A PRECISION, LOW - LEVEL
DISCRIMINATOR.

A Thesis
Submitted to
the Faculty of Graduate Studies and Research
University of Manitoba

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by
Hartley Bruce Harland
October 1959

ABSTRACT

A precision, low-level integral discriminator, having a long term stability of better than 1.2 millivolts, and a sensitivity of 2 millivolts, and a sharpness of triggering of 1 millivolt, has been developed. Since this circuit will trigger on pulses having a magnitude of less than 0.5 millivolts, it is expected that a sensitivity of 0.5 millivolts with a stability of 0.1 millivolts may be achieved, by the use of more stable resistors and a Sorensen line regulator which is functioning properly.

A differential discriminator, employing this integral discriminator and the Gatti system for determining the window width, has been developed.

PREFACE.

The material presented in this thesis was obtained at the Physics Laboratories of the University of Manitoba, during the period September 1958 - September 1959, under the direct supervision and guidance of Dr. K. I. Roulston.

The author wishes to express his deep sense of gratitude to Dr. Roulston for his able guidance, constant encouragement and valuable suggestions during the progress of this work. Acknowledgement is also due to Mrs. Flora McKechnie for accepting the typing work.

Financial assistance from The National Research Council is gratefully acknowledged.

TABLE OF CONTENTS

CHAPTER PAGE

CHAPTER PAGE

LIST OF FIGURES AND PLATES.

LIST OF TABLES.

CHAPTER I

INTRODUCTION

STATEMENT OF THE PROBLEM

A discriminator, as the name implies, is an electronic device which distinguishes between voltage pulses having different magnitudes. The purpose of this study is to develop a precision, low-level discriminator. This refers to a very stable device having a range of operation from about five millivolts, or less, to about one volt, and capable of discriminating between pulse heights having a separation as small as one or two millivolts.

The most frequently used discriminator for scintillation counting equipment, consists of a pair of pentodes or triodes, having plate to grid capacitive coupling in the forward direction, and direct cathode coupling for positive feedback. Normally, one of the tubes is conducting and the other is biased off, so that a pulse of a certain minimum amplitude is necessary to cause the circuit to trigger.

JUSTIFICATION FOR DISCRIMINATORS

The justification for the existence of integral and differential discriminators lies mainly in the use of proportional detectors in nuclear physics. Practically every nuclear apparatus has a component whose function is to detect particles. When the signal emitted by the detector depends appreciably upon the type of particle, the detector may be used to identify the particle or to distinguish between different particles. Detectors which yield signals depending upon the energy of the incident particle, termed proportional counters, can be used to measure this energy. Discriminators are used to measure the output pulse heights from these proportional detectors, and thus determine the energies of the incident particles.

PROBLEMS INHERENT IN PRESENT DISCRIMINATING SYSTEMS

The necessary characteristics of a discriminator to be used for a particular task, will depend upon such variables as the maximum pulse repetition frequency which it will encounter, the energy range to be analyzed and the accuracy with which this energy spectrum must be analyzed. The thresholds of conventional pulse-amplitude discriminators range from about two volts to about one hundred volts. In some applications this necessitates a voltage amplification exceeding 10^5, preceding the discriminator; however, for scinillation counting equipment, a gain of 10^3 is usually more than enough. In order to maintain a threshold stability of 1% referred to the detector, the voltage gain of the amplifier should be stable to much better than 1%. Such stabilities are fairly readily attainable through the use of large amounts of negative feedback.

Since discriminators find their widest use with scintillation counting equipment, consider this case in particular. The output pulse height from the photomultiplier tube in a scintillation counter is generally in the range from a few millivolts to about one volt.

Conventional electronic circuits for discriminating purposes are not sufficiently sensitive, accurate, or stable to permit operation directly from the output of the photomultiplier tube. The output pulses are amplified by a linear pulse amplifier in order that they may be conveniently handled by conventional discriminators. Since the range of operation of the discriminators extends over only about 20 to 50 times the minimum threshold value, this requires frequent changes in amplifier gain in order to cover the complete energy spectrum. This is no longer a serious problem, however, since many present amplifiers have linearities of almost .2%. These amplifiers are rarely completely stable due to variations in D.C. levels within the amplifier, caused by temperature fluctuations and ageing. Both long-term and short-term variations result.

The most serious problem encountered by pulse amplifiers for scintillation work is overloading. Since fairly high gains are required when measuring the lower end of the energy spectrum, the larger pulses tend to drive the control grids of the vacuum tubes positive with respect to their cathodes, so that they draw grid current. This causes the coupling condensers to charge up, with the result that until they discharge, the apparent heights of the incoming pulses will be badly distorted. This results in a badly distorted energy spectrum, as measured by the discriminator. Also, these larger pulses tend to drive the tubes to saturation, causing temporary paralysis which increases the dead time of the circuit, increasing the resolving time. There are a number of methods for overcoming this problem of overloading; however, the result is a bulky, expensive amplifier.

If a sufficiently sensitive and stable discriminator could be designed, such that operation in the range from a few millivolts to one volt could become a reality, it would be particularly suited to operation with scintillation counting equipment. One could then dispense with the complex and expensive pulse amplifier. Such a discriminator would also be useful for use with much smaller pulses, since they would require less amplification than is currently required for use with conventional discriminators.

ADVANCEMENTS IN DISCRIMINATOR DESIGN

From time to time, workers in the field have attempted to improve the stability and sharpness of triggering of the conventional discriminators. Probably the most important advancement has been the use of a diode load on the cut-off tube, as suggested by Moody and developed by Kandiah. (1) This resulted in a marked improvement in the sharpness of triggering, and resulted in the use of thresholds down to 100 millivolts, having a stability of about 1%. This circuit was also capable of operation down to 20 millivolts, with a stability of 10%, and to even lower levels with larger stability factors.

Kandiah also made use of a number of less important innovations, in order to obtain a circuit of this stability and sensitivity.

CHAPTER II

PRESENT PROJECT

INTRODUCTION

The present project can be divided into two main sections, Integral Operation and Differential Operation. The integral discriminator to be discussed basically involves the combination of two previously existing electronic devices, the Kandiah diode load and the amputating or window amplifier. In reality, it is an extension of the Kandiah principle. The differential discriminator makes use of the integral discriminator just developed, and the Gatti-Piva system for determining the window width.

INTEGRAL DISCRIMINATOR.

Conventional Discriminator. The most frequently used discriminator for scintillation counting equipment, consists of a pair of pentodes or triodes, having plate to grid capacitive coupling in the forward direction and direct cathode coupling for positive feedback. Normally, one of the tubes is conducting and the other is biased off, so that a pulse of a certain minimum amplitude is required to cause the circuit to trigger. Figure 1. is a diagram of a conventional discriminator.

When measuring positive pulses, V_1 is biased beyond cut-off, and V_2 passes a current determined by the voltage divider in the grid circuit and the cathode resistor R_6. Above a certain minimum pulse level, if a

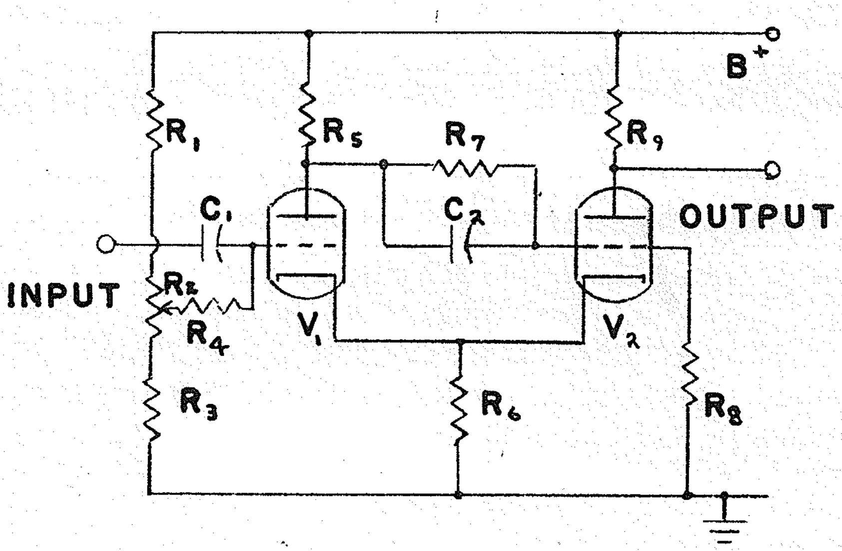

FIGURE I - CONVENTIONAL DISCRIMINATOR

Positive pulse is applied to V_1, the circuit will switch over to V_1 conducting and V_2 cut-off. The circuit triggers at such a pulse level that the mutual conductance, G_1, of the first tube exceeds a certain critical value. The threshold will vary markedly from one tube to another used for V_1, since the grid voltage of a tube for a given conductance, particularly low conductance, has a considerable spread and is dependent upon the grid-to-cathode contact potentials. An important property in this circuit is the back-lash, that is, the difference between the input-pulse level, on the rising edge, at which the circuit triggers forwards, and the level at the trailing edge at which it triggers back to its original state. This second level is lower than the first by about 2 volts, in most conventional discriminators. Heater voltages play a significant role, since a 10% change causes a variation of about 100 millivolts in the threshold when measuring pulses of about 10 volts in amplitude. The minimum pulse width which can operate the circuit depends upon the stray capacitances in the circuit.

<u>Kandiah Discriminator</u>. Figure 2. is a simplified circuit diagram of the Kandiah Discriminator. In Kandiah's circuit, both trigger tubes are normally conducting, V_1 , conducting somewhat less than V_2. The circuit normally remains in a stable condition because of the low impedance of the diode, V_3, which is passing a steady current. If one had the ideal case in which the resistance of the diode V_3 is practically zero when it is conducting, and infinite when it is not, and if R_2 and

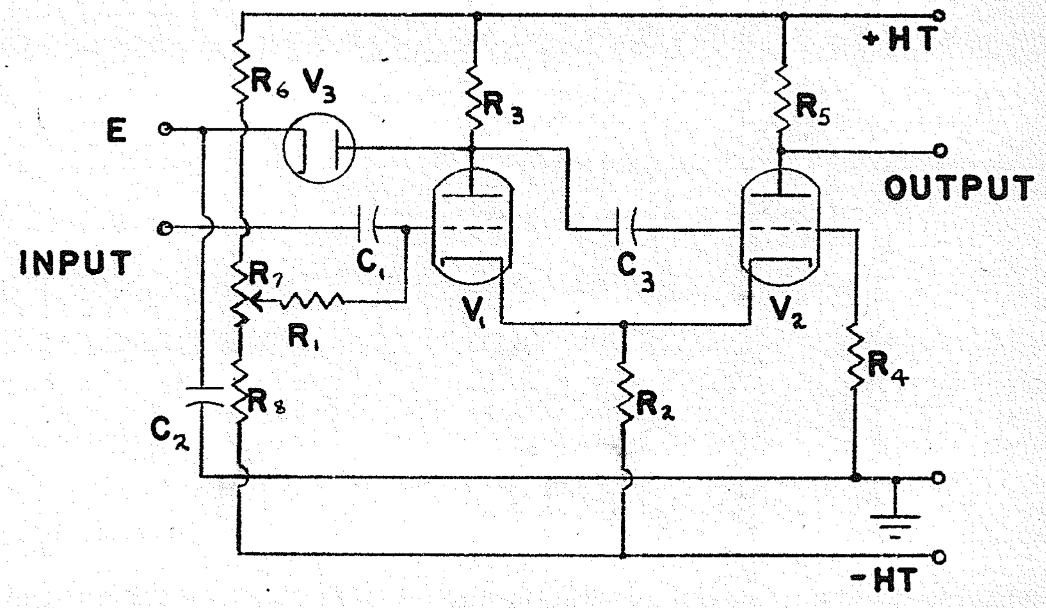

FIGURE 2 - KANDIAH DISCRIMINATOR

R_3 were quite large resistances, the application of a positive pulse to the grid of V_1 would increase the current through V_1 by an amount exactly equal to the decrease in current through V_2, and also equal to the decrease in current through V_3, providing that the common cathode did not move. Under such a condition, the plate voltage of V_1 would remain stationary until all the current passing through the diode had been transferred to V_1. Past the instant that the diode was cut-off, the plate voltage of V_1 would begin to move. If once the diode becomes cut-off, the amplification of V_1 becomes great enough to permit triggering, triggering will occur immediately following the cut-off of the diode. It is the sudden increase in the plate load of V_1, once the diode is cut off, that increases the amplification of V_1 sufficiently to permit triggering. On triggering, all of the current in V_2 is transferred to V_1. The grid of V_2 will be driven above zero potential when the circuit triggers back, and will return to zero potential with the time constant C_3R_4. A diode is sometimes connected across R_4 in order to reduce this overshoot to a reasonably small value.

In practise it is impossible to realize a " perfect diode". As a result, the plate voltage of V_1 does move somewhat before the diode is cut-off. Since the impedance of the diode does not change sharply with changes in current, the transfer characteristic for the circuit, prior to triggering, that is, prior to cut-off of the diode, is not linear. As a result, the triggering point is not as sharply defined as it would be with a "perfect diode". This circuit, however, is a decided improvement over the conventional discriminator.

The Amputating or Window Amplifier. A window amplifier is an electronic device having a characteristic similar to that shown in Figure 3. Input pulses having less than a certain definite pulse height produce no output signal. Above this critical value, there is a range over which the device acts like a linear amplifier. Above a second, but not so critical value, the device is driven to saturation, so all input pulses above this value produce the same output pulse. In a limited sense, this device only amplifies over a relatively narrow range of input pulse heights.

