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TITLE UTILIZATION OF REFLECTIONS FROM TRANSMISSION LINE ELEMENTS TO PRODUC POSITIVE ELECTRICAL PULSES OF 0.006 MICROSECONDS DURATION AT HIGH REPETITION RATES

AUTHOR FRANK MURRAY PELTON

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UTILIZATION OF REFLECTIONS FROM TRANSMISSION LINE ELEMENTS TO PRODUCE POSITIVE ELECTRICAL PULSES OF 0.006 MICROSECONDS DURATION AT HIGH REPETITION RATES

By

Frank Murray Pelton

A THESIS

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ABSTRACT

The art of short pulse production has previously been limited by the lack of a suitable interstage inversion element usable for pulses of less than 0.05 microseconds duration. This paper treats the use of the short circuit terminated transmission line to accomplish this inversion.

Inherent in the process when applied to triangular pulses is a desirable reduction in pulse duration by a factor of two. Thus it is relatively simple to accomplish an overall reduction of pulse duration of more than two to one per amplifier stage.

Application of this method was made in a pulse generator and amplifier capable of producing 100 watt positive triangular pulses of 0.005 microseconds duration at a pulse repetition rate of 800 kc.

The study of the production of pulses less than 0.005 microseconds and at repetition rates of greater than 800 kc. is contemplated as the study made shows no limitation at these values.

PREFACE

The development of this thesis is the outgrowth of the need for a very short gating pulse in the production of a special waveform similar to a recurrent sawtooth voltage. The inversion method with the shorted transmission line as applied to short pulse generation is an original contribution to the art by the author. The originality is in evidence by the lack of previous work in the literature and also by the anxiety expressed by the U.S. Armed Forces in obtaining the method.

The reader should be cautioned that the inversion principle as applied to pulse production is being submitted to the Office of Naval Research for Patent Application in the author's name, and any commercial utilization other than continued research will be prohibited in the event the patent is granted. This method has been made available to the Office of Naval Research and through them it will be made available to the U.S. Armed Forces for National Defense uses, royalty free.

The author wishes to thank Dr. J. A. Strelzoff for his help in editing this thesis and to both him and Mr. Noah Kramer for their suggestions as to method of mathematical solution, and to Dr. R. D. Spence for discussion relative to the interpretation of certain technical phenomena.

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CHAPTER I

1.1 Introduction

The production of very short pulses is important in many fields at the present time. The art is in a stage of rapid advancement due to the recent need for pulses in the range below 0.01 microsecond duration and at repetition rates greater than 1 Mc/s. The methods previously used are unsatisfactory and most have serious limitations. The author has developed a method utilizing a short circuit terminated transmission line as the interstage inversion element in a typical pulse peak amplifier. The previous limits in short pulse generation have been considerably surpassed, and 100 watt positive pulses of 0.006 microseconds duration have been produced at an 800 kc. repetition rate by a pulse generator incorporating this new inversion process. A brief account of existing methods will now be given.

At the end of the war, the Radiation Laboratories published a series of books listing most of the work done during the war period, 1940-45. Using these as a starting point, the common pulse generation methods will be considered. They may be generally classified into multivibrator, blocking and regenerative, delay line amplifiers and line type pulsers, non-linear peakers, and peak amplifiers.

Chance[1] mentions the production of pulses of 0.1 microsecond by certain multivibrator circuits and shows some which are suitable for 0.5 microseconds. These are limited by the pulse power available and the presence of both tube and stray capacitances. The loading affects the transient operation and thereby causes an increase in the pulse rise time and the overall pulse duration.

Blocking oscillators and regenerative oscillators are limited primarily by the characteristics of the pulse transformer which is used. Pulses as short as 0.12 microseconds duration were produced by cascading two such oscillators.[2] The rise time was .03 for 200 v. pulse. At the present time, the Raytheon transformer type UX 7307 is advertised as capable of the production of pulses of 0.05 microseconds duration, and is generally considered to be about the limit for blocking oscillators at this time.

Delay line amplifiers or tail clipping circuits in general, require pulses with fast rise times on which to operate, and in themselves do not increase the rise time of the pulses. This limits the magnitude available before the clipping action begins.

Line pulsers are capable of producing pulses of 0.01 microsecond but are limited in their application because of the slow repetition rates necessitated by the deionization time of the thyratron tube used to initiate the pulse.[3]

Non-linear peaking coils have been used recently to produce pulses of 0.01 microsecond[4] duration but the power output is limited by the very small dimensions necessary to obtain the short response.

Peak amplifiers also have been used to produce pulses in this range. Negative pulses of 0.02 microseconds duration with a rise time of only 0.003 microseconds have been produced with a sine wave peak amplifier.[5] Mention has been made of the use of this type generator up to 5 Mc. repetition rates.[6] If a suitable method of pulse inversion was available, peak amplifiers could produce pulses which incorporated the full gain bandwidth possibilities of a given tube.

1.2 Peak Amplifiers

Peak amplifiers are ideally suited to pulse amplification and pulse shortening. They consist primarily of a grid biased amplifier tube with a suitable plate load impedance. Video compensated plate circuits may be necessary in some cases. A positive grid wave form, usually a triangular pulse, or a sine wave form, is biased so that only a desired portion of its positive peak causes conduction in the tube. The selection of a tube with very high mutual transconductance, such as the 6AG7, together with high dissipation provide an efficient switch action at quite low impedance when operated in the positive grid region. The negative pulse appearing at the plate is then inverted by a suitable means and the process is repeated. Thus the total gain-band width factor of the tube used is utilized. For short pulses at low duty rates, the applied plate voltage and the instantaneous power in the pulse may be many times the continuous rated values for the tube.

Short negative pulses are very useful as markers and time modulators in cathode ray tube display work as their apparent polarity may be controlled by proper connection to the circuits involved. However, for most applications such as triggering, further shortening, gating and pulse amplifier circuits in general, a positive pulse is required. Thus a suitable means of inversion of the negative plate pulse is required. Assuming that pulses are desired which would not be passed by the available pulse transformers generally used for this process, other methods of inversion will be considered.

1.3 The "Normally On" Inversion Stage

A "normally on" amplifier stage, that is one whose tube is normally in a conducting state, when driven with a negative pulse produces a positive plate output pulse equal to the power dissipated in its normal state. This assumes the grid signal is sufficient to drive the tube to cut-off bias. The disadvantage of this inversion process is immediately apparent in the d.c. plate supply power loss in maintaining the tube at high dissipation. If this process is to be used, mention should be made that if the negative peak of the input signal is "taken off" with a non-linear diode before application to the amplifier tube, considerable shortening is obtained because of the diode's characteristics. Although no experimental evidence has been obtained, it would appear feasible to cascade such diode stages, each with its own bias, to cause further shortening of the negative pulse. This would entail having a large negative pulse with which to start. For most applications, the inefficiency of this method prohibits its use.

1.4 The Need for a New Inversion Method

Other than the above methods, no standard method of pulse inversion is available. Pulse transformers will pass only about a 0.05 microseconds pulse and "normally on" stages are so inefficient that they cannot be used. It is apparent that if shorter pulses are to be produced by peak amplifiers, some satisfactory method of inversion is necessary. To obtain a short time constant, i.e. the response of the tube and its associated inversion network to to produce the desired pulse (volts/sec per volt applied), the product of the impedance and the shunt capacitance must be made low. Thus both of these factors are made as low as possible as is consistent with reasonable design considerations.

The remainder of this thesis will consider the use of the short circuit terminated transmission line to accomplish this inversion.

CHAPTER II

2.1 The Characteristics of the Short Circuit Terminated Transmission Line

Consider the ideal transmission system[7] shown in figure 1. The voltage v(t) is assumed to be produced by an impedanceless generator.

It has been shown[8] that the voltage at any point along the transmission line is

$$e(x,t) = \frac{Z_0}{Z_G + Z_0}\left\{ f(t - vx) - \left[\frac{Z_0 - Z_T}{Z_0 + Z_T}\right] f\left[t - (2d - x)v\right] + \left[\frac{Z_0 - Z_G}{Z_0 + Z_G}\right]\left[\frac{Z_0 - Z_T}{Z_0 + Z_T}\right] f\left[t - (2d + x)v\right] + \cdots \right\} \qquad (2.1)$$

Now if either Z_g or Z_t is less than the characteristic impedance of the transmission line, a negative reflection will result. Furthermore, if the impressed voltage pulse v(t) has terminated before the reflection arrives, the voltage e(o,t) will show polarity opposite to that of v(t). As this is the desired result for this application, use is made of this phenomena. For maximum inversion, the output end of the line is short-circuited, i.e. $Z_t = 0$, and Z_g is made equal to the characteristic impedance of the transmission line to suppress further reflections. The voltage e (o,t) then becomes

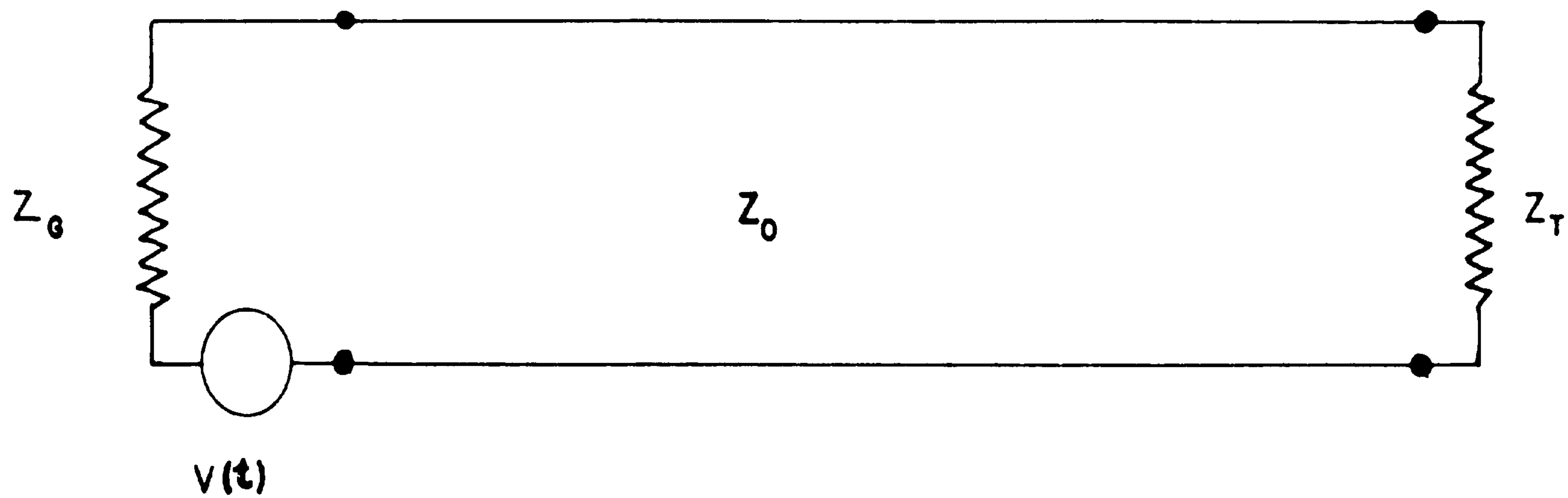


FIG. 1

2.2 Analysis for a Square Wave Applied Voltage

For an elementary analysis, assume that the applied voltage function is of the form

$$\left.\begin{array}{ll} e = 0 & t < 0 \\ e = 1 & 0 < t < 1 \\ e = 0 & 1 < t \end{array}\right\} \qquad (2.2)$$

Considering the delay time 2d in equation (2), three cases become of interest:

(1) For $2d > 1$, the reflected pulse appears at the input of the line after a delay time of $2d-1$ and the two pulses may be observed quite independently as is shown in Fig. 2.

(2) For $2d < 1$, the reflected pulse appears at the input of the line while the voltage $v(t)$ is still applied and the addition of these produces a voltage $e(o,t)$ such that

$$\begin{array}{ll} e = 0 & t < 0 \\ e = 1 & 0 < t < 2d \\ e = 0 & 2d < t < 1 \\ e = -1 & 1 < t < 4d \\ e = 0 & 4d < t \end{array}$$

This is shown in Fig. 3.

(3) If $2d=1$, the voltage rises instantaneously from 1 to -1 at $t=1$ as is shown in Fig. 4. This obviously provides the greatest voltage change per unit of time for any of the three cases being considered.

2.3 Analysis for Applied Voltage of Triangular Pulse

When a practical application of this system is attempted, the transient response of the networks enters into the consideration and this maximum applied voltage change is important in that it doubles the rise time of the resultant pulse. This effect may be more readily seen if the addition of 2 triangular pulses is considered. This is shown in Fig. 5. In this interpretation, it should be pointed out that the leading edge of the triangular pulse is produced by the charging of the shunt capacitance of the associated networks during the time an effective square wave voltage is applied. The trailing edge is formed by the discharge of the same capacitance after the effective square wave applied voltage is terminated. Thus this is not a contradiction to the cases discussed in Sect. 2.2.

2.4 Differentiation by a Shorted Line

If a transmission line is very short compared to the input voltage frequency components, the shorted line appears as a capacitance. The input termination together with the reflected wave, which becomes apparent as the charge impressed on the equivalent capacitance, forms a differentiating circuit similar to the familiar R-C differentiator.

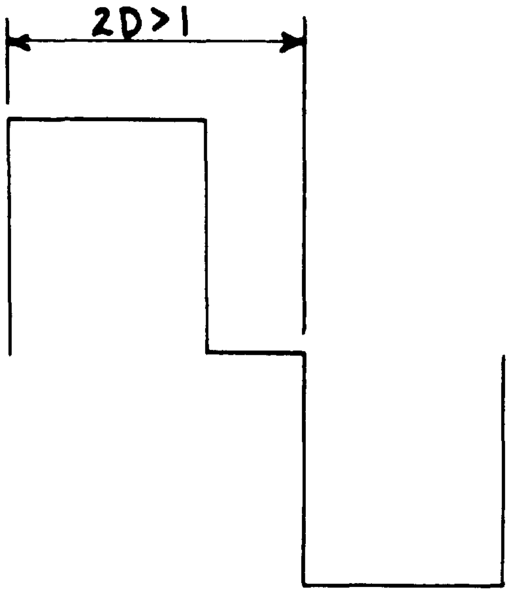


FIG. 2

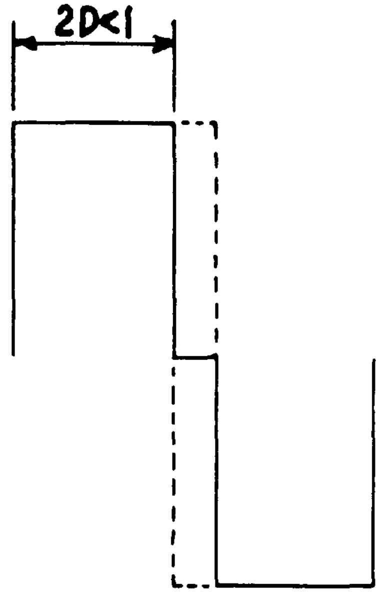


FIG. 3

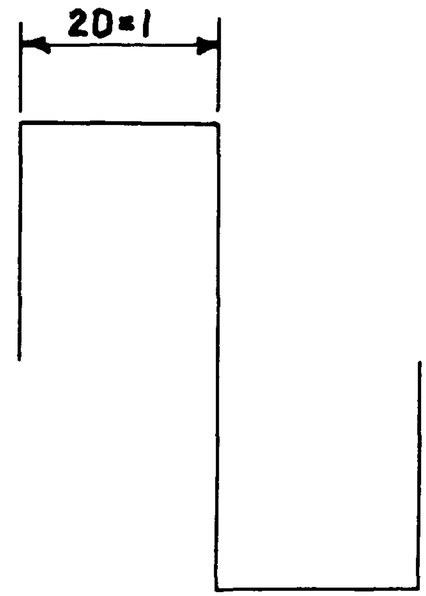


FIG. 4

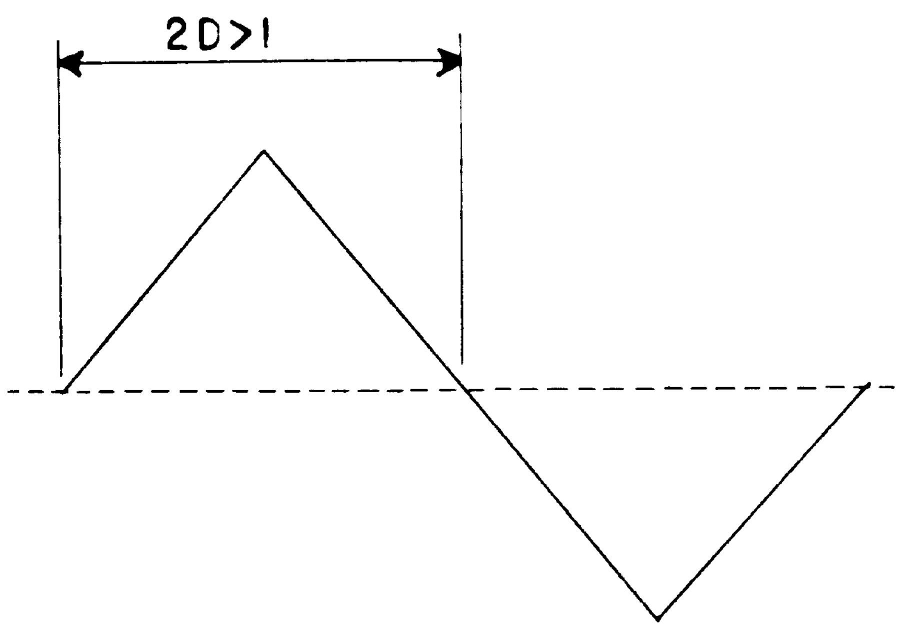


FIG. 5

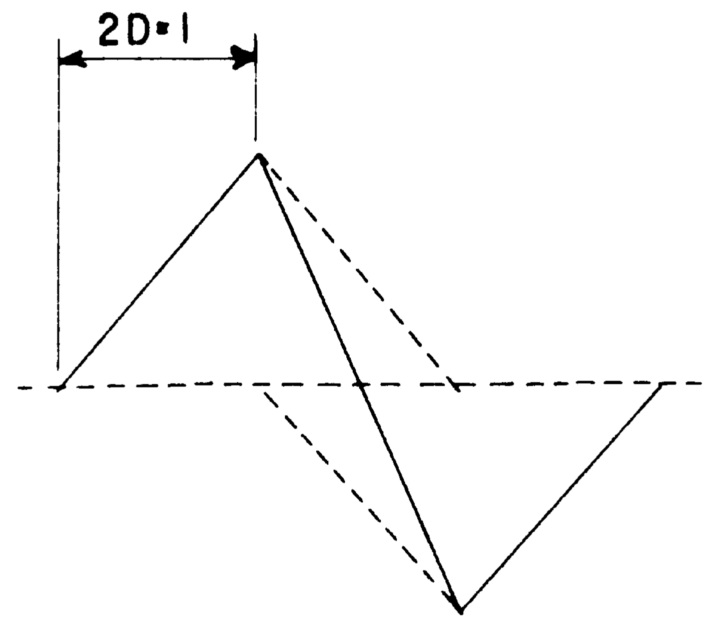


FIG. 6

CHAPTER III

3.1 Experimental Results for Square Wave Applied Voltage

In equation (2) reflection from the sending end was suppressed by the input termination of Z_o, the characteristic impedance of the transmission line. In the practical application, however, it is impossible to obtain an impedanceless voltage source and hard to obtain a source with an impedanceless than the Z_o of a natural line. Also the reactive component of the internal impedance of most physical generators is large enough to show considerable deviation from the ideal case.

To partially overcome these difficulties, an artificial line was constructed with characteristic impedance of 1000 ohms, and driven by a pulse generator as shown in Fig. 7.

The three cases considered in Sect. 2.2 are shown in the oscillographic photographs in Figs. 8, 9, and 10. The attenuation of the line accounts for the decreased amplitude of the reflected pulse.

3.2 Differentiation Action of Shorted Line

The differentiating properties of a short circuit terminated electrically short transmission line were also experimentally demonstrated by the setup in Fig. 7. The applied voltage and the

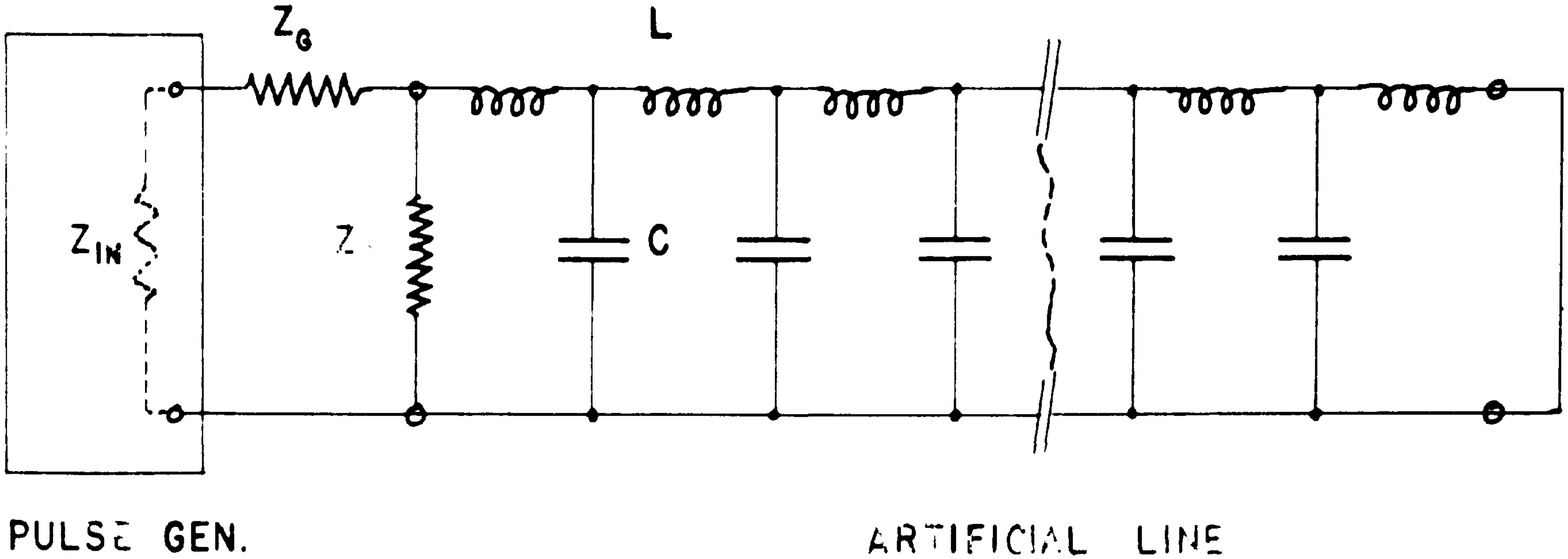


FIG. 7

voltage $e(o,t)$ are shown in the oscillographic photographs in Fig. 11.

