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RADIO SECTION

THE DEVELOPMENT OF A MULTI-CATHODE DECADE GAS-TUBE COUNTER

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SUMMARY

After the Introduction, which deals briefly with the speed limitations of the present type of cold-cathode gas-tube counter, the mechanism which produces a reduction in the breakdown voltage of a gap adjacent to a discharging gap is outlined and typical curves are given demonstrating the relationship between this reduction in breakdown voltage and other important parameters. A simple type of multi-cathode tube is described, together with a first development, which has led to the G10/240E, a multi-electrode decade counter capable of operating at speeds up to 20 kc/s. Important design features of this multi-electrode tube are treated in detail, and a method of computing the d.c. tolerance range of this type of tube is given. After a discussion of the derivation of important limits on the driving pulse and other circuit parameters, typical performance figures are quoted, and reference is made to the exhaustive type of automatic testing to which each tube is subjected in production. In conclusion, a few very general remarks are made concerning the way in which the tube may be used.

(1) INTRODUCTION

The basic element of a counting circuit is a device which has two stable positions, the oldest of these devices being the relay, which was used in the first counting circuits to be developed. The suitability of the gas-discharge tube as such a device was first recognized by Wyn-Williams[1] who, in 1931, presented to the Royal Society a paper which disclosed some basic circuits using hot-cathode thyratrons. From that time many varied approaches have been made to the problems which are associated with counting, and as a result a number of specialized electronic devices have been developed. In the paper it is not intended to discuss such tubes generally, but to deal only with the development of the multi-cathode gas-tube which has now emerged as the result of the development of the Wyn-Williams circuit using cold-cathode trigger tubes, and more recent studies of some of the fundamental properties of the gaseous discharge.

Modern counter design using individual cold-cathode tubes may be represented by the circuit shown in Fig. 1, the operation of which has been described elsewhere.[2]

The upper speed limitation of this circuit is governed by the time a tube takes to extinguish and de-ionize after its period of conduction. The precise relationship between deionization time and maximum frequency is complex, since it is dependent upon circuit parameters as well as upon tube characteristics. As a result of considerable experimental work, Odell has shown that in the circuit described the following approximate empirical relationship exists between maximum frequency f and deionization time τ:

$$f = \frac{1}{12\tau}\ \text{kc/s} \qquad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where τ is measured by means of rectangular pulses, and is expressed in milliseconds.

Eqn. (1) shows that any improvement in the deionization time of the gas tube will be reflected by a corresponding increase in its maximum operating speed.

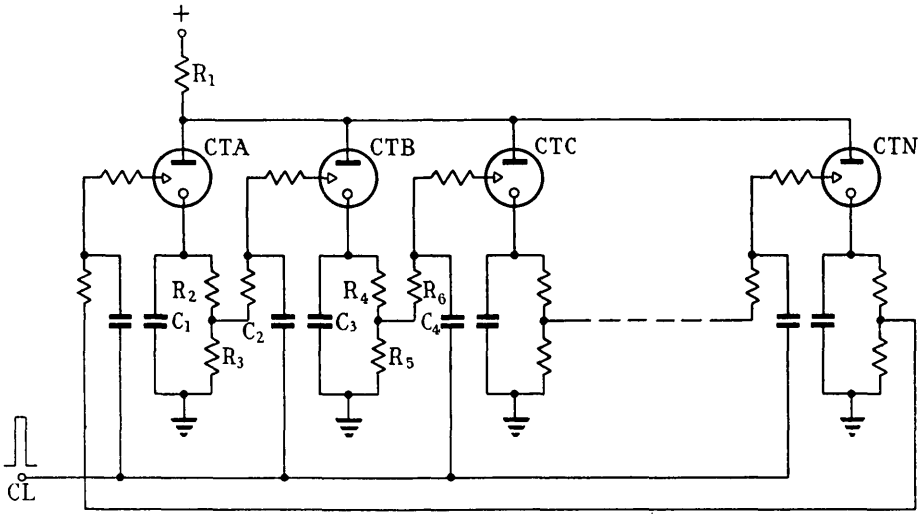

Fig. 1.—A modern counter circuit using individual gas tubes.

Since the maximum reliable counting rate using gas-discharge tubes was approximately 1 kc/s, it will be appreciated that considerable scope for improvement in tube design existed. It was this realization which led to a general investigation into the possibility of making use of multiple elements in a single tube, and the multi-cathode tube, with its inherent advantage of moving an established discharge round an array of electrodes (as compared with initiating fresh discharges in individual tubes), has been the result. Since work on the deionization processes in

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cold-cathode glow-discharge tubes has been made in parallel with this development, it has been possible to apply the results obtained in the development of a multi-cathode-tube decade counter capable of operating at speeds in excess of any other existing type of gas-discharge-tube circuit. Before describing the mutli-cathode counter, a brief discussion of the ignition of a discharge under primed conditions and of the process of deionization following a discharge will be given.

(2) IONIZATION COUPLING

The initiation of a discharge is dependent upon the presence of an electron or electrons within the gap, and in certain circumstances the absence of such an electron may lead to long delays after the application of a field across the gap which should normally produce breakdown. Such a delay is known as the statistical delay, and it has long been appreciated that this may cause considerable variations in the measurement of breakdown voltages. Such variations may be eliminated by some form of priming such as that used by Meek[3] in 1935 for measurements of arc breakdown in air. It was an extension of this technique which was used in the study of the effect of a priming gap upon an adjacent parallel gap. Such an arrangement lends itself to a simple electrode structure when the anodes of the priming and primed gap are made common elements. The reduction in the normal breakdown voltage of the primed gap brought about by the proximity of the priming discharge has been described as ionization coupling, ϕ, which has been defined, as a percentage, as follows:

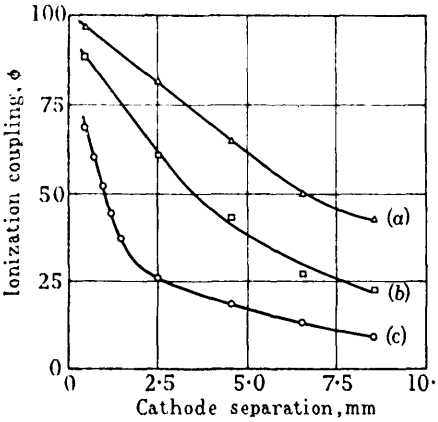

Fig. 2.—Curve showing ionization coupling as a function of gap separation and gas pressure:—
(*a*) 60 mm (*b*) 80 mm (*c*) 100 mm

$$\phi = \frac{V_{BN} - V_{BP}}{V_{BN} - V_M} \times 100\%$$

where V_{BN} is the normal breakdown voltage of the gap
V_{BP} is the breakdown voltage of the gap under the influence of priming
and V_M is the normal glow-maintaining voltage.