Such a device is shown in Figure 4, and it is discussed in a paper by Francis and Bell, titled, "Precision Single-Channel Analyzer". V_1 is a cathode follower whose purpose is to adjust the D.C. level of the grid of V_2, as well as to pass the input signals along to V_2. Normally, V_1, V_3 and V_4 are conducting substantially, and V_2 is conducting somewhat less. When a positive pulse enters V_1, the grid of V_2 rises, and the tube begins to draw more current. This causes the plate voltages of V_2 and V_4 to fall somewhat, which causes part of the diode current to be transferred to V_2, thus almost completely compensating for the increase in grid voltage on V_2. The voltage of the plate does not drop substantially until the grid voltage of V_2 has risen high enough to cause the diode to be cut-off. Before the diode is cut-off, the small drop in plate voltage of V_2 is fed

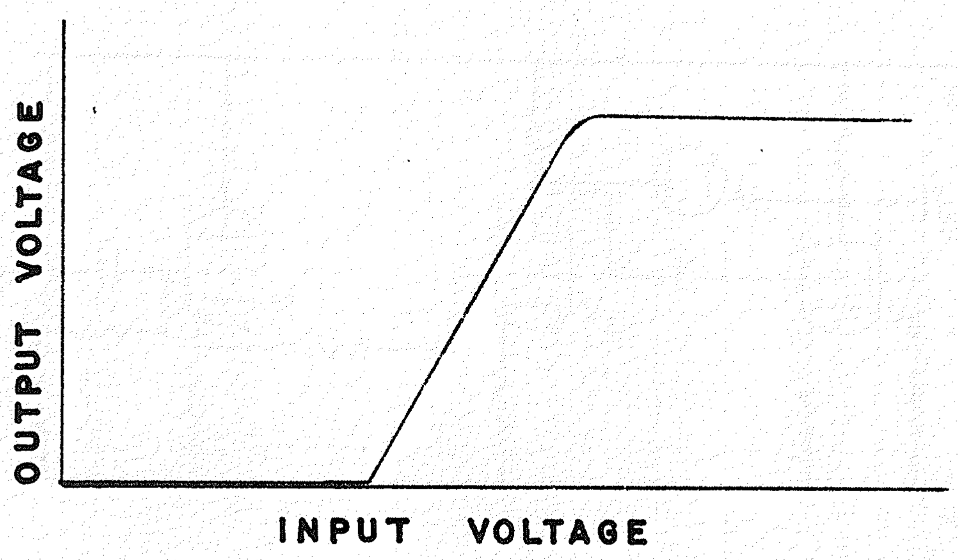

FIGURE 3 - WINDOW AMPLIFIER CHARACTERISTIC

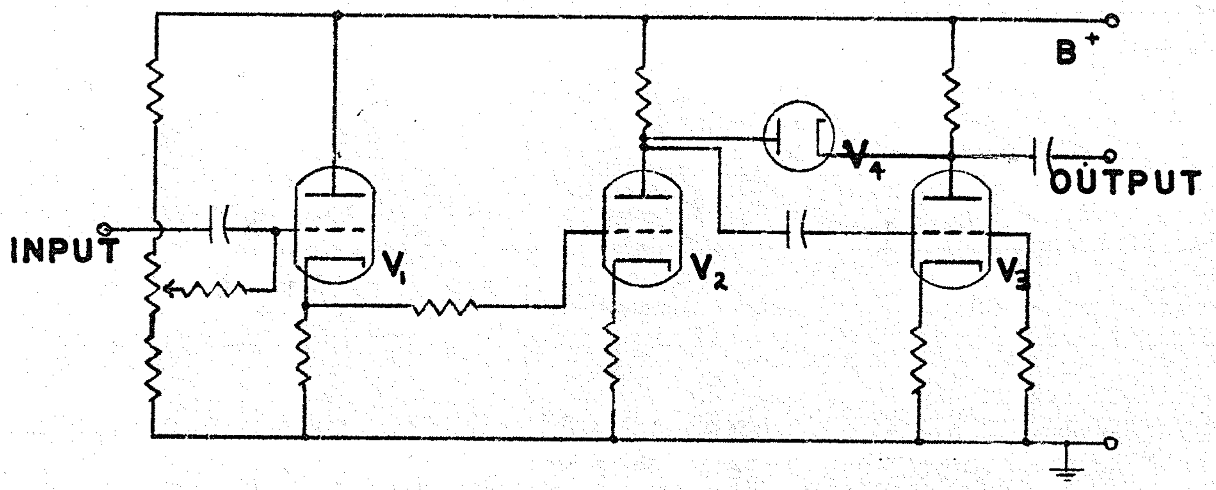

FIGURE 4 - SIMPLIFIED WINDOW AMPLIFIER

to the grid of V_3 , which causes V_3 to conduct less. This tends to cause the cathode voltage of V_4 to rise, causing the diode to be cut-off more rapidly. The actual direction of the motion of the cathode voltage of V_4 is very sensitive to the gain of V_3. The higher the gain of V_3, the more rapidly will the diode be cut-off. Once the diode is cut-off, the device acts like a conventional amplifier right up to the point of saturation, when the characteristic again levels out. The result is amplification only over a definite range.

Present Discriminator Circuit Tested. The present circuit consists of a window amplifier in which V_2 and V_3 have a common cathode load, for purposes of positive feedback to cause triggering, or alternatively, it is a Kandiah discriminator in which the cathode of the diode is connected between the split plate loads of the second trigger tube, instead of being taken to a fixed potential. Figure 5 is the circuit diagram of the integral discriminator just developed.

In Kandiah's arrangement, the diode cathode potential is fixed and the diode current is switched over to the cut-off or slightly-conducting tube just prior to triggering. In this arrangement, only one end of the diode moves, and as a result, the plate voltage of the cut-off tube does drop, somewhat, prior to triggering. In the present arrangement, the switching of the diode current over to the cut-off tube is faster, since both ends of the diode move and do so in opposite directions. The current through the plate load of the cut-off tube remains essentially constant, but that through the plate load of the conducting tube decreases, causing the

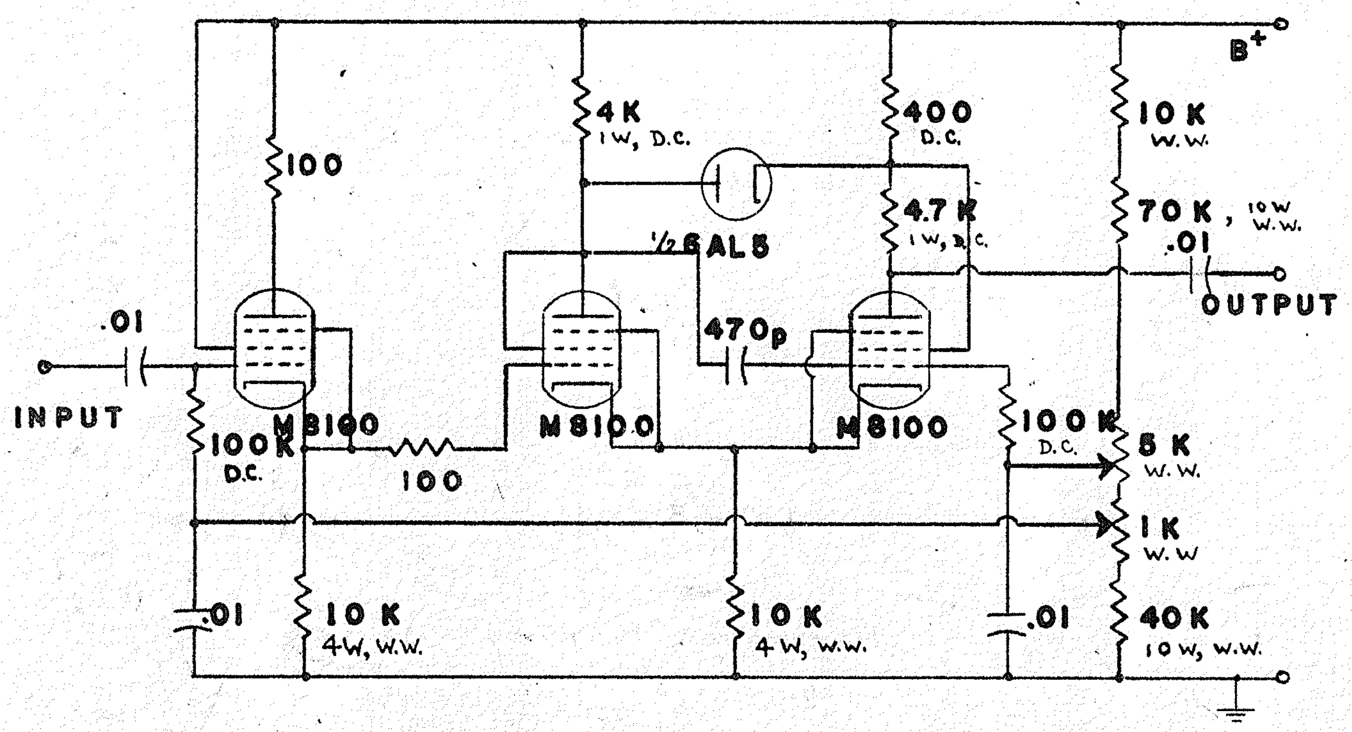

FIGURE 5 - INTEGRAL DISCRIMINATOR JUST DEVELOPED

cathode of the diode to rise. Since this transfer of current is more rapid in the present arrangement, the compensation is more nearly complete, resulting in a smaller drop in the plate voltage of the cut-off tube prior to triggering. This results in a more nearly horizontal transfer characteristic prior to triggering, than in the Kandiah case, so results in a sharper break in the transfer characteristic curve. Figure 6 shows the transfer characteristics of the Conventional, Kandiah and Present Discriminators. If the slope of this transfer characteristic is small enough prior to the break in the curve, that is, the cut-off of the diode, and if immediately following the break the slope is such as to cause triggering, the circuit will trigger right at the break in the curve. This defines the trigger point more sharply than in the Kandiah arrangement, where, instead of a sharp break in the curve, one gets a smooth curve which increases in slope fairly rapidly.

DIFFERENTIAL DISCRIMINATOR

The circuit in the previous section is an integral discriminator, that is, it merely determines whether or not the pulse height is larger than the threshold value of the discriminator, which is pre-set. A differential discriminator determines whether or not the pulse height is within a certain pre-determined range, termed the window, immediately above a pre-determined level.

The differential discriminator just developed makes use of the integral discriminator previously developed to determine the threshold, and the Gatti-

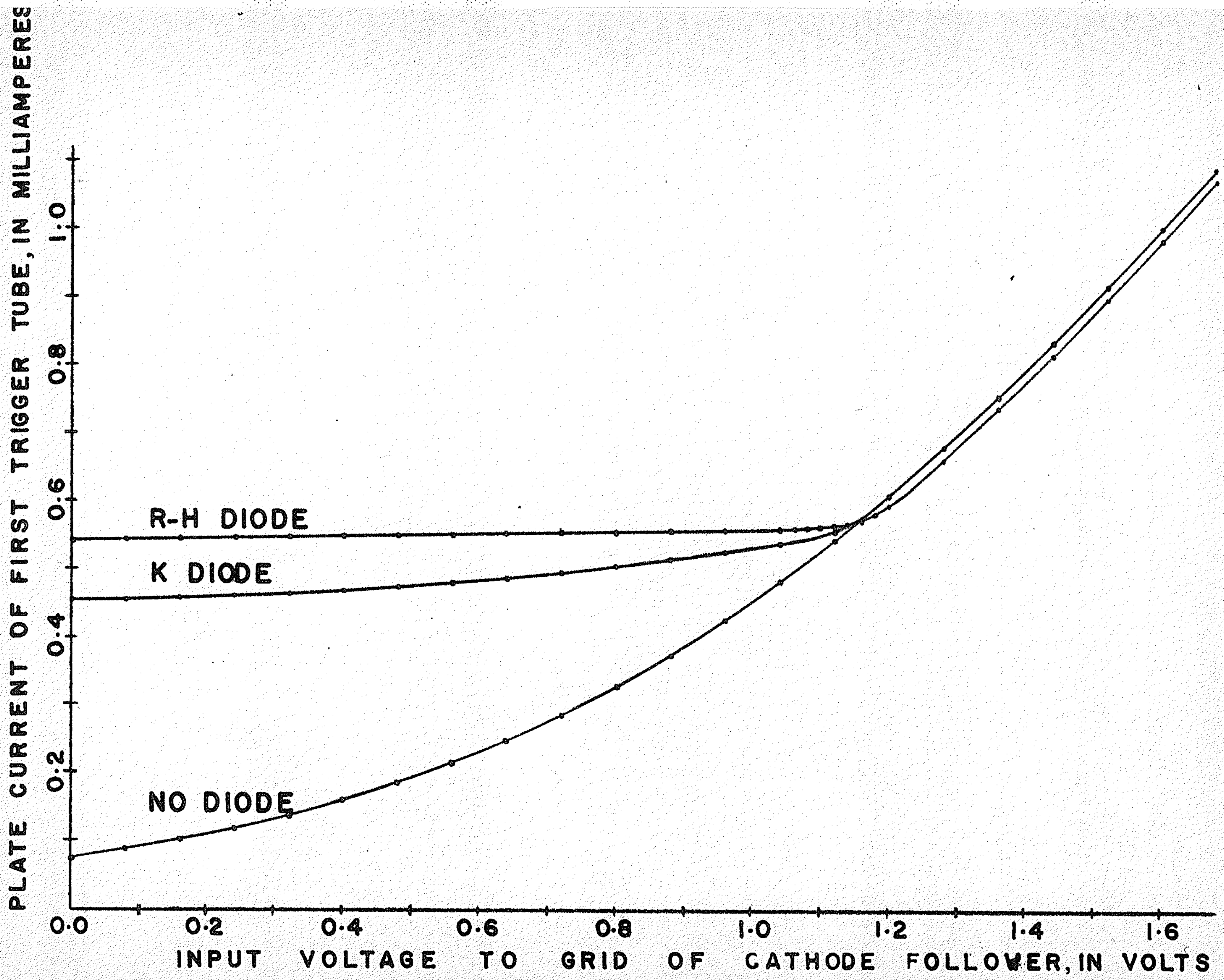

FIGURE 6 - STATIC TRANSFER CHARACTERISTICS

Piva (2) system for determining the window width. Figure 7 shows a simplified block diagram of the circuit and its associated wave forms.

For the moment, ignore all time delays associated with the circuitry, other than the delay specifically shown. The circuit requires long flat-topped pulses for its operation. These step pulses enter the pulse shaper, emerge as rectangular pulses, and pass on to the two integral discriminators. Discriminator #2 is biased to trigger on the smallest pulse to be encountered. Its output is a rectangular pulse, and when properly attenuated determines the window width of the differential discriminator. Discriminator #2 has two functions: to determine the window width of the differential discriminator, and to help in registering a coincidence output at the proper time. The pulse from the shaper is delayed before going to discriminator #2. The window pulse from discriminator #2 is fed to the pulse adder, which adds this pulse to the pulse coming directly from the shaper, at a time $t_1 - t_0$ after the leading edge of the main pulse. The output from the adder activates discriminator #1.

Let E be the threshold of discriminator #1, ΔE, the window width, and E_s, the signal pulse height just after the pulse shaper. There are three possibilities. If $E_s > E$, discriminator #1 will trigger at t_0. If $E \geq E_s \geq E-\Delta E$, discriminator #1 will trigger at t_1. If $E_s < E-\Delta E$, discriminator #1, will not trigger. Only those pulses in the range $E \geq E_s \geq E-\Delta E$ are to be counted. Therefore, it is arranged that a coincidence output can only be registered for pulses which trigger the circuit at t_1. The output of discriminator #2, occuring at t_1, gates the

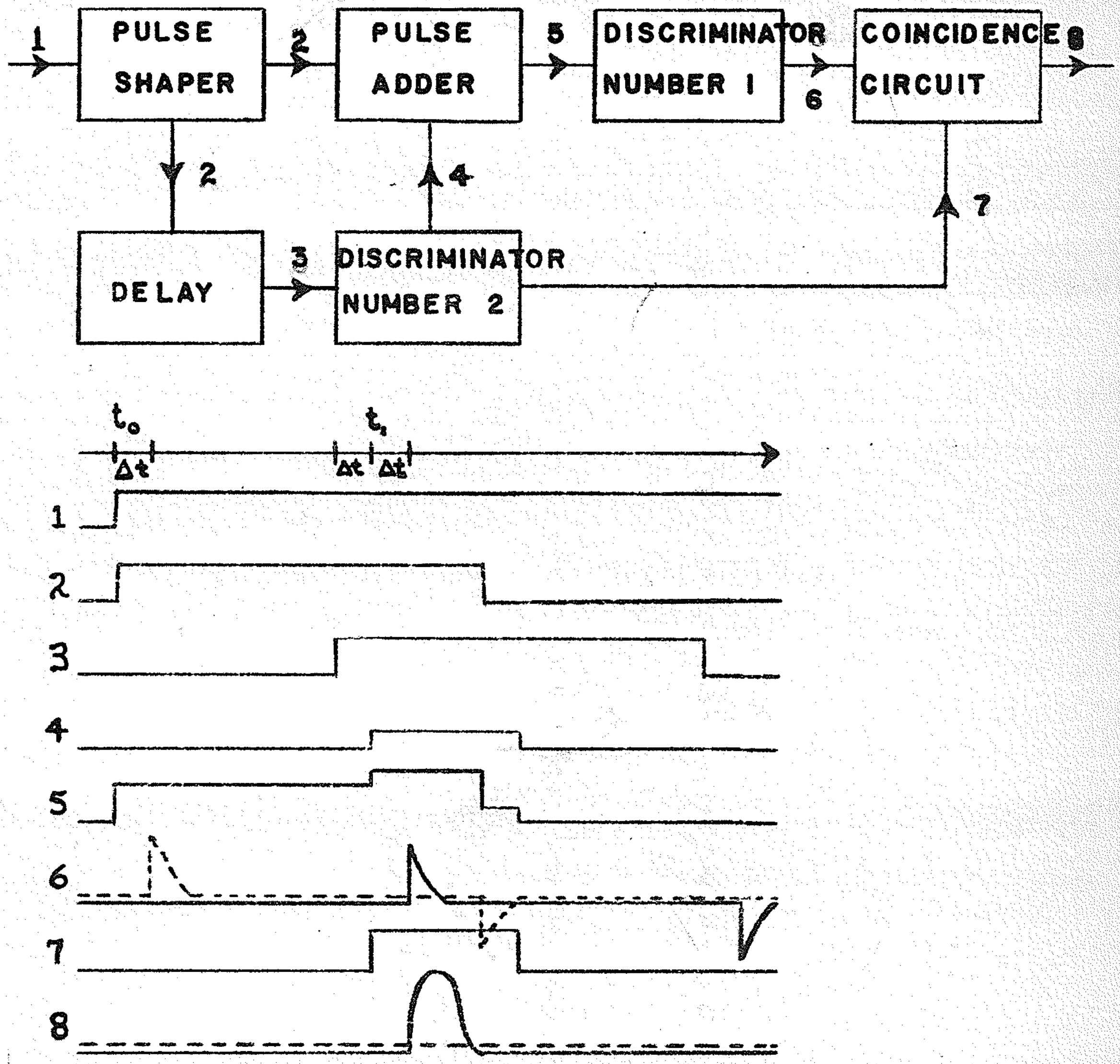

FIGURE 7 - BLOCK DIAGRAM & ASSOCIATED WAVE FORMS OF DIFFERENTIAL DISCRIMINATOR

coincidence circuit at t_1. A coincidence can then only be registered if discriminator #1 triggers at t_1.