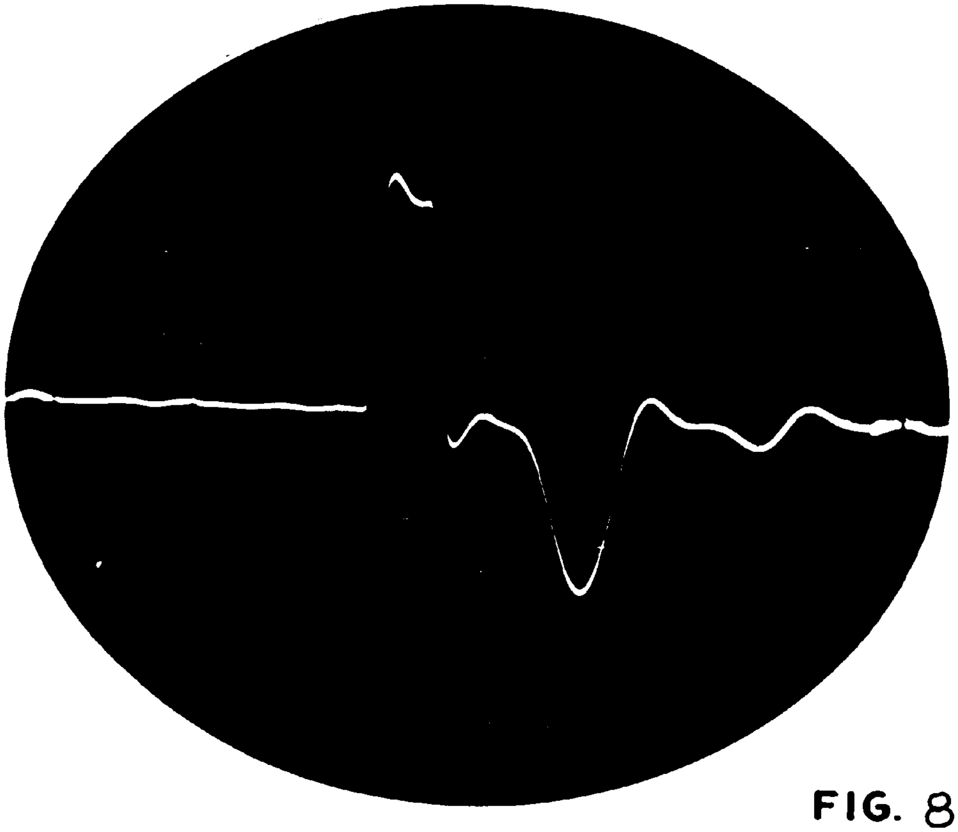


FIG. 8

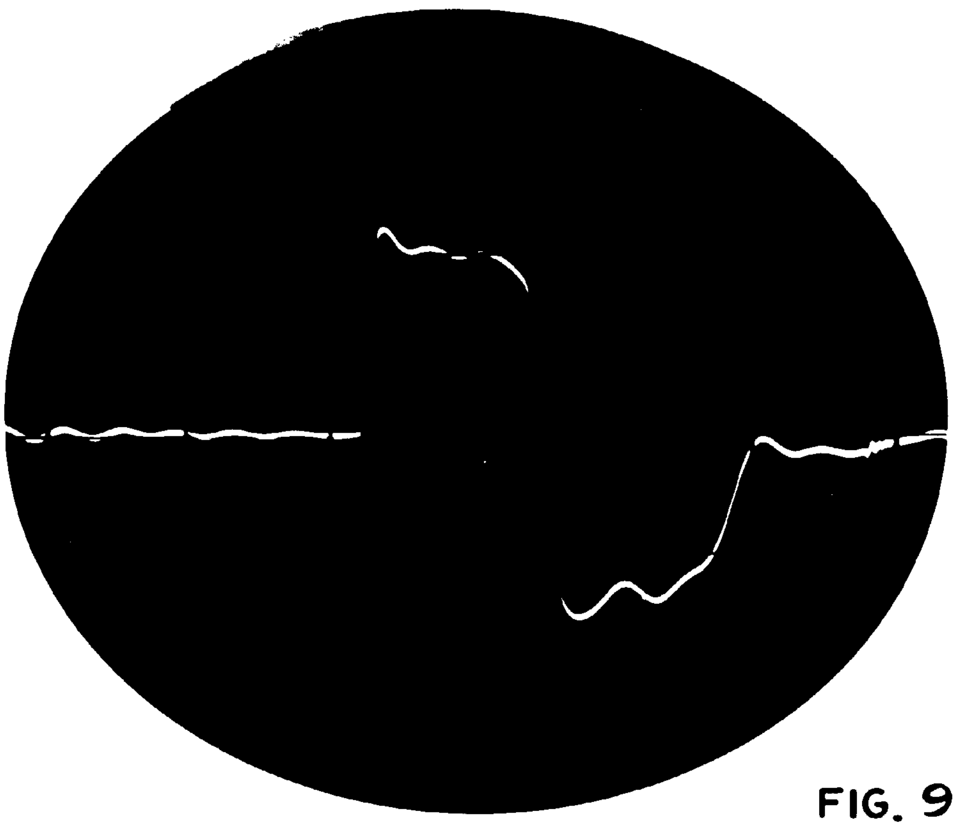


FIG. 9

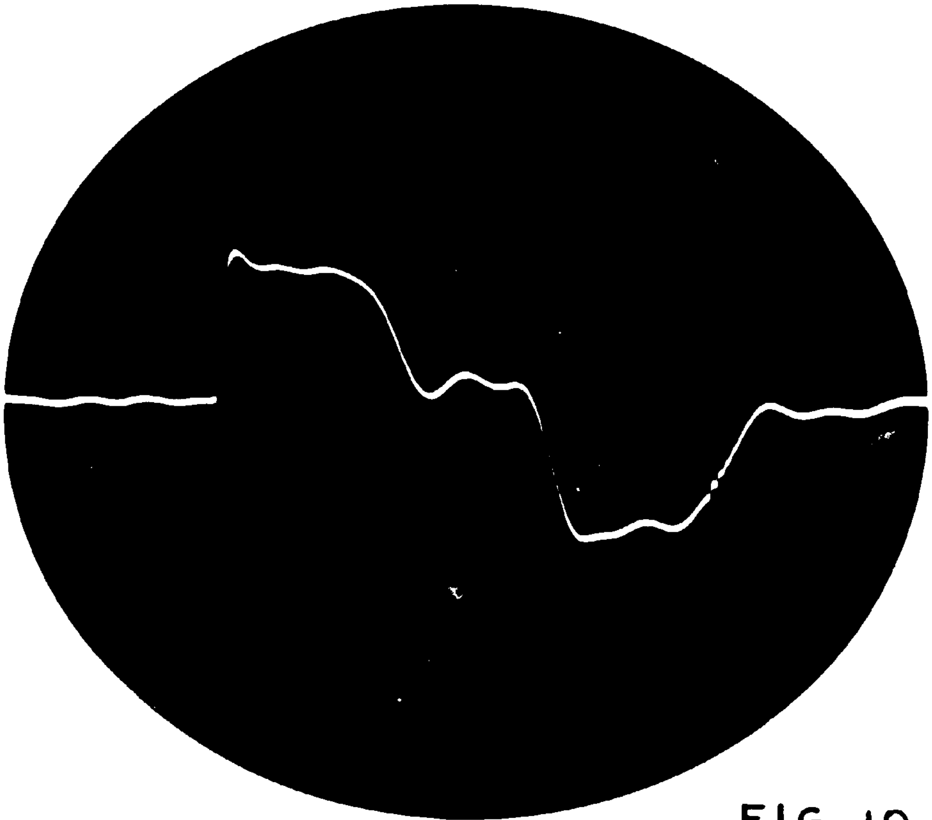


FIG. 10

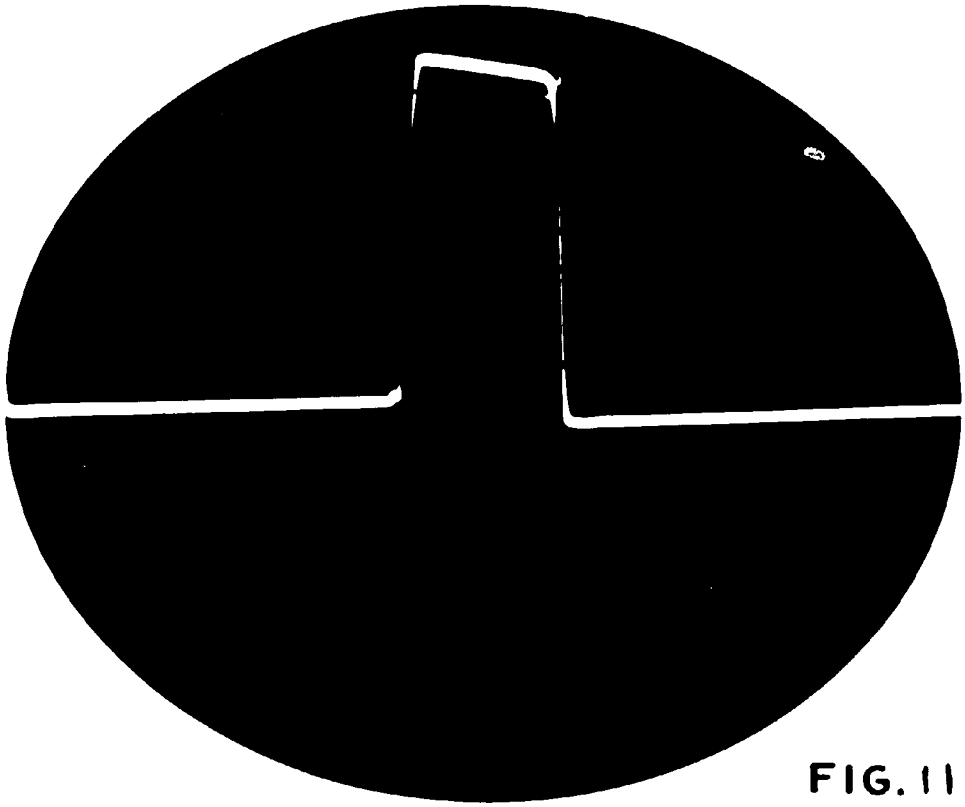


FIG. 11 a

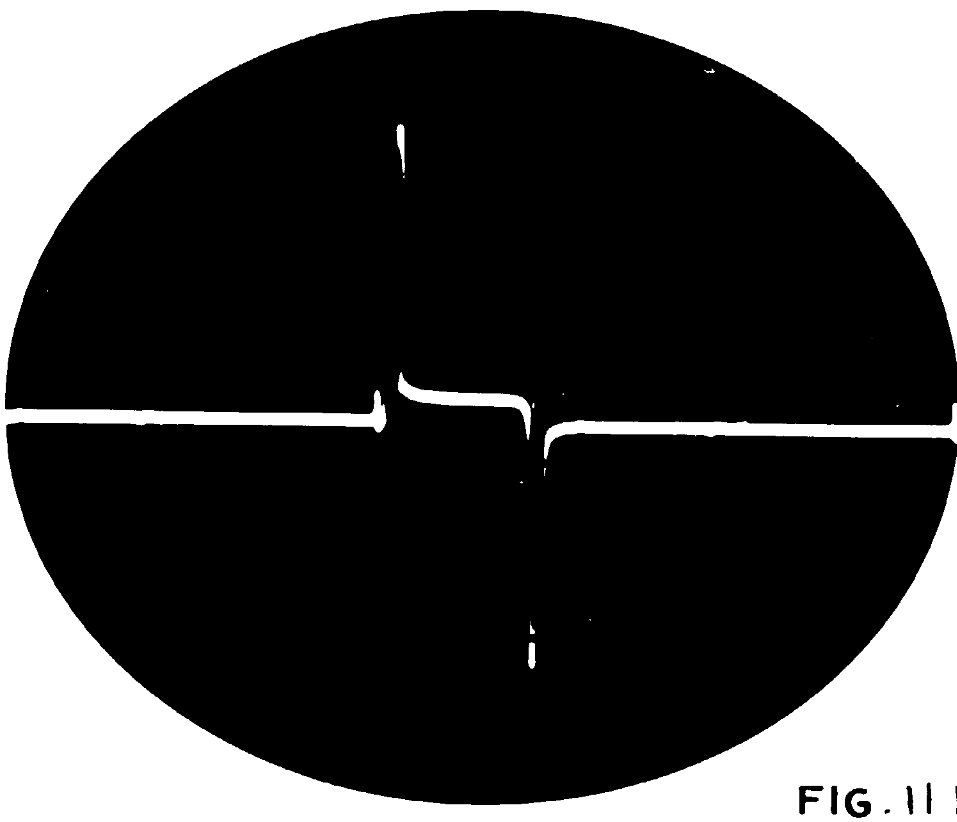


FIG. 11 b

CHAPTER IV

4.1 The Typical Peak Amplifier Stage

As mentioned in Sect. 1.2, the choice of a tube for peak amplifier application is primarily determined by the transconductance (G_m) and the plate and grid dissipation. In addition, for very short pulse work, a large gain-bandwidth product is desired. The 6AG7 tube, which is quite well suited for this application, was used for the experimental work in connection with this problem. For pulses less than 0.05 microseconds duration, two 6AG7 tubes were paralleled to increase the available dissipation, and the resulting circuit is shown in Fig. 12. The components used are listed below:

R_1	2k	C_2	0.006 mfd.
R_2	100	C_3	0.006 mfd.
R_3	10k	C_4	0.006 mfd.
R_4	50k	C_5	0.05 mfd.

V_1 & V_2 6AG7

Plate supply voltage = 400 volts

Screen supply voltage = 250 volts

This circuit was driven by a 100 volt positive triangular pulse at an impedance of 100 ohms.

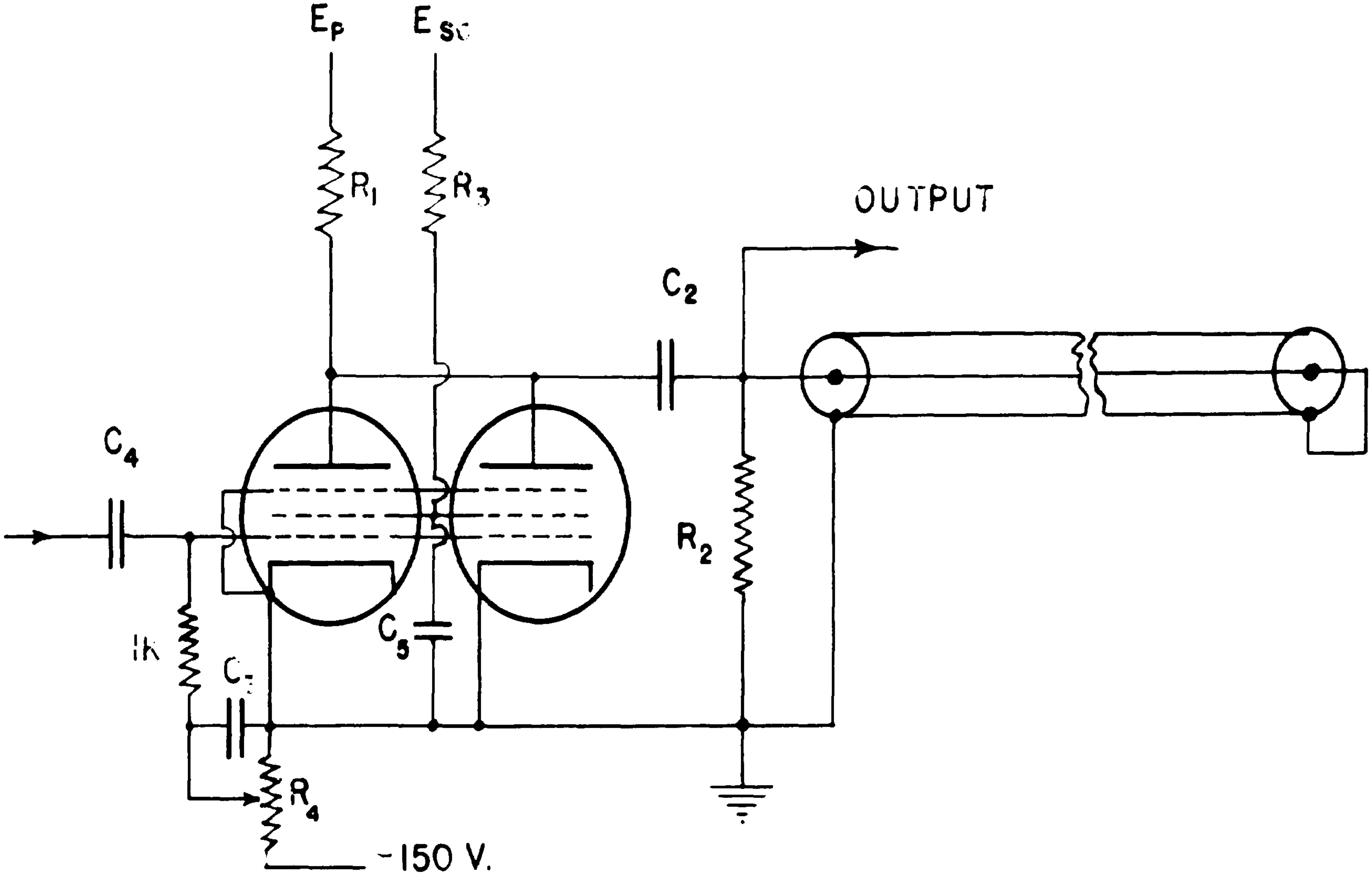


FIG. 12

4.2 Equivalent Circuit for the Typical Peak Amplifier

The procedure normally used in deriving an equivalent A.C. circuit of an amplifier containing a pentode tube is to replace the tube by a constant current source in series with the equivalent plate resistance of the tube. For positive pulsed tubes however, it is more convenient to replace the tube by an equivalent plate resistance in series with a switch, leaving the plate power supply connections intact. This is justified as follows:

Reference to the positive pulsed grid operating characteristics for the 6AG7 tube,[9] Figures 13 and 14, show that its plate resistance is nearly constant after the grid is 25 volts positive. As the amplifier in Figure was driven by a 100 volt positive triangular pulse, only about 1/8 of the period of the driving pulse is used to produce the leading edge of the effective square plate resistance function. If that time period is neglected, the tube may be replaced by an equivalent plate resistance in series with a switch. Determining the average plate resistance per tube from Figure 14, this value is halved because of the paralleled stage, and used in the equivalent circuit. The equivalent circuit obtained with these assumptions is shown in Figure 15. C_1 is the output capacitance of the paralleled 6AG7 stage. To facilitate calculations, the circuit of Fig. 15 is represented on the nodal basis in Fig. 16.

