A "SCALE-OF-TWO" HIGH-SPEED COUNTER USING HARD VACUUM TRIODES

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In experiments on radioactive and artificial nuclear disintegration it is often necessary to count particles which may be arriving at a very high rate. By means of an ionization chamber and amplifier or by a discharge device the arrival of a particle may be made to produce an electrical impulse of short duration. Various schemes for recording or counting these amplified electrical impulses at high speed have been described. One of the most satisfactory devices for this purpose is the "scale-of-two" thyratron counter originated by Wynn-Williams*, which is satisfactory for counting impulses arriving at a rate of from only one in a few minutes up to two or three thousand a minute.

This thyratron counter is remarkably free from delicate adjustments, but experience shows that thyratrons cannot be relied on to the same extent as hard vacuum valves. From constant use it became evident that it was necessary to check the operation of the counter at frequent intervals. A fault might develop due to a thyratron changing its characteristics as it neared the end of its useful life, or due to a sudden draught. Some specific faults have been discussed in a previous paper†. While this counter is in general very reliable the need was felt for a counter which needed less supervision. It is believed that the valve scale-of-two counter to be described in this paper represents a step towards this ideal. Further, if it is required, the valve counter may be adapted to count at very much higher rates than the thyratron counter, which is necessarily restricted by the time required for extinguishing the arc in a thyratron. While it seems most important to emphasize the greater reliability and speed of the valve counter, it may also be noted that the price of the valves is in this country only a fraction of that of the thyratrons.

Mode of operation

It may be recalled that the principle of the scale-of-two counter is that successive stages each divide the counting rate by two. The second stage is operated by every second impulse, the third stage by every fourth impulse, the

* Wynn-Williams, *Proc. Roy. Soc.* A, 136 (1932), 312.

† Lewis, *Proc. Camb. Phil. Soc.* 30 (1934), 543.

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mechanical recording meter or a fourth stage is then operated by every eighth impulse.

A unit which passes on one impulse for every two it receives is thus seen to be the essential feature of a scale-of-two counter. The circuit which forms this unit in the valve counter to be described is shown in Fig. 1.

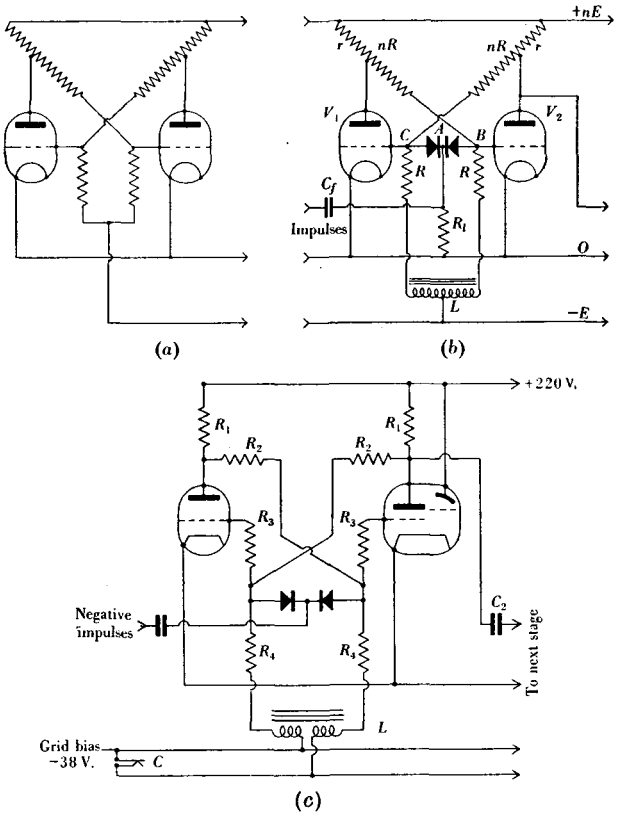


Fig. 1.

On consideration it will be seen that the circuit of Fig. 1 (*a*) has two stable conditions. The balanced condition in which the currents are equal in the two symmetrical halves of the circuit may be seen to be unstable, for if from this state the anode current of one valve is slightly increased its anode potential will fall. This will reduce the grid potential of the other valve, decreasing its anode current and hence increasing its anode potential. This in turn increases the grid potential of the first valve, further increasing its anode current. So the process will continue until the anode current of the second valve is reduced to zero.