Ionization coupling ϕ is dependent upon electrode separation, anode/cathode gap length, gas pressure and current in the priming discharge. The main properties of ϕ can be demonstrated by Figs. 2 and 3, which show the result of some measurements made on these parameters. Fig. 2 shows the variation of ϕ with horizontal separation of the two gaps, and also indicates the variations introduced by changes in pressure. The curves follow an approximate reciprocal relationship, and show quite clearly that 100% coupling can be achieved providing that the gap between the two cathodes is made sufficiently small. The critical separation is equal to the length of the cathode dark-space, since when the separation is less than this the primed cathode comes under the influence of the positive ion space-charge of the priming discharge, and conduction occurs immediately the anode voltage reaches the maintaining voltage of the primed gap. At separations in excess of this, the coupling varies linearly with priming current, as shown in Fig. 3. The termination of the linear sections of these curves corresponds to the priming discharge entering abnormal glow, at which point the diffusion characteristics are considerably modified as the voltage across the gap increases with current. (It will be remembered that in the "normal" glow region the voltage across the gap remains constant, independent of changes in the current and that this is the region normally used in cold-cathode gas-tube stabilizers.)

Measurements on the rate of establishment of ϕ showed that when the coupling is less than 100% the total value of coupling is made up by contributions from photons, electrons and ions in the priming discharge, and that their relative contributions are approximately 60 : 27·5 : 12·5. When the geometry is such as to permit 100% coupling, which is derived from the positive-ion space-charge distortion in the priming gap, this level is

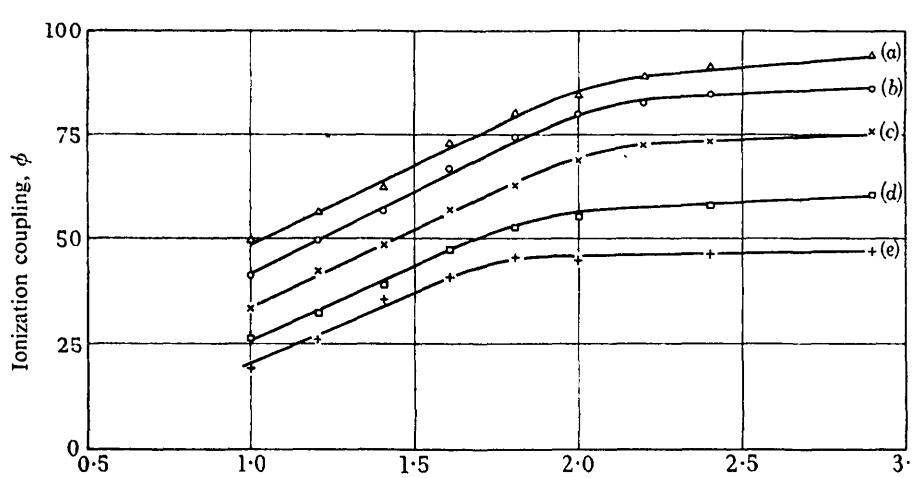

Fig. 3.—Curve showing ionization coupling as a function of priming current and cathode spacing:—
(*a*) 0·5 mm (*b*) 0·75 mm (*c*) 1·0 mm (*d*) 1·25 mm (*e*) 1·5 mm

reached simultaneously with the establishment of the priming discharge, and high-speed operations may be contemplated.

(3) DEIONIZATION TIMES

An experimental and theoretical investigation has been made into the design factors which determine the natural deionization time of the glow-discharge tube. This has shown that, in the various types of cold-cathode glow-discharge tubes at present available, deionization times of the order of a millisecond are the result of using the inert gases associated with cathodes of low work function, such as barium or potassium. During a discharge in these tubes a large number of metastable atoms are created, and since the work functions of the cathodes are of the order of two or three volts, and the life of metastables with energies in excess of this figure is of the order of milliseconds, electrons may be liberated at the cathode at any instant during that time. Such a condition, which is equivalent to excess priming, leads to a reduction in the normal breakdown voltage, with the result that, if the anode voltage is raised to its normal operating level within that period, a spurious breakdown may occur which may render the circuit valueless.

Since the metastable atoms are electrically neutral particles, no electrode design feature in such a tube can completely eliminate these long periods, and to obtain a short deionization time it is necessary to include in the gas mixture a suitable deionizing agent. Such an agent can lead to the destruction of the cathode surface and necessitates the use of materials of higher work function such as nickel or molybdenum. A number of suitable polyatomic gases used as deionizing agents are well known and are commonly employed in self-quenching Geiger–Müller counters, but these have the disadvantage of short lives and, as a result, have not been found suitable for application in the normal glow-discharge tube. However, it has been found that hydrogen, which relies upon its molecular dissociation for its deionizing properties, is most suitable. When a collision occurs between a metastable atom with higher energy than the dissociation level of hydrogen (4·2 volts), the hydrogen molecule may dissociate and at the same time may return the metastable atom to its ground state or to a level approximately 4·2 volts lower than its original level. Thus, in a short time all metastable atoms with energies in excess of 4·2 volts are either returned to levels below this figure or to their ground states. Such a gaseous mixture may therefore be employed with cathodes whose work functions are higher than the dissociation level of hydrogen. For example, it is possible to use such metals as nickel and molybdenum, both of which are relatively unaffected by the presence of hydrogen in the gas mixture.

If a sufficient quantity of hydrogen is present as an admixture to neon and argon, the deionization time of such a combination becomes almost entirely dependent upon the time taken for the removal of the positive ions from within the gaseous volume. This time can be restricted to a minimum by a limitation of the diffusion volume, the elimination of stray fields produced by charges on insulators, etc., and the provision of a controlled clearing field.

(4) THE COMBINATION OF IONIZATION COUPLING AND CATHODE BIASING IN ONE TUBE

By a combination of the effect described as ionization coupling for priming purposes and the cathode biasing arrangement for extinguishing, it became possible to consider the design of a new type of multi-cathode tube. The principle on which such a tube operates is shown schematically in Fig. 4, which also illustrates the waveforms encountered in a counting operation. The anode is designated by the letter A, K_1 and K_3 being used as main cathodes, and K_2 as a transfer cathode. The basic features of the design are such that a discharge at any one gap has a major influence on an adjacent gap only. Current flowing in the A–K_1 gap does not therefore necessarily produce a discharge in A–K_3 but under certain conditions it can reduce the breakdown voltage of A–K_2 to its maintaining voltage. Initially the electrode K_2 is biased positively and starts to conduct only when a negative-going pulse is applied to the input at CL. As K_2 goes negative with the pulse, the anode tends to follow it. If the time-constant C_2R_2 is made high with respect to the leading edge of the negative pulse, the voltage across A–K_1 falls below the maintaining voltage of that gap and the discharge taking place there is extinguished. The discharge has therefore been transferred from A–K_1 to A–K_2. During the length of the pulse the gaps A–K_1 and A–K_3 are equally primed by the discharge at the transfer electrode. However, the pulse-length is made short in comparison with the time-constant C_2R_2 so that K_1 is effectively biased positively when the trailing edge of the negative pulse arrives. Under these conditions, as the anode voltage rises with the trailing edge of the pulse a discharge is initiated in A–K_3. As the condenser in the cathode circuit of K_3 charges, the anode voltage also rises, as shown by the curves in Fig. 4(*b*). In this way, a single negative pulse applied to the electrode K_2 transfers the discharge from A–K_1 to A–K_3.

