A Triode Vacuum Tube Scale-of-Two Circuit*

HAROLD LIFSCHUTZ AND J. L. LAWSON
University of Michigan, Ann Arbor, Michigan

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A vacuum tube scale-of-two is described using triodes. Accurate high speed tests of the resolution time showed this to be 6.5×10^{-6} seconds. New methods of interpolation are also presented.

INTRODUCTION

ELECTRONIC circuits for counting the pulses from Geiger-Müller tubes and ionization chamber, linear amplifier combinations have been largely responsible for making the techniques using these instruments into practical and important methods for nuclear physics. The well-known thyratron counting circuit of Wynn-Williams[1] has been widely adopted for scaling down the rate of counting into a mechanical recorder and recently vacuum tube circuits have also been developed for this purpose. This is mainly necessary because of the large fluctuations in the intervals between pulses of a random distribution such as is obtained from radioactive substances. The shortest time intervals are the most probable so that even at low counting rates many of the pulses come too close together to be resolved by the recording circuit. To show the magnitude of this effect it may be noted that a mechanical recorder capable of counting about 5000 periodic pulses per minute will show noticeable counting losses at only 50 random counts per minute.[2] Therefore, exceptionally high speed devices are necessary for nuclear work and this is one of the main reasons for the development of the vacuum tube type of scale counter.

The thyratron type of scale-of-two circuit, while very satisfactory for much work has, nevertheless, serious limitations in speed as well as a number of other undesirable features which, for later purposes of comparison with vacuum tube counting circuits, may be briefly enumerated. The thyratron is inherently limited in speed by its deionization time and has serious limitations in stability. The minimum time constant, *RC*, which has so far been used in a thyratron scale-of-two circuit giving stable performance is about 10^{-4} sec. As pointed out by Wynn-Williams, this limits the maximum scaling ratio, by which the input counting rate may be scaled down, to about eight. For, at higher ratios, the circuit will no longer be limited by the mechanical recorder, but by the resolving time of the first scale-of-two stage. Thus, tests show that the fastest thyratron scales-of-eight are capable of recording up to approximately 3,000 random counts per minute without appreciable losses and this, then, represents about the maximum random counting speed without loss for thyratron scaling circuits. However, in these tests the circuit was probably still partly limited by the Cenco mechanical counter so that a somewhat higher limit may perhaps be taken.

If broad pulses, from an ionization chamber, for example, are to be counted by a thyratron type of scale circuit, the speed of the circuit may have to be reduced in order that the circuit does not count two pulses for each input pulse. This is due to the fact that a scale-of-two will oscillate if the potential on the control grid of the thyratron is kept above the trigger point. A broad input pulse, especially of large amplitude, may keep the potential above the trigger point long enough for the circuit to make two oscillations. Thus the circuit must be carefully adjusted to the type of input pulse being counted or a pulse sharpener may be used. Also, if the pulses arrive too close together, the circuit may jam. That is, *both* thyratrons in the scale-of-two may arc, in which case the circuit becomes inoperative. This tendency to jam also limits the minimum time constants that may be used in the scale of two. Finally, the circuit only responds to pulses of positive polarity. This reduces the flexibility of

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* A preliminary report was presented at the Chicago meeting of the American Physical Society, November, 1937.

[1] C. E. Wynn-Williams, *Reports on Progress in Physics* (1936) p. 239.

[2] H. Lifschutz, O. S. Duffendack and M. Slawsky, Phys. Rev. **51**, 1027 (1937).

the circuit, as, if negative pulses are to be counted, their polarity must be reversed in some manner.

A little consideration shows that the above difficulties might be overcome if a scaling circuit could be devised using vacuum tubes. Such circuits have been devised by W. B. Lewis,[3] by Stevenson and Getting[4] and in this laboratory.[5] The fact that Lewis had devised such a circuit was mentioned by Wynn-Williams in the *Reports on Progress in Physics* for 1936 and recently his paper has been published, although a copy has not yet arrived at our library so that we cannot compare his circuit to the others that have been developed. Stevenson and Getting's circuit uses a principle essentially the same as the one developed in this laboratory, although the circuits have been developed completely independently. Our circuit, as will be shown later is somewhat different and is simpler in that it uses triodes instead of pentodes, uses fewer tubes and is about three times as fast while having extremely good stability. Such circuits have been successfully used in this laboratory for the past five months.

