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An Experimental and Theoretical Investigation of the Characteristics of a Magnetic Amplifier

Merle H. Wittmeyer

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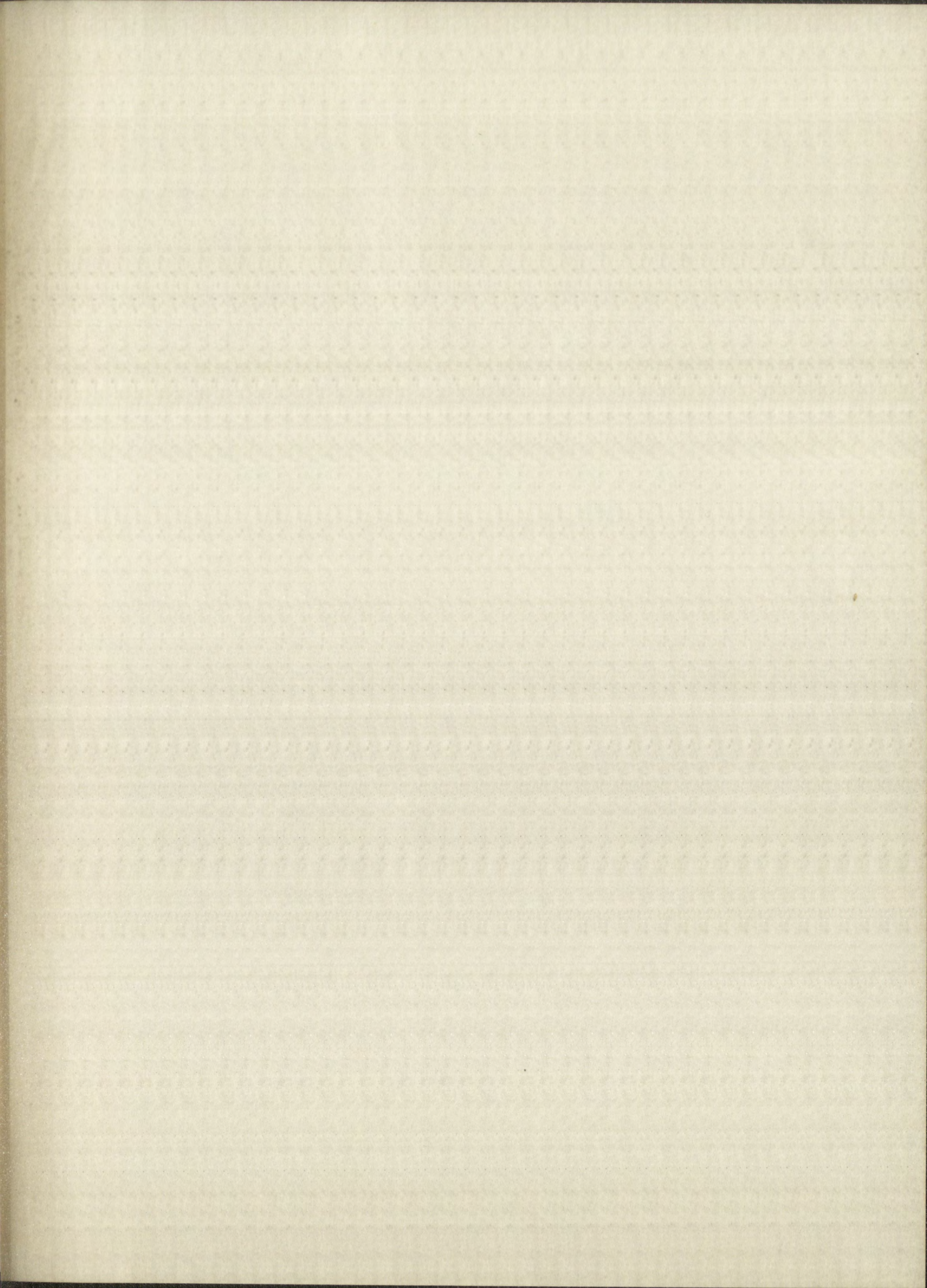
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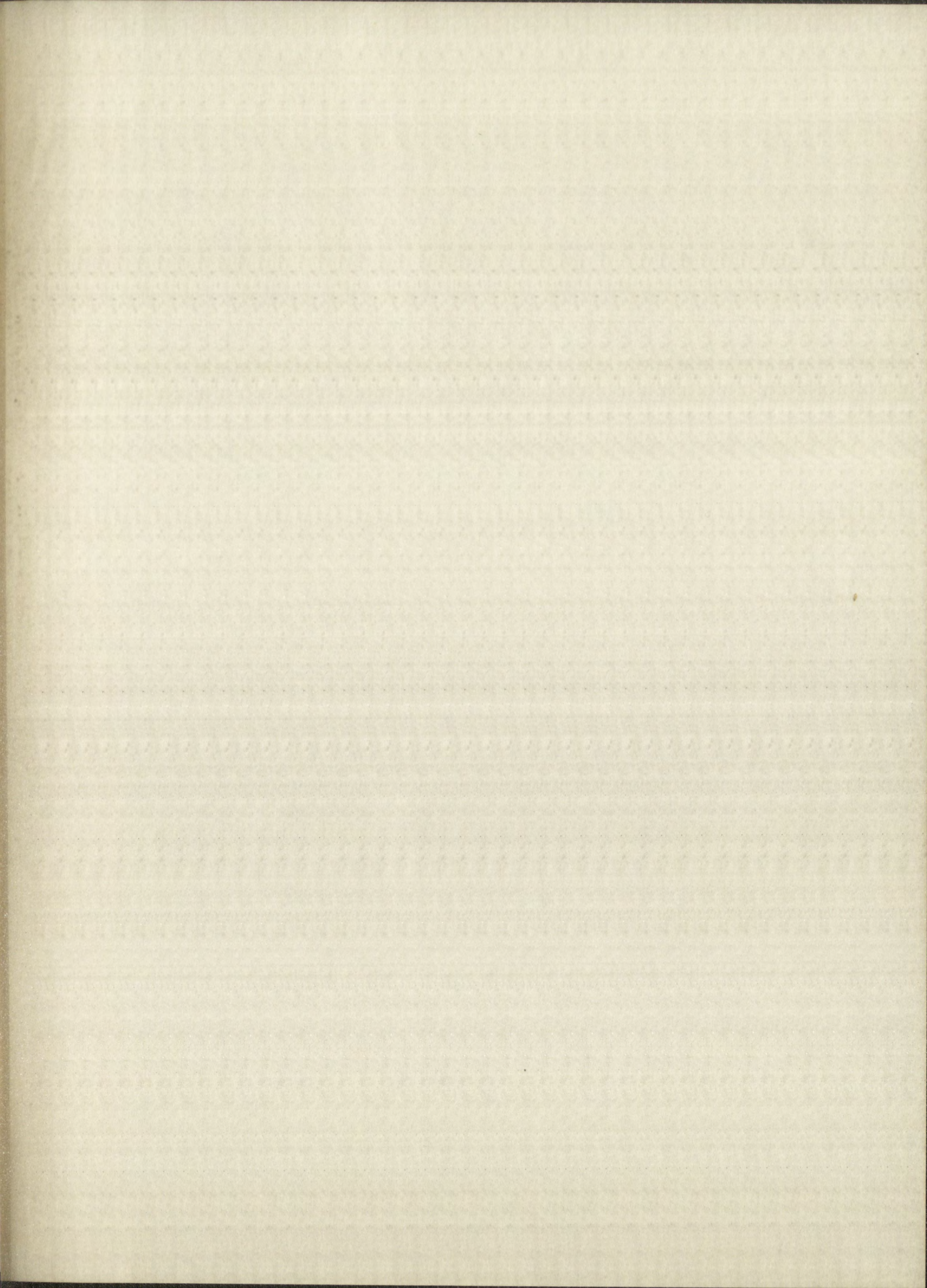
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AN EXPERIMENTAL AND THEORETICAL INVESTIGATION
OF THE CHARACTERISTICS OF A MAGNETIC AMPLIFIER

By

Merle H. Wittmeyer

A Thesis

In partial fulfillment of the
Requirements for the Degree of
Master of Science in Electrical Engineering

The University of New Mexico
1954

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Herle H. Wittmeyer

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In partial fulfillment of the
Requirements for the Degree of
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The University of New Mexico
1954

This thesis, directed and approved by the candidate's committee, has been accepted by the Graduate Committee of the University of New Mexico in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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EFFICIENCY
ERASE BOND
ADJACENT

CHAPTER I

THE PROBLEM AND METHOD OF INVESTIGATION

Many excellent analyses of magnetic amplifiers have been published. As in every investigation, however, there are many details not explained. The purpose of this investigation was to explain some of the details of magnetic amplifier characteristics.

I. THE PROBLEM

Specifically, the static characteristics of a magnetic amplifier were determined experimentally and analyzed in more detail than had previously been done.

Most magnetic amplifier analyses present and analyze the transfer characteristics. There is, however, much to be said in favor of the characteristic curve method. The latter method was used in this investigation.

In addition, most analyses have been limited to the regions near the point of maximum power gain, an important region and one that can be easily analyzed.

However, the characteristics in the region of larger load resistance are also interesting and may, in some cases, be more useful than those in the region usually studied.

This investigation extended both the experimental and theoretical study into the large load region.

THE PROPERTIES OF THE TRANSDUCER

Many excellent papers have been published, and in many instances, there are many details not included. The purpose of this paper is to give a general idea of the basic principles of the transducer and its characteristics.

1. INTRODUCTION

Specifically, the basic characteristics of a transducer are its sensitivity, its linearity, and its stability. In more detail, when the transducer is used, it is found that the output is proportional to the input, and that the output is stable over a long period of time.

Most transducers are designed to measure a physical quantity, such as pressure, temperature, or displacement. The transducer converts this quantity into an electrical signal, which can be measured and recorded. The transducer is usually designed to be as accurate as possible, and to have a wide range of operation.

In addition, the transducer is usually designed to be as simple as possible, and to have a low cost. This is because the transducer is often used in a large number of applications, and it is important that it be easy to use and to maintain.

However, the transducer is also designed to be as reliable as possible. This is because the transducer is often used in critical applications, and it is important that it be able to operate for a long time without failure.

This investigation was carried out in order to determine the basic properties of the transducer, and to see how these properties can be used to design a transducer for a specific application.

II. METHOD OF INVESTIGATION

The experimental work consisted of the necessary studies for instrumentation and the actual determination of the amplifier static characteristics.

The theoretical study consisted of calculation of the usual first approximation to the characteristics, analysis of the errors of this method, and computation of the necessary corrections to extend the region of analysis.

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CHAPTER II

EXPERIMENTAL INVESTIGATION OF THE STATIC CHARACTERISTICS OF A MAGNETIC AMPLIFIER

In general, a magnetic amplifier is used to control the voltage, current or power of some load. If it is to be an amplifier, then the variation in output voltage, current or power must be greater respectively than the variation in control voltage, current or power.

The output of a magnetic amplifier is a function of both the control signal and of the size and character of the load. Its characteristics may then be portrayed as a family of curves of either constant control signal or constant load. The former method was used in this investigation and is described in Section I. of this chapter. The details of experimental technique are included in Section II. The actual results of the experiment and the conclusions are contained in Section III.

I. THE EXPERIMENTAL METHOD

The magnetic amplifier used in this project was a Vickers number 36A34 educational magnetic amplifier used with the DDL connections. A diagram of the amplifier with associated load is shown in Figure 1. In the diagram R_L is the load resistance, and N_g and N_c are respectively the

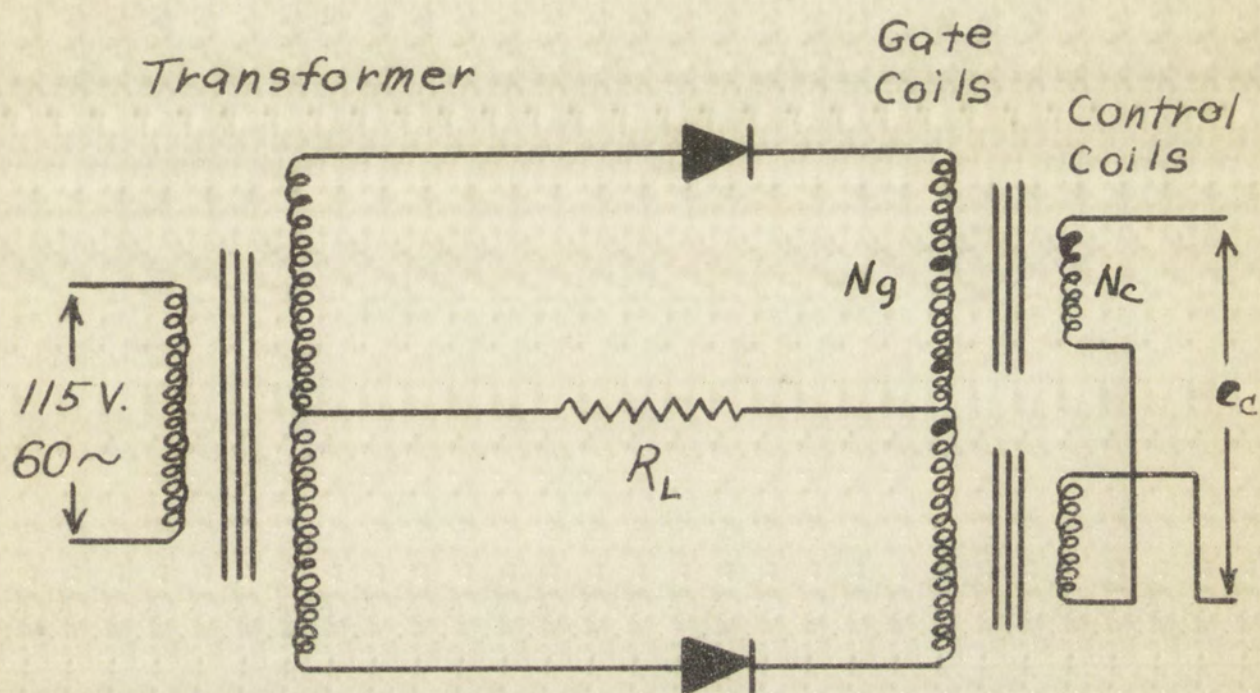


Figure 1

Experimental Connection Diagram
for Vickers Type 36A34 DDI
Educational Magnetic Amplifier

turns of the gate and control windings of the two reactors.

Leaving the details of analysis to Chapter III, it may be stated briefly that such a magnetic amplifier is a controlled, full-wave, center-tapped rectifier. Control is obtained by increasing the current through the control windings, which results in the reactors saturating sooner in each cycle and thus increasing the output.

In this experiment the simple case of a purely resistive load was used. Arbitrarily, the voltage amplification was analyzed, rather than power or current.

As mentioned previously, the magnetic amplifier characteristics can be presented as a family of curves of constant load resistance. Such a set of curves is shown in Figure 2. Such curves may be obtained by holding all parameters constant except the control signal, which is varied smoothly over the control range. A record is made of the load resistance used and of corresponding values of input and output. The load resistance is next changed to some other value and the process repeated until the family of curves has been obtained.

If, in a specific application, the load resistance coincides with the value for one of the curves, then the amplifier output can readily be determined. On the other hand, if some intermediate value of load resistance is used, then the output can be found only by interpolation

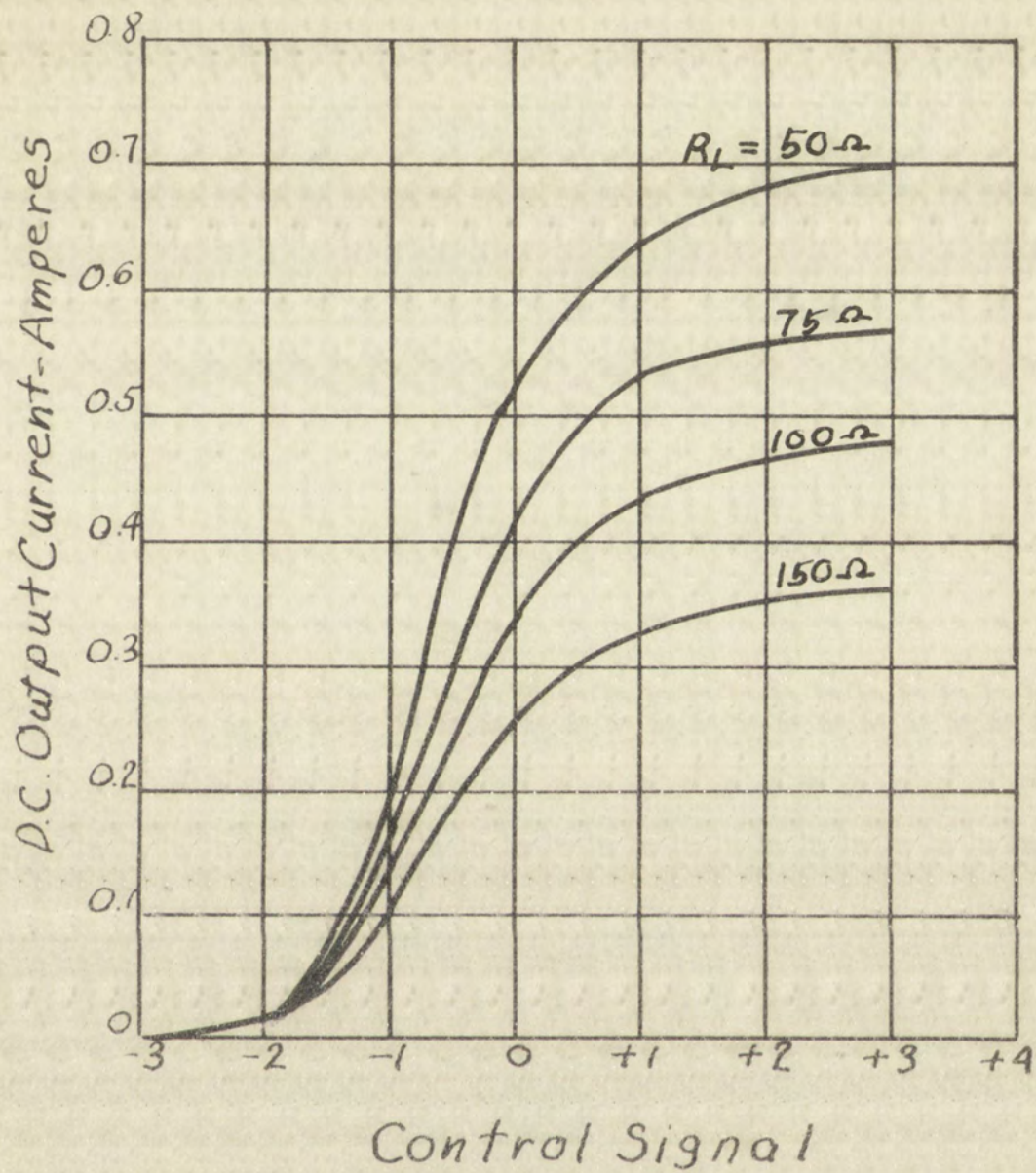


Figure 2
Typical Transfer Curves
For A Magnetic Amplifier

between the irregularly curved lines. This is neither an easy nor an accurate process.

