PROBLEMS ENCOUNTERED IN THE CONSTRUCTION OF A PROPORTIONAL COUNTER SPECTROMETER

by

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INTRODUCTION

A description of counter spectrometers is useful in placing the proportional counter tube in the scheme of spectrometric investigation. The present state of information concerning the nuclei of atoms is one such that counter spectrometers are in constant use determining particle and photon energies from those of the softest x-rays up to energies of billions of electron volts.

The crystal scintillation counter is limited to higher intensities by high natural background. Ion chambers are useful only above 150 kev. Differential absorption methods are tedious and are also limited in their use by natural background. The proportional counter may be used to measure low energies in the presence of high background radiation. Soft x-rays hitherto concealed in other high intensity emmissions may be located. The physical nature of the counter tube enables its use in low energy spectrometric investigation of radioactive gases. These and other uses make the proportional counter a useful addition to the instruments of nuclear physics.

Counter tubes in general are arrangements of two electrodes in a gas with a potential difference between them. A photon or particle incident on the gas with sufficient energy to ionize the gas will suffer inelastic collisions with the gas molecules. Upon collection at the electrodes of ions so formed, a voltage pulse is produced by the passage of the collected charge through a resistance in series with the source of potential difference. In such a system, the incident particle or, in the case of electromagnetic radiation, the initial photo-electron dissipates all its energy in inelastic collisions. It has been experimentally determined by Curran and Craggs (10, p. 19) and Curran, Cockroft and Insch (9) that the average energy lost per collision by the initial electron is a characteristic of the gas. Thus the number of electrons and positive ions released is proportional to the energy of the incident ray or particle.

If the electrode voltage is insufficient to accelerate primary electrons to ionizing energies, no further inelastic collisions occur and the primary electrons and ions alone produce the pulse. A counter tube operating in this range is an ion chamber. As the voltage is increased above that required to give primary electrons ionizing energies, secondary inelastic collisions occur and the charge collected is larger than that released by the incident particle or ray. For a given incident energy, the voltage height of the pulse produced increases exponentially with the electrode potential difference. At constant electrode voltage in a certain range of electrode voltage, depending upon geometric configuration and upon gas filling, the pulse output voltage is proportional to incident energy. The higher the electrode voltage, the larger the proportionality factor or, as it is termed, the gas gain. A counter tube operated in this manner is a proportional counter.

At voltages above the proportional region the gas gain continues to increase but becomes dependent on incident energy until the Geiger threshold is reached at which point all incident rays or particles produce pulses of approximately the same height. In a small electrode voltage range above this point, the Geiger plateau (10 to 25 percent of the electrode voltage), the tube operates as a Geiger counter, and at higher voltage goes into continuous gaseous discharge.

Proportional counter pulses must be amplified since pulses of ten volts or larger are required to operate a pulse height selector or as it is sometimes called "kick-sorter" or "differential pulse height discriminator". Thus a pulse amplifier and pulse height selector are needed. Also a stable source of high voltage is required for the counter electrode voltage.

Several reports on work done with proportional counters have been published. The best resolution for low energy x-rays was reported by Bernstein, Brewer and Rubinson (2), who gave several examples of counting rates plotted against pulse height. The points plotted were counting rate for pulses having heights lying in a one and one half volt interval or channel. If resolution is evaluated by the ratio of the voltage width of a peak at half-maximum intensity to the pulse height voltage at the maximum, the best resolution is about 20 percent. It was found that proportional counter pulses had rise times varying from 0.3 to 0.8 microseconds. Gas gains as high as 10^7 can be obtained if extreme high voltage stability (better than 0.01 percent) is maintained.

Curran, Angus and Cockroft (6) at Glasgow were able to resolve the $K\alpha$ and $K\beta$ x-rays of copper and nickel. They also found very good linearity of gas gain for photon energies of from two to forty kilo-electron volts.

The earliest successful applications of proportional counters reported were made by the Glasgow group of workers. The beta-decays of H^3(7), C^{14} (1) and S^{35} (4) in gaseous form were investigated by this group. With proportional counters they were able to extend the information to the lower energies. Curran, Cockroft and Insch (9) measured the energy expenditure per ion pair of electrons in several gases. They were able to detect single quanta of ultra violet light (8) by photo-electrons liberated at the cathode of a proportional counter tube.

THE AMPLIFIER

A linear pulse amplifier (Plate V) for use with a proportional counter must satisfy the following requirements: it must amplify pulses of the order of millivolts or less in size in the presence of occasional pulses as much as a thousand times larger; the initial rise time of the pulse must be reproduced in order that the gain be not dependent on pulse amplitude or rise time. High counting rates of small pulses should not disturb the d-c levels of any points enough to change the amplifier gain.

The range of linear response is determined by two factors, the rise time, T_R and the clipping time, T_C. These quantities are more revealing criteria of performance than bandwidth measurements. Elmore and Sands (11, p. 126) define T_C as the time constant for decay at the output of a step voltage applied at the input of the amplifier. When, as is usual, one coupling time constant is less than others in the amplifier by a factor of one hundred or more, it is equivalent to T_C. T_R is determined by the plate load time constants in the amplifier. For calculation purposes, this time constant for a single stage, T_P, is the product of the plate load resistance and the total capacitance to ground of the plate itself. If one T_P is much larger than every other, the overall rise time is given by,

$$T_R = \sqrt{2\pi}\, T_P$$

For n stages of amplification without feedback each having a different rise time, T_i.

$$T_R = \sqrt{\sum_1^n T_i^2}$$

If feed back is used, T_R may be calculated approximately in terms of the upper half-power frequency, F_2 where:

$$T_R F_2 \cong \frac{1}{3}$$

These above relationships are from Elmore and Sands (11, ch. 3, sect. 4).

The amplifier was constructed with slight modifications from plans obtained from the designers (14).

