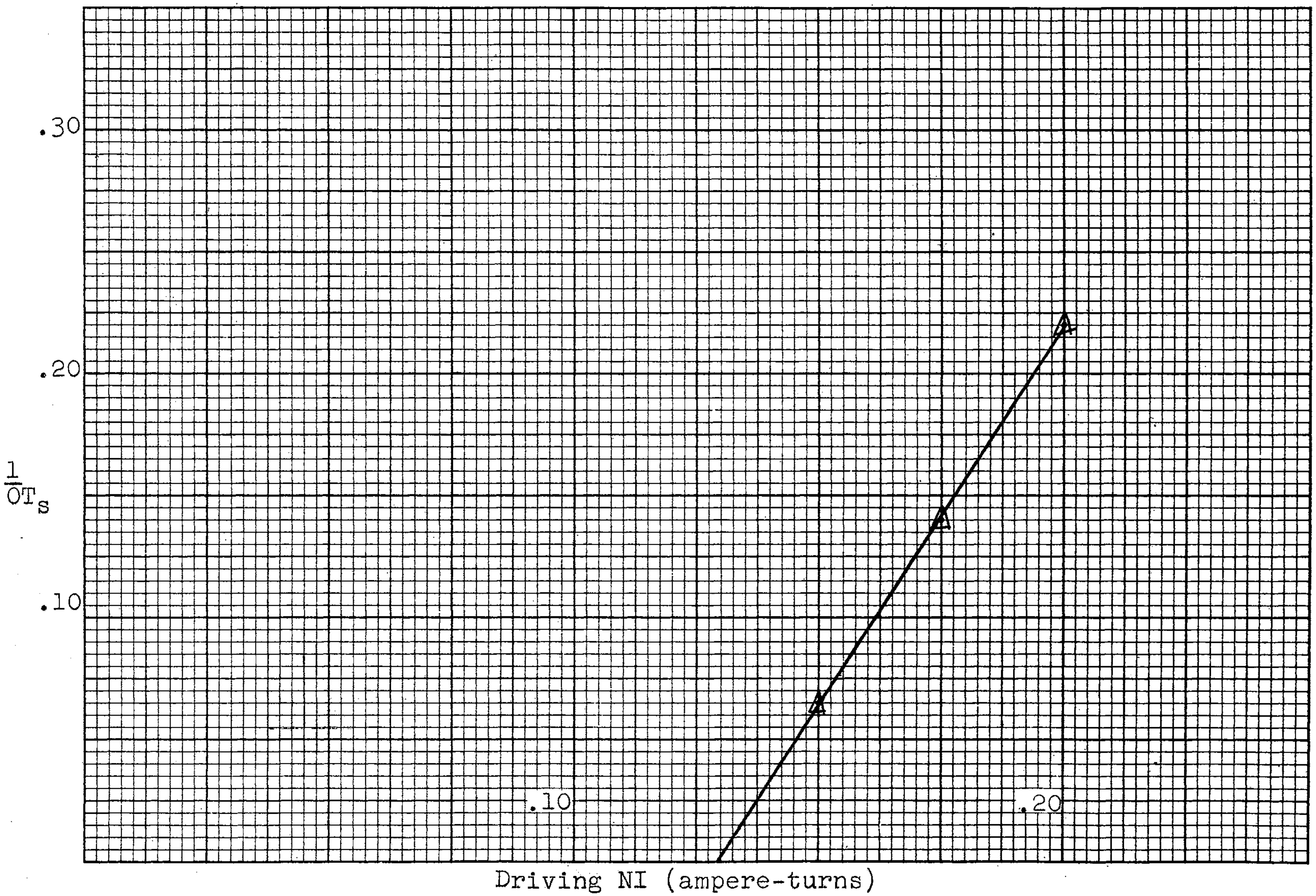


Figure 22. Open Circuit Switching Time Versus Driving NI

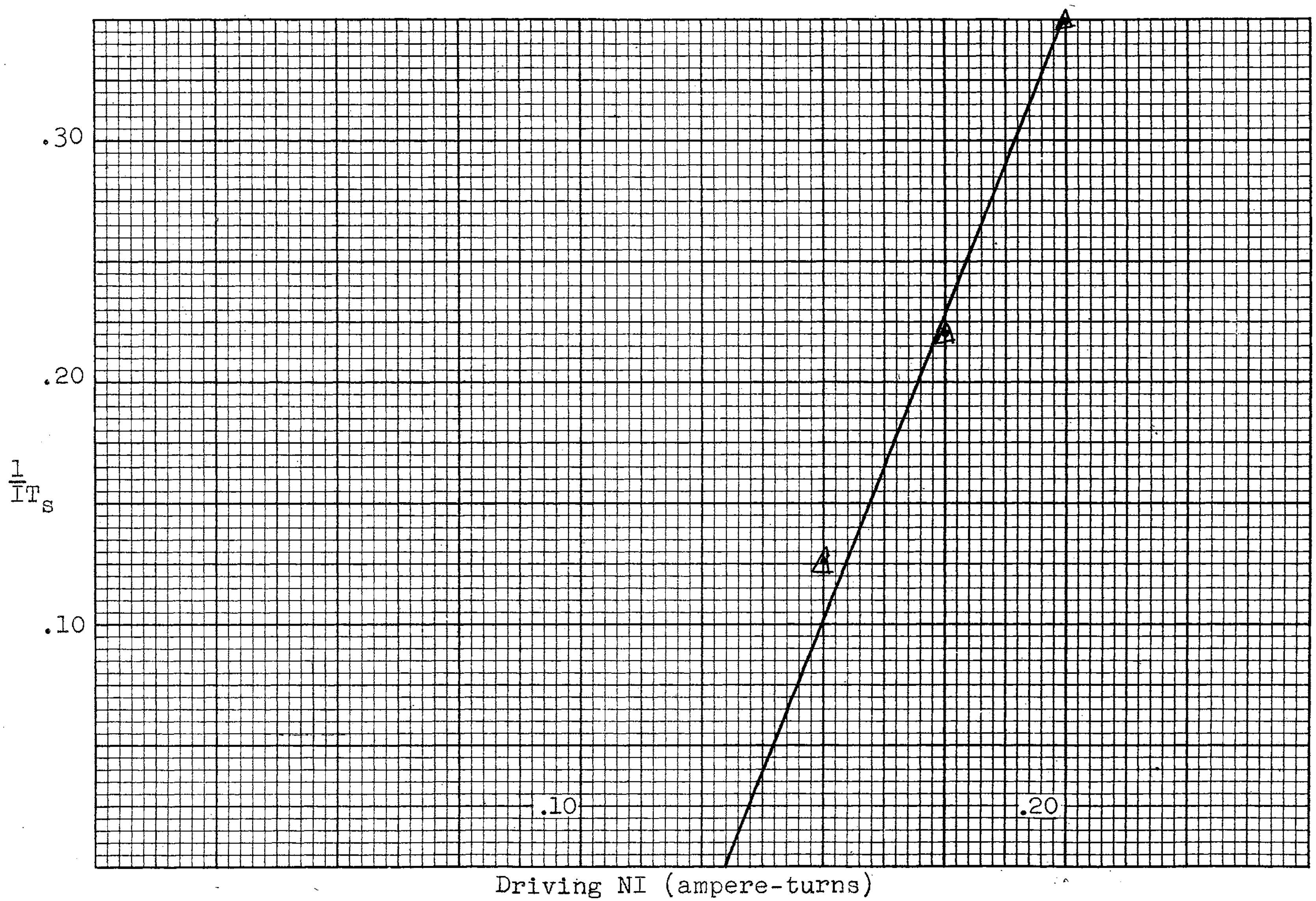


Figure 23. Integrated Switching Time Versus Driving NI

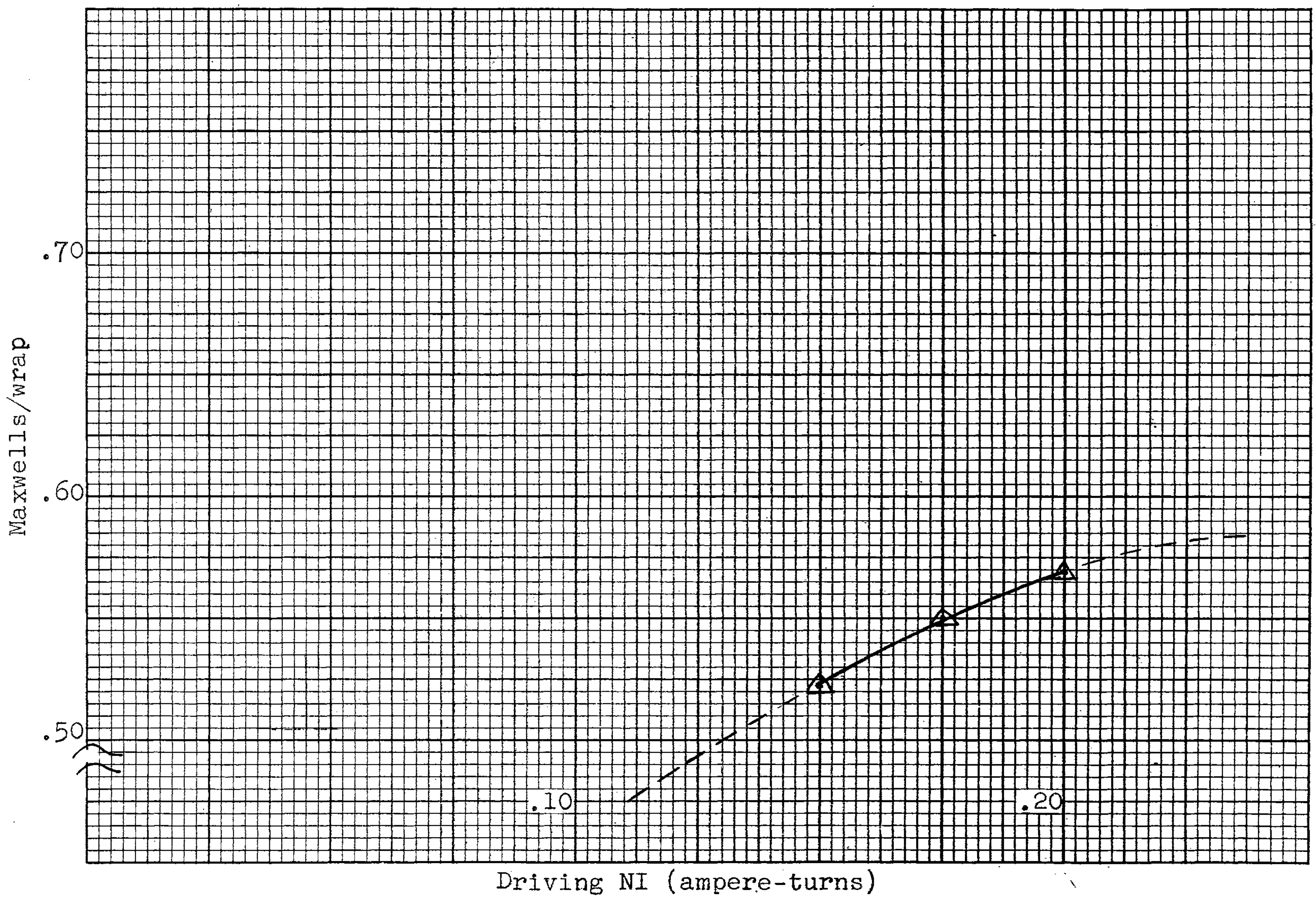


Figure 24. Maxwells/wrap Versus Driving NI

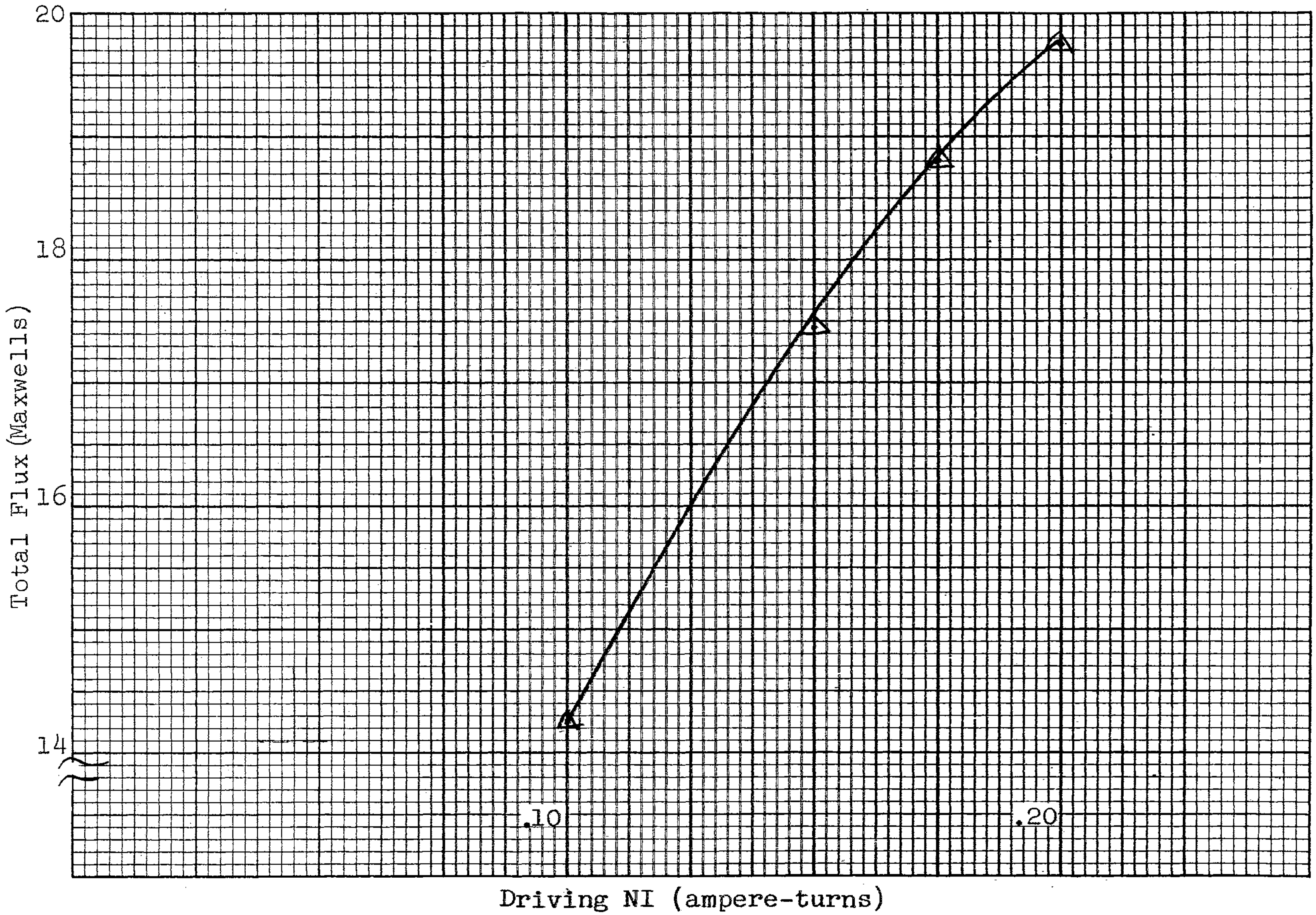


Figure 25. Total Flux in Maxwells Versus Driving NI

CHAPTER VII

SUMMARY

The purpose of this study was to incorporate an a-c Miller integrating amplifier to measure core characteristics and to ascertain the effects of core diameter upon the flux response and switching time while the magnetomotive force (NI) was held constant. Also, the effects of varying the magnetomotive force was to be determined. At the same time, a simplified test setup for obtaining data to be used in design was to be constructed.