Most conventional circuits which require shaped rectangular pulses, accomplish this shaping by charging a condenser having associated circuitry which has a long time constant for discharge, and then shorting out this condenser with a vacuum tube at the appropriate time. This gives a reasonably horizontal flat-topped pulse, providing that a long enough time constant is used. However, there are a number of associated problems when using this circuit, such as a pedestal on the output rectangular pulse. This can be overcome, but at the expense of making the circuit rather sensitive to fluctuations in D.C. levels.

Figure 8 is a circuit diagram of the differential discriminator just developed. This discriminator accomplishes the shaping of pulses by the use of a shorted delay line. The input pulses are transformed into step waves by means of condenser discharge with a long time constant. These step waves drive a cathode follower, which in turn drives the open end of a shorted delay line constructed from HH2000 cable.

The Gatti system for differential discrimination lends itself well to multi-channel operation, since the classification of the pulses in the different channels is accomplished by a single discriminator for each channel, instead of two having thresholds corresponding to the boundaries of the channel as done in conventional fast pulse analyzers. The use of a single discriminator for each channel is made possible through the shaping of the incoming pulses so that they are made to carry an element containing the

All resistors are carbon, ½-watt, and in ohms, unless specified otherwise.
All capacitors are in micro-farads, unless specified otherwise.

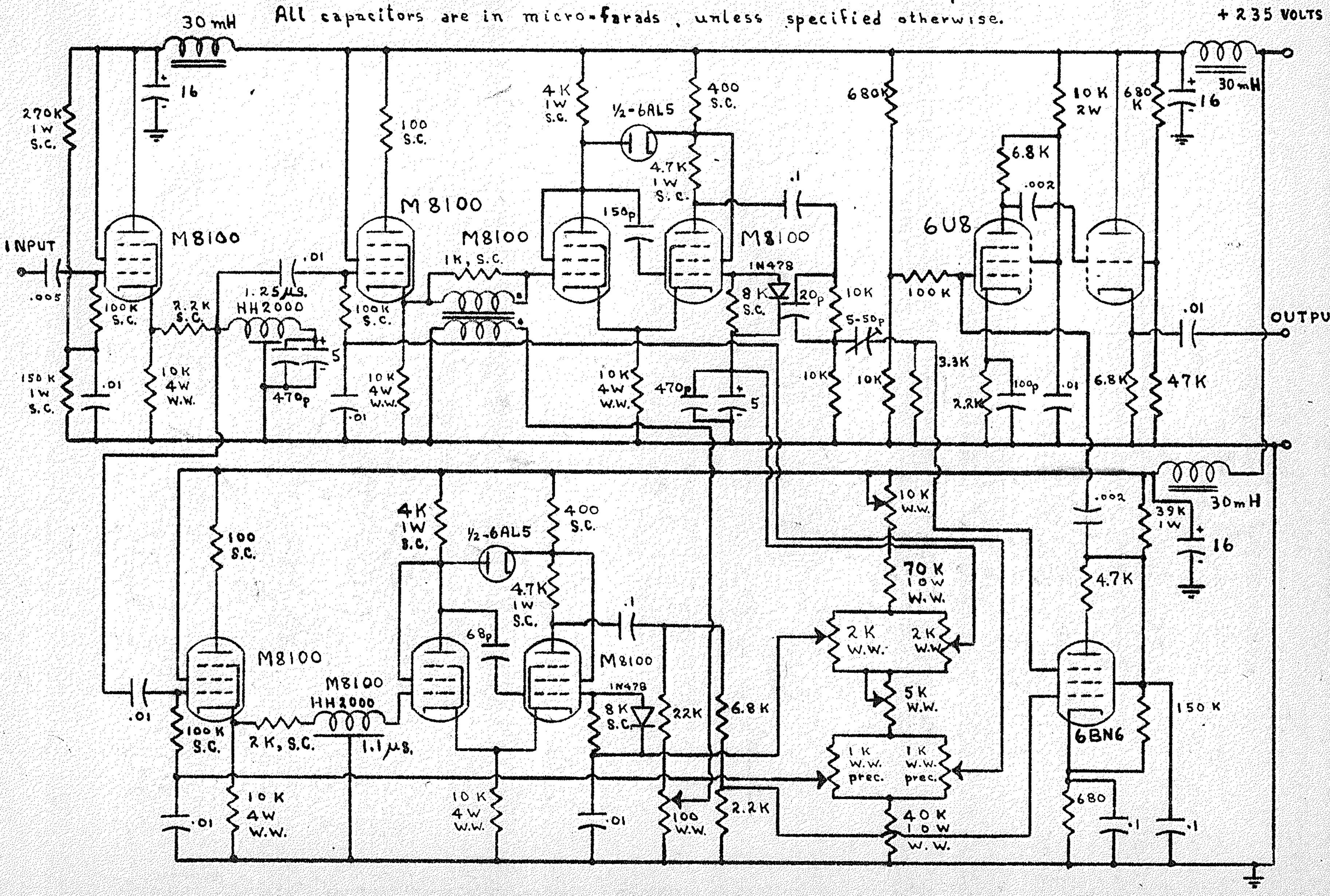

FIGURE 8-DIFFERENTIAL DISCRIMINATOR JUST DEVELOPED

information relative to the channel width, while preserving the original information relative to the height of the pulse itself. Then the thresholds of the discriminators need only to define the positions of the channels, no more their width.

Using the Gatti system, fluctuations on the threshold value do not influence the window width, but only the position of the channel. For multi-channel operation, the width is a constant for all channels, because it is defined by a single physical system, the pulse-shaper circuit.

CHAPTER III

THEORETICAL DISCUSSION OF THE CIRCUITRY.

The purpose of this chapter is to discuss, from a theoretical point of view, some of the factors affecting the stability, sensitivity, and sharpness of triggering of the two discriminators just developed. This discussion will be limited to the integral discriminator, since the factors affecting it will also affect the differential discriminator.

CONDITIONS FOR TRIGGERING

It is assumed that the various parameters of the discriminator circuit have been adjusted so that triggering occurs immediately after the diode, which is connected between the plate circuits of the two trigger tubes, ceases to conduct.

In the present circuit, the diode, while conducting, reduces the effective plate load of the first trigger tube to a relatively small value. As a result, until the diode ceases to conduct, the amplification at the plate of the first trigger tube is insufficient to permit triggering. Once the diode ceases to conduct, the circuit triggers providing that the necessary mutual conductance, gm, for the first trigger tube, as calculated for a conventional discriminator, is present.

The purpose of this section is to calculate the gm required for triggering for a conventional discriminator. Figure 9 (a) is an equivalent circuit for the cathode-coupled pair. Subscripts, 1, refer to the cut-off tube, and 2, to the conducting tube.

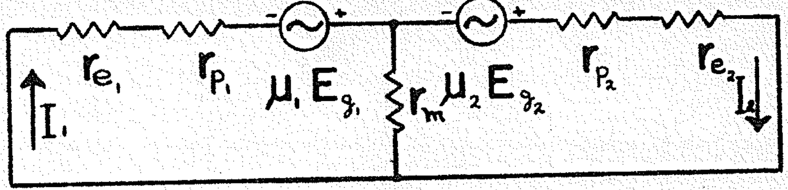

FIGURE 9(a) - EQUIVALENT CIRCUIT FOR TRIGGER CIRCUIT

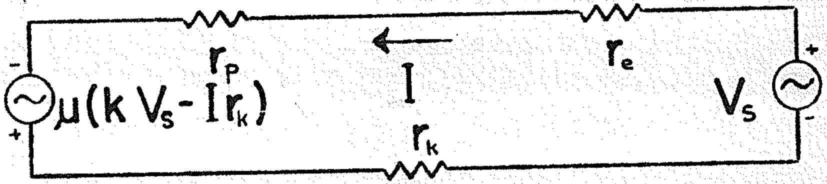

FIGURE 9(b) - EQUIVALENT CIRCUIT FOR CATHODE FOLLOWER

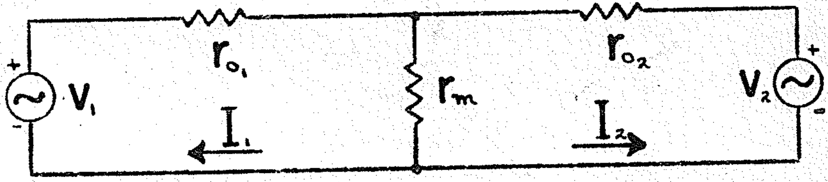

FIGURE 9(c) - EQUIVALENT CIRCUIT FOR TRIGGER CIRCUIT

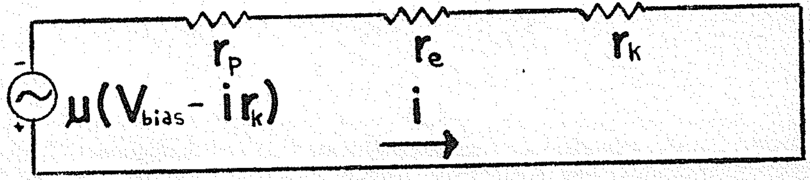

FIGURE 9(d) - EQUIVALENT CIRCUIT FOR CATHODE FOLLOWER

r_e - plate load
r_p = plate impedance
r_m - common cathode load
r_k = cathode load (of cathode follower)
r_o = output impedance (of cathode follower)

V_s - voltage signal (due to B+ change)
$V_{1,2}$ - cathode follower equivalent generator voltage
V_{bias} = D.C.grid voltage

V is the signal voltage.

In the diagram: r_e is the load resistance

r_p is the plate resistance

μ is the amplification factor

r_m is the common-cathode resistance.

The circuit equations are:-

1. $\mu_1 Eg_1 = r_m(I_1 - I_2) + I_1(r_{e_1} + r_{p_1})$

2. $\mu_2 Eg_2 = -r_m(I_1 - I_2) + I_2(r_{e_2} + r_{p_2})$

where:

$$Eg_1 = V - r_m(I_1 - I_2)$$

$$Eg_2 = I_1 r_{e_1} + r_m(I_1 - I_2)$$

Rearranging:

1. $I_1(r_{e_1} + r_{p_1} + (\mu_1+1)r_m) = \mu_1 v + I_2 r_m(\mu_1+1)$

2. $I_1(\mu_2 r_{e_1} + r_m(\mu_2+1)) = I_2(r_{e_2} + r_{p_2} + r_m(\mu_2+1))$

Dividing, we obtain:

$$X = \frac{\mu_1 v + I_2 r_m(\mu_1+1)}{I_2 Y}$$

where : $X = \dfrac{r_m(\mu_1+1) + r_{e_1} + r_{p_1}}{r_m(\mu_2+1) + \mu_2 r_{e_1}}$ and $Y = r_{e_2} + r_{p_2} + r_m(\mu_2+1)$

Therefore: $I_2(XY - r_m(\mu_1+1)) = \mu_1 v$

For instability, we require that I_2 become very large for v = constant, say zero. Therefore, the condition for instability is:

$$XY - r_m(\mu_1 + 1) = 0$$

Consider that:

$r_m = 10^4$ ohms

$r_{e_1} = 4x10^3$ ohms

$r_{e_2} = 5.1 \, x10^3$ ohms

$\mu_1 = \mu_2 = 50$

$g_{m_2} = 3900 \, \mu$ mhos

$r_{p_2} = \mu_2 / g_{m_2} = 12.82 \times 10^3$ ohms

$r_{p_1} = \mu_1 / g_{m_1} = 50/g_{m_1}$

Then : $X = \dfrac{5.14 \times 10^5 + r_{p_1}}{7.1 \times 10^5}$, $Y = 5.279 \times 10^5$ ohms

Solving for gm_1 : $g_{m_1} = 291.5$ μmhos.

This is the minimum value of g_{m_1} for which the circuit will trigger once the diode ceases to conduct.

STABILITY REQUIRED FOR THE B$^+$ SUPPLY VOLTAGE

B$^+$ supplies can be made as stable as required by the use of sufficient negative feedback, and stable enough reference voltages and components. However, high stability is obtained at the expense of greater complexity of circuitry and higher cost. It is, therefore, necessary to know what minimum stability can be tolerated in the B$^+$ supply output voltage.

Cathode follower Circuit. Figure 9 (b) is an equivalent circuit for the cathode follower.

Here, v_s is the fluctuation in the B$^+$ voltage, I is the A.C. component of the plate current, k is the fraction of v_s that appears at the control grid, and v_o is the output voltage. The circuit equation is:-

$$\mu \, (kv_s - Ir_k) + v_s = I(r_p + r_k + r_e)$$

$$I = \frac{v_s(\mu k+1)}{r_k(\mu+1)+r_p+r_e}$$

Therefore: $\Delta v_o = I r_k = \dfrac{r_k v_s(\mu k+1)}{r_k(\mu+1) + r_p + r_e}$

= the change in v_o

Consider that:-

$r_k = 10^4$ ohms
$r_e = 10^2$ ohms
$r_p = 12.5 \times 10^8$ ohms
$\mu = 50$
$k = 0.326$

Then: $\Delta v_o = 0.331 v_s$

$= 1.015\ k v_s$

The change in the cathode voltage, Δv_o, is not important in itself, but rather in the effect that it has on the threshold of the trigger circuit.

Cathode-Coupled Trigger Pair. A change in the B^+ voltage, v_s, causes a fraction of this change to be applied to the control grids of the two trigger tubes. v_s is also applied directly to the plate circuits of the two trigger tubes, causing a second-order effect. Since this circuit may be considered as a pair of cathode-coupled cathode followers, the first order effects due to v_s will cancel. The resultant change in the triggering point due to v_s will be a second-or third-order effect. As far as v_s is concerned, both trigger tubes may be considered to be triode-connected.

