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Argonne National Laboratory

TRANSISTOR SCINTILLATION SPECTROMETER

by

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Electronics Division

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ABSTRACT

The equipment described is an AC-operated portable scintillation spectrometer consisting of a preamplifier, a linear pulse amplifier, a single-channel pulse-height analyzer, a linear count-rate meter, a scaler, and a high-voltage power supply. The operation and performance of the circuits are discussed. The instrument is accurate and reliable, light in weight, and consumes low power.

I. INTRODUCTION

The development of this instrument was initiated by the request of the U.S. Atomic Energy Commission for an accurate portable scintillation spectrometer. The design objectives were to develop a versatile instrument which could be used for all the purposes that existing vacuum tube spectrometers are currently being used, with additional advantages of improved reliability and small size.

In this report the circuitry and performance of the experimental instrument are described. Since it is written primarily for users and circuit designers, operating principles are not discussed. The circuits should not be considered as a final design, nor the performance figures as specifications.

II. DETECTOR AND PREAMPLIFIER

The detector consists of a thallium-activated sodium iodide crystal and an RCA 6655 photomultiplier tube. The crystal is 2 in. in diameter and 2 in. long. The photomultiplier tube was chosen because of its good resolution and high gain.

The multiplier feeds a two-transistor complementary feedback amplifier of nearly unity voltage gain. A schematic diagram of the preamplifier is shown in Fig. 1. The load resistance of the multiplier is R_1 in parallel with r_i, the midband input resistance of the preamplifier. An approximate value of r_i is given by the expression

$$r_i \approx B_1 B_2 R_L \quad ,$$

where B_1 and B_2 are the small signal current gains of T_1 and T_2, and R_L, the load resistance, is about 500 ohms. Since r_i is greater than 1 megohm, the

input resistance is approximately R_1. The total load capacity of the multiplier is about 25 $\mu\mu$f, of which more than 10 $\mu\mu$f are fixed. The 2-μsec integrating time constant is therefore relatively independent of active elements.

III. LINEAR PULSE AMPLIFIER

Circuit Description

The amplifier in its general configuration is modeled after a well-known vacuum tube pulse amplifier circuit.* This configuration was chosen because of its good linearity and gain stability. A schematic diagram of the linear pulse amplifier is shown in Fig. 2.

The 500-ohm, 10-turn potentiometer at the input serves as a continuous linear input attenuator. Following it are two almost identical feedback loops. Each loop has two complementary amplifying stages and an emitter follower, all directly coupled. To increase the input resistance of the middle stages, a 220-ohm unbypassed resistor is used in each of the emitter-legs of T_2 and T_5. This also provides local feedback and minimizes the voltage-gain variations from transistor to transistor. The quiescent operating point of each transistor is stabilized by tying its base to a firm voltage level and by placing a large bypassed resistance in series with the emitter.

The use of transistors of alternate polarity in each feedback loop affords certain design conveniences. In the quiescent condition each transistor draws only a small current, nominally 1 mamp. A negative pulse at the input is of such polarity as to increase the current in each transistor. There is no collector voltage accumulation even though the three stages are directly coupled. The feedback occurs between points which conveniently yield themselves to direct coupling.

Following the two feedback loops, the pulse is coupled through a short time constant, RC, to an emitter follower. The short time constant reduces the duration of the pulses presented to the analyzer, and makes them of a uniform length of about 5 μsec at the base. This is done to make the dead time of the analyzer more compatible with that of the amplifier, as the time required by the analyzer to process a pulse is longer than the pulse duration.

Circuit Performance

The voltage gain of each feedback loop is about 17. The maximum over-all voltage gain of the amplifier, including the loss due to the short time constant, is 250. The rise time (10 - 90%) is 0.25 μsec. Each feedback ring has a ratio of open to closed loop gain of about 20. The noise output of the amplifier with maximum gain is less than 15 mv peak to peak. This noise referred to the

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*W. C. Elmore and M. Sands, Electronics, McGraw-Hill Book Company, Inc., New York (1949).

amplifier input is about 20 μv RMS. With the preamplifier connected to the amplifier, the noise at the output with maximum gain is 75 mv peak to peak, which is less than 1% of the maximum analyzable pulse. This noise corresponds to a 90-μv RMS noise signal at the input to the preamplifier. The maximum pulse height out of the amplifier is 12 volts. A change in the ambient temperature from 25 to 50°C results in a change of the total gain of the preamplifier and amplifier of less than 1%. A change in line voltage from 100 to 130 volts did not produce a noticeable change in gain.

IV. PULSE-HEIGHT ANALYZER

Circuit Description

This is a single-channel integral or differential pulse-height analyzer. The block diagram is shown in Fig. 3 and the schematic diagram appears in Fig. 4. The window level discriminator is essentially a biased off emitter follower. Although T_1 usually is not conducting, when an input pulse exceeds the bias level, T_1 conducts and T_2 cuts off. The bias is adjustable by means of the window level 10-turn helipot. The maximum analyzable pulse is about 9 volts. The portion of the pulse which exceeds the bias level is amplified by the linear window amplifier, a single feedback loop of voltage gain of about 10, similar to that previously described. The upper level window discriminator consists of two parts. The first part, T_7 and T_8, is basically the same as the window level discriminator, T_1 and T_2. The second part is an emitter-coupled monostable multivibrator. Transistor T_{10} is normally conducting; its base is tied, through three diodes, to a firm voltage source. Transistor T_9 is normally cut off by about 0.8 volt. The multivibrator will be triggered by any pulse from the window amplifier which exceeds the bias level of T_7 by 0.8 volt. Diodes D_2 and D_3 temperature compensate for D_1 and the emitter-to-base junction of T_8. The largest pulse that the upper level window discriminator can reject is 9 volts, or 10% of the maximum analyzable input pulse. The window width can be adjusted linearly from zero to 10% by means of the 10-turn helipot associated with T_7 and T_8. The lower level window discriminator is similar to the second half (T_9 and T_{10}) of the upper level discriminator.

Transistors T_{15} and T_{16} constitute a monostable collector-coupled multivibrator. For every pulse from T_{14} a positive square pulse appears at the collector of T_{16}. This pulse is differentiated so as to produce a positive and a negative spike. The positive spike is clipped by diode D_4. The negative spike is delayed with respect to the trigger pulse by about 1 μsec, the "on-time" of the multivibrator. Transistors T_{17} and T_{18} make up the anticoincidence circuit. Transistor T_{17} is normally cut off. In differential operation the collector of T_{17} is connected to the emitter of emitter follower T_{18}. In the absence of a pulse from the upper level discriminator, a negative pulse from T_{16} is coupled to the output via T_{18}, diode D_5, and emitter follower T_{19}. If the upper discriminator is triggered, a negative pulse will appear at the

base of T_{17} driving it to saturation. The pulse from T_{16} can no longer go through T_{18} as it is now cut off. The positive pulse produced by T_{17} is prevented by diode D_5 from appearing at the output. Potentiometer P_5 is adjusted so that the positive pulse produced by T_{17} completely overlaps the negative pulse of T_{18}. When switch S_1 is in the integral position, T_{17} is disconnected from T_{18} and all pulses from the lower level discriminator produce output pulses.

Circuit Performance

The threshold stability of the upper and lower level discriminators is better than 0.5 mv/°C for ambient temperatures from 25 to 50°C. When the ambient temperature of the preamplifier, amplifier, and analyzer was raised from 25 to 50°C, the window level was observed to shift by less than 0.5% of the maximum pulse height. For the same ambient temperature excursion, the maximum window width changed by 1%. A line voltage change from 100 to 130 volts produced a shift of the window level of less than 0.1%.

Linearity checks of the entire system of the preamplifier, amplifier, and analyzer were performed, with results as shown in Fig. 5. Integral linearity is a measure of the deviation of the input pulse height versus window level curve of a particular system from the integral characteristic of a perfectly linear system. The maximum deviation expressed in per cent of maximum pulse height is known as integral nonlinearity. The integral nonlinearity of this system is 0.15% for any window level setting between 1.5 and 100%. Differential linearity is a measure of the change in slope of the integral characteristic. It is therefore a measure of the change in amplifier gain and analyzer window width as a function of window level. The differential characteristic is the window width versus window level curve.

The dashed line in Fig. 5 shows the differential characteristic of a perfectly linear system. The characteristic of this system varies above and below the ideal line. The maximum deviation from this line expressed in per cent of the nominal window width is known as differential nonlinearity. As seen in Fig. 5, the differential nonlinearity for this system is 5%. The linearity checks were made with a precision exponential pulse generator connected to the input of the preamplifier, and a count-rate meter connected to the output of the analyzer.

V. LINEAR COUNT-RATE METER

Circuit Description

This rate meter covers a range from 100 to 10,000 counts per second full scale in five steps. The schematic diagram is shown in Fig. 6. The circuit consists of a complementary trigger pair, T_1 and T_2, a diode pump, and

an electrometer feedback amplifier. The trigger circuit, which is similar to the one reported by Eklund and Work,* is particularly suited for this application. In the quiescent condition T_1 and T_2 are not conducting. The application of a negative pulse to the input turns on T_1 and T_2 regeneratively until both transistors bottom. During this time C_Q, which was initially charged to +10 volts, discharges through the low impedance path indicated. When the discharge process is completed, the transistors cut off regeneratively and C_Q charges to its previous voltage. The trigger circuit is on for less than 1.5 μsec, just long enough to fully discharge and recharge C_Q. The rate meter can be calibrated with the built-in 60 PPS pulse generator. Capacitor C_Q is adjusted until accurate reading is obtained on the lowest range. Thereafter, all the scales are properly calibrated.

The amplifier consists of the subminiature electrometer tube V_1 and two transistors, T_3 and T_4. The feedback loop is closed through the parallel combination of capacitor C_T and resistor R_T. The voltage gain of the amplifier without feedback is over 1000. An electrometer tube input stage is desirable because of the high resistance at the amplifier input. The amplifier output voltage on all ranges varies from zero to +10 volts full scale. A meter on the front panel provides visual indication, and a connector on the rear panel is provided to drive a 10-mv recorder. When the range switch is in the "zero" position, the meter sensitivity is increased from 10 volts to one volt full scale. This facilitates accurate zero setting of the meter, thus preventing the pump diodes from conducting. Three time constants are available for each range. The approximate statistical probable error is also shown in Fig. 6.