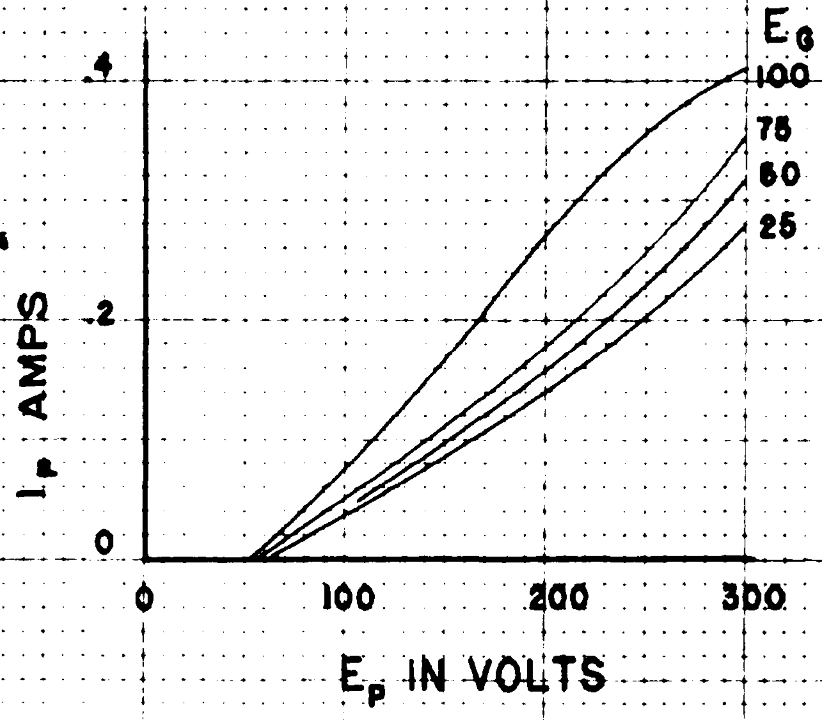


FIG. 13

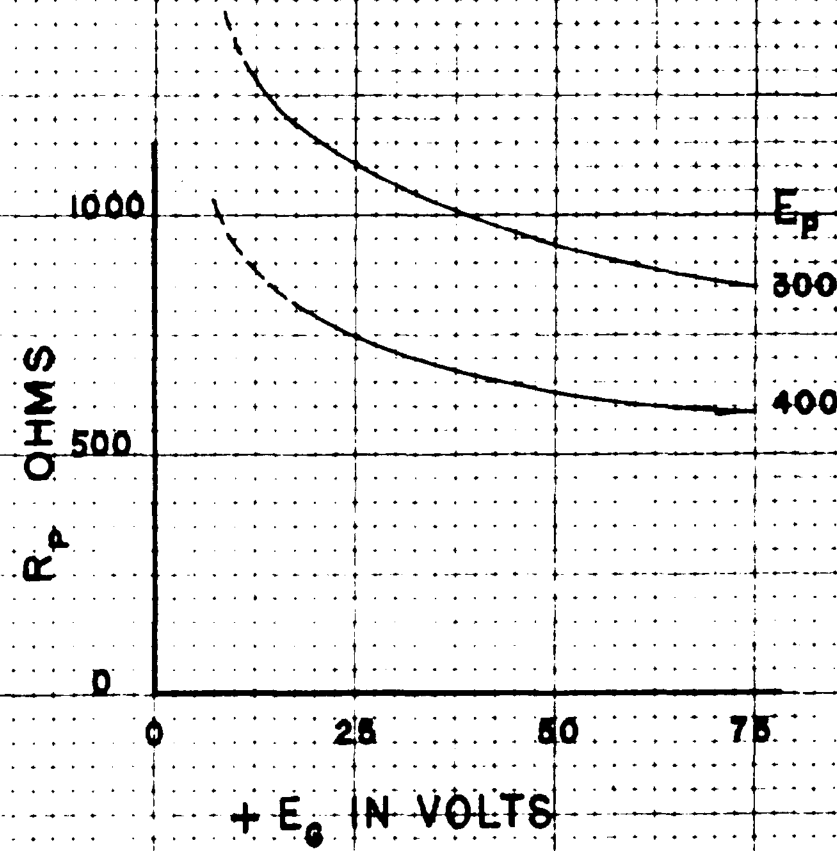


FIG. 14

6AG7 CHARACTERISTICS

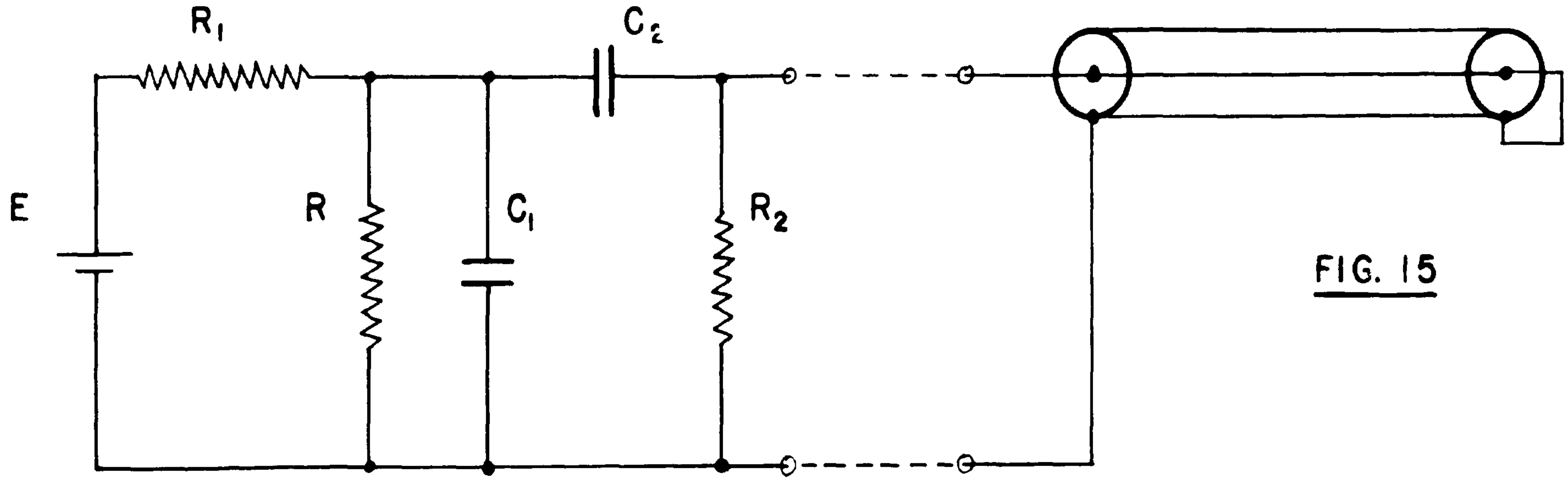


FIG. 15

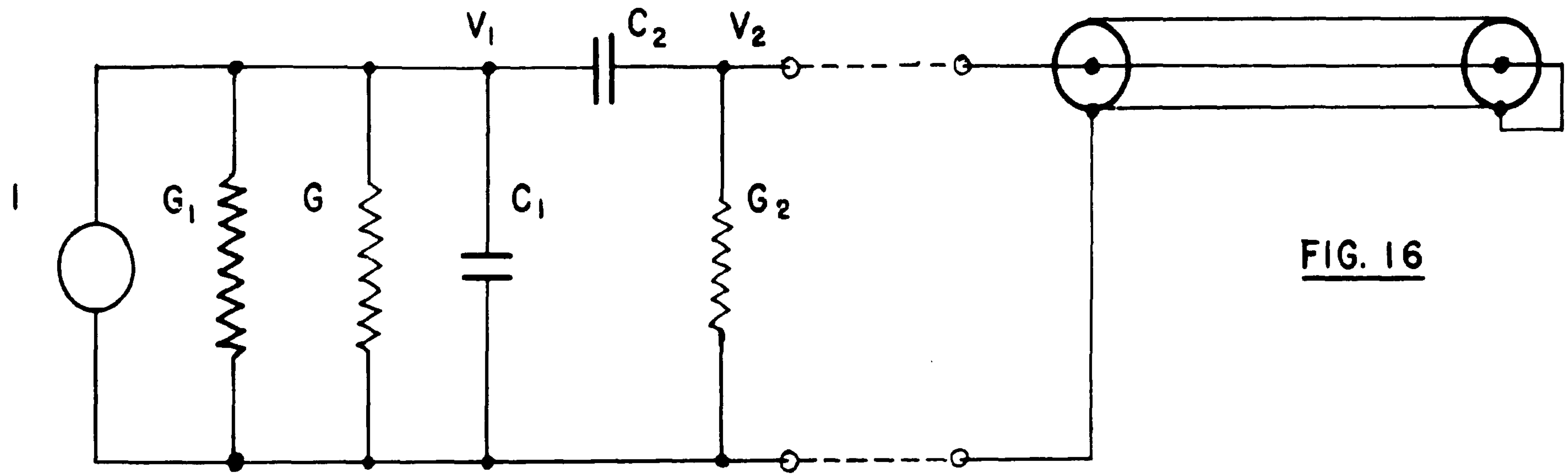


FIG. 16

4.3 Method of Solution Used

Using the method of LaPlace transformations,[10] the transform of the output of the peak amplifier will be found first without the line connected. Next, the transform of the impedance function looking back from the output terminals is calculated. The application of Thevenin's Theorem to this system allows an analogous solution to that used in Sect. 2.2: it is considerably complicated by the equivalent input impedance Z_g. After the complete solution has been found in terms of the LaPlace transform, the inverse transformation will be calculated obtaining the resultant pulse waveform as a function of time.

4.4 Leading Edge of Negative Pulse

The nodal equations for Figure 16 are

$$I = \left[G + G_1 + (C_1 + C_2)p\right] v_1(t) - C_2 p\, v_2(t) \tag{4.1}$$

$$0 = -C_2 p\, v_1(t) + \left[G_2 + (C_2 + C_3)p\right] v_2(t) \tag{4.2}$$

where $p = d/dt$

Taking the LaPlace transform of equations (4.1 & 4.2)

$$\frac{I}{s} = \left[G_1 + G + (C_1 + C_2)s\right] v_1(s) - (C_1 + C_2)e_1 - C_2 s\, v_2(s) + C_2 e_2 \tag{4.3}$$

(4.4)

$$0 = -C_2 s\, v_1(s) + C_2 e_1 + \left[G_2 + (C_2 + C_3)s\right] v_2(s) - (C_2 + C_3) e_2$$

Solving (4.3) and (4.4) for $v_2(s)$

$$V_2(s) = \frac{a_0 s + a_1}{A s^2 + B s + C} \tag{4.5}$$

where

$$a_0 = C_2^2 e_2 + (C_1 + C_2)(C_2 + C_3) e_2$$

$$a_1 = I C_2 + (G + G_1)(C_2 + C_3) e_2 - C_2 e_1 (G + G_1)$$

$$A = (C_1 C_2 + C_1 C_3 + C_2 C_3)$$

$$B = (G + G_1)(C_2 + C_3) + G_2 (C_1 + C_2)$$

$$C = G_2 (G + G_1)$$

Assume roots of the denominator of (4.5) so

$$s^2 + \frac{B}{A} s + \frac{C}{A} = (s + \alpha)(s + \beta) \tag{4.6}$$

The inverse LaPlace transformation of (4.6)" is

$$V_2(t) = \frac{a_0}{A}\left[\frac{\left(\frac{a_1}{a_0} - \alpha\right)}{(\beta - \alpha)} \varepsilon^{-\alpha t} + \frac{\left(\frac{a_1}{a_0} - \beta\right)}{(\alpha - \beta)} \varepsilon^{-\beta t}\right] \tag{4.7}$$

and is the value of the output voltage for the interval of time during which the amplifier is pulsed.

4.5 Trailing Edge of Pulse

Similarly, to find the initial conditions for the discharge transient,

$$V_1(s) = \frac{d s^2 + e s + f}{s\left[D s^2 + E s + F\right]} \tag{4.8}$$

Again assume roots so that

$$\left(s^2 + \frac{e}{d} s + \frac{f}{d}\right) = (s + \gamma)(s + \delta) \tag{4.9}$$

$$\left(s^2 + \frac{E}{D} s + \frac{F}{D}\right) = (s + \gamma_1)(s + \delta_1)$$

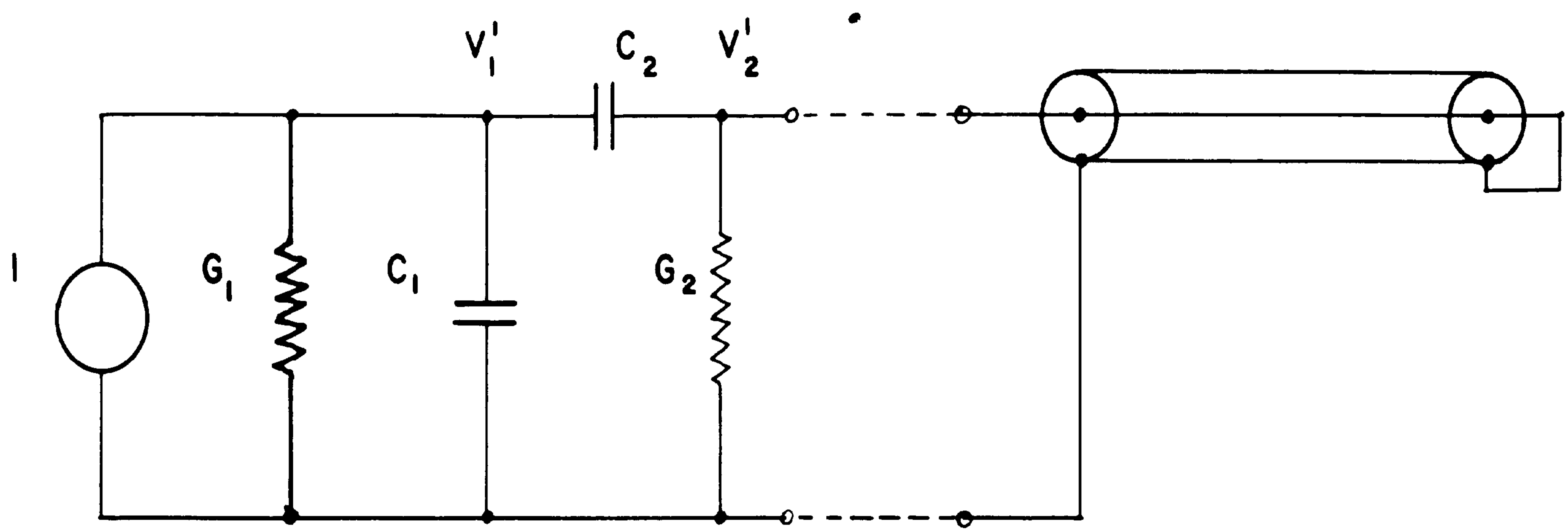


FIG. 17

where $d = C_2^2 e_1 + (C_2+C_3)\left[(C_1+C_2)e_1 - 2C_2e_2\right]$

$e = G_2(C_1+C_2) + (G+G_1)(C_2+C_3+G)$

$f = G_2 I$

$D = C_2^2 + (C_2+C_3)(C_1+C_2)$

$E = G(C_1+C_2) + (G+G_1)(C_2+C_3)$

$F = G(G+G_1)$

Taking the inverse LaPlace transformation of (4.9)[12]

$$v_1(t) = \frac{d}{D}\left[\frac{\gamma\delta}{\gamma_1\delta_1} - \frac{(\gamma-\gamma_1)(\delta-\gamma_1)}{\gamma_1(\delta_1-\gamma_1)}\varepsilon^{-\gamma_1 t} - \frac{(\gamma-\delta_1)(\delta-\delta_1)}{\delta_1(\gamma_1-\delta_1)}\varepsilon^{-\delta_1 t}\right] \qquad (4.10)$$

At time $t=2\tau$, (2τ=duration of the input driving pulse) the equivalent circuit has changed to that shown in Fig. 17. $v_1(t)$ and $v_2(t)$ have initial values e_1' and e_2' calculated from equations (4.7 and 4.10). The equations for Fig. 17 are

$$I = \left[G_1 + (C_1+C_2)p\right]v_1(t) - C_2 p\, v_2(t) \qquad (4.11)$$

$$0 = -C_2 p\, v_1(t) + \left[G_2 + (C_2+C_3)p\right]v_2(t) \qquad (4.12)$$

The LaPlace transformations of the above are

$$\frac{I}{s} = \left[G_1 + (C_1+C_2)s\right]v_1(s) - (C_1+C_2)e_1' - C_2 s\, v_2(s) + C_2 e_2' \qquad (4.13)$$

$$0 = -C_2 s\, v_1(s) + C_2 e_1' + \left[G_2 + (C_2+C_3)s\right]v_2(s) - (C_2+C_3)e_2' \qquad (4.14)$$

whereby

$$v_2'(s) = \frac{a_0'(s) + a_1'}{A's^2 + B's + C'} = \frac{a_0'}{A'}\left[\frac{s + \frac{a_1'}{a_0'}}{(s+\alpha')(s+\beta')}\right] \qquad (4.15)$$

where $a_0' = C_2^2 e_2' + (C_1+C_2)(C_2+C_3)e_2'$

$a_1' = IC_2 + G_1(C_2+C_3)e_2' - C_2 e_1' G_1$

$A' = (C_1C_2 + C_2C_3 + C_1C_3)$

$B' = G_1(C_2+C_3) + G_2(C_1+C_2)$

$C' = G_1 G_2$

The inverse transformation yields

$$v_2'(t) = \frac{a_0'}{A'}\left[\frac{\left(\frac{a_1'}{a_0'} - \alpha'\right)}{(\beta'-\alpha')}\,\varepsilon^{-\alpha' t} + \frac{\left(\frac{a_1'}{a_0'} - \beta'\right)}{(\alpha'-\beta')}\,\varepsilon^{-\beta' t}\right] \qquad (4.16)$$

This is the trailing edge of the pulse produced by the amplifier circuit.

4.6 Output Impedance of Fig. 16

The impedance if the network looking toward the tube from the input terminals of the shorted line is

$$Z = \frac{1}{G_2 + C_3 s + A_1 s\left(\frac{s+\alpha_1}{s+\beta_1}\right)} \qquad (4.17)$$

where

$$A_1 = \left(\frac{C_1 C_2}{C_1 + C_2}\right)$$

$$\alpha_1 = \frac{(G + G_1)\,C_2}{C_1 C_2} = \frac{G + G_1}{C_1}$$

$$\beta_1 = \frac{G + G_1}{C_1 + C_2}$$

4.7 Solution with Shorted Line Attached

Applying Thevenin's Theorem to the system, the equivalent voltage is that derived as the output pulse from the tube circuit without the line attached, and the equivalent series impedance is that shown in (4.17) with the change $G = G \quad t < 2\tau$

$G = 0 \quad t > 2\tau$

thus v_2 is used with Z, and v_2' is used with Z'

From Sect. 4.3,

$$v_2(s) = \frac{a_0 s + a_1}{A s^2 + B s + C} \tag{4.6}$$

The solution of Fig. 1 is shown by Goldman[13] to be

$$\tilde{E}(x,s) = \frac{F Z_0}{Z_G + Z_0} \left\{ \varepsilon^{-s\sigma x} - \left[\frac{Z_0 - Z_T}{Z_0 + Z_T}\right] \varepsilon^{-s\sigma(2d-x)} \right.$$

$$\left. + \left[\frac{Z_0 - Z_T}{Z_0 + Z_T}\right]\left[\frac{Z_0 - Z_G}{Z_0 + Z_G}\right] \varepsilon^{-s\sigma(2d+x)} + \cdots \right\} \tag{4.18}$$

The insertion of the terminal conditions in this case give the voltage across the impedance Z_g to be

$$E(z_g,s) = \frac{\left(\frac{a_0 s + a_1}{As^2 + Bs + C}\right)\left(\frac{1}{G_2 + C_3 s + A_1 s\left(\frac{s+\alpha_1}{s+\beta_1}\right)}\right)}{Z_0 + \left(\frac{1}{G_2 + C_3 s + A_1 s\left(\frac{s+\alpha_1}{s+\beta_1}\right)}\right)} \left\{ 1 - \varepsilon^{-2s\sigma d} \right.$$

$$\left. + \left[\frac{Z_0 - \left(\frac{1}{G_2 + C_3 s + A_1 s\left(\frac{s+\alpha_1}{s+\beta_1}\right)}\right)}{Z_0 + \left(\frac{1}{G_2 + C_3 s + A_1 s\left(\frac{s+\alpha_1}{s+\beta_1}\right)}\right)}\right] \varepsilon^{-2s\sigma d} + \cdots \right\} \tag{4.19}$$

where the subscript 1 has been added to distinguish the coefficient in the expression for the impedance. Further expansion gives

$$V_2(s) = \frac{a_0}{A}\left[\frac{(s+\frac{a_1}{a_0})(s+\beta_1)}{z_0\left[G_2(s+\beta_1) + C_3 s\,(s+\beta_1) + A_1(s+\alpha_1) + \frac{1}{z_0}(s+\beta_1)\right](s+\alpha)(s+\beta)}\right]\left\{1\right.$$

$$\left. - \epsilon^{-2s\sigma d} + \left[\frac{z_0\left[G_2(s+\beta_1) + C_3 s\,(s+\beta_1) + A_1(s+\alpha_1)\right] - (s+\beta_1)}{H(s+\alpha_3)(s+\beta_3)}\right]\epsilon^{-2s\sigma d} + \cdots\right\}$$

(4.20)

where the assumed roots of the denominator of the last term of equation (4.19) are such that

$$z_0\left[G_2(s+\beta_1) + C_3 s\,(s+\beta_1) + A_1(s+\alpha_1) + \frac{1}{z_0}(s+\beta_1)\right] - (s+\beta_1) = H(s+\alpha_3)(s+\beta_3)$$

and

$$Hz_0\left[G_2(s+\beta_1) + C_3 s\,(s+\beta_1) + A_1(s+\alpha_1) + \frac{1}{z_0}(s+\beta_1)\right](s+\alpha)(s+\beta)(s+\alpha_3)(s+\beta_3) =$$
$$K_2(s+\delta_2)(s+\delta_3)(s+\delta_4)(s+\delta_5)(s+\delta_6)(s+\delta_7)$$

Inspection of this shows the voltage $E_g(t)$ to be the sum of four exponentials in terms of t minus unit step function u (t-b) times the same 4 exponentials in terms of (t-b) plus the unit step function at (t-b) times the 6 exponential terms evolving from the last term of equation (4.20)

It is assumed that the number of reflections used in this derivation are sufficient to approximate the experimental case. The inverse LaPlace of equation (4.20) is given in equation (4.21).

$$U_2(t) = K \sum_{k=2}^{k=5} \frac{\left(\frac{a_1}{a_0} - \gamma_k\right)(\beta_1 - \gamma_k)(\gamma_k - \gamma_k)}{(\gamma_2 - \gamma_k)(\gamma_3 - \gamma_k)(\gamma_4 - \gamma_k)(\gamma_5 - \gamma_k)} \varepsilon^{-\gamma_k t}$$

$$- K\, U(t-b) \sum_{k=2}^{k=5} \frac{\left(\frac{a_1}{a_0} - \gamma_k\right)(\beta_1 - \gamma_k)(\gamma_k - \gamma_k)}{(\gamma_2 - \gamma_k)(\gamma_3 - \gamma_k)(\gamma_4 - \gamma_k)(\gamma_5 - \gamma_k)} \varepsilon^{-\gamma_k (t-b)}$$

$$+ K_1\, U(t-b) \sum_{k=2}^{k=7} \frac{\left(\frac{a_1}{a_0} - \delta_k\right)(\beta_1 - \delta_k)(\alpha_3 - \delta_k)(\alpha_4 - \delta_k)(\delta_k - \delta_k)}{(\delta_2 - \delta_k)(\delta_3 - \delta_k)(\delta_4 - \delta_k)(\delta_5 - \delta_k)(\delta_6 - \delta_k)(\delta_7 - \delta_k)} \varepsilon^{-\delta_k (t-b)}$$

NOTE: $b = 2\upsilon d$

Equation (4.21)

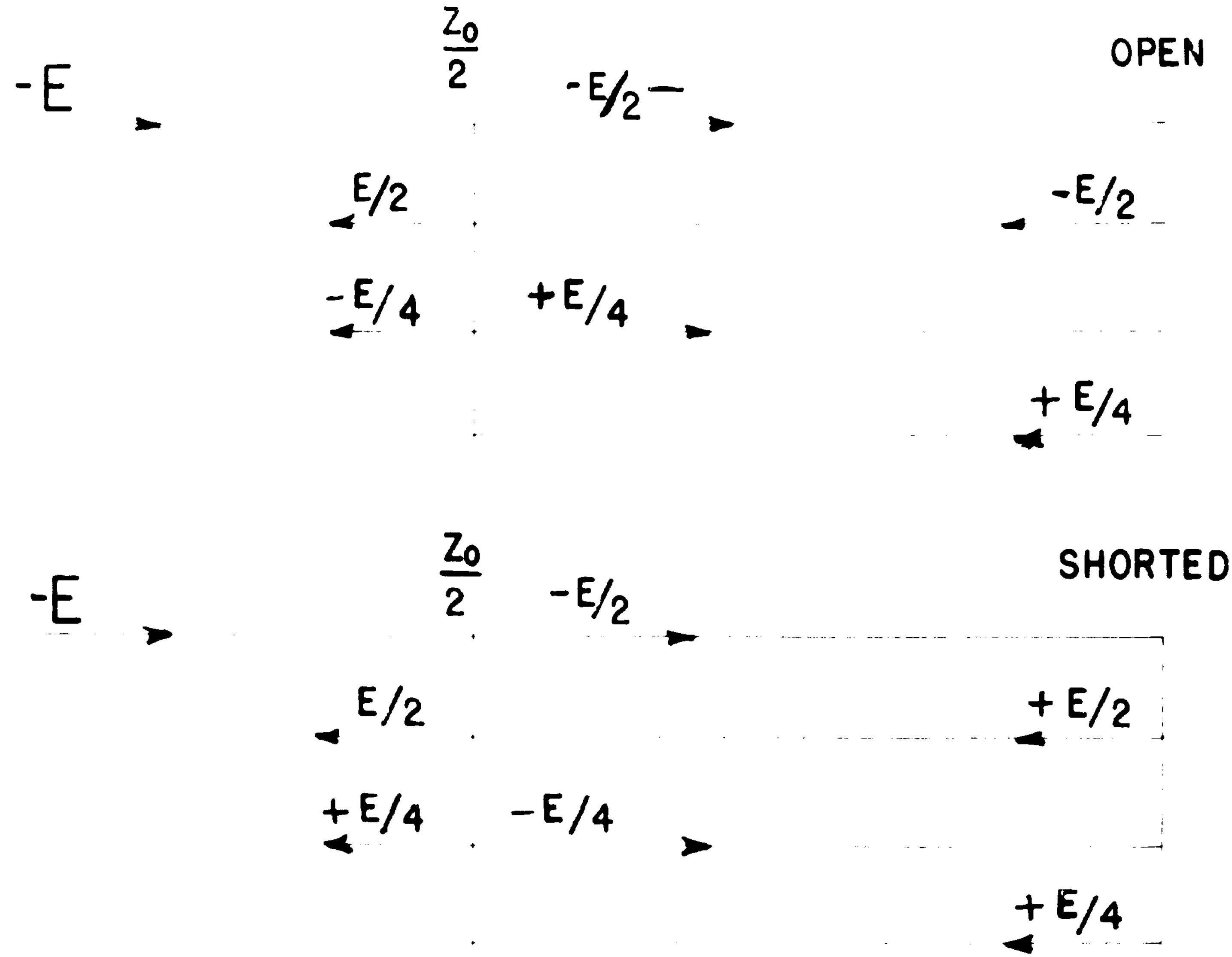
CHAPTER V

5.1 Photographic Data on Reflection Process

The fastest sweep available in the laboratory was 0.1 microsecond/cm. and to provide interpreted data, the pictures were taken using a 0.1 microsecond negative triangular pulse.

Figures 21, 22, and 23 show an approximately square negative pulse of 0.12 microsecond duration, the reflection from an open line of 0.20 microseconds delay and the reflection from the same line when shorted. The reduction in amplitude is due primarily to the mismatch at the termination and not to the attenuation in the line. This is obvious on noticing the second reflection starting at 0.40 microseconds; in both cases it is positive as it should be when evaluating the reflections on the basis of the diagram and the boundary reflection analysis[14] shown in Fig. 20. It should be noted that for many cases, this type analysis is sufficient.

Readjustment of the pulse generator produced the pulse shown in Fib. 24. This is approximately triangular in shape and of duration of about 0.15 microseconds. It should be noted that the leading edge, i.e. that part of the pulse produced by the effective square negative pulse impressed on the network, takes about 0.05 microseconds to come to maximum amplitude. The series of pictures in Figures



$\frac{Z_0}{2}$
OPEN
-E
-E/2
E/2
-E/2
-E/4
+E/4
+E/4
$\frac{Z_0}{2}$
SHORTED
-E
-E/2
E/2
+E/2
+E/4
-E/4
+E/4

FIG. 20

25 through 30 show the effect of the variation of the length of the delay line on the resultant pulse waveform. Particular notice should be given to the time at which the reflected pulse produces the change in polarity. These all correspond to case 2 discussed in Sect. 2.2 and show definitely the cancellation period and the change in pulse length predicted by this simple addition of the original and reflected pulses.