Let k_1 be the fraction of v_s appearing at the control grid of the first trigger tube, v_1. Let k_1^1, be the fraction of v_s appearing at the plate of v_1. Let k_2 be the fraction of v_s appearing at the control grid of the second trigger tube, v_2. Let k_2^1 be the fraction of v_s appearing at the screen of v_2.

Figure 9 (c) is an equivalent circuit for the cathode coupled pair. r_{o_1} is the output impedence of v_1 and r_{o_2} is the output impedance of v_2, looking in at their cathodes.

The effective grid voltages are:

$$v_{g_1 \text{ eff.}} = k_1 v_s + \frac{k_1^1 v_s}{\mu_1}, \quad v_{g_2 \text{ eff}} = k_2 v_s + \frac{k_2^1 v_s}{\mu_2}$$

If A_1 and A_2 be the amplifications of the two cathode followers, the two generators driving into their output impedances are,

$$v_1 = A_1 . v_{g_1 \text{ eff.}} \quad , \quad v_2 = A_2 . v_{g_2 \text{ eff.}}$$

The circuit equations are:

1. $v_1 = I_1(r_{o_1}+r_m) + I_2 r_m$
2. $v_2 = I_1 r_m + I_2(r_{o_2} + r_m)$

Solving:

$$I_1 = \frac{v_1 - I_2 r_m}{r_{o_1} + r_m} \quad \text{and} \quad I_2 = \frac{v_2 r_{o_1} + r_m(v_2 - v_1)}{r_{o_1} r_{o_2} + r_m(r_{o_1} + r_{o_2})}$$

The change in the cathode potential is:

$$\Delta v_m = r_m(I_1+I_2) = r_m \frac{v_1 + r_{o_1} \dfrac{(v_2 r_{o_1} + r_m(v_2 - v_1))}{r_{o_1} r_{o_2} + r_m(r_{o_1} + r_{o_2})}}{r_{o_1} + r_m}$$

For a cathode follower: $A = \dfrac{\mu}{\mu + 1}$, $r_o = \dfrac{r_p + r_e}{\mu + 1}$

Providing that the slope of the dynamic transfer characteristic for the cut-off tube does not change due to a change in the B^+, and this seems reasonable in a first order approximation at least, the change in the triggering point, ΔT.P., will be given by $(\Delta v_m - v_{g_1 \, eff.})$.

Therefore:

$$\Delta T.P. = \frac{r_m v_1 + \dfrac{r_{o_1}\left(v_2 r_{o_1} + r_m (v_2 - v_1)\right)}{r_{o_1} r_{o_2} + r_m (r_{o_1} + r_{o_2})}}{r_{o_1} + r_m} - v_{g_1 \, eff.}$$

Comparing the two terms in the numerator of the first term in the expression for ΔT.P., it is found that the second term is smaller than the first by more than four orders of magnitude.

Therefore: $$\Delta T.P = \left\{ \frac{r_m A_1}{r_m + r_{o_1}} - 1 \right\} v_{g_1 \, eff.}$$

To minimize ΔT.P. it is required that $A_1 \Rightarrow 1$ and $r_{o_1} \rightarrow o$. In practice, these limits cannot be obtained but they can be approached by using vacuum tubes having relatively large μ and g_m and relatively small r_p.

Now: $r_m = 10^4$ ohms $\qquad k_1 = 0.331$

$r_{e_1} = 4 \times 10^3$ ohms $\qquad k_1^1 = 0.988$

If it is assumed that the circuit triggers at the value for g_{m_1}, as calculated for the conventional discriminator, and that $\mu = 50$, then:

$A_1 = 0.980$ and $r_{o_1} = 3.43 \times 10^3$ ohms.

Then: $\Delta T.P. = -0.094 \, v_s$

However, in actual practice near the triggering point, the value of

g_m, is approximately 750 μ mhos. If $\mu = 50$, then $A = 0.98$ and $r_{o_1} = 1.39 \times 10^3$ ohms.

Then: $\Delta T.P. = -0.049\ v_s$

In order to maintain $\Delta T.P. = 1$ millivolt, requires that $v_s \leq 20.4$ millivolts.

STABILITY REQUIRED IN CERTAIN RESISTORS.

Variations in the triggering point can arise from variations in the component values of certain resistors. The cathode resistors, the plate resistors across the diode, and the bias chain resistors are most sensitive when variations in the triggering point are to be considered. Variations in the values of resistances include both noise and temperature coefficient effects. Certain resistances will require to be of the low-noise variety and also be made from materials having a very small temperature coefficient of resistance.

Cathode follower circuit. Figure 9(d) is an equivalent circuit for the cathode follower, i is the total instantaneous current, v bias is the D.C. voltage on the control grid, and v_o is the output cathode voltage. The circuit equation is:- $\mu(v \text{ bias} - i\, r_k) = i\,(r_p + r_e + r_k)$

Cathode load. If r_k changes to a value $r_k + \Delta r_k$, the current changes to a value $i + \Delta i$, and the circuit equation becomes:

$$\mu(v \text{ bias} - (i + \Delta i)(r_k + \Delta r_k)) = (i + \Delta i)(r_p + r_e + \Delta r_k + r_k)$$

Then: $$\Delta i = i \left(\frac{r_p + r_e + r_k(\mu + 1)}{r_p + r_e + (r_k + \Delta r_k)(\mu + 1)} - 1 \right)$$

Now: $v_o = i\, r_k$

Therefore, the change in v_o, $\Delta v_o = i\, \Delta r_k + r_k \Delta i$

Therefore: $$\frac{\Delta v_o}{v_o} = \frac{\Delta r_k}{r_k} + \frac{r_p + r_e + r_k(\mu + 1)}{r_p + r_e + (r_k + \Delta r_k)(\mu + 1)} - 1$$

Now: $r_k = 10^4$ ohms

$r_e = 10^2$ ohms

$r_p = 1.25 \times 10^4$ ohms

$\mu = 50$

Consider that $v_o = 80$ volts and that we require $\Delta v_o \leq 1$ millivolt.

This requires that: $\Delta r_k \leq 5.18$ ohm or ≤ 0.0518 %

Plate load. If r_e changes to a value $r_e + \Delta r_e$, the current changes to a value $i + \Delta i$, and the circuit equation becomes:

$$\mu(v \text{ bias} - r_k(i + \Delta i)) = (i + \Delta i)(r_p + r_e + \Delta r_e + r_k)$$

Then: $$\Delta i = i\left(\frac{r_k(\mu+1) + r_p + r_e}{r_k(\mu+1) + r_p + r_e + \Delta r_e} - 1\right)$$

$$\Delta v_o = r_k \Delta i$$

Therefore: $$\frac{\Delta v_o}{v_o} = \frac{r_k(\mu+1) + r_p + r_e}{r_k(\mu+1) + r_p + r_e + \Delta r_e} - 1$$

Consider that: $v_o = 80$ volts and that $\Delta v_o \leq 1$ millivolt. This requires that $\Delta r_e \leq 6.4$ ohms or 6.4%.

Cathode-Coupled Trigger Pair. Figure 9(c) is an equivalent circuit for the trigger circuit. The circuit equations are:

$$v_1 = i_1(r_{o_1} + r_m) + i_2 r_m$$

$$v_2 = i_2(r_{o_2} + r_m) + i_1 r_m$$

Here, i_1 and i_2 are the total instantaneous currents, and v_1 and v_2 are the D.C. potentials of the control grids.

$$v_1 = A_1 v \text{ bias}_1 \qquad V_2 = A_2 v \text{ bias}_2$$

$$= A_1 k_1 E_{bb} \qquad = A_2 k_2 E_{bb}$$

The voltage of the cathode, v_m, is given by: $v_m = r_m(i_1+i_2)$

The expression for v_m will be the same as that obtained for Δv_m in the section dealing with changes in the triggering point due to fluctuations in the B^+.

Therefore:
$$v_m = \frac{r_m v_1 + r_{o_1}\dfrac{(v_2 r_{o_1} + r_m(v_2 - v_1))}{r_{o_1} r_{o_2} + r_m(r_{o_1} + r_{o_2})}}{r_{o_1} + r_m}$$

The second term in the numerator is smaller than the first by more than four orders of magnitude.

Therefore:
$$v_m = \frac{r_m v_1}{r_{o_1} + r_m}$$

The change in the value of the common cathode voltage, Δv_m, due to changes in the values of the resistors, is given by:

$$\Delta v_m = \frac{(r_{o_1} + r_m)(r_m \Delta v_1 + v_1 \Delta r_m) - r_m v_1(\Delta r_{o_1} + \Delta r_m)}{(r_{o_1} + r_m)^2}$$

Now: $v_1 = A_1 k_1 E_{bb}$ Where: $A_1 = \dfrac{\mu_1}{\mu_1 + 1}$

and: $r_{o_1} = \dfrac{r_{p_1} + r_{e_1}}{\mu_1 + 1}$

Therefore: $\Delta v_1 = E_{bb} A_1 \Delta k_1$

$$\Delta r_{o_1} = \frac{\Delta r_{e_1}}{\mu_1 + 1}$$

Consider that: $r_m = 10^4$ ohms. $E_{bb} = 236$ volts

$r_{e_1} = 4 \times 10^3$ ohms $\mu_1 = 50$

$r_{p_1} = 6.67 \times 10^4$ ohms $k_1 = 0.331$

Common-Cathode Load. If only r_m varies then:

$\Delta r_{o_1} = 0$ $A_1 = 0.98$

$\Delta v_1 = 0$ $v_1 = 76.55$ volts

$r_{o_1} = 1.386 \times 10^3$ ohms

Then: $\Delta v_m = 8.18 \times 10^{-4}\, \Delta r_m$

Since ΔT.P. = Δv_m, in order to keep ΔT.P. $\leq$ 1 millivolt requires that $\Delta r_m \leq 1.22$ ohms or 0.0122%

Plate Load of Cut-off Tube. If only r_{e_1} varies, then:

$\Delta r_{o_1} = 1.960 \times 10^{-2}\, \Delta r_{e_1}$

$\Delta v_1 = 0$

Then: $\Delta v_m = -1.157 \times 10^{-4}\, \Delta r_{e_1}$

In order to keep ΔT.P. $\leq$ 1 millivolt, requires that $\Delta r_{e_1} \leq 8.64$ ohms or 0.216%.

Upper Portion of Plate Load of Conducting Tube. The expression used in the immediately preceeding section for Δv_m will not handle the situation where the plate load of the conducting tube varies, since r_{e_2} does not appear in this expression.

However, both the equivalent circuit and the circuit equations are symmetrical in the subscripts 1 and 2. Therefore, one can interchange the subscripts in the expressions for Δv_m, Δr_o and Δv without loss of their mathematical validity.

Therefore: $$\Delta v_m = \frac{(r_{o_2}+r_m)(r_m\Delta v_2+ v_2\Delta r_m) - r_m v_2(\Delta r_{o_2} + \Delta r_m)}{(r_{o_2} + r_m)2}$$

$$\Delta v_2 = E_{bb}A_2\Delta k_2$$

$$\Delta r_{o_2} = \frac{\Delta r_{e_2}}{\mu_2+1}$$

Consider that: $r_m = 10^4$ ohms $\quad E_{bb} = 236$ ohms

$r_{e_2} = 4x\ 10^2$ ohms $\quad k_2 = 0.347$

$r_{p_2} = 1.25 \times 10^4$ ohms $\quad \mu = 50$

If only r_{e_2} varies then:

$\Delta r_{o_2} = 1.960 \times 10^{-2}\ \Delta r_{e_2}$ $\quad r_{o_2} = 252.9$ ohms

$\Delta v_2 = 0$ $\quad A_2 = 0.98$

$v_2 = 80.25$ volts

Then: $\Delta v_m = -1.496 \times 10^{-4}\ \Delta r_{e_2}$

The change in the voltage across r_{e_2} is $8.4 \times 10^{-3}\ \Delta r_{e_2}$. This voltage will appear across the diode, and since the gain of the first trigger tube is very nearly unity, $\Delta T.P = (8.4 - 0.15) \times 10^{-3}\ \Delta r_{e_2}$. To keep $\Delta T.P. < 1$ millivolt requires $\Delta r_{e_2} < 0.145$ ohms or 0.036%.

Bias Chain. Variations in the values of resistors in the bias chain may be accounted for by making use of the expression for v_m derived in the section dealing with variations in the values of resistors in the trigger circuit.

$$v_m = \frac{r_m v_1}{r_{o_1} + r_m} = \frac{r_m v_2}{r_{o_2} + r_m} \text{ to a very good approximation,}$$

where: $v_1 = A_1 k_1 Ebb$ and $v_2 = A_2 k_2\, Ebb$

Since r_{o_1} and r_{o_2} are independent of k_1 and k_2, only v_1 and v_2 vary in the expression above.

Therefore: $\Delta v_m = \dfrac{r_m A_1 Ebb\, \Delta k_1}{r_{o_1} + r_m} = \dfrac{r_m A_2 Ebb \Delta k_2}{r_{o_2} + r_m}$

Therefore: $\dfrac{\Delta v_m}{v_m} = \dfrac{\Delta k_1}{k_1}$ and $\dfrac{\Delta v_m}{v_m} = \dfrac{\Delta k_2}{k_2}$

Consider that:

$v_m = 87.5$ volts
$k_1 = 0.331$
$k_2 = 0.347$

Suppose that k_1 and k_2 were to vary, independently. In order that $\Delta T.P. \leq 1$ millivolt would require that:

$\Delta k_1 \leq 3.78 \times 10^{-6}$ or 1.14×10^{-3} %
$\Delta k_2 \leq 3.97 \times 10^{-6}$ or 1.14×10^{-3}%

It is more likely that k_1 and k_2 would change together, and in the same direction. In such a situation there would be a large measure of compensation.

LEAKAGE RESISTANCE OF CERTAIN CONDENSERS.

Condensers have finite leakage resistances which fluctuate in magnitude between widely separated limits. Fluctuations in the leakage current cause fluctuations in certain of the operating potentials within the circuit. The minimum leakage resistance that can be tolerated, in order that the fluctuations in the triggering point will be < 1 millivolt, will be calculated for each of the condensers shown in Figure 5.

Cross-Coupling Condenser. The leakage current must pass through about 143,000 ohms on its way to ground. If the grid voltage of the conducting trigger tube is to be stable to < 1 millivolt, the leakage current must be $< 7 \times 10^{-9}$ amperes. Since the D.C. potential drop across the condenser is about 151 volts, the leakage resistance must be greater than 2.16×10^{10} ohms.

Input Condenser. The leakage current must pass through about 140,000 ohms. If the grid voltage of the cathode follower is to be stable to < 1 millivolt, the leakage current must be $< 7.14 \times 10^{-9}$ amperes. If the D.C. level of the input pulses is at ground potential, the D.C. potential drop across the condenser is about 77 volts. Therefore, the leakage resistance must be greater than 1.08×10^{10} ohms.

Output Condenser. Since μ is approximately 50 for a triode-connected M8100, a change of 50 millivolts at the screen of the conducting trigger tube is equivalent to a change of 1 millivolt at its control grid. If the screen is to be stable to < 50 millivolts, the leakage current through the 400 ohm resistor must be $<1.2 \times 10^{-4}$ amperes. If the output is taken to ground potential, the D.C. potential drop across the condenser is approximately 204 volts. Therefore, the leakage resistance must be be greater than 1.7×10^{6} ohms.

