health and safety laboratory

A TRANSISTORIZED PULSE HEIGHT ANALYZER FOR GAMMA SPECTROSCOPY

Robert T. Graveson

UNITED STATES ATOMIC ENERGY COMMISSION
NEW YORK OPERATIONS OFFICE

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ABSTRACT

A scintillation detector has a pulse height output which is a linear function of the energy of impinging gamma radiation. A pulse height analyzer system determines the amplitude distribution of this train of pulses. The system also displays this information graphically in a form which is convenient for further analysis.

The Gamma Spectrometer has been completely transistorized, providing increased reliability, size reduction and reduced power consumption. This has made possible its application to measurements in the field.

Transistor circuits for pulse amplification, pulse amplitude discrimination, and for pulse shaping by a 1 microsecond monostable trigger circuit are described. A discriminator amplifier system is used to improve the stability of gate settings. The differential between gates may be set over a 1 volt range at any base level. The unit will accept pulses whose amplitudes lie between 0. 1 and 10 volts, and whose rise time is between 0. 1 and 0. 3 microseconds. It will operate to a maximum rate of approximately 100, 000 pulses per second.

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HASL NO. 59

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I. INTRODUCTION

Many radionuclides release energy in the form of gamma photons. Each such nuclide has a characteristic emission energy which may be used to identify it specifically. A scintillation detector develops an output pulse which is a linear function of the energy of the impinging gamma radiation. If a pulse height analyzer is placed in the output circuit, it may be used to determine the amplitude distribution of these pulses, and thus produce a graphic description of the gamma energy spectra.

The transistorized Gamma Spectrometer system, illustrated in Figure 1, consists of a Scintillation Detector Head, Pulse Height Analyzer, Automatic Base Line Drive, Linear Count Rate Meter, and Low Voltage Power Supply. The Scintillation Detector Head includes the scintillation sodium iodide crystal, a photomultiplier tube with its high voltage supply, and pulse amplifiers. The output pulses, developed in response to the incident gamma photons, will range from 0 to 10 volts. The Pulse Height Analyzer is designed to accept only those input pulses that fall within a narrow amplitude range. The position of this acceptance "slit" may be varied over the input amplitude range to determine the count rate at each pulse height. The manual base level control may be replaced by an Automatic Base Line Drive, which continuously varies the amplitude discriminator settings, so that the input pulse distribution may be progressively sorted into an amplitude spectrum. The output of the Pulse Height Analyzer is monitored by a Linear Count Rate Meter, whose output is proportional to the count rate of the gamma photons after amplitude discrimination. Power for the complete system is supplied by the Low Voltage Power Supply. The output is displayed on an X-Y recorder. The X axis measures the base line voltage, and is proportional to the gamma energy. The Y axis records the output of the Count Rate Meter,

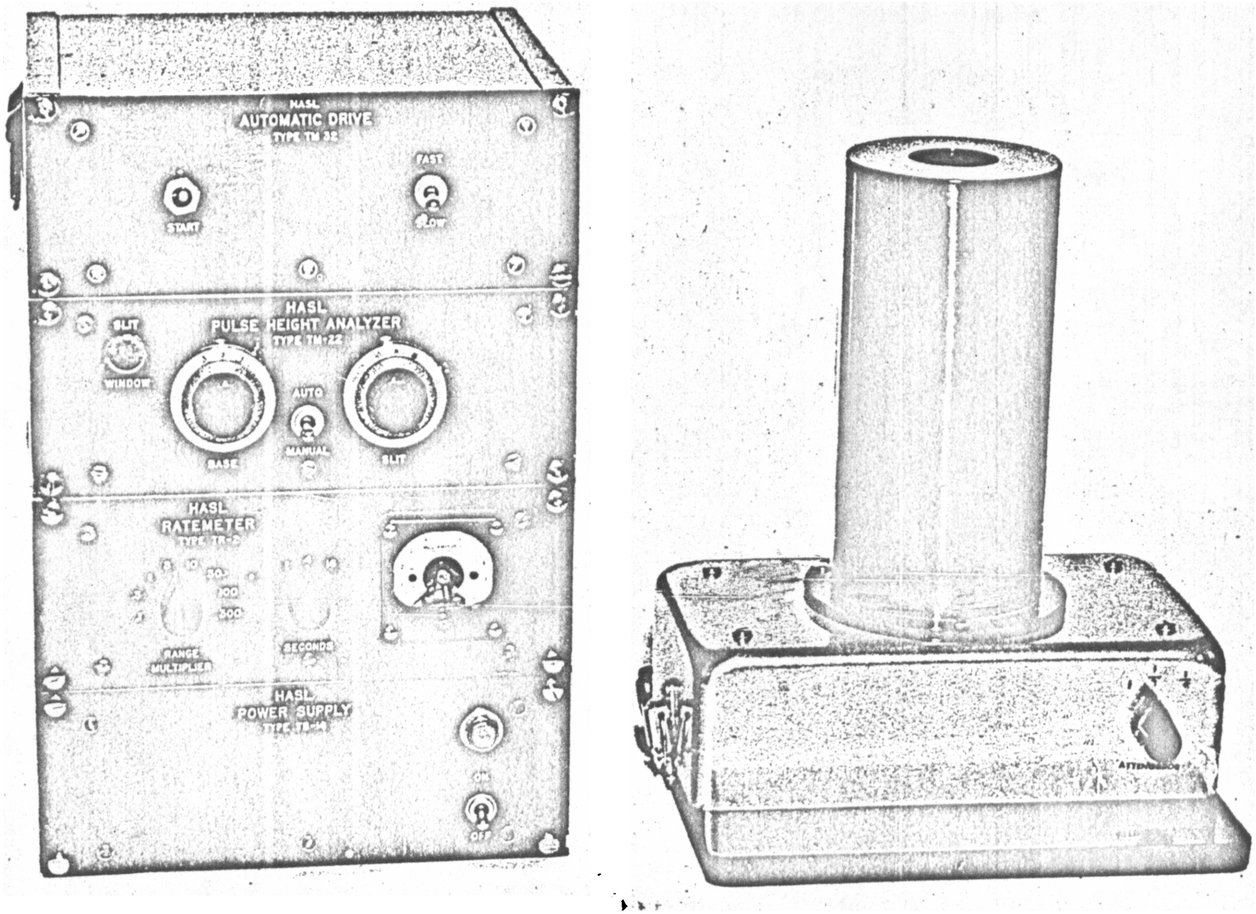


Figure 1

Transistor Gamma Spectrometer

and is proportional to the count rate of the pulses that fall within the slit at each base line position.