A condition in which only one valve passes anode current is thus seen to be stable. Moreover, since the circuit is symmetrical there are two such stable conditions.

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This circuit and its properties have been known for many years*, but in order that it may be used in a scale-of-two counter, it is necessary to provide some simple means of triggering the circuit, that is to say changing from one stable state to the other. This is accomplished by the circuit of Fig. 1 (*b*). Impulses of negative potential are applied at the point A. If in the initial stable state V_2 is passing no anode current, A is almost at the same potential as C, and is positive with respect to B. The rectifier AB will therefore be in a non-conducting state, and very little of a negative impulse at A is passed on to B, whereas a large proportion of the impulse will be passed on to C through the rectifier AC across which there was initially a negligible potential difference. The negative impulse thus reaching the grid C causes the anode current of V_1 to fall; the potential of B therefore rises, and, if the impulse is sufficiently large, B will reach the potential of C. In this state the currents in the two symmetrical halves of the circuit are equal. It has been seen that this condition is unstable, and from it the system may pass to either of its stable states, but the inductance L is included to continue the change of relative potential of B and C, so that the stable state which results is not that from which the system started. Since the circuit is quite symmetrical successive impulses drive the system alternately from one stable state to the other.

A counter comprising three of these scale-of-two units followed by an output stage operating a mechanical recording meter has been found most generally useful.

Circuit details of practical counters

The basic circuit may be modified to meet special requirements. For example, it is usually necessary to have some means of ascertaining which valve of the pair is passing anode current. This may be done simply and cheaply by including in the anode circuits uncalibrated milliammeters of the type sold for visual tuning indicators in wireless sets. If this course is adopted the most suitable valves, paying due regard to price, would be 2 V. battery valves of the L type ($\mu = 15$, $R_a = 10{,}000$ ohms). It may be noted that it is quite satisfactory to heat the filaments of such valves with A.C. A rather more attractive scheme is to replace one of the valves in each pair by a cathode-ray (electron eye) tuning indicator, the circuit of a unit including these is shown in Fig 1 *c*. If these are adopted the triode must be of the H type ($\mu = 25$–90). A.C. filament heating cannot satisfactorily be used for battery valves of this type owing to the variation of the characteristics over the A.C. cycle. These valves must therefore be of the indirectly heated cathode type, if A.C. is used for filament heating.

For convenience three complete specifications are given below Fig. 2, for counters meeting certain requirements. One or more counters of each of these specifications have been in satisfactory operation for some months.

* For a recent bibliography see A. T. Starr, *Wireless engineer*, 12 (1935), 601.

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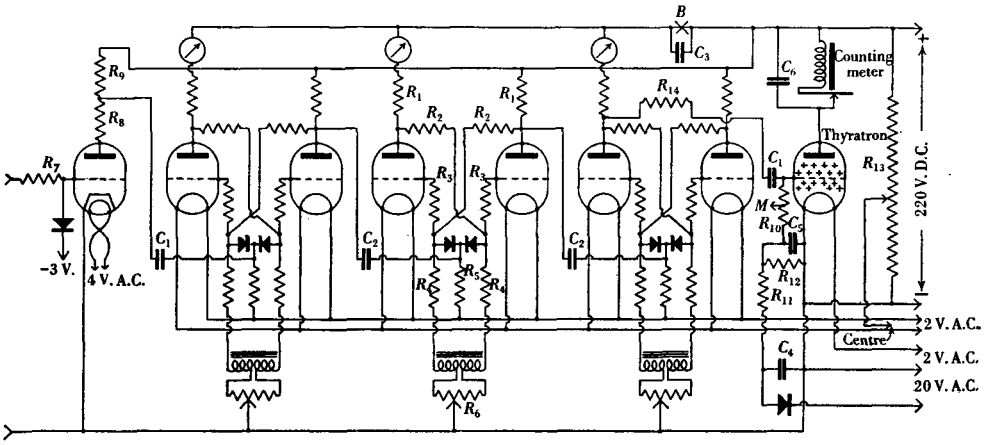