<u>Noise Filter Condensers.</u> The two 0.01 micro-farad condensers, which are connected between the two bias control center taps and ground, in combination with the two 100,000 ohm grid resistors, form noise filters. The leakage resistances of these condensers are in parallel with the lower portion of the bias chain. This reduces the effective resistance of the bias chain, so reduces the bias voltages. If the bias voltages are to be stable to < 1 millivolt in about 80 volts, that is, stable to a factor which is $< 1.25 \times 10^{-5}$, the leakage resistances must be greater than $43{,}000/1.25 \times 10^{-5} = 3.44 \times 10^{9}$ ohms.

CHAPTER IV

EXPERIMENTAL MEASUREMENTS.

The purpose of this chapter is to discuss the experimental techniques involved in developing and testing the circuitry and to record the results of the measurements conducted upon the circuitry. A number of methods were used in the measuring of the parameters affecting the two discriminators, but in every case, the measurements were repeated several times in order to be certain that they were reproduceable. Only reproduceable results will be incorporated into this thesis.

TRANSFER CHARACTERISTICS OF THE TRIGGER CIRCUIT.

The stability, sensitivity and sharpness of triggering of a trigger circuit are mainly dependent upon the shape of the dynamic forward transfer characteristic of the cut-off tube in the trigger circuit. The transfer characteristic is a plot of the plate voltage versus the control grid voltage. The slope of this curve at any point, is the amplification of the stage at this point.

The circuit requires a minimum loop amplification which is slightly greater than unity, to enable it to trigger. This in turn requires a certain minimum amplification from the grid to the plate of the cut-off trigger tube, in order to enable the circuit to trigger. This minimum amplification will occur at some point on the transfer characteristic curve. However, tube and component parameters vary slightly with time, resulting in a narrow range of amplifications at which the circuit triggers. If the rate of change of the slope of the transfer characteristic is small at this point, the point at which triggering will occur will vary between relatively widely separated limits. If, on the other hand, the necessary amplification should be realized in a region where the slope is changing rapidly, triggering will occur between relatively close limits. The circuit developed incorporates a diode which causes a fairly sharp bend to appear in the transfer characteristic. Preceding the bend, the slope is too small to permit triggering. Triggering then occurs on the bend.

Static Transfer Characteristics. Figure 6 is a modified form of the static transfer characteristics for three different arrangements. These curves were obtained by applying a known D.C. potential to the control grid of the cut-off trigger tube, and measuring the resultant D.C. current passing through the plate load resistor by means of a Simpson D.C. Milliammeter. The plate - to - grid cross-coupling condenser was disconnected for these measurements. Since these characteristics are only true for static conditions, they do not form an accurate basis for comparison of the three arrangements tested, but merely give an indication of what one may expect.

The curve labelled "no diode" was obtained by removing the diode from the integral discriminator shown in Figure 5. This curve is the characteristic for a conventional discriminator having the same component values as the discriminator just developed. The curve labelled "R-H diode" was obtained using the discriminator as shown in Figure 5. The curve labelled "K diode" was obtained by connecting the cathode of the diode to what was a very nearly constant potential, somewhat smaller than the B^+.

The cathode was connected to a B^+ voltage divider composed of a 2,200 ohm resistor and a 100,000 ohm resistor, the 2,200 ohm resistor being connected to the B^+. The resultant potential of the cathode of the diode was then the same as in the R-H diode case. This is very nearly the case of a Kandiah discriminator having the same components as the discriminator just developed. Here the cathode of the diode moves up slightly as the diode current decreases, whereas in the Kandiah discriminator the diode cathode remains at a fixed potential. As a result, this curve will be slightly sharper than that for the Kandiah discriminator.

Dynamic Transfer Characteristics. Figure 10 is composed of sketches of the dynamic transfer characteristics, up to the triggering point, and then the triggering over of the circuits, for the conventional, Kandiah and R-H discriminators, reproduced from oscilloscope traces. The output from the pulser unit was fed to the external sweep terminals of the oscilloscope and also to the input of the discriminator, the output of the discriminator being taken from the plate of the first trigger tube and fed to the vertical deflection input of the oscilloscope.

Figure 11 is composed of sketches of oscilloscope traces of the motion of the common cathode of the trigger pair, obtained in the same manner as the curves in Figure 10.

THE EFFECT OF VARIATIONS IN THE SUPPLY VOLTAGES UPON THE THRESHOLD.

Variations on both the B^+ and heater voltages cause variations on the threshold for triggering. The following measurements were conducted upon the integral discriminator as shown in figure 5.

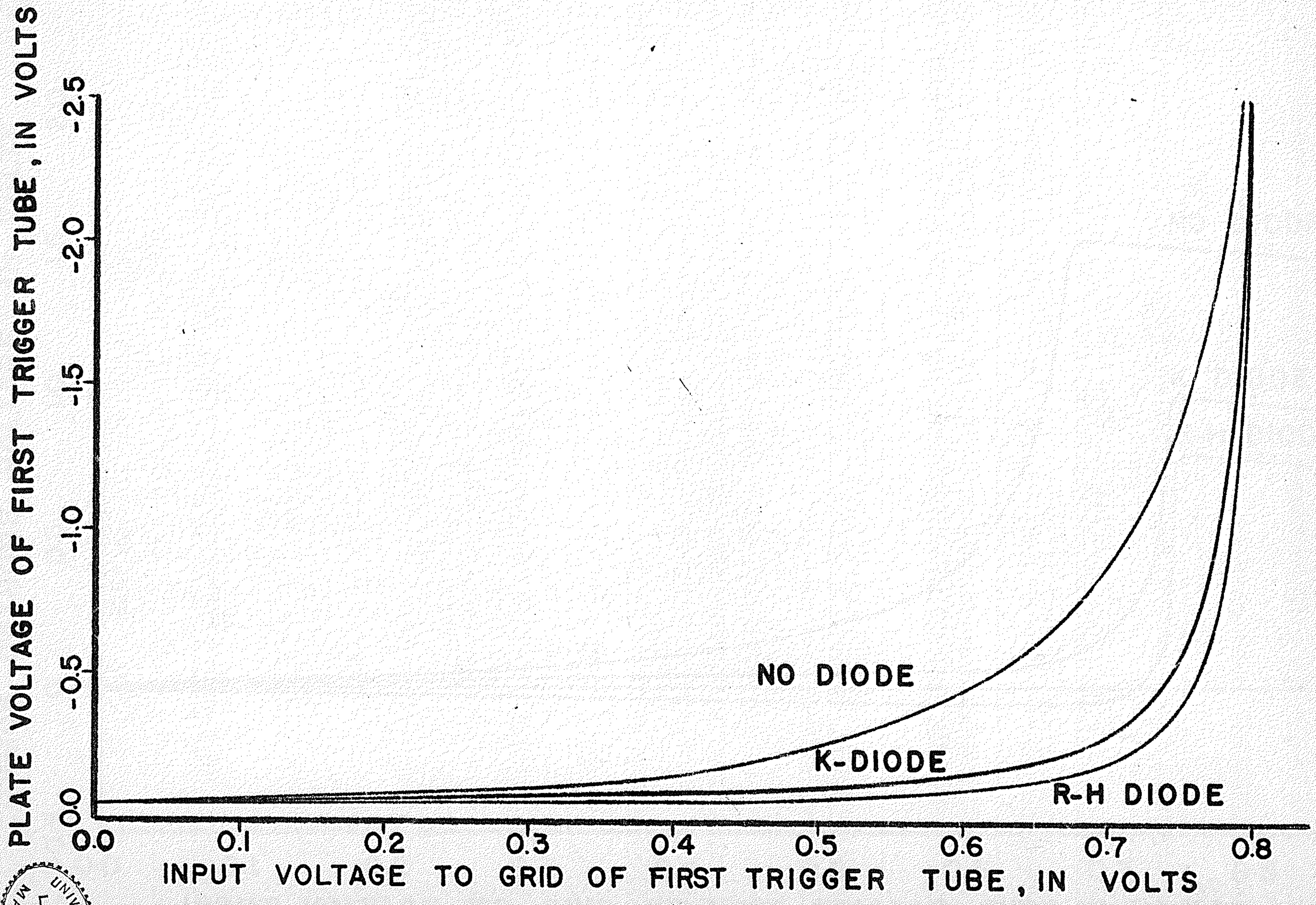

FIGURE 10 - DYNAMIC TRANSFER CHARACTERISTICS

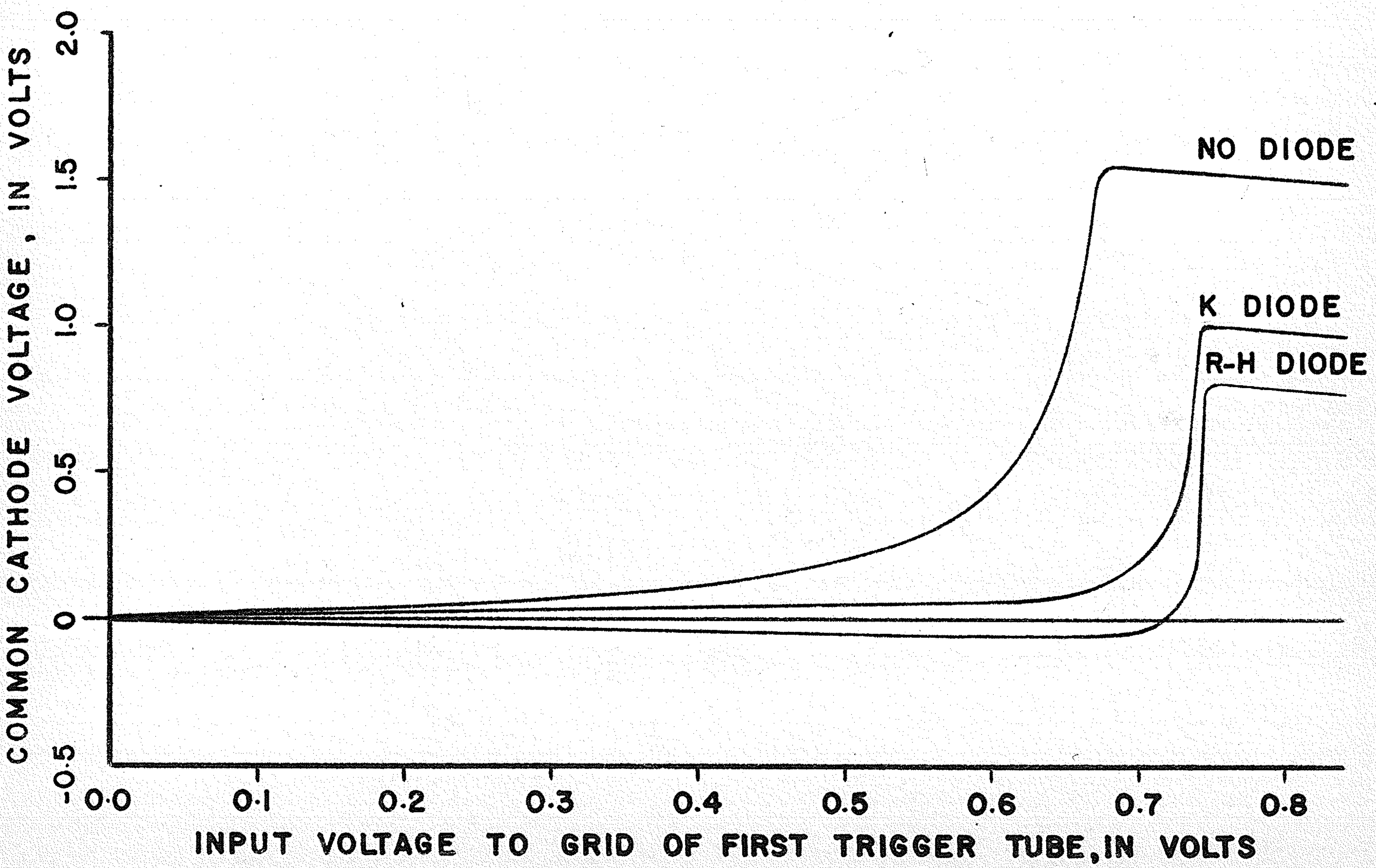

FIGURE 11 - DYNAMIC CATHODE CHARACTERISTICS

Variations on the B^+. The B^+ voltage was varied by changing the fraction of the B^+ voltage applied to the control grid of the amplifier in the voltage stabilizer, by means of a voltage divider. The change in the B^+ voltage could be set and measured to better than two millivolts, by a method which will be discussed in a section in Chapter 5 titled "B^+ Stabilizer". The triggering point, for a particular setting of the bias control, was determined by observing the minimum setting of the helipot of a calibrated pulser unit, for which the discriminator would just trigger, as determined by connecting the output of the discriminator to a glow-tube scaler. The change in the triggering point caused by a change in the B^+ voltage, was determined by observing the difference between the helipot settings of the pulser, for the two triggering points. It was found that a change of 530 millivolts on the B^+ voltage caused a shift of 1 millivolt on the triggering point.

Variations on the Heater Voltage. Four different tests were made in order to find out how variations on the heater voltage affected the triggering point. The heater voltage was varied by means of a variac and measured by means of a Weston Voltmeter, Model 433. The heater voltage could be set and read to better than five millivolts. The variation in the triggering point was determined by the method used in the preceeding section, and could be determined to better than o.2 millivolts.

Figure 12 contains plots of the variation in the triggering point with the variation in the heater voltage, for three of the four tests

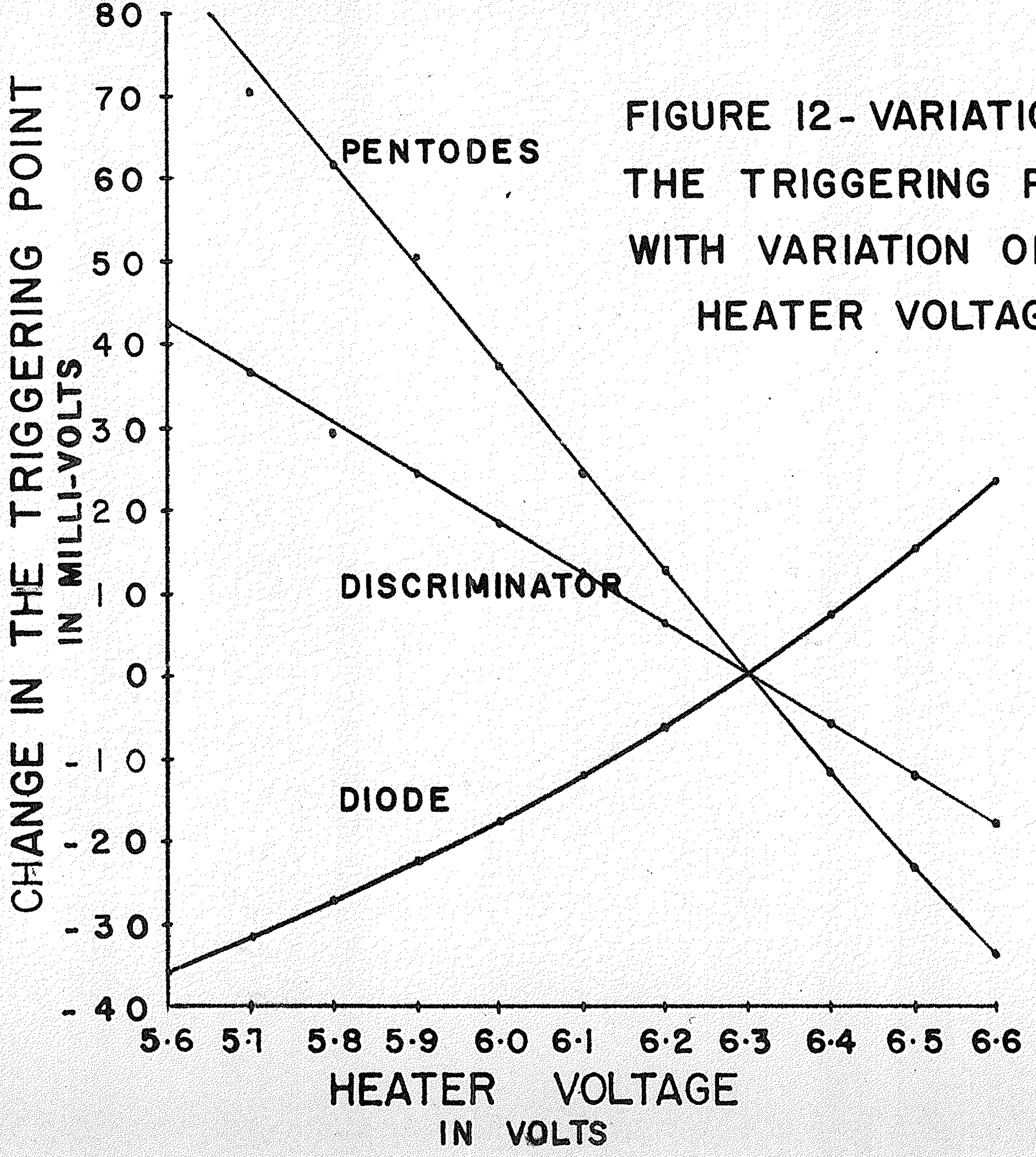

FIGURE 12- VARIATION OF THE TRIGGERING POINT WITH VARIATION OF THE HEATER VOLTAGE

conducted. The curve labelled "Pentodes" was obtained by varying the heater voltage of the three pentodes, while keeping the heater voltage of the vacuum diode constant at 6.3 volts A.C. The curve labelled "Diode" was obtained by varying the heater voltage of the vacuum diode, while keeping the heater voltage of the pentodes constant at 6.3 volts A.C. The curve labelled "Discriminator" was obtained by varying the heater voltage on all four vacuum-tubes in the integral disriminator. These three curves were brought into coincidence at 6.3 volts by shifting them vertically.