Circuit Performance

The rate meter circuit has a nonlinearity of about 1% of full scale. The correspondence between ranges is 0.1% of full scale. To compensate for the negative temperature coefficient of the feedback resistors, a zener diode, D_1, with a positive temperature coefficient is used to regulate the collector voltage of T_1. As the temperature rises the charge deposited on C_T increases so as to offset the decrease in the resistance of R_T, and to keep the voltage drop across it substantially constant. As the ambient temperature was changed from 25 to 50°C, a change in the output voltage of less than 1% of full scale was observed on the 100-count per second range. On higher ranges, the deviation was less. On the 10,000-count per second range, the change was negligible. The "zero" shift due to such a temperature excursion is 0.1% of full scale.

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*M. H. Eklund and G. A. Work, A Low-range Beta-Gamma Survey Meter, Research and Development Technical Report UNSRDL-TR-255 NE 051-500 (February 3, 1958).

VI. SCALER

Circuit Descrption

The scaler consists of a gated driver and six identical cascaded decade counting units (DCU's). The schematic diagram is shown in Fig. 7. When the level switch is in the "count" position, the input pulses are amplified by the driver transistors T_A and T_C and produce an output pulse which triggers the first DCU. The scaler can be gated by an external timer when the lever switch is in the appropriate position. When the lever switch is in the "off" position, there will be no output trigger pulse. In this position T_B is in saturation, thereby cutting off T_A.

Each decade counter consists of a blocking oscillator driving a 7155 miniature glow transfer tube, and an inverter coupling the output pulse to the succeeding DCU. The drive circuit is similar to the one reported by Kandiah.* A negative pulse triggers blocking oscillator, transistor T_1. Its collector swings positive and negative as shown in Part A of Fig. 8. Resistance R_1 limits the peak current through T_1. Resistance R_2 assures adequate damping of the negative swing, and R_3 limits the amplitude and duration of the pulse. The waveform at the collector of T_1 is transformer coupled to the glow tube guides. During the first part of the positive swing of the collector of T_1, capacitor C charges through diode D_1; a 100-volt negative pulse is thereby produced at guide No. 1. During the negative swing, D_1 is nonconducting. The voltage across capacitor C adds to the negative swing to produce a negative pulse at guide No. 2, comparable in amplitude to the pulse at guide No. 1. The waveform of the guide pulses is shown in Part B of Fig. 8. The output is coupled from the "0" cathode to T_2. Transistor T_2 is an inverter-driver which improves the rise time of the trigger pulse to the next decade counter. To reset the glow to the "0" cathode, the guides and cathodes 1-9 are raised well above the "0" cathode potential. This prevents the glow from forming anywhere but on the "0" cathode.

The plate voltage for the glow transfer tubes is provided by the 425-volt power supply (see Fig. 9). The output of this supply is regulated by means of two 200-volt, 10-watt zener power regulators. The supply delivers 6-mamp, one mamp for each tube. The voltmeter on the rear panel can be switched to check the output voltage of this supply.

Circuit Performance

The maximum continuous counting rate of the scaler is 2 x 10^4 counts per second, limited only by the dissipation of T_1. The pulse pair resolution, limited by the 7155 glow transfer tube, is 10 μsec. The scaler was temperature tested over an ambient temperature range of 25 to 50°C. No noticeable change was observed in the maximum counting rate, resolving time, or gating accuracy.

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*K. Kandiah, Nuclear Instruments, 2 (2), 109 (February 1958)

VII. HIGH-VOLTAGE POWER SUPPLY

Circuit Description

This supply provides the negative high voltage for the photomultiplier. It has a maximum voltage of 1000 volts, which is variable from 600 to 1000 volts in steps of 100 volts (see Fig. 10). Two regulators are used in this supply, a diode regulator and a series regulator. The diode regulator consists of a series resistor, and ten 100-volt zener diodes as the shunting element. The series regulator consists of a reference element, a DC amplifier, and a silicon transistor with a dynamic range of 80 volts as the series element. In order not to upset the current through the sense string, an electrometer tube input stage is used. As the high voltage is changed, the input to the series regulator and the sense string are changed to as to maintian constant the voltage across the series element T_2. The neon lamps across T_2 and the grid of V_1 protect these elements from exceeding their ratings during the initial warm-up and during adjustment of the high voltage. A voltmeter on the rear panel can be switched to measure the high voltage or the collector voltage of T_2.

Circuit Performance

A 0.1% change in the high voltage was observed when the ambient temperature was increased from 25 to 50°C. The output voltage changed by 0.05% when the line voltage was varied from 100 to 130 volts. The output ripple is less than 100 mv peak to peak. The collector voltage of the series transistor T_2 can be adjusted by means of the potentiometer P_6. If at 25°C and 117 volts line voltage, the collector voltage is adjusted to 25 or 30 volts, then upon raising the ambient temperature to 50°C and the line voltage to 125 volts, the collector voltage will not increase above 60 volts. If, on the other hand, at 25°C the line voltage is only 105 volts, the collector voltage will not drop below 10 volts. Thus, under average operating conditions, T_2 will remain well within its dynamic range. If, however, under severe conditions the collector voltage rises above 65 volts, the "not regulating" neon lamp on the front panel will notify the operator to readjust P_6.

VIII. LOW-VOLTAGE POWER SUPPLY

With the exception of the scaler, all the circuits in this instrument are designed to work exclusively from the positive and negative 22-volt supply. The schematic diagram of this supply is shown in Fig. 11. The positive and negative supplies are virtually identical, the only exception being that opposite polarities are grounded. The maximum output current of each supply is 150 mamp, although less than 100 mamp are used. A change of 0.2% in the output voltage was observed when the ambient temperature was varied from 25 to 50°C. The output voltage changed by less than 0.1% when the line voltage was increased from 100 to 130 volts, or when the load was changed from its maximum to no load. The peak to peak ripple is less than 10 mv.

Two fuses, F_{+22} and F_{-22}, serve as overload protection for each supply. The 25-volt zener diodes, D_1 and D_2, protect all circuits from overvoltage. In the event the regulator of one supply fails and the voltage should reach 25 volts, the zener diode will draw sufficient current to blow fuse F_{22}. Since the positive and negative supplies have a common load, a reverse polarity voltage will appear on the inoperative supply bus. This voltage will be limited by the forward drop of the zener diode to about 0.5 volt.

The negative 45-volt supply is used for the scaler. It is regulated by a 10-watt zener power regulator and supplies 20 mamp. The voltmeter on the rear panel can be switched to check any of the voltages of this supply.

IX. SCINTILLATION SPECTROMETER

Figure 12 shows a gamma-ray spectrum of Cs^{137} obtained with this instrument. The Cs^{137} photopeak displays a resolution of 7.7%. The spectrum was taken with window width of 1% and a counting interval of 100 seconds per step.

The instrument operates on standard line voltage of 105-130 volts AC at 60 cps, and has a power consumption of 0.65 amp at 117 volts AC. The spectrometer also includes a mercury switch exponential pulse generator which generates 3 precision pulse heights. When the "input selector" switch on the front panel is turned to the pulse generator position, pulses are applied to the input of the amplifier. Thus the amplifier-analyzer combination can be checked for linearity, the count-rate meter for correct calibration, and the scaler for accuracy. Since the amplifier has a continuous gain adjustment, any part of the amplifier-analyzer dynamic range can be checked for linearity.

The packaged instrument (see Fig. 13) without the preamplifier and photomultiplier weighs 35 pounds. The case is made of anodized aluminum and measures 11 x 12 x 18 inches. Most of the circuit components are mounted on plug-in printed circuit cards. The various circuit elements, such as amplifier, analyzer, etc., are built on seven $9\frac{1}{2}$ x $3\frac{1}{4}$-in. cards, and each of the decade counters is built on a 3 x 3-in. card. A sample of each is shown in Fig. 14.

Bulky components, such as transformers, filter capacitors, etc., are mounted on the slide-in unit below the printed circuit cards. All the operational controls, such as amplifier gain, window level control, etc., are mounted on the front panel (see Fig. 15). The controls, which seldom require adjustment, are mounted on the printed circuit cards and are accessible . from the top when the side covers are removed. The various connectors for the preamplifier, recorder, etc., as well as the voltmeter, are mounted on the rear panel (see Fig. 16). Four quarter-turn screw fasteners hold each

side cover to the unit. The front and rear covers protect the panels when the instrument is transported. The front cover has a compartment to house the cables when not in use. Both covers can be completely removed when the instrument is to be used.

At this writing the first version of the spectrometer has been in use for six months. A second unit is being constructed. Several design changes have been included in the circuits and construction of the second unit. All the individual circuit elements for the second unit have been in operation for some time, and the complete unit is now being checked out.

ACKNOWLEDGMENTS

Thanks are due to many members of the Electronics Division and the ANL Central Shops, particularly to Thomas Brill for his support of the development of this instrument, to Harry T. Ryan who did most of the development of the decade counters, and to Thomas W. Hoffer for his helpful suggestions and good workmanship in the construction of this unit.

Notes Pertaining to All Schematics

Unless otherwise specified:

1. All PNP transistors RCA 2N370.
2. All NPN transistors GE 2N169A.
3. All resistors $\frac{1}{2}$ watt, ± 5% tolerance.
4. C.F. denotes carbon film resistors, $\frac{1}{2}$ watt, ± 1% tolerance.
5. * denotes wire wound resistors ± 1% tolerance.
6. All resistance values in ohms.
7. Capacitance values one and less in μf, over one in $\mu\mu$f.
8. Electrolytic, tantalum, and high voltage capacitors ratings in μf/volts.
9. All rotary switches nonshorting.