The entire series of pictures in Figures 21 through 30 were taken with vertical calibration at 240 volts/div. and the horizontal calibration at 0.2 microseconds div.

A composite multi-exposure is shown in Fig. 31. The wave forms are distorted due to the amplifier in the oscillograph but the relative amplitudes and time displacements are sufficiently accurate to show the variations expected. Tabular data of line lengths is shown on the following page.

5.2 Delay Line Data

The following data gives the length of the delay lines used to produce the oscillograms in Figures 25 through 30.

Figure	Length	Calc. Delay
25	10.5 ft.	0.0315 usec
26	6.5	0.0195
27	3.25	0.00974
28	2.08	0.00623
29	1.38	0.00413
30	0.84	0.00252

The delay was calculated on the basis of two way transit time and a velocity of propagation factor of 0.695. The lines used in Figures 26 through 30 are the lines used in conjunction with the pulse amplifier unit described in Chapter VI.

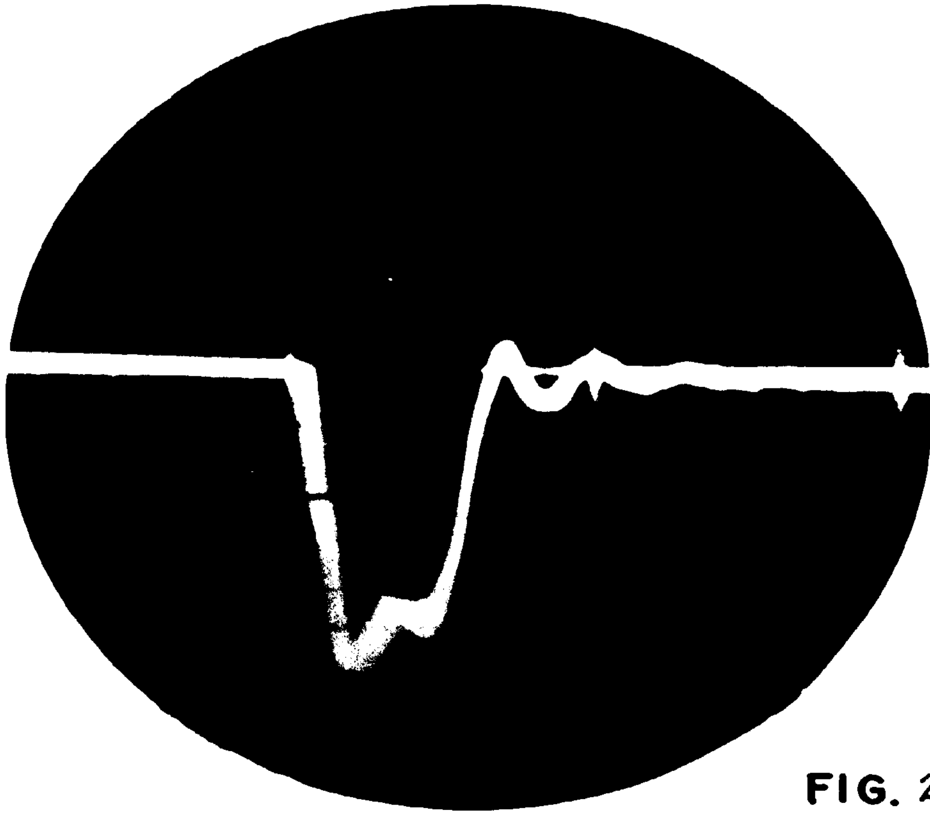


FIG. 21

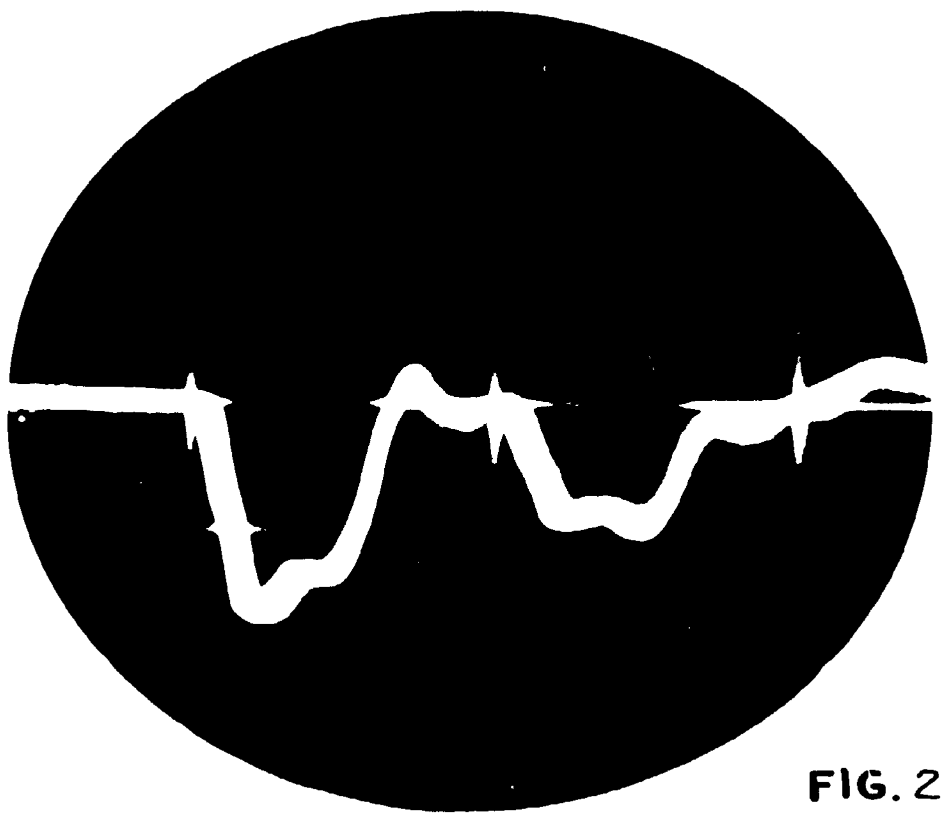


FIG. 22

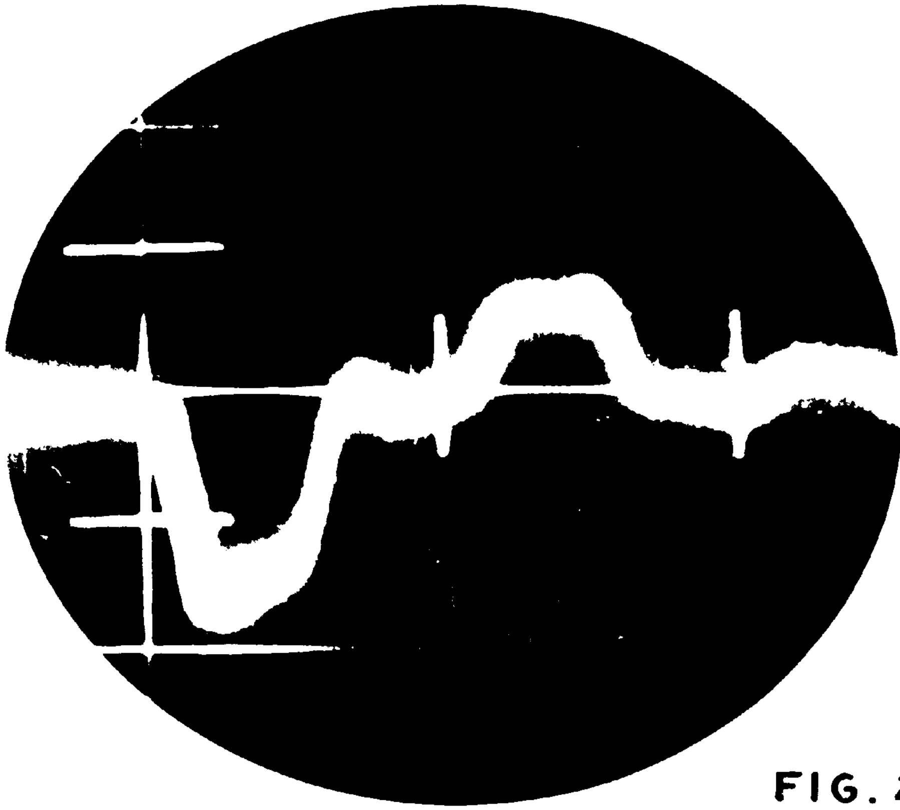


FIG. 23

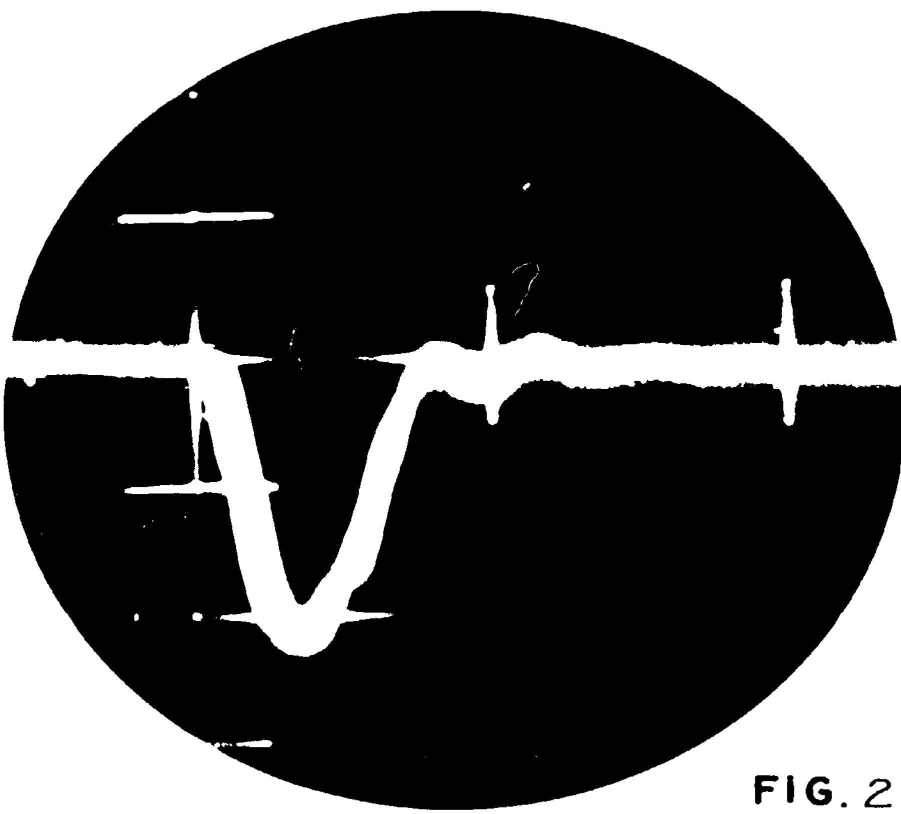


FIG. 24

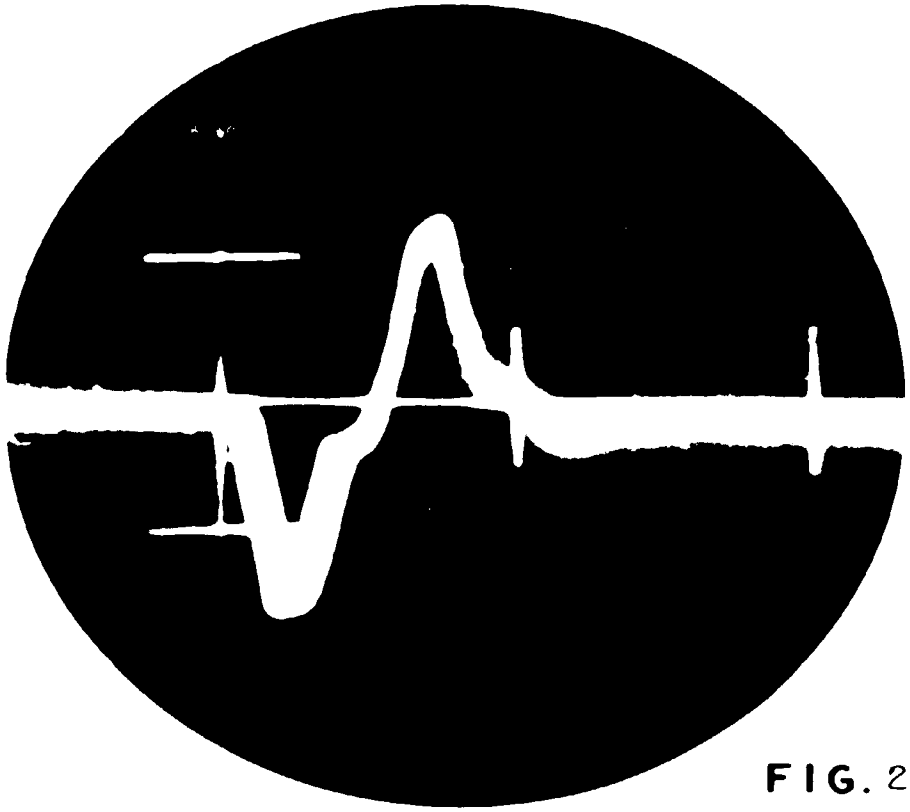


FIG. 25

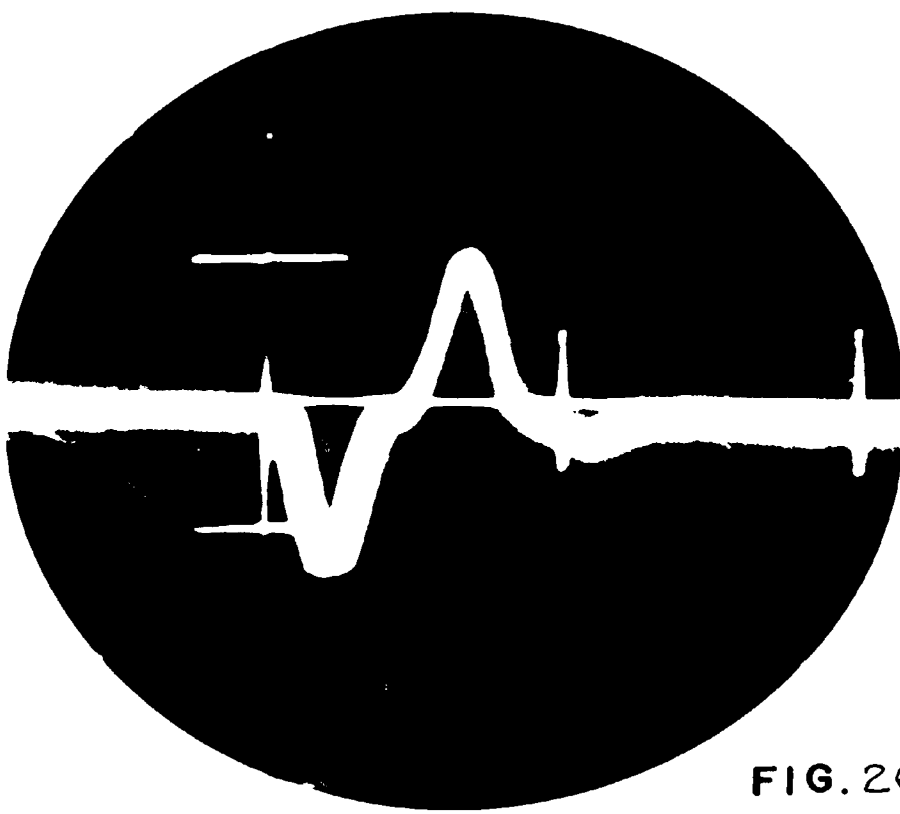


FIG. 26

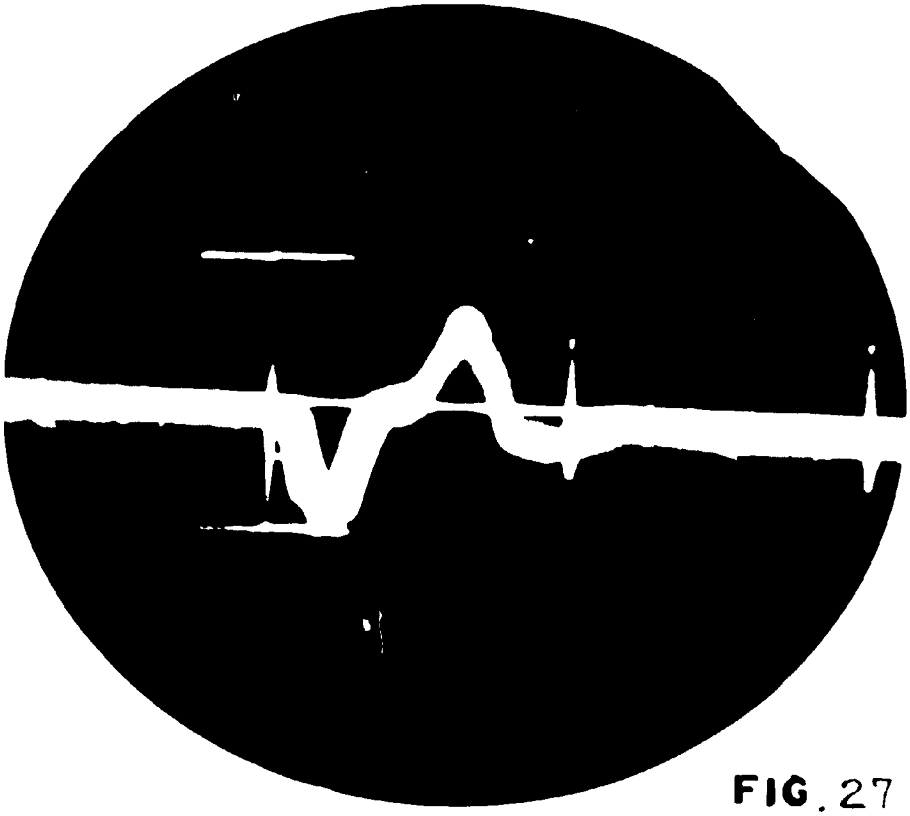


FIG. 27

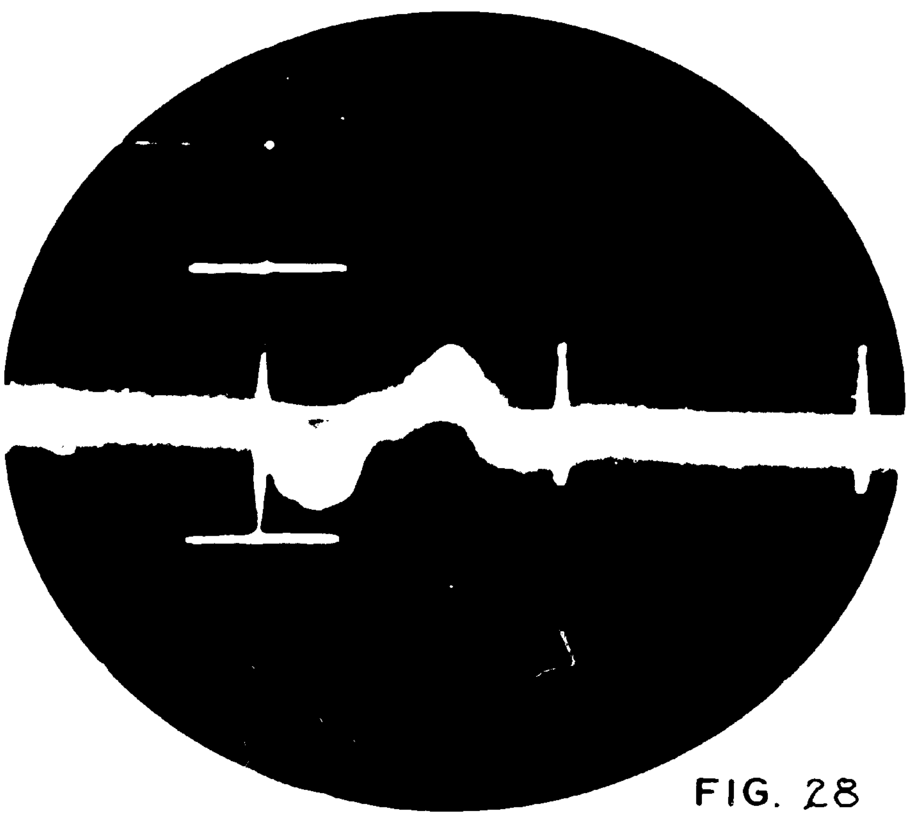


FIG. 28

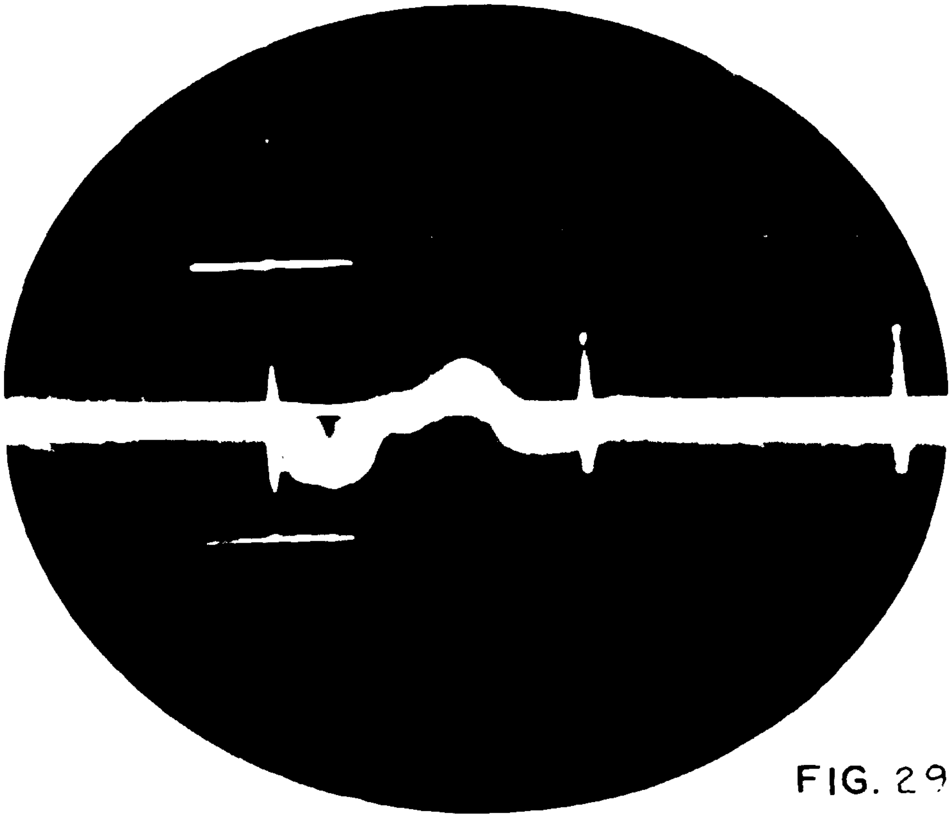


FIG. 29

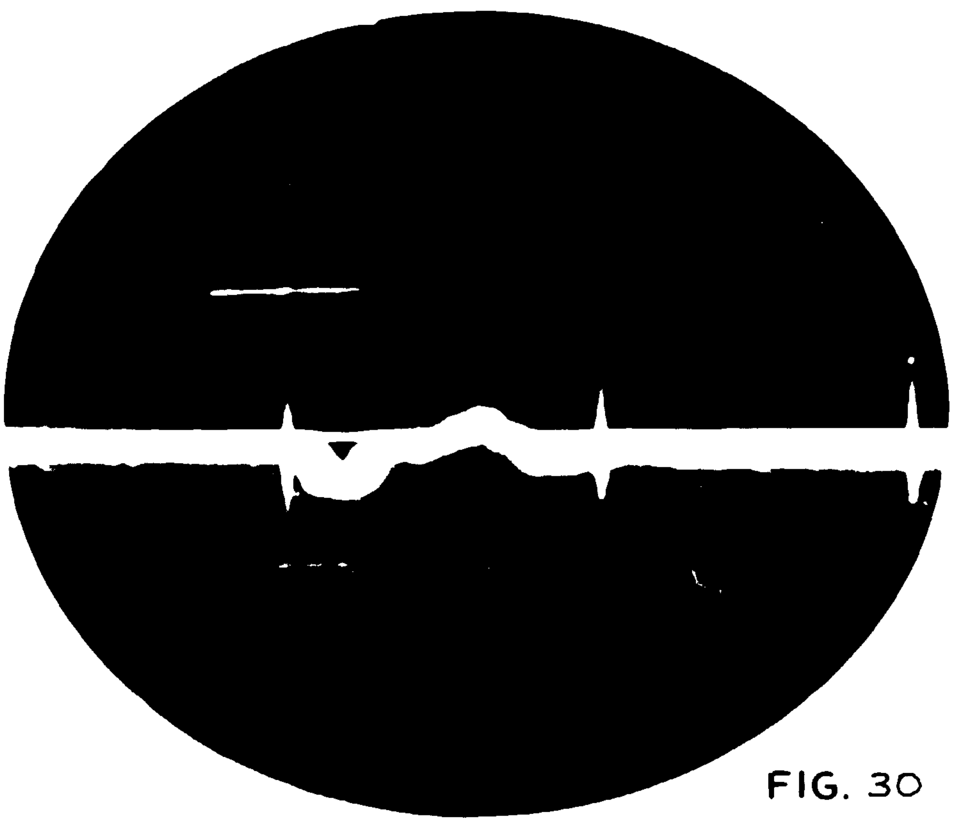


FIG. 30

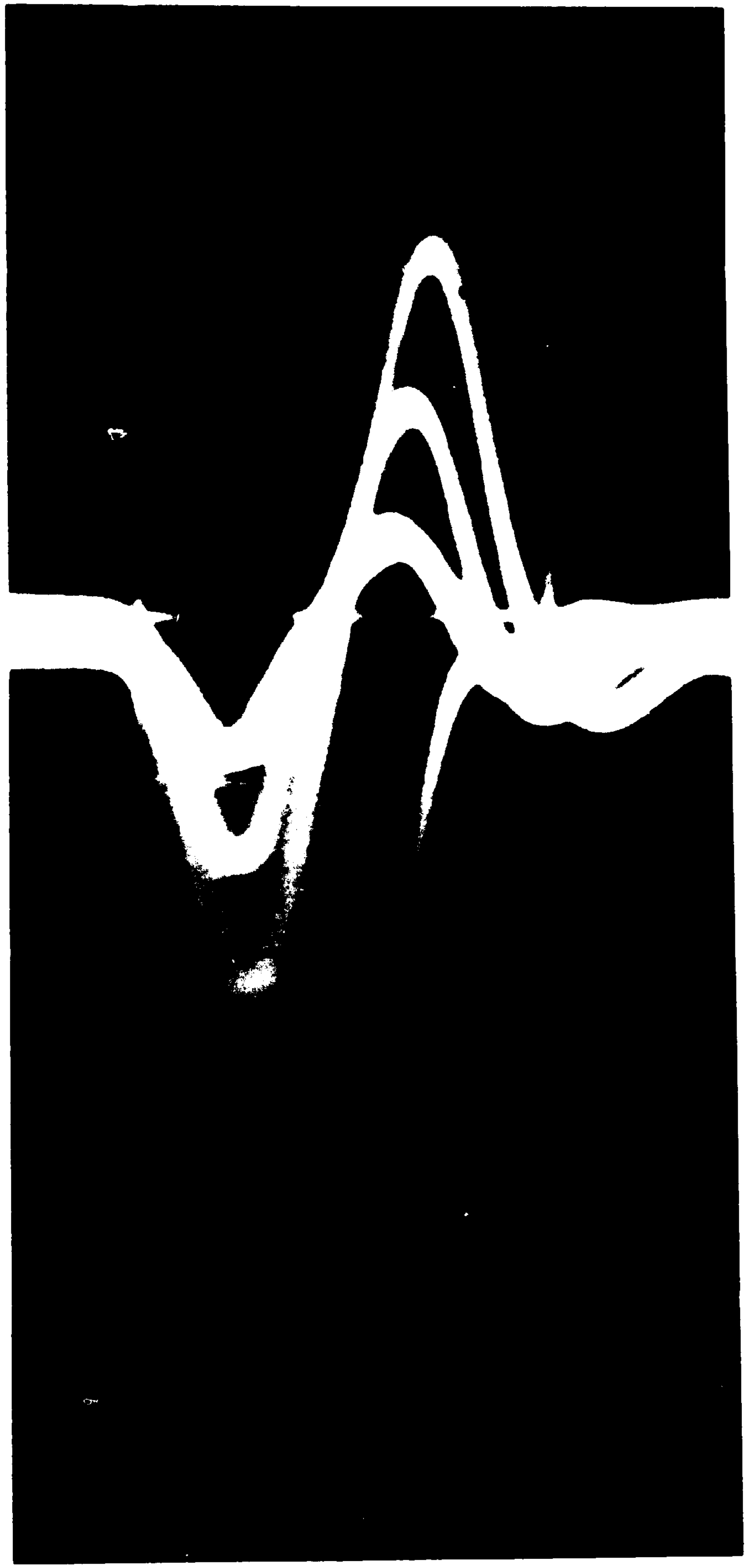


FIG. 31

CHAPTER VI

6.1 The Pulse Generator Unit

The principle of pulse inversion by shorted transmission lines has been applied in the construction of a generator capable of producing positive pulses of 0.006 microseconds duration at repetition rates of 400 kc. to 800 kc. The pulse generator and all of its associated parts were designed and constructed by the author. Although considerable time was spent in this work, the inversion method and the end result of its application is of primary interest in this thesis, and therefore the details of design and construction have been omitted. The pictures and diagrams are mostly self explanatory, but brief explanations have been included where necessary.