Due to its greater flexibility and as an aid to analysis, a method was used in the experimental investigation which is practically the same as, and was suggested by, the method of obtaining direct-current generator external characteristics. Literature obtained later showed that this was not an original application.¹

The magnetic amplifier was connected as shown in Figure 3. The autotransformer was used to adjust the supply voltage, E_{ac} , read by voltmeter, V_1 , so that the applied voltage was always 115 rms. volts either side of the center tap. To obtain the characteristic curves of the amplifier, the control voltage, e_c , read on voltmeter, V_3 , was set to the desired value by adjusting the direct-current supply source, E_c , and the resistor, R_2 .

The load resistance, R_L , was then varied over the required range and corresponding readings taken of the direct-current load voltage, E_L , on voltmeter, V_2 , and the load direct current, I_L , on ammeter, A_1 . Other control voltages were then selected and the process repeated until the desired data had been obtained. These data are recorded in Table 1 and plotted in Figure 4.

¹Bulletin 20-B on Magnetic Amplifiers, (Vickers Electric Division. St. Louis, 1950).

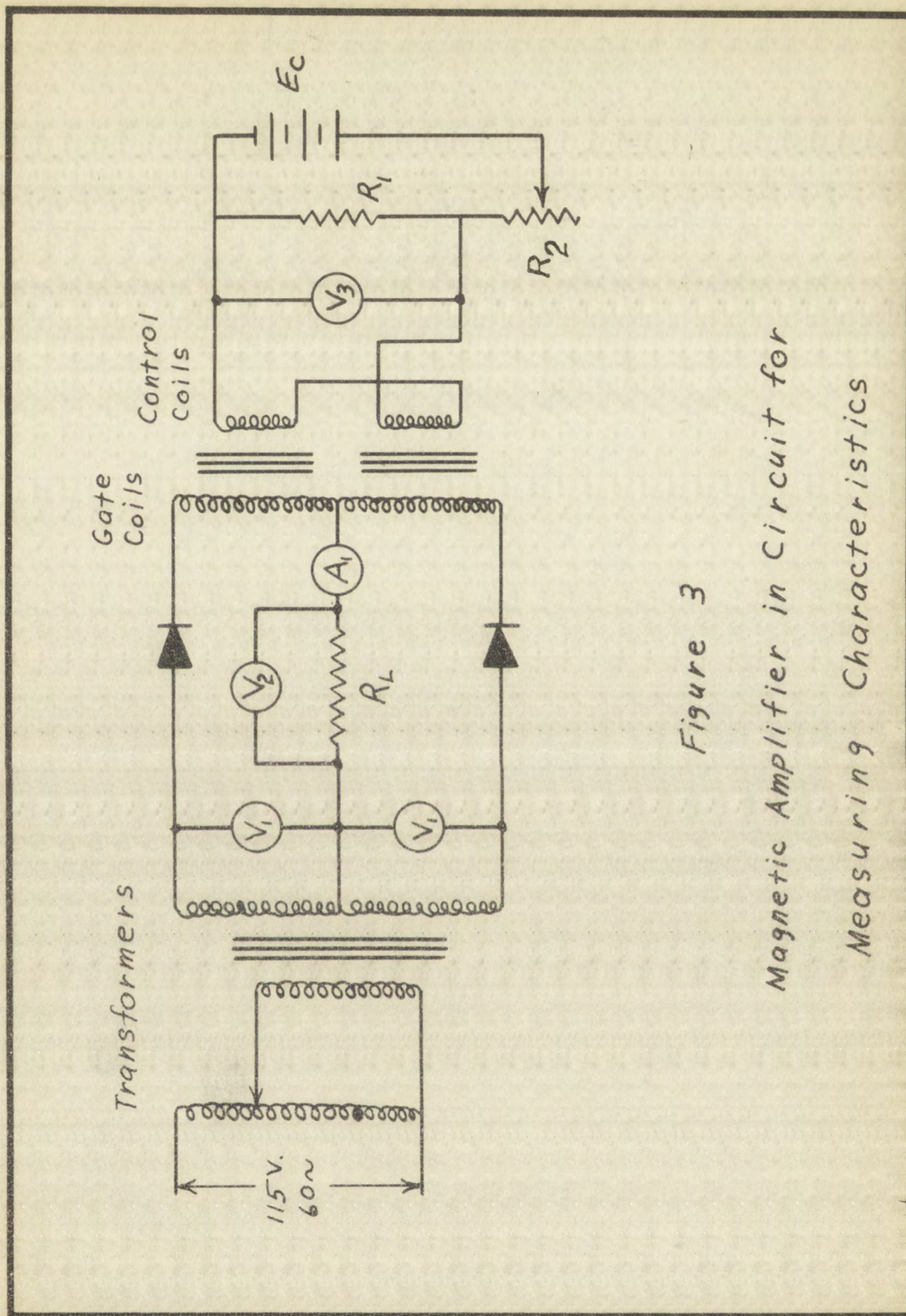
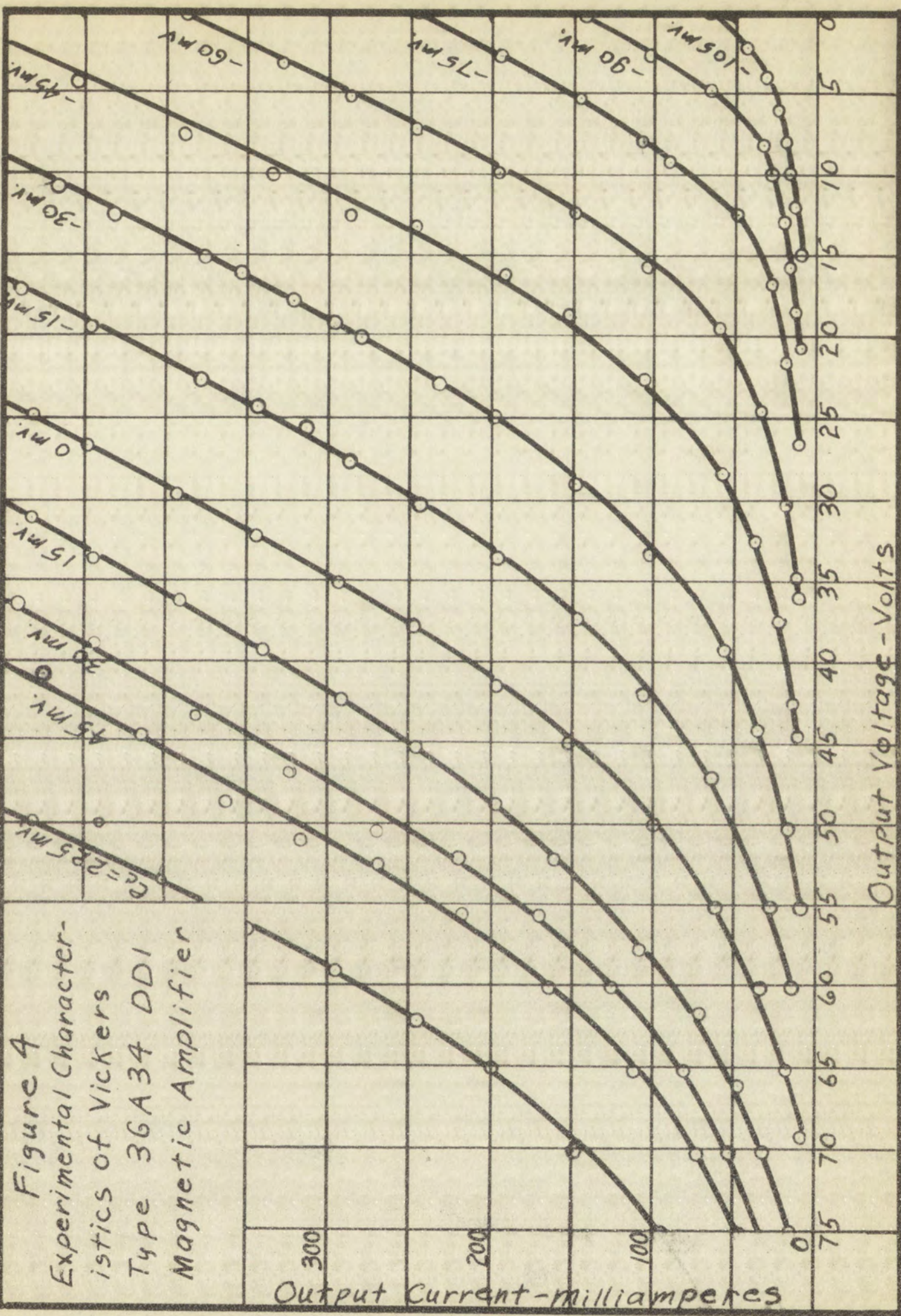
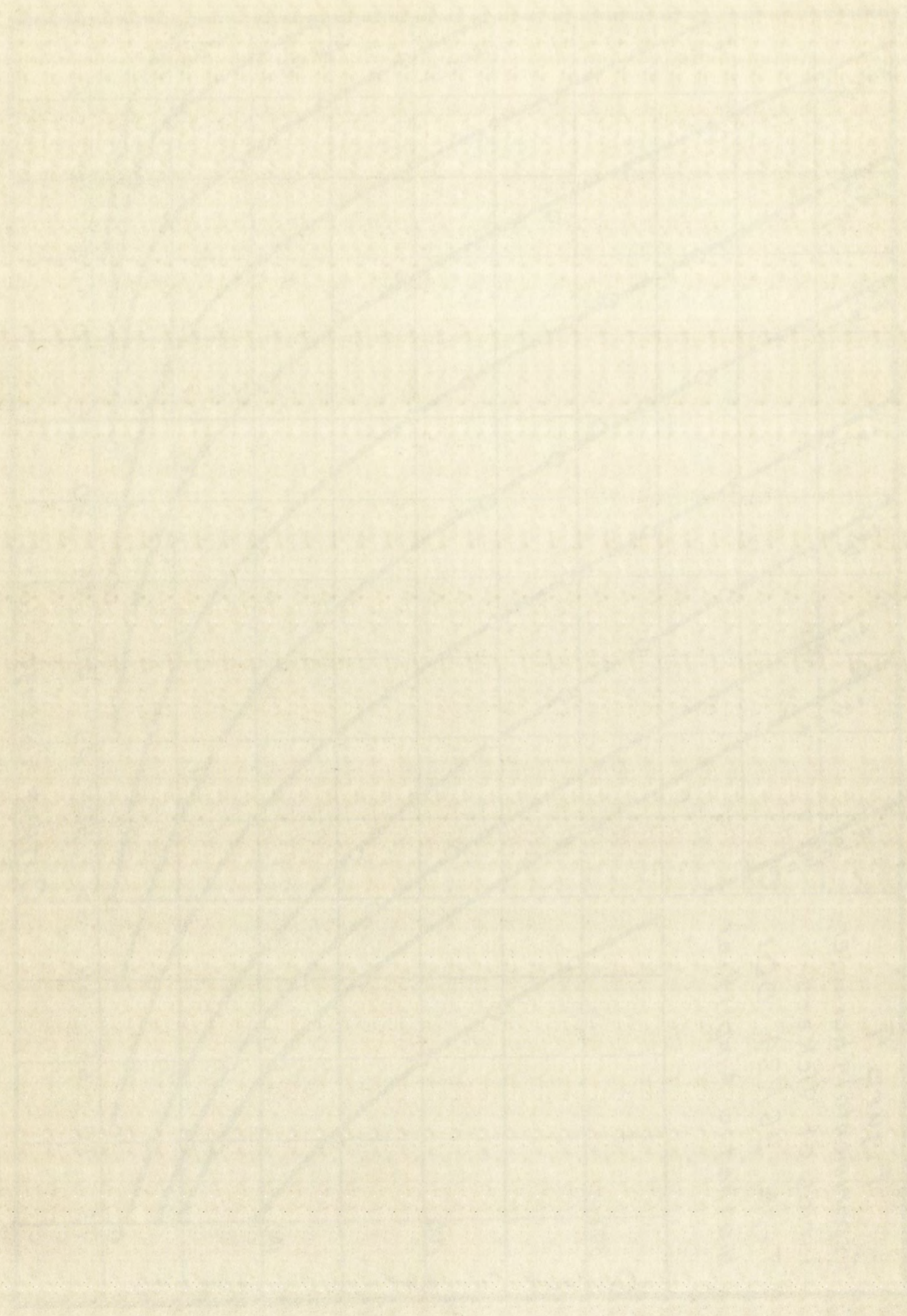


Figure 3
Magnetic Amplifier in Circuit for
Measuring Characteristics





II. EXPERIMENTAL DETAILS AND TECHNIQUE

To minimize the chance of drawing erroneous conclusions, all meters were calibrated. Standard calibration procedures were used.² Since a reliable standard cell was not available, the 1.0 volt position of the 1.5 volt direct-current scale of a Simpson Model 260 multimeter was arbitrarily selected as a standard after comparison with a one-quarter per cent dynamometer voltmeter. By the use of potentiometric methods all other voltmeters and ammeters were calibrated relative to this assumed standard. The dynamometer type voltmeter was used to transfer calibration to the alternating-current meters. All resistances used in the potentiometer had guaranteed accuracies within one per cent. Reading errors on all instruments were within one per cent. Actual errors in meter data should be within two per cent.

To aid in the theoretical analysis, additional data were obtained. The resistance of all windings and the inductance of each gate winding of the amplifier were measured with a General Radio Type 650A impedance bridge. For the values measured, the rated accuracy of this bridge is one per cent for resistance and ten per cent for inductance.

²Smith, Arthur Whitmore, Electrical Measurements in Theory and Application (New York: McGraw-Hill Book Company, Inc., 4th Ed., 1948).

To obtain the value of the constant k , all necessary measurements were made. Since a reliable value of k was not available, the value of k was determined by direct measurement of a known quantity. The experimentally determined value of k was compared with the value of k obtained from the theoretical calculation. The results of the experiment are shown in Table I. The value of k obtained from the experiment is in good agreement with the value of k obtained from the theoretical calculation. The value of k obtained from the experiment is 1.5×10^{-4} and the value of k obtained from the theoretical calculation is 1.5×10^{-4} .

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Oscillograms were made which showed the variation of output wave-shape, both for variation in load resistance and variation in control signal. An electronic switch was used with the oscilloscope to superimpose the sixty cycle power source wave-shape.

The voltage-current characteristics of one of the rectifiers were measured. These data are recorded in Table II of Appendix C and graphed in Figure 15 of Appendix B.

III. RESULTS, CONCLUSIONS AND COMPARISONS

With the external characteristics of the magnetic amplifier plotted as in Figure 4 it is very easy to determine the output to any desired resistive load. If some load voltage is assumed, the corresponding load current may be calculated by ohms law. The load line for this resistance is then drawn from the origin through the point determined by the corresponding values of load current and voltage. Several such load lines have been drawn on the characteristic curves in Figure 5.

The output voltage corresponding to a given control voltage can, of course, be read on the voltage scale directly below the intersection of the load line and the curve for the control voltage.

For loads in the vicinity of 100 to 200 ohms there

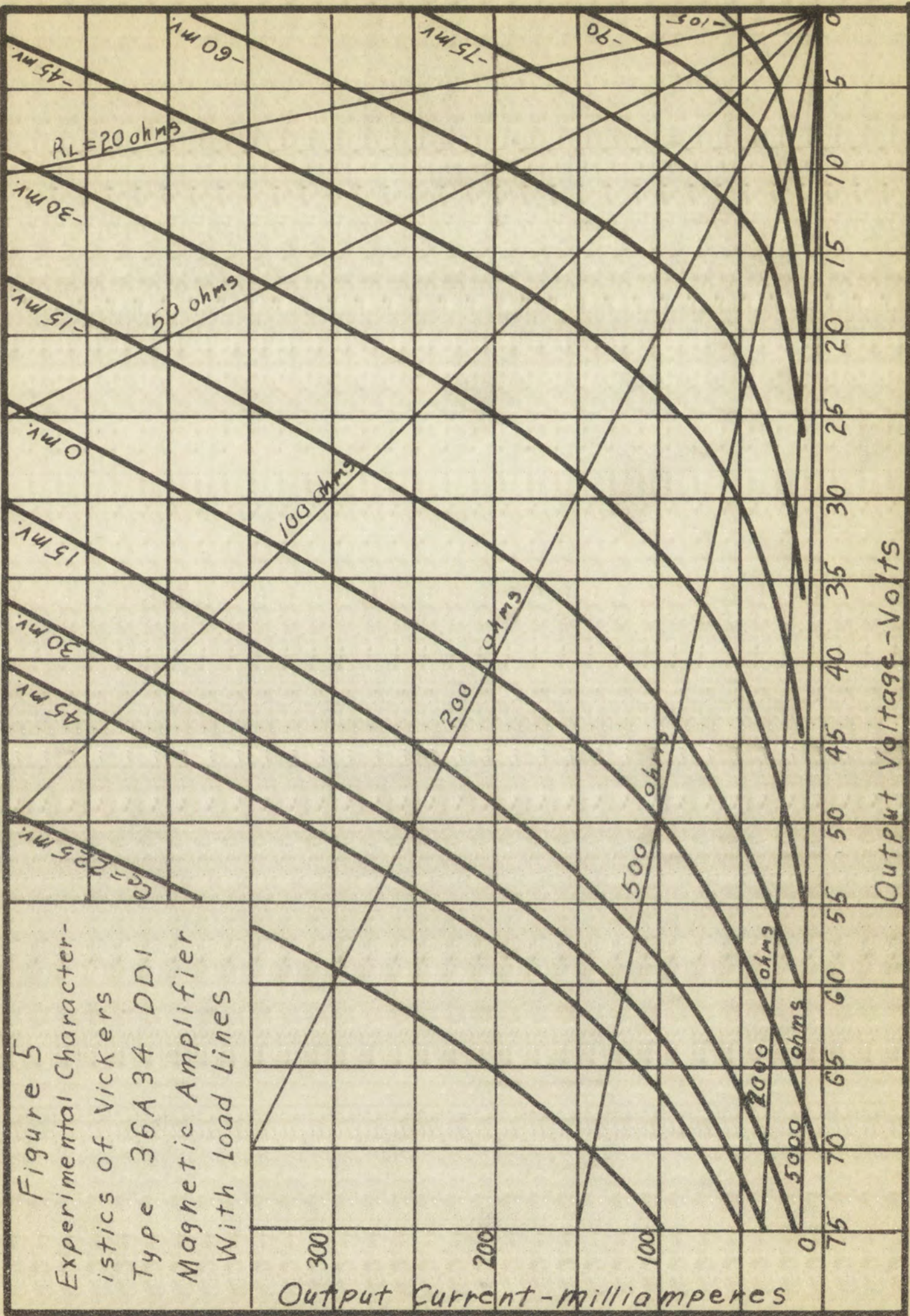
Oscilloscope wave-shape which shows the variation of output wave-shape, both for variation in load resistance and variation in control signal. An electronic switch was used with the oscilloscope to superimpose the sixty cycle power source wave-shape.

The voltage-current characteristics of one of the rectifiers were measured. These data are recorded in Table II of Appendix E and graphed in Figure 13 of Appendix B.

III. RESULTS, CONCLUSIONS AND RECOMMENDATIONS

With the external characteristics of the magnetic amplifier plotted as in Figure 4 it is very easy to determine the output for any desired load resistance. If some load voltage is assumed, the corresponding load current may be calculated by Ohm's law. The load line for this resistance is then drawn from the origin through the point determined by the corresponding values of load current and voltage. Several such load lines have been drawn on the characteristic curves in Figure 5.