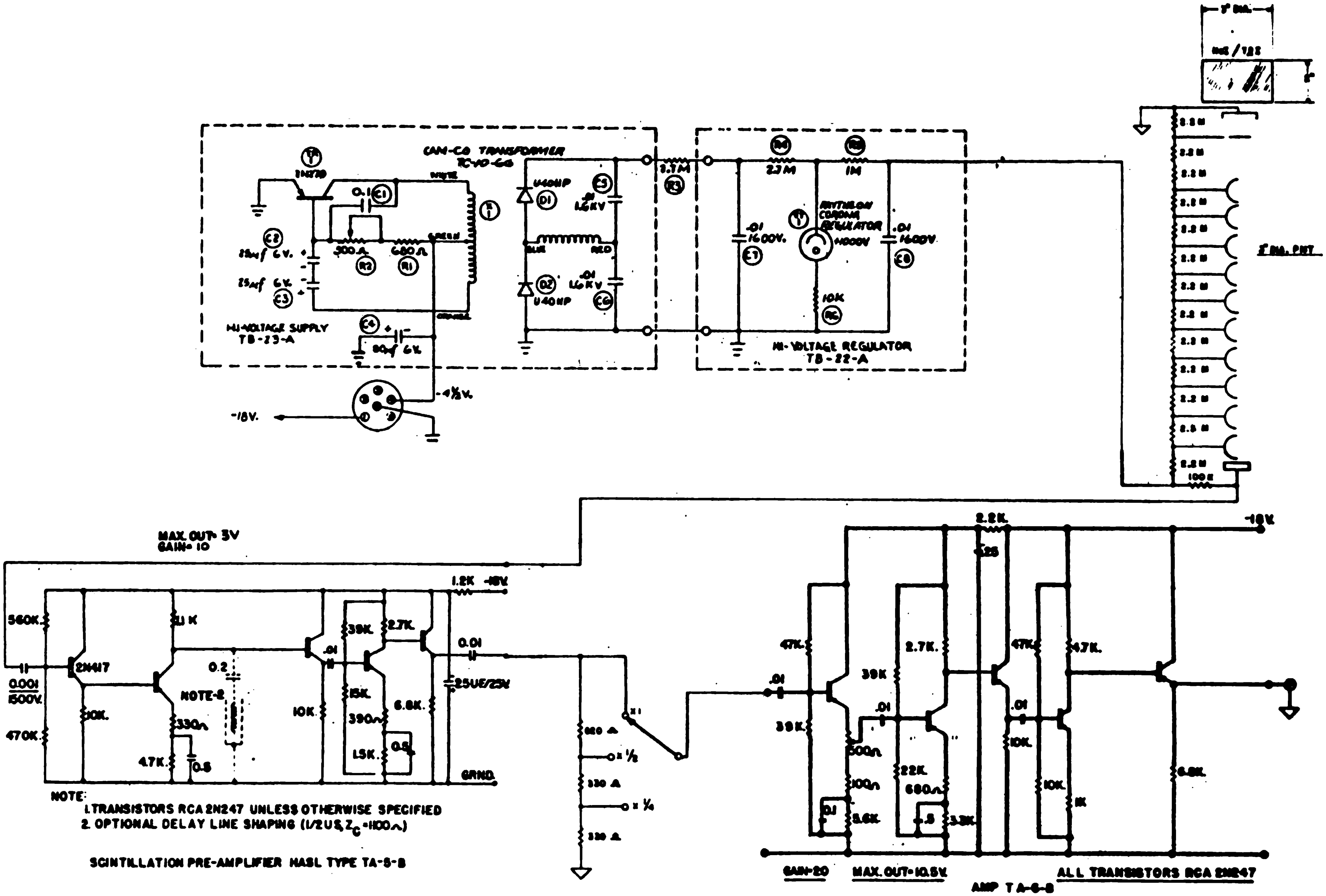
The Gamma Spectrometer system has been transistorized to provide a simpler, and more reliable unit for identification and measurement of radioactive isotopes. The transistor circuits are reproducible; and because of their small size and low power consumption, it is feasible to assembly a battery operated unit for field applications.

II. SCINTILLATION DETECTOR HEAD

The scintillation detector, Figure 2, is a sodium iodide (thallium iodide activated) crystal which has the property of converting gamma energy to light photons. The detector is optically coupled to a photomultiplier tube which converts the light photons to electrons, and then provides an electron gain of between 100, 000 and 300, 000 by means of ten secondary emissive dynode surfaces. The output of the photomultiplier tube is an RC integrating network consisting of the anode load resistor and the distributed capacitance of the photomultiplier tube anode circuit. The integrated pulse at this point has a 0. 2 microsecond rise time and approximately a 5 microsecond decay time constant. The voltage amplitude is between 10 and 100 millivolts for an incident 1 Mev gamma photon.

The photomultiplier tube requires approximately 1000 volts for normal operation. This is supplied by a transistor blocking oscillator power supply.[1] This supply operates from 6 volts at an input current of approximately 20 milliamperes and develops, through the voltage doubler system, 1200 volts at 40 microamperes. The output high voltage is regulated to 1000 volts by a corona regulator tube.

The pulse signal at the photomultiplier tube anode drives a preamplifier which has a gain of 10. A 1/2 microsecond shorted delay line clips the overall pulse width to 1 microsecond. The output of the preamplifier is connected to the main amplifier through an attenuator switch which is used to vary the gamma energy calibration in predetermined steps. The main amplifier has a voltage gain which may be adjusted from 2 to 20, and a maximum pulse output of 10 volts. The



SCINTILLATION DETECTOR HEAD

FIGURE 8

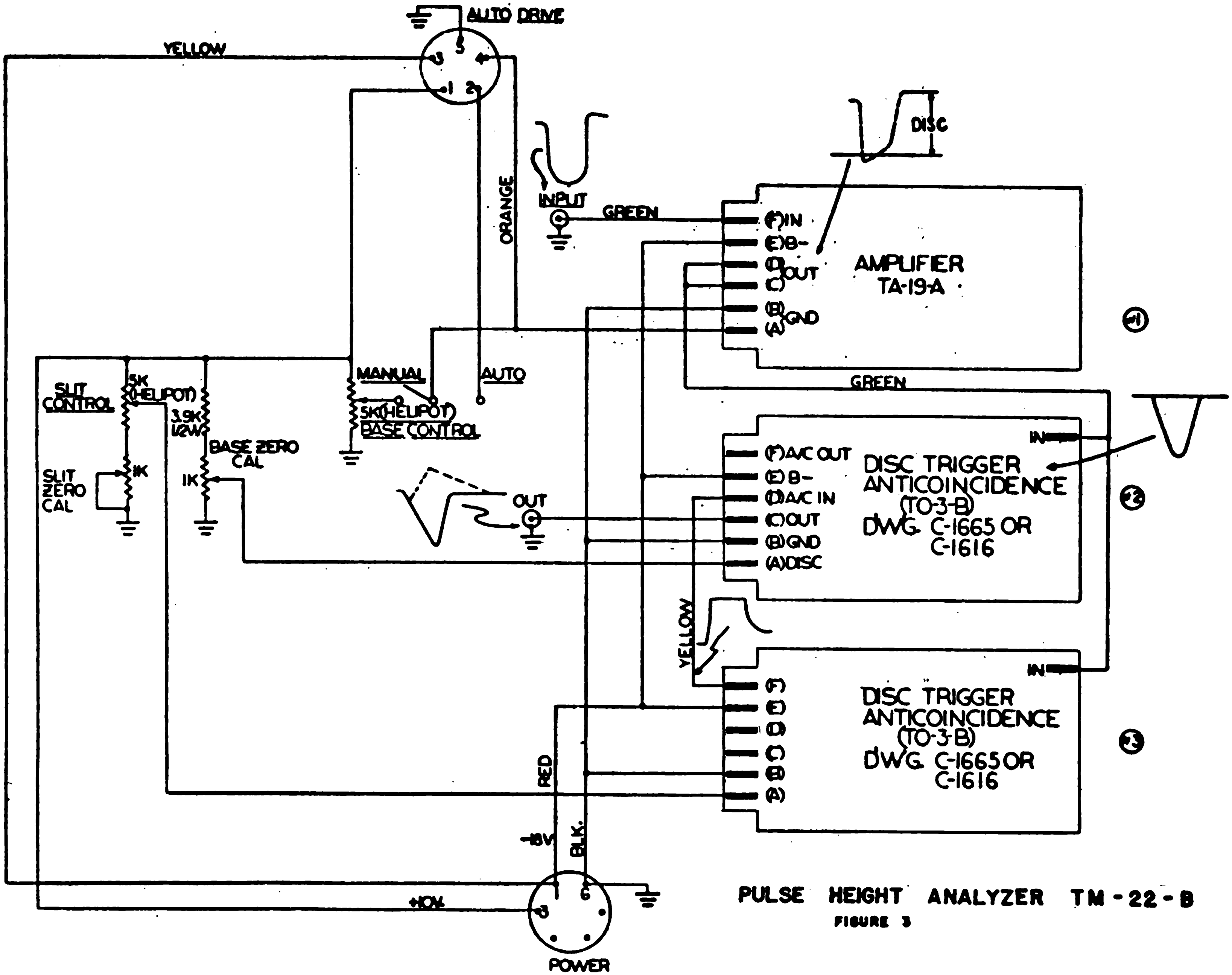
design of the preamplifier and amplifier uses emitter degeneration to minimize temperature effects, and emitter follower coupling stages between the voltage amplifier stages to develop high input and low output impedance.[2]