Description of Circuit

It was noted that there existed in the literature two types of frequency meters used for nuclear work, one using thyratrons and one using vacuum tubes. Since the thyratron type was simply a Wynn-Williams scale-of-two, an investigation was made to see whether or not the vacuum tube type of frequency meter could be adapted for use in a scaling circuit. Such a frequency meter consisted of an ordinary multivibrator circuit. However, a multivibrator[6] cannot be made to divide by two because it is a.c. coupled. It was seen that the use of *direct* coupling made possible operation as a scale-of-two.

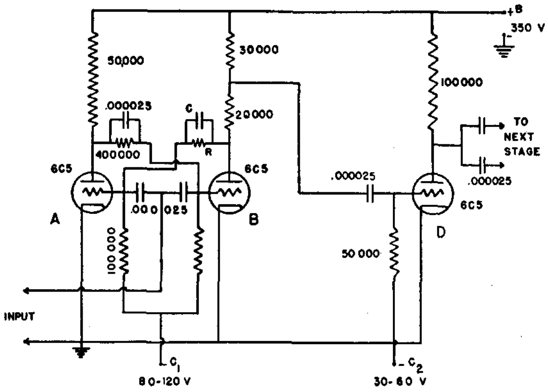

FIG. 1. Showing the scale-of-two and rectifying coupling tube to the next stage of scale-of-two. Resistance values are in ohms and capacitance in microfarads.

Referring to Fig. 1, which represents the vacuum tube scale-of-two circuit, it is seen that the scaling tubes consist of two triodes, *A* and *B*, the pulses being applied to their grids in parallel through resistance-capacity coupling. The output of tube *A* is direct coupled to tube *B* by a resistor from its plate to the grid of *B*. Likewise tube *B* is direct coupled to tube *A*. Thus, a regenerative circuit is obtained; a small pulse applied to the grid of either of the tubes is amplified by that tube and then by the second tube, from which it is fed back to the first tube as a larger pulse. This regenerative cycle goes on until one of the tubes is driven to plate current cut-off due to the negative potential of its grid, when, of course, the process stops. The circuit is then in a stable condition with one of the tubes passing plate current, as its grid potential is relatively high, while the other is nonconducting as its grid potential has cut the current off. The potential on the grid of tube *B*, for example, is equal to the plate voltage of tube *A* minus the *IR* drop in the coupling resistor, *R*, and minus the bias C_1. According to whether or not tube *A* is conducting or nonconducting, its plate voltage will be low or high respectively and, accordingly, the grid potential of *B* will be low or high respectively. This shows how the grid potential of the tubes varies during the course of the regenerative cycle. It is important to note that the circuit remains in the equilibrium condition solely because *direct* coupling is used. Let us assume, then, that tube *A* is conducting and tube *B*, nonconducting. If a pulse is now applied to the input, it will be amplified by tube *A* if a negative pulse and by tube *B* if a positive pulse. The regenerative cycle then takes place as just described until the plate current of tube *A* is cut off.

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[3] W. B. Lewis, Proc. Camb. Phil. Soc. **33**, 549 (1937).

[4] E. C. Stevenson and I. A. Getting, R. S. I. **8**, 414 (1937).

[5] H. Lifschutz and J. L. Lawson, Bull. Am. Phys. Soc. November 11, 1937. Also a brief account in a paper by Duffendack, Lifschutz and Slawsky, Phys. Rev. **52**, 1231 (1937).

[6] See, e.g., F. E. Terman, *Radio Engineering,* first edition, p. 273.