The output voltage corresponding to a given control voltage can, of course, be read on the voltage scale directly from the intersection of the load line and the curve for the control voltage. For loads in the range of 100 to 500 ohms there



is a center region which gives quite linear amplification, while at either extreme of control current the amplification decreases. Loads of lower resistance than 100 ohms may cause excessively large load current to flow. Loads of 200 ohms or more produce load lines which lie in the curved region of the control curves. However, control is still reasonably linear over nearly as large a region as with a 100 ohm load until the load resistance becomes larger than 500 ohms.

There is a striking similarity between the characteristics of the magnetic amplifier in Figure 4 and the characteristics of a triode vacuum tube. The only major difference is that there is no voltage scale for the total applied voltage, only a scale for the voltage across the load.

It is at once obvious that the method of linear approximations³ can be applied to the amplifier characteristics in the linear region to obtain an equivalent circuit for low frequency operation, using a resistance, R_g , corresponding to the plate resistance of a vacuum tube, and an amplification factor, μ , exactly the same as the μ of a vacuum tube. Computations, shown in Appendix A,

³Martin, Thomas L. Jr., Electronic Circuits (New York: Prentice-Hall, Inc., to be published 1954).

is a center region which is linearly expanded
while at other points the expansion
tion decreases. Some of the expansion
may occur excessively large local expansion
of 200 or more percent. The linear
curved region of the center is, however, confined to
still reasonably linear expansion. The linear
with a 100 ohm load still the linear expansion is
larger than 200 ohms.

There is a still a difference between the region
variation of the magnetic field. The linear
characteristics of a linear expansion. The linear
difference is that there is no linear expansion of the linear
applied voltage, only a linear expansion of the
load.

It is an error to assume that the region of linear
expansion is linearly expanded. The linear
factor in the linear expansion is linearly expanded.
cut for the linear expansion, which is linearly expanded.
corresponding to the linear expansion of the linear
and an amplified linear expansion, which is linearly expanded
of a vacuum tube. The linear expansion is linearly expanded.

Linear expansion of a vacuum tube. The linear expansion is linearly expanded.
Linear expansion of a vacuum tube. The linear expansion is linearly expanded.

yield average values of $R_g = 58$ ohms and $\mu = 500$. The equivalent circuit⁴ of the amplifier is shown in Figure 6. From this the voltage amplification is given by

$$A = \frac{e_L}{e_c} = \mu \frac{R_L}{R_g + R_L} \quad (1)$$

⁴Ibid.

yield average values of $\mu = 53$ and $r = 500$. The equivalent circuit of the amplifier is shown in Figure 6. From this the voltage amplification is given by

$$(1) \quad A = \frac{e_c}{e_i} = \mu \frac{R_L}{R_L + R_i}$$

CHAPTER III

THEORETICAL INVESTIGATION OF THE MAGNETIC AMPLIFIER

In this chapter, an approximate analysis of the magnetic amplifier is presented in Section I. In Section II some of the errors of the approximate method are indicated and the necessary corrections computed. In Section III the final theoretical and the experimental results are compared.

I. THE APPROXIMATE ANALYSIS

As stated previously, the type of magnetic amplifier studied is essentially a controlled rectifier. Since such rectifiers have been thoroughly analyzed elsewhere⁵, the remaining problems are concerned with the properties of the controlling elements.

In a magnetic amplifier these control elements consist of coils, often called gate windings, placed in each rectifier leg. These coils have ferromagnetic cores which are characterized by hysteresis loops with small area and nearly rectangular shape, closely approximating the idealized hysteresis loop shown in Figure 7. Control windings

⁵Davis, W. L. and Weed, H. R., Industrial Electronic Engineering (New York: Prentice-Hall, Inc., 1953) Chapters 3 and 4.

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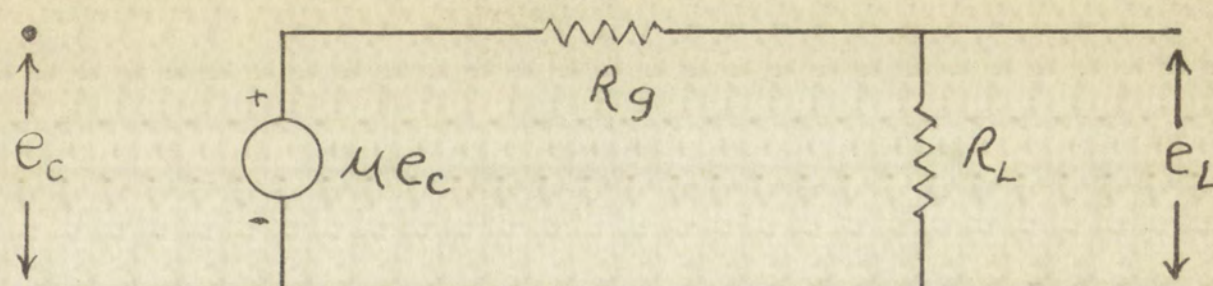


Figure 6

Equivalent Circuit of Vickers Type

36A34 DDI Magnetic Amplifier

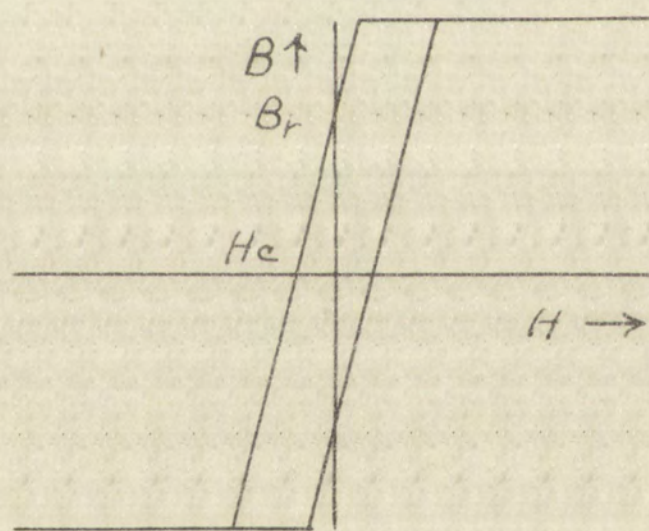


Figure 7

Idealized Hysteresis Loop

are placed on each core.

Under steady state conditions, at the beginning of alternate half cycles, the associated rectifier allows voltage to be applied across its gate winding in series with the load. At this time there will be some initial value of magnetic flux in the core, due to both the control signal and the reset⁶ signal received during the non-operating half cycle. If the sum of the load and gate resistances is much less than the reactance of the unsaturated core, then essentially all the applied voltage will appear across the gate winding inductance, necessitating a change in flux which at any time will be given by

$$\Delta \phi = \frac{1}{N_g} \int_0^t e dt = \frac{1}{N_g} \int_0^t E_m \sin \omega t dt \quad (2)$$

if the applied voltage is sinusoidal. When the core flux reaches the saturation value the inductance of the core becomes zero, assuming a flat top on the hysteresis loop, and all applied voltage appears across the gate and load resistances. With the assumptions made, the load current suddenly increases at saturation to many times the value before saturation. The load, or gate, current for such a half cycle of operation is shown in Figure 8. For a full-wave type rectifier this wave-shape is repeated each half

⁶Ramey, R. A., On The Control of Magnetic Amplifiers AIEE Trans., Vol. 70, Part II, pp. 2124-2128.

are placed on each end.

Under steady state conditions at the

alternating field applied, the magnetic field

refuses to be magnetized and the field is

with the field. At this time the field is

value of magnetization in the steady state

trial signal and the steady state magnetization

operating with the field. The value of the field

resistance is much less than the resistance of the

resonance cone, then approximately all the energy

appears across the gap. In this case, the

a change in the field at the time will be

$$\Delta \phi = \frac{1}{2} \mu_0 H \Delta B$$

if the applied field is small. In this case

resonance the resistance is much less than

becomes zero, and the field is the same

and all applied with the same field. In this

resonance, the resistance is much less than

and the field is the same. In this case

before resonance, the field is the same

half cycle of operation is shown in Figure 1.

wave type results in this case. In this case

the field is the same. In this case

the field is the same. In this case

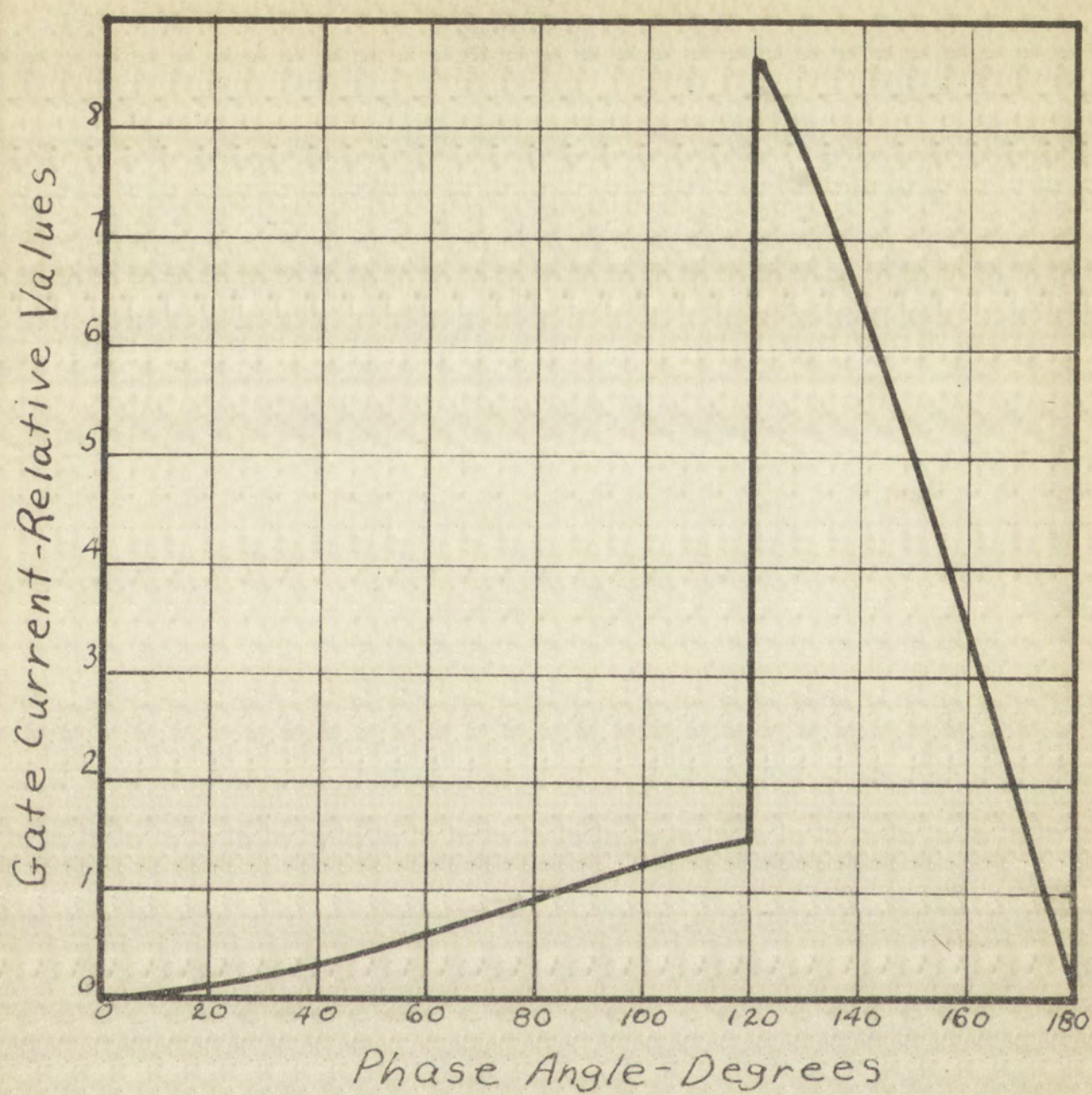


Figure 8

Gate Current of a Magnetic Amplifier

cycle, the two gate windings conducting alternately.

The approximate direct-current load voltage may be found by calculating the direct-current voltage available due to the conducting period of the amplifier and then multiplying by the ratio of the load resistance to the sum of the load and gate resistances. The gate resistance must include both the winding and rectifier resistances. The equation is

$$E_L = \frac{R_L}{R_L + R_g} \frac{E_m}{\pi} \int_{\phi_f}^{\pi} \sin \phi d\phi \quad (3)$$

or

$$E_L = \frac{R_L}{R_L + R_g} \frac{E_m}{\pi} (1 + \cos \phi_f) \quad (4)$$

where R_L is the load resistance, R_g is the gate resistance, E_m is the maximum applied voltage, and ϕ_f is the angle at which the gate winding saturates or "fires", using the terminology of gas tubes.

If the control signal is held constant, the curve for the corresponding load voltage as a function of load resistance is then easily calculated by substitution of various values of load resistance. These curves for constant control signal are straight lines.

If the control voltage, e_c , is changed, then, in general, the flux level of the core at the beginning of a cycle is changed due to the change in control current.

cycle, the two parts of the cycle are
 The magnitude of the induced EMF is
 found by calculating the time-derivative of the flux
 due to the magnetic field of the coil in the
 multiplying by the value of the total resistance in the
 sum of the induced EMF and the voltage drop across the
 must include both the induced EMF and the voltage drop across the
 The equation is

$$E = \frac{R}{R + R_L} \frac{d\Phi}{dt}$$

$$E_L = \frac{R_L}{R + R_L} \frac{d\Phi}{dt}$$

where R_L is the load resistance, R is the resistance of the coil
 E_L is the induced EMF in the load, and E is the induced EMF in the coil
 which the flux is the same as the flux in the coil
 resistance of the coil.

It is the induced EMF in the coil which is the source of the induced current
 for the counter EMF in the coil is the same as the induced EMF in the coil
 resistance in the coil is the same as the resistance in the coil
 voltage across the coil is the same as the voltage across the coil
 at any instant of time the induced EMF in the coil is the same as the induced EMF in the coil
 If the induced EMF in the coil is the same as the induced EMF in the coil
 general, the induced EMF in the coil is the same as the induced EMF in the coil
 a cycle is the same as the induced EMF in the coil

Saturation is then reached at a different time so that the firing angle is also changed. This in turn changes the output voltage.

As the first step in determining the control characteristics, the current in the gate winding during the non-firing part of the cycle was computed. Under these conditions the supply voltage is applied to a circuit consisting of the gate inductance, L , the gate resistance, R_g , and the load resistance, R_L , in series. The loop voltage equation is

$$E_m \sin \omega t = L \frac{di_{L1}}{dt} + (R_g + R_L) i_{L1} \quad (5)$$

where ω is the angular frequency of the supply voltage, and i_{L1} is the current in the gate winding and the load during the non-firing part of the conducting half cycle.

Using Laplace transform methods⁷, noting that at

$$t = 0 \quad i_{L1} = 0 \quad (6)$$

and substituting the equality

$$R = R_g + R_L \quad (7)$$

⁷ Gardner, M. F. and Barnes, J. L., Transients in Linear Systems (New York: John Wiley and Sons, Inc., 1951) Vol. 1.

Saturation is then reached at a different time to that
the firing angle is also changed. This in turn changes
the output voltage.
As the first step in determining the control char-
acteristics, the current in the gate winding during the
non-firing part of the cycle was computed. Under these
conditions the supply voltage is applied to a circuit con-
sisting of the gate inductance, L_g , the gate resistance,
 R_g , and the load resistance, R_L , in series. The loop
voltage equation is

(6)
$$E_m \sin \omega t = L_g \frac{di_g}{dt} + (R_g + R_L) i_g$$

where ω is the angular frequency of the supply voltage,
and i_g is the current in the gate winding and the load
during the non-firing part of the conducting half cycle.
Using Laplace transform methods, noting that at

(a)
$$t = 0, \quad i_g = 0$$

and substituting the equality

(7)
$$R = R_g + R_L$$

the transformed equation was found as

$$E_m \frac{\omega}{s^2 + \omega^2} = (sL + R) I_{L1}(s) \quad (8)$$

or

$$I_{L1}(s) = \frac{\omega E_m / L}{(s + R/L)(s^2 + \omega^2)} \quad (9)$$

$$= \frac{\omega E_m}{L} \left[\frac{A}{s + R/L} + \frac{B}{s + j\omega} + \frac{B^*}{s - j\omega} \right] \quad (10)$$

where

$$A = \frac{1}{s^2 + \omega^2} \Big|_{s = -R/L} = \frac{1}{(\frac{R}{L})^2 + \omega^2} \quad (11)$$

$$B = \frac{1}{(s + R/L)(s - j\omega)} \Big|_{s = -j\omega} = \frac{j \frac{R}{L} - \omega}{2\omega (\frac{R^2}{L^2} + \omega^2)} \quad (12)$$

the transformed and linear form is

$$E_m = \frac{w}{2\pi f} (2\pi f) = w$$

or

$$I_m = \frac{w}{(2\pi f) \cdot \frac{1}{2\pi f}} = w$$

$\frac{w}{2\pi f}$	$\frac{1}{2\pi f}$	$\frac{1}{2\pi f}$
$\frac{w}{2\pi f}$	$\frac{1}{2\pi f}$	$\frac{1}{2\pi f}$
$\frac{w}{2\pi f}$	$\frac{1}{2\pi f}$	$\frac{1}{2\pi f}$

where

$$A = \frac{1}{2\pi f} = \frac{1}{2\pi \cdot 1000} = 1.59 \times 10^{-4} \text{ sec}$$

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REWORK

$$B = \frac{1}{2\pi f} = \frac{1}{2\pi \cdot 1000} = 1.59 \times 10^{-4} \text{ sec}$$

Taking the inverse transform,

$$i_{L_1} = \frac{\omega E_m}{L} \left\{ \frac{1}{\left(\frac{R}{L}\right)^2 + \omega^2} e^{-\frac{R}{L}t} + 2 \operatorname{Re} \left[\frac{j \frac{R}{L} - \omega}{2 \omega \left(\frac{R^2}{L^2} + \omega^2\right)} e^{-j\omega t} \right] \right\} \quad (13)$$

$$i_{L_1} = \frac{E_m}{Z} \left[\sin(\omega t - \varphi) + \frac{\omega L}{Z} e^{-\frac{R}{L}t} \right] \quad (14)$$

where

$$Z = \sqrt{(\omega L)^2 + R^2} \quad (15)$$

$$\varphi = \tan^{-1} \frac{\omega L}{R} \quad (16)$$

If the equality $\theta = \omega t$ is used, the equation becomes

$$i_{L_1} = \frac{E_m}{Z} \left[\sin(\theta - \varphi) + \frac{\omega L}{Z} e^{-\frac{R}{\omega L}\theta} \right] \quad (17)$$

Since the assumption has been made, for this simplified analysis, that $\omega L \gg R$ it follows that $Z \cong \omega L$ and $\varphi = \tan^{-1} \frac{\omega L}{R} \cong \tan^{-1} \infty = \frac{\pi}{2}$. In addition the angle θ is never greater than π . With these substitutions the

Testing the inverse...

$$\frac{1}{L} = \frac{E_m}{L} \left(\frac{R}{L} + \omega \right)$$

$$\frac{1}{L} = \frac{E_m}{L} \left(\frac{R}{L} + \omega \right)$$

where

$$L = \sqrt{L^2 + R^2}$$

$$Y = \tan^{-1} \frac{R}{L}$$

If the equality holds, the system is linear.

$$\frac{1}{L} = \frac{E_m}{L} \left(\frac{R}{L} + \omega \right)$$

Since the assumption has been made, the...