The pre-amplifier consists of one three stage feedback loop and two cathode followers, one for use alone having a gain of one from high to low impedance, the other with the feedback loop having a gain of forty from high to low impedance. The main amplifier contains two feedback loops and one cathode follower. Each feedback loop is two stages of amplification and one cathode follower and has a calculated wideband gain of about one hundred. Three bandwidths are available by switching the feedback coupling in the first loop.

The clipping time constant was originally in the main amplifier input, but was moved to the input of the final feedback loop. The change was made in order to prevent double-pulsing in the final feedback loop. The cathode follower in this loop will pass a negative pulse of only seven volts. Thus a negative over-shoot on the input pulse in excess of about 0.07 volt was amplified by the unfedback gain and appeared at the plate of V5, about ten times as large as the feedback controlled pulse would have been. Bottoming or plate current limiting in V5 occurred with cutting off of V6 followed by a positive pulse on the return of V5 to normal current. Moving the clipping constant reduced the over-shoot itself and improved the amplifier performance. A diode restorer in the grid of V4 reduced the cut-off time but increased the double-pulsing and so was of no advantage.

The preamplifier was direct coupled to the main amplifier input and the continuous gain control increased to 0.3 megohm. Also three of the resistors available for the coarse gain control were wire-wound. These caused oscillation at the leading edge of a fast pulse. A ten thousand ohm resistor shunted across the two smaller ones compensated for their inductance, but the larger one (800 ohms) was not compensated. It should be replaced when a stable, non-inductive, 800 ohm resistor is available.

Tables 1 and 2 give performance data on the amplifier. The pulse acceptance ratio is the ratio of the amplitude of the largest pulse that does not give rise to spurious pulses to that of the smallest pulse that the pulse height selector will count accurately. The delay time is the time lag of the output pulse after the input pulse.

Table 1. Amplifier gain.

Bandwidth (megacycles)	Calculated gain[1]		Measured gain	
	Cathode follower input	Pre-amplifier input	Cathode follower input	Pre-amplifier input
2	13,300	399,000		
0.5	17,000	510,000		
0.1	22,000	660,000	8,400	336,000

Table 2. Pulse characteristics of the amplifier.

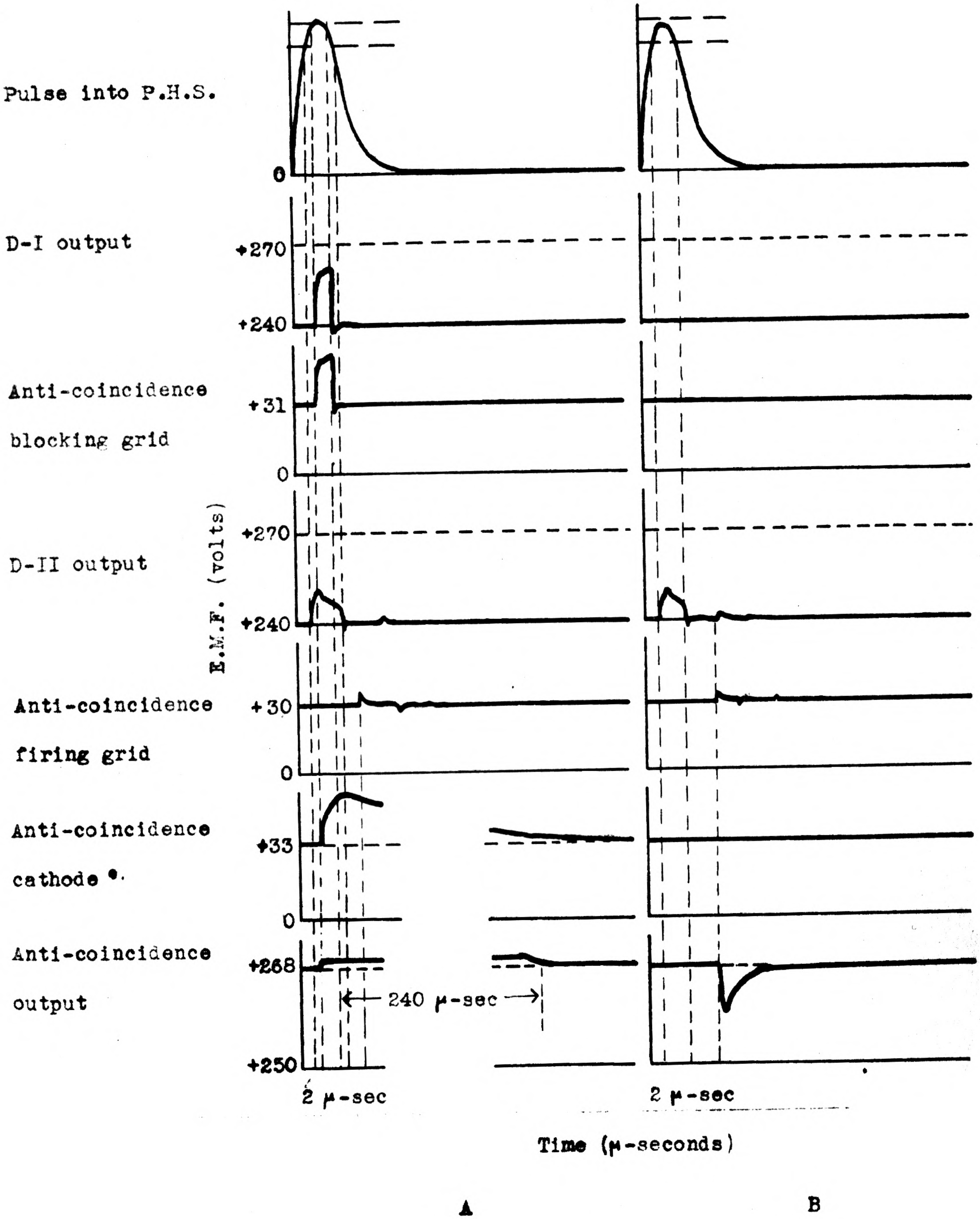
Bandwidth (megacycles)	2	0.5	0.1
Delay time (micro-seconds)	1	2	1
Rise time (micro-seconds)	1.3	3	10
Pulse width (micro-seconds) at 10% maximum height	5	20	50
Pulse acceptance ratio	100	20	10
Preamplifier input noise level (micro-volts)			42

[1] Elmore and Sands (11, p. 58).