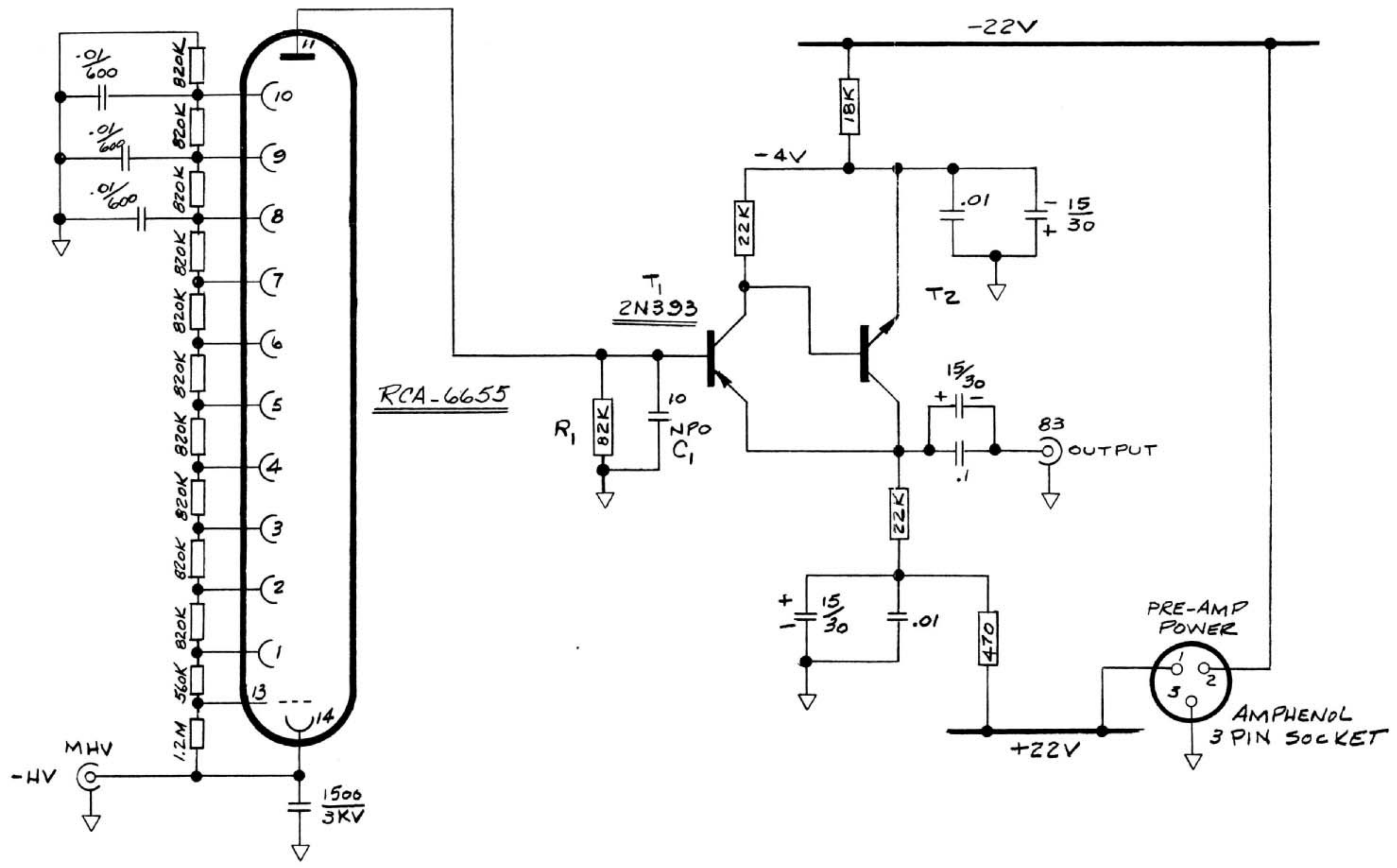


Fig. 1. Preamplifier

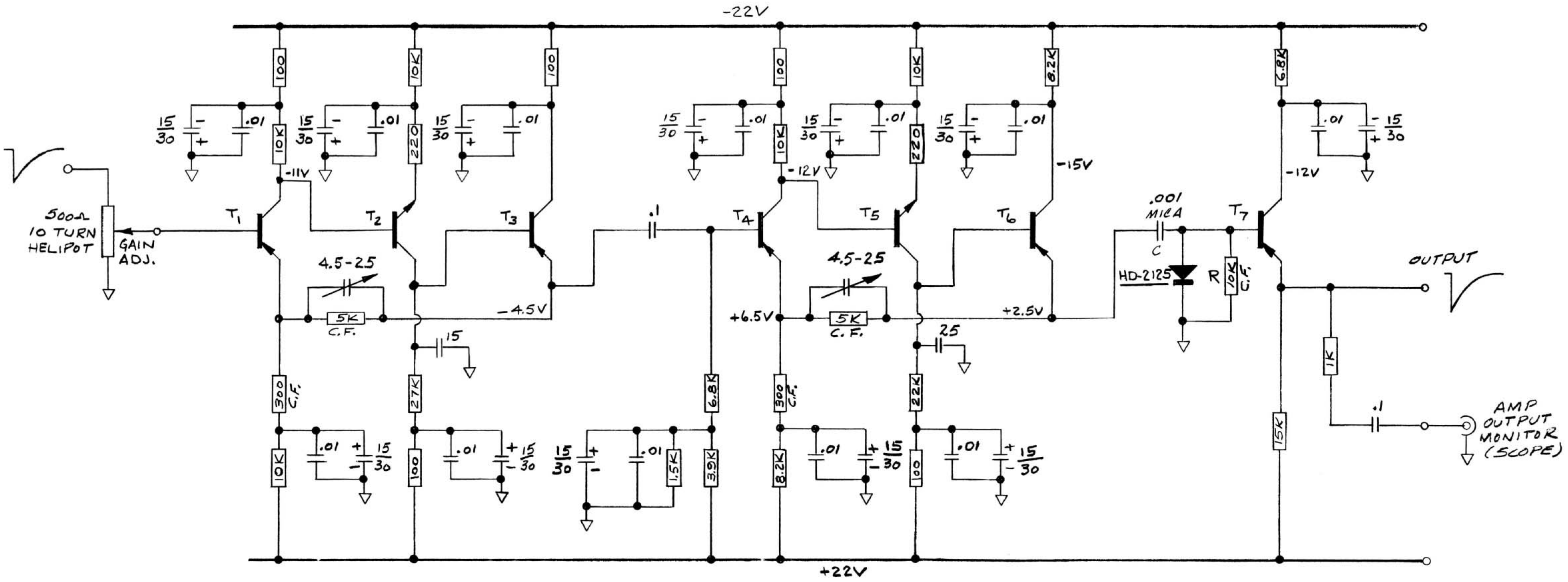


Fig. 2. Linear Pulse Amplifier

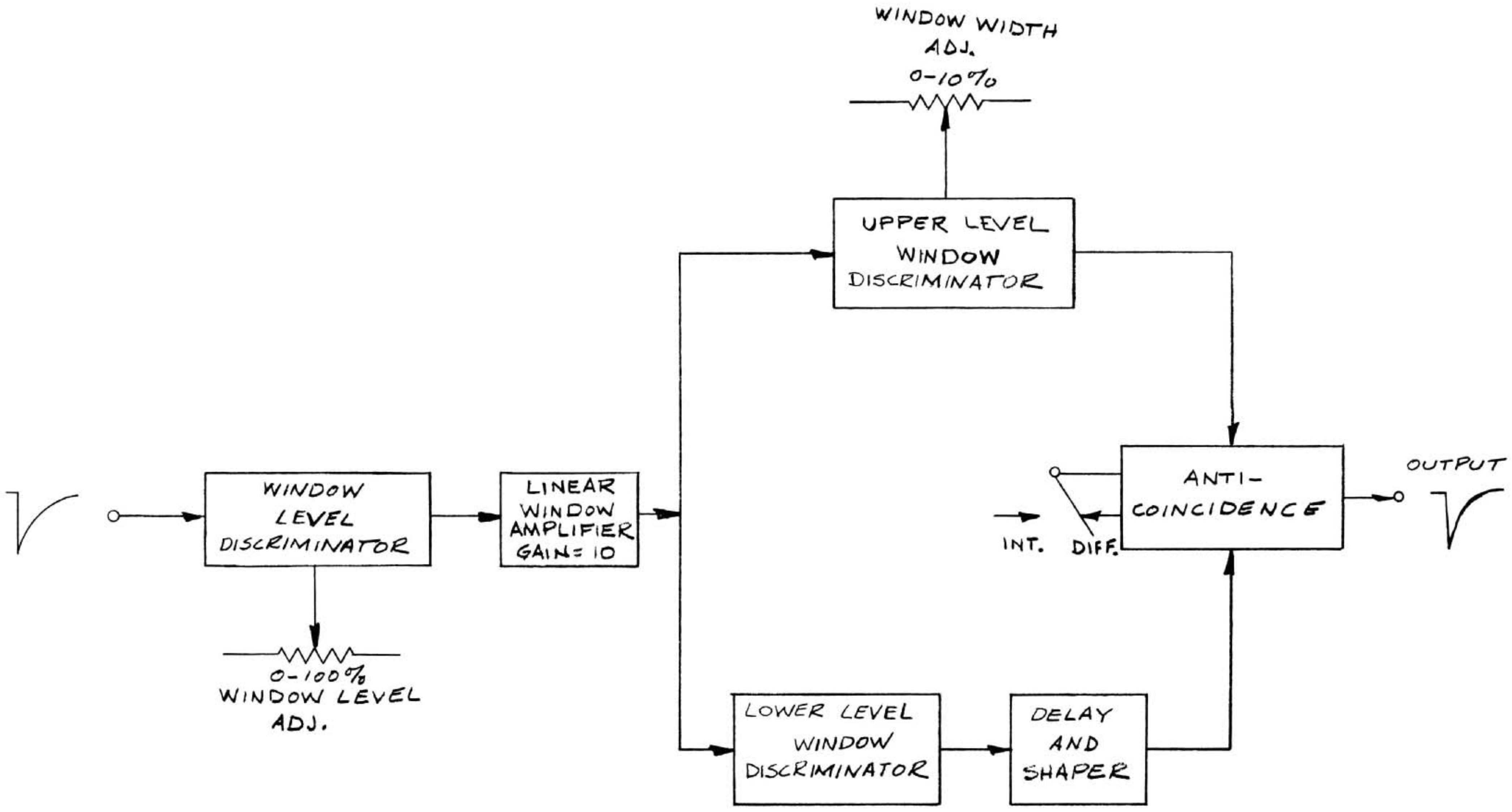