The gamma energy calibration is adjusted in coarse steps by changing the corona regulator in the high voltage supply. The gain adjustment in the main amplifier provides fine control, and normally is adjusted so that a 0.75 million electron volt (Mev) gamma photon will produce a 10 volt output pulse. The three position tap switch between the preamplifier and the main amplifier provides attenuation steps of X1, X1/2 and X1/4 so that a 10 volt output pulse will correspond to 0.75, 1.5 and 3 Mev respectively.

III. PULSE HEIGHT ANALYZER

The Pulse Height Analyzer produces an output pulse whenever the input signal exceeds a base amplitude level, and does not exceed a top amplitude level. The difference between the top and the base discrimination level results in a slit through which the input pulse is transmitted to the output. The slit may be adjusted within a range from 0 to 1 volt. The position of this slit may be adjusted to accept input pulses whose amplitudes fall within a range from 0.1 to 10 volts.

The unit (Figure 3) consists of three etched circuit boards, the first is a discriminating amplifier, and the other two are identical univibrators which are used for the top and bottom pulse gates. The base line control sets the level of an input discriminator. The portion of the input pulse exceeding this level passes through a gain of 10 amplifier and is connected to the inputs of both gates. Each gate has an input discriminator followed by a univibrator. The base gate is set to trigger at 1 volt. This corresponds to 0.1 volt tripping level when referred to the input of the amplifier. The second, or top gate, may be adjusted to trigger from 1 to 11 volts by the slit width control. This, then, corresponds to a 0 to 1 volt setting, above the base gate, when referred to the amplifier input.



PULSE HEIGHT ANALYZER TM-22-B

FIGURE 3

The output is derived from the base trigger through a normally-open "AND" gate. The top trigger closes this gate whenever the input pulse exceeds the top tripping level, and rejects the output pulse.

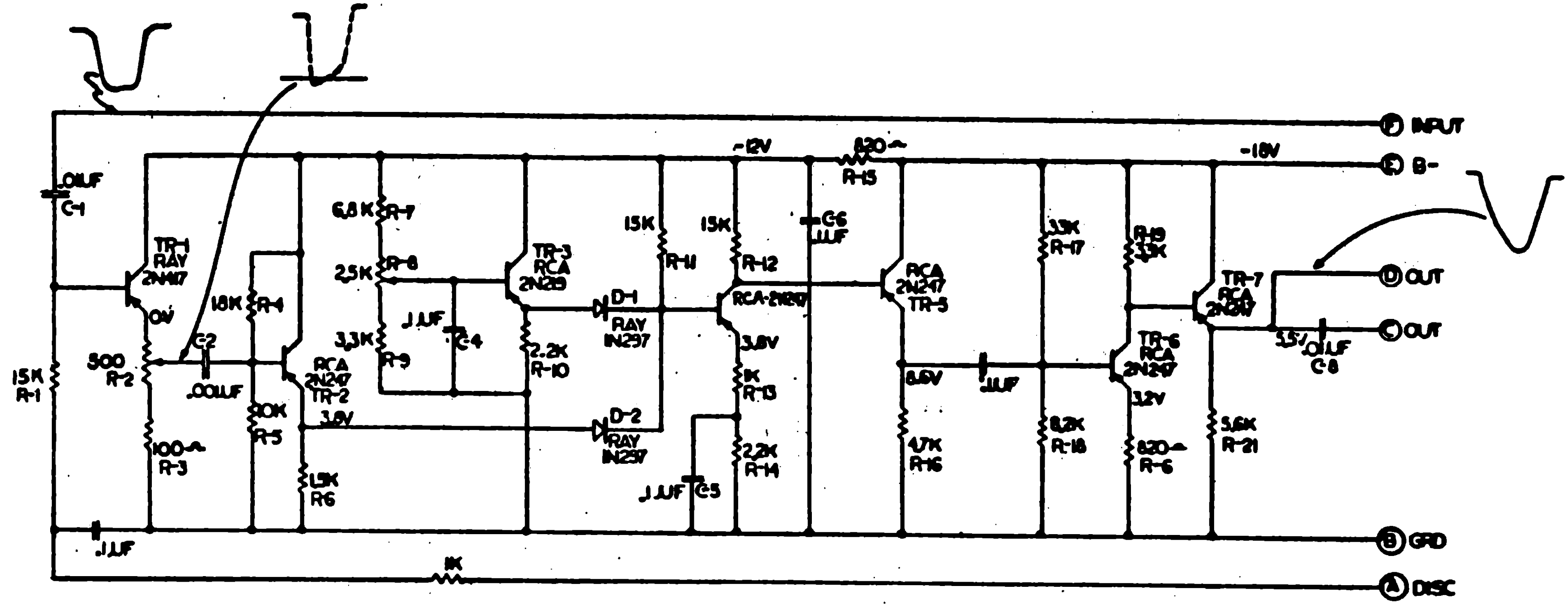
Discriminating Amplifier

This circuit board includes an input discriminator, an amplifier with a gain of 10 (Figure 4). The discriminator is a back-biased transistor (TR-1) which operates in a cutoff condition. The amount of cutoff is nearly equal to the applied positive base bias. Since the transistor is off, the base to collector leakage current is not multiplied in the collector emitter circuit. However, it acts in conjunction with the input 22,000 ohm resistor to decrease the applied discriminator voltage. The voltage drop due to leakage current will vary approximately 80 millivolts as the temperature varies from 0° to 45° C. The effect of leakage current has been discussed in more detail in a report which describes this type of discriminator.[3]

Very large input pulses, which would overload the amplifier, are limited to a maximum amplitude of approximately 1 volt by an "AND" gate. The overload operates by transferring the signal current in a diode (D-2) to the overload diode (D-1) of the "AND" gate. This potential biasing on the overload diode is adjusted to a 1 volt differential by the overload control. An emitter follower stage acts as a buffer between the control and the diode. The four stage amplifier utilizes emitter degeneration and emitter follower coupling. The overall voltage gain is ten and the amplifier is similar to the amplifiers used in the Scintillation Detector Head.