The fourth test was conducted using the crystal diode, 1N478, in place of the vacuum diode, 6 AL 5. Varying the heater voltage on the pentodes produced the same curve as the one labelled "Pentodes" in Figure 12.

THE EFFECT OF VARIATIONS IN THE VALUES OF RESISTORS UPON THE THRESHOLD.

Shifts in the triggering point due to changes in the values of certain resistors, were measured by paralleling these resistors with a much larger resistance and measuring the resultant shift in the triggering point. Table I is a list of the resultant shifts in the triggering point due to 1% reduction in the values of certain resistances.

Component	Change in Component Value	Shift in Triggering Point in millivolts.
r_{k_1}	-1%	7.5
r_{e_1}	-1%	not measurable
r_m	-1%	-5.5
r_{e_2}	-1%	not measurable

Component	Changes in Component Value	Shift in Triggering Point in millivolts
r_{e_2}	-1%	-3.0
r_{b_3}	-1%	0.3

TABLE I. Variations in the Triggering Point With Variations In the Values of Certain Resistances.

Shifts marked "not measurable", are < 0.05 millivolts in magnitude.

In Table I. :

r_{k_1} = plate load of cathode follower.
r_{e_1} = cathode load of cathode follower.
r_m = common-cathode load of trigger pair.
r_{e_2} = plate load of cut-off trigger tube
r_{e_3} = upper portion of plate load of conducting trigger tube.
r_{b_3} = lower portion of plate load of conducting trigger tube.

BIAS LINEARITY OF THE INTEGRAL AND DIFFERENTIAL DISCRIMINATORS.

The D.C. potential of the control grid of the cut-off tube in the trigger circuit is indirectly adjusted by means of a helipot in the bias chain. Since this helipot is used to adjust the threshold for the discriminator, it is necessary to know whether or not it controls the threshold in a linear manner.

In obtaining the bias curve, flat-topped pulses having a decay time constant of about 50 μ seconds were used. The hellipot setting was varied, and for each setting the minimum pulse height which would cause triggering was determined. The helipot controlling the bias is of the 10 turn variety, and its control dial has 1000 divisions. Figure 13 is a plot of the minimum pulse height necessary for triggering versus the bias dial setting.

WINDOW WIDTH LINEARITY OF THE DIFFERENTIAL DISCRIMINATOR.

The differential discriminator requires flat-topped pulses for its operation. Since these flat-topped pulses are obtained by using a shorted delay line to clip the incident step-waves, which have a finite time-constant for decay, these pulses are not perfectly flat but instead show an exponential droop. If all the incident step-waves have the same time-constant, and this is the case, the droop at any definite point on the output rectangular pulses from the pulse shaper is a constant fraction of the pulse height.

Since the window width is controlled by adding a flat-topped pulse on to the main one at about 3/2 μ seconds after the leading edge of the main pulse, the actual window width which the discriminator sees is the height of the window pulse minus the droop, which is approximately 3% of the height of the main pulse at this point.

It is obvious that the window width will decrease as the pulse height increases. This argument has assumed that no other factors affect the window width.

Since it is necessary to know precisely how the window width varies with threshold setting, the window width linearity curve, shown in Figure 14, was determined. For each setting of the bias control, the minimum and

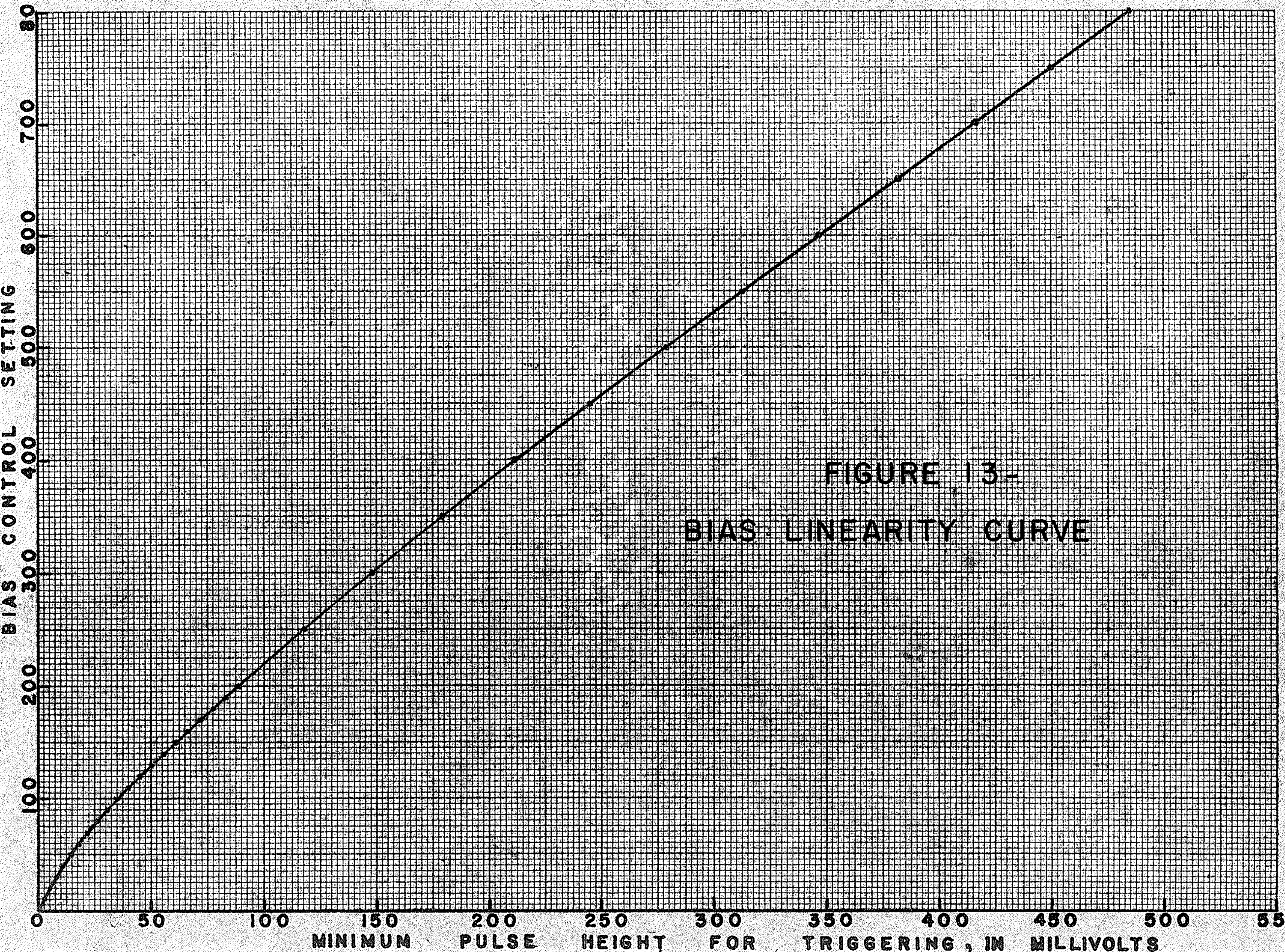

FIGURE 13-
BIAS LINEARITY CURVE

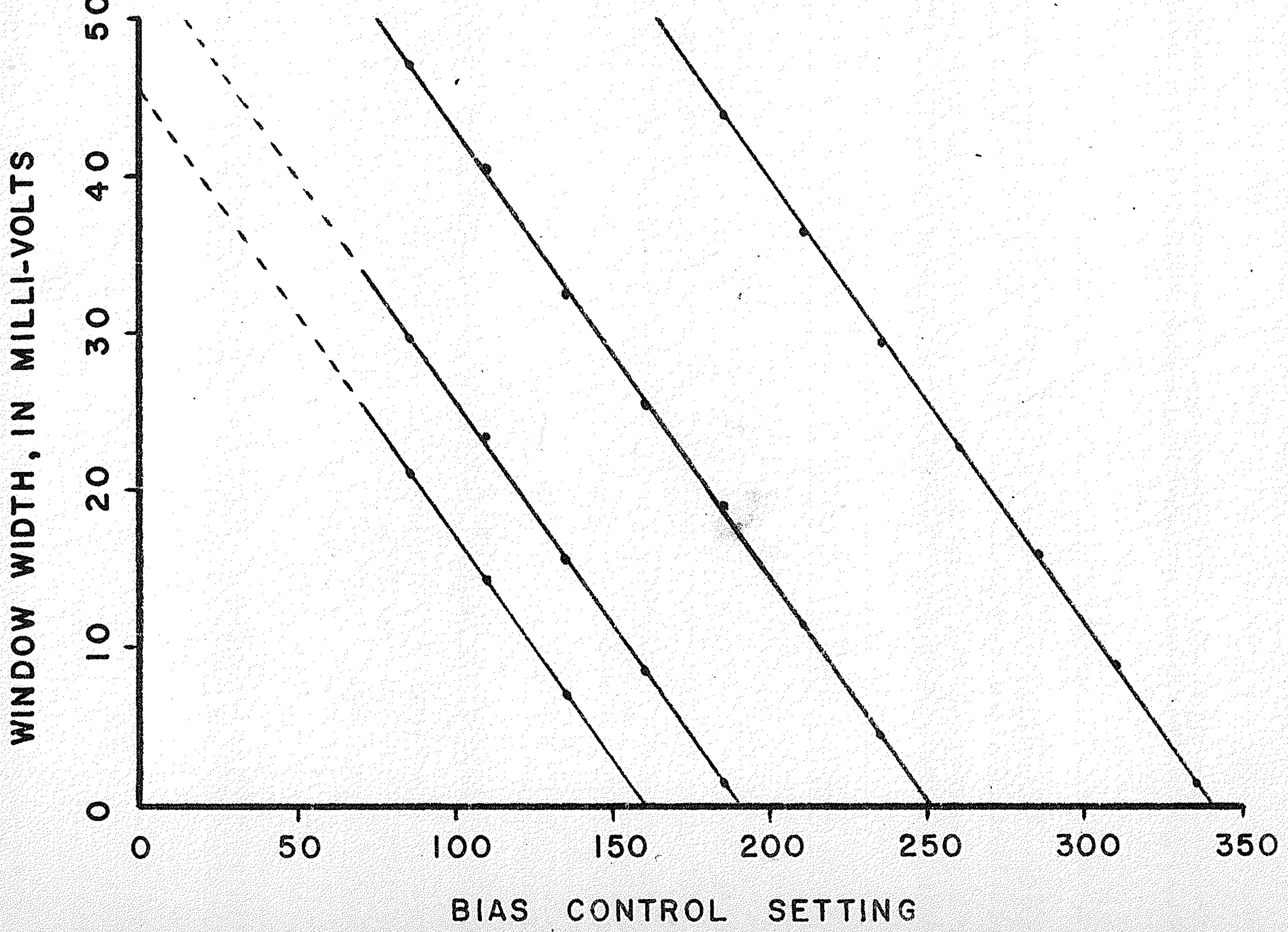

FIGURE 14- VARIATION OF WINDOW WIDTH WITH THE BIAS

maximum pulse heights for which triggering occurred at the added step, were obtained. The difference between these two pulse heights was considered to be the effective window width. In Figure 14, this effective window width is plotted against the bias setting for several values of the window width step, which is added onto the main pulse.

SENSITIVITY, STABILITY AND SHARPNESS OF TRIGGERING OF THE INTEGRAL DISCRIMINATOR.

The discriminator was found to trigger on pulses of less than 0.5 millivolts in magnitude. However, at this bias setting the circuit is very close to the oscillation point, so is somewhat unstable. Operation should probably be confined to pulses $\geq$ 2 millivolts, in order to avoid the possibility of spurious oscillation occurring.