EXPLANATION OF PLATE I

Waveforms at various points in the pulse height selector. Part A shows waveforms for a pulse higher than the channel setting. Part B shows waveforms for a pulse whose height lies in the channel. Note that the latter portion of the time scale has been compressed in the bottom two figures of Part A.

PLATE I



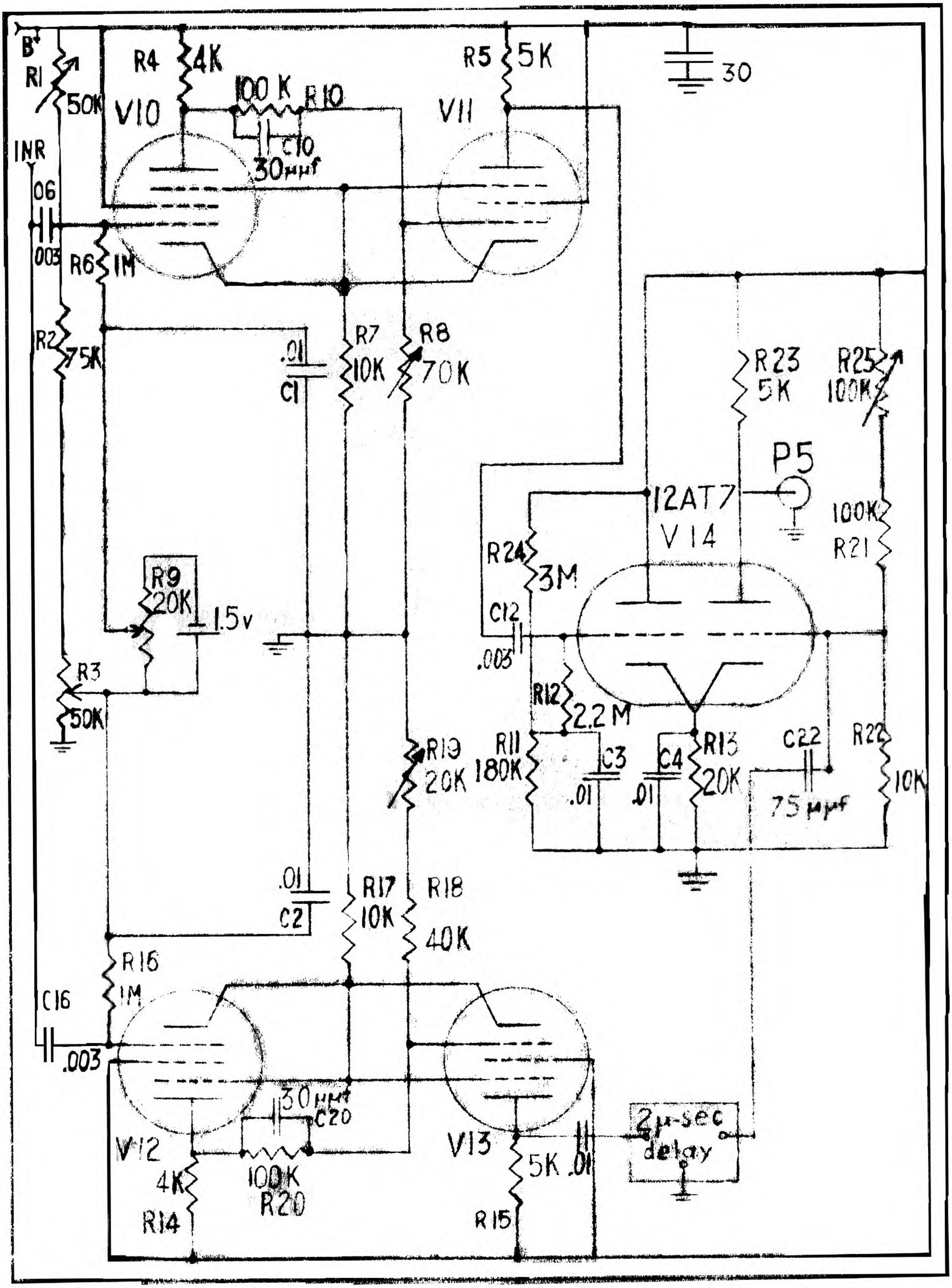
Pulse into P.H.S.
0
D-I output
+270
+240
Anti-coincidence
blocking grid
+31
0
D-II output
E.M.F. (volts)
+270
+240
Anti-coincidence
firing grid
+30
0
Anti-coincidence
cathode *.
+33
0
Anti-coincidence
output
+268
240 μ-sec
+250
2 μ-sec
2 μ-sec
Time (μ-seconds)
A
B

EXPLANATION OF PLATE II

Schematic of the pulse height selector

V 10 and V 11 are D-I, V 12 and V 13 are D-II and V 14 is the anti-coincidence tube

PLATE II


B+
R1
50K
R4
4K
100 K
R10
C10
30μμf
V10
R5
5K
V11
30
INR
06
.003
R6
1M
R2
75K
.01
C1
R7
10K
R8
70K
R23
5K
R25
100K
P5
12AT7
V 14
100K
R21
R24
3M
C12
.003
R9
20K
1.5v
R3
50K
R12
2.2M
R11
180K
C3
.01
C4
.01
R13
20K
C22
75 μμf
R22
10K
R19
20K
.01
C2
R17
10K
R18
40K
R16
1M
C16
.003
30μμf
C20
V12
4K
R14
100K
R20
V13
5K
.01
R15
2μ-sec
delay

THE PULSE HEIGHT SELECTOR

The pulse height selector (Plate I) was developed to produce an output signal each time the voltage height of a pulse at the input lay within a set voltage interval (the channel). The random time distribution of pulses usually observed and the finite duration of each single pulse prevent exact performance of this function. Nearly simultaneous pulses add in size creating a false pulse height. The usual procedure is to shape the pulses into as short a duration as is possible without affecting the amplitudes and to render the pulse height selector inoperative for a time after each pulse such that it is closed to any pulse following the first by less than this time.