Discriminating Trigger

Both the base and top gates are identical and consist of an amplitude discriminator, a univibrator transistor pair, a diode anti-coincidence gate, and an output emitter follower amplifier (Figure 5). The discriminator is a back-biased transistor, and is similar to the input stage of the discriminating amplifier. The univibrator consists of a transistor pair in a regenerative connection. The second transistor

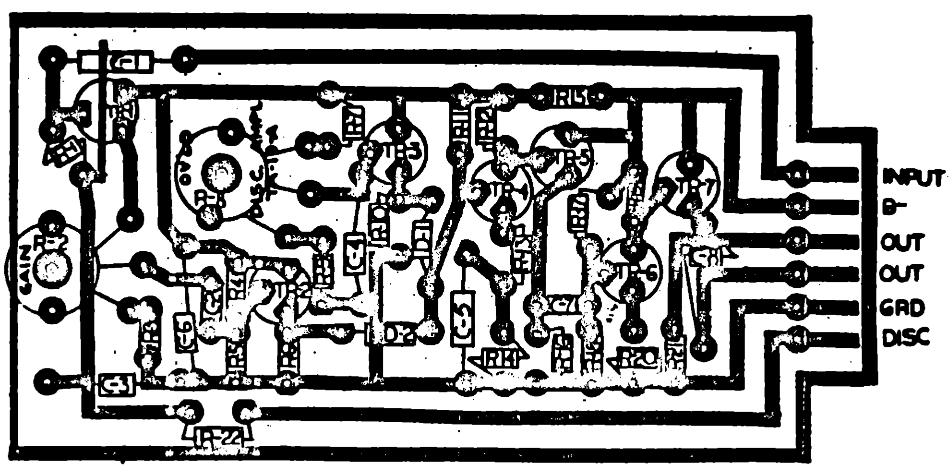


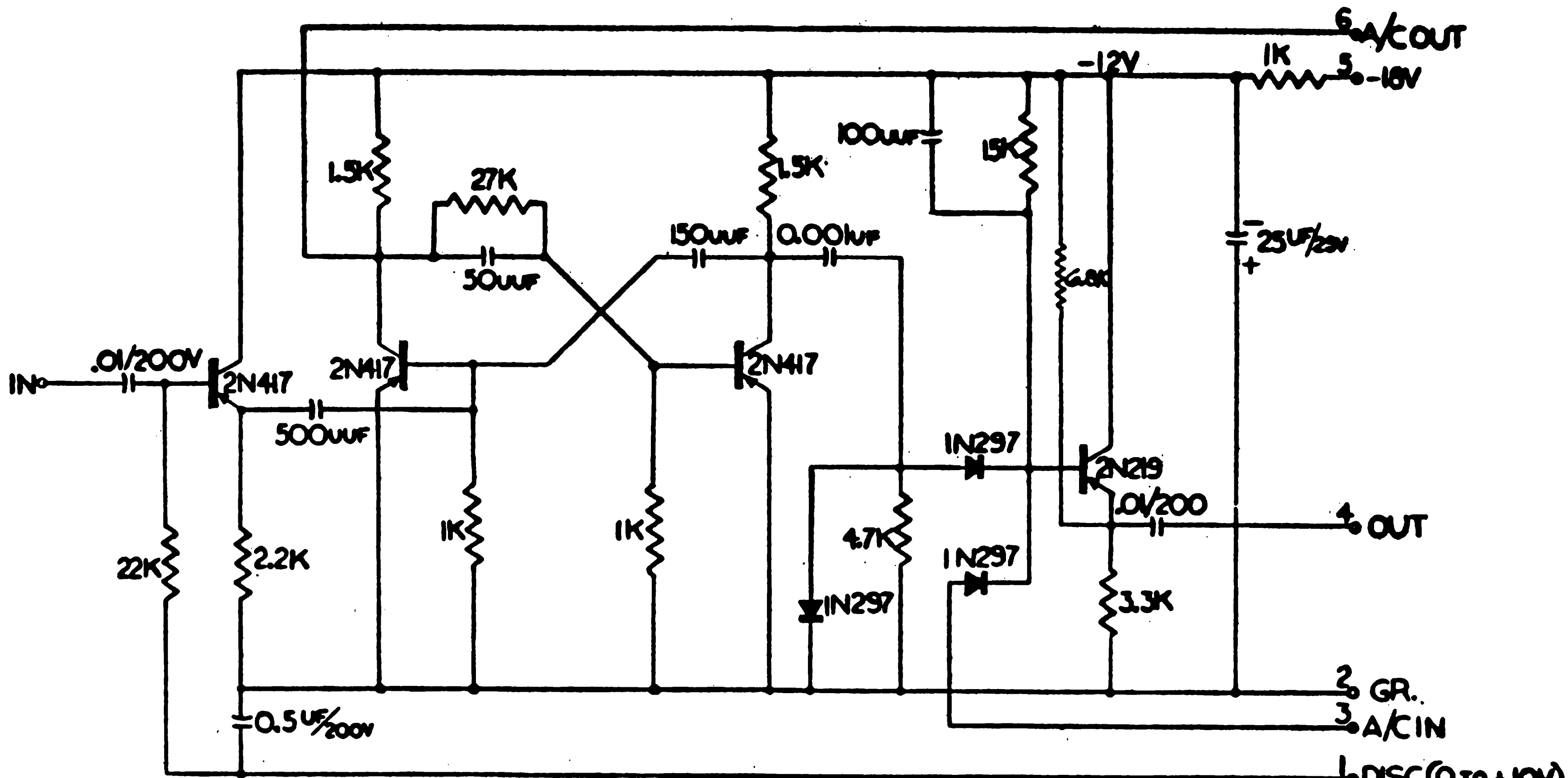
DISC AMPLIFIER TA-19-A

FIGURE 4

DISC 0—10V
GAIN 2—10
OVERLOAD 10V OUT,
1V AMPL. SECT IN

ALL RESISTORS .01 WATT





DISCRIMINATOR TRIGGER
TYPE TO-3-B

FIGURE 5

is held in saturation by the coupling resistor to the off-side collector. The capacitor in the opposite base-collector coupling controls the output pulse width. This is about 1.1 microseconds for the circuit shown. The tripping sensitivity of the univibrator is approximately 1/4 volt, and this is added as a constant amount to the discriminator level. Thus, when the input discriminator base voltage is varied from 0 to 10 volts, the tripping sensitivity, referred to the input, varies from 1/4 to 10-1/4 volts.