The stability of the discriminator was determined by recording over both long and short time intervals the minimum pulse height which would cause triggering, for a fixed bias setting. The short term stability was found to be better than 0.5 millivolts, and the long term stability better than 1.2 millivolts. The short term stability was also determined by means of an oscilloscope photograph of the dynamic transfer characteristics, as shown in Figure 15. The pulses from the pulser unit were used to sweep both the discriminator and the oscilloscope. These pulses were fed directly to the external sweep terminals of the Tektronix oscilloscope, and through a 1000 times attenuator before going to the integral discriminator. One division on the horizontal scale is equivalent to three millivolts at the discriminator input. One division on the vertical scale corresponds to five volts at the plate of the cut-off trigger tube, which

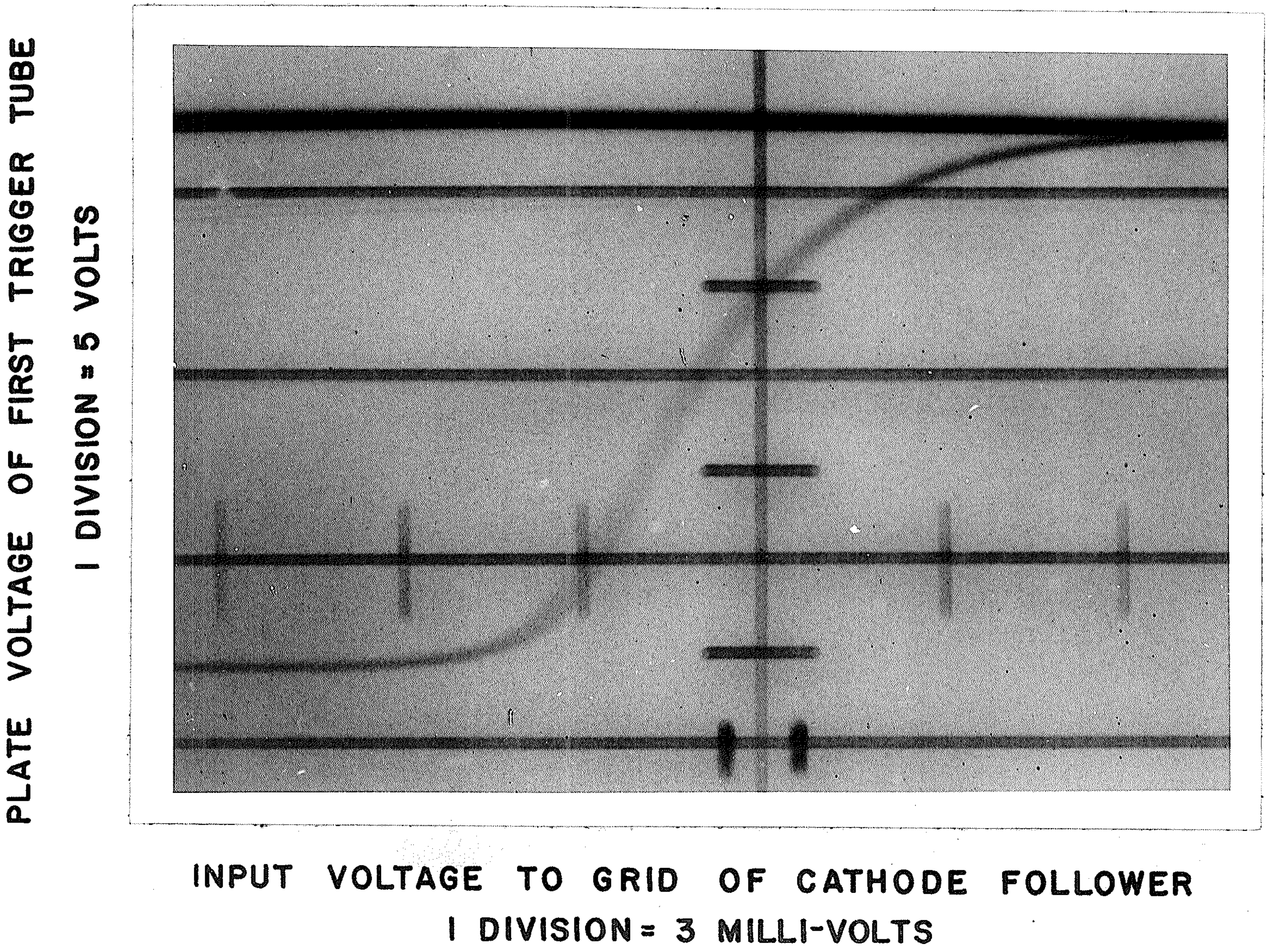

FIGURE 15-SHORT TERM STABILITY

was connected to the vertical input of the oscilloscope. From the width of the trace at the triggering point, the stability over the five minute period of the exposure would seem to be $\leq$ 0.3 millivolts.

The sharpness of triggering of the integral discriminator was determined by the following procedure. The input pulses were supplied by the pulser unit which supplied 60 pulses per second, and the output of the discriminator was fed to a glow-tube scaler. For a fixed bias setting, the input pulse heights were varied and the number of times that the circuit triggered in a fixed time interval was determined by the scaler. Figure 16, which shows the results of these measurements, is a plot of the input pulse height versus the number of times the discriminator triggered in one minute.

SENSITIVITY AND STABILITY OF THE DIFFERENTIAL DISCRIMINATOR.

The differential discriminator will trigger on pulses of about 1 millivolt in magnitude. However, when operating at levels below 10 millivolts, the discriminator frequently begins to oscillate. Oscillation sometimes occurs when operating at threshold levels as great as 25 millivolts. When either one, of the two integral discriminators involved, is disconnected, the remaining integral discriminator operates with a stability and sensitivity similar to that of the integral discriminator discussed earlier in this chapter. The instability seems to be largely due to an interaction between the two integral discriminators.

When operating well away from the oscillation point, at thresh-

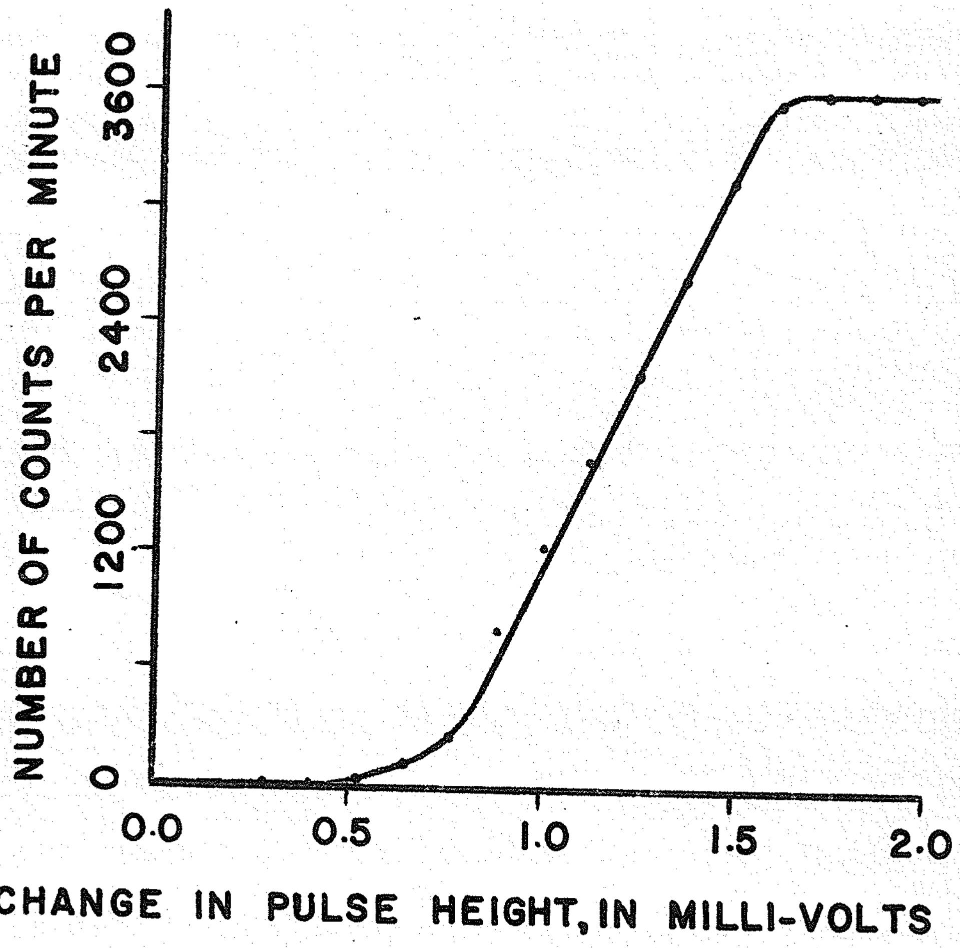

FIGURE 16- SHARPNESS OF TRIGGERING

holds which are larger than say 50 millivolts, the following stabilities were measured by the same procedure as used when determining the stability of the integral discriminator. The short term stability, over a period of 10 minutes, was found to be better than 2 millivolts. The long term stability was found to be of the order of 6 or 7 millivolts. Investigation of this instability suggested that it was due to radiation and capacitive pick-up, and also to the method used for adding the window pulse on to the main pulse. As the circuit now stands, the stability is not good enough to permit low-level operation.

CHAPTER V

A DISCUSSION OF THE DIFFICULTIES ENCOUNTERED AND THE RESULTS OF THE EXPERIMENTAL MEASUREMENTS

This chapter has three aims: to discuss the difficulties encountered in developing two discriminators which would meet the sensitivity and stability requirements; to discuss the results of the experimental measurements; and to compare experimental results with theoretical calculations. This chapter will be divided into three main sections. The first section will deal with results and difficulties common to both the integral and differential discriminators. The second section will deal with results pertaining only to the integral discriminator. The third section will deal with results and difficulties pertaining only to the differential discriminator.

RESULTS AND DIFFICULTIES COMMON TO BOTH THE INTEGRAL AND THE DIFFERENTIAL DISCRIMINATORS.

Transfer Characteristics. On the basis of the static transfer characteristics shown in Figure 6 it would seem that for the discriminator just developed, the stability and sensitivity should be somewhat better than the stability and sensitivity for the Kandiah discriminator. Since the characteristic for the R-H discriminator has a smaller slope prior to the bend, than the slope for the Kandiah discriminator, there is less chance for triggering to occur prior to the bend in the characteristic. Although it is difficult to tell from the curve, the bend for the R-H discriminator should be somewhat sharper than that for the Kandiah discriminator, improving the sharpness of triggering.

The proper basis for comparing these two discriminators is a comparison of their dynamic transfer characteristics. However, these are difficult to obtain, because each circuit will trigger at some point, obscuring the true shape of the characteristic above this point. The dynamic transfer characteristics in Figure 10 seem to indicate that the relative sharpness of triggering of the R-H discriminator as compared with the Kandiah discriminator, is about the same as indicated by the static transfer characteristics for these two circuits.

Figure 11 suggests that the triggering point is more sharply defined for the R-H discriminator than it is for the Kandiah discriminator. In the Kandiah discriminator the cathode of the diode remains at a constant potential. In the R-H discriminator, the common-cathode voltage of the trigger pair drops prior to triggering, resulting in a net decrease in the current passing through the upper portion of the plate load of the conducting trigger tube. This causes the cathode of the diode to rise, which causes the diode to be cut-off more rapidly than in the Kandiah case, resulting in an improvement in the compensation for the drop in the plate voltage of the cut-off tube.

The transfer characteristics indicate that the stability and sensitivity of the discriminator just developed, are better than the stability and sensitivity of the Kandiah discriminator.

Choice of Vacuum Tubes. Conventional discriminators tend to perform best when using sharp cut-off pentodes in the trigger circuit. In the circuit just developed, however, a more important factor to be considered was the minimizing of differences in tube characteristics among tubes of the same type. The M8100 was chosen because all tubes of this type are supposed to have characteristics within 1% of the mean characteristics for this tube type. When using M8100 's, tubes can be replaced without a serious resultant change in operating characteristics.

B^+ Stabilizer. The B^+ power supply used in this project was patterned after a United States Navy Preferred Circuit. The Preferred Circuit was reputed to have a long term stability of about 300 millivolts in 300 volts and an output impedance of about 10 ohms. When first constructed, the stabilizer was found to have a stability of about 7 volts in 235 volts. This instability was found to be mainly due to temperatures effects. The use of fairly large wattage wire wound resistors, cooled by a fan, improved the situation considerably. However, the sampling chain was not stable enough, so it was replaced by precision laboratory resistance boxes. It is intended that eventually the sampling chain will be constructed from oil-bathed manganin wire-wound resistors. The reference voltage was supplied by an OG3, which was found to be very sensitive to temperature changes. This condition was remedied by wrapping the bulb of the OG3 with aluminum foil, in order to dissipate its heat more effectively. At this point, the long term stability was fairly good, but the short term stability was very poor. It was found that the fluctuations were due to pick-up by an unconnected pin in the base of the OG3. This was remedied by connecting this pin to an adjacent pin. The schematic diagram for the stabilizer is shown in Figure 17.

The output voltage of the stabilizer, about 235 volts, was monitored by an Esterline-Angus recorder. Approximately 90 volts, of the 235 volts, was obtained from a precision laboratory voltage divider, backed-off by a 90 volt dry battery, and the difference voltage fed to a D.C. amplifier before going to the recorder. In this way, fluctuations on the B^+ voltage as small as 2 millivolts could be detected and measured.

By using a Sorenson regulator to supply the 117 volt A.C. power to operate the stabilized B^+ power supply, a short term stability of about 2 millivolts, and a long term stability of about 25 millivolts was realized for the B^+ supply voltage.

It was then found that the stability necessary for the B^+ voltage, to reduce changes in the triggering point to below 1 millivolt, was 530 millivolts in 235 volts. This is not in agreement with the value of about 20 millivolts as calculated theoretically. This would seem to indicate that the assumption to the effect that the shape of the transfer characteristic does not change with a change in the B^+ voltage, was false.

Underline: <u>Heater Voltage Stability</u>. The triggering point was found to be quite sensitive to changes in the heater voltage. From Figure 12 it can be seen that an increase of 1% in the heater voltage applied to the diode, at 6.3 volts, causes the triggering point to rise by about 4.4 millivolts.

All condensers are in micro-farads unless specified otherwise.
All resistors are carbon, ½ watt, and in ohms, unless specified otherwise.

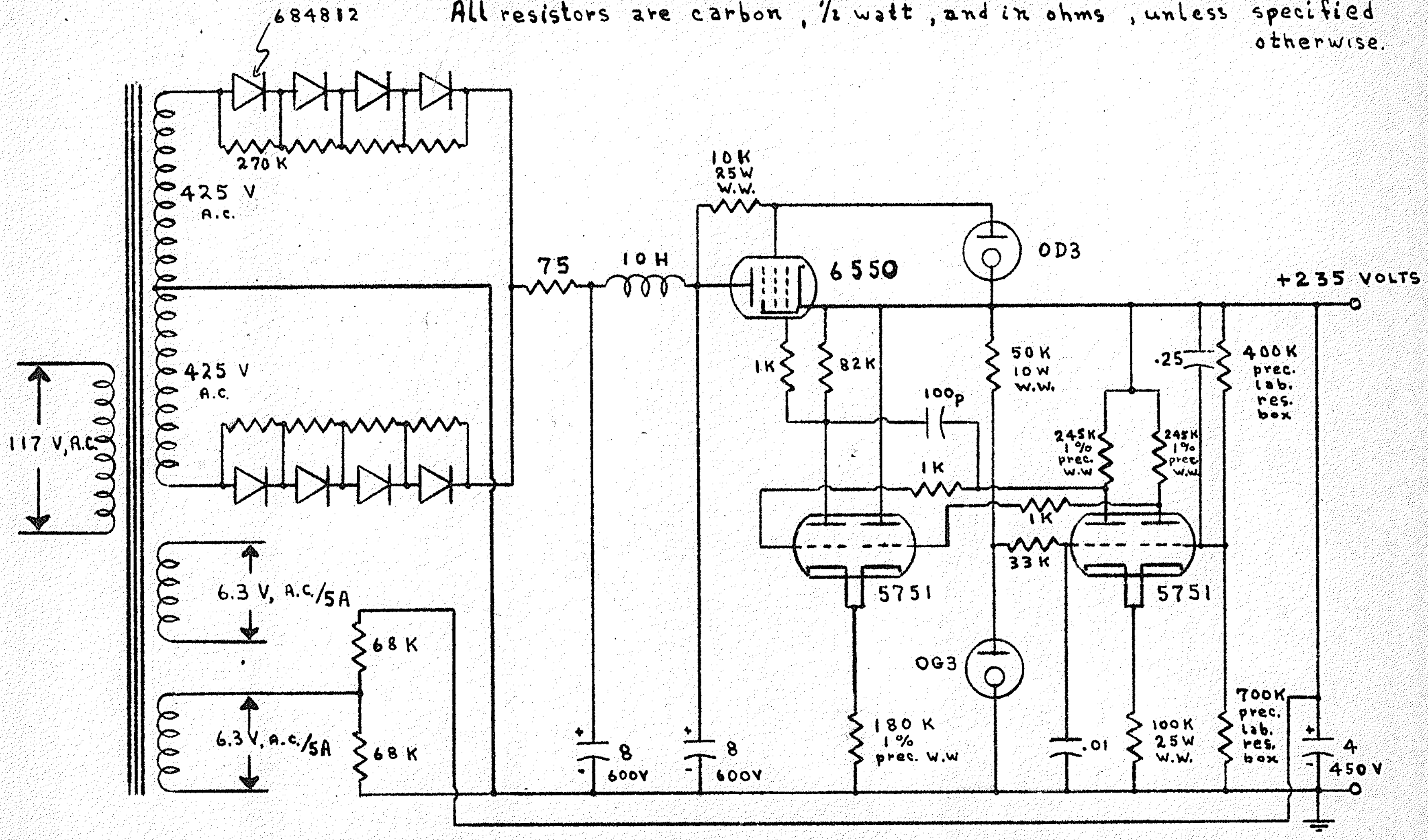

FIGURE 17- B+ SUPPLY & STABILIZER

An increase of 1% in the heater voltage of the pentodes, at 6.3 volts, causes the triggering point to fall by about 7.8 millivolts. When the heater voltage on all tubes is increased by 1%, at 6.3 volts, the triggering point falls by about 4.2 millivolts. The use of a vacuum diode, instead of a crystal diode, as a plate load for the cut-off trigger tube, introduces a compensation of approximately 46% for changes in the triggering point due to changes in the heater voltage of the pentodes. To reduce fluctuations in triggering point due to fluctuations in the heater voltage to below 1 millivolt at 6.3 volts, requires a stability in the heater supply voltage of about 15 millivolts or 0.24%. The 117 volts A.C. for the power supply is supplied by a Sorensen regulator, which should be capable of maintaining the heater voltage to within the required tolerance.