Fig. 2. Thyratron output circuit. R_{10} = two 50,000 ohms in series. $R_{11} = R_{12} = 10{,}000$ ohms. $R_{14} = 50{,}000$ ohms. $C_4 = 10\mu$F., 50 V. electrolytic. $C_5 = 25\mu$F. 25 V. electrolytic. $C_6 = 1\mu$F. with 100 ohms series resistance. Thyratron, Mazda B.T. 8 (or similar). Counting meter, Standard Telephones, Type 4007J (300 ohms) with 500 ohms extra series resistance, also modified by stiffening the springs and fitting a spring instead of gravity hold on the ratchet and also a break contact. (As an alternative the Siemens meter (2300 ohms) similarly modified may be used, but these are not constructed to stand long use.) Grid bias rectifier, Westinghouse type H 10 (or special).

Specifications 1 *and* 2. Discriminator valve, Osram MH41. Other valves Mazda L2 (or Hivac L210). Westectors W6 (or WM26) (W6 also used before the discriminator valve). Visual tuning indicators, Bulgin type VT50 (5000 ohms). $R_{13} = 2000$ ohms, potentiometer 50 W. rating connected across the 220 V. D.C. supply. (This supply voltage is not at all critical, but must be free from sudden surges.)

Specification 1. $R_1 = R_7 = R_9 = 40{,}000$ ohms. $R_4 = R_5 = 100{,}000$ ohms. $R_2 = 200{,}000$ ohms. $R_3 = 1$ mΩ (but 100,000 ohms in first stage). $R_6 = 10{,}000$ ohms. $R_8 = 0$. $C_1 = 0{\cdot}002$ μF., $C_2 = 0{\cdot}001$ μF., $C_7 = 0{\cdot}0015$ μF. Choke $L = 60$ Henries centre tapped. Grid bias 48–62 V.

Specification 2. $R_1 = 25{,}000$ ohms. (Total including visual tuning indicators.) $R_2 = R_7 = R_9 = 40{,}000$ ohms. $R_3 = R_5 = 100{,}000$ ohms. $R_4 = 20{,}000$ ohms. $R_6 = 5000$ ohms. $R_8 = 50{,}000$ ohms. $C_1 = C_7 = 0{\cdot}001$ μF. $C_2 = 0{\cdot}0005$ μF. Choke L, two 2000-ohm headphone bobbins, with core filled with straight stalloy stampings (i.e. open magnetic circuit).

Specification 3. Discriminator valve Osram MH41 (or Mullard 904V). Other valves Mullard 904V and TV4 (electronic tuning indicator). Westectors WX6. $R_1 = R_2 =$ 250,000 ohms. $R_3 = R_4 = 100{,}000$ ohms. $R_5 = \infty$. $R_6 = 0$. $R_7 = R_8 = R_9 = 40{,}000$ ohms. $C_1 = C_2 = 0{\cdot}0002$ μF., $C_7 = 0{\cdot}0005$ to valve output stage. Choke, two 2000-ohm headphone bobbins on centre limb of two interleaved E-shaped stampings of laminic (or other high permeability alloy). With valve output the H.T. current is less than 40 mA., so H.T. and grid bias potentials may be obtained from rectified A.C. or batteries.

Note. The headphone bobbins were obtained from Grafton Electric Co., 54 Grafton St, London, W.1, and are No. 28/12 in their list. These bobbins should be threaded over the stampings so that the bobbins are adjacent to minimize magnetic leakage between them. The windings should be connected so that if considered as a continuous winding the grid bias connexions would be taken to points at the centre of the winding.

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The circuit constants are not critical, but the values of the choke L and the between stage coupling condensers must exceed a certain minimum, which is determined by the other circuit constants. If the counter is to have a short resolving time these minimum values should not be greatly exceeded. It is recommended that these components should be chosen so that there is sufficient latitude to allow common potentials to be applied to all the stages of the complete counter, to allow for normal differences between valve characteristics so that all valves are interchangeable and to allow the ordinary departures $\pm 5\,\%$ of resistances from their marked values.