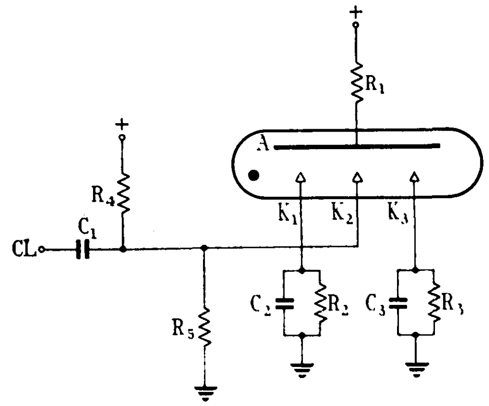

Fig. 4A.—A simple multi-cathode tube.

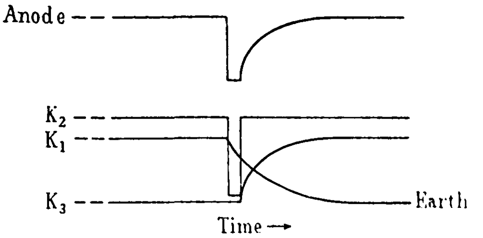

Fig. 4B.—Waveforms encountered in transferring a discharge from K_1 to K_3.

Fig. 5 shows a schematic arrangement of a tube which makes use of two sets of transfer electrodes placed alternately between main cathodes. By constructing the electrodes in a circle and applying pulses alternately to the input circuits P_1 and P_2, it is possible to make the discharge travel continuously around the array. The parallel *RC* networks in the cathode circuits may be alternately commoned if outputs from the individual cathodes are not required.

Counters have been made on this basis, but their usefulness was limited by the twin-input-pulse system; in the next tube to be described the cathodes have been designed to produce a

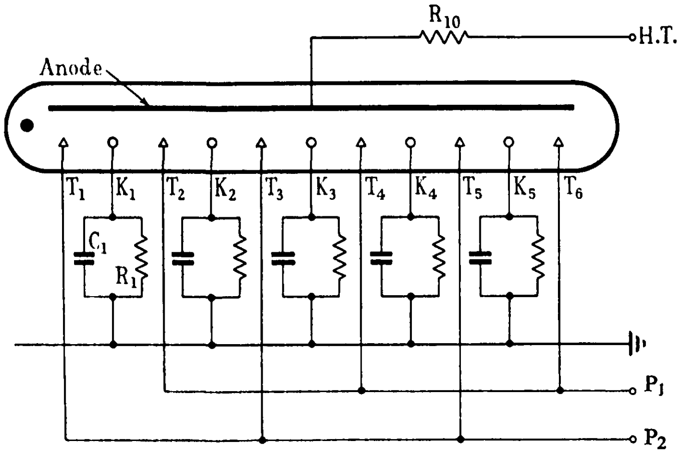

Fig. 5.—The schematic arrangement of a multi-cathode tube with twin-pulse inputs.

directional coupling effect which makes a single-input-pulse system practical.

(5) THE MULTI-CATHODE DECADE COUNTER G10/240E

Fig. 6 is a diagrammatic representation of the decade counter G10/240E in its basic circuit. The tube is constructed with the cathodes in a circle; hence the cathodes adjacent to K_1 are K_{10} and K_2. In addition to ten main cathodes the tube has ten transfer cathodes, each associated with a main cathode, as indicated by the suffixes. The remaining electrodes in the tube are the anode and the shield plates. The arrow is used to indicate that the cathodes are asymmetrical and prime the forward transfer electrode to a greater extent than the preceding one. It is this particular feature which allows the use of a single-pulse input system, since each cathode provides selective priming in the forward direction and thereby eliminates the use of complicated circuit techniques to produce a continuous movement of the glow in one direction.

The anode is supplied through a resistor R_1 with a voltage V_3 which is in excess of the normal breakdown voltage of the gap. The main cathodes are earthed through parallel *RC* circuits (R_2C_2), and the transfer cathodes are biased at a positive voltage V_1 which is sufficient to prevent any transfer cathode from firing except under the influence of a negative-going pulse. The shield is supplied with a suitable positive voltage V_2 which may be derived from the potentiometer R_4 and R_5. On the application of V_3 to the anode, one of the anode/main-cathode gaps will fire, which we will assume is A–K_1, and because of the asymmetry of the cathode, the transfer cathode T_2 is primed in excess of any other gap in the tube. A suitable negative pulse P_1 is then applied to the transfer electrode system, as shown in Fig. 7 and, providing the relationship between pulse width and cathode *RC* time-constant is correct, the glow will thereby be transferred to the next main cathode in the array. By reducing the inter-cathode space to a sufficiently small distance, a discharge between T_2 and the anode provides 100% coupling to K_2, so that as the anode voltage rises with the trailing edge of the negative pulse P_1, it is caught and held at the maintaining voltage of gap A–K_2 as that gap fires. The condenser in K_2 circuit charges, and as it does so the anode voltage rises to a level determined by the resistances in the circuit, the maintaining voltage of the gap and the voltage V_3. Thus, by the application of a pulse the glow has been transferred from K_1 to K_2, and further pulses, which may be applied at any interval of time down to 50 microsec, will cause the glow to proceed from main cathode to main cathode round the array. From this it can be seen that on every tenth pulse the glow will transfer from K_{10} to K_1, and either the voltage developed across the resistance from K_1 to earth, or the visible glow, may be used as an indication of a count of ten.

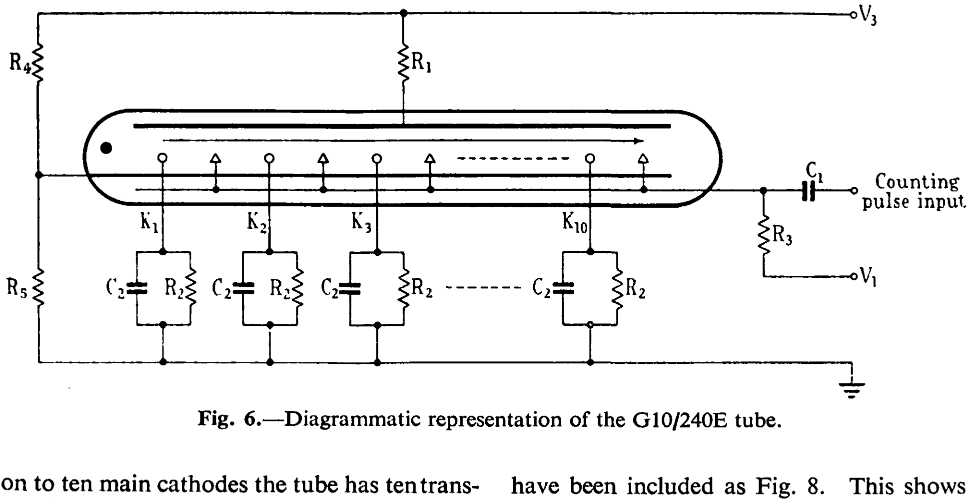

Fig. 6.—Diagrammatic representation of the G10/240E tube.