Tube B is now, of course, conducting. It is clear, therefore, that the circuit is only stable for the condition in which the tubes are at opposite ends of their $I_p - E_g$ characteristics, and, therefore, jamming is impossible. Due to the direct coupled regeneration, an incoming pulse causes an extremely rapid phase reversal of the tubes, or tripping of the circuit from one equilibrium state to another. As was seen, this tripping occurs independently of the polarity of the input pulse. The direct coupling causes the circuit to have *two* equilibrium states. It is this property that makes possible an electrical division by two. For, according to whether tube B, for example, is in the conducting or nonconducting state, its plate potential will be respectively low or high due to the IR drop in its plate resistor. Its plate potential, therefore, rises and falls as the circuit is tripped by the input pulses, an increase or decrease of plate potential occurring on *alternate* pulses. By transmitting these plate potential changes to a circuit which responds only to the positive changes, an electrical division by two is accomplished. Such a circuit may be a thyratron tube used to operate a mechanical counter. Or, as shown in the diagram, these pulses are fed to another triode by RC coupling. This triode is biased past cut-off so that it passes only every other pulse to the next scale of two. This process may be repeated using N successive stages of scale of two to obtain any scaling ratio, 2^N, desired.

Referring to Fig. 1, it will be noted that the coupling resistors, R, are by-passed by condensers, C. These condensers prevent any tendency of the circuit to remain always in one of the two equilibrium states due to any asymmetry which may be present, which causes one of the states to be more stable than the other. As the potential across these condensers cannot change instantaneously, the rapid plate potential changes are transmitted to the grids of the tubes through these condensers rather than through the large coupling resistors. By this means, strong coupling is achieved which forces the circuit to trip even though it may have a preference for one of the two equilibrium states. The coupling resistors, R, drop the voltage from the plate supply so that this high positive potential is kept off the grids of the tubes and proper biasing can be achieved with ordinary values of grid bias supply, C_1. If negative pulses are applied to the input, a larger negative grid bias C_1, makes the circuit respond to smaller input pulses and similarly if positive pulses are applied, a smaller value of grid bias will allow response to weaker input pulses.

As this circuit cannot oscillate, there is no danger of a possibility of getting two or more output pulses for each input pulse in the same manner in which this may occur with a thyratron scale of two. However, a broad pulse having both a steep rise and a steep fall might cause two counts to be registered since the circuit will respond to pulses of both positive and negative polarity. This would occur if the circuit completed the regenerative cycle initiated by the steep rise of the input pulse in time to respond to the pulse of opposite polarity due to the steep fall. However, it is not difficult to avoid this possibility as the time constants in the circuit of the coupling triodes, D, and the grid circuit of the scaling tubes may be made so small as to assure very narrow pulses.

Broad input pulses must be of quite large amplitude to trip the circuit as most of the signal is lost across the exceedingly small coupling condensers. This difficulty does not exist for sharp pulses such as are obtained with Geiger-Müller counters, sweep circuit oscillators, or a small condenser discharging through a resistor. In general, the high frequencies present in any pulse having a steep wave front will make it possible for a relatively weak input pulse to be transmitted through the coupling condensers and trip the circuit. In order to use the circuit for counting the relatively broad pulses from ionization chamber, linear amplifier combinations, it is necessary to use either a pulse sharpener or a counting circuit with larger coupling condensers. In either case the circuit is slowed down somewhat. Getting[7] has used a thyratron two-pulse oscillator to obtain sharp pulses for testing the resolution time of recording circuits. A single thyratron with a self-stopping arrangement as given by Dunning[8] may be used as a pulse sharpener, as the discharge pulse from a thyratron has a steep wave front. In order to make the speed of the thyratron circuit as great as possible,

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[7] I. A. Getting, R. S. I. 8, 412 (1937).

[8] J. R. Dunning, R. S. I. 5, 387 (1934).

a quenching condenser should not be used, the capacity of the tube and leads serving this purpose. A large plate resistor and high values of negative grid bias are necessary. Such a circuit does not give oscillations even for very broad input pulses which keep the grid potential above the trigger point for relatively long periods. This is true even when the thryatron circuit is made slow enough to operate a Cenco mechanical counter, the usual application of this circuit. According to the above, it is, therefore, advisable to construct the input to the scaling circuit so that a toggle switch allows application of the input pulses either directly to the scaling circuit or to a thyratron pulse sharpener and thence to the scaling circuit. Thus, either type of input can be used according to whether or not G-M pulses or ionization chamber pulses are being counted.