This was accomplished by designing and building an a-c Miller integrator in order to obtain the flux characteristics of the cores. Although essentially the same results could have been arrived at by means of graphical integration, the ease, accuracy, and rapidity of electronic integration was realized. However, as all high gain wide bandwidth integrating amplifiers are prone to oscillate, the final integrating amplifier described in Chapter IV was not arrived at without a fair share of difficulties. A complete set of data from a core with an inside diameter of 0.050 inches was not obtained due to the fact that the limit of the integrator was reached. (See Figures 20b and

21b.) It will be noticed that the core switched (OT_s) in approximately 1.4 microseconds.

Although extremely fast film was used, some difficulty was encountered when photographing only one sweep at a time. A method of biasing the core in one state and letting the Unit Pulser free run was attempted in order to get a brighter trace on the phosphor. This would have been a workable setup had it not been for the jitter of the Unit Pulser which was encountered at the frequencies involved.

Cores of various diameters ranging from 0.050 to 0.125 inches diameter with tape thickness of 1/8-mil were tested and the observations recorded through the use of the 53/54L preamplifier and the Tektronix 545 oscilloscope. The results in terms of ampere-turns, switching time, and flux have been shown by various characteristic curves in Chapter VI.

It will be noticed that the normal B-H relationship of these magnetic cores, although perhaps helpful, does not directly contain the information necessary to design a particular core or circuits using these cores. The information obtained from the switching time versus ampere-turns curves and the flux versus ampere-turns curves is quite readily adapted to design methods while, at the same time, the B-H relationship can be obtained by knowing the core dimensions.

Although characteristic curves are obtainable by experimental procedures, this author knows of no satisfactory mathematical model which will predict the voltage output of a thin core. As previously mentioned in Chapter II, in order to solve problems in magnetic theory, it is essential to have a relationship between B and H or, equivalently, a relationship between M and one of the magnetic field vectors. These relationships depend on the nature of the magnetic material and are usually obtained experimentally.

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