It cannot be too strongly emphasized that the choke and coupling condenser are the most important elements in the circuit. If any of the three specifications given are followed exactly no trouble should be experienced, but if any alteration is made it is likely that the choke will also have to be changed. It has not seemed worth while to attempt to obtain any rule for specifying the inductance, since the choke is readily adjusted by altering the core.

It has been found that under certain circumstances the resolving time of the counter is extremely long, of the order of 1/100 sec. This effect has not been explained, but the condition has been found to be associated with a value of the choke which is too *small* or with too *small* a coupling condenser. If the circuit potentials are not critical or not near their permissible limits, and if the coupling condenser is of not less than twice the capacity needed for operation of the counter in slow time, the effect has not been encountered.

Apart from such abnormal conditions it was found experimentally that the size of the inductance required depended on the duration of the applied impulse, that is to say on the time constant of the coupling condenser and its leak resistance. Only a very small inductance is required if this time constant is small but then a slow impulse would be without effect on the circuit. On the other hand, if a large inductance and long time constant is adopted, the minimum resolving time of the counter is lengthened. This restriction is not however severe; specification 1 having $CR = 0{\cdot}0002$ sec., $L = 60$ Henries counted the cycles of 50 cycle A.C. and also impulses lasting only 1/40,000 sec. and could resolve, i.e. count separately impulses only 1/5000 sec. apart. Specification 2 has a resolving time probably less than 1/20,000 sec. but is insensitive to A.C. of frequency less than 1000 c./sec. Specification 3 has a very wide range, counting 50 cycle A.C. and having a resolving time of 1/10,000 sec. This circuit is somewhat different from the first two, the leak resistance being omitted and the coupling condenser being small.

One or two further details may be noted. The balancing potentiometers R_6 are not absolutely essential, and are omitted altogether in specification 3. In specifications 1 and 2 the allowances for differences of valve characteristics, etc., are not so great, and these potentiometers provide a convenient means of finding if the circuit is asymmetrical and correcting this to obtain a greater margin of safety.

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The special input valve is usually referred to as the discriminator valve, for by providing it with a large negative grid bias, only impulses large enough to overcome this bias cause the valve to conduct and an impulse to be passed on. If the original impulse is very large the valve might be damaged, so the resistance R_7 is included in series with the grid to limit the grid current. The impulse passed on by this valve should not be too great; this is limited by the choice of R_8 and R_9. It has been found an advantage with specification 2 to include a Westector in the grid circuit of the discriminator valve. This prevents a slow impulse with superimposed irregularities from being counted as more than one impulse. For when the slow impulse exceeds the "cut off" grid bias the Westector becomes conducting and by-passes the superimposed irregularities from the grid of the valve. This Westector is shown in Fig. 2.

The counter may conveniently be reset to zero by momentarily opening the contact C (specification 3, Fig. 1 (c)). In the other specifications, either due to the use of balancing potentiometers R_6 or to using a choke without a split winding, this cannot be applied. A contact B has been used (see Fig. 2), but this has not proved satisfactory in every case. A reliable method is to interrupt three of the grid circuits as is done by contact C in specification 3, but using three independent contacts.

Perhaps the most generally applicable output stage is a thyratron operating a telephone call counting meter. This is shown in the circuit of the complete counter in Fig. 2. The reliability of a thyratron used in this simple way is probably sufficient to justify its inclusion. It should, however, be mentioned that precautions are necessary to prevent the surge produced on breaking the thyratron anode circuit from reaching the input circuit of the counter. For this reason it is preferable to use an electro-mechanical counting meter designed to operate on a small current. Unfortunately, such meters do not appear to be commercially available yet, at least in this country. Suitable mechanisms can, however, be constructed. A pair of hard vacuum valves operating such a counter has been used to replace the thyratron output stage. The circuit adopted is shown in Fig. 3. This operates a counting meter which requires 25 mA. at 100 V. and which operates in 1/80 sec. or less.

Where milliammeters are used in the anode circuits it has been found convenient to attach paper numbers to the pointers. These are 1 in the first stage, 2 in the second and 4 in the third. These numbers may then be added into the count if at the end the corresponding meters are registering anode current.