plotted analysis. The result is...

and $\psi = \tan^{-1} \frac{R}{L}$ is the phase...

is never greater than $\frac{\pi}{2}$.

equation becomes

$$i_{L_1} = \frac{E_m}{\omega L} \left[\sin \left(\theta - \frac{\pi}{2} \right) + e^{-\frac{R}{\omega L} \theta} \right] \quad (18)$$

or

$$i_{L_1} = \frac{E_m}{\omega L} \left(\cos \theta + e^{-\frac{R}{\omega L} \theta} \right) \quad (19)$$

If it is assumed that $\omega L = 10R$ at least, and using the fact that $\theta = \frac{\pi}{2}$ at the most, then the maximum value of $R/\omega L$ is $\frac{\pi}{20}$ or 0.157. The maximum change in the exponential term is $1 - 0.855$ or 0.145. In the same time the cosine term changes from minus one to zero. Thus as a first approximation

$$i_{L_1} = \frac{E_m}{\omega L} (1 + \cos \theta) \quad (20)$$

Arbitrarily assuming that the core flux with zero control signal is zero after reset, the flux at saturation is

$$\phi_s = \frac{\mu N_c l_c A}{l} + \frac{\mu N_g l_g A}{l} \quad (21)$$

equation becomes

$$(11) \quad \frac{F_m}{\omega L} = \left[\sin \left(\theta - \frac{\pi}{2} \right) + e^{-\frac{R}{\omega L} \theta} \right]$$

or

$$(12) \quad \frac{F_m}{\omega L} = \frac{F_m}{\omega L} (\cos \theta + e^{-\frac{R}{\omega L} \theta})$$

It is assumed that $\omega L = 10R$ at least, and using the fact that $\theta = \frac{\pi}{2}$ at the most, then the maximum value of $\frac{F_m}{\omega L}$ is $\frac{1}{10}$ or 0.1. The maximum change in the exponential term is 1-0.833 or 0.167. In the same time the cosine term changes from minus one to zero. Thus as a first approximation

$$(20) \quad \frac{F_m}{\omega L} = \frac{F_m}{\omega L} (1 + \cos \theta)$$

Additionally assuming that the core flux with zero control signal is zero after reset, the flux at saturation

is

$$(21) \quad \Phi_s = \frac{4 \mu N^2 A}{l} + \frac{2 \mu N^2 A}{l}$$

where μ is the permeability, A is the area, and l is the length of the core. Or

$$\Phi_s = \frac{\mu A N_c i_c}{l} + \frac{\mu A}{l} N_g \frac{E_m}{\omega L} (1 + \cos \theta_f) \quad (22)$$

If the value of $(1 + \cos \theta_f)$ from this equation is substituted in equation (4) the result is

$$E_L = \frac{R_L}{R_L + R_g} \frac{\omega L l}{A \pi \mu N_g} \left(\Phi_s - \frac{\mu A}{l} N_c i_c \right) \quad (23)$$

Differentiating,

$$\frac{dE_L}{d l_c} = \frac{R_L}{R_L R_g} \frac{\omega L}{\pi} \frac{N_c}{N_g} \quad (24)$$

This may be put in a slightly different form by substituting

$$\omega = 2 \pi f, \quad L = N_g^2 \frac{\mu A}{l}. \quad (25)$$

where μ is the permeability of the core, and l is the length of the core.

$$\Phi_2 = \frac{M_2 I_2}{l} = \frac{N_2 I_2}{l}$$

If the ratio of the number of turns is N_1/N_2 , then the ratio of the fluxes is Φ_1/Φ_2 .

$$\frac{\Phi_1}{\Phi_2} = \frac{N_1 I_1}{N_2 I_2} = \frac{N_1}{N_2} \frac{I_1}{I_2}$$

Therefore,

$$\frac{d\Phi_1}{d\Phi_2} = \frac{N_1}{N_2} \frac{dI_1}{dI_2}$$

This may be written as $\frac{d\Phi_1}{d\Phi_2} = \frac{N_1}{N_2} \frac{dI_1}{dI_2}$.

or

$$\frac{d\Phi_1}{d\Phi_2} = \frac{N_1}{N_2} \frac{dI_1}{dI_2}$$

The result is

25

$$\frac{dE_L}{di_c} = \frac{R_L}{R_L + R_g} \frac{2f\mu A}{l} N_g N_c \quad (26)$$

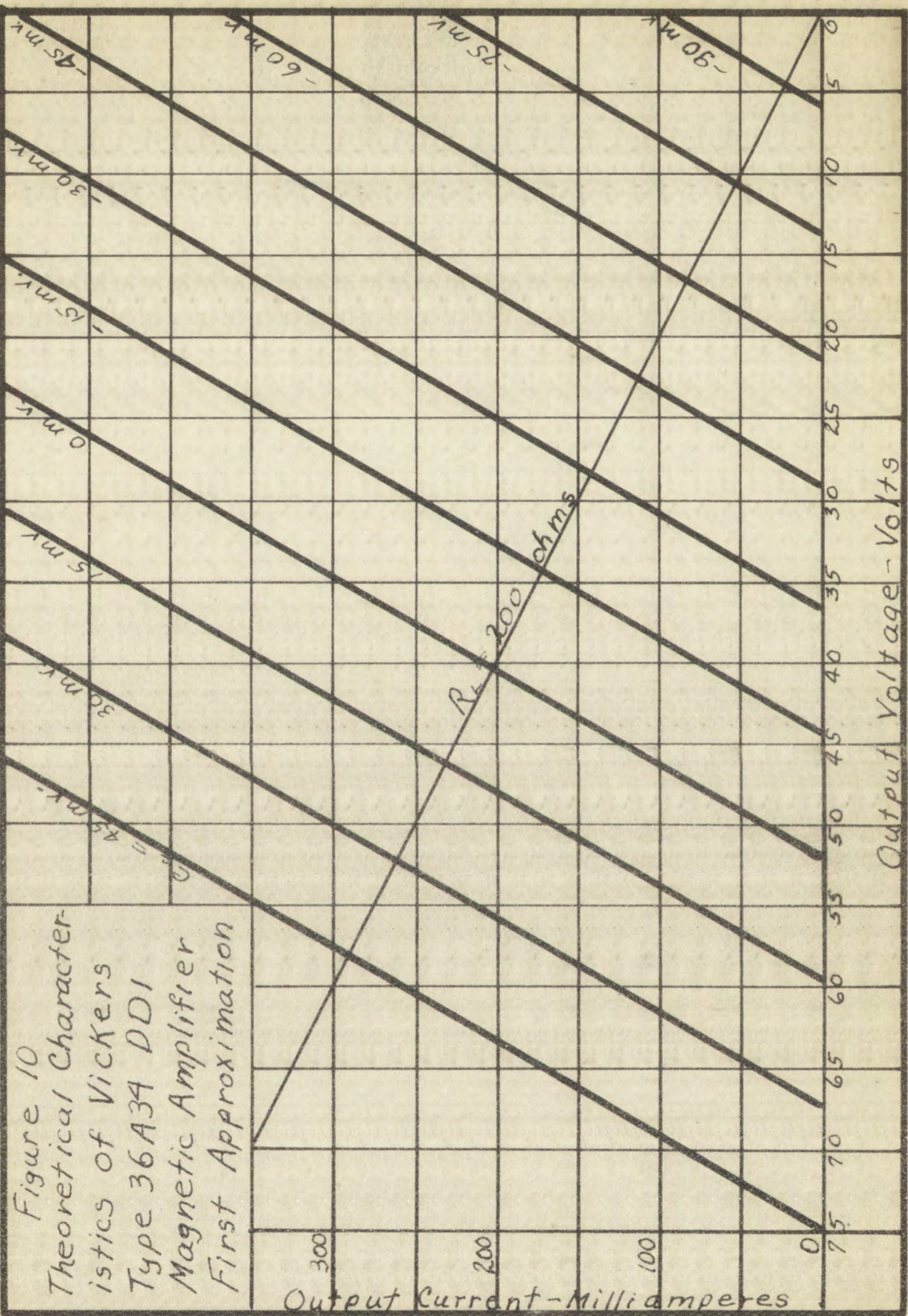
or

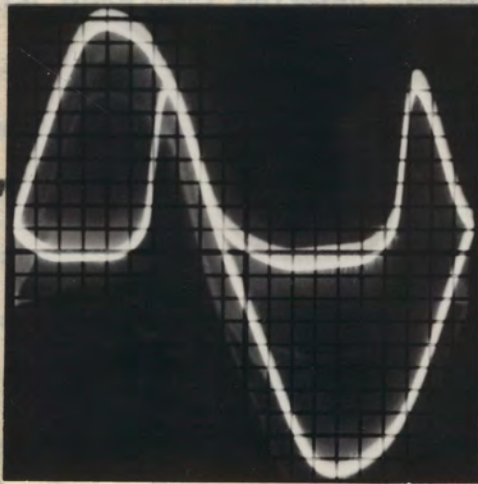
$$\frac{dE_L}{de_c} = \frac{R_L}{R_L + R_g} \frac{2f\mu A}{R_c l} N_g N_c \quad (27)$$

where R_c is the resistance of the control winding.

The point of interest to this discussion is that, if the permeability is constant, then the output voltage is a linear function of control current or voltage. The characteristic curves should then be a set of equally-spaced, parallel lines, ceasing abruptly at the extremes of control, where the core is always saturated or never saturated.

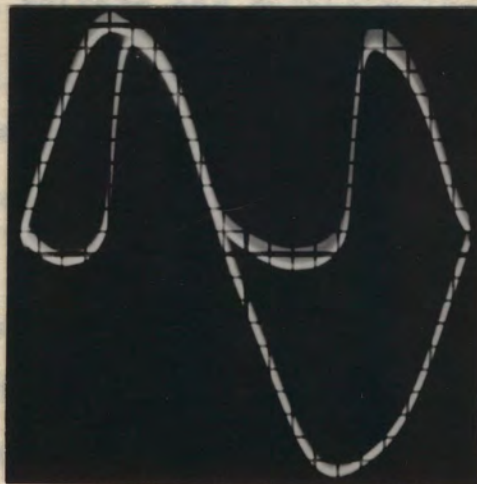
If the core dimensions and permeability, as well as winding data were available, then the static characteristics could be directly computed. Such data were not available for the magnetic amplifier studied. However, oscillograms were available, taken for $e_c = 0$ and $e_c = -52.5 \text{ mV}$, with a load resistance of 200 ohms. These are shown in Figures 9a and 9b, respectively. From these the corre-





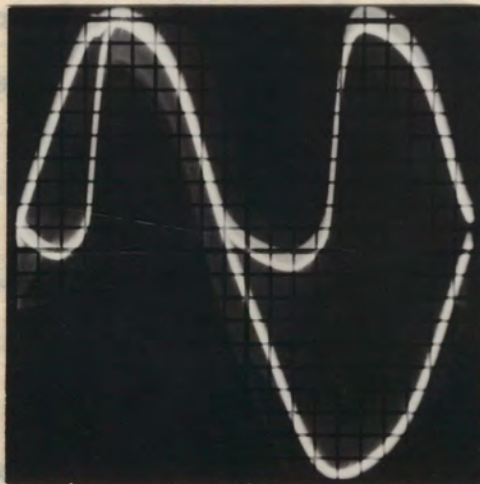
$$e_c = -52.5 \text{ mv.}$$

$$\theta_f = 121^\circ$$



$$e_c = 0.0 \text{ mv.}$$

$$\theta_f = 80^\circ$$



$$e_c = +52.5 \text{ mv.}$$

Figure 9

Oscillograms Showing the Variation of
Output With Control Signal. $R_L = 200 \text{ ohms}$

sponding firing angles were estimated and thus a connection obtained between control voltage and output voltage. Since previous results showed that for this approximation the control was linear, the family of characteristic curves can be linearly interpolated and extrapolated, and drawn with a slope of $1/r_g$. The results of this approximate method are shown in Figure 10.

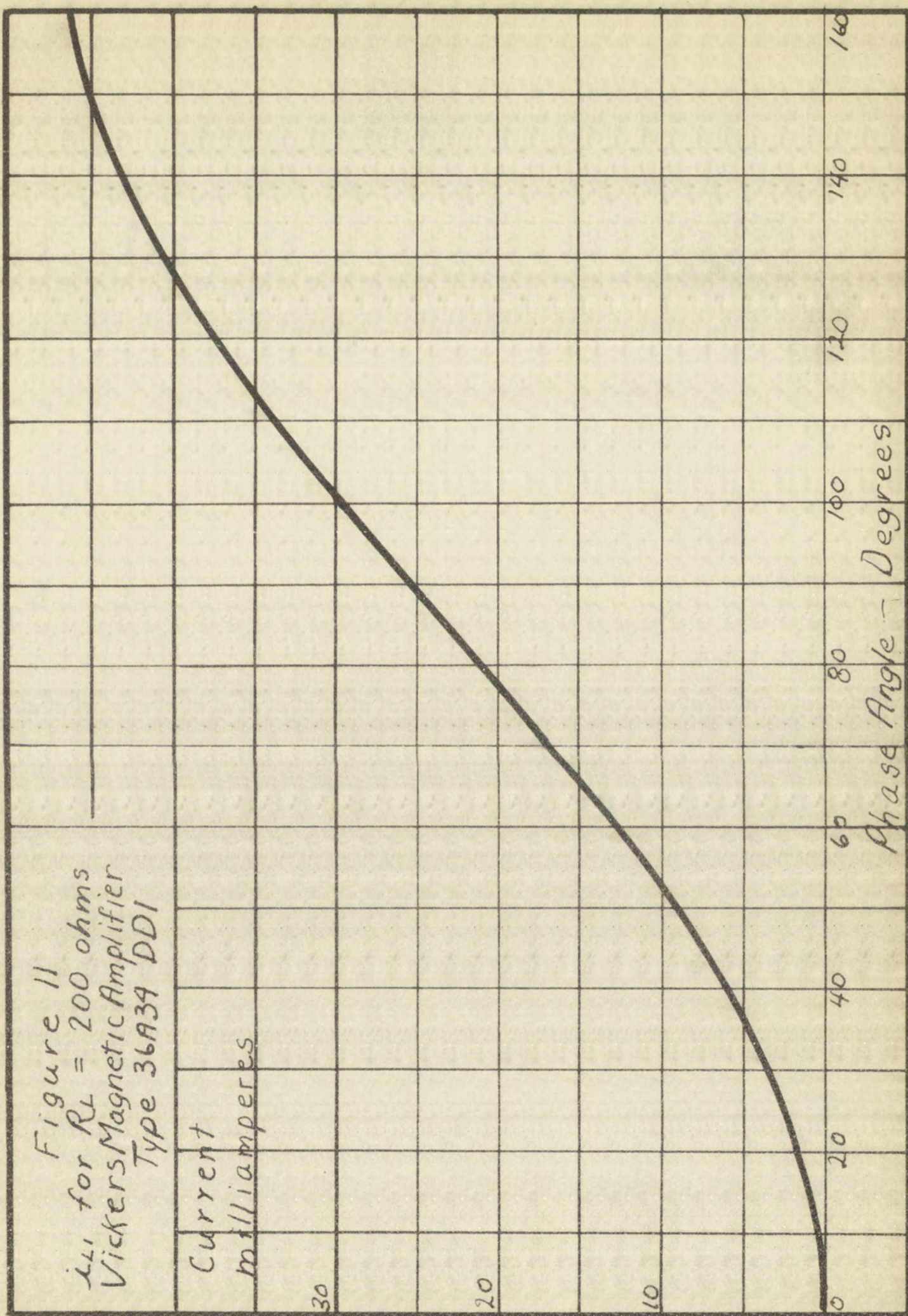
Since a hysteresis curve of the cores was not available it was impossible to predict where control ceased.

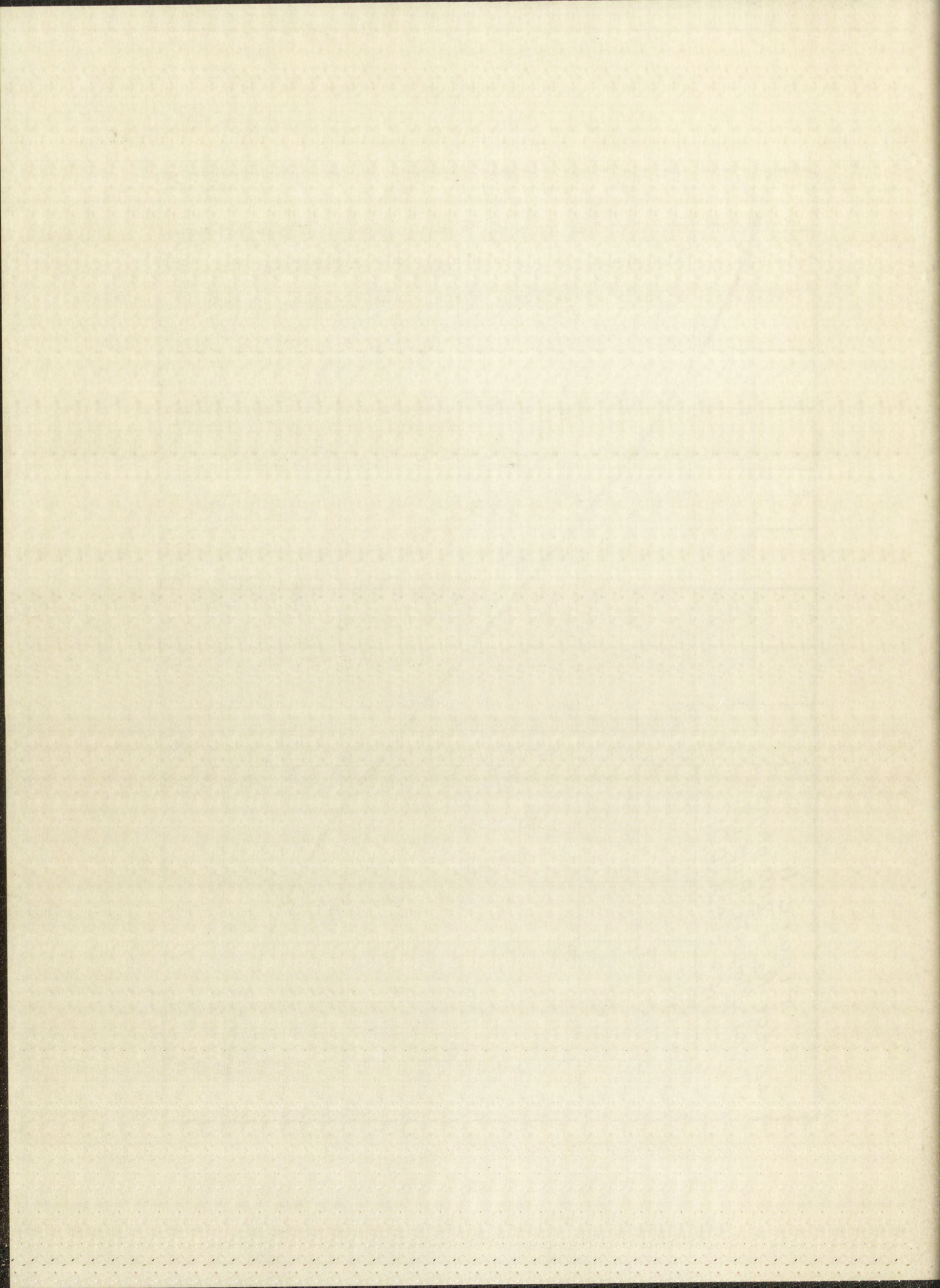
The method of determining the equivalent rectifier resistance, both for the firing and non-firing conditions is given in Appendix II.