The pulse height selector was constructed on the same chassis as the main amplifier. The channel was formed by two Schmitt triggers used as voltage amplitude discriminators and biased apart by the voltage called the "channel width". The Schmitt trigger circuit is bistable. Its two stable modes of operation are determined by the potential of the input grid. The pairs of vacuum tubes, D-I, D-II and D-III (Plate II), with their associated circuits are Schmitt trigger circuits. Excellent descriptions of their operation are given by Higginbotham, Gallagher and Sands (13) and Elmore and Sands (11). The essential characteristics of the Schmitt trigger are good stability, high sensitivity and fast response to changes of the input grid voltage about the triggering point. Once triggered from its quiescent state, the discriminator returns to its normal mode at an input grid voltage about three volts lower than the triggering voltage. Thus a plot of output versus input voltage for cyclic operation results in a curve enclosing an area. This effect is termed "hysteresis", and determines three volts as the smallest pulse height for which the circuit is useful. However, in the present application, the usefulness was limited by the size of the largest pulse which the amplifier produced. The input grid of the Schmitt trigger will draw current if raised more than one hundred volts above its trigger point. When pulses occurred of one hundred eighty volts, as was the case, the input condenser charged through the grid with a time constant of a few micro-seconds. On cessation of grid current, the input time constant became its normal 300 micro-seconds. Thus the circuit became unreliable when operated to select pulses less than ten volts high.

The circuits D-I and D-II were arranged so that the triggering point was 70 volts. The d-c level of the input grid of D-II (E_{gf}) was controlled directly by R3 (see Plate II). The channel width voltage was provided by batteries and controlled by R9 so that the d-c level of D-I (E_{gb}) was less than E_{gf} by the channel width. Thus a pulse in the channel was one such that, when its voltage was added to E_{gb}, the sum was less than 70 volts, and when added to E_{gf}, the sum was greater than 70 volts. A pulse lying in the channel fired D-II. A pulse higher than the channel fired both D-I and D-II. D-I and D-II were identical for d-c conditions. During a change; i.e., at high frequencies, D-II had a much lower output plate impedance since it worked into a two micro-second delay line of 1500 ohms characteristic impedance. Thus a smaller pulse was produced than at the output of D-I.

The output of D-I was coupled directly to the "blocking" grid of V14, and the output of D-II was coupled through a two micro-second delay line to the "firing" grid of V14. Typical waveforms are shown in Plate I. A pulse of height less than the channel setting affected nothing. A pulse lying in the channel triggered D-II, and a positive pulse arrived at the anti-coincidence firing grid two micro-seconds later. The d-c level of this grid lay just above cut-off so that a negative pulse appeared at the anti-coincidence output. A pulse of greater height than the channel setting triggered D-II and then D-I. As D-I fired, a positive pulse about 25 volts high appeared at the blocking grid. The anti-coincidence circuit acted as a cathode follower, cutting off the firing section of V14 by more than 20 volts and charging C4 before the delayed pulse from D-II reached the firing grid. At the end of the pulse from D-I, the blocking grid returned to its normal d-c level, but C4, unable to discharge rapidly, left the firing section cut off for 240 micro-seconds longer. This cut-off time was controlled by the value of C4. The anti-coincidence circuit was left blocked for this comparatively long time in order to prevent counting of pulses occuring close behind large pulses that caused blocking and subsequent shut off of the amplifier.

THE HIGH VOLTAGE SUPPLY

The high voltage supply (Plate V) was a regulated 5 kilo-volt R. F. power supply. The regulator consisted of two cascaded difference amplifiers utilizing degenerative feedback from the high voltage output. Coupling the VR105 to the regulated source as is done when possible was avoided since it would have constituted a regenerative feedback loop. Therefore the reference voltage was dependent on the unregulated source. Characteristics for the average VR tube are given in Elmore and Sands (11).

In the regulator itself were three separate feedback loops and one compensating coupling. There were, in addition to high voltage output feedback, the plate-to-grid feedback in the current tubes necessitated by the coupling of the final difference amplifier plate load R11 (Plate VI) to the unregulated supply, and the coupling through R12 and R14 of the regulated oscillator plate voltage to the reference grid of the final difference amplifier. The first of these was regenerative and compensation for this feedback and for that due to the variations in VR tube current was provided by feeding a proper portion of the unregulated source voltage to the reference grid of the difference amplifier. The second was necessitated by need of a d-c voltage at the reference grid from such a source that the aforementioned compensation could be applied. Another regulated source would not have sufficed. At the same time this feedback was degenerative, speeding the compensating action of the regulator and increasing the apparent power supply internal resistance. This last property is not of great importance since the maximum average current in a proportional tube is of the order of tenths of microamperes allowing the high voltage source to have as much as one megohm internal resistance. In this supply, the impedance for pulses was made lower than the d-c resistance by switching a .015 microfarad condenser across the output terminals after having allowed it to charge in series with a ten megohm resistor. For pulses of a millisecond duration, the impedance is effectively that of the condenser alone.

Two measures of ability to compensate for variations in supply mains voltages are commonly used in comparing power supplies. The stabilization ratio "S_o" is defined by:

$$S_o = \frac{\Delta E_i/E_i}{\Delta E_o/E_o}$$

where E_o is the voltage at the output terminals and E_i is the supply mains voltage. The smoothing factor "α_o" is defined by:

$$\alpha_o = \frac{\Delta E_o}{\Delta E_i}$$

and is chiefly a measure of ripple attenuation.