(5.1) Design Features

In order to give an idea of the type of construction used in the valve, a cut-away sketch and section of the assembly have been included as Fig. 8. This shows how the piece-parts fit together in the completed assembly illustrated in Figs. 12 and 14. The individual piece-parts will now be described in some detail, so that the various design features may be appreciated.

(5.2) The Cathode

It will be seen that the tube functions without complicated circuit technique because of the directivity of the "coupling" derived from the cathode glow. To achieve this, the main cathode, which is constructed from nickel sheet and is shown diagrammatically in a section of the array in Fig. 9, has been designed to consist of two parts. The first, which is adjacent to the transfer cathode has been called the "tail" and is a narrow strip of metal which, because of the high ratio of diffusing current to conducted current for an electrode of this type, has a high maintaining voltage and low saturation current. The second part is a rectangular "plate" from which the principal cathode discharge takes place. When the cathode fires, the glow is initiated on the tail under 100% coupled conditions from the

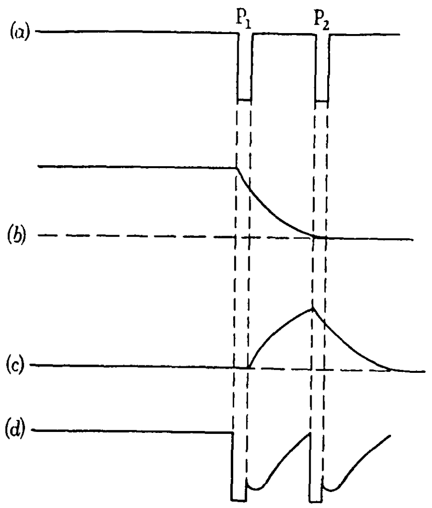

Fig. 7.—Typical waveforms obtained during transfer in a multi-electrode tube.

(*a*) Transfer cathode (*b*) Main cathode K_1 (*c*) Main cathode K_2 (*d*) Anode

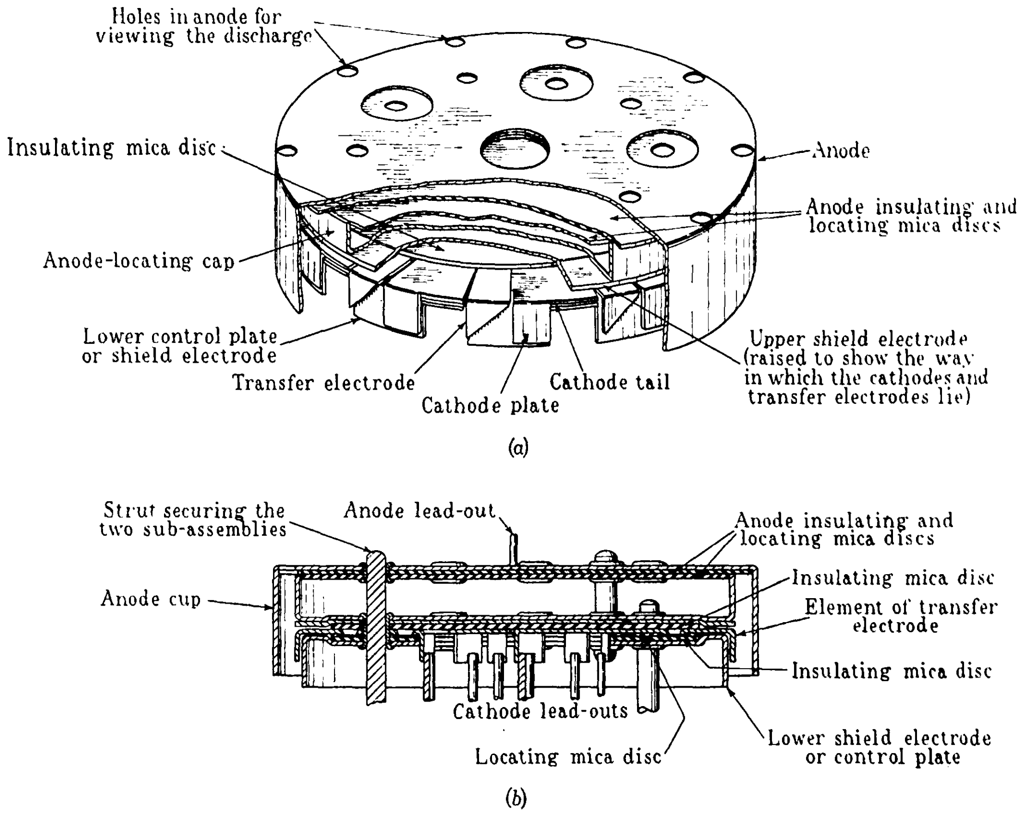

Fig. 8.—Sketch showing the electrode assembly of the G10/240E tube.

preceding transfer discharge. As the current builds up, the glow spreads along the tail until it reaches the plate, on to which it spreads and finally completely transfers. Fig. 10 shows typical I_a/V_a characteristics of such a cathode, and it can be seen there that a difference of 13 volts exists between the maintaining voltages of the two sections, so that the transfer of the glow from the one to the other is a definite and complete operation.

The separation between the electrodes (which successively act as cathodes as the discharge moves round the array) has in all cases been designed to be less than the length of the normal cathode dark-space, and thus 100% coupling between all gaps is provided. Furthermore, the coupling is established as soon as the priming discharge is formed, and consequently this mechanism does not impose any limitations on the maximum operating speed. The only time limitations in the physical operations so far described are therefore associated with the rate at which the glow spreads over the cathode surface, and also in the time taken for it to transfer completely from the tail to the plate of the cathode.

When the glow has transferred completely to the plate of the cathode, the coupling to the forward transfer cathode is, by design, again 100%, and to the preceding transfer cathode a lower figure determined by the horizontal spacing. This spacing is, in practice, the length of the cathode tail, and has been designed to ensure a minimum difference of 40 volts in coupled breakdown voltage to the transfer cathodes in the forward and backward direction.