The anticoincidence circuit uses two diodes in a conventional "AND" connection. The anticoincidence, or rejecting diode, is directly connected to the normally off transistor of the univibrator in the top gate. During the triggering cycle this diode is clamped to 0 volts, closing the gate. The count pulse is derived from the normally on transistor, and is differentiated prior to being applied to its diode. The differentiation insures that the count signal terminates before the end of the anticoincidence signal. Thus, the two triggers do not require close matching or adjustment of their pulse width. A shunt diode improves the recovery of the differentiation capacitor. A small capacitor (100 uuf) across the "AND" resistor integrates the narrow pulse which might appear when the top gate fires slightly later than the bottom gate. The time constant of the integrating circuit is 3/4 microsecond, and will reject the count pulse even though the top gate triggers up to 1/4 microsecond later, due to the finite rise time of the input pulse. The output emitter follower isolates the external load from the anticoincidence circuit.

IV. AUTOMATIC BASE LINE DRIVE

The base line control on the Pulse Height Analyzer adjusts the position of the analyzing slit over the range of 0 to 10 volts. This control may be replaced by a time based sweep voltage to automatically analyze the pulse amplitude spectra of the input pulses. The automatic drive has two speeds; fast, to rapidly scan the pulse height spectra, and slow, to permit the use of a longer rate meter time constant so that statistical fluctuations in the spectra may be reduced.

The first transistor of the automatic drive is the sweep generator (Figure 6). It is operated as a grounded emitter stage and has condenser feedback from collector to base. The collector-emitter voltage normally sits at saturation, about 0.2 volts, due to a base current through the resistor network. When the collector-emitter voltage is set to a starting potential, by charging the feedback condenser from a momentary switch, the stage will return to its initial condition to a time determined by the RC time constant. The voltage across this transistor at any time is described by:

$$e = Ech\, e^{-\frac{t}{(BRcC)}} + KEb\left(1 - e^{-\frac{t}{(BRcC)}}\right)$$

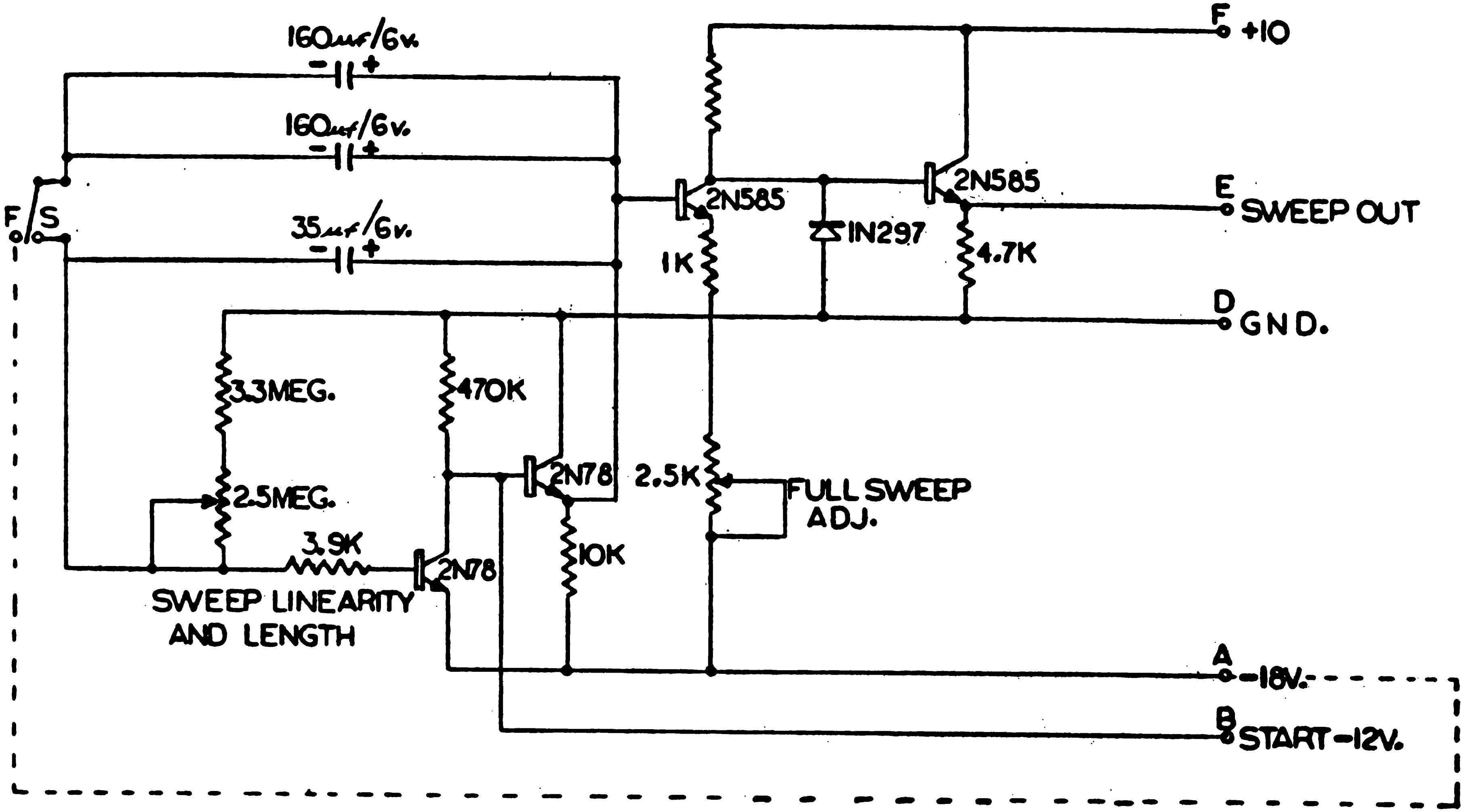
and

$$K = \left(1 - \frac{BR_c}{R_b}\right)$$

Where E_b is the supply voltage, Ech is the initial starting voltage, B the transistor current gain, C the feedback capacitor in farads, and Rc and Rb the collector load and base biasing resistors respectively in ohms.

When the term BR_c/R_b is greater than one, a decreasing exponential with a time constant of BR_cC is obtained. Thus, the basic RC time constant has been multiplied by the current gain of the transistor. Only a portion of this exponential falls between the starting potential and the transistor saturation potential. The smaller the portion of the exponential used, the closer the output will approach a linear sweep.

An emitter follower stage is coupled directly to the sweep transistor and provides the power gain necessary to charge the feedback condenser quickly when starting. The starting potential is limited to 6 volts because of the maximum voltage rating of the small dimension, high capacitance, electrolytic condensers used for feedback in the sweep transistor. The output sweep voltage must start at zero volts and must end at +10 volts. However, the sweep stage starts



TRANSISTOR SWEEP TO - 20 - A

FIGURE 6

from collector saturation, about 0.2 volts, and ends at 6 volts. The third transistor has a voltage gain of two and this may be adjusted by controlling the emitter degeneration. Thus, the collector voltage starts at -2 volts and ends at +10 volts. A diode clamps the initial voltage to, or slightly below, zero to insure a reproducible starting point to the sweep. The output transistor is used in an emitter follower stage to isolate the sweep from the output load.