Certain crystal diodes have a smaller D.C. resistance to forward currents than is the case for most vacuum diodes, such as the 6AL5 used in this circuit. The use of a crystal diode having a smaller forward resistance than the 6AL5, would result in more complete compensation for the drop in the plate voltage of the cut-off tube prior to triggering. This would sharpen the triggering point, and also improve the stability of triggering, in so far as the transfer characteristic is concerned. A crystal diode is not used in this circuit because it does not compensate for fluctuations in the triggering point due to fluctuations in the heater voltage applied to the pentodes.

Variations in the Partition Current. Pentodes are normally used in low level trigger circuits, although they introduce one problem not common to triodes. The screen of the pentode is normally taken to a fixed potential, and the screen current is fairly well defined. However, when working at very low levels, a slight fluctuation in the partition of the cathode current between the plate and screen circuits causes a substantial change in the plate voltage. This is not permissible in a trigger circuit which is to work down to about 1 or 2 millivolts, with a stability of 1 millivolt. It was found necessary to triode-connect the cut-off trigger tube, and to connect the screen of the conducting trigger tube to the intersection of the two resistors in the split plate load of the conducting trigger tube. In this arrangement, the conducting tube is not really triode-connected, but fluctuations in the partition current will not affect the potentials applied to the two ends of the diode. Figure 5 shows the schematic diagram of the integral discriminator, which makes use of the preceding arrangement.

Linearity of Bias Control. Figure 13 shows that the bias control is certainly not linear, especially when working at low levels. When discriminating pulses having magnitudes greater than about 250 millivolts, the bias control controls the threshold in a linear manner. However, below about 40 millivolts, the bias control is quite non-linear. At about 250 millivolts, 1 division on the bias control is equivalent to 0.70 millivolts of pulse height. At levels which approach zero millivolts in pulse height, 1 division on the bias control is only equivalent to about 0.28 millivolts of pulse height. As a result, when using these two discriminators at threshold levels which are below 250 millivolts, the bias linearity curve will be required in setting the bias control to give the proper threshold.

Variations in Component Values of Certain Resistances. It may be seen from Table 1 that the triggering point is reasonably sensitive to changes in the component values of certain resistances. All resistances, in the integral discriminator units of the two discriminators developed, are high quality components in order to reduce noise effects. Where high stability in component value is not of utmost importance, stabilized carbon resistors are used. Where high stability is necessary, such as in the cathode load and bias chain resistors, wire wound resistors are used. For best results, the bias chain should be constructed from resistors made from the same materials, having relatively large wattage ratings, and having the same rated wattage per ohm of resistance. By using a fan to maintain a fairly constant ambient temperature, the fluctuations in the triggering point due to variations in the component values of the resistances in the circuit, should be within the 1 millivolt range.

If it be necessary to work at threshold levels of 1 millivolt or less, the stability of the discriminator must be improved. Under such a circumstance, the maximum fluctuation in the threshold, due to any one resistance, should be limited to 0.1 millivolts or less. This may introduce more severe restrictions on the type of resistors used. Table 2 contains the following results for certain resistors: the theoretically calculated stability necessary in order to reduce the fluctuations in the triggering point to less than 0.1 millivolts; the experimentally determined stability required to reduce fluctuations to less than 0.1 millivolts; and the type of resistor required in order to obtain this stability. It will be assumed, that in portions of the circuitry not drawing an appreciable current, the temperature fluctuations to be considered will be about 5 centigrade degrees. Where an appreciable current is drawn it will be assumed that temperature fluctuations of 20 centigrade degrees must be considered.

Component.	Theoretically Required Stability, in Percent	Experimentally Required Stability, in Percent	Component Type Necessary
r_{k_1}	5.2×10^{-3}	1.3×10^{-2}	Manganin wire-wound
r_{e_1}	6.4×10^{-1}	not measurable	Deposited carbon
r_m	1.2×10^{-3}	1.8×10^{-2}	Manganin wire-wound
r_{e_2}	2.2×10^{-2}	not measurable	Deposited carbon
r_{e_3}	3.6×10^{-3}	3.3×10^{-2}	Evanohm wire-wound.
r_{b_3}	---	3.3×10^{-1}	Evanohm wire-wound
Resistance between the taps of the bias chain	2.0×10^{-5}	----	Manganin wire-wound.

TABLE 2 - Stabilities and Component Types Necessary for a 0.1 Millivolt Stability In The Threshold.

SENSITIVITY, STABILITY AND SHARPNESS OF TRIGGERING OF THE INTEGRAL DISCRIMINATOR.

Figure 16 shows that the circuit moves from a state of not triggering to one of triggering on every pulse, with a change in pulse height of very nearly 1 millivolt. This is a decided improvement over existing discriminators, and is adequately good for low-level operation.

The integral discriminator will operate down to 2 millivolts with a long term stability of < 1.2 millivolts and a short term stability of < 0.5 millivolts. This limit of 2 millivolts is imposed by the long and short term instabilities in the circuit. Since the circuit will trigger on pulses having a magnitude of < 0.5 millivolts, it may be possible to reduce the 2 millivolt limit to about 0.5 millivolts, by improving the stability. The two most important factors to be considered in improving the stability, are the heater voltage variations and the resistor stabilities.

The Sorensen A.C. line regulator, used with this discriminator, is not regulating as well as the specifications given in its manual. If the Sorensen were regulating properly, the heater voltage variations should not be an important problem. If the resistances, which have an appreciable effect upon the triggering point, were of the types as listed in Table 2, variations in the component values of resistances should not be an important factor in determining the stability of the discriminator. Then, the only appreciable variations in the triggering point should be due to variations in the vacuum-tube characteristics. The resultant stability should be very good, possibly < 0.1 millivolts, so that operation down to 0.5 millivolts would be possible.

RESULTS AND DIFFICULTIES ASSOCIATED WITH THE DIFFERENTIAL DISCRIMINATOR.

The designing of a low-level differential discriminator, making use of the Gatti system for determining the window width, would seem to involve a fairly straight forward procedure, once the low-level integral discriminator was operating properly. However, a number of difficulties arose.

The shaping of pulses was accomplished by means of a cathode follower driving a shorted delay line. This produced reasonably clean rectangular pulses. These pulses show the droop due to the finite decay time-constant of the input step wave. It was found rather difficult to terminate the delay line properly. As a result, small pips appeared beyond the rectangular pulses, due to reflections at the ends of the delay line. The heights of these pips were proportional to the heights of the rectangular pulses, and since they were much smaller in magnitude, did not interfere with the operation of the discriminator.

The two major difficulties encountered were instability and window width variations. It seems probable that the instability can be reduced to a reasonable level, but the variation of the window width with the threshold setting may be very difficult to overcome.

VARIATION OF THE WINDOW WIDTH WITH THE THRESHOLD SETTING.

It may be seen from Figure 14 that the window width varies linearly with the threshold setting, that is, the bias control setting. It was expected that the window width would be constant in magnitude with variations in the bias control setting, except for variations in the window width due to the droop of the flat-topped pulse. Since this is not the case, it is necessary to change both the setting of the threshold control and the height of the window pulse, when a different threshold is required. This is not desirable, since it complicates the operation of the discriminator.

The change in the window width with a change in the input pulse height, seems to be due to the motion of the common-cathode of the trigger tubes. When the height of the main pulse arriving at the grid is insufficient to cause triggering, the voltage of the common cathode drops rapidly and then rises relatively slowly. The magnitude of the drop in the cathode voltage, the subsequent rate of rise, and the level to which it rises, depend upon the threshold setting and the height of the main pulse. It was expected that by delaying the arrival of the window pulse by 1.5 micro-seconds after the arrival of the leading edge of the main pulse, the cathode voltage would have enough time to return to a level such that the window width would be a constant for all threshold settings. Obviously, this is not the case.

It is possible that the window width may be made very nearly constant by making use of very long rectangular pulses and delaying the arrival of the window pulse to a much later time. However, the shaping and delaying of these pulses would require the use of very long delay lines. This would increase the instability due to radiation pick-up. The droop on the rectangular pulse would become an important problem, possibly requiring the use of a different method for shaping the pulses.

Another possible method for correcting variations in the window width due to the droop on the rectangular pulse and the variations in the threshold setting, involves the adding of two pulses onto the main pulse. Previously, it was necessary that the main pulse droop somewhat, in order that if triggering were to occur due to it alone, this triggering would occur near the leading lead of the main pulse. Otherwise, a slight ripple on the main pulse might cause triggering at any point along this pulse. The alternative procedure requires that the flat-topped pulse have no droop.

This may be accomplished by connecting a parallel combination of a small resistor and a capacitor, having the same time constant as the input stepwave, in series with the cathode load of the pulse shaper. Now, if the threshold is set so that the main pulse is too small, by a reasonably large margin, to cause triggering, the main pulse should not affect the window width appreciably. Two rectangular pulses, of short duration, are then added onto the main pulse. The smaller pulse is added near the leading edge of the main pulse, and the larger pulse is added at some later time, possibly of the order of one micro-second after the addition of the smaller pulse. This smaller added pulse should not affect the threshold as seen by the larger added pulse. The sum of the main pulse and the smaller added pulse would determine the height of the input pulse and the difference in heights of the two added pulses would determine the window width. This method seems more feasible than the one suggested previously.

Sensitivity and Stability of the Differential Discriminator. The sensitivity of the discriminator is adequate, since the two integral discriminators involved will trigger on pulses of < 1 millivolt. However, the discriminator, at the present, is so unstable at low levels that oscillation occurs unless the threshold is set above approximately 20 millivolts. This minimum threshold of 20 millivolts is not adequate for low-level operation.

At thresholds greater than 50 millivolts, the long term stability was found to be better than 7 millivolts and the short term stability better than 2 millivolts. This is not acceptable. This instability seems to be due to radiation and capacitive pick-up, and to the method employed for adding the window pulse on to the main pulse.

Radiation and capacitive pick-up can be reduced to an acceptable level by proper shielding of certain components. The two trigger circuits should be completely shielded from each other to reduce capacitive feed. Most of the radiation pick-up is probably due to the use of long delay lines. This pick-up can be minimized by encasing the delay lines in grounded copper tubing, or by putting the coiled delay lines in a grounded metal box.

The more serious problem is the adding of the window pulse. Three methods were tried, and none of them was particularly successful. The first method tried was the introducing of the window pulse onto the main pulse at the shorted end of the delay line in the pulse shaper, by means of a White cathode follower. The delay line was shorted through the low output impedance of the White cathode follower, and the window pulse was added by applying it to the grid of this cathode follower. This method would have been acceptable except that the window discriminator triggered several times for each input pulse. This is not satisfactory.

The second method tried was the introducing of a negative window pulse onto the grid of the conducting trigger tube, by means of a White cathode follower and the delay line then used for determining the pulse length of the output from the trigger circuit. This method was not successful, and the delay lines had to be removed subsequently, since difficulty in properly terminating them caused reflections which induced oscillation.

The final method tried used a pulse transformer to apply the window pulse to the grid of the first trigger tube. This arrangement is shown in Figure 8. The transformer adds the window pulse to the main pulse with very little distortion, but results in large extraneous signals being applied to the grid. These extraneous signals frequently cause the circuit to trigger, resulting in instability. However, it should be possible to find a method of introducing the window pulse such that instability does not result.

CHAPTER VI.

CONCLUSIONS

The operating characteristics of the integral and differential discriminators just developed, on the basis of the material submitted in this thesis, may be summarized as follows:

Integral Discriminator. The integral discriminator developed meets the requirements of a precision, low-level discriminator for use with or without preliminary amplification. It may be used directly from the output of a scintillation counter.

The discriminator has a sensitivity of better than 1 millivolt, although operation should be restricted to thresholds which are ≥ 2 millivolts, because of the instability present for smaller threshold settings. The discriminator has a sharpness of triggering which is slightly greater than 1 millivolt, that is, the discriminator will move from a state of not triggering to one of triggering on every input pulse with a change in the threshold of slightly greater than 1 millivolt. The discriminator has short-and long-term stabilities which are better than 0.5 millivolts and 1.2 millivolts respectively.

Without modification, this circuit seems to be somewhat superior to that developed by Kandiah. It is possible, however, that by replacing certain resistors with more stable ones, and by replacing the Sorensen line regulator with one which is operating properly, discrimination down to about 0.5 millivolts with a stability of about 0.1 millivolts may be achieved.

Differential Discriminator. The differential discriminator just developed, in its present state of development, does not meet the requirements of a precision, low-level discriminator. The instability present limits operation to thresholds greater than 20 millivolts. The discriminator has short - and long- term stabilities of approximately 2 millivolts and 7 millivolts respectively. However, a more serious fault is the variation of the window width with a variation of the threshold setting.

It is probable that by methods discussed in the previous chapter, the stability may be improved to such a degree that operation at thresholds as low as 1 or 2 millivolts, with a threshold stability of better than 0.5 millivolts, may be achieved. It is also possible that constancy of window width may be achieved, so that operation with window widths having a stability of better than 1%, and as narrow as 1 millivolt, may be possible.

REFERENCES

NUMBER

1. K. Kandiah - Proc. Inst. E. E. 101, pt.II,239-247,(1953)
2. E. Gatti - Il Nuovo Cimento 11, 153, (1954)
3. C. Cottini, E. Gatti, and P. Principi- Energia Nucleare 6 , 73-6, (1951)
4. W.C. Davidson and R.B. Frank- Rev.Sci.Instr. 27, 15,(1956)
5. Jacques Mey - Rev.Sci.Instr. 30, 232-4,(1959)
6. W. L. Buys - J. Phys. Radium. 15, 582, (1954)
7. L. S. Bagdasaryan and V.M. Kharitonov-Pribory i Tekh. Ekspt. No.1, 70-2, (1959)
8. V.P. Voronkov and A.M. Frolov-Pribory i Tekh.Ekspt. No.3, 40-2, (1957)
9. V. V. Okorokov - Pribory i Tekh, Ekspt. No.6, 63-7,(1958)
10. L. Costrell and R.E. Brueckmann-Nuclear Instr. 3,350-8,(1958)
11. Almon E. Larsh - Nucleonics 17, No. 3, 92-94 (1959)