II. THE REFINED, OR EXTENDED METHOD

As the first step in refining the previous approximate analysis, allowance was made for the fact that the current flowing during the non-firing part of each cycle is not exactly a cosine function in any case, but is the sum of a cosine and exponential term. For the case of a load resistance of 200 ohms, this current was computed using equation (17). The computed data are recorded in Table III and graphed in Figure 11.

Using the values of firing angle determined from oscillograms, the value of the gate current at firing was





determined for the values $e_c = 0$ and $e_c = -52.5 \text{ mv.}$ Using linear interpolation, the firing-time gate current was determined for other values of control voltage. The corresponding values of firing angle were then read from the graph of Figure 11. These values, substituted in equation (4), gave the output for a load of 200 ohms. The new set of characteristic curves was then drawn through this set of points at a slope of $1/R_g$. These curves are shown as the dashed lines in Figure 12.

The next step taken in improving the analysis was to allow for the fact that the current flowing during the non-firing part of the cycle is not zero.

The contribution of the non-firing period to the output voltage is

$$V_i = \frac{1}{\pi} \int_0^{\theta_f} R_L i_{L1} d\theta \quad (28)$$

Substituting the value of i_{L1} from equation (17),

$$V_i = \frac{E_m R_L}{\pi Z} \int_0^{\theta_f} \left[\sin(\theta - \varphi) + \frac{\omega L}{Z} e^{-\frac{R}{\omega L} \theta} \right] d\theta \quad (29)$$

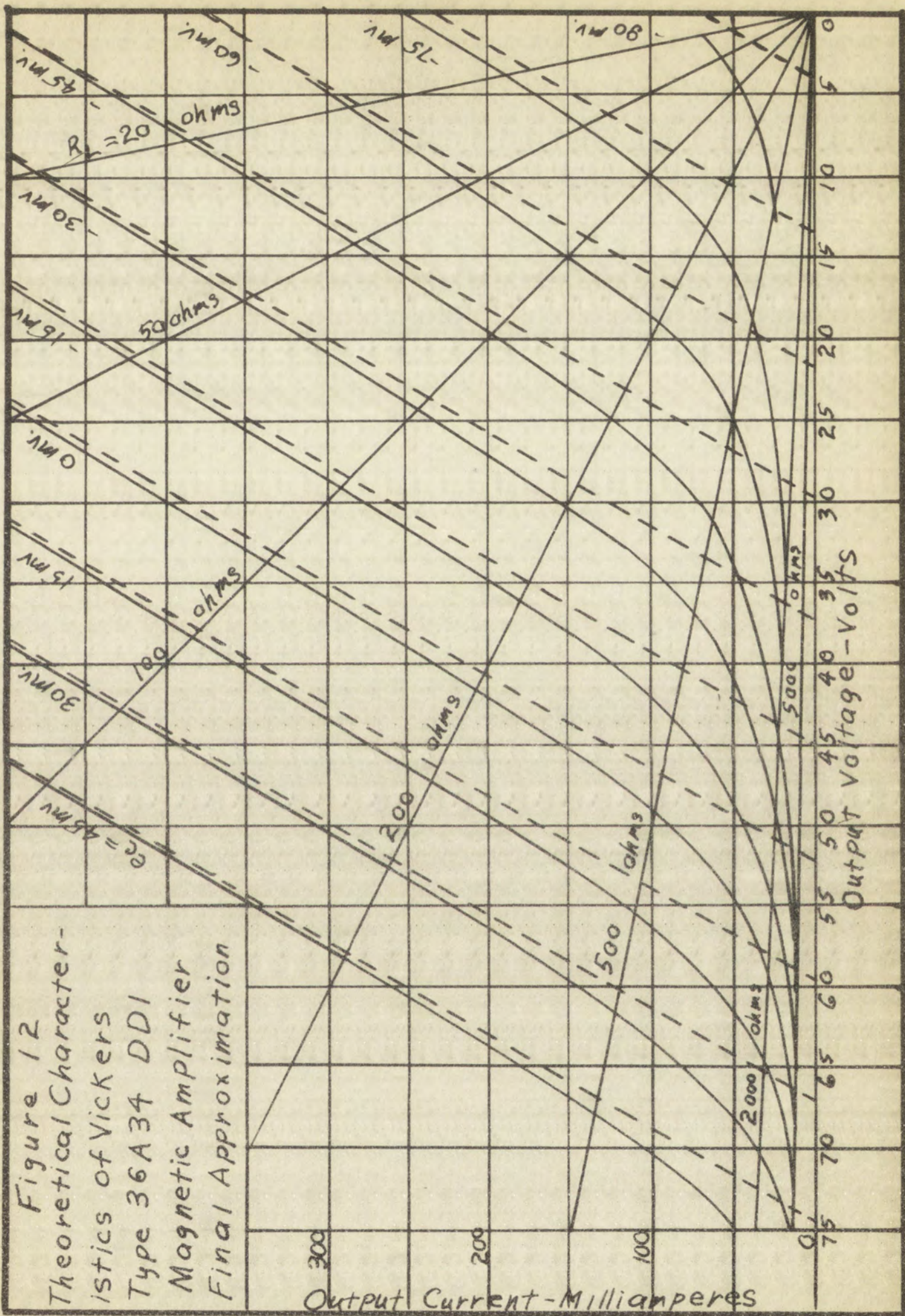
determined for the system. The linear relationship between the
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 graph of Figure 1. The linear relationship between the
 (4). The linear relationship between the
 of characteristic curves. The linear relationship between the
 of points of a line. The linear relationship between the
 the dashed lines in Figure 1.
 The next step is to determine the linear relationship between the
 no allow for the fact that the output voltage is not linear
 non-linear part of the curve is not zero.
 The non-linear part of the curve is not zero.
 output voltage is

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Substituting the value of

$$V = \frac{E_m E_c}{N \cdot L}$$



After integrating,

$$V_1 = \frac{E_m R_L}{\pi Z} \left[\cos \psi - \cos (\Theta f - \psi) + \frac{\omega^2 L^2}{R Z} (1 - e^{-\frac{R}{\omega L} \Theta f}) \right] \quad (30)$$

where the angles are in radians.

Using the firing times already computed and several values of load resistance, these data were computed. They have been recorded in Table IV. In Figure 12 these corrections have been added to the results of revision one. The final theoretical characteristic curves are the solid lines.

III. COMPARISON OF THEORETICAL AND EXPERIMENTAL RESULTS

In Figure 13 the final theoretical curves for the magnetic amplifier have been retraced for comparison with the experimental curves. The shape of the final curves is, in general, a much better approximation to the shape of the experimental curves than the first approximation shown in Figure 10.

However, the theoretical calculations are useless for predicting the amplifier characteristics at both extremes of control signal. From the experimental results it is apparent that a control signal of +30 mv. already

reaches into the knee of the hysteresis curve and that beyond this point the curve rapidly flattens out so that there is little control. Below -75 mv. control is also poor since the negative control signal is so strong that the peak current flowing after firing drives the flux only into the knee of the hysteresis curve. These two points take account of the fact that although ordinarily a rectangular hysteresis loop is assumed, in practice the loop will always have a rounded transition region. To complete the analysis in these extreme regions it would be necessary to have a hysteresis loop of the core material. Such a curve could not be obtained from the manufacturer, nor was time available to prepare good instrumentation to obtain the hysteresis curve⁸.

The theoretical curves would match the experimental ones better if they were shifted slightly to the right. An error of this magnitude might easily have been introduced in determining the firing angle from the oscillograms.

⁸Lord, H. W., Dynamic Hysteresis Loop Measuring Equipment AIEE Trans., Vol. 71, Part I, pp. 269-272.

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CHAPTER IV

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

I. SUMMARY AND CONCLUSIONS

For experimental determination of the characteristics of a magnetic amplifier, the characteristic curve method was used. The flexibility of the method and ease of obtaining an equivalent circuit were indicated.

For theoretical calculation of the characteristics of a magnetic amplifier, the normal simplifying assumptions were made and applied to the calculation of the characteristic curves, or external characteristics. The limitations of this method were indicated.

Corrections were then made to allow for non-linearity of control due to the voltage drop across the load resistance and for the increased output due to the current flow during the non-firing part of the cycle.

Comparison of theoretical and experimental results showed that the refined method gave an overall better approximation to the shape of the amplifier characteristic curves, especially for large values of load resistance.

Part II

THEORY OF THE ELECTRIC CIRCUIT

1. BASIC DEFINITIONS

For experimental determination of the resistance of a conductor, the following method is used. The circuit is connected to a battery and a voltmeter is connected in parallel with the conductor. The current is measured by an ammeter connected in series with the conductor. The resistance is then calculated from the ratio of the voltage to the current.

The resistance of a conductor is defined as the ratio of the voltage across the conductor to the current through it. It is denoted by the symbol R .

The resistance of a conductor depends on its material, length, and cross-sectional area. It is directly proportional to the length and inversely proportional to the cross-sectional area.

The resistance of a conductor is also affected by temperature. For most materials, the resistance increases with increasing temperature.

The resistance of a conductor can be measured by the following methods:

- 1. Direct measurement using a Wheatstone bridge.
- 2. Indirect measurement using a voltmeter and an ammeter.

The resistance of a conductor is a scalar quantity and is measured in ohms (Ω).

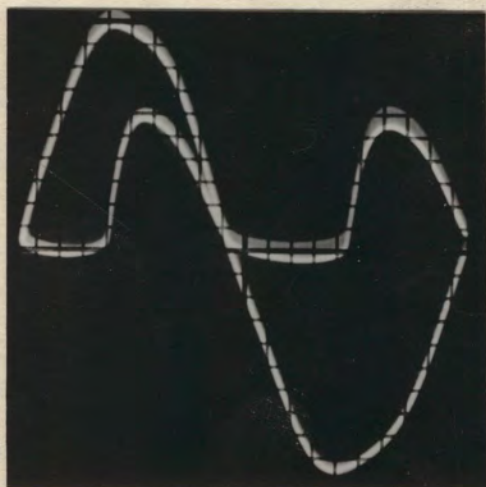
II. RECOMMENDATIONS

Quite obviously the investigation is far from complete. Some points to investigate are listed below.

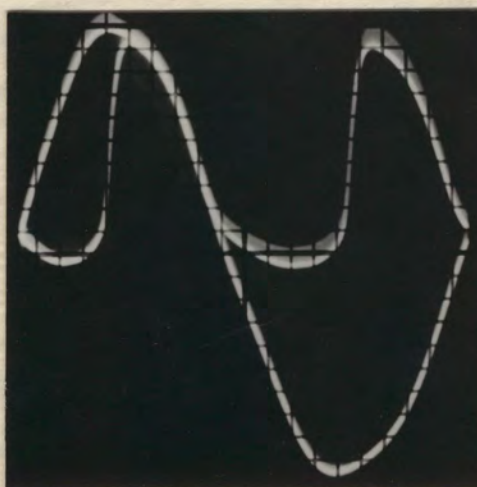
1. Deviation from Linearity at the Extremes of Control. If considerable care and work were exercised to obtain a good dynamic hysteresis loop of the core material, then the separation of the control curves could be determined graphically.

2. Variation of Firing Angle as a Function of Load Resistance. With the approximations used in this analysis, it appears that the firing angle should increase as the load is increased. However, the oscillograms of Figure 14 did not bear this out, showing that the firing angle was constant for moderate load values and then actually decreased with increasing load in some cases. Here, again, the hysteresis loop could be used to give a better approximation, since the actual current at all times could be calculated, rather than assuming that firing takes place instantaneously. A graphical method might be the easiest for the transition region, for the inductance changes constantly over this region.

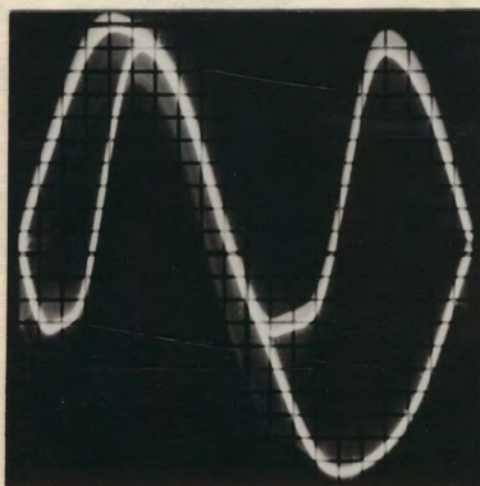
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$R_L = 50 \text{ ohms}$



$R_L = 200 \text{ ohms}$



$R_L = 2000 \text{ ohms}$

Figure 14

Oscillograms Showing the Variation of
Output With Load Resistance. $e_d = 0 \text{ mv.}$

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COMPUTATION OF EQUIVALENT CIRCUIT PARAMETERS

The value of R_g , the gate or equivalent resistances of the magnetic amplifier was determined from the definition

$$R_g = \frac{\Delta E_L}{\Delta I_L} \quad \left| \begin{array}{l} e_c \text{ constant} \end{array} \right.$$

Several computations were made over the region from maximum current to a load resistance of 300 ohms. The values were then averaged. The average value obtained for R_g was 58 ohms.

The value of the amplification factor, μ , was determined from the data

APPENDIX A

$$\mu = \frac{\Delta E_L}{\Delta e_c} \quad \left| \begin{array}{l} I_L \text{ constant} \end{array} \right.$$

Several computations over the control region were made and averaged. The average value obtained for μ was 500.

The data for these computations have been recorded in Table VI of Appendix C.

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COMPUTATION OF EQUIVALENT CIRCUIT PARAMETERS

The value of R_g , the gate or equivalent resistance of the magnetic amplifier was determined from the definition

$$R_g = \left. \frac{\Delta E_L}{\Delta I_L} \right|_{e_c \text{ constant}}$$

Several computations were made over the region from maximum current to a load resistance of 300 ohms. The values were then averaged. The average value obtained for R_g was 58 ohms.

The value of the amplification factor, μ , was determined from the definition

$$\mu = \left. \frac{\Delta E_L}{\Delta e_c} \right|_{I_L \text{ constant}}$$

Several computations over the control region were made and averaged. The average value obtained for μ was 500.

The data for these computations have been recorded in Table VI of Appendix C.

APPENDIX B

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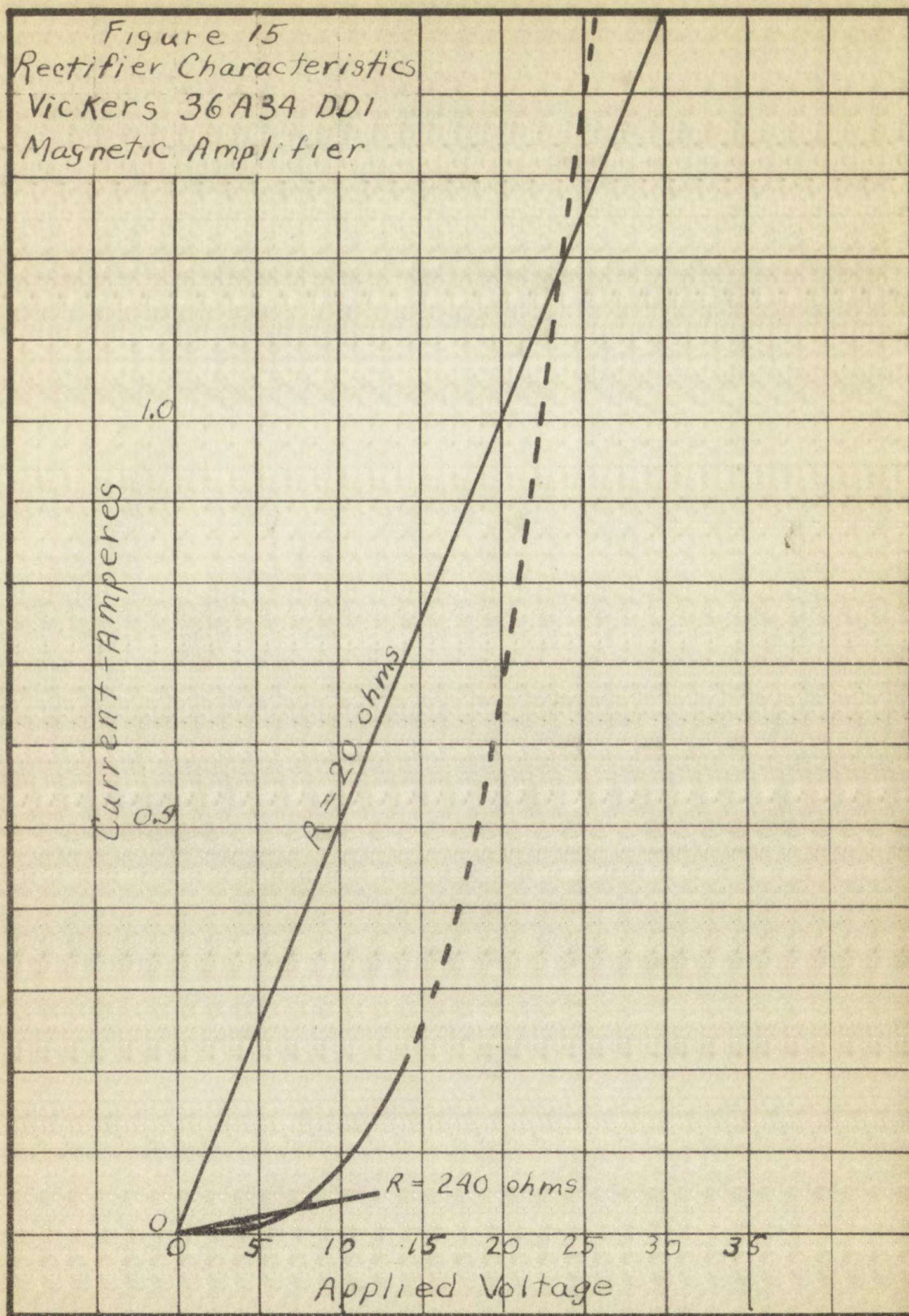
DETERMINATION OF EQUIVALENT RESISTANCES OF A RECTIFIER

Since the characteristics of the rectifiers, as shown by Figure 15, are very non-linear, it was necessary to determine linear approximations to these characteristics.

The equivalent resistance of 240 ohms was judged to be a good approximation to the resistance during the non-firing part of a cycle and was used in computations of i_{L1} .

The equivalent resistance of 20 ohms was estimated to be the best fit for currents flowing during the firing part of each cycle and was used to compute the gate resistance, the gate resistance being the sum of winding and rectifier resistances, or 58 ohms.

Figure 15
Rectifier Characteristics
Vickers 36A34 DD1
Magnetic Amplifier



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APPENDIX C

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TABLE I
EXPERIMENTAL DATA FOR THE MAGNETIC AMPLIFIER

Control voltage = +225 mv.		Control voltage = +45 mv.	
E_L	I_L	E_L	I_L
93.0 v.	10.0 ma.	84.5 v.	9.30 ma.
90.0	19.0	80.0	24.5
85.0	37.0	75.0	46.0
80.0	65.5	70.0	72.0
75.0	94.5	65.0	112.
70.0	148.	60.0	163.
65.0	199.	55.5	216.
62.0	245.	52.5	268.
59.0	295.	51.0	316.
56.5	350.	48.6	362.
53.5	402.	44.5	414.
50.0	440.	40.8	474.
49.9	482.		