The normal saturation current of the tail must be small compared with the operating current of the tube, to ensure that the mechanism of transfer from tail to plate is rapid and effective. The area of the tail has therefore been made a minimum, and is the thickness of the nickel sheet used for the cathode times the length of the tail. The shield-electrode system is designed to restrict the glow to this edge, which is necessary to ensure satisfactory counting.

The rate of spread of glow along the tail, and its subsequent transfer to the plate, represent the ultimate speed limitation of the present tube. This has been measured under normal operating conditions, and the time taken for the spread and transfer of the glow is 15 microsec; the corresponding figure obtained for the glow to spread across the transfer cathode is

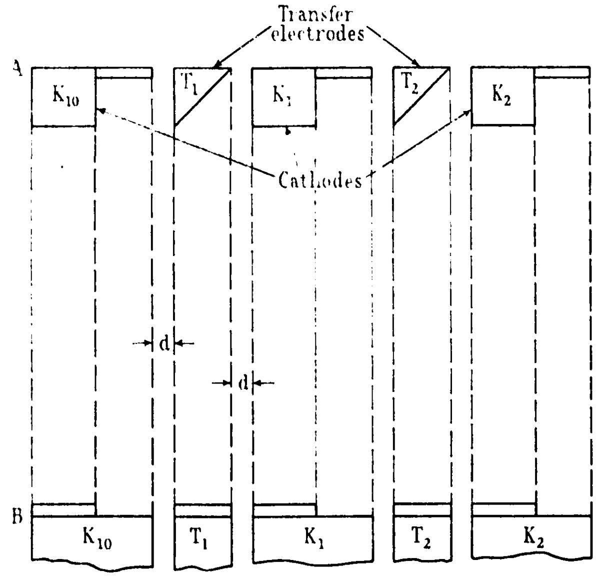

Fig. 9.—Diagrammatic representation of the cathode and transfer-electrode array.
(*a*) Cut-away section.
(*b*) Cross-section.

5 microsec. From these measurements a maximum operating speed for the tube of 50 kc/s can be expected, and in fact, tubes have been operated at speeds up to 45 kc/s. However, the circuit tolerances at these speeds are very narrow, and for practical applications a limit of 20 kc/s has been set.

The cathodes, together with other piece-parts used in the original design of the tube are shown in Fig. 11.

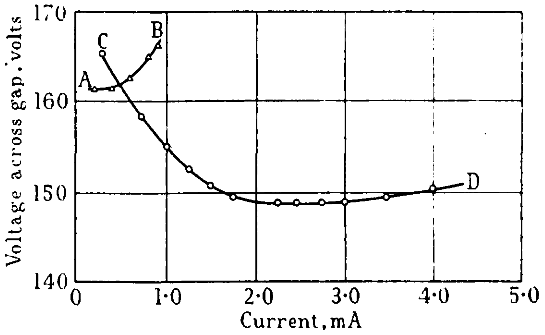

Fig. 10.—Current/voltage characteristics of the "tail" and plate of a main cathode.

(5.3) The Transfer Electrode

The transfer electrode and other piece-parts are illustrated in Fig. 11. The one shown has one member cut away, and was made in this manner to satisfy an early circuit requirement. Later the requirement disappeared, and the electrode is now made complete with ten legs.

A further modification, which has been illustrated in Figs. 8 and 9, was the reduction in the conducting area of the electrode. The purpose of this was to bring about a small degree of directivity, in the transfer cathode, which assists the operation of the valve.

(5.4) The Shield Plates

The function of shield plates, or screen electrodes, is to restrict the glow on the cathode to discrete areas. These are positioned in such a way as to be in the cathode dark-space, where they will restrict the influence of the positive-ion space-charge at the cathode to areas which are unscreened. Their

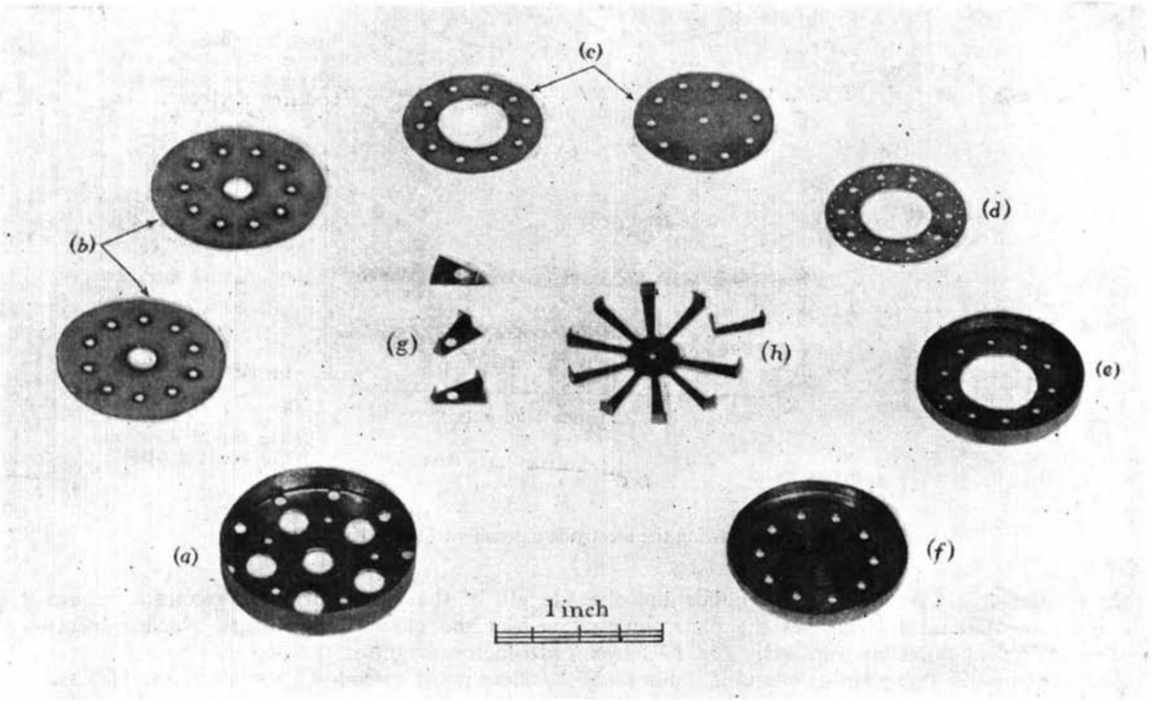

Fig. 11.—Piece-parts of the G10/240E tube.

(*a*) Anode cup.
(*b*) Anode-locating mica disc.
(*c*) Insulating mica disc.
(*d*) Cathode-locating mica disc.
(*e*) Lower control plate or screen electrode.
(*f*) Upper control plate or screen electrode.
(*g*) Cathodes.
(*h*) Transfer electrode.

importance in the design of the present tube is obvious, since the successful operation of the tube depends on the limitation of the glow to the restricted area of the tail and the establishment of a stable glow on the cathode plate.