The counting meter is made to record multiples of eight directly*, and before each count it is run on to the next thousand to avoid the necessity of performing a subtraction to obtain the nett count. This is done by closing the contact M which in the case of the thyratron output earths the grid of the thyratron. This

* Lewis, *Proc. Camb. Phil. Soc., loc. cit.*

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contact is released electrically or mechanically when the meter reaches the next thousand. It may conveniently be coupled to the contact C (or B) so that the whole counter is reset to zero by one operation.

General discussion of high-speed counting requirements

When particles arrive at random at a rate of m per *minute* the chance that a second particle may arrive within $1/m$ *second* after any particle is $\frac{1}{m}\frac{m}{60} = 1{\cdot}6\%$. If the counter is only able to count separately two impulses more than $1/m$ *second* apart, there will then be a loss of 1·6 % when counting at a mean rate of m impulses per *minute*, or a 2 % loss at 1·2 m impulses per minute. This we generally

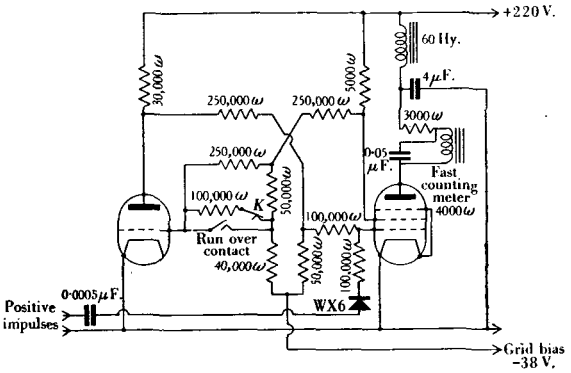


Fig. 3. Valves. Triode, type L. Pentode, Mazda AC2/PEN, normal operating characteristics anode current 32 mA., bias −5V., slope 8 mA./V. Contact K is opened by operation of counting meter. Run over contact is equivalent to contact M, Fig. 2.

take as the maximum permissible counting rate. It is necessary that no further loss should be introduced by the mechanical recording meter. If this cannot operate twice in less than $1/p$ sec., and if it operates for every eighth impulse, there is a chance of loss if nine impulses occur within $1/p$ sec., that is to say, if eight particles should follow a certain particle which trips the mechanical counter (1/8 of all the particles are in this category) within $1/p$ sec. Since eight particles are lost each time this occurs, the loss will be $8 \times 1/8$ of the chance that 8 particles or more arrive in a given interval of $1/p$ sec., viz.*

$$\frac{x^8 e^{-x}}{8!} + \frac{x^9 e^{-x}}{9!} + \frac{x^{10} e^{-x}}{10!} + \ldots,$$

where $x = \frac{n}{60p}$ and n is the mean rate of arrival of the particles. If, however, any of these 8, 9, 10, etc., particles arrive within $1/m$ sec. after another, it will not be

* Bateman, *Phil. Mag.* 20 (1910), 704.

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recorded by the first stage and will not therefore introduce loss by the mechanical counter. This chance is q^2p/m, where $q = 8, 9, 10$, etc. The nett loss by the recording meter is therefore

$$\frac{x^8e^{-x}}{8!}\left(1-\frac{64p}{m}\right)+\frac{x^9e^{-x}}{9!}\left(1-\frac{81p}{m}\right)+\frac{x^{10}e^{-x}}{10!}\left(1-\frac{100p}{m}\right)+\ldots.$$

In normal practice the loss by the other stages of the counter is quite negligible. A few illustrative examples are tabulated below for the special case where the resolving time of the first stage is 1/5000 sec. and the resolving time of the meter is 1/25 sec.