METHODS OF INTERPOLATION

Two new methods of interpolation have been devised. If the number of counts during a run is not an exact multiple of the scaling ratio, the difference between the actual number and the reading of the mechanical recorder is obtained by some method of interpolation. The first method, which we will call the meter method, passes the plate current from one of the tubes in each scale of two through a common milliameter. The plate current of the first scale of two is adjusted to be one unit, that of the second stage two units, the third four units, and so on according to the scheme 2^N. At the beginning of a run, the meter reading is zero as all the tubes feeding the meter are put in the nonconducting equilibrium state by a reset, in this case simply a switch in the cathode leads to these tubes by which the plate current may be broken for an instant. After the first input pulse, the meter tube in the first scale of two becomes conducting and as it draws a plate current of one unit, the meter reads one. Similarly, for the second pulse the meter tube in the second scale of two becomes conducting while the first meter tube goes back to the nonconducting state. As the second tube draws a current of two units, the meter shows two pulses have been counted. Similarly, as successive pulses come in the meter reading goes up in uniform steps and then falls back to zero when a number of counts equal to the scaling ratio has been reached.

The meter may be made direct reading by adjusting the current unit to be equal to one unit on the meter, the main adjustment being made by proper choice of the plate resistors. For large ratio scale counters, it may be preferable to run the meter from separate indicator triodes *direct* coupled to the respective tubes in the scale-of-two stages. This, therefore, allows free choice of the plate resistors and plate voltage for the scale of two tubes, this choice then being fixed solely by the time constants desired. However, the use of separate indicator triodes is usually not necessary, being mostly a matter of individual preference, so that interpolation may be accomplished with the sole addition of a meter to the counting circuit. If desired, the meter may be shorted out of the circuit during a run by a toggle switch.

The second interpolation method uses an electron ray tube, such as the 6E5, direct coupled to the scale of two stage. According to whether or not the "eye" of the tube is open or closed, the number N assigned to that scale of two is or is not to be added to the reading of the mechanical recorder. The electron ray tube is, of course, extremely fast and does not react back on the scaling circuit.

PERFORMANCE OF THE CIRCUIT

Scales of two, four, eight, and sixteen have been built. The exact circuit details may vary according to the size of outfit being built. All have been found to be very stable and relatively easy to adjust for successful operation.

In order to test the speed of the circuit, periodic pulses were used as it is difficult to test such a high speed circuit with random pulses. An accurately calibrated low frequency oscillator and a radiofrequency oscillator calibrated with a precision of one-half of one percent were used to supply input pulses to a scale of sixteen. The output of the scale of sixteen was fed to a cathode-ray oscillograph. For each input counting rate, the output counting rate was determined by the aid of an accurately calibrated sweep circuit. It was found that the input counting rate was scaled down exactly by a factor of sixteen for *all* input counting rates up to 155,000 per sec. or 9,300,000 per minute. Above this rate skipping occurred as was evidenced by a ratio greater than sixteen being found. The skipping depends on the phase relations between the input pulses and the regenerative cycle in the first scale of two, so that every *n*th pulse may be missed. The observed scaling ratio increased as the input counting rate was increased beyond the above maximum, showing that the skpping increased as expected. The skipping was a stable phenomenon as the pulse pattern on the cathode-ray oscillograph remained stationary and the abnormal scaling ratios were reproducible. Below 155,000 pulses per sec. no skipping or electrical resonance effects were found as a scaling ratio of sixteen was observed through a *continuous* change in input frequency all the way up to this limit. The continuous change in output frequency was followed with the sweep circuit. As expected, it was found that the circuit could be forced to follow higher frequencies by increasing the input amplitude. Therefore, the resolution time is to some extent dependent on the amplitude of input pulse. Ordinary values of pulse amplitude are sufficient to obtain the resolution time given above.