The basic pulse was obtained by applying suitable wave shaping circuits to a sinusoidal waveform. This choice was made primarily because of the necessity for a small amount of jitter in the observation of very short pulses. Two stages of peak pulse amplification utilizing pulse transformers as interstage coupling provided a negative 100 watt triangular pulse of approximately 0.1 microseconds duration. The pulse repetition rate was variable from 400 kc. to 800 kc.

In addition, a cathode follower take off stage triggered a multivibrator square wave generator operating at about 200 kc. This gated a linear saw tooth generator whose output was amplified and used as the sweep for a built in pulse monitoring oscilloscope. The square wave output of the multivibrator was also used as a blanking signal and applied to the grid of the type 3BP1A cathode ray tube.

The negative pulse output of the basic generator was inverted by means of a shorted transmission line and further peak amplification was applied. Four more applications of this process using the basic amplifier circuit of Fig. 12 with appropriate lengths of RG7U coaxial line resulted in a 100 watt output pulse with a positive duration of approximately 0.006 microseconds. This pulse duration was not a limiting value but was considered ample to show the merit of this method of pulse inversion in that it far exceeds the published results at this time.

The block diagram of the pulse generator is shown in Fig. 32 and the voltage waveforms relative to chassis of the points indicated by the circled numbers are shown in Figures 33 through 50. Figures 51 through 58 show the constructional details of the units comprising the pulse generator and the method of mounting.

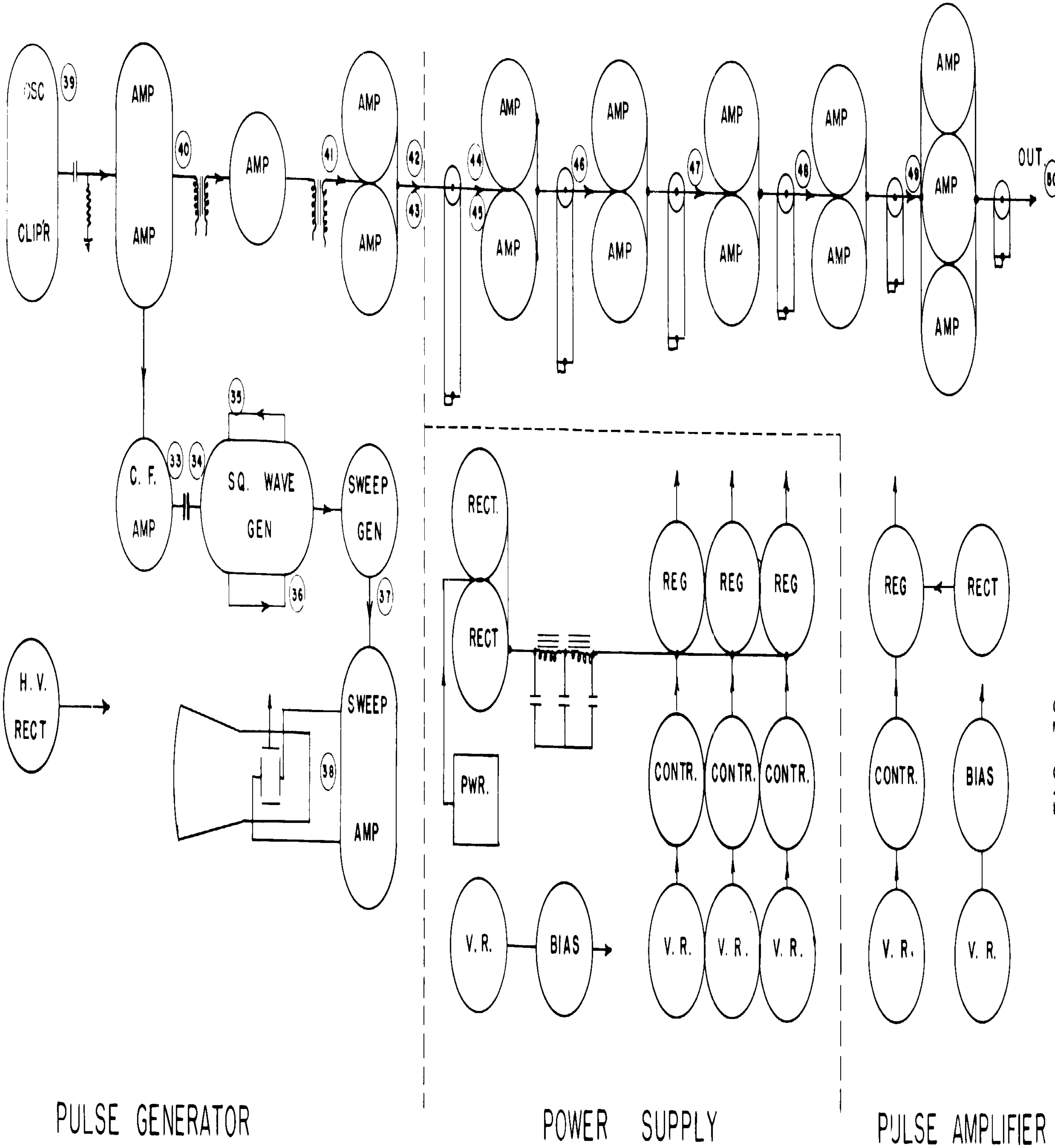
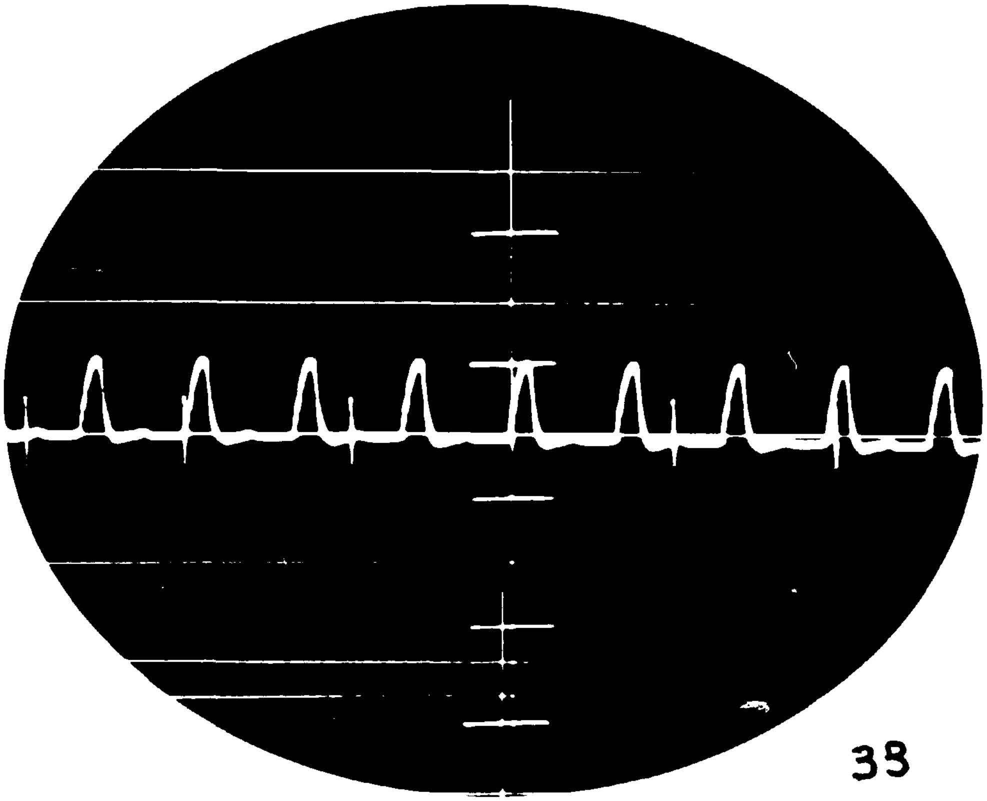

OSC
CLIP'R
AMP
AMP
AMP
AMP
AMP
C. F.
AMP
SQ. WAVE
GEN
SWEEP
GEN
SWEEP
AMP
H. V.
RECT
RECT.
RECT
PWR.
REG
CONTR.
V. R.
BIAS
RECT
OUT
PULSE GENERATOR
POWER SUPPLY
PULSE AMPLIFIER

FIGURE 32



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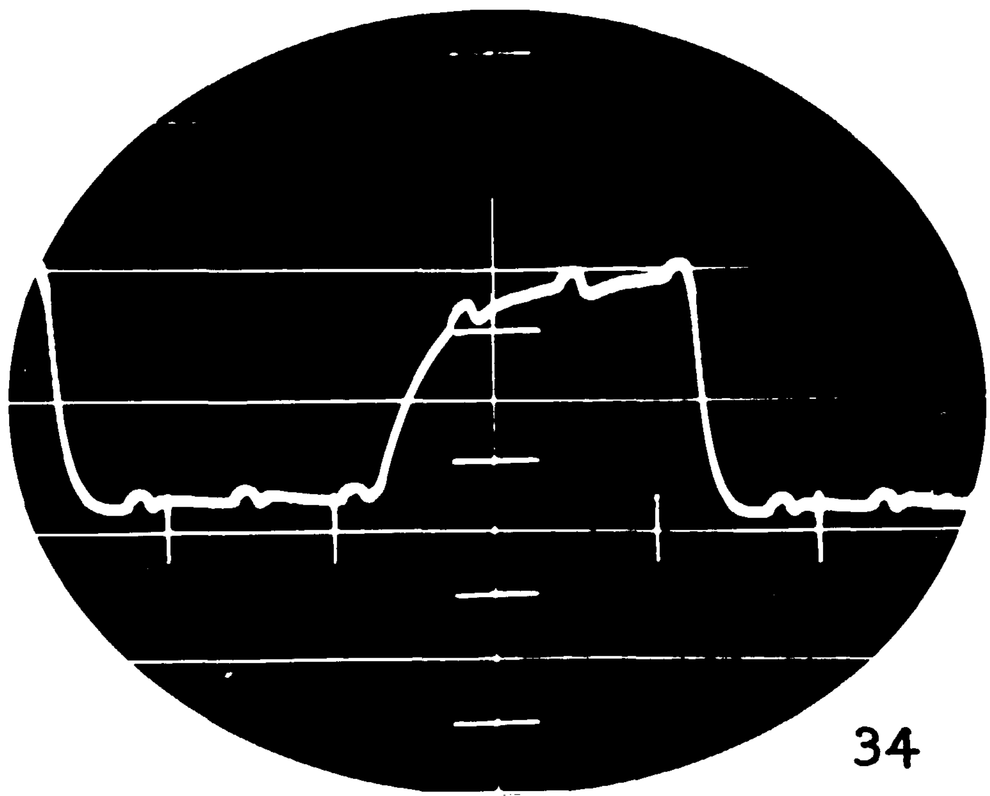

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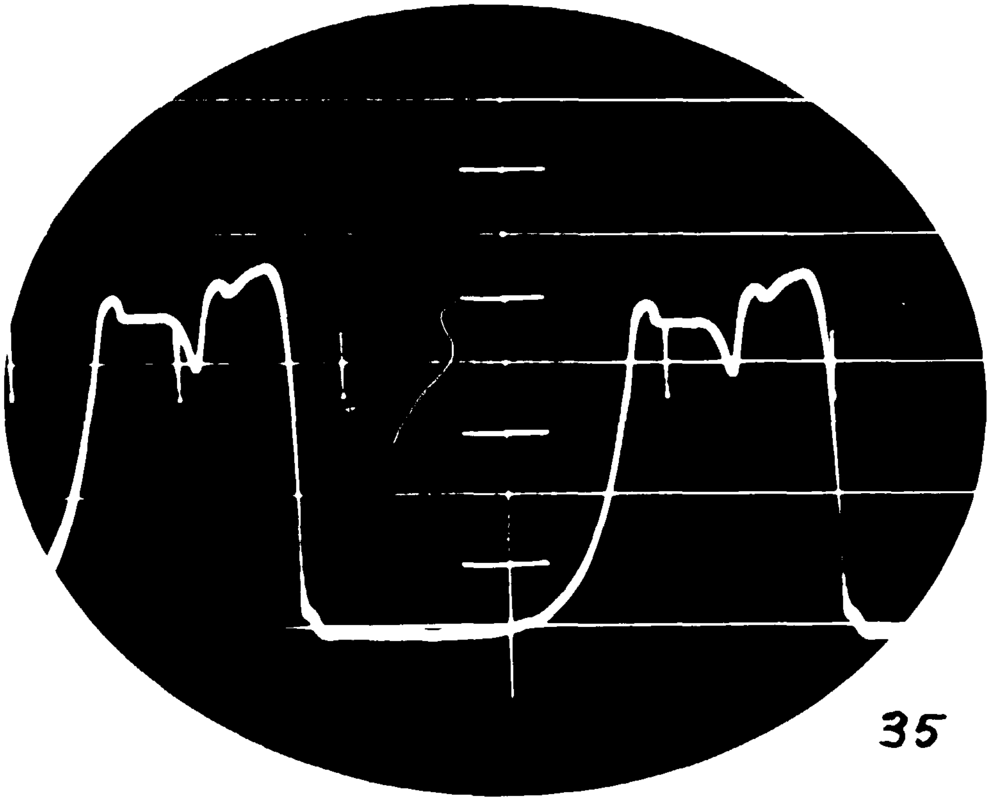

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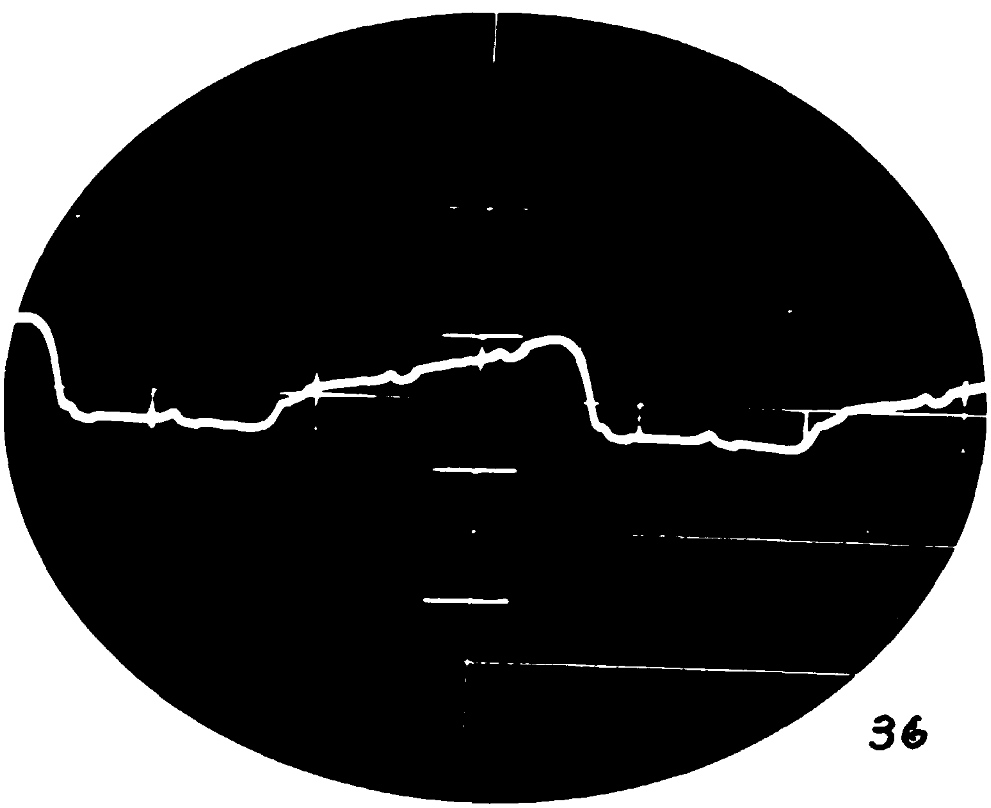

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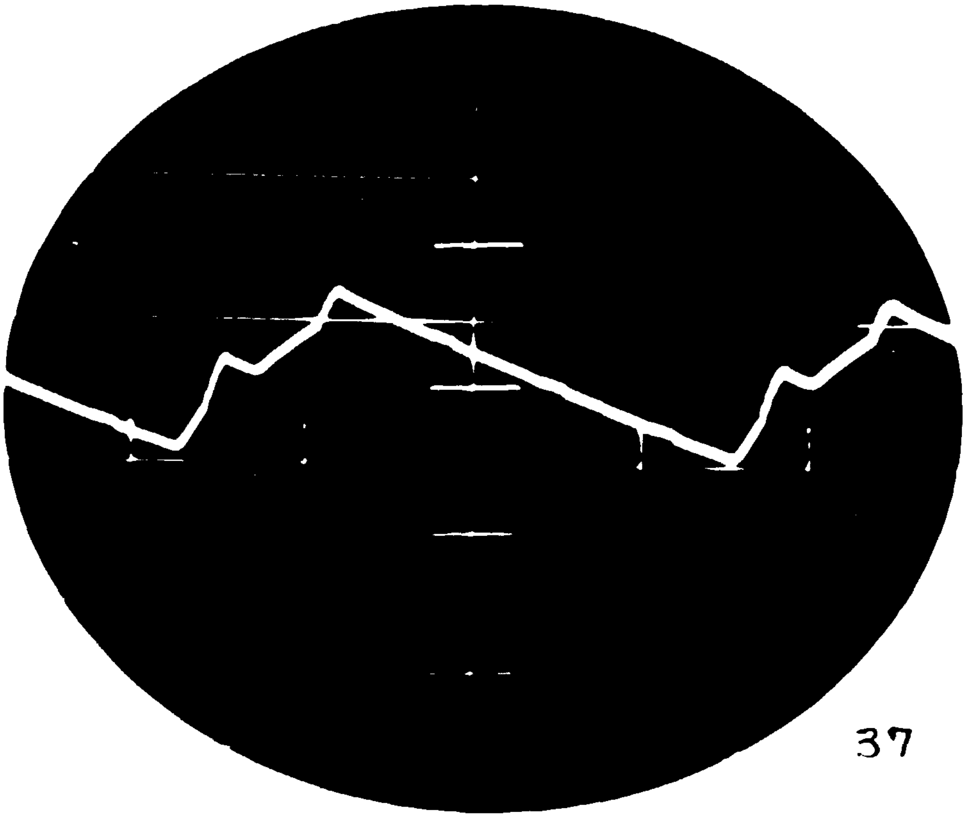