It is anticipated that the life of the multi-cathode gas tube will be dependent upon the capability of the tube to withstand any effects introduced by sputtering from the cathodes. Changes introduced in this way generally do not depend directly on the loss of material from the cathode, but in the bridging of gaps between adjacent electrodes by conducting films. Simple designs of multi-cathode tubes have been made in which the cathode electrodes were located by mica discs with which they were in physical contact, but after a few million operations the effect of sputtering interfered considerably with the insulation between electrodes, causing the tube to fail. It will readily be observed, however, that the control of the glow by means of shield plates eliminates this immediate limitation to life by the creation of a gap between the conducting area of the cathode and surfaces adjacent to it.

The shield electrodes have also been used to perform the mechanical function of clamping the electrode assembly together. Fig. 12 shows the cathode and transfer electrode sub-assembly partially assembled, illustrating how the various electrodes are spaced and located with respect to each other. The completed sub-assembly is also seen on the same photograph, where the clamping of the electrodes by the shield electrodes is obvious.

Fig. 11 illustrates the original design of the lower shield electrode which was later abandoned in favour of a castellated structure. As previously stated, it is essential that the glow-discharge should be limited to the small selected edge of the cathode to ensure the continual operation of the tube, and it was found that the original electrode was not entirely satisfactory from this point of view, since the radius of curvature on the bend of the cup did not provide the clear-cut limits required. In the later form of the lower shield electrode the edge adjacent to the tail which provides the glow control projects slightly above the level of the tail, thus providing a very efficient control. The castellation is necessary in order to prevent the cathodes from conducting on their surfaces facing away from the anode, hence the rather elaborate shape.

To produce the corresponding improvement on the upper side of the cathode tail, the upper shield electrode was also modified, and is now a disc. The original glow-control cup is now mounted on it, and acts as the anode-location cup. The anode sub-assembly consists of an anode made in the form of a cup, and two mica discs, the first of which is a tight fit inside the anode-location cup and the second insulates the anode from its location cup. Common struts which pass through the two sub-assemblies are used to hold the two rigidly together.

The anode assembly thus completely surrounds the cathode and transfer electrodes sub-assembly, and thereby eliminates any effects due to surface charges[5] which may appear on the walls of the glass envelope. Holes have been cut in the top of the anode so that the glow-discharge on the plate of each cathode may be seen through the end of the glass bulb, and a visual indication of the position of the count is thus available.

The G10/240E has been designed not only as a counting tube but also as a distributor, and therefore each cathode has an external connection. Employing the tube purely as a counter would allow the use of common *RC* circuits and reduce the number of cathode lead-outs to three.

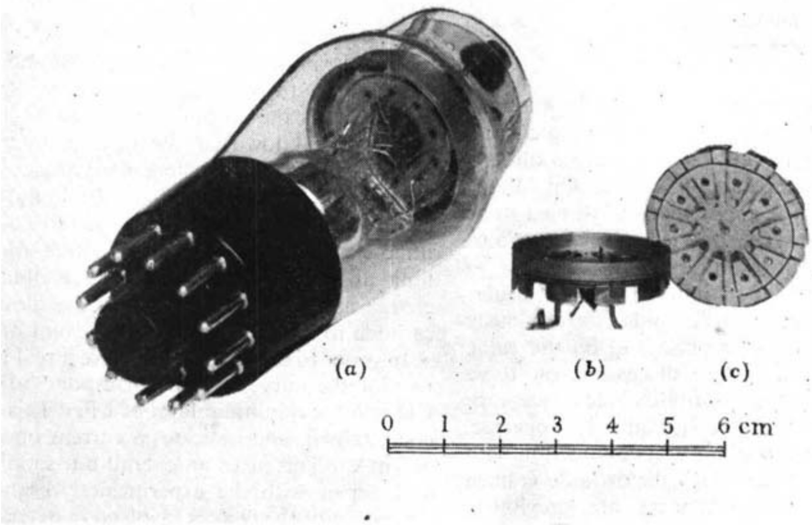

Fig. 12.—Cathode and transfer-electrode sub-assembly.

(*a*) Multi-electrode valve showing cathode and transfer electrodes located inside anode cup.
(*b*) Cathode, transfer and screen electrodes sub-assembly.
(*c*) Cathode and transfer electrodes fitted into locating mica (without upper screen electrode).

(5.5) Operating Limits

The d.c. operating limits of the circuit shown in Fig. 6 will now be determined by the use of typical voltage/current characteristics. It will be assumed in this discussion that no prior limits are reached owing to the use of potentiometer chains from the h.t. supply to provide both the shield and transfer electrode bias, and initially the operating limits will be determined for set circuit conditions and a variable positive supply voltage. (This may be considered as equivalent to working with an unstabilized h.t. supply.)

(5.6) Minimum H.T. Supply

The two major considerations which determine the lower limit at which the tube operates are the minimum stable current and the cathode bias derived across the cathode resistance. The former limit is imposed by the necessity of using a stable glow so that the ionization coupling to the forward transfer-cathode is correspondingly stable. A typical anode-current/anode-voltage characteristic has been plotted (AB) in Fig. 13, and there the minimum current has been set at 2·75 mA.

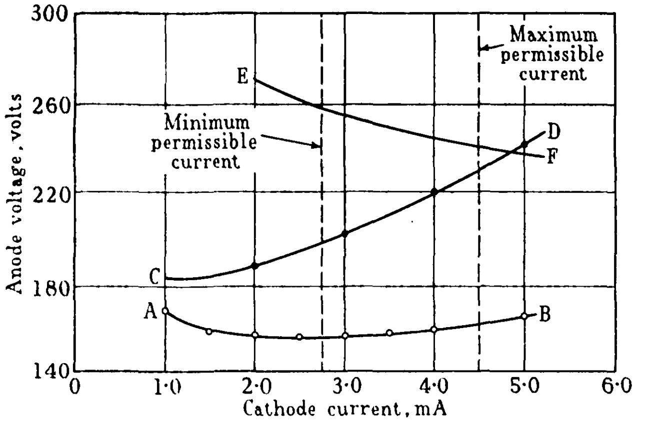

Fig. 13. Typical cathode-current/anode-voltage characteristics and coupled breakdown voltages of adjacent cathodes.

On the assumption that the cathode resistance is 15 kilohms, the curve CD has been drawn to give the anode working characteristic. The minimum h.t. supply voltage is now given directly by the addition of the anode voltage at 2·75 mA to the voltage drop across the anode load. If the anode load is assumed to be 30 kilohms, the h.t. supply must be not less than 285 volts, otherwise unreliable operating will result.