TABLE I (continued)

EXPERIMENTAL DATA FOR THE MAGNETIC AMPLIFIER

Control voltage = +30 mv.		Control voltage = +15 mv.	
E_L	I_L	E_L	I_L
82.5 v.	8.90 ma.	78.5 v.	8.50 ma.
76.0	28.5	75.0	14.5
70.0	52.5	70.0	31.0
65.0	80.5	66.0	47.0
60.0	125.	61.5	71.0
55.5	169.	57.5	107.
52.0	218.	52.0	160.
50.3	269.	48.6	196.
46.7	323.	45.1	244.
43.3	381.	42.1	291.
38.8	443.	39.1	339.
36.3	489.	36.1	392.
		33.6	444.
		31.2	482.

TABLE I (continued)

EXPERIMENTAL DATA FOR THE MAGNETIC AMPLIFIER

Control voltage = +20 mv.		Control voltage = +15 mv.	
R_f	I_f	R_f	I_f
88.5 v.	8.50 ma.	75.5 v.	8.50 ma.
75.0	38.5	75.0	14.5
70.0	42.5	70.0	21.0
65.0	80.5	65.0	42.0
60.0	122.	61.5	71.0
55.5	166.	54.5	107.
52.0	218.	52.0	180.
50.5	288.	48.5	198.
46.5	325.	45.1	244.
45.5	337.	42.1	291.
38.5	429.	30.1	229.
34.5	480.	28.1	295.
		23.5	444.
		21.2	492.

TABLE I (continued)
EXPERIMENTAL DATA FOR THE MAGNETIC AMPLIFIER

Control voltage = 0 mv.		Control voltage = -15.0 mv.	
E_L	I_L	E_L	I_L
69.0 v.	8.40 ma.	60.0 v.	14.0 ma.
65.0	18.0	55.0	28.0
60.0	34.0	46.9	64.5
55.0	61.5	41.8	106.
50.0	100.	37.2	146.
44.8	151.	33.4	196.
41.2	196.	30.2	243.
37.6	247.	27.5	287.
35.0	293.	26.3	305.
32.2	344.	24.1	344.
29.6	393.	22.6	379.
26.7	449.	19.4	446.
24.8	482.	17.2	489.

TABLE I (continued)

EXPERIMENTAL DATA FOR THE MAGNETIC AMPLIFIER

Control voltage = 0 mv.		Control voltage = +15.0 mv.	
E_L	I_L	E_L	I_L
68.0 v.	8.40 ma.	60.0 v.	14.0 ma.
65.0	16.0	55.0	38.0
60.0	34.0	46.5	64.5
55.0	61.5	106.	106.
50.0	100.	146.	146.
44.8	151.	196.	196.
41.5	198.	243.	243.
37.6	247.	297.	297.
35.0	293.	306.	306.
32.5	344.	343.	343.
28.8	393.	378.	378.
26.4	440.	440.	440.
24.0	488.	488.	488.

TABLE I (continued)
EXPERIMENTAL DATA FOR THE MAGNETIC AMPLIFIER

Control voltage = -30.0 mv.		Control voltage = -45.0 mv.	
E_L	I_L	E_L	I_L
55.0 v.	9.0 ma.	44.4 v.	10.0 ma.
50.0	17.0	42.2	13.0
44.0	35.0	37.2	23.5
39.1	55.5	32.4	36.5
33.2	102.	28.1	57.5
28.8	148.	22.4	105.
24.8	197.	18.5	152.
22.8	232.	16.1	192.
20.0	279.	13.2	247.
19.1	296.	12.4	287.
17.7	322.	10.0	335.
16.0	354.	7.5	389.
15.0	376.	4.3	455.
12.5	432.		
10.8	467.		

TABLE I (continued)

EXPERIMENTAL DATA FOR THE MAGNETIC AMPLIFIER

Control voltage = -30.0 mv.		Control voltage = -45.0 mv.	
$\frac{E}{I}$	$\frac{I}{I}$	$\frac{E}{I}$	$\frac{I}{I}$
55.0 v.	9.9 ma.	44.4 v.	10.0 ma.
50.0	17.0	43.8	13.0
44.0	35.0	43.8	23.5
38.1	55.5	43.4	34.5
33.8	103.	42.1	47.8
33.8	165.	42.4	103.
34.8	197.	42.5	168.
33.8	338.	42.1	168.
30.0	378.	42.2	237.
19.1	396.	42.4	287.
17.7	398.	40.0	295.
16.0	354.	4.5	389.
15.0	376.	4.0	455.
12.5	452.		
10.3	497.		

TABLE I (continued)
EXPERIMENTAL DATA FOR THE MAGNETIC AMPLIFIER

Control voltage = -60.0 mv.		Control voltage = -75.0 mv.	
E_L	I_L	E_L	I_L
35.8 v.	10.0 ma.	26.4 v.	10.0 ma.
34.4	11.5	21.3	19.0
29.6	19.0	16.5	27.5
24.3	33.5	12.3	49.0
19.1	59.0	7.80	108.
15.3	103.	5.20	146.
12.1	148.	2.55	194.
9.80	196.	0.00	246.
7.20	246.		
5.20	286.		
3.10	329.		
0.00	390.		

EXPERIMENTAL DATA FOR THE STUDY OF THE EFFECT OF VOLTAGE ON THE RATE OF REACTION

Control voltage = 50.0 v. Control voltage = 50.0 v.

Time (min)	Conc. (M)	Rate (M/min)	Time (min)	Conc. (M)	Rate (M/min)
0.00	0.00	0.00	0.00	0.00	0.00
1.00	0.01	0.01	1.00	0.01	0.01
2.00	0.02	0.02	2.00	0.02	0.02
3.00	0.03	0.03	3.00	0.03	0.03
4.00	0.04	0.04	4.00	0.04	0.04
5.00	0.05	0.05	5.00	0.05	0.05
6.00	0.06	0.06	6.00	0.06	0.06
7.00	0.07	0.07	7.00	0.07	0.07
8.00	0.08	0.08	8.00	0.08	0.08
9.00	0.09	0.09	9.00	0.09	0.09
10.00	0.10	0.10	10.00	0.10	0.10
11.00	0.11	0.11	11.00	0.11	0.11
12.00	0.12	0.12	12.00	0.12	0.12
13.00	0.13	0.13	13.00	0.13	0.13
14.00	0.14	0.14	14.00	0.14	0.14
15.00	0.15	0.15	15.00	0.15	0.15
16.00	0.16	0.16	16.00	0.16	0.16
17.00	0.17	0.17	17.00	0.17	0.17
18.00	0.18	0.18	18.00	0.18	0.18
19.00	0.19	0.19	19.00	0.19	0.19
20.00	0.20	0.20	20.00	0.20	0.20

TABLE I (continued)
EXPERIMENTAL DATA FOR THE MAGNETIC AMPLIFIER

Control voltage = -90.0 mv.		Control voltage = -105.0 mv.	
E_L	I_L	E_L	I_L
20.5 v.	10.0 ma.	14.8 v.	10.0 ma.
18.2	13.0	11.7	13.5
16.1	15.5	9.80	16.0
12.7	20.0	7.70	19.0
9.80	27.0	5.80	24.0
8.05	33.5	3.75	31.5
4.55	65.5	2.05	44.0
2.50	103.	0.00	66.5
0.00	144.		

TABLE 1 (continued)

EXPERIMENTAL DATA FOR THEORETICAL CALCULATIONS

Control voltage = -30.0 v.			
R_L	I_L	R_L	I_L
20.5 v.	10.0 ma.	11.5 v.	2.5 ma.
16.2	13.0	11.1	1.8
16.1	15.5	9.30	1.50
12.7	20.0	7.75	1.10
9.80	27.0	6.75	0.8
8.05	35.5	5.75	0.75
4.15	55.5	3.15	0.4
2.80	105.	0.80	0.05
0.00	145.		

EFFICIENCY
 USE BOND
 CONTENT

TABLE II
CHARACTERISTICS OF THE RECTIFIERS
(VICKERS RECTIFIERS HL2CUNICV)

Voltage	Current
0.0 volts	0.000 amperes
2.0	0.000
4.0	0.000
6.0	0.004
8.0	0.033
10.0	0.079
11.8	0.135
13.8	0.196
14.4	0.221

CHARACTERISTICS OF THE BOND (VOLTAGE AND EFFICIENCY)

Voltage		Efficiency	
Volts	Watts	Volts	Watts
100.0	0.00	10.0	0.00
200.0	0.00	20.0	0.00
300.0	0.00	30.0	0.00
400.0	0.00	40.0	0.00
500.0	0.00	50.0	0.00
600.0	0.00	60.0	0.00
700.0	0.00	70.0	0.00
800.0	0.00	80.0	0.00
900.0	0.00	90.0	0.00
1000.0	0.00	100.0	0.00

EFFICIENCY

ERASE BOND

RECORD

TABLE III
COMPUTED DATA FOR i_{L1} , THE LOAD CURRENT
DURING THE NON-FIRING PERIOD

R_L θ	20 ohms i_{L1}	50 ohms i_{L1}
0 deg.	0.0000 amp.	0.0000 amp.
10	0.0004	0.0004
20	0.0016	0.0016
30	0.0035	0.0035
40	0.0061	0.0061
50	0.0092	0.0092
60	0.0129	0.0129
70	0.0169	0.0169
80	0.0211	0.0211
90	0.0255	0.0255
100	0.0299	0.0298
110	0.0341	0.0339
120	0.0379	0.0378
130	0.0413	0.0412
140	0.0442	0.0439
150	0.0464	0.0462
160	0.0480	0.0477

COMPUTED DATA FOR THE 21st COMMENT
DURING THE 100-THIRTY PERIOD

SS class	SS class	R
1	1	0
0.0000	0.0000	0
0.0000	0.0000	10
0.0010	0.0010	20
0.0020	0.0020	30
0.0030	0.0030	40
0.0040	0.0040	50
0.0050	0.0050	60
0.0060	0.0060	70
0.0070	0.0070	80
0.0080	0.0080	90
0.0090	0.0090	100
0.0100	0.0100	110
0.0110	0.0110	120
0.0120	0.0120	130
0.0130	0.0130	140
0.0140	0.0140	150
0.0150	0.0150	160

TABLE III (continued)
 COMPUTED DATA FOR i_{L1} , THE LOAD CURRENT
 DURING THE NON-FIRING PERIOD

R_L	100 ohms	200 ohms
θ	i_{L1}	i_{L1}
0 deg.	0.0000 amp.	0.0000 amp.
10	0.0006	0.0005
20	0.0016	0.0017
30	0.0035	0.0035
40	0.0061	0.0061
50	0.0092	0.0092
60	0.0129	0.0128
70	0.0169	0.0168
80	0.0211	0.0210
90	0.0254	0.0252
100	0.0297	0.0295
110	0.0338	0.0334
120	0.0376	0.0371
130	0.0408	0.0404
140	0.0436	0.0430
150	0.0457	0.0451
160	0.0473	0.0464

TABLE III (continued)
 COMPUTED DATA FOR i_{L1} , THE LOAD CURRENT
 DURING THE NON-FIRING PERIOD

R_L	500 ohms	2000 ohms
θ	i_{L1}	i_{L1}
0 deg.	0.0000 amp.	0.0000 amp.
10	0.0004	0.0003
20	0.0016	0.0015
30	0.0035	0.0033
40	0.0060	0.0057
50	0.0091	0.0085
60	0.0126	0.0116
70	0.0163	0.0149
80	0.0204	0.0182
90	0.0247	0.0215
100	0.0284	0.0246
110	0.0321	0.0273
120	0.0355	0.0297
130	0.0385	0.0314
140	0.0409	0.0326
150	0.0425	0.0331
160	0.0435	0.0329

TABLE III (continued)
 COMPUTED DATA FOR i_{L1} , THE LOAD CURRENT
 DURING THE NON-FIRING PERIOD

R_L	5000 ohms
θ	i_{L1}
0 deg.	0.0000 amp.
10	0.0004
20	0.0014
30	0.0030
40	0.0051
50	0.0074
60	0.0098
70	0.0123
80	0.0147
90	0.0169
100	0.0188
110	0.0203
120	0.0213
130	0.0218
140	0.0218
150	0.0212
160	0.0201

TABLE III (continued)

COMPUTED AND NOTED IN THE FIELD

TABLE III (continued)

TABLE III (continued)

TABLE III (continued)

TABLE III (continued)

TABLE III (continued)

TABLE III (continued)

TABLE III (continued)

TABLE III (continued)

TABLE III (continued)

TABLE III (continued)

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TABLE III (continued)

TABLE III (continued)

TABLE III (continued)

TABLE III (continued)

TABLE III (continued)

TABLE III (continued)

TABLE III (continued)

TABLE III (continued)

TABLE III (continued)

TABLE IV

V_1 , THE CONTRIBUTION OF THE NON-FIRING PERIOD
TO THE OUTPUT VOLTAGE FOR VARIOUS LOAD
RESISTANCES AND CONTROL VOLTAGES

R_L	20 ohms		R_L	50 ohms	
	e_c	V_1		e_c	V_1
	-30 mv.	0.14 v.		0 mv.	0.23 v.
	-45	0.18		-15	0.29
	-60	0.22		-30	0.36
	-75	0.27		-45	0.45
	-90	0.34		-60	0.56
				-75	0.70
				-90	0.94

THE COURT REPORTER AND THE COURT REPORTER
TO THE COURT REPORTER AND THE COURT REPORTER
THE COURT REPORTER AND THE COURT REPORTER

2	2	2	2
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THE COURT REPORTER AND THE COURT REPORTER
THE COURT REPORTER AND THE COURT REPORTER
THE COURT REPORTER AND THE COURT REPORTER

TABLE IV (continued)

V_1 , THE CONTRIBUTION OF THE NON-FIRING PERIOD
TO THE OUTPUT VOLTAGE FOR VARIOUS LOAD
RESISTANCES AND CONTROL VOLTAGES

R_L	100 ohms		R_L	200 ohms	
	e_c	V_1		e_c	V_1
	45 mv.	0.18 v.		45 mv.	0.38 v.
	30	0.26		30	0.50
	15	0.35		15	0.75
	0	0.46		0	0.94
	-15	0.58		-15	1.13
	-30	0.73		-30	1.44
	-45	0.90		-45	1.75
	-60	1.12		-60	2.25
	-75	1.40		-75	2.76
	-90	1.88		-90	3.76

TABLE 1 (continued)

THE COSTS OF THE VARIOUS TESTS
TO THE OUTPUT OF THE
RESISTANCE AND NOISE TO THE

R_p	100 ohms	V_i	V_o
-------	----------	-------	-------

45 mv.	0.15 v.	15 mv.	0.25 v.
30	0.25	30	0.25
15	0.25	15	0.25
0	0.40	0	0.40
-15	0.30	-15	0.30
-30	0.75	-30	0.75
-45	0.50	-45	0.50
-60	1.15	-60	1.15
-75	1.40	-75	1.40
-90	1.68	-90	1.68

OFFICIAL
BASE BOND
HAG CONFEY

TABLE IV (continued)

V_1 , THE CONTRIBUTION OF THE NON-FIRING PERIOD
TO THE OUTPUT VOLTAGE FOR VARIOUS LOAD
RESISTANCES AND CONTROL VOLTAGES

R_L	500 ohms	R_L	2000 ohms
e_c	V_1	e_c	V_1
45 mv.	0.89 v.	45 mv.	3.37 v.
30	1.28	30	4.76
15	1.72	15	6.34
0	2.24	0	8.15
-15	2.83	-15	10.20
-30	3.54	-30	12.64
-45	4.35	-45	15.40
-60	5.37	-60	18.85
-75	6.69	-75	23.10
-90	9.03		

TABLE 1 - Continued

TO THE OUTPUT VOLTAGE FOR VARIOUS LOADS
REGISTERED AND OUTPUT VOLTAGE

R L	e _c	500 ohms		2000 ohms	
		R L	e _c	R L	e _c
45 mv.		0.89	45 mv.	3.37	
30		1.32	30	4.78	
15		1.73	15	6.19	
0		2.14	0	7.60	
-15		2.55	-15	9.01	
-30		2.96	-30	10.42	
-45		3.37	-45	11.83	
-60		3.78	-60	13.24	
-75		4.19	-75	14.65	
-90		4.60			

TABLE IV (continued)

V_1 , THE CONTRIBUTION OF THE NON-FIRING PERIOD
TO THE OUTPUT VOLTAGE FOR VARIOUS LOAD
RESISTANCES AND CONTROL VOLTAGES

R_L 5000 ohms	
e_c	V_1
45 mv.	7.34 v.
30	10.3
15	13.6
0	17.2
-15	21.2
-30	25.8
-45	30.9

TABLE 1 - CONTINUED

TO THE UNITED STATES OF AMERICA
FROM THE UNITED STATES OF AMERICA

1000

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1000	96
1000	97
1000	98
1000	99
1000	100

EFFICIENCY
ERASE BOND
CONTENT

TABLE V

MISCELLANEOUS DATA ON THE MAGNETIC AMPLIFIER
VICKERS 36A34, DDL CONNECTED,
EDUCATIONAL MAGNETIC AMPLIFIER

Gate coil inductance	16.5 henry
Gate coil resistance	38.0 ohms
Control winding resistance (Winding C)	6.9 ohms
A. C. Supply:	60 cycles, 230/115 volts
Rated load:	0.35 average amperes
Power output:	20 watts (50° C. vise)
Optimum load:	60 ohms
Rectifiers used:	Two Vickers Type H12CUNICV
Control signal:	Three ampere-turns d. c.