Mean rate No./min.	Loss by first pair %	Loss by meter %	Nett loss %
1500	0·5	7×10^{-4}	0·5
3000	1·0	0·07	1·1
4500	1·5	0·75	2·3
6000	2·0	3·2	5·2
7500	2·5	8·0	10·5

THE "WATCH-DOG" CIRCUIT

The telephone call-counting meters* which we use cannot be made to operate in less than 1/25 sec. Where this is not sufficiently rapid it is best to use some other electro-mechanical recording device, which can be made to operate in a shorter time, but in default of this some advantage may be obtained by using a certain circuit which employs two thyratrons and operates an ordinary telephone call-counting meter. This circuit is shown in Fig. 4, and has been named the "watch-dog" circuit from its mode of operation. While thyratron V_1 is engaged in recording the arrival of an impulse the second thyratron V_2 is left "on guard" to record the arrival of any further impulse. If V_2 records an impulse while thus left on guard, this fact is communicated to V_1 as soon as V_1 is again free to record it. This is achieved as follows. On the return stroke of the recording meter the anode circuit of V_2 is broken, and if V_2 has struck in the interval, the potential of the point A will rise from the arc potential to the supply voltage and this rise is communicated to the grid of V_1 by the condenser C, so that V_1 records another impulse again leaving V_2 on guard. V_2 is put on guard by the closing of the contact AB operated by the armature of the telephone call-counting meter. It is not difficult to arrange that this contact is made in 1/150 sec. after thyratron V_1 has been struck. The resolving time of the counter is then 1/150 sec. with the reservation that if an impulse is followed by two or more within 1/25 sec. only two impulses are recorded.

* Standard Telephones, type 4007J.

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This circuit finds two applications. Used with a scale of two counter to record every eighth impulse it extends the upper limit of counting speed from 5000 per minute to about 10,000 per minute. The calculation of the loss introduced at high speeds is somewhat involved and will not be discussed here beyond pointing out that the counter will miss 8 impulses when $8m$ impulses arrive within $(m-1)/25$ sec. after any given impulse which trips the counter.

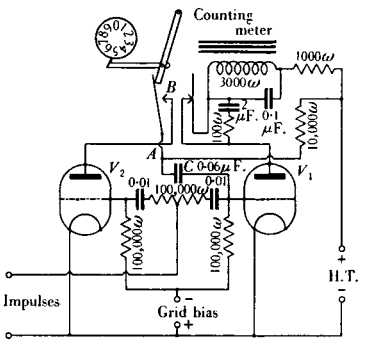


Fig. 4.

In the other application of the watch-dog circuit, it is used alone without any scale-of-two counter for recording impulses from a Geiger counter where speeds up to 500 per minute are commonly required. A single thyratron operating a telephone call counting meter requiring 1/25 sec. for its operation will miss 2 % at a rate of 30 per minute and 20 % at a rate of 300 per minute. The number missed by the watch-dog counter having a resolving time of 1/150 sec. operating a meter requiring 1/25 sec. is tabulated below.

Mean rate per min.	Loss due to pairs within 1/150 sec. %	Loss due to threes within 1/25 sec. %	Loss due to fours within 1/25 sec. %	Total losses %
150	1·6	0·45	0·03	2·1
300	3·3	1·64	0·22	5·2
400	4·4	2·72	0·48	7·6
500	5·5	4·0	0·88	10·4

Although these losses are by no means negligible they begin to rise rapidly only at counting speeds where the ordinary Geiger counter itself fails to give accurate counts.

It seems however that the well-known Geiger counter circuit will no longer be much used for fast counting now that the advantages of the Wynn-Williams* circuit have been pointed out by Neher and Harper†. In the usual Geiger counter

* Wynn-Williams, Brit. Pat. No. 421341.

† Neher and Harper, *Phys. Rev.* 49 (1936), 940.

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circuit the discharge in the counter is extinguished by the fall of potential across a high series resistance. In the Wynn-Williams and Neher and Harper circuit extinction is aided by a valve or thyratron connected in parallel with the counter. This permits counting at very much higher speeds, for which some high-speed recording counter such as a scale-of-two counter is required.

Summary

A high-speed recording counter circuit is described which has proved very reliable. The basic circuit element employs two triodes in a symmetrical circuit which has two stable conditions. The circuit is triggered alternately from one stable state to the other by the applied impulses acting through a circuit comprising two "Westector" cuprous oxide rectifiers and an inductance.

It is easily possible to make a counter operate accurately at a speed of 20,000 random impulses a minute, provided that the associated recording meter operates in less than 1/100 sec.

A "watch-dog" thyratron recording circuit is also described. This is useful where the slow speed of the mechanical recording meter would introduce loss.

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