The second consideration, that of minimum permissible bias on the cathode at the end of the transfer pulse, is obviously dependent on the width of the transfer pulse and on the value of the cathode shunt capacitance. Any discussion on these particular circuit parameters must necessarily include a reference to the maximum speed at which the tube is required to operate, since the value of cathode shunt capacitance in conjunction with the anode load determines the rate at which the cathode voltage rises. If the cathode and anode resistances are previously selected to be 15 kilohms and 30 kilohms, a cathode condenser of 0·004 μF will charge to a minimum of 40 volts in 80 microsec. Having determined the value of the shunt condenser, one can use its time-constant with the cathode resistor to determine the maximum pulse-width.

The figure of 40 volts has been selected as the minimum bias which must be developed across the cathode resistance during the discharge, and is a design figure which has been used in the development of a high-speed trigger tube, the G1/370K. This figure is sufficient to allow the use of crystal rectifiers in gating networks associated with the input to the high-speed trigger tube which then may act as the gate between successive stages of decade counters.

Since the main cathodes adjacent to the transfer cathodes are symmetrically spaced, the coupling derived from a discharge at the transfer electrode is the same at both cathodes, and the process of completing the step forward relies on the adequacy of the voltage bias on the previously discharged cathode to prevent it refiring whilst breakdown occurs in the next cathode in the forward direction.

In Section 5.1 it was shown that the directivity of the cathode is achieved by making the maintaining voltage of the tail a minimum of 10 volts higher than that of the cathode. In this case the higher maintaining voltage of the tail means that the bias on the previous cathode at the end of the pulse must be 10 volts higher than would be necessary if the transfer had been to an electrode of similar maintaining voltage. Experiments on the deionization time of a parallel gap in a neon-argon-hydrogen gas mixture, similar to that employed in this tube, have shown that after a time of approximately eight microseconds the major effect of the previous discharge has completely disappeared, so that until the top limit in speed is reached an additional residual bias to compensate for this effect is not required. Pre-production tubes have shown that variations in characteristics of the individual electrodes can be limited to a maximum of five volts, and in the determination of the minimum bias this figure has to be added to the 10 volts derived for the difference between the maintaining voltages of the tail and plate of the cathode. An additional 10 volts bias on the cathode, making 25 volts, will then be sufficient to ensure the forward cathode firing after a discharge at an intermediate transfer cathode under all conditions. A 0·004 μF condenser discharging through 15 kilohms from 40 volts reached a level of 25 volts in 20 microsec, which is therefore the maximum pulse-width which may be used for transfer using these particular circuit values at the minimum level of h.t. supply.

(5.7) Maximum H.T. Supply

The maximum to which the h.t. supply may be raised without causing the tube to fail may be determined by reference to Fig. 12. As the current conducted by a cathode increases, the primed breakdown of the next cathode in the array falls as shown by curve EF. Since the voltage on the anode rises with increase of current, owing to the voltage developed across the cathode resistor, the two curves EF and CD will eventually intersect, as shown. This constitutes the upper safe operating limit above which it is possible to obtain a simultaneous discharge at two cathodes, or for the glow to transfer from one cathode to another without the advent of a transfer pulse.

In order to use Fig. 13 to derive a real tolerance, it is necessary to plot the curves which correspond to the maximum level of CD and the minimum level of EF. This has been done with the chart shown, and indicates a current operating range of 2·75 to 4·5 mA. This gives an overall h.t. supply tolerance of 78 volts, and agrees with the experimental results within 5%. A consideration of the factors involved in determining this figure shows quite simply that for a given current range and cathode resistance of 15 kilohms the tolerance on the h.t. supply voltage is given as:

$$V_T = (4\cdot 5 - 2\cdot 75)(15 + R_A) \text{ volts} \quad . \quad . \quad (2)$$

where V_T is the number of volts over which the h.t. supply may be varied,

R_A is the anode load in kilohms,

and the current range is in milliamperes.

The current range of the tube, which appears as one factor on the right-hand side of eqn. (2), is determined very largely by the geometrical design of the tube. The second factor, on the other hand, is determined by the circuit and the nominal voltage of the h.t. supply. It is obvious then that the value of V_T is influenced by the circuit in which the tube is used, so that if, for example, the anode resistance were increased from 30 to 120 kilohms the tolerance on the h.t. supply would correspondingly increase from approximately 70 to 200 volts. This would, as indicated, necessitate a shift upwards in the nominal h.t.

supply from the design figure of 330 volts, but the disadvantages of such a shift would in some circumstances be outweighed by the advantages of the increased tolerances thus obtained.

(5.8) Minimum Pulse-Amplitude

In a preceding Section there was some discussion on the width of the pulse required to complete transfer. In that case the only consideration was that of ensuring that sufficient bias remained on the cathode condenser at the termination of the pulse to prevent the cathode refiring. The pulse width, however, is also related to the pulse amplitude, in that the total power available in the pulse must be sufficient not only to initiate the discharge at the transfer cathode, but also to ensure that the glow spreads across the surface of the electrode from the point of initiation to the edge adjacent to the next main cathode. This then ensures that the required coupling in the forward direction is achieved.

The rate of spread of glow across an electrode surface is dependent on, in addition to the physical form of the cathode, the voltage applied across the associated gap, and therefore the minimum pulse-amplitude has to be determined in conjunction with the minimum pulse-width. In the circuit shown in Fig. 6 the direct voltage at which the transfer electrode system is biased is derived from a potentiometer across the h.t. supply line, and the maximum bias consequently occurs at the same time as maximum current through the tube. The minimum pulse-amplitude is dependent upon the level of this bias which, with the component values selected, is maintained at a few volts positive with respect to a conducting cathode at all times.

There are several modes by which the glow may be transferred from one cathode to another. The one previously described in which a negative transfer pulse extinguishes the first cathode and holds the anode potential below the maintaining potential to all other cathodes has been designated Mode I. In this mode the transfer cathode conducts current in excess of that conducted by the gap being extinguished and thus demands a relatively low-impedance pulse source.

In Mode II, a reduced pulse-amplitude is used, so that the initiation of the discharge in the transfer gap extinguishes the glow at the previous cathode but is insufficient to hold off the discharge at the new cathode. In this case the current taken by the transfer electrode is equal to, or in excess of, the main gap current.

Mode III. A further reduction in pulse amplitude produces a further modification in the manner in which the transfer takes place. In this case the current flowing in the previous cathode is reduced but the discharge is extinguished only by the initiation of the main discharge at the next gap. In this mode the transfer cathode conducts a relatively low current which may be less than that taken by the main cathodes but which must be sufficient to provide adequate coupling to the forward adjacent cathode.

Other modes may be introduced as small variants of any of the previous ones. One, for example, represents the case when the bias on the transfer electrode system is insufficient to hold the transfer electrode inoperative under conditions of high coupling, so that it starts to conduct before the beginning of the transfer pulse. The application of the pulse then increases the current through the transfer gap and reduces the anode voltage in the manner previously described.