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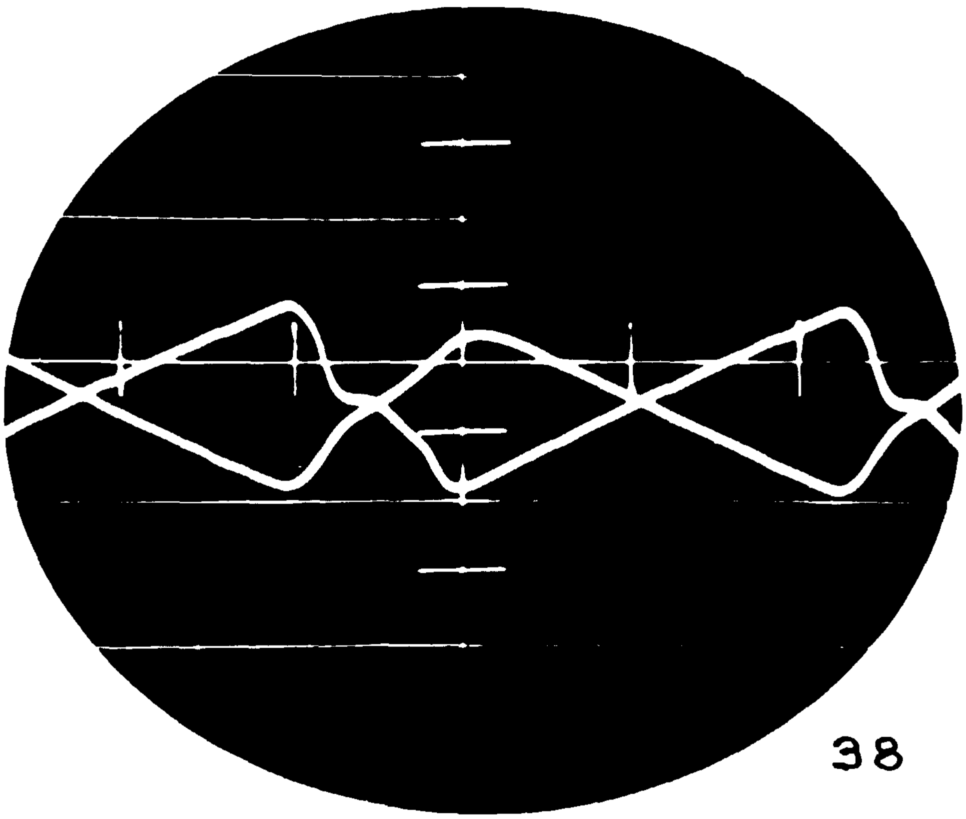

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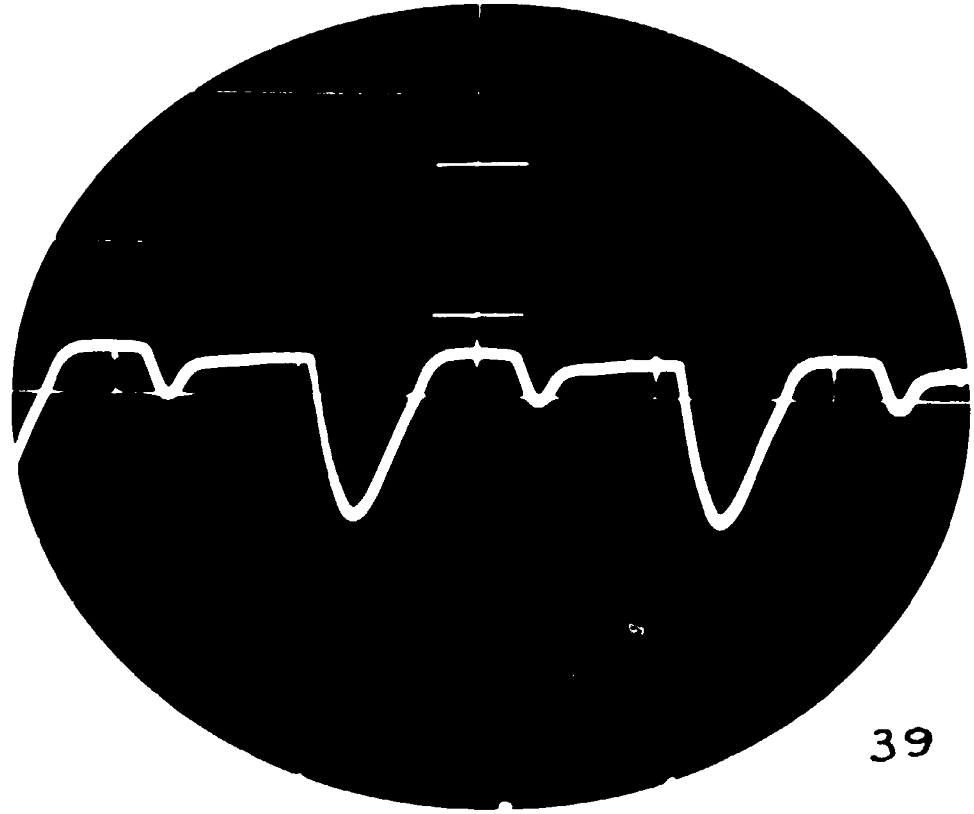

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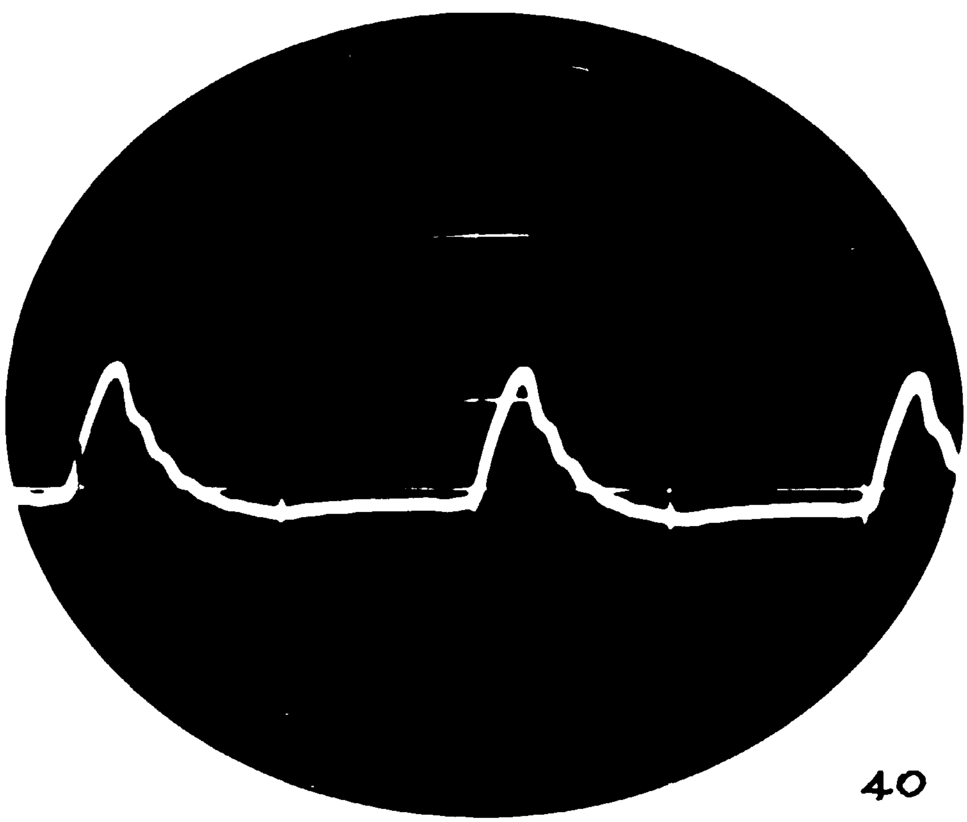

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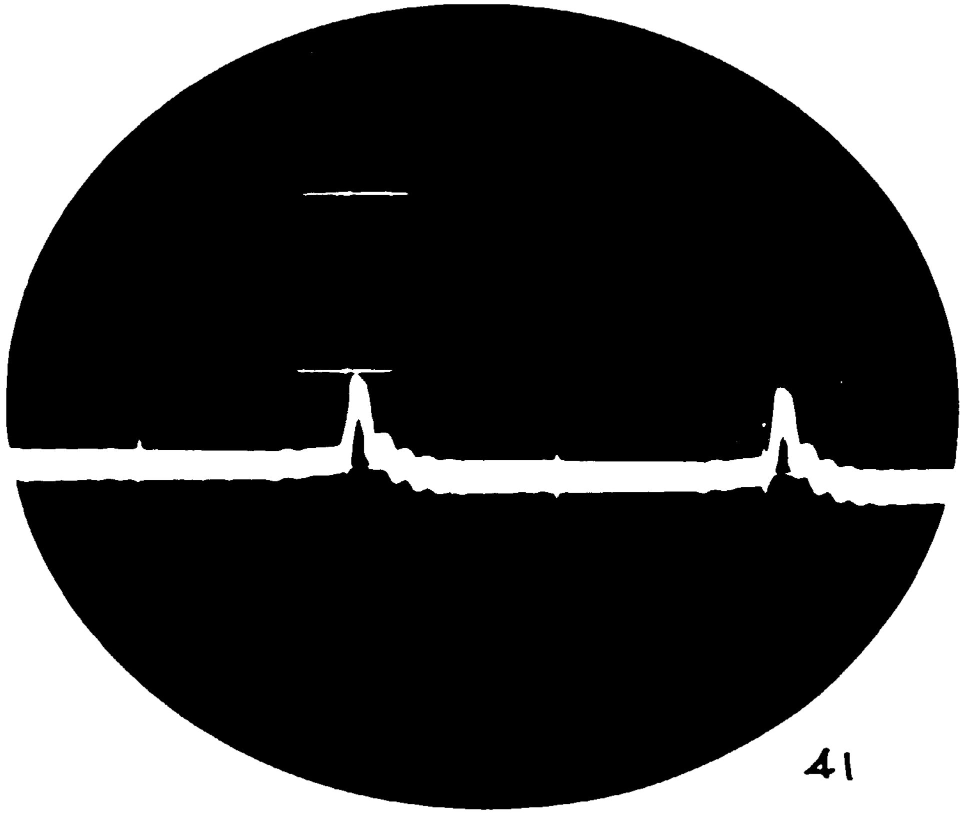

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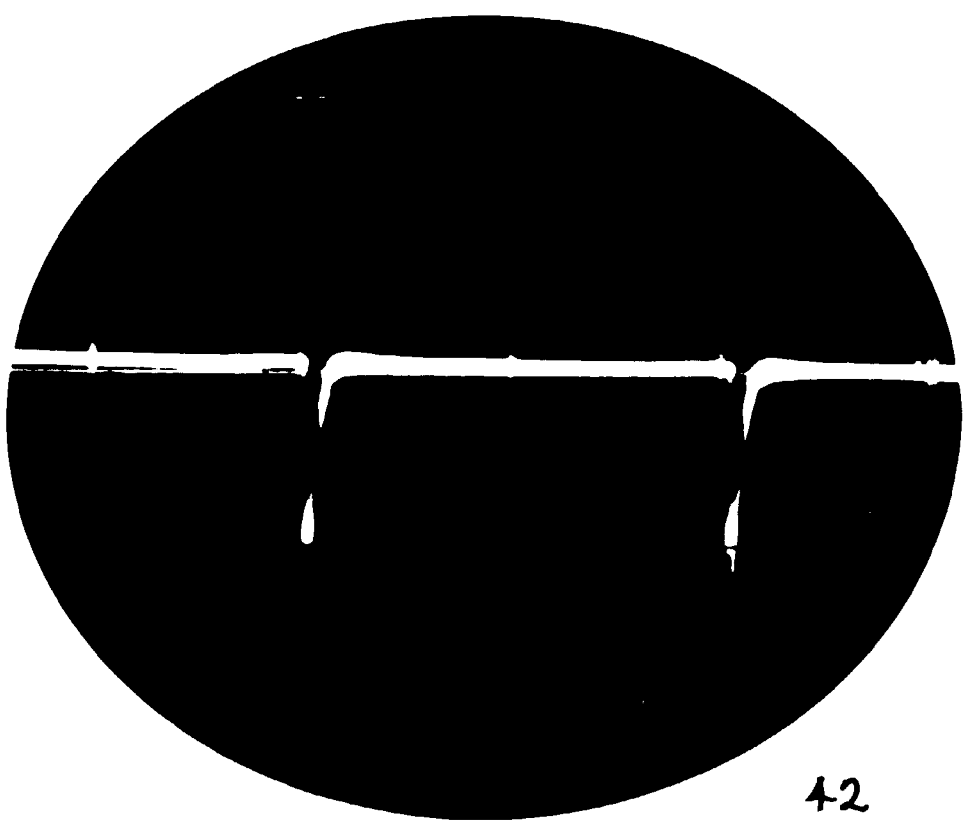

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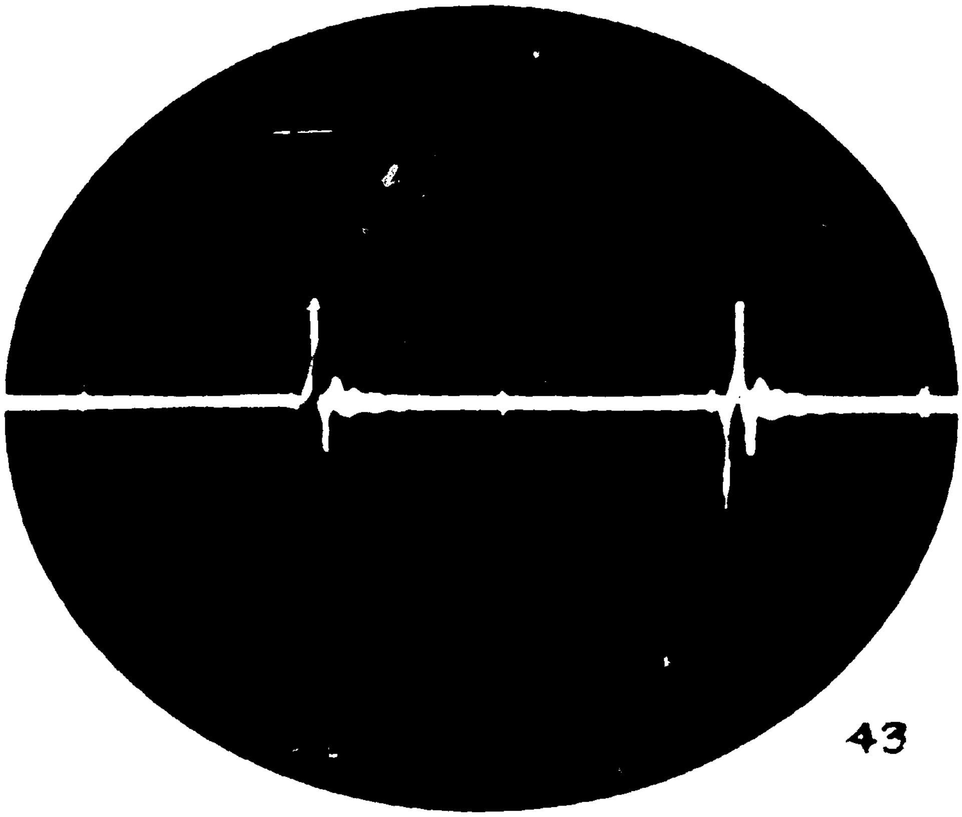

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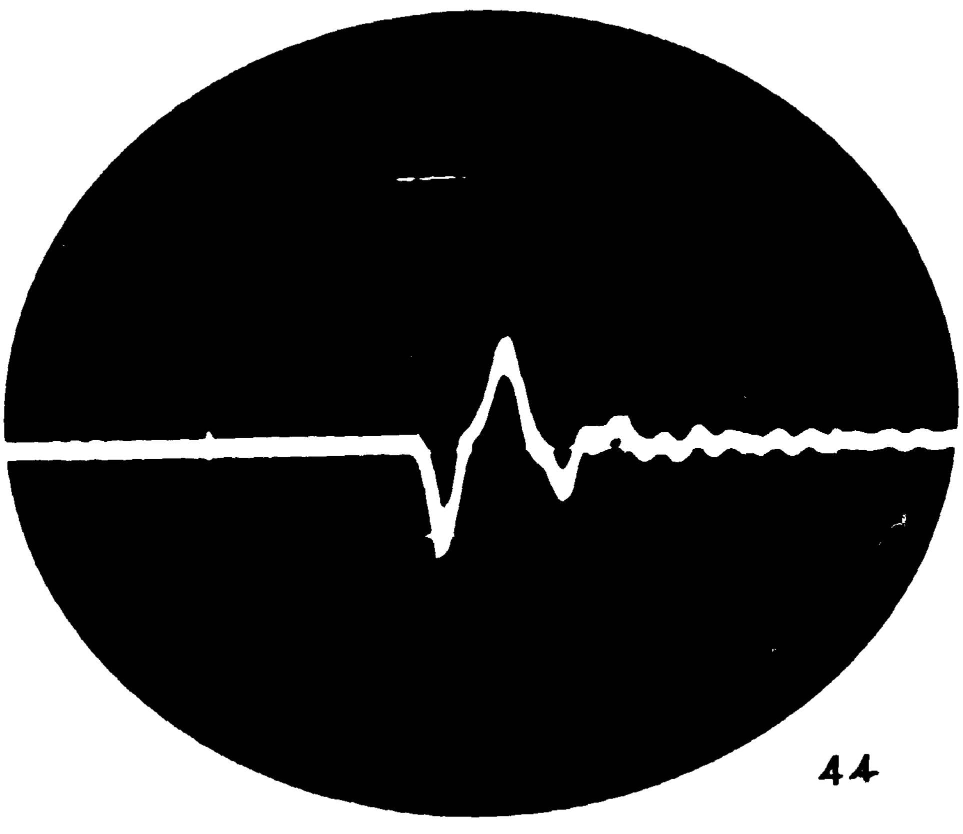

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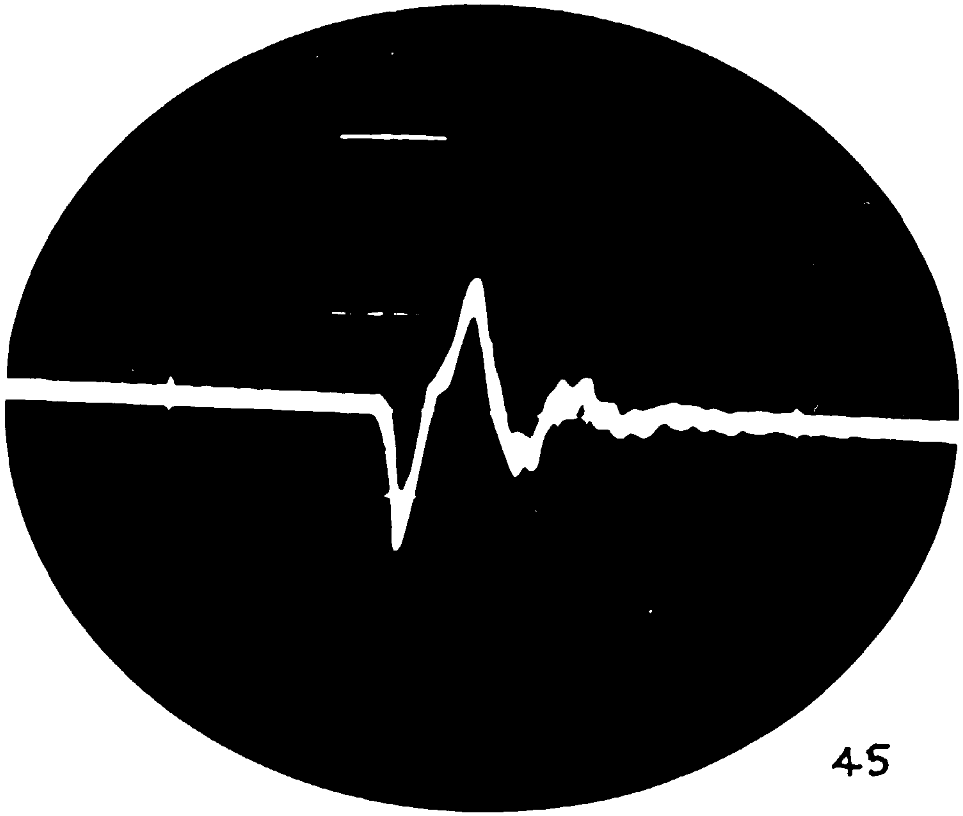

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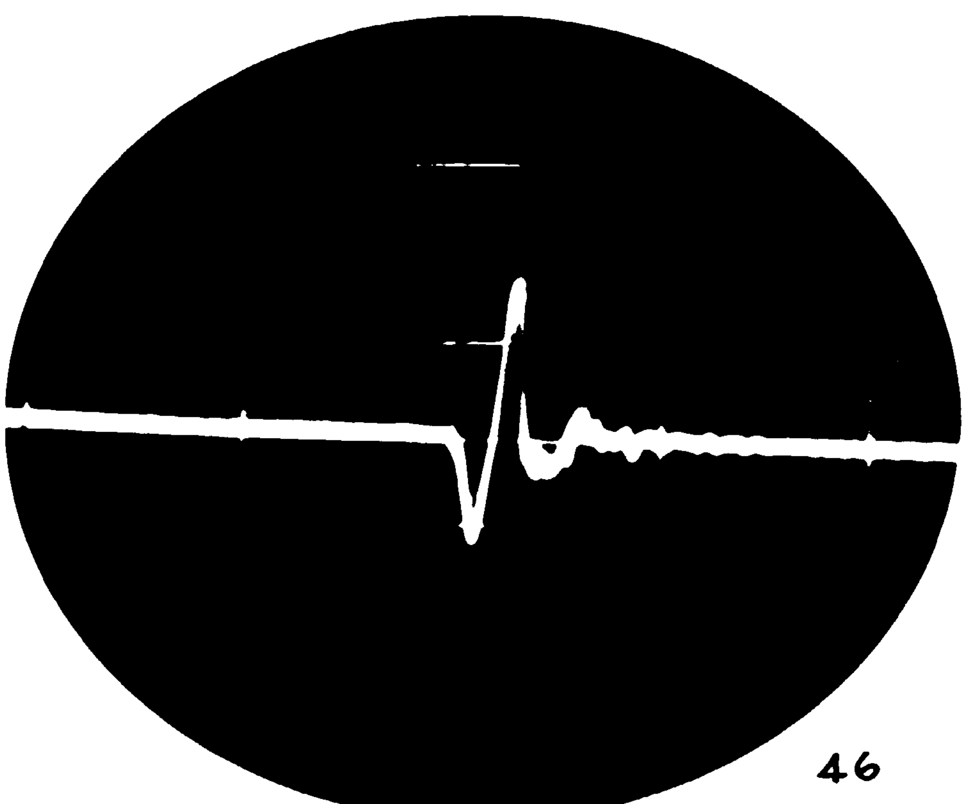