The resolution time of the scale-of-two shown in Fig. 1 may accordingly be taken as 6.5×10^{-6} sec. Applying the simple correction formula given by Skinner[9] and emphasized by Ruark and Brammer[10] the maximum *random* counting rate N_{max} may be shown to be equal to $1/\tau$, where τ is the resolution time. Therefore, N_{max} equals 155,000 random counts per sec. Of more importance, however, is the maximum *random* counting speed with negligible loss, say of one percent. Applying the same formula we obtain 1550 pulses per second or 93,000 per minute which may be compared to the 3000 per minute obtainable with thyratron scale counters. The counting loss theory in this case is probably not entirely valid as some pulses are counted even when separated by less than 6.5×10^{-6} sec. The question might also be raised as to whether or not the Volz[11]-Schiff[12] equation $N_{\text{max}}=1/e\tau$ should be applied rather than the equation $N_{\text{max}}=1/\tau$. The point at issue is whether or not the scale-of-two goes through its regenerative cycle independently of the input signal. This mode of operation is certainly true to a large degree, as can be seen from the previous description of the operation of the circuit. Therefore, the first counting loss equation has been adopted rather than the Volz-Schiff formula. It is important to note, however, that the maximum random rate of counting without appreciable counting losses is the same on both theories.

According to the above, the speed of the circuit is so great that the scaling ratio it is advantageous to use is only limited by the cost and size of the outfit. It is often a distinct practical advantage to use a large scaling ratio, also, because the total number of counts that can be recorded without the Cenco counter repeating its reading is increased.

In Fig. 2 is given the complete circuit diagram for a scale of sixteen. A few explanatory remarks will be in order. The triodes are of the metal shell, self-shielding type. Two input sections are used, appearing as the first four tubes in the diagram. By means of the toggle switch, the pulses may be fed directly into a discriminator circuit very similar to that used by Wynn-Williams (the third and fourth tubes), or to an 885 thyratron pulse sharpener stage (the first and second tubes) and thence into the discriminator. Thus, a negative input pulse is required in order to get through the discriminator. The negative grid bias on the pulse sharpener is 250 volts. At the top of the diagram are four indicator triodes for running the interpolation meter. The meter portions of the plate currents of these tubes are adjusted to have values of 1/15, 2/15, 4/15 and 8/15 ma, so that a one ma meter having a 0–15 scale is used and is direct reading. These current values are kept constant by stabilizing the voltage across the plate resistors by means of two watt neon glow lamps with the resistors removed from the bases. Other size lamps would probably be suitable also. In order to adjust the current through the neon lamps to the proper value of about two ma necessary in order that they may stabilize, the bias on the indicator tubes is controlled by potentiometers as shown. The direct coupling of the indicator tubes to the scales-of-two is also made through these poten-

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[9] S. M. Skinner, Phys. Rev. **48**, 438 (1935).

[10] A. E. Ruark and F. E. Brammer, Phys. Rev. **52**, 322 (1937).

[11] H. Volz, Zeits. f. Physik **93**, 539 (1935).

[12] L. I. Schiff, Phys. Rev. **50**, 88 (1936).