Fig. 3. Block Diagram of Single Channel Pulse-height Analyzer

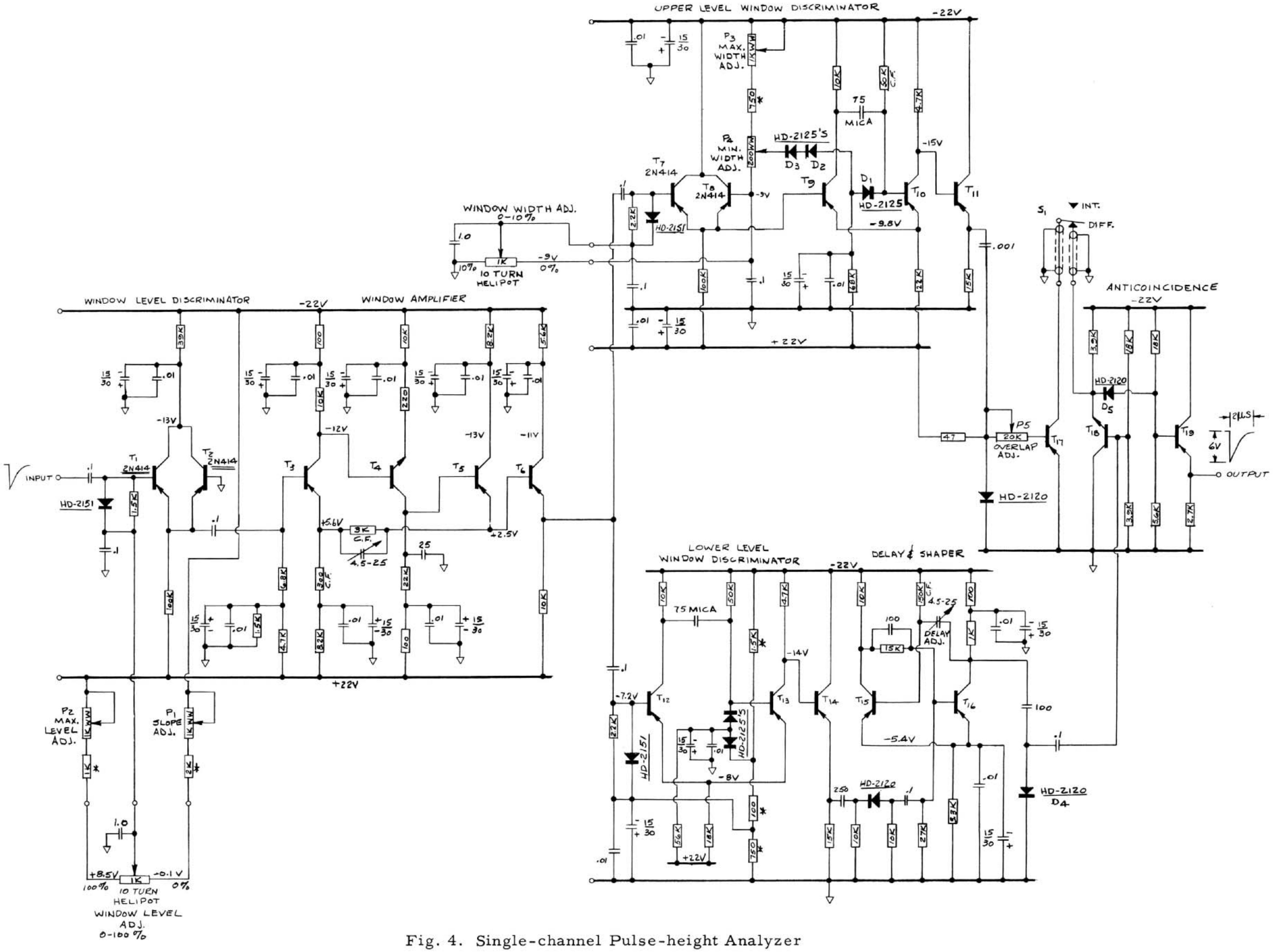


Fig. 4. Single-channel Pulse-height Analyzer

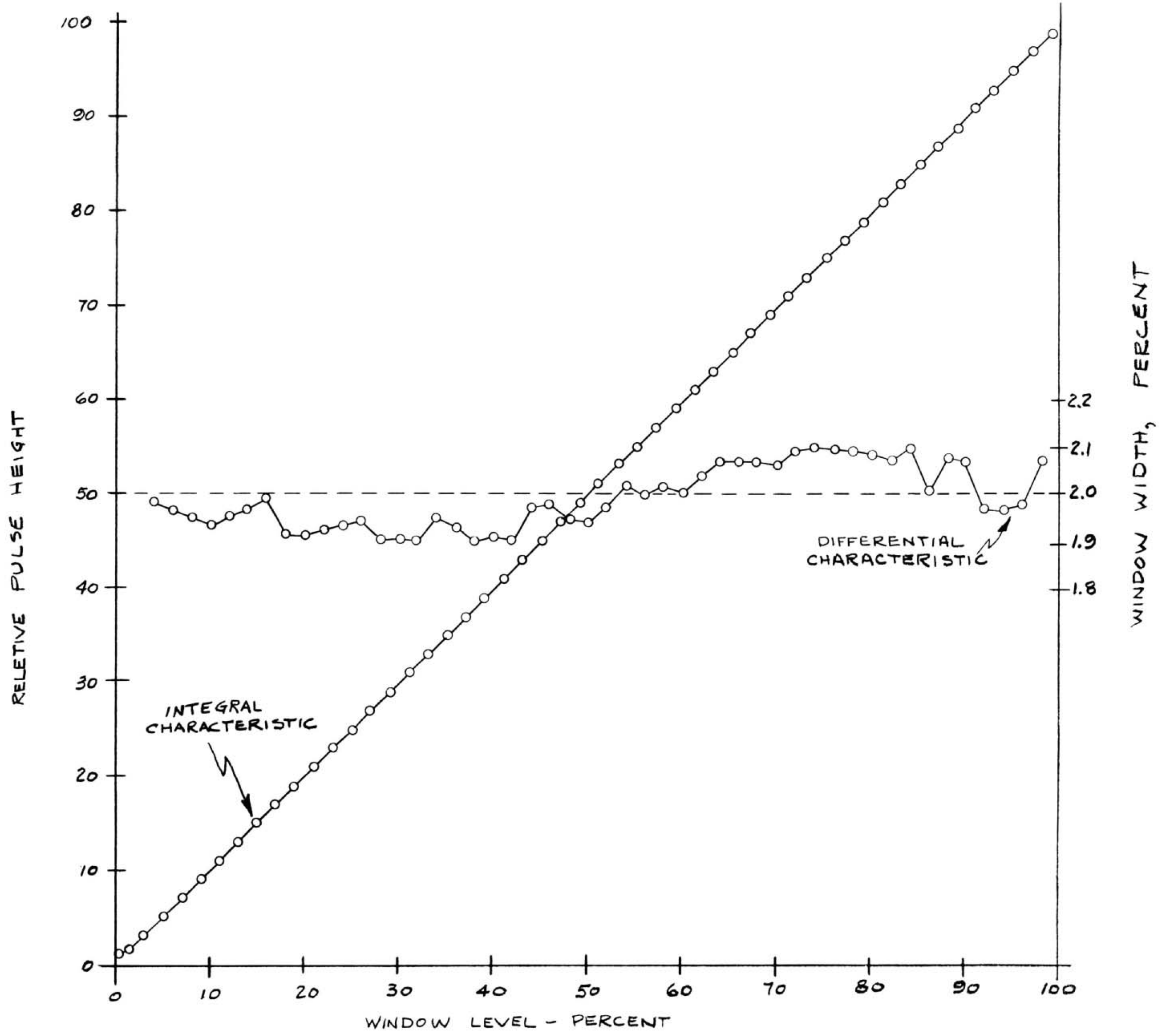
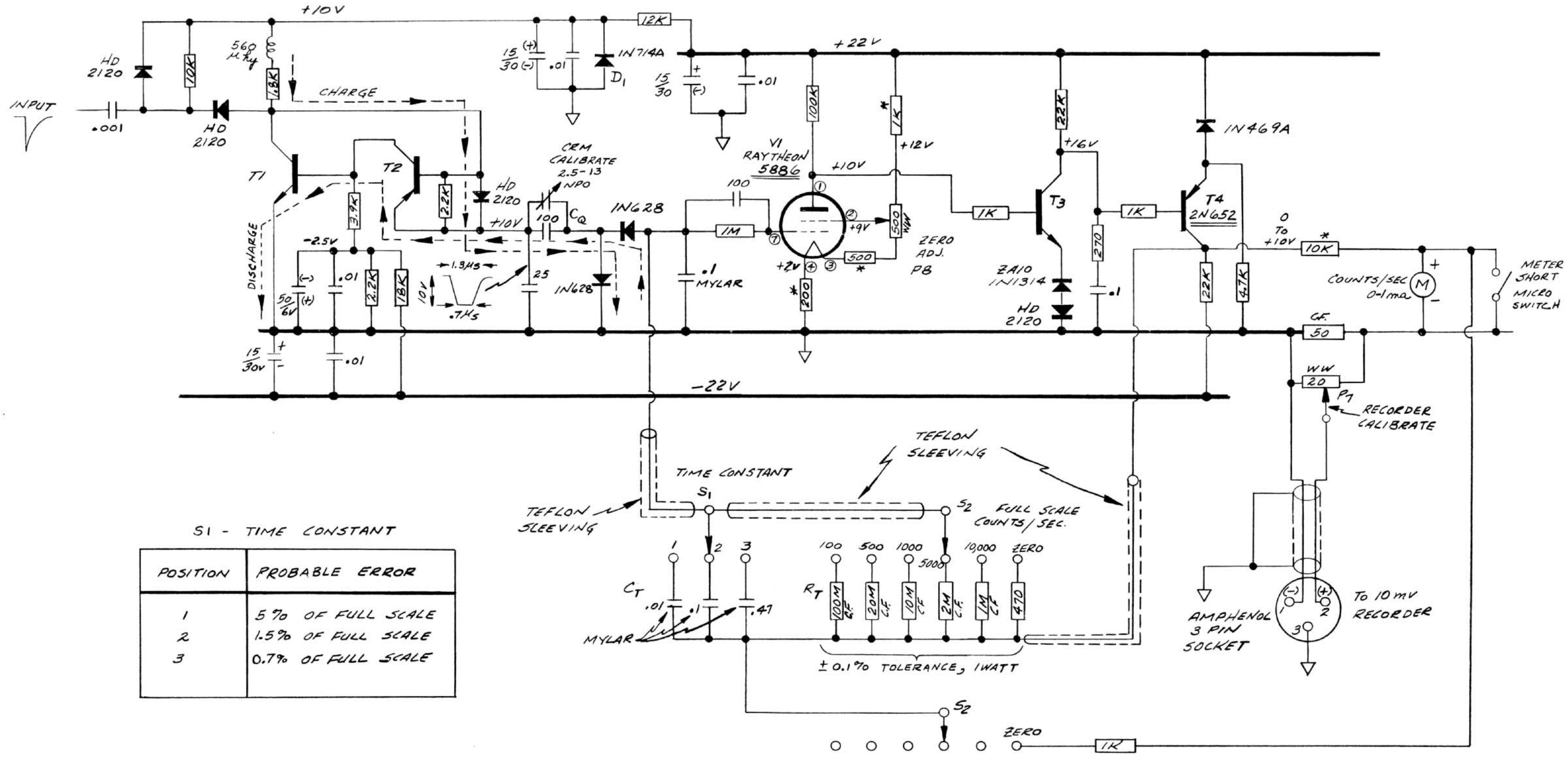