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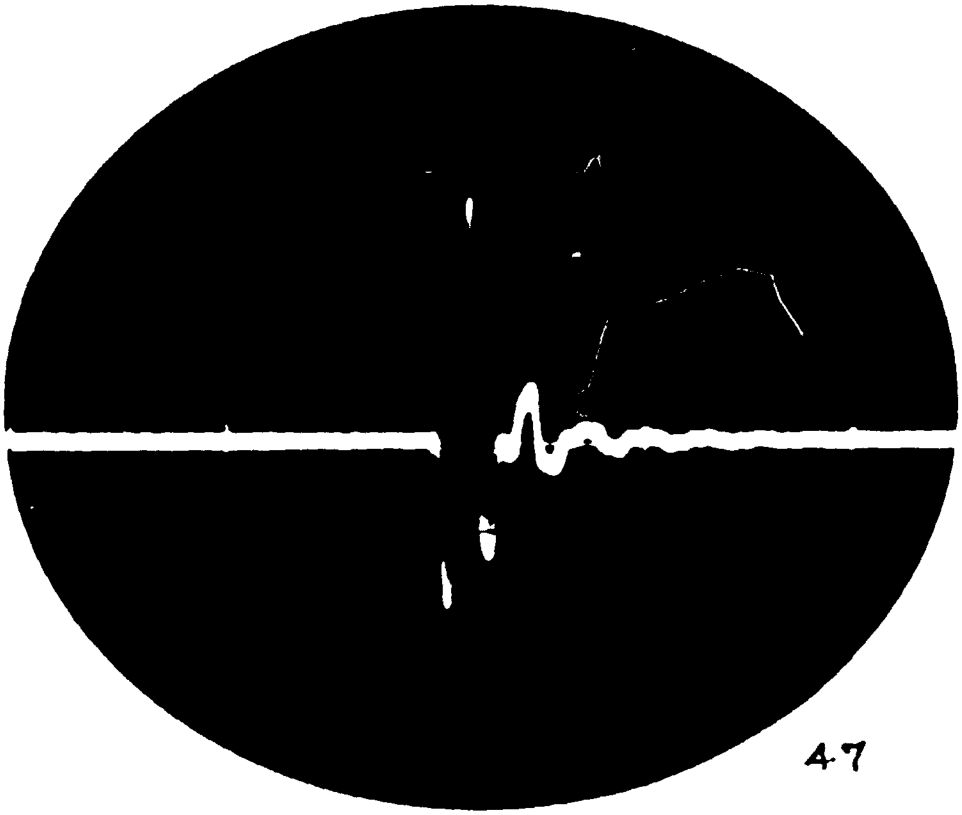

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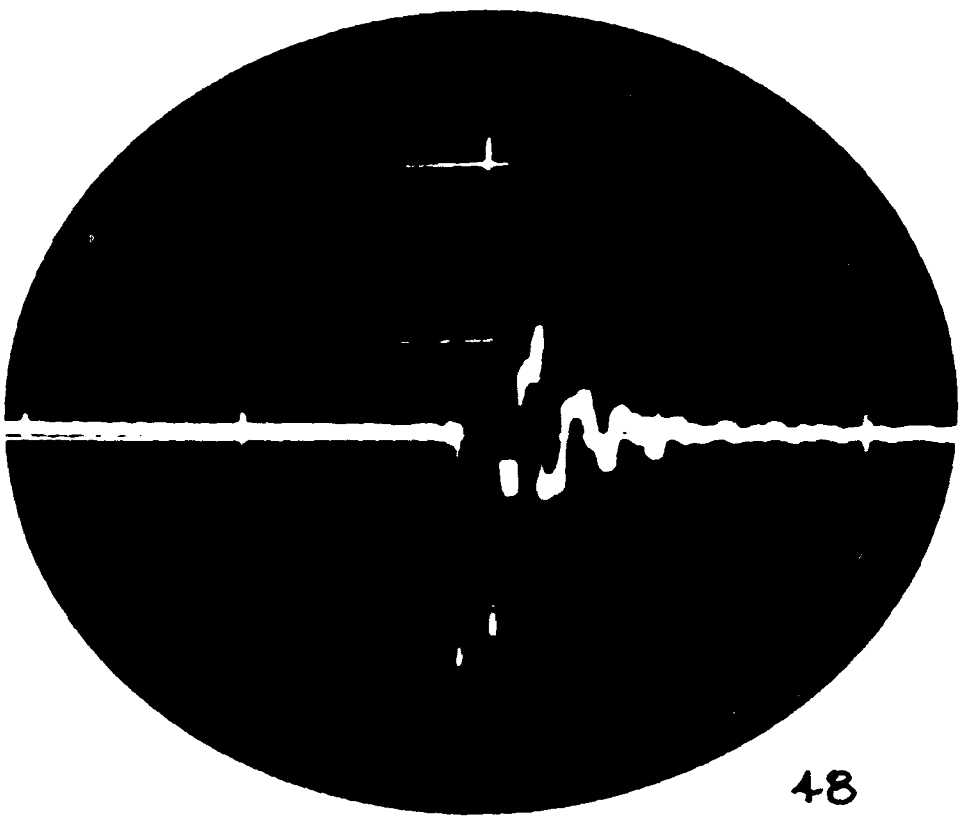

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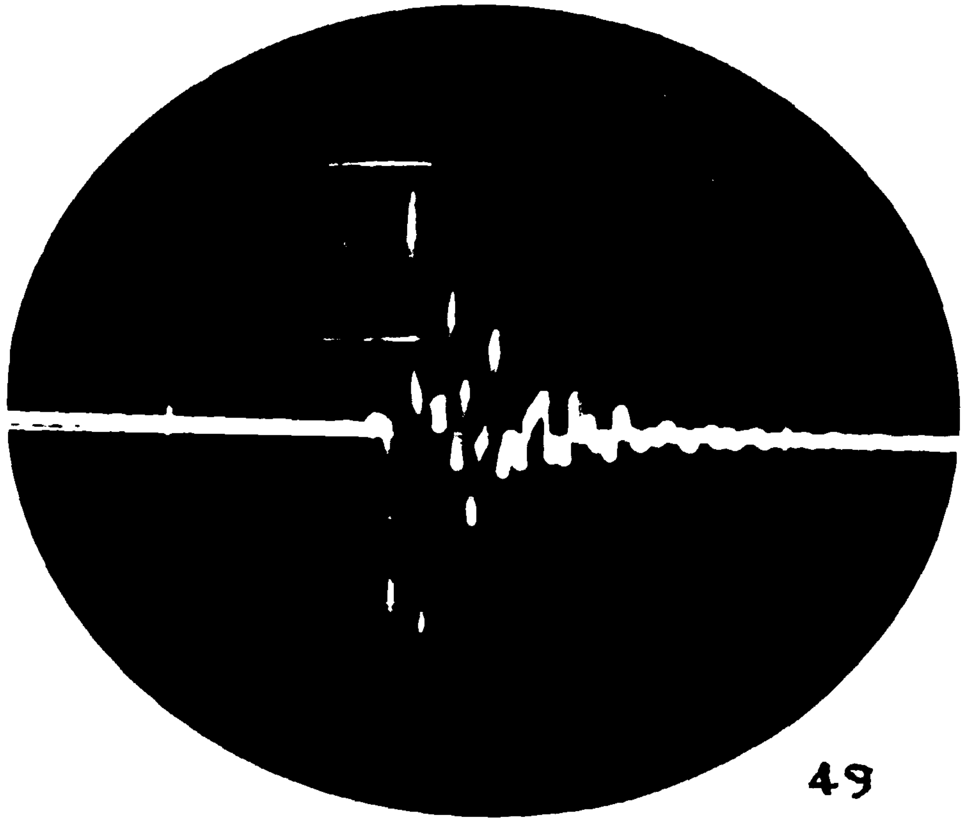
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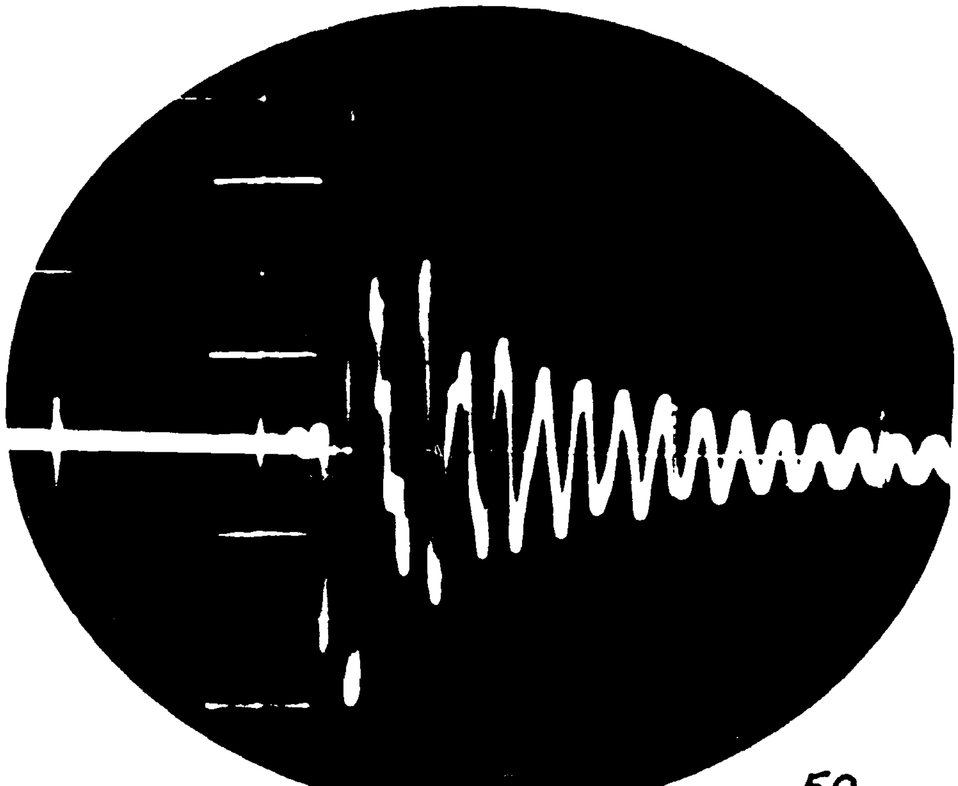
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6.2 Data on Pictures of Units

Figure 51. Front view of completely assembled pulse generator unit. The panels included are: (top to bottom) (1) basic pulse generator and monitor oscilloscope, (2) peak pulse amplifier and 250 volt d.c. regulated supply, (3) 450 volt d.c. power supply including 3 separately regulated channels.

Figure 52. Rear view of completely assembled pulse generator unit. Note the connection of the reflection coaxial cables on the pulse amplifier chassis. To make the unit more compact, these cables were coiled and placed in the side of the rack cabinet.

Figure 53. Top view of basic pulse generator chassis. The C.R.T. intensity, focus, astigmatism and positioning controls are grouped around the shielded C.R.T. The high voltage supply is seen just below the C.R.T.

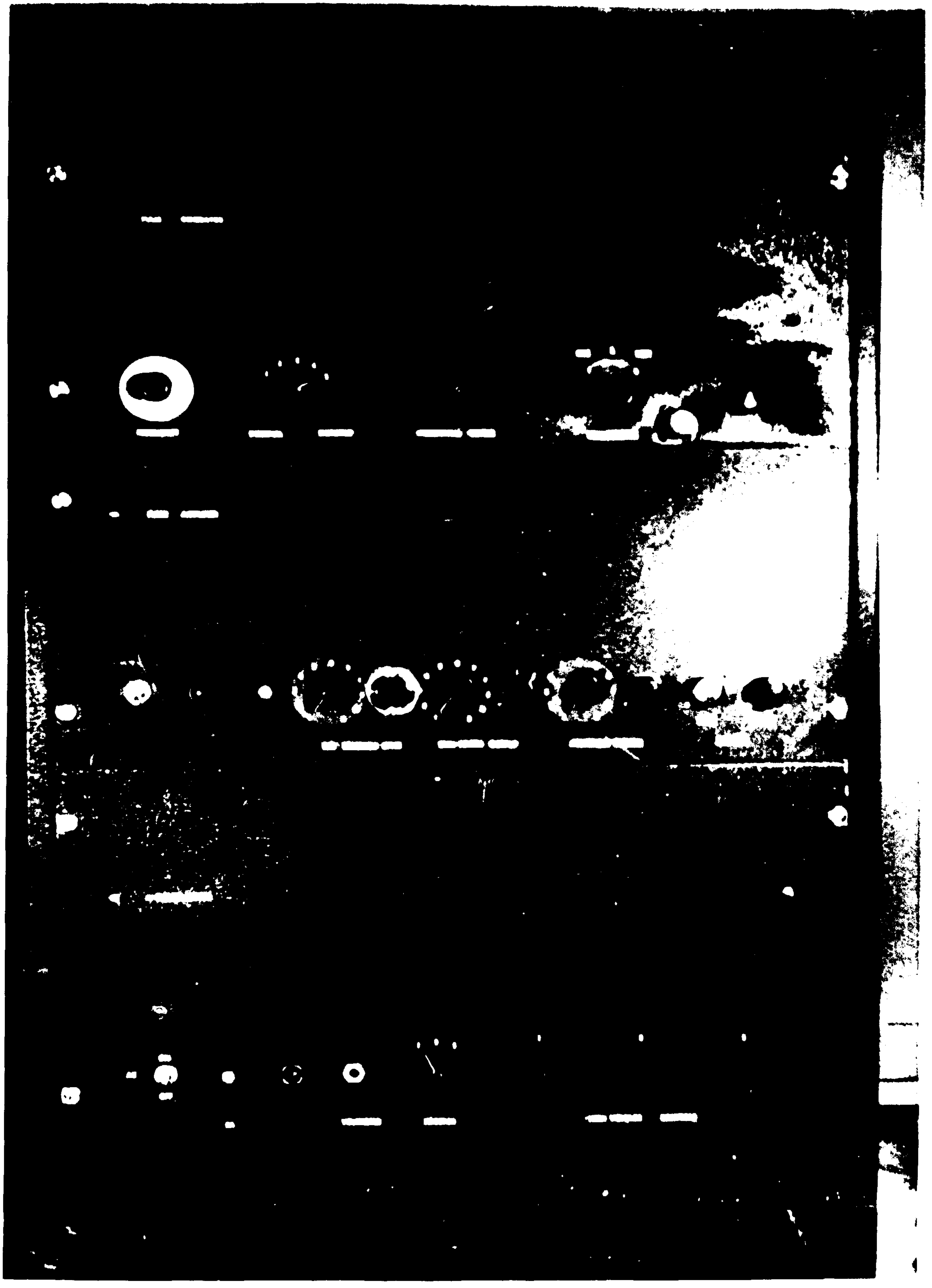
Figure 54. Bottom view of basic pulse generator chassis. Filament, high voltage, and bias voltage connections are cabled and run next to the chassis. The signal wiring is done with bus bar to maintain low capacitance.

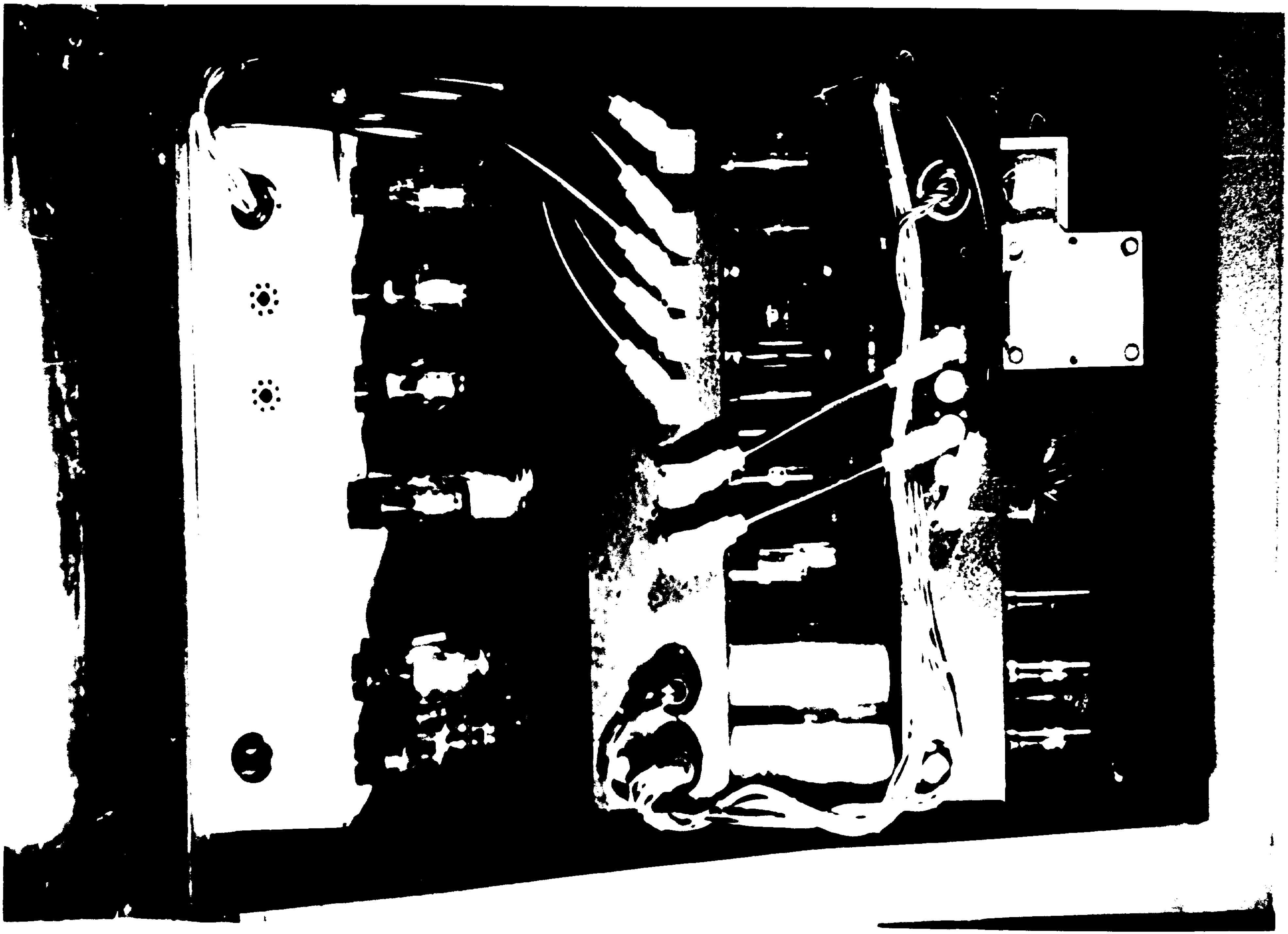
Figure 55. Top view of pulse amplifier chassis. A 250 volt, 250 milliampere regulated supply is mounted at the top of the picture. The remainder of the unit is the repetition of the basic peak pulse amplifier of Figure 12.

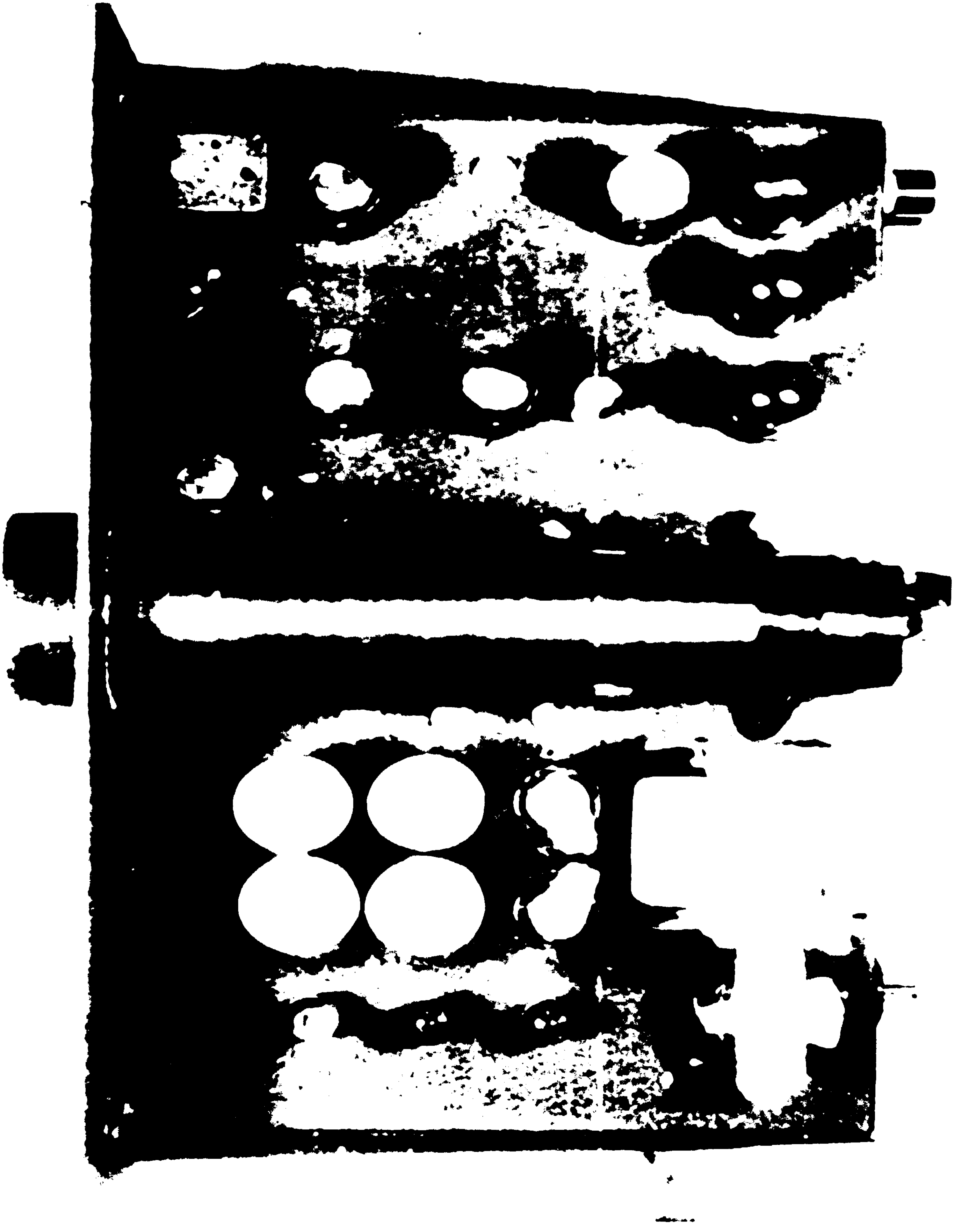
Figure 56. Bottom view of pulse amplifier chassis, showing the type of construction used. The maintenance of very low capacitance wiring was essential in producing the fast rise times.