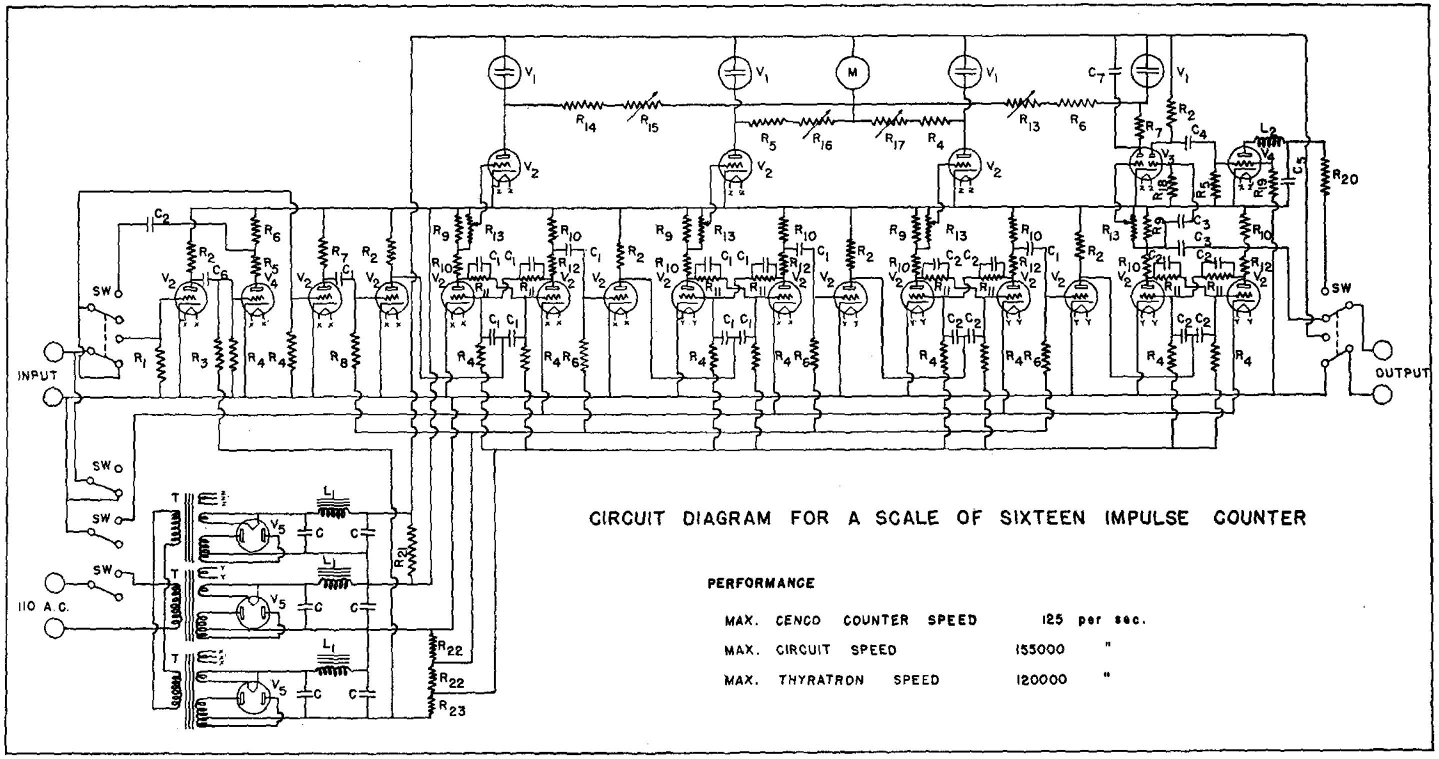

FIG. 2. Table of values.

R_1 = 1,000,000 ohms, 1 watt
R_2 = 100,000, 2 watt
R_3 = 250,000 2 watt
R_4 = 100,000 1 watt
R_5 = 200,000 1 watt
R_6 = 50,000 1 watt
R_7 = 50,000 2 watt
R_8 = 20,000 1 watt
R_9 = 25,000 2 watt
R_{10} = 30,000 2 watt
R_{11} = 400,000 1 watt
R_{12} = 20,000 2 watt
R_{13} = 100,000 potentiometer
R_{14} = 500,000 1 watt
R_{15} = 1,000,000 pot.
R_{16} = 500,000 pot.
R_{17} = 250,000 pot.
R_{18} = 500,000 1 watt
R_{19} = 300,000 1 watt
R_{20} = 7500 10 watt w.w.
R_{21} = 25,000 10 watt w.w.
R_{22} = 2500 10 watt w.w.
R_{23} = 15,000 10 watt w.w.
C = 8–8 μf dry electrolytic
C_1 = 0.000025 μf 600 v mica
C_2 = 0.00005 μf 600 v mica
C_3 = 0.0001 μf 600 v mica
C_4 = 0.0002 μf 600 v mica
C_5 = 0.1 paper
C_6 = 0.5 paper
C_7 = 1.0 paper
L_1 = 50 henry, 60 ma choke
L_2 = 8 mh r.f. choke
V_1 = neon 115 v 2 watt glow lamps with resistors removed
V_2 = type 6C5
V_3 = type 6N7
V_4 = type 885 thyratron
V_5 = type 80