Fig. 5. Linearity of Amplifier-analyzer Combination



S1 - TIME CONSTANT

POSITION	PROBABLE ERROR
1	5% OF FULL SCALE
2	1.5% OF FULL SCALE
3	0.7% OF FULL SCALE

Fig. 6. Linear Count-rate Meter

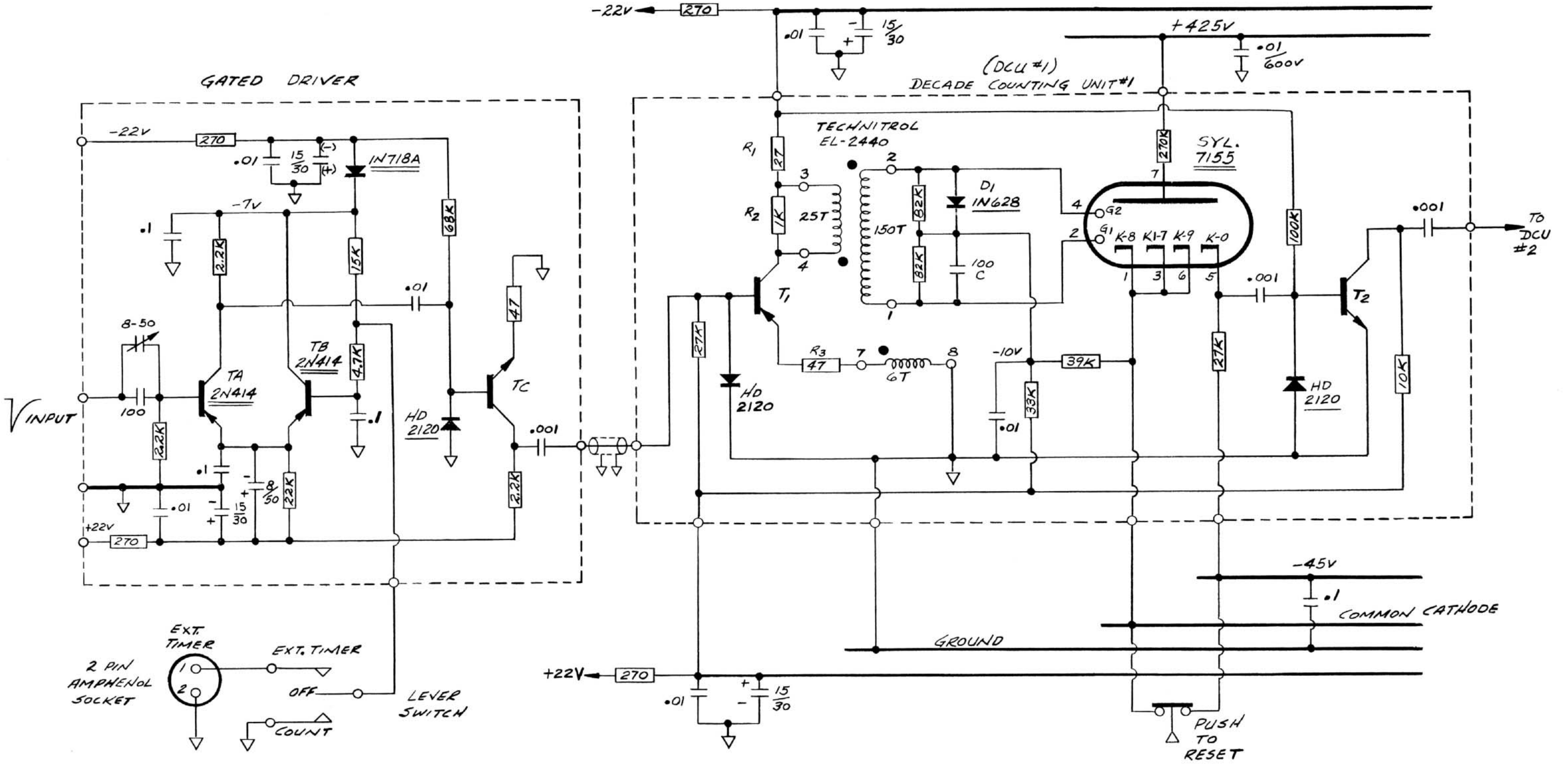

GATED DRIVER
-22V
270
.01
15/30
(-)
(+)
1N718A
-7V
.1
2.2K
15K
68K
.01
8-50
TA
2N414
TB
2N414
4.7K
TC
47
INPUT
100
2.2K
.1
8/50
22K
.1
HD
2120
.001
2.2K
.01
15/30
+22V
270
EXT. TIMER
2 PIN
AMPHENOL
SOCKET
1
2
EXT. TIMER
OFF
COUNT
LEVER
SWITCH
-22V
270
.01
15/30
+425V
.01/600V
(DCU #1)
DECADE COUNTING UNIT #1
TECHNITROL
EL-2440
R1
27
R2
1K
3
25T
4
2
150T
1
82K
82K
D1
1N628
100
C
270K
SYL.
7155
7
4
G2
2
G1
K-8
K1-7
K-9
K-0
1
3
6
5
T1
27K
HD
2120
R3
47
7
6T
8
-10V
39K
.01
33K
27K
.001
100K
HD
2120
T2
10K
.001
TO
DCU
#2
-45V
.1
COMMON CATHODE
GROUND
+22V
270
.01
15/30
PUSH
TO
RESET