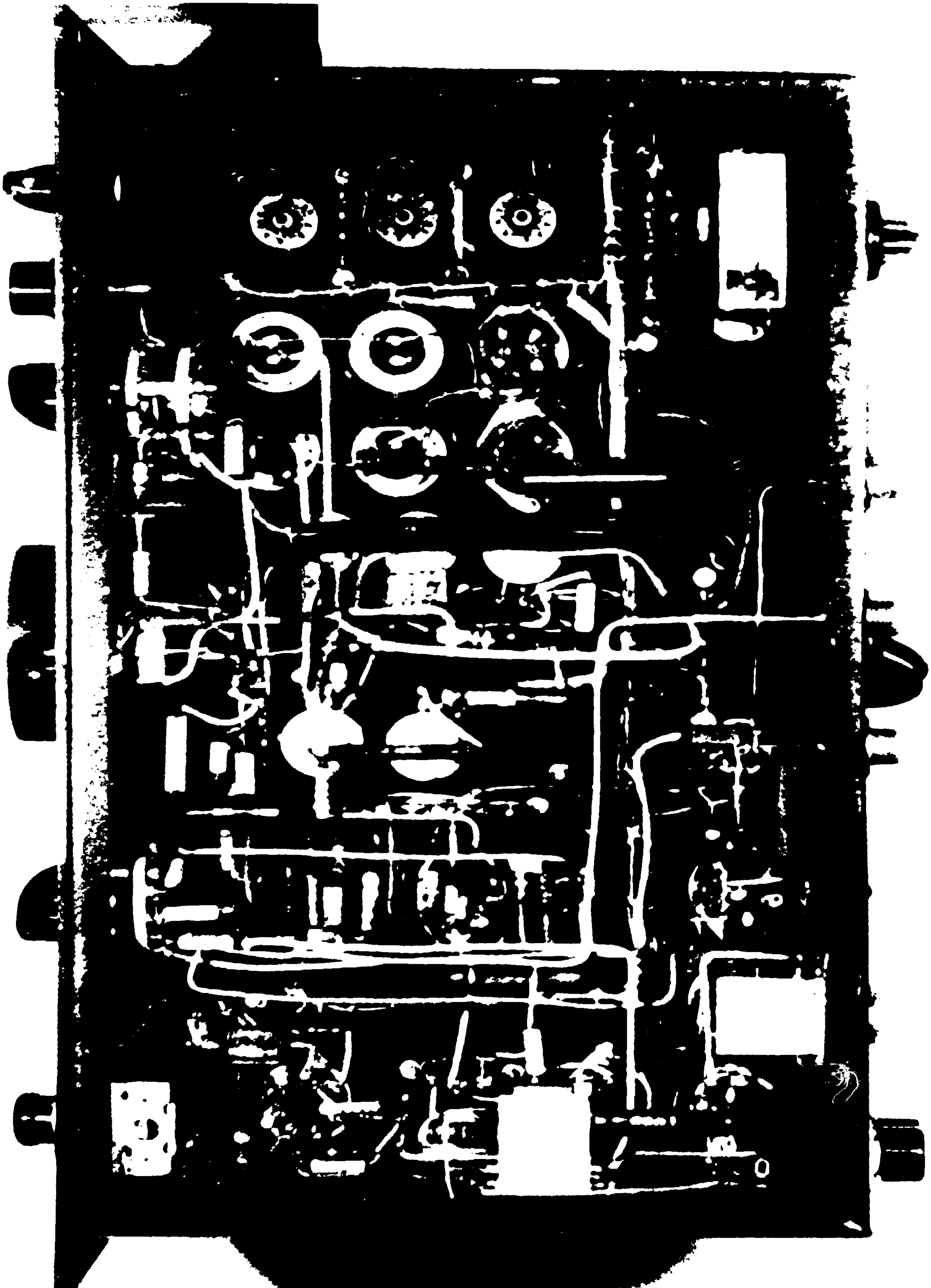
Figure 57. Top view of 450 volt power supply chassis. Paralleled rectifiers were used to obtain low impedance. Three separately regulated output channels supply 200-450 volts at 65 milliamperes each.

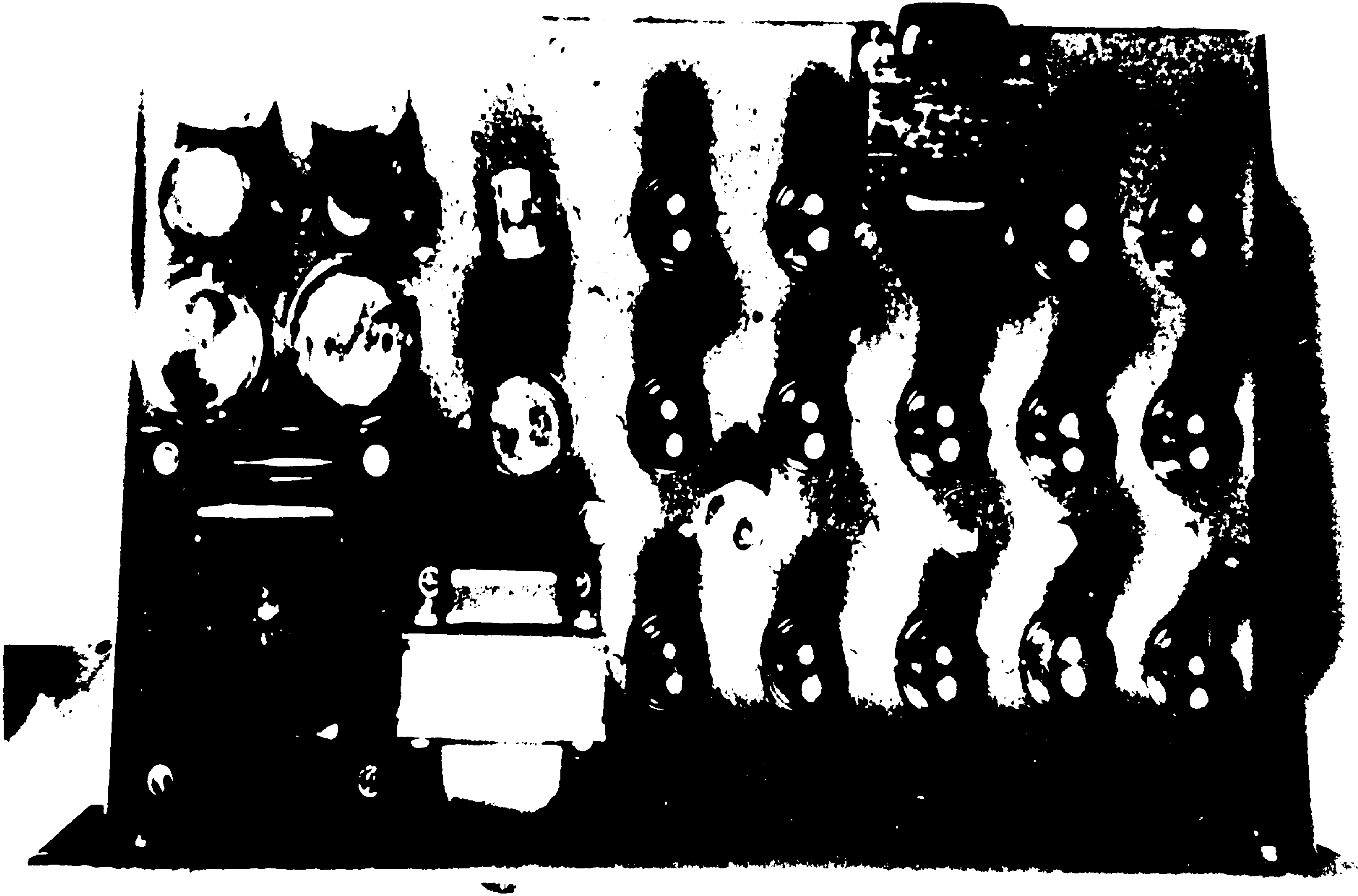
Figure 58. Bottom view of power supply chassis showing layout and method of construction.

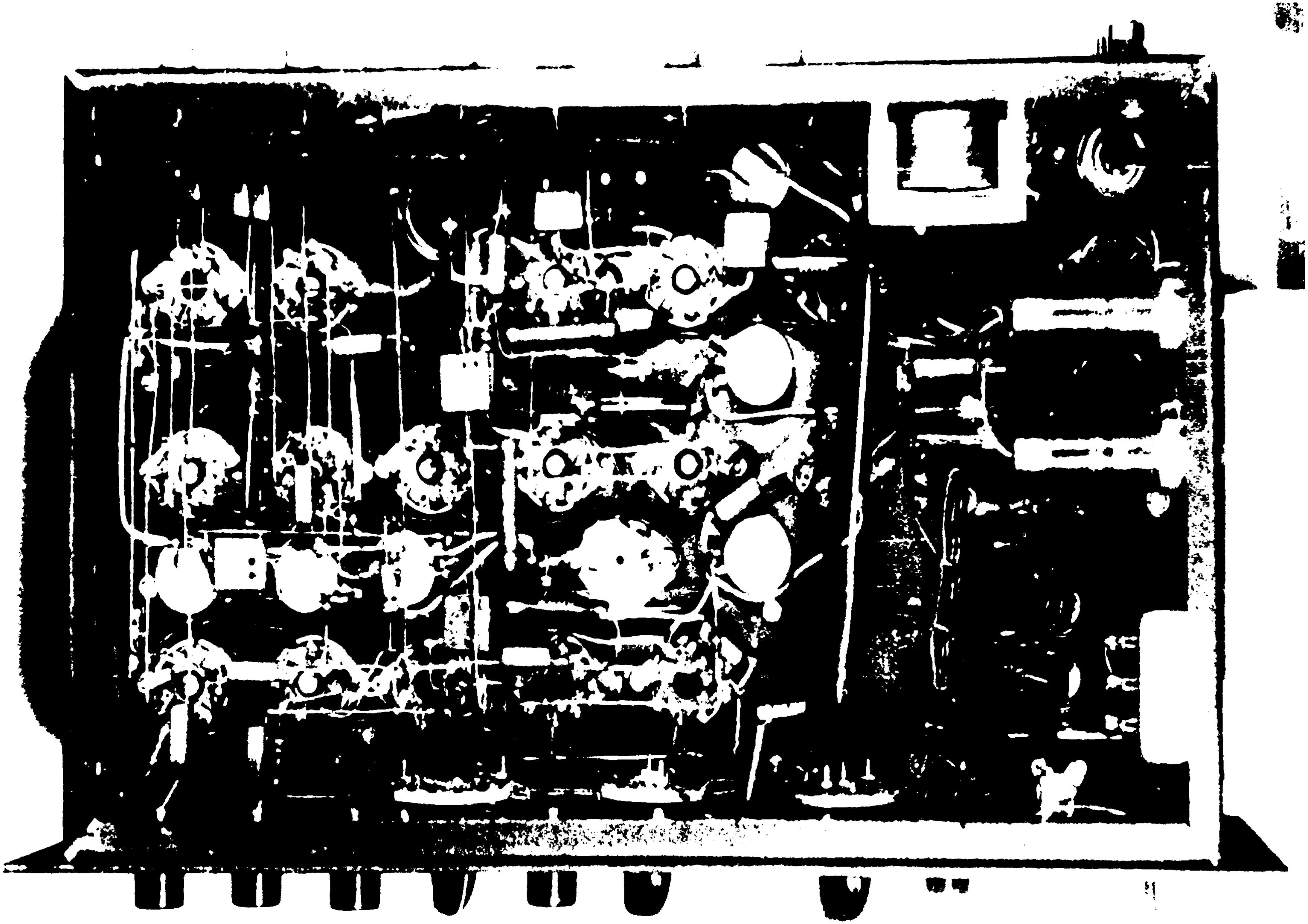


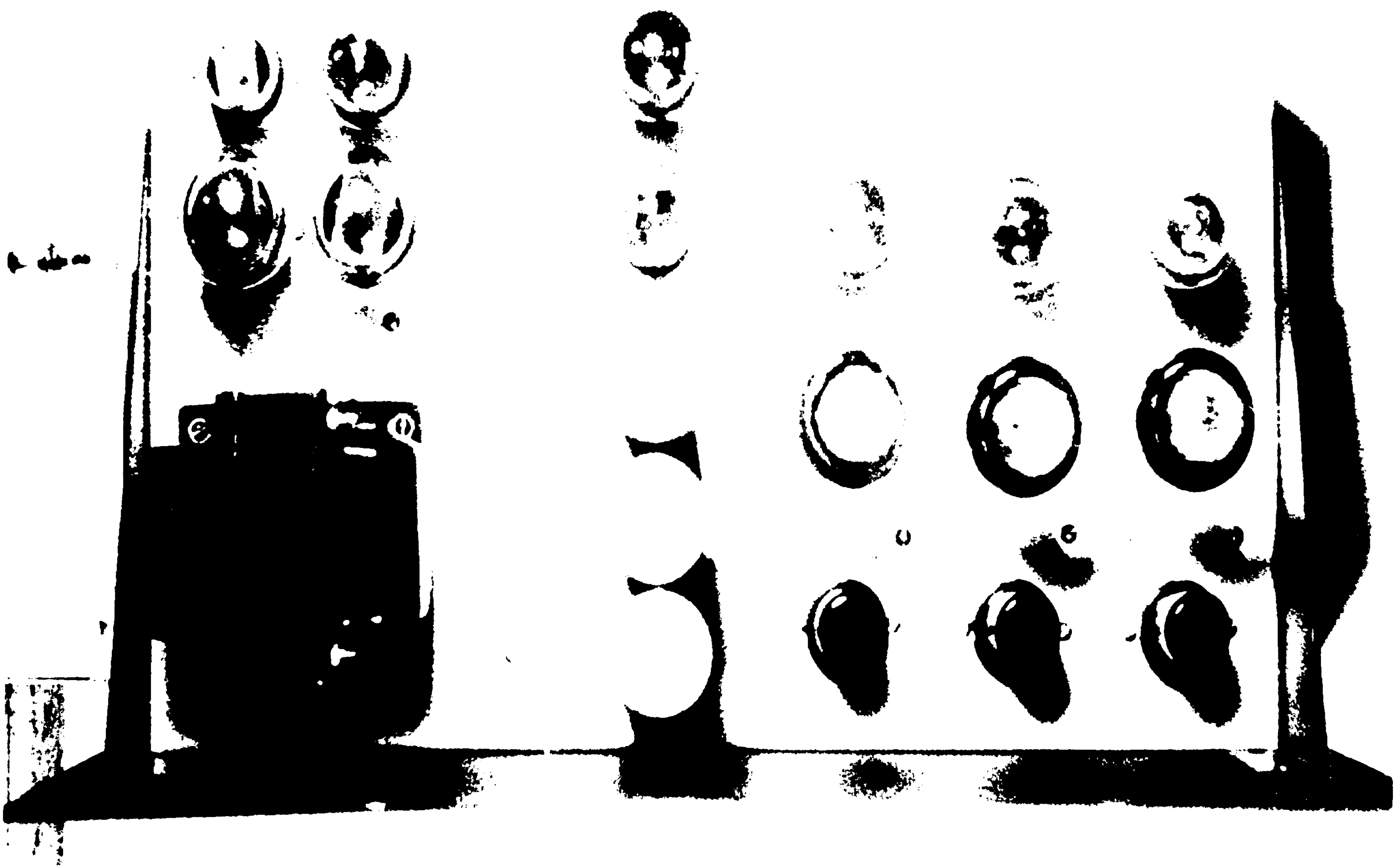


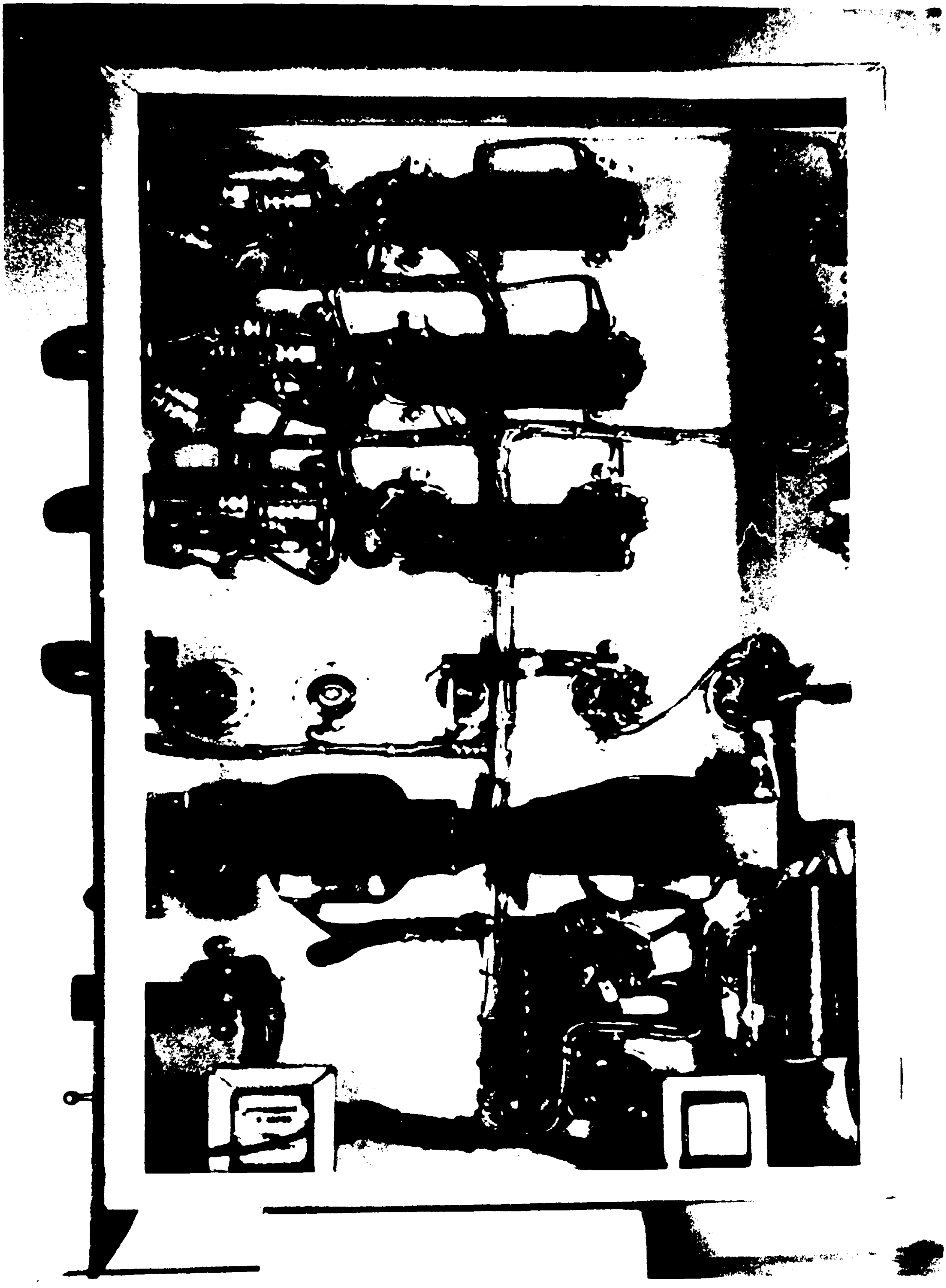












CHAPTER VII

7.1 Conclusions

The results obtained by this inversion method are significant. The inversion process is simple, efficient and provides a pulse duration reduction by a factor of two if desired. No difficulty was encountered in obtaining the results described in Chapter VI, and the author deems it likely that through refinements in design this method will enable the production of pulses of durations less than 0.001 microsecond and of repetition rates greater than 20 Mc. The factor of the inversion being relatively independent of repetition frequency (other than overlapping of the driving pulse) will make it very useful in an amplifier for time modulated pulse systems such as P.T.M. and P.C.M.

The general applications of pulses such as those obtained by the unit described are numerous: radar, time measurement, computers, jamming, television, video testing, gating and the use in the study of physical phenomena in other fields are but a few. Obviously, this advancement in the art of pulse production provides the opening of an entire new field in which the limitations of pulse duration and, or pulse repetition frequencies have been removed to relatively remote values.

7.2 Suggestions for Further Study

It is the author's intention to continue this work and to determine the values of the limits set up by this method. Further refinement of the physical construction and application of V.H.F. type tubes of low transit time should provide a considerable extension of the values attained in the unit described in Chapter VI. It is suggested that others continue research in this field in addition to studying the adaptation of the method discussed to the needs of short pulses in other fields. Many applications may arise which are not evident at the present time.

Some suggestions for the study of ideas which might be suitable for theses material follow:

(1) Transmission of short d.c. pulses in wave guides (not radio frequency pulses)

(2) Radiation of short d.c. pulses from antennae.

(3) Study of the production of shorter pulses.

(4) Study of pulse production at higher repetition rates.

(5) Design and development of marker generator of 0.005 microseconds duration pulses at a 20 Mc. repetition rate. (i.e. 0.005 microseconds markers).

(6) Design of a variable width pulse generator at high repetition rates suitable for video testing of very wide band amplifiers.

(7) Design and development of a high speed synchroscope with calibration timing markers for the measurement of very short pulses.

(8) Study of gas discharge using an adaptation of the pulse method described.

(9) The production of pulses of 0.005 microseconds duration at very high powers. (Suitable for magnetron keying)

(10) Study of noise reduction in sampling type receivers by a decreased open time.

(11) Study of a colored television intensity modulation tube using these short pulses.

(12) Study of pulsing characteristics of magnetron and klystron oscillators for pulses below 0.01 microsecond.

(13) The design and development of a device utilizing a coaxial tee, by providing a cancellation in such a manner to obtain an increased rise time over the method described in this thesis.

(14) The design and development of a high resolution radar system using the short pulses available by this method.

An unlimitednumber of ideas in the field of physics and electronics may be found and no doubt the applications will vary widely.

Communications to the author in care of Mich. State College regarding advancements and continued research in either development or application will be appreciated.

APPENDIX A

Short Pulse Measurement

The problem of pulse measurement is one which requires a very specialized cathode ray oscillograph or synchroscope. For pulses of duration below 0.05 microseconds, a sweep speed of at least 20 inches/microsecond is desireable. This is evidenced by the photographs in Figures 46 through 50, showing the resultant pulses from the pulse generator amplifier unit. As the base of the pulse is of the same order of magnitude as the fluorescent line width on the cathode ray tube, accurate measurements were obviously not possible.

Sweep generation of the order of 20 to 100 inches per microsecond require the use of line type[15] sweep generators which must be operated by thyratron tubes. This again limits the sweep recurrence to a few thousand cycles per second. Problems of jitter become very evident and triggering problems must be handled in such a way that the observed pulse is also the sweep triggering pulse. For recurrent pulses (a train of similar pulses evenly spaced) it would be desireable to delay the sweep triggering pulse so that the sweep would be initiated by the pulse preceeding the one being observed. This would eliminate the necessity of using a delay line or delaying amplifier which might introduce distortion into the observed pulse. To the author's knowledge, this feature has not been incorporated in any of the commercially available oscillographs.

The new 5XP-series tubes developed by DuMont for pulse observation has made the use of amplifiers unnecessary for most work. Deflections sensitivities of 30 volts/inch are attained with direct connection to the vertical deflection plates. The overall accelleration voltage may be made as high as 20 Kv. This is the ideal system for fast pulse measurement.

High speed synchroscopes are available from both DuMont[16] and Tektronix[17] but in general, the price is prohibitive for general school use. Both of these scopes contain vertical deflection amplifiers of the distributed constant (line-type) type which are useful to 75 Mc. DuMont can furnish information on special request. Tektronix has a model #517 in production which sells for about $3500.00. The Hewlett-Packard Co.[18] produces both distributed line type and travelling wave type amplifiers which are very useful for short pulse amplification.

Circular sweeps such as those used in radar "J" scopes[19] could be utilized for pulse duration measurements either by intensity modulation or by central electrode deflection tubes provided some method of stabilizing the circular sweep frequency (sine wave RF voltage) and synchronizing this source with that of the pulse repetition frequency. Laboratory tests showed difficulty in maintaining stable synchronization between two separate oscillators at 1 Mc. but if the pulse source (i.e. the sine wave driving voltage in the pulse generator) could also be used for the circular sweep source, it should be possible to maintain jitter at a minimum.

The fastest calibrated sweep presently available at Michigan State College is 0.1 microsecond/cm. in the form of the Tektronix Model 511A oscillograph. Most of the pulse work was done by terminating the measuring coaxial cable directly at the cathode ray tube deflection plates. The tube used is a 5CP1A, not particularly adapted for this type use, so the results were not very good. Undoubtedly some of the reflections and oscillations present in the observed pulse are due to the leads from the termination of the coax and the deflection plates. Those contemplating the construction of a synchroscope for this use are advised to use the 5JP-series of tubes for recurrent pulses or the 5XP-series for single transients. If funds are available, the 5XP-series would be most desirable for either case as the higher accelleration voltage and deflection sensitivity is necessary for very fast writing rates and small deflection voltages which generally occur in short pulse observation.

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