The calculated values of these quantities are approximately as follows

$$\alpha_o \cong \frac{1}{\mu \beta_o G}$$

$$S_o \cong \frac{E_o}{E_i} \mu \beta_o G$$

where μ is the amplification factor of the current tubes, β_o is the fedback fraction of E_o, and G is the gain of the regulator amplifier. These quantities had the measured values $\mu=1$, $\beta_o=0.0147$, $G=860$ giving

$$\alpha_o \cong 0.08$$

$$S_o \cong 750$$

The measured d-c internal resistance was

$$R_o \cong 1 \text{ megohm}$$

α_o and S_o could not be measured accurately enough to have significance, and the value for R_o is probably high since fifty microamperes variation in the power supply out-put current was required for a measurable variation in E_o.

After a two-hour warm-up period, no drift in E_o was observed. A variation in E_o could be observed only to one part in five hundred so that all that can be said is that the stability was at least as good as two tenths of one percent. The longest period of time over which this determination was reliable was four hours.

THE PROPORTIONAL COUNTER TUBE

Proportional counter tubes as reported in the literature involved the use of large glass-to-metal seals. The simplest tube required two short metal tubes with a glass tube between and a glass end seal to a tungsten center wire support. The end metal tube was then soldered to the counter end-plate and the other metal tube was used as the guard ring. Since an expert glass-worker was not easily available and demountable tubes were desired, the design shown in Plate III was used. Long tubes having windows at the center were chosen so that there would be no counting at the ends of the chamber. It was thought that special efforts to compensate for end-effect would thus be avoided. The center wire was simply stretched through the Stupakoff seals, visually centered and soldered in place.

Several waxes were tried for the glass-to-metal seals. Apiezon "W" was found lacking in mechanical strength while the Gelva 2.5[1] was softened by alcohol in the tube filling. Parlin[2], a high melting point wax was found satisfactory.

The gas fillings were of tank argon and absolute ethyl alcohol. No special purifying methods were used. Each time the tube was filled, it was first pumped down to forepump pressure, filled with the gas mixture, pumped out, left at forepump pressure for several hours, then filled and sealed.

The Amphenol 83-1SP plugs and 83-1R receptacles which are commonly used at voltages up to 2500 volts were found unsatisfactory. Breakdown occurred which, though negligible in other applications, were large enough to overload the amplifier. Frequent cleaning improved the situation but was not effective enough. Connectors were made by knocking the insulators out of the Amphenol connectors. A two inch sheath of lucite with a socket for the center wire in its base was mounted in the female chassis connector, a quarter inch of the center wire of the cable was bared, and a drop of solder placed on the

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[1] Shawinigan Products Corporation, New York.
[2] E. I. DuPont de Nemours and Company, Parlin, New Jersey.

EXPLANATION OF PLATE III

Details of tube construction. The drawing is in 1:1 scale for tube no. 2. The crosshatched portions are in 1:1 scale for both tubes. All materials are brass except where otherwise specified. All wax seals were made with Parlin wax.

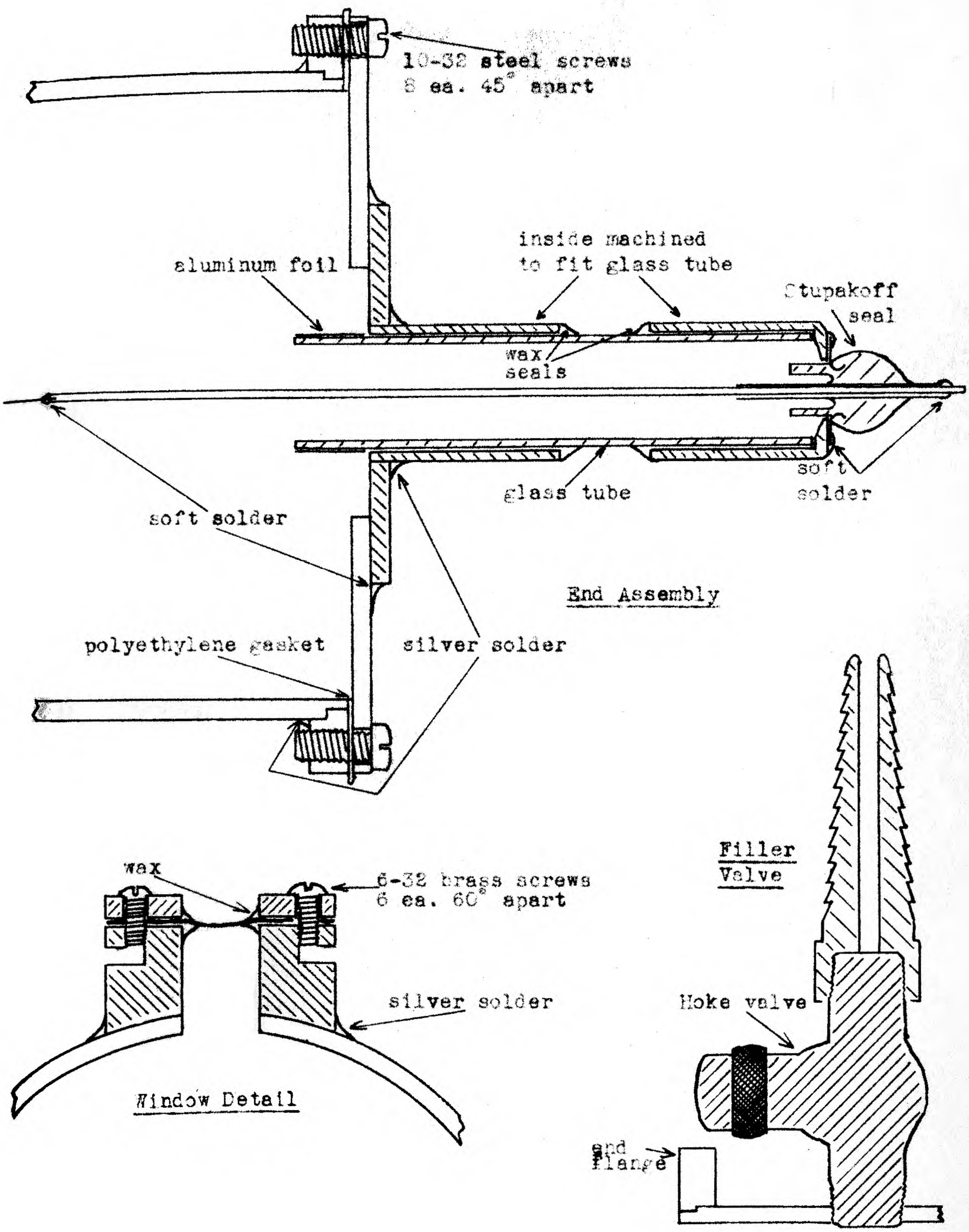
Tube dimensions are as follows:

	Tube no. 2	Tube no. 3
Inside diameter	4"	3"
Inside length	$16\frac{1}{2}$"	$9\frac{1}{2}$"
Center wire diameter	3 mil.	3 mil.
Center wire length	$12\frac{1}{2}$"	$5\frac{1}{2}$"
Window material	1 mil. aluminum	1 mil. aluminum
Window location	center	center
Support Wire	16 gauge copper	16 gauge copper

Tube no. 2 had two diametrically opposed windows.

Tube no. 3 had a single window.

PLATE III


10-32 steel screws
8 ea. 45° apart
inside machined
to fit glass tube
aluminum foil
Stupakoff
seal
wax
seals
soft solder
glass tube
soft
solder
End Assembly
polyethylene gasket
silver solder
wax
6-32 brass screws
6 ea. 60° apart
silver solder
Window Detail
Filler
Valve
Hoke valve
end
flange

end of the wire. Then the male connector was mounted on the wire, and the solder drop trimmed to fit the socket. This connector has functioned satisfactorily.

Bare wire was found unsatisfactory for voltages above about twenty-five hundred volts. Corona invisible in a darkened room was severe enough to cause large pulses. Wire with molded polyethylene insulation was used and large smooth conducting shields connected to the guard rings covered joints where insulation was broken.

It was found that the cathode radius at the end plates of the counter tube (Plate III) was so small that a nearly ionizing electric field was produced in the counter volume in spite of the glass insulators protruding into the interior of the tube between the cathode and center wire. The configuation was such that when the electrode potential was high enough for manganese K-x-rays (from radioactive K-capture in Fe^{55}) to produce measurable pulses, the breakdown at the ends was too intense to allow counting although the x-ray pulses could be observed on a cathode ray tube oscilloscope coupled to the amplifier output. Sixteen gauge copper wire supports for the center wire were installed and the insulators protruding inside the counter volume were wrapped with aluminum foil to lessen the static charge collection.

Shielding was accomplished by placing the counter tube and preamplifier inside a large metal box. A cable of seven individually shielded strands was used between the preamplifier and main amplifier. Coaxial cable was used for the high voltage lead to the cable connector mounted on the shield box and the center lead was connected directly to the guard rings. The center wire was coupled through a fifty micromicrofarad ceramic high voltage condenser to the preamplifier input and through a twenty megohm resistor to the high voltage. Grounding of the shield did not appear to affect the op-

EXPLANATION OF PLATE IV

Fig. 1. Block diagram of apparatus

Fig. 2. Diagram of fluorescent x-ray source

PLATE IV

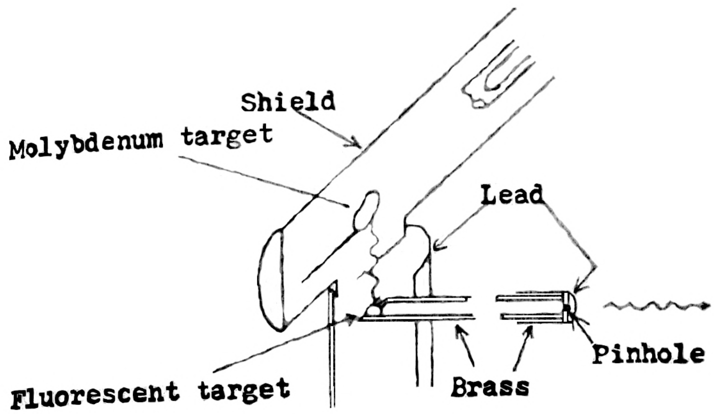


Fig. 1.