Fig. 7. Scaler

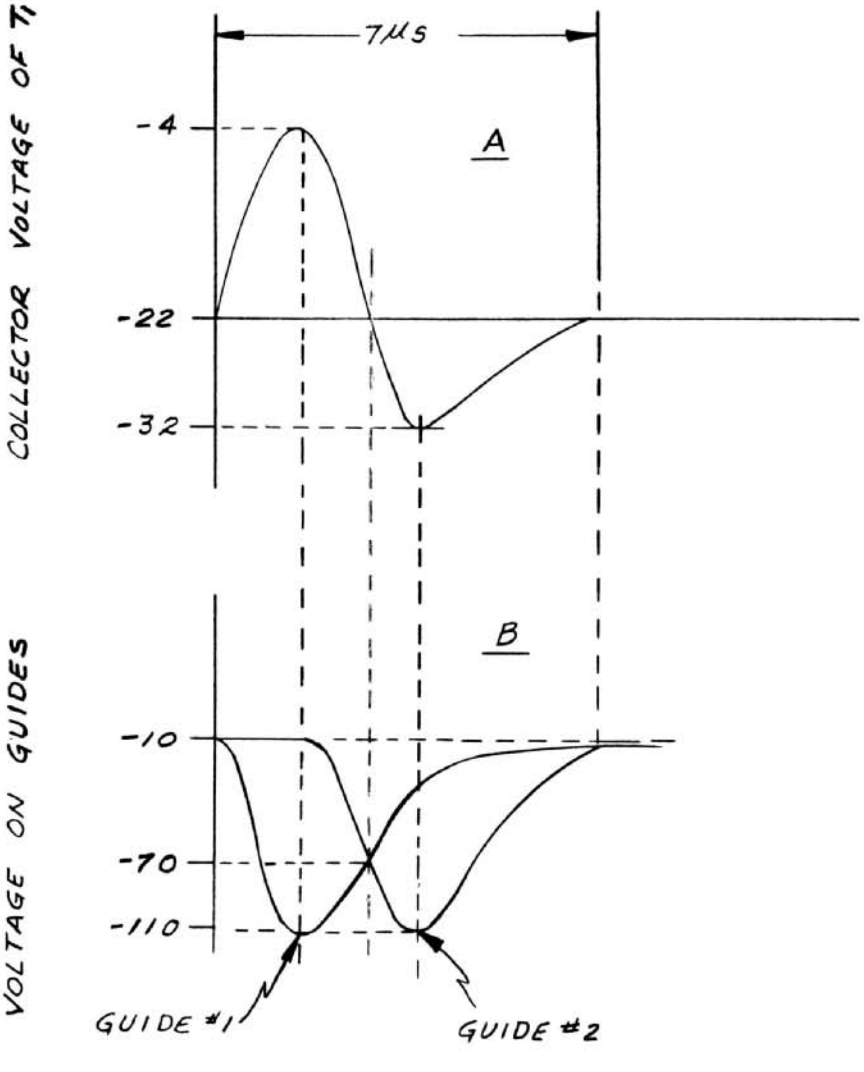


Fig. 8. Waveforms on Decade Counter

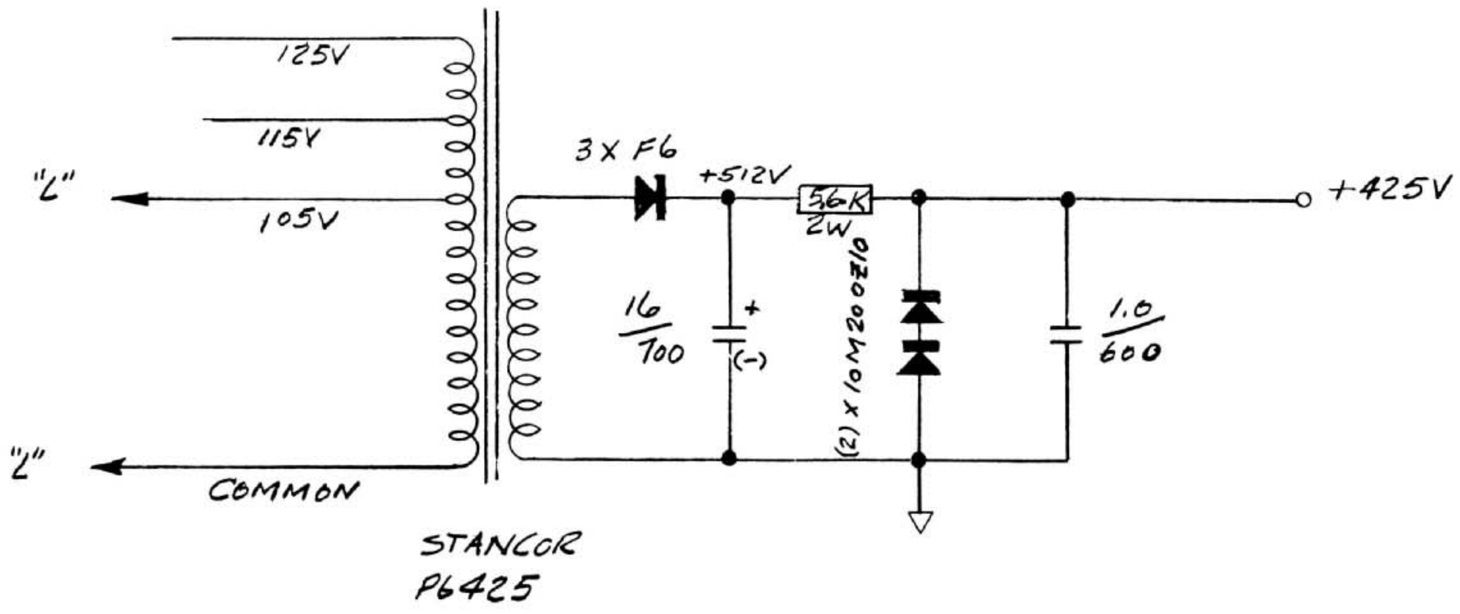


Fig. 9. Positive 425-volt Power Supply

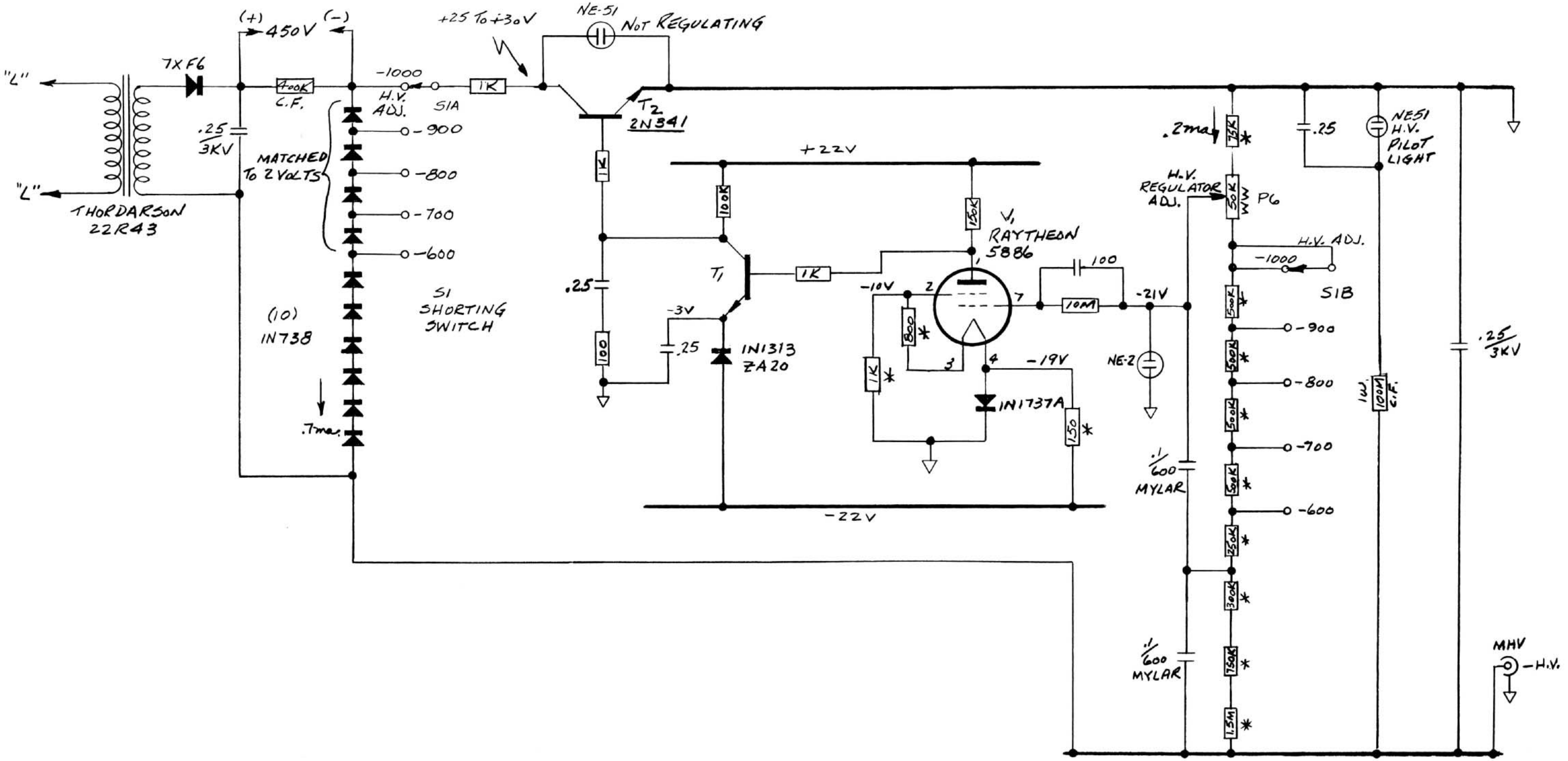
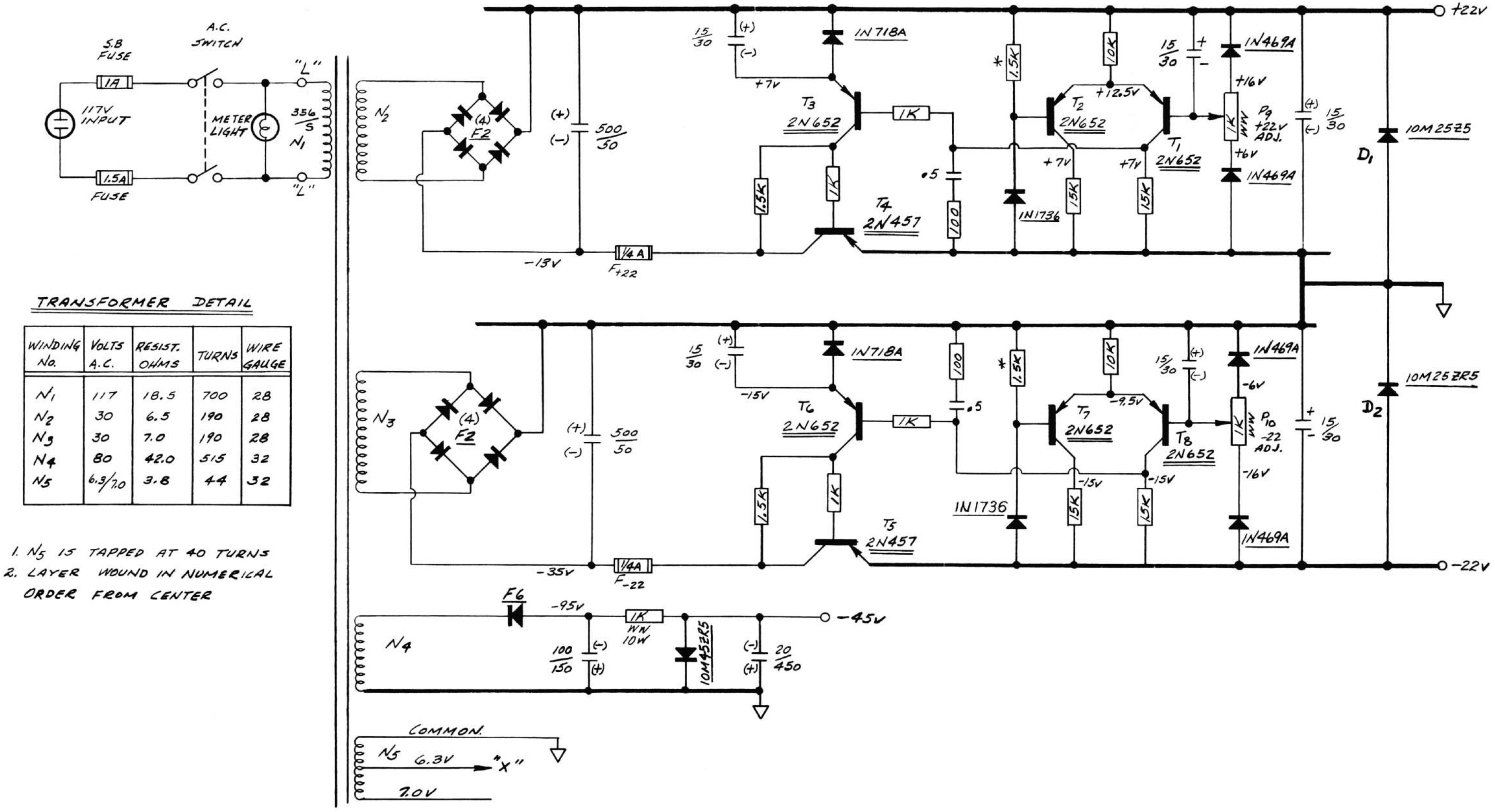