T = 700 volt c.t. power transformers rated at 60 ma and having 2.5, 5.0, and 6.3 v filament windings
SW are toggle switches.
M is a Weston model 301 meter having a full scale deflection of one milliampere but having a 0–15 scale.

The help of Mr. A. W. Tyler in the construction of the scale-of-16 is greatly appreciated.

tiometers. It should be noted that a bias is obtainable for the indicator tube, even when the scaling tube to which it is coupled is nonconducting, because of the current through the plate, coupling, and grid resistors in the scale of two section. It will also be noted that the potential of the cathode of the indicator triodes and output tube is about 350 volts above ground. This is because the power supplies are connected in series, rather than in parallel, an alternative method of construction. The series method is perhaps a little simpler and does not require any grid bias supply to the indicator triodes. The one microfarad damping condenser shown in the last indicator section protects the interpolation meter when the needle falls back to zero by slowing the rate of fall. A self-stopping 885 thyratron stage[8] has been adopted for operating the Cenco mechanical recorder. It is believed that this is the simplest and most reliable method for this purpose. Three power supplies are used. This is the simplest and best practice for an outfit of this size. One power supply provides plate voltage for the indicator and output tubes, another for all the scaling tubes, and the third supplies all the grid biases. Thus, interaction is reduced to a minimum. The power transformers and filter chokes are rated at 60 ma. The filter condensers are 8–8 microfarad dry electrolytics. The circuit condensers are 600 volt mica and practically all the resistors are type B I.R.C. moulded resistors of the one or two watt size, as needed. A start and stop switch by which the input may be shorted to ground is provided at the input end, and also the cathode lead reset switch is shown. The entire outfit is mounted on a commercial 11″×17″×3″ steel sub-panel. The cost complete as shown in Fig. 2 is approximately $55.00 including a Weston model 301 milliameter for interpolation, but not including the Cenco counter. It is clear that the vacuum tube type of scaling circuit has advantages of size, cost and power required.

CONCLUSION

Several modifications of the circuit details which may be useful for some purposes, present themselves. Twin triode tubes may be used for the scales of two and also for coupling and interpolation. Such circuits have been tested and found practical, although single triodes through out reduce interaction and no doubt represent the best practice. A brief attempt has been made to adapt 6E5 electron ray tubes to the scaling circuit. These would obviously be self-interpolating. However, no success has so far been obtained with this modification.

The use of the present circuit as a frequency meter of very great speed also seems promising. The design would be very similar to the well-known thyratron type due to Hunt.[13]

The resolution time of the scaling circuit is about equal to the resolution time of the Geiger-Müller tube itself. However, the circuits used for quenching and coupling the G-M tube to the recording circuit do not make full use of the resolving time of the tube, even when Neher-Harper[14] coupling is used. Thus, further progress lies in the direction of increasing the speed of such coupling devices. The limit of this whole method is reached when the number of counts per minute or intensity is so large that ordinary ionization methods of detection are preferable and for some purposes this limit may be very low. Also, at very high counting rates the frequency meter method may be preferable, as this avoids the use of high ratio scaling circuits.

In conclusion, we wish to express our indebtedness to Mr. A. W. Tyler for help in the development of the scale of sixteen. Finally, support from the Horace H. Rackham Endowment Fund, which made this work possible, is gratefully acknowledged.

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[13] F. V. Hunt, R. S. I. **6**, 43 (1935).

[14] H. V. Neher and W. W. Harper, Phys. Rev. **49**, 940 (1936).