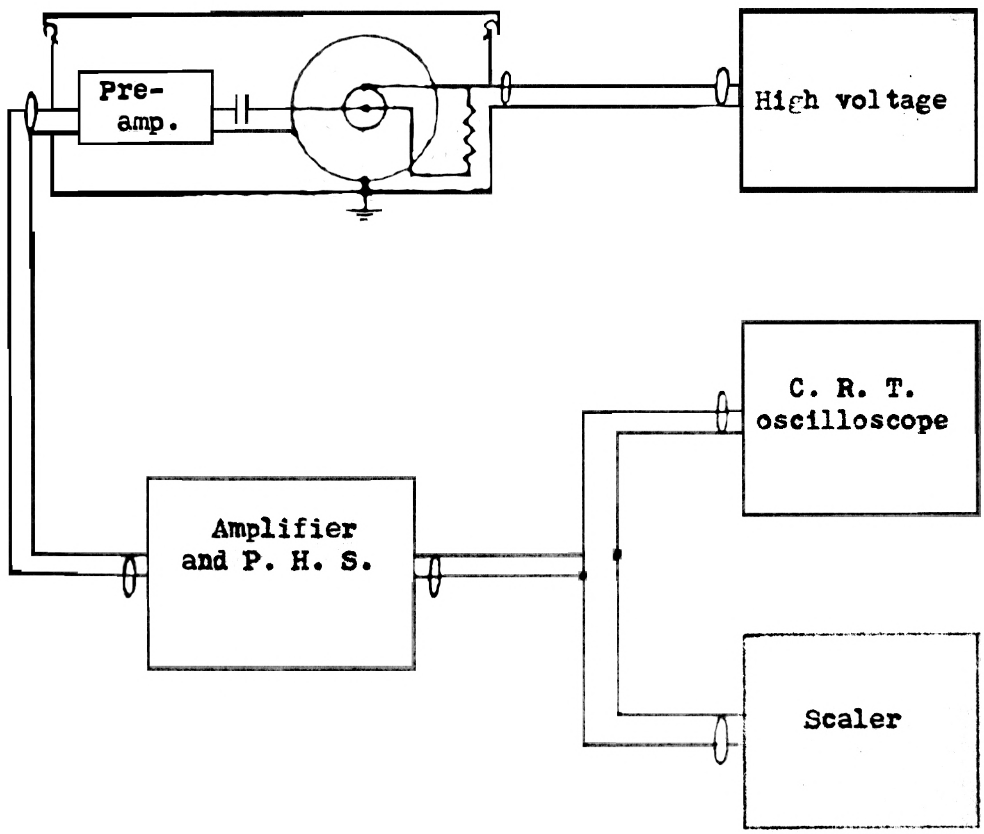


Fig. 2.

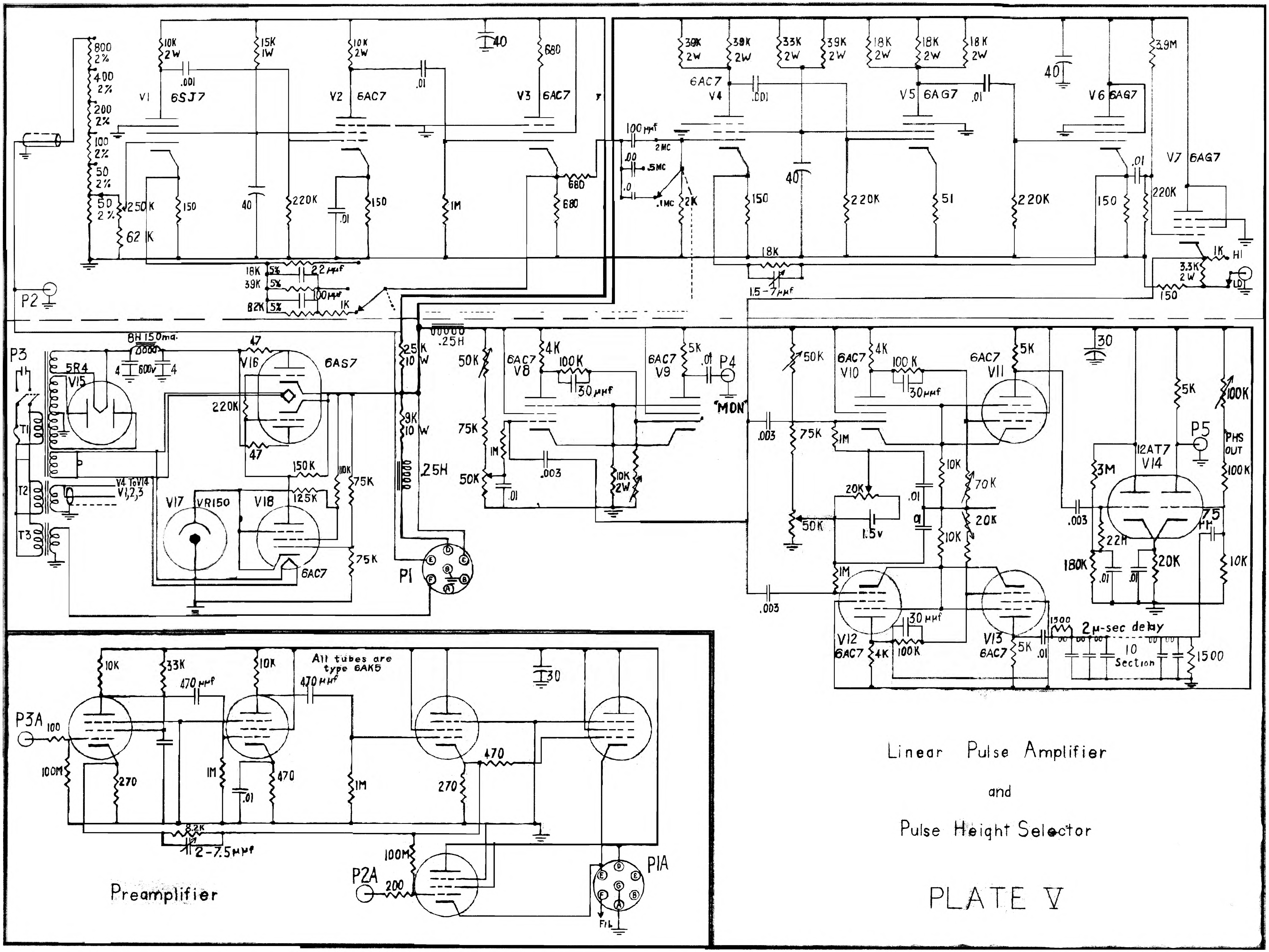
eration. A block diagram of the apparatus is shown in Fig. 1 of Plate IV.

Two sources were used in testing the tube for operation. One, the radioactive iron isotope of mass fifty five produced manganese K x-rays by K-capture process. The absorption coefficient of aluminum was high enough that only four-tenths of the intensity of the incident wavelength arrived inside the tube. Even so, peaks at 1.2 (aluminum fluorescent x-rays) and 5.9 kev would have been observed if the tube had been operating. No peaks were found at all.

The other test radiation was fluorescent x-rays from a barium acetate target placed in an x-ray beam (Fig. 2, Plate VI) and yielded two peaks, which could not be interpreted, due to malfunction of the equipment. Subsequent work was done on the electronic equipment in an attempt to correct these difficulties.