Fig. 10. Negative 600 to 1000-volt Power Supply



TRANSFORMER DETAIL

WINDING No.	VOLTS A.C.	RESIST. OHMS	TURNS	WIRE GAUGE
N_1	117	18.5	700	28
N_2	30	6.5	190	28
N_3	30	7.0	190	28
N_4	80	42.0	515	32
N_5	6.3/7.0	3.8	44	32

1. N_5 IS TAPPED AT 40 TURNS
2. LAYER WOUND IN NUMERICAL ORDER FROM CENTER

Fig. 11. Low-voltage Power Supply

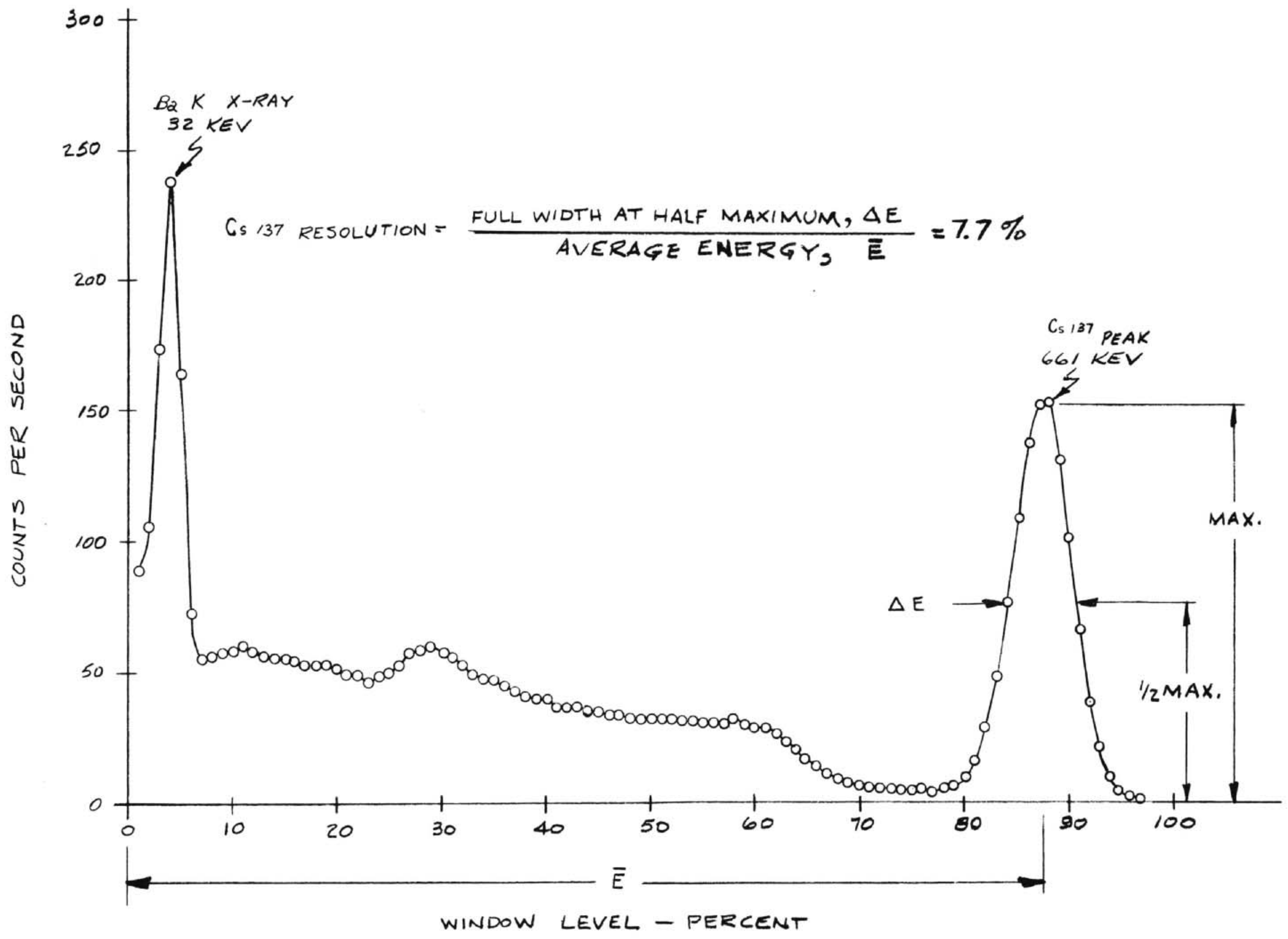


Fig. 12. Gamma-ray Spectrum of Cs^{137}