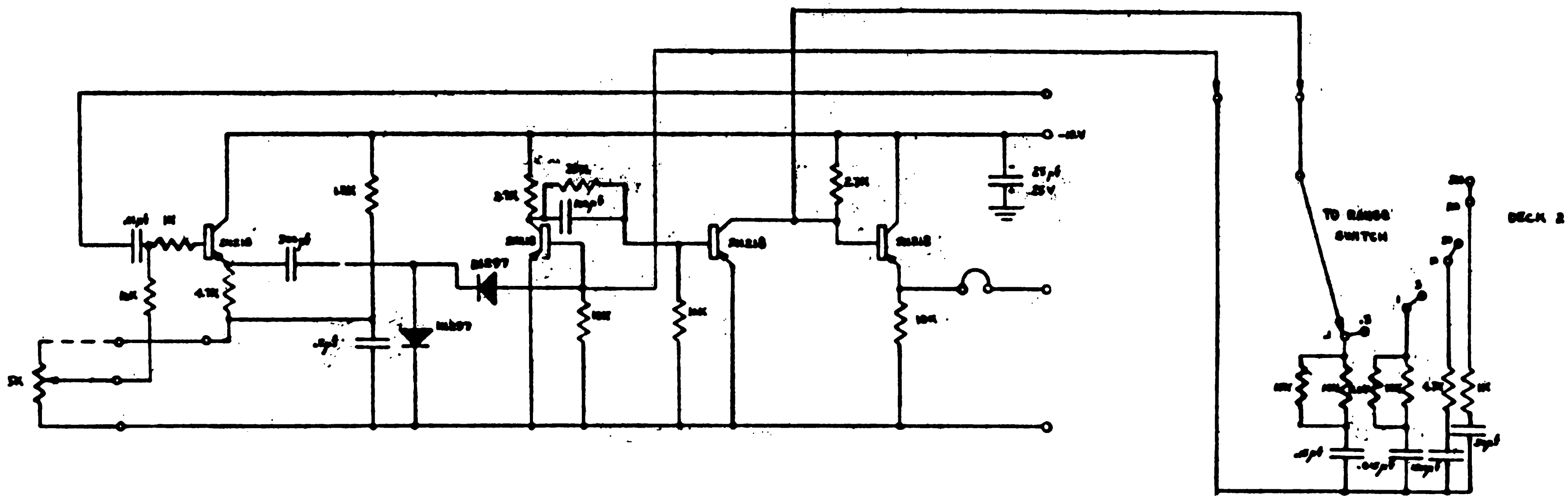
The output is recorded on an X-Y recorder so absolute linearity of sweep is not required. Using the values indicated, the sweep deviates from linearity less than 20%. Two sweep speeds are provided. The 35 microfarad feedback condenser gives an overall time base of 1.5 minutes, and the total capacitance (355 uf) results in a 15 minute time for the complete voltage sweep.

V. LINEAR COUNT RATE METER

The Linear Count Rate Meter is constructed on three printed circuit boards. The pulse width trigger converts any input pulse to a fixed amplitude, fixed width output pulse. The width is selected by a rotary switch to change the count rate ranges. The count rate convertor transforms these pulses to an average current proportional to their rate of arrival. The third section is the time constant section which selects the integration time constant, and therefore the response speed of the output indicator.

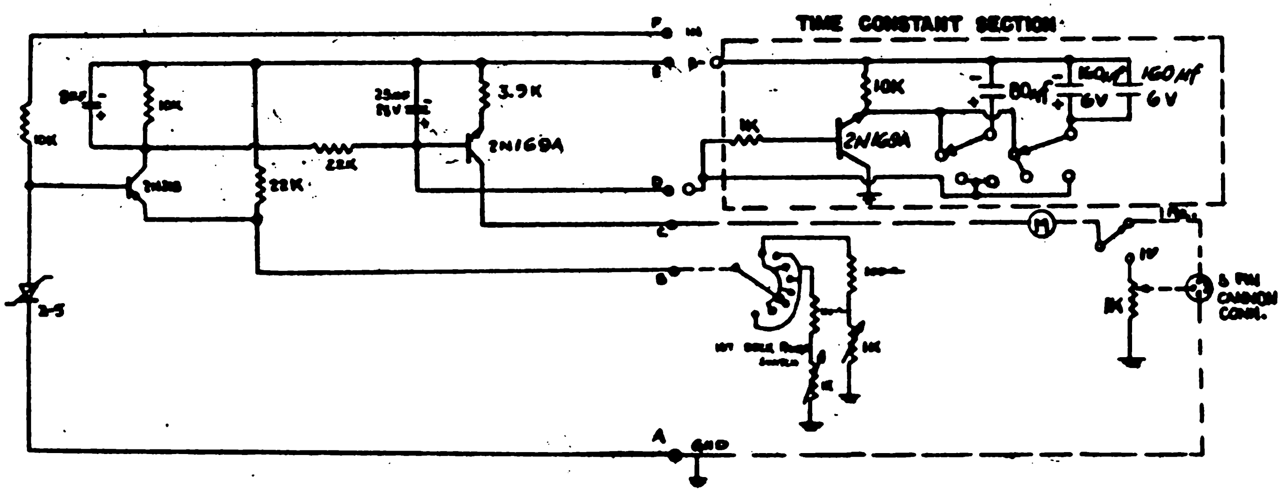
Pulse Width Trigger

(Figure 7a) The first transistor is an amplitude discriminator which rejects small pulses below its preset level. The univibrator transistor pair converts any input pulse exceeding the preset discriminator level to a fixed amplitude, fixed width pulse. The pulse width, t, may be varied to provide the various count rate ranges by selecting the time constant in the regenerative feedback loop. The use of a resistive - capacitive, rather than a straight capacitive, feedback loop results in lower loading of the collector circuit when wide output widths are generated. Thus, the output pulse has a faster rise and is more



PULSE WIDTH TRIGGER (A) TO-4-A MODIFIED

PULSE WIDTH CONTROL FOR LINEAR RATEMETER UNIT TYPE TR-2



LINEAR COUNT RATE CONVERTER (B) TR-3-A

LINEAR COUNT RATEMETER

FIGURE 7

nearly rectangular. An emitter follower stage isolates the univibrator from the input to the count rate convertor.

Count Rate Convertor

A zener diode (Z-5) is used to clamp the input pulse to a fixed amplitude, E, which will be independent of the supply voltage and univibrator characteristics. The input transistor converts the voltage pulse to a current pulse. Since the base-emitter voltage drop for a transistor is nearly zero, the magnitude of the collector current, during the pulse, will be inversely proportional to the emitter resistor, R_e. A small negative bias is applied to the emitter to insure that this stage is off during the rest of the cycle.