EXPLANATION OF PLATE V

Schematic of pulse amplifier and pulse height selector



Linear Pulse Amplifier

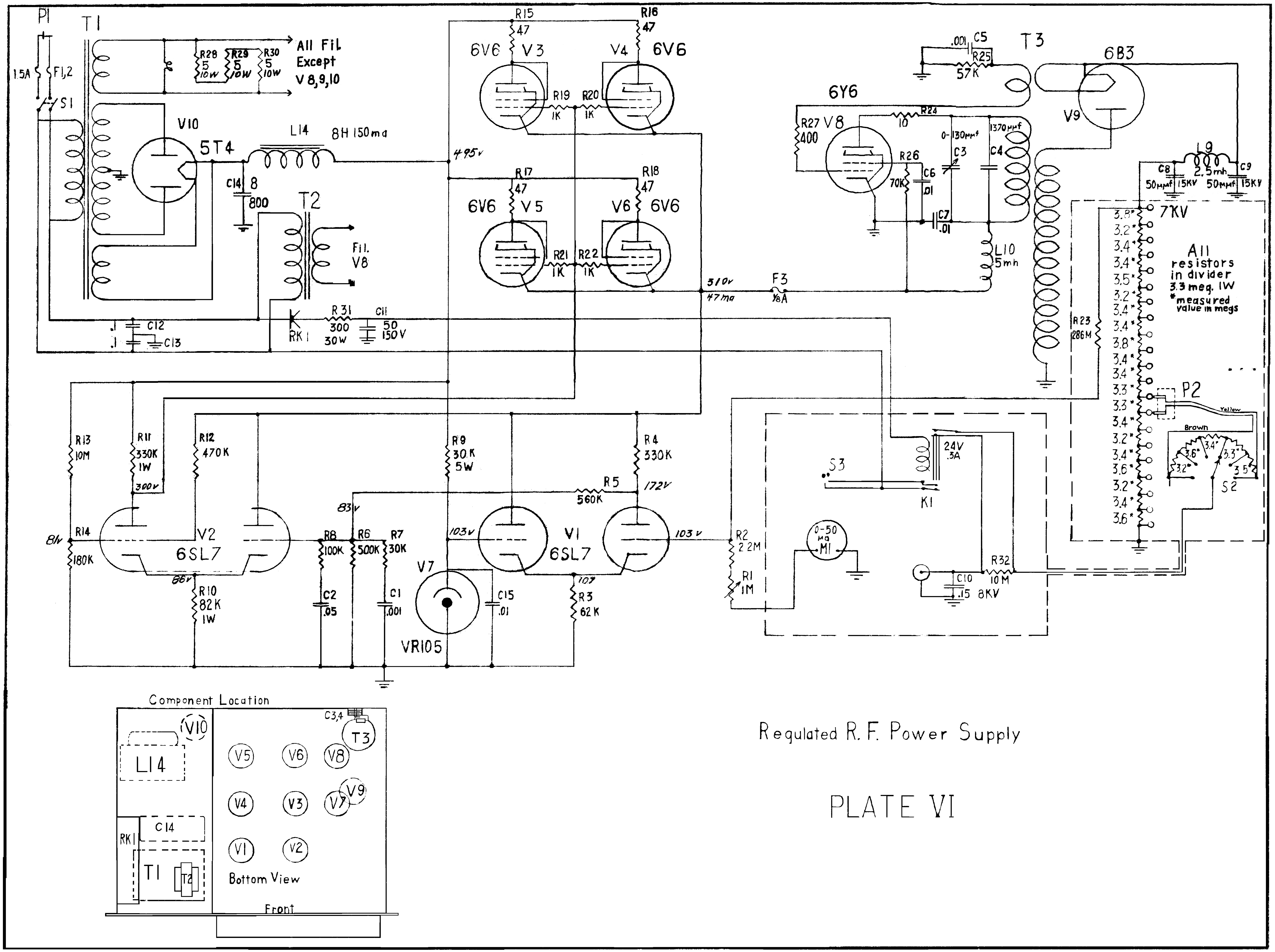
and

Pulse Height Selector

PLATE V

EXPLANATION OF PLATE VI

Schematic of high voltage power supply



Regulated R. F. Power Supply

PLATE VI

SUMMARY

Although no new information was obtained, a simple pulse height selector suitable for use with low intensity sources was developed. It has the advantage of economy over others reported. For example Elmore and Sands (11, p. 228) use seventeen tubes for a differential discriminator which will handle higher counting rates.

The performance of the amplifier was acceptable, but gains as high as those reported for the unit by its designers were not achieved.

As well as available methods could determine, the high voltage supply functioned satisfactorily.

The basic instrumentation for further investigation has been completed.

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MASTER OF SCIENCE

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OF AGRICULTURE AND APPLIED SCIENCE

1952

In the field of nuclear investigation, the proportional counter tube has displayed advantages over other types of counter spectrometers. It may be used for spectrometric investigation of gaseous radioactive sources and with sources of lower energies and weaker intensities than other spectrometers.

The counter tube is used in conjunction with a linear pulse amplifier, a pulse height selector, scaler and high voltage power supply. The amplifier is necessary since pulses of the order of a millivolt or less are produced by proportional counters, and a circuit which will accurately discriminate against all pulses but those with heights in a small voltage interval requires minimum pulse heights of at least ten volts.

The linear amplifier and pulse height selector and a high voltage supply were constructed and tested individually. As well as could be determined with available test equipment, these instruments performed acceptably. Several proportional counter tubes were constructed but when tested in conjunction with the other instruments, the equipment as a whole did not operate satisfactorily.

Some modifications were made in the amplifier and pulse height selector after the last test of the entire unit. Shortage of time prevented further tests.

It is thought that a method of triggering a cathode ray tube sweep with the counter pulse being viewed would enable some degree of isolation of the trouble.