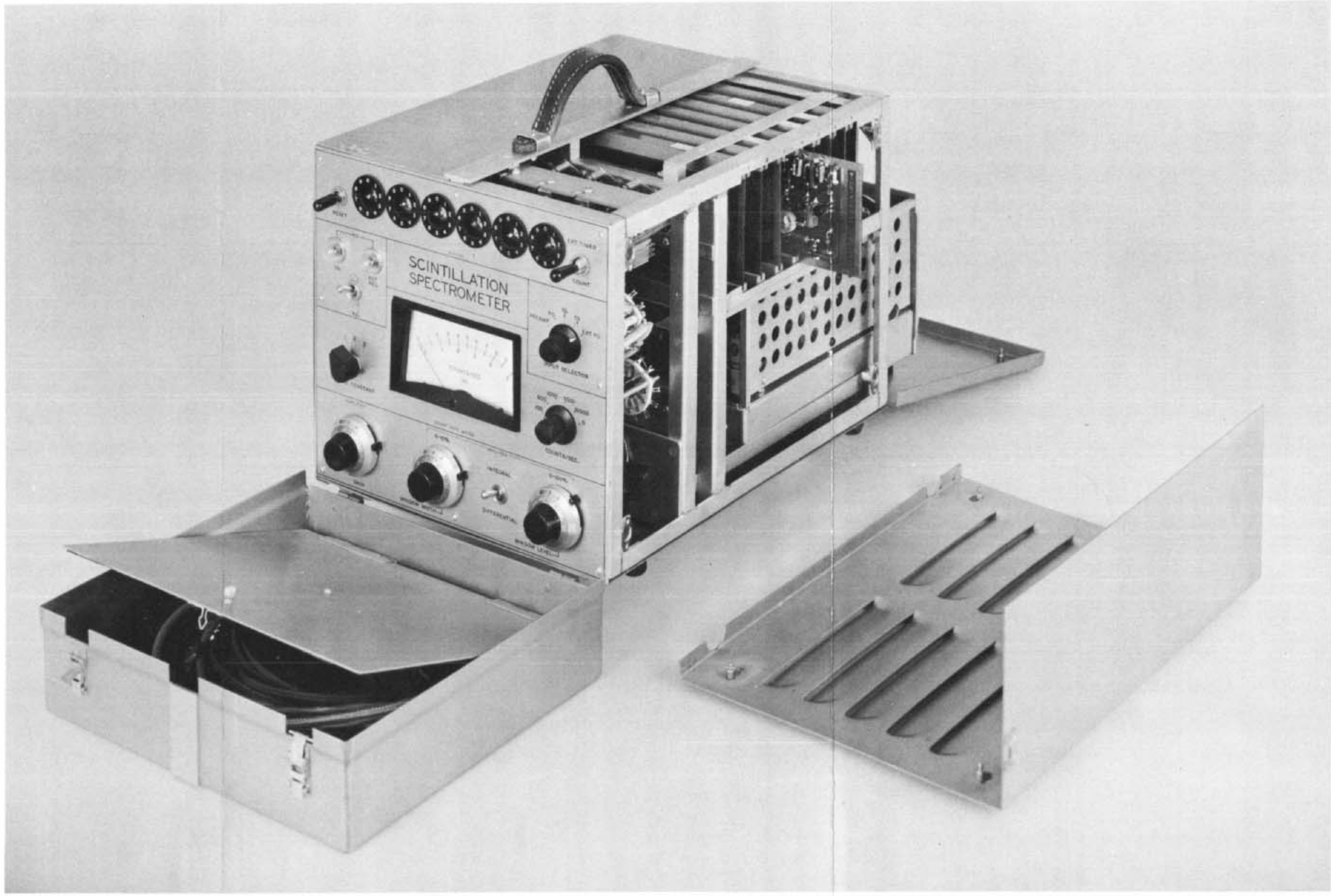


Fig. 13. Complete Assembly

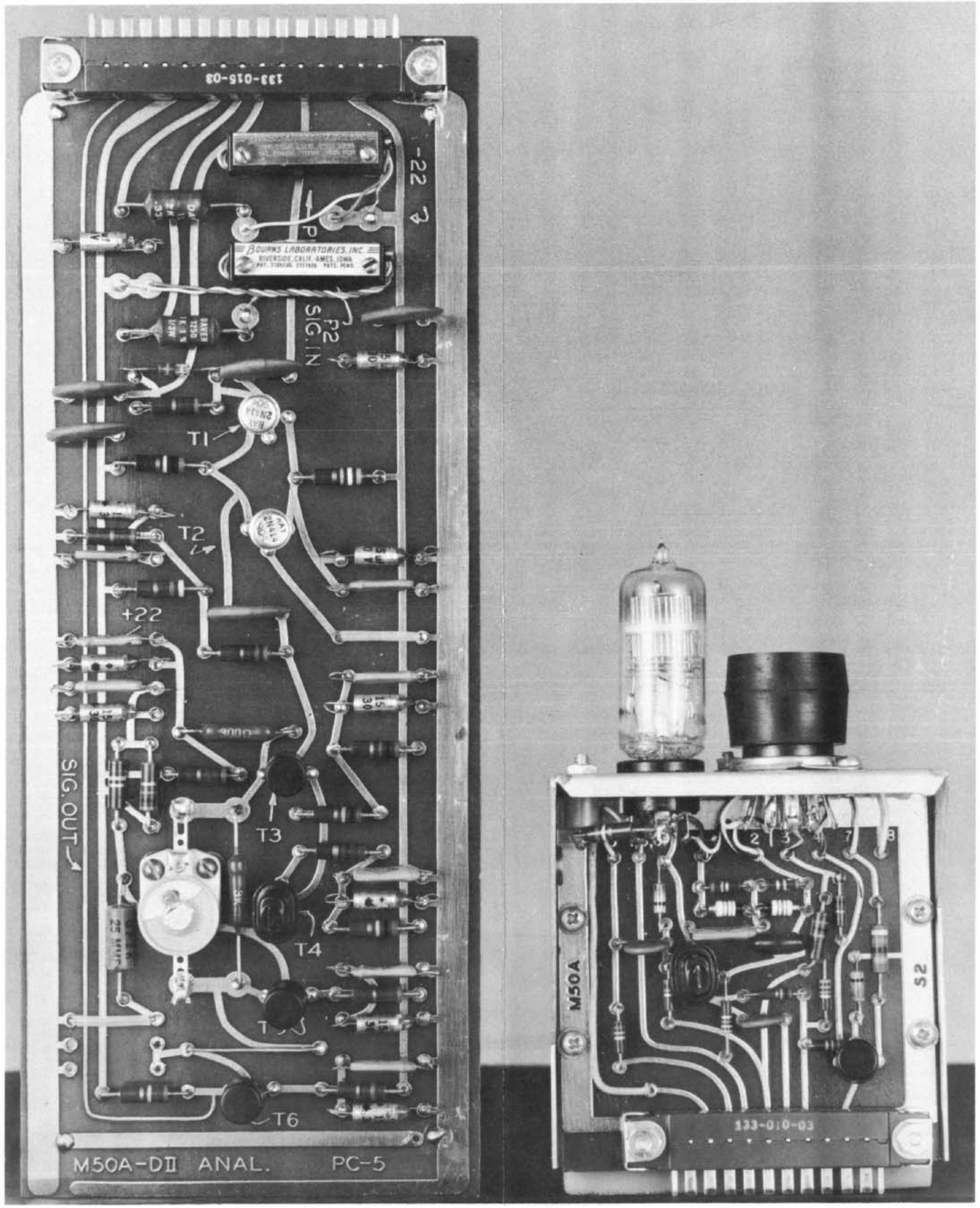


Fig. 14. Printed Circuit Cards

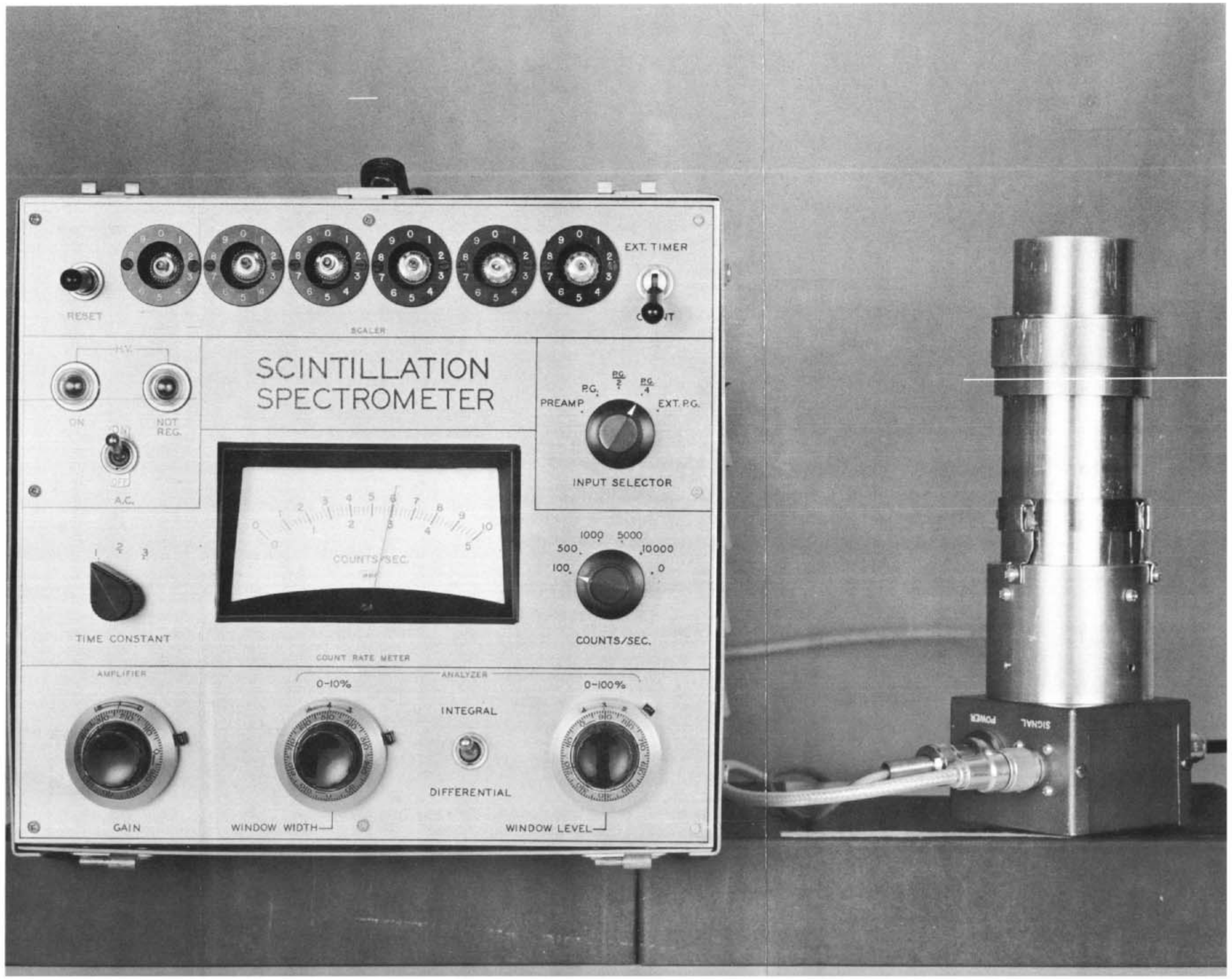


Fig. 15. Front View

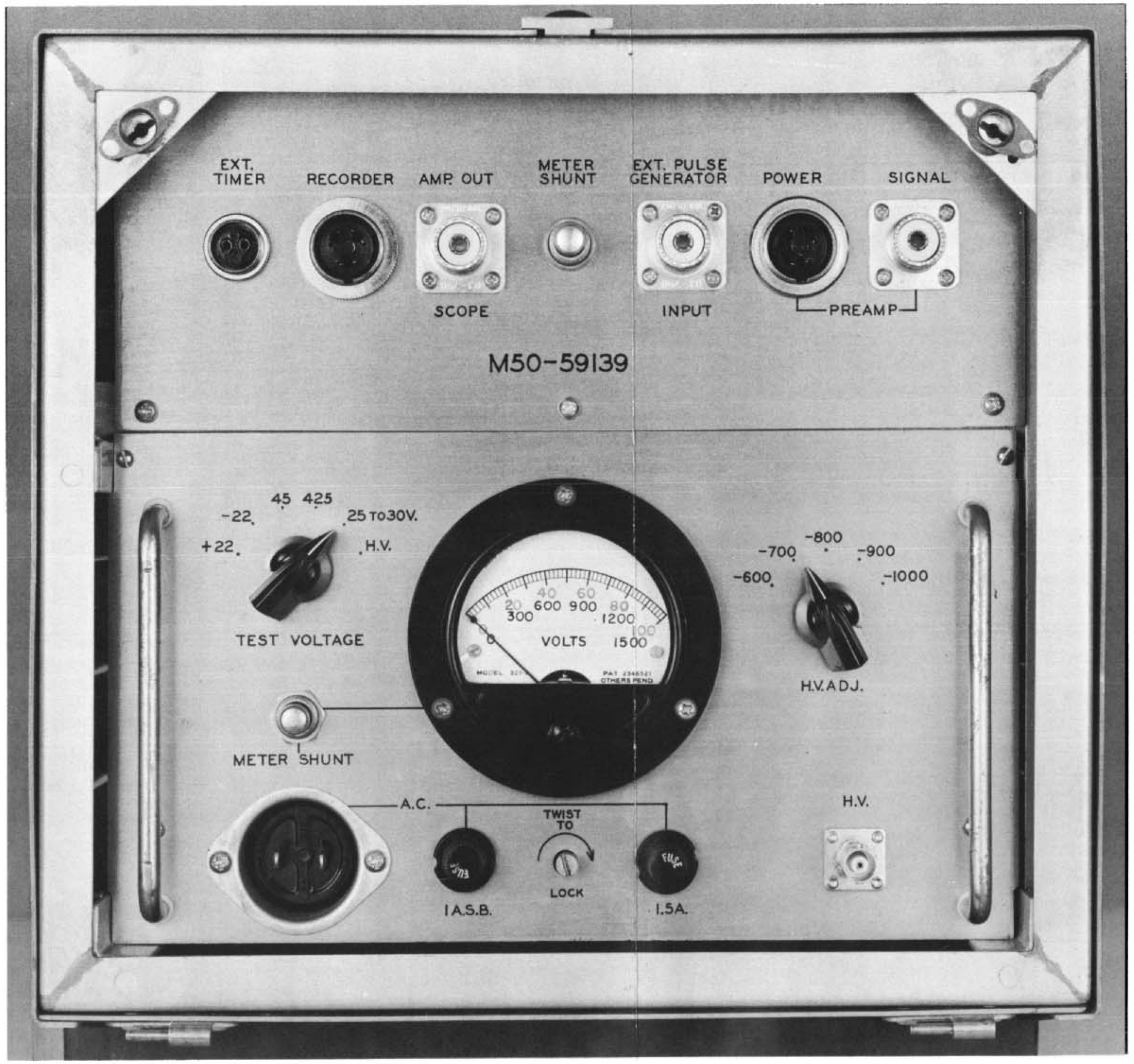


Fig. 16. Rear View

Price $1.00 . *Available from the Office of Technical Services,*
Department of Commerce, Washington 25, D.C.