The voltage developed across the load resistor, R_L, of this stage is determined by the integration of the current pulse over a period equal to the mean time of arrival of the input pulses.[4] This is inversely proportional to the count rate. The developed voltage, e, is described by:

$$e = nEt\, R_L/R_e$$

Where n is the counting rate, E is the pulse amplitude in volts, t is the pulse width in seconds, and R_L and R_e are the collector and emitter resistors respectively in ohms. The maximum input voltage, E, is clamped by the zener diode and is constant; the resistors are fixed for a specific design and calibration setting; thus the developed voltage is proportional to the count rate and to the pulse width. Four basic pulse widths are provided by the Pulse Width Trigger also. Two values of emitter resistance are selected to give X1 and X3 scale multiplication. The complete unit has eight count rate ranges, from 10 to 30,000 counts per second, in steps of about 3. Calibration is controlled on the X1 and X3 groups of ranges by separate calibration potentiometers in the emitter of the transistor voltage to current convertor stage. Calibration of the four decade scale steps is controlled by the RC time constants in the regenerative loop of the pulse width univibrator.

The developed voltage, e, is converted to a current in the second transistor, which is a meter amplifier. The collector current is determined by the developed voltage at the base, and the emitter resistance. This collector current is 1 milliampere at full scale and is independent of the meter, or recorder, impedance. A 1000 ohm resistor may be switched in to develop 1 volt for operating potentiometer type of recorders.

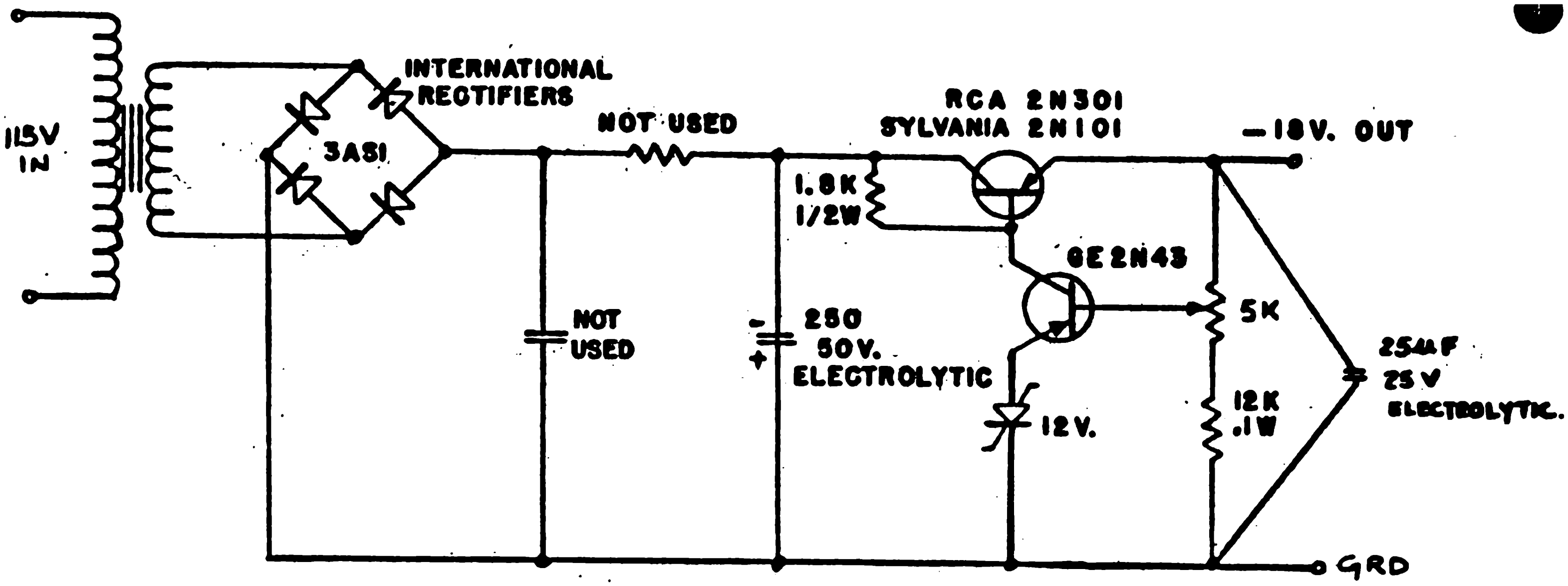
The basic integration circuit is the load resistor and its associated 2 microfarad condenser. Additional time constant is supplied by an additional RC network consisting of a resistor between the first stage load resistor and the meter amplifier, and shunt capacitors. Additional capacitors, located in the time constant section, are switched into the circuit to give a 1, 4 or 16 second time constant. An emitter follower stage is used to keep unused time constant condensers charged to the developed voltage. The switching of additional time constant does not affect the scale reading, except to provide more integration and thus to smooth instantaneous variations in the recorded trace.

VI. LOW VOLTAGE POWER SUPPLY

The complete Gamma Spectrometer requires three stabilized voltages, -18 volts at 50 milliamperes as collector supply, -6 volts at 25 milliamperes for operation of the high voltage supply, and +10 volts at 5 milliamperes for the Pulse Height Analyzer discriminators. The Low Voltage Power Supply may take two forms, a battery pack for field operation, or an A.C. line operated supply.

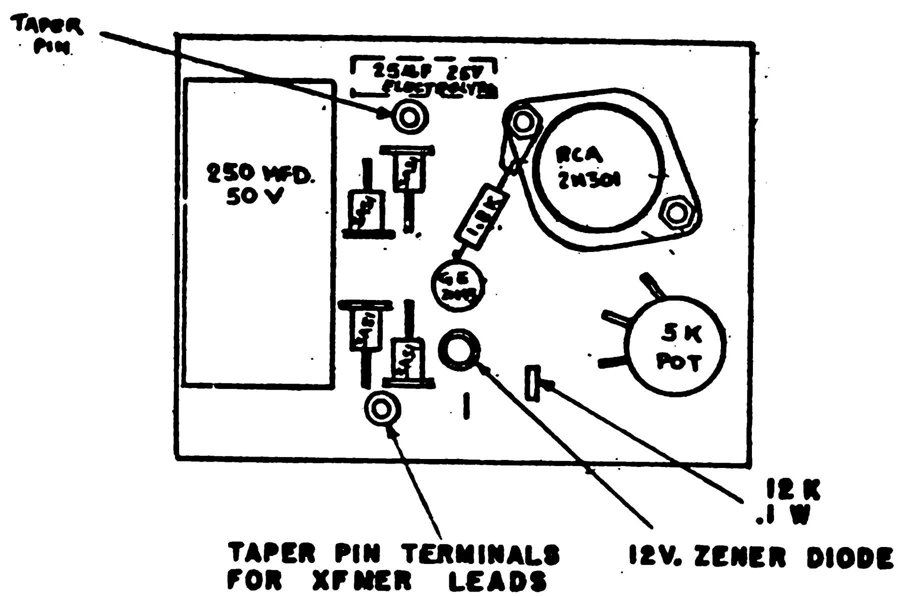
An A.C. operated, regulated -18 volts, 200 milliampere supply is shown in Figure 8. It uses a bridge rectifier across the output of a 25 volt filament transformer. The regulator section has a series transistor with shunt transistor control. A 12 volt Zener diode provides the reference voltage.

The -6 volt, 25 milliampere supply is similar. A 6.3 volt filament transformer is used and due to lower power requirements, a 150 milliwatt transistor has been substituted as the series element. The +10 volt, 20 milliampere regulated supply is constructed as the compliment of the -6 volt supply by replacing the PNP transistors with NPN types.