RESEARCH REPORT ON THE
EFFECTS OF THE
ELECTRIC FIELD ON THE
GROWTH OF PLANTS

Gate cell resistance
Gate cell resistance
Control voltage (V)
Control voltage (V)
A. C. voltage
Rated load
Power supply
Optical density
Resistance ratio
Control voltage

EFFICIENCY
ELECTRIC
ELECTRIC
ELECTRIC

TABLE VI (continued)

DATA FOR COMPUTATION OF EQUIVALENT CIRCUIT PARAMETERS

AMPLIFICATION FACTOR DATA			
I_L	E_L	e_c	
0.100 amp.	49.0 v.	0.090 v.	545
0.200	45.8	0.090	509
0.300	37.2	0.075	496
0.400	29.6	0.060	494
0.500	28.3	0.060	472
Average			503

RECEIVED BY THE
UNITED STATES DEPARTMENT OF THE ARMY
WASHINGTON, D. C. 20315

ANNUAL REPORT OF THE

Item	1964	1965	1966	1967
1. Personnel	100.0	100.0	100.0	100.0
2. Materials	100.0	100.0	100.0	100.0
3. Services	100.0	100.0	100.0	100.0
4. Supplies	100.0	100.0	100.0	100.0
5. Other	100.0	100.0	100.0	100.0
Total	500.0	500.0	500.0	500.0

EFFICIENCY
BASE BOND
PAGE CONTENT

TABLE VI
DATA FOR COMPUTATION OF EQUIVALENT CIRCUIT PARAMETERS

EQUIVALENT RESISTANCE DATA			
e_c	E_L	I_L	R_g
15 mv.	42.3 v.	0.70 amp.	60.4
0	40.5	0.70	57.8
-15	40.6	0.70	58.0
-30	40.6	0.70	58.0
-45	38.4	0.70	54.8
-60	27.5	0.50	57.0
-75	28.6	0.45	63.6
Average			58.5

TABLE 1. SUMMARY OF DATA FOR THE YEAR 1964

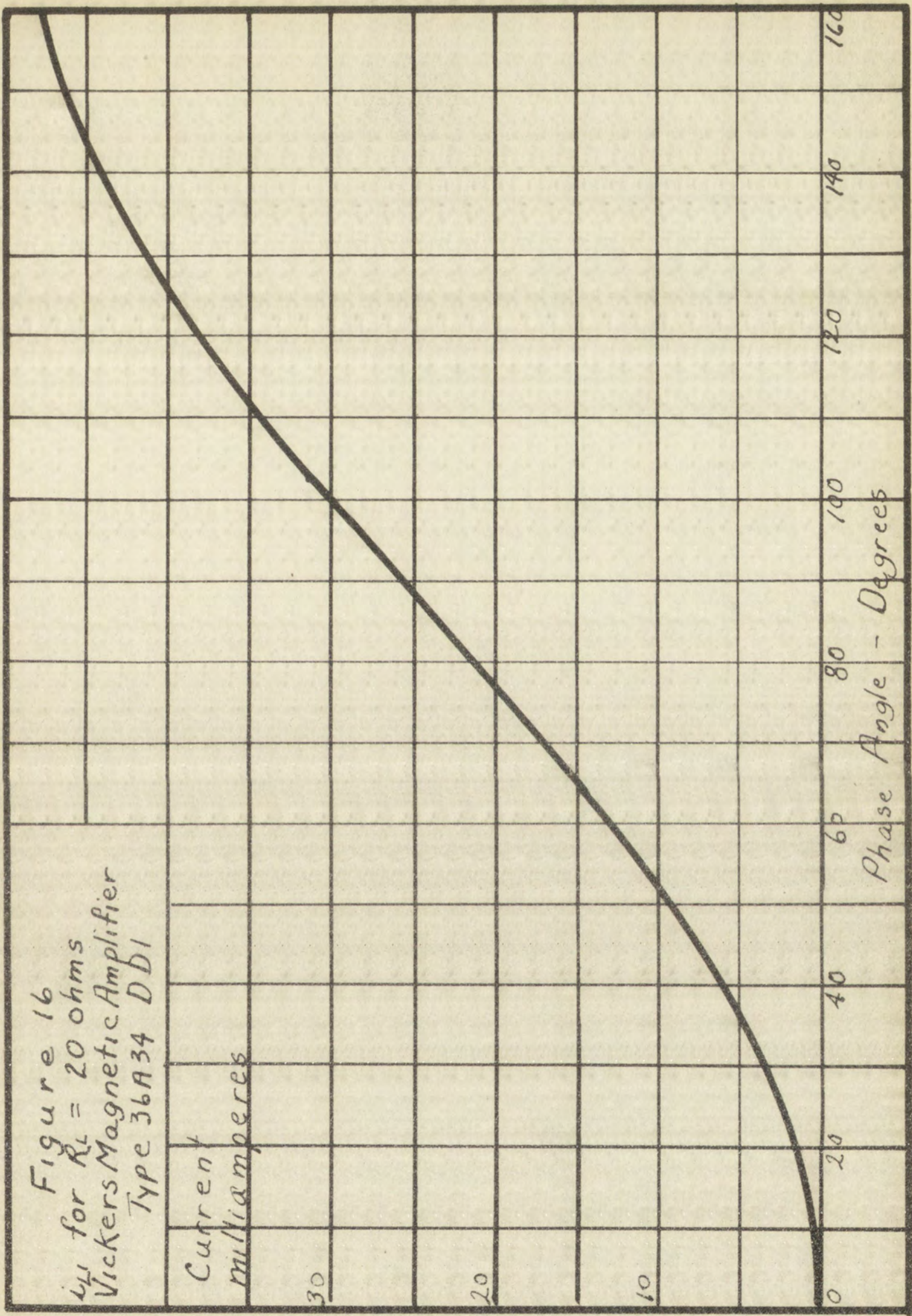
UNITED STATES DEPARTMENT OF AGRICULTURE

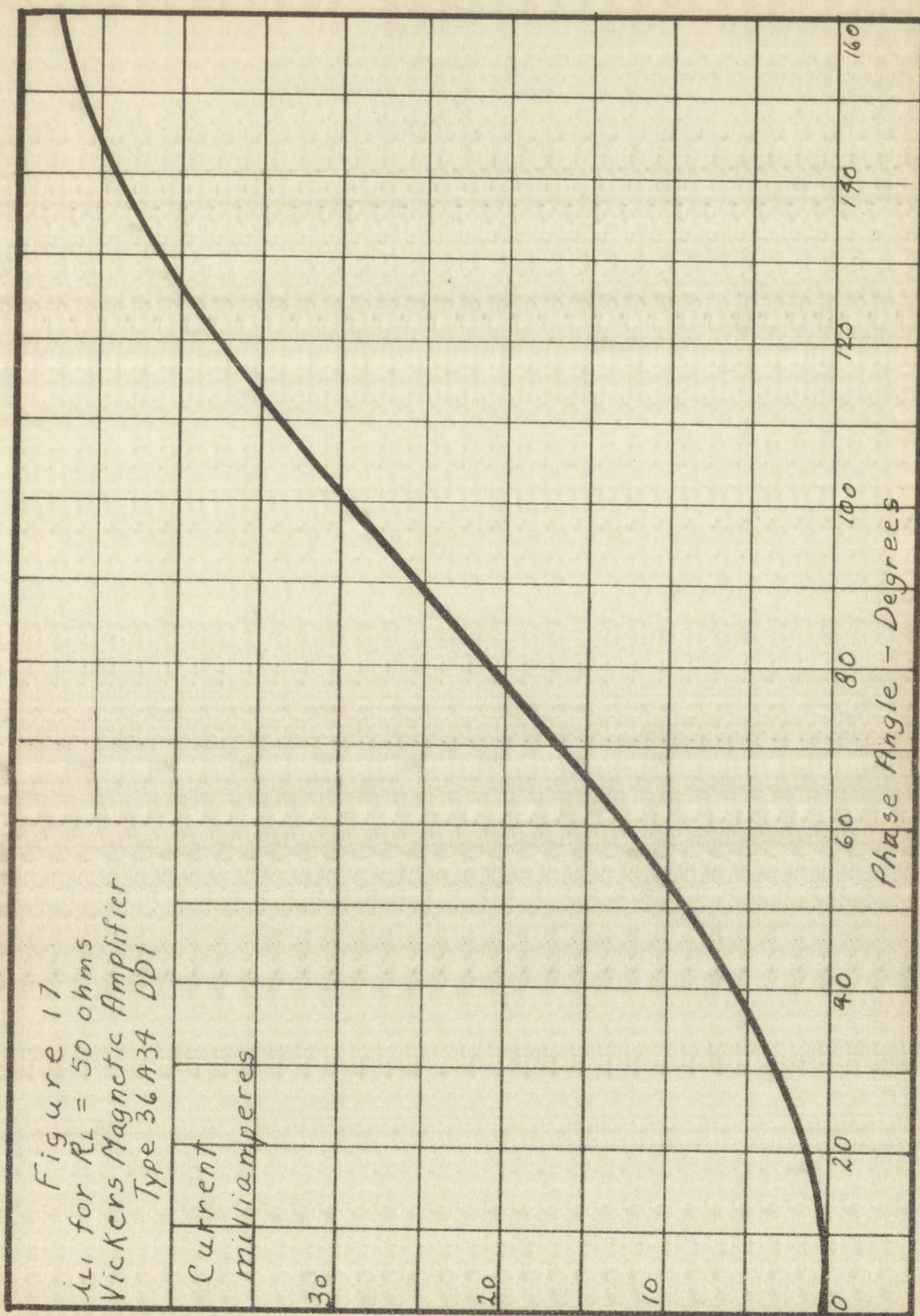
UNITED STATES DEPARTMENT OF AGRICULTURE			
TABLE 1. SUMMARY OF DATA FOR THE YEAR 1964			
1964	1963	1962	1961
1.00	0.95	0.90	0.85
2.00	1.90	1.80	1.70
3.00	2.80	2.70	2.60
4.00	3.70	3.60	3.50
5.00	4.60	4.50	4.40
6.00	5.50	5.40	5.30
7.00	6.40	6.30	6.20
8.00	7.30	7.20	7.10
9.00	8.20	8.10	8.00
10.00	9.10	9.00	8.90
11.00	10.00	9.90	9.80
12.00	10.90	10.80	10.70
13.00	11.80	11.70	11.60
14.00	12.70	12.60	12.50
15.00	13.60	13.50	13.40
16.00	14.50	14.40	14.30
17.00	15.40	15.30	15.20
18.00	16.30	16.20	16.10
19.00	17.20	17.10	17.00
20.00	18.10	18.00	17.90
21.00	19.00	18.90	18.80
22.00	19.90	19.80	19.70
23.00	20.80	20.70	20.60
24.00	21.70	21.60	21.50
25.00	22.60	22.50	22.40
26.00	23.50	23.40	23.30
27.00	24.40	24.30	24.20
28.00	25.30	25.20	25.10
29.00	26.20	26.10	26.00
30.00	27.10	27.00	26.90
31.00	28.00	27.90	27.80
32.00	28.90	28.80	28.70
33.00	29.80	29.70	29.60
34.00	30.70	30.60	30.50
35.00	31.60	31.50	31.40
36.00	32.50	32.40	32.30
37.00	33.40	33.30	33.20
38.00	34.30	34.20	34.10
39.00	35.20	35.10	35.00
40.00	36.10	36.00	35.90
41.00	37.00	36.90	36.80
42.00	37.90	37.80	37.70
43.00	38.80	38.70	38.60
44.00	39.70	39.60	39.50
45.00	40.60	40.50	40.40
46.00	41.50	41.40	41.30
47.00	42.40	42.30	42.20
48.00	43.30	43.20	43.10
49.00	44.20	44.10	44.00
50.00	45.10	45.00	44.90
51.00	46.00	45.90	45.80
52.00	46.90	46.80	46.70
53.00	47.80	47.70	47.60
54.00	48.70	48.60	48.50
55.00	49.60	49.50	49.40
56.00	50.50	50.40	50.30
57.00	51.40	51.30	51.20
58.00	52.30	52.20	52.10
59.00	53.20	53.10	53.00
60.00	54.10	54.00	53.90
61.00	55.00	54.90	54.80
62.00	55.90	55.80	55.70
63.00	56.80	56.70	56.60
64.00	57.70	57.60	57.50
65.00	58.60	58.50	58.40
66.00	59.50	59.40	59.30
67.00	60.40	60.30	60.20
68.00	61.30	61.20	61.10
69.00	62.20	62.10	62.00
70.00	63.10	63.00	62.90
71.00	64.00	63.90	63.80
72.00	64.90	64.80	64.70
73.00	65.80	65.70	65.60
74.00	66.70	66.60	66.50
75.00	67.60	67.50	67.40
76.00	68.50	68.40	68.30
77.00	69.40	69.30	69.20
78.00	70.30	70.20	70.10
79.00	71.20	71.10	71.00
80.00	72.10	72.00	71.90
81.00	73.00	72.90	72.80
82.00	73.90	73.80	73.70
83.00	74.80	74.70	74.60
84.00	75.70	75.60	75.50
85.00	76.60	76.50	76.40
86.00	77.50	77.40	77.30
87.00	78.40	78.30	78.20
88.00	79.30	79.20	79.10
89.00	80.20	80.10	80.00
90.00	81.10	81.00	80.90
91.00	82.00	81.90	81.80
92.00	82.90	82.80	82.70
93.00	83.80	83.70	83.60
94.00	84.70	84.60	84.50
95.00	85.60	85.50	85.40
96.00	86.50	86.40	86.30
97.00	87.40	87.30	87.20
98.00	88.30	88.20	88.10
99.00	89.20	89.10	89.00
100.00	90.10	90.00	89.90

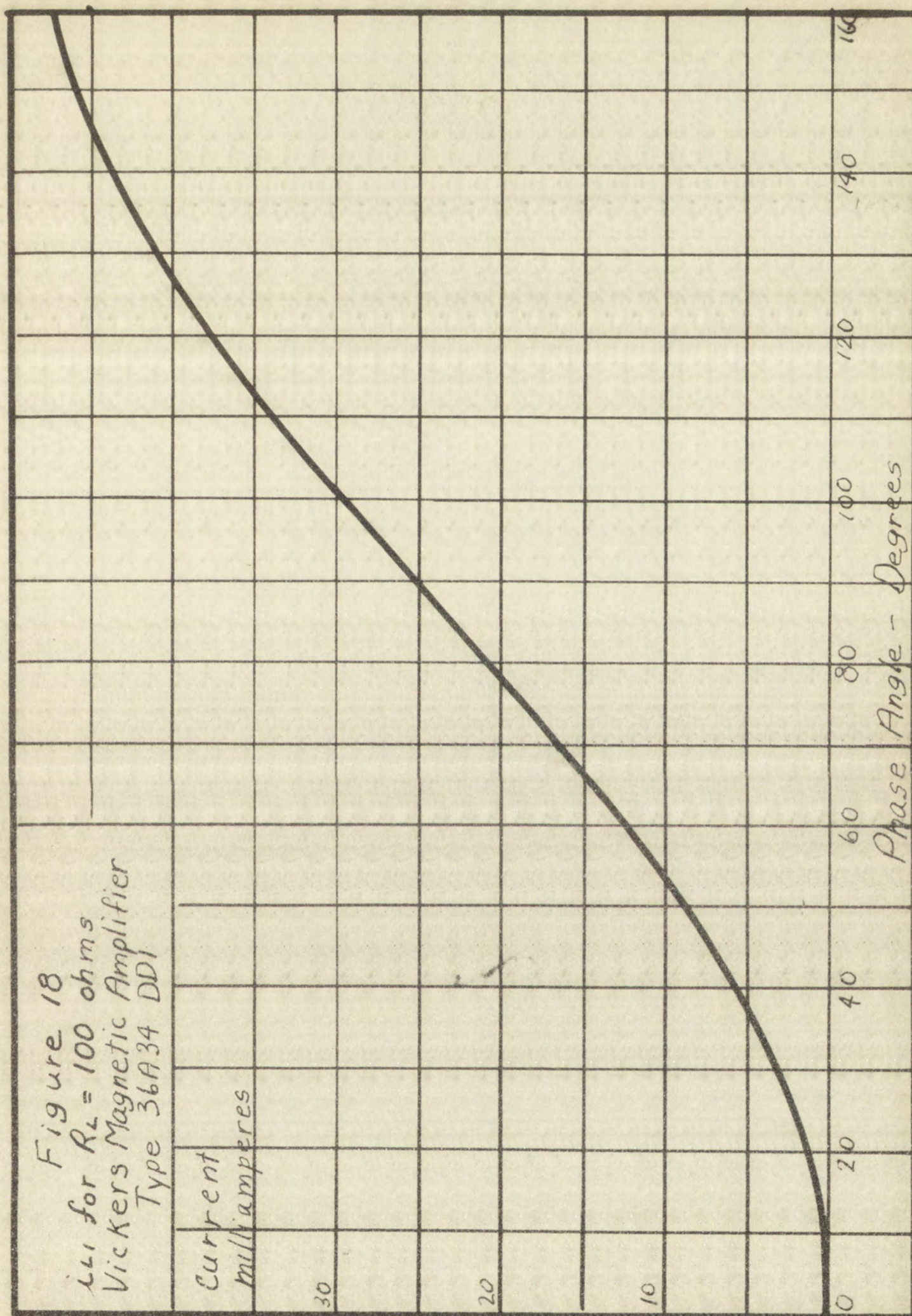
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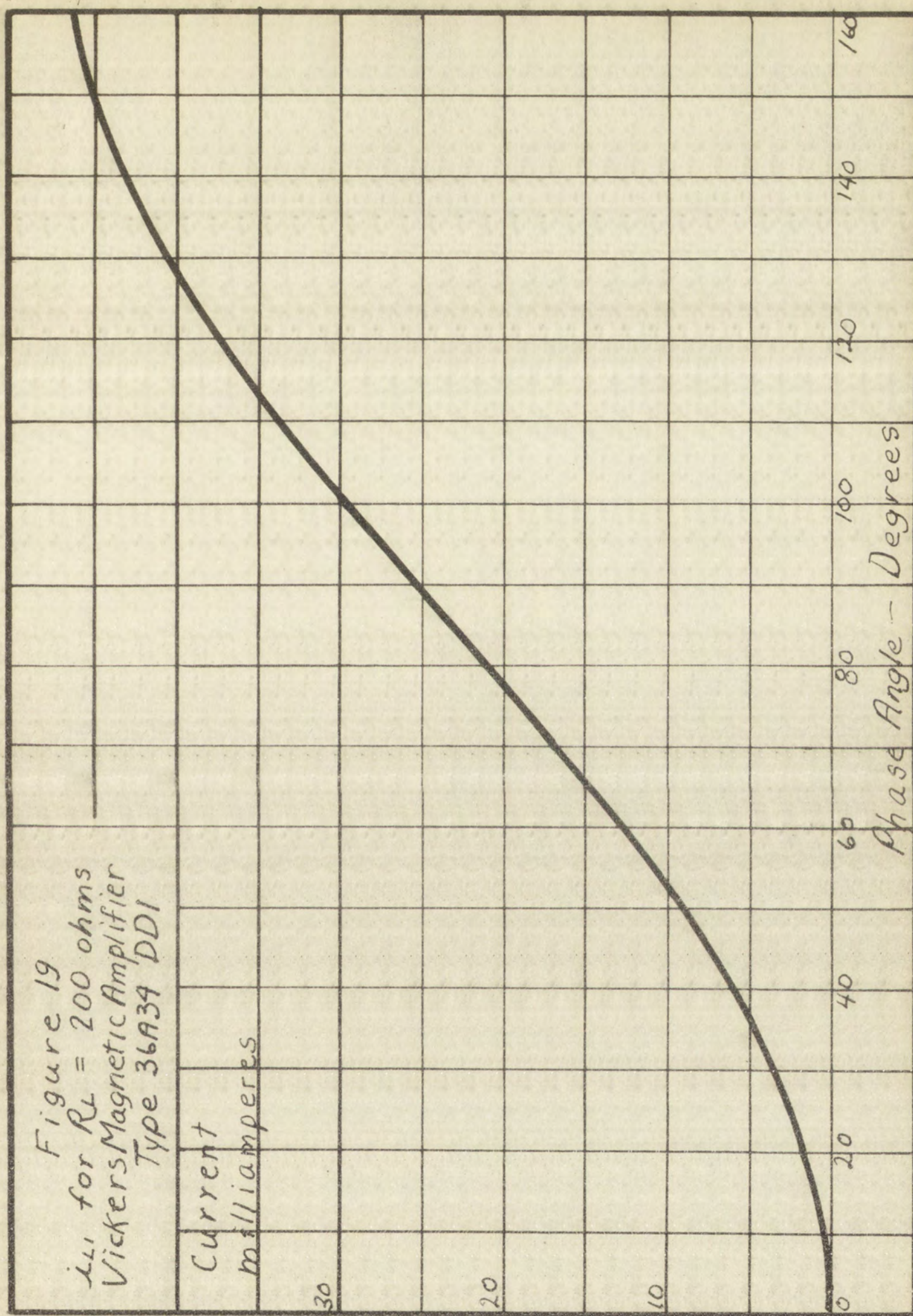
5-2