POWER SUPPLY TB-14-A

FIGURE 8



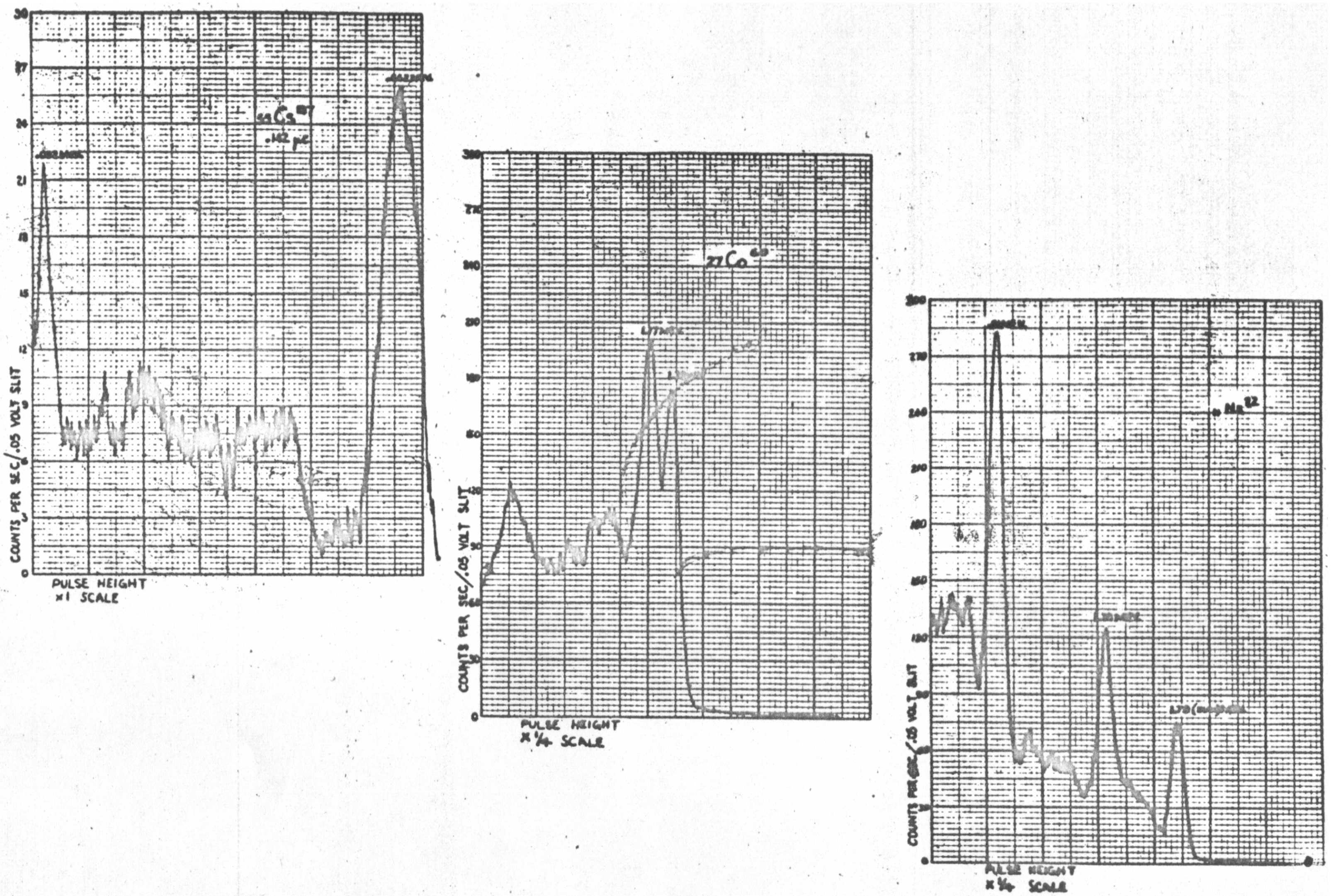
VII. TEST RESULTS

Radiation Characteristics

The characteristic spectral curves for three radioactive isotopes are shown in Figure 9. Cesium (Cs-137) emits an X-ray at 0.032 million electron volts (Mev) and a 0.662 Mev gamma photon. Each photon is detected as a monoenergetic line. However, the spectral line is broadened by statistical deviations in the light emission from the phosphor, and in the number of photoelectrons emitted by the cathode of the photomultiplier tube.[5] The broadening of the energy line affects the ability to detect two closely spaced spectral lines. The overlapping effect of energy resolution is indicated by the two lines (1.17 and 1.33 Mev) from Cobalt 60. The third isotope, Sodium-22, emits a 0.51 Mev gamma photon from the annihilation of its positron and a 1.28 Mev gamma photon. These are emitted simultaneously and occasionally both interact in the scintillation detector within the time resolution of the phosphor. When this occurs, a third peak is observed which is the sum of the two energies (0.51 plus 1.28 equals 1.79 (Mev) absorbed by the scintillation crystal.

The Pulse Height Analyzer has been applied to the measurement of the characteristic K-alpha X-ray emission from radioactive isotopes. Additional pulse amplification expands the energy scale to cover a range from 0.007 to 0.075 Mev. Since higher energy photons often are present, the phosphor thickness is reduced to 3/16 inch to lower the gamma efficiency above 0.1-0.2 Mev. An overload gate, as used with the Discriminating Amplifier (page 8), prevents amplifier distortion by rejecting excess pulse height. This system has been used to detect characteristic K-alpha radiation from isotopes with atomic numbers greater than 27 (Cobalt 60 - 0.0069 Mev).

A Cesium Iodide phosphor has been used to detect alpha particles.[6] These particles are completely stopped by a 0.001 inch thick crystal. The spectral line has an energy resolution of 2-3% which is narrow enough to operate the alpha energies from many common isotopes.



RADIOACTIVE ISOTOPE SPECTRA

FIGURE 9

Operational Experience

The use of transistors has resulted in a more compact, and more reliable, Gamma Spectrometer. Several units have been operated for over a year, demonstrating the long life and stability of the transistor circuits. The unitized construction has facilitated modification of the basic system to include isotopic identification by X-ray and alpha spectra.

The circuit stability depends upon minimizing the effects of variability in transistor characteristics. Aging and temperature change have similar effects on circuit operation, varying the transistor current gain, beta, and the collector-base leakage current, Ico.

The beta varies about 20% over a temperature range from 0° to 45° C. and affects the voltage gain of the four amplifying stages. The emitter feedback in each stage stabilizes the voltage gain of the complete amplifying section to within 2% of its value at 25° C.[2]

The Ico leakage current in germanium transistors approximately doubles for each 10° C. temperature rise. In this unit, the Ico increase is significant only in the operation of the discriminating stages, and then only at the upper end of the 0°-45° C. temperature range. This leakage current flows through the discriminator base resistor producing a 0.08 volt shift in the amplitude rejection level, at 45° C.[3] This is a constant voltage drop anywhere in the 0.1 to 10 volt range of the pulse height discriminator, and results in a 0.8% shift in the energy scale of the gamma spectral curves.

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