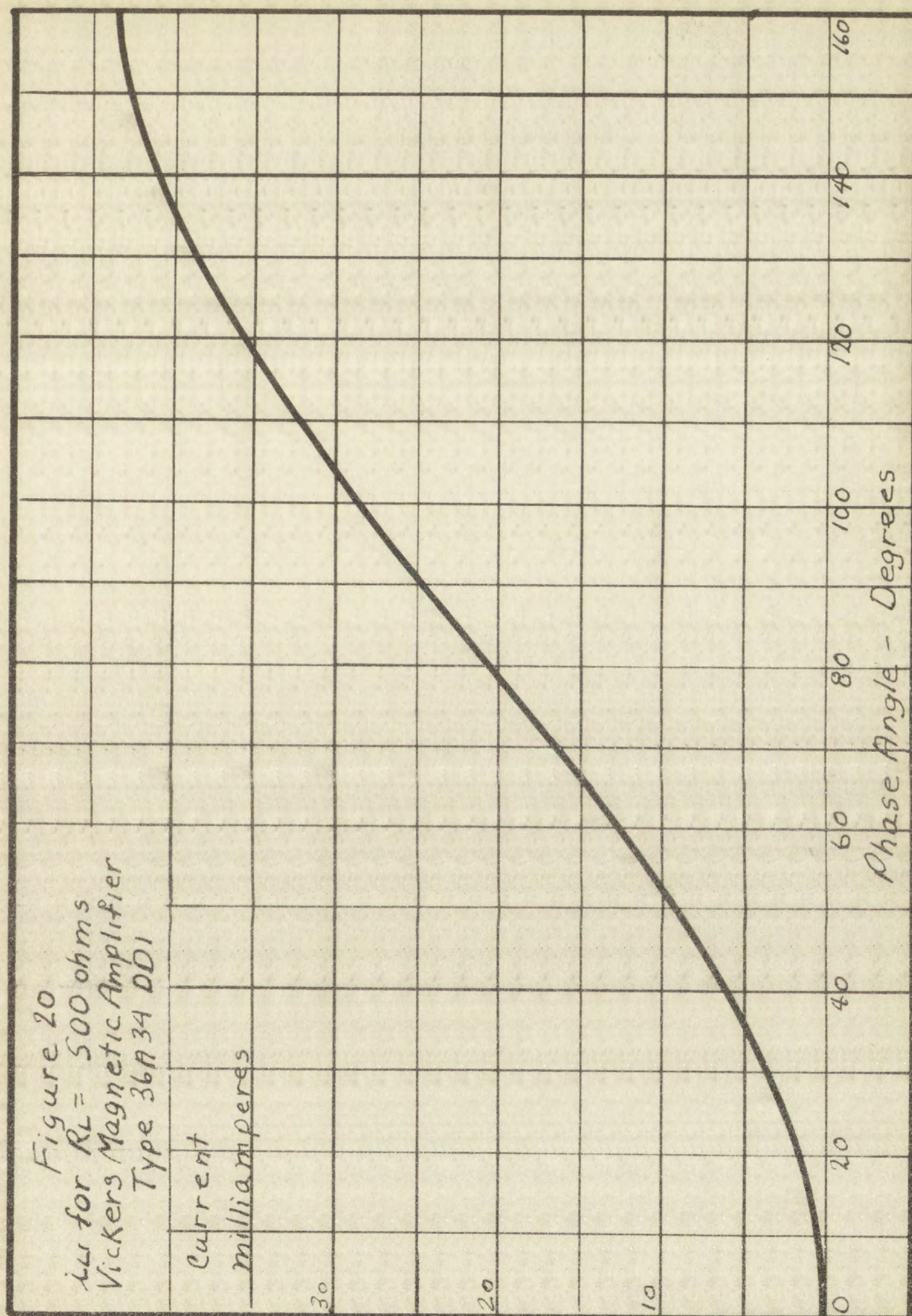
APPENDIX D











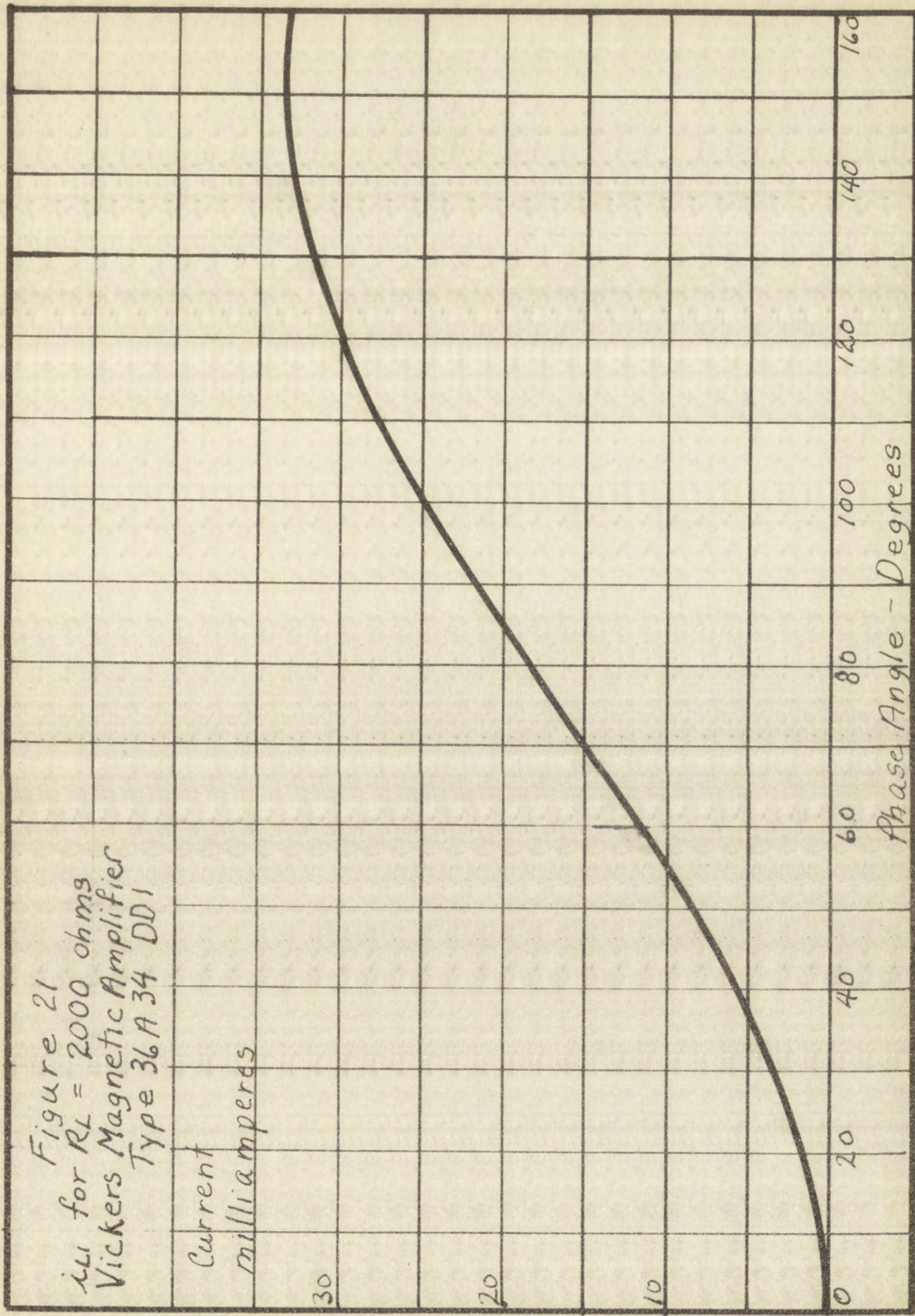
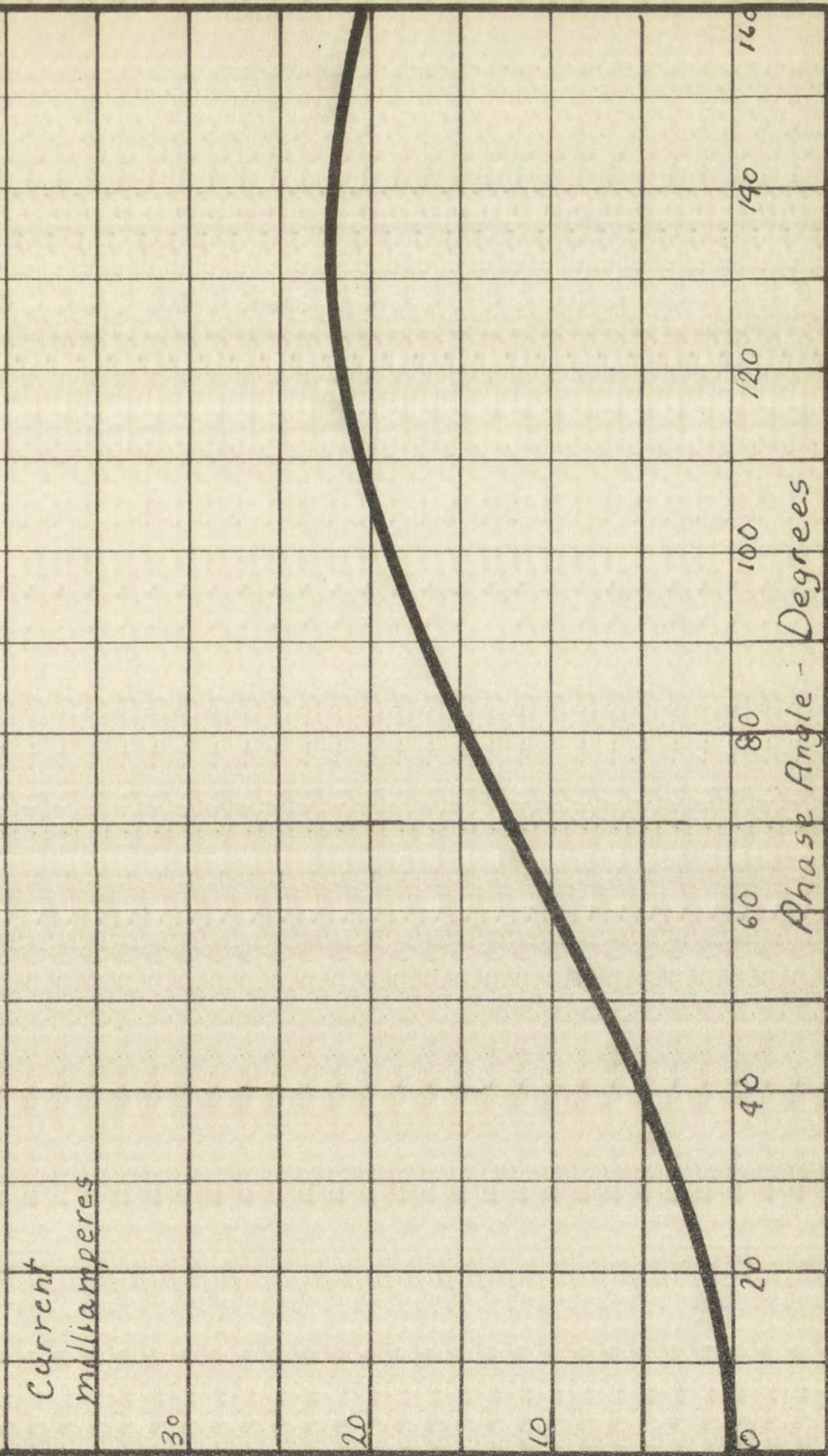
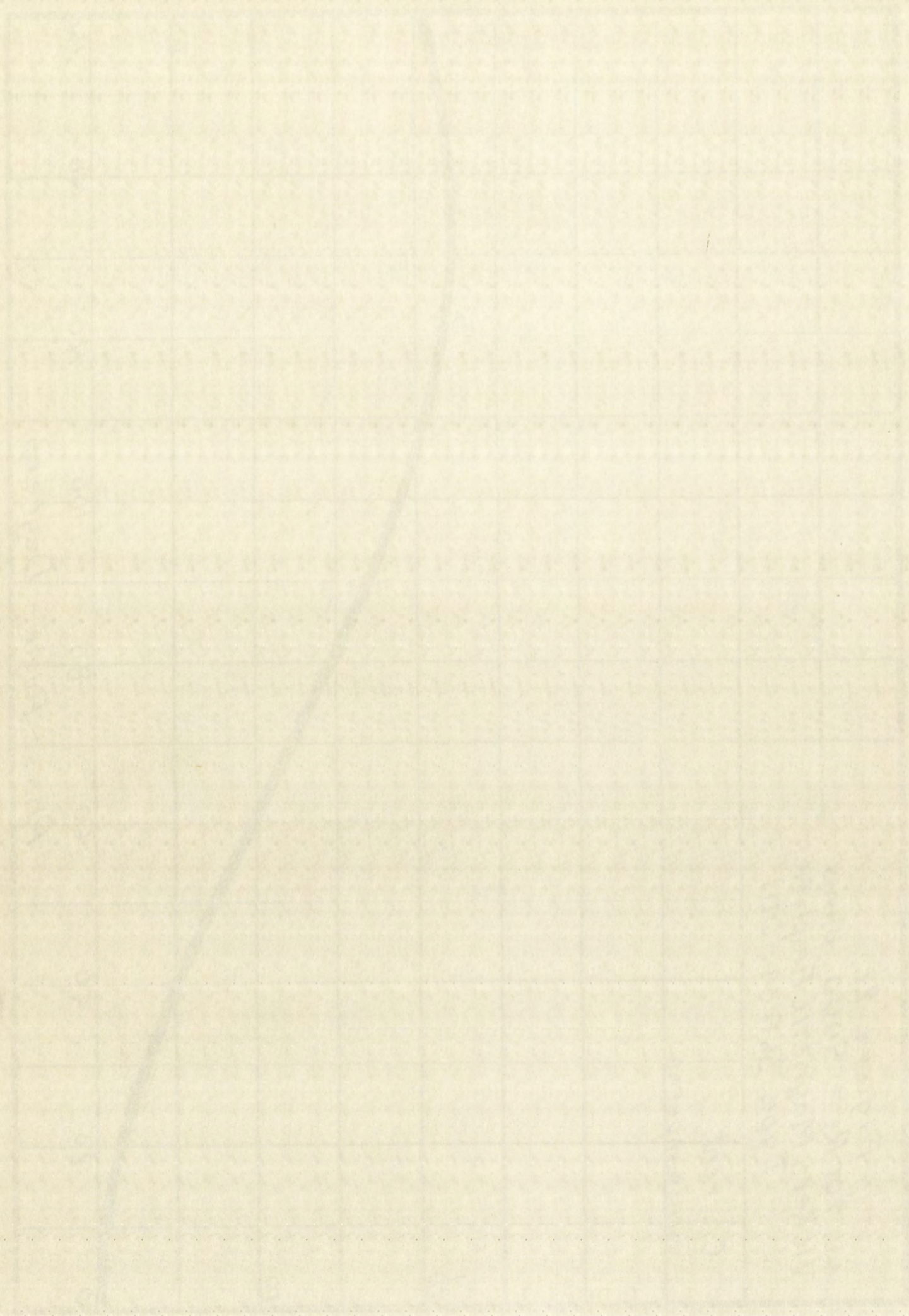


Figure 22
 i_{L1} for $R_L = 5000$ ohms
 Vickers Magnetic Amplifier
 Type 36A34 DD1





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JOHN H. EMMETT, Attorney General

By _____, Secretary

Approved: _____, Assistant Secretary

Witness my hand and the seal of the Department of Justice, at Washington, D.C., this 1st day of January, 1911.

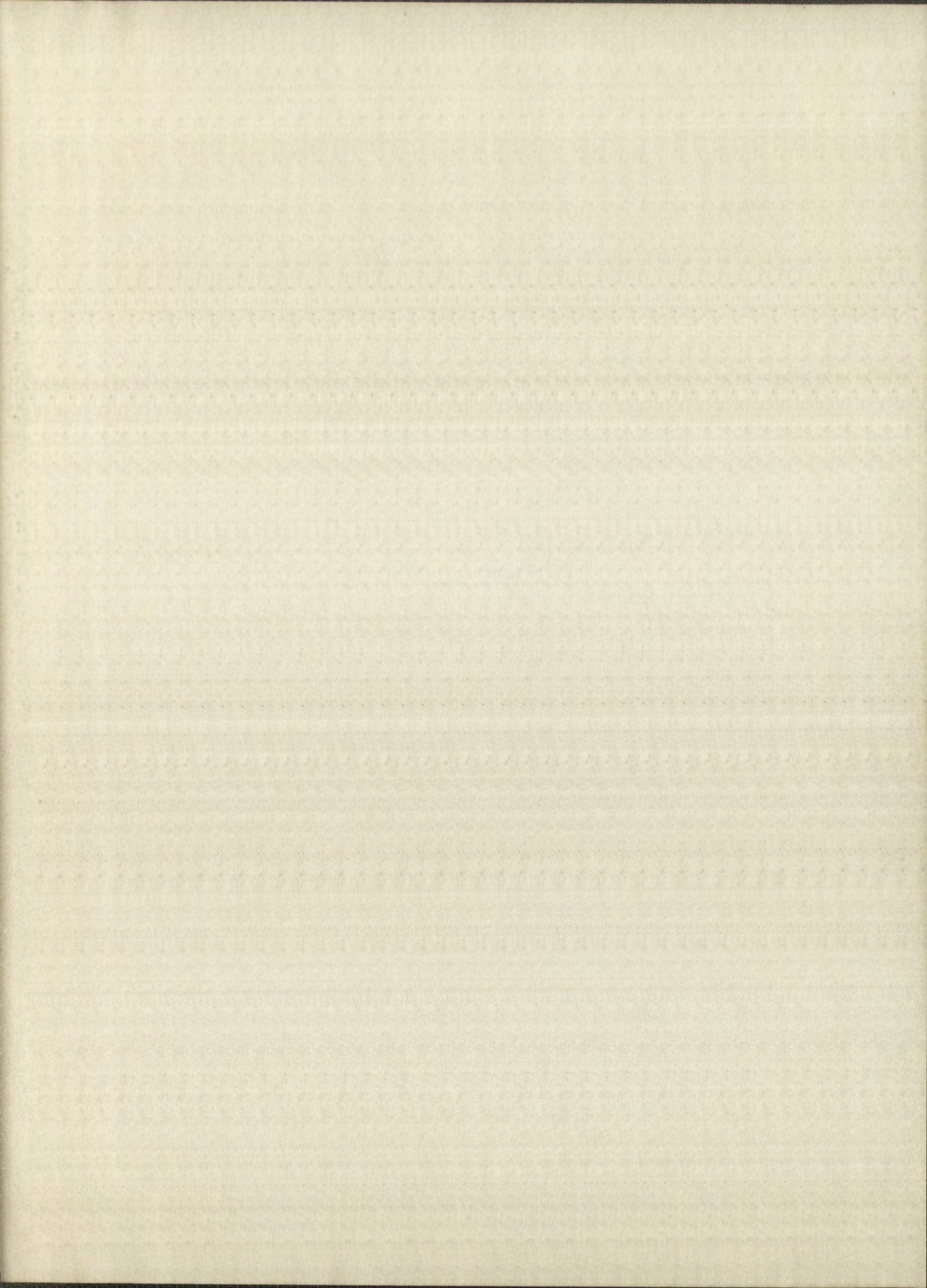
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