The three modes which have been described do not correspond to any absolute region of operation, but merge into each other with variations of current conducted and transfer-pulse amplitude. They are of academic rather than practical value, since in any circuit with components and pulses of normal tolerance each mode of transfer may be met at different points in the operating range.

(5.9) Maximum Pulse-Amplitude

If an ideal circuit were used in which there was no variation in the h.t. supply voltage, with an infinitely low-impedance pulse source, the maximum pulse-amplitude would then be set by the pulse breakdown of the transfer electrode to shield-plate gap, and would be in the region of 200 volts. In practice, however, a lower limit is generally imposed by the anode/control-plate breakdown voltage, which may be reached by capacitative pick-up of the negative-going pulse on the control-plate electrodes. The magnitude of the negative pulse appearing on the control plate is dependent upon the input impedance to that electrode, and when this is high the momentary increase in voltage between it and the anode may be sufficient to cause spurious discharges to take place, leading to false operation. With the selected control-plate potentiometer supply, the pulse amplitude may be increased to 160 volts without reaching this limit.

The following operating conditions have been selected as a result of investigations following the above lines:

H.T. supply voltage ..	330 volts ± 20.
Transfer electrode bias .	65 nominal (derived by potentiometer of 68 kilohms and 18 kilohms from h.t. supply).
Cathode resistor ..	15 kilohms.
Anode resistor	30 kilohms.
Cathode condenser ..	0·005 μF.
Pulse amplitude ..	130 volts ± 20.
Pulse-width	16 ± 4 microsec.
Shield electrode bias ..	110 nominal (derived by potentiometer of 56 kilohms and 30 kilohms from h.t. supply).

All component tolerances are ± 5%.

Under all conditions the output developed across the cathode resistor is greater than 40 volts. This enables the tube to be used in conjunction with the G1/370K tube, referred to in Section 5.6, in straight scaling circuits in which the trigger tube is used as a gate between successive counters. Production samples of the two tubes are illustrated together in Fig. 14, indicating the small volume occupied by a scale-of-ten counter as a section of a multiple-stage counter.

(5.10) Testing Technique

The G10/240E tube operates periodically over the pulse repetition range of 0–20 kc/s, and when the manner in which it should be tested in production was considered, it was apparent that tests at low- and high-frequency counting should be made. Also, because wide circuit-tolerances are available, it was thought that each limit should be tested in turn to ensure that the final product satisfied the specification in all respects. Obviously a test schedule involving testing the various combinations of a number of circuit parameters could not be carried out manually, and for this purpose an automatic test routiner has been developed.

The test routiner produces groups of pulses in which the pulse repetition frequency is 5 kc/s and the group frequency is 3 c/s. When the test starts, the home, or zero, cathode is conducting, and the first group of pulses is fed to the tube, which operates under its nominal circuit conditions. After the ten pulses have passed, a circuit checks that the discharge on the home cathode has been extinguished by the first pulse and re-established by the tenth. It also checks that the voltage developed across the cathode resistor is not less than 40 volts. The circuit conditions are then switched by uniselectors and relays so that most of the adverse conditions which are liable to be encountered in circuit practice are similarly tested on groups of ten pulses. Twenty-four combinations are possible, and the twenty-fifth

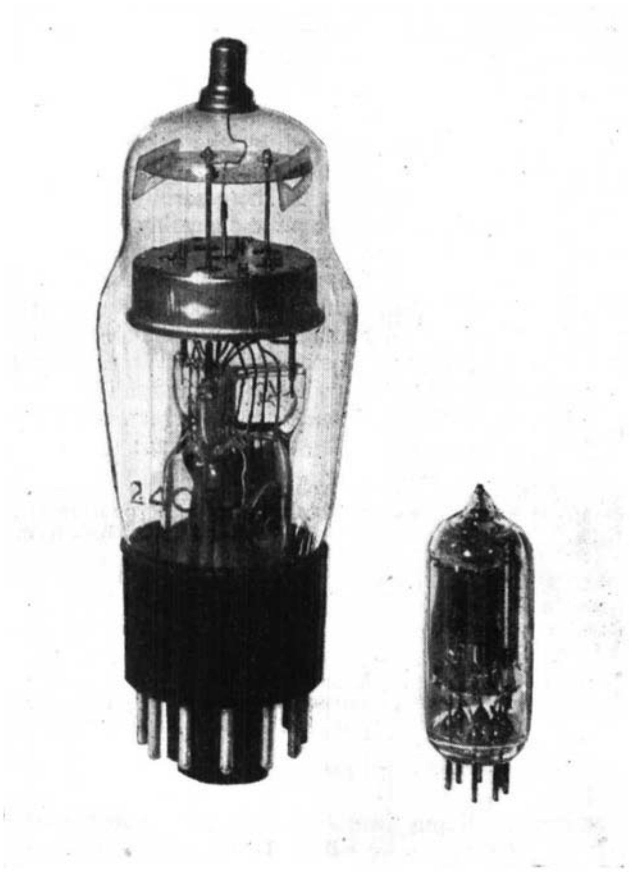

Fig. 14.—The G10/240E and G1/370K tubes.

group fed to the valve is one of 11 pulses, so that the final discharge takes place from number one cathode and not the home, or zero, cathode. Simultaneously, the cycle of tests is restarted. Each cathode then acts as the home cathode for the sequence of 25 tests, and on completion of the 250th test there is an indication that the test is complete.

A series of lamps indicate which cathode is acting as the home cathode and which particular test is being carried out at any instant. In the event of a failure, the cathode and test on which the failure occurs is indicated and the test routine is discontinued. By an analysis of failure it is therefore possible to deduce the cause and to watch the trend of the product with time.

(6) GENERAL

Because it was envisaged that the tube would find other applications besides straightforward counting, all cathodes have been brought out to separate pin connections, and this has necessitated the use of a duodecal base and top-cap anode. A single-ended version has recently been produced which uses a loctal base and provides separate lead-outs for the first and last cathode, and commons alternate cathodes in two groups. This tube is considerably smaller than those illustrated, being only one inch in length.

Since activated cathodes are not employed there are no photoelectric effects, and the valve may be used equally well in bright sunlight, artificial lighting, darkness, etc. The operation of the tube is unaffected by strong magnetic fields produced by transformers, etc., but very strong magnets ($H > 200$ oersteds) held close to the glass may distort the electrode assembly.

(7) CONCLUSIONS

Recent studies of the physics of the glow-discharge, and a growing demand for new types of tools in counting and computing, have led to considerable advances in gas-tube techniques. The tube which has been described represents one of the first stages in this development, and is one of a number of tubes now available for exploitation. In the examination of the detailed mechanism of the counting operation of the G10/240E tube, some limitations of the type have been indicated, but in no case are they restrictive in application. In fact, adequate tolerances exist on all circuit parameters, and the tube is now being applied in a variety of circuits both as a counting and as a distributing element.

(8) ACKNOWLEDGMENTS

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(9) REFERENCES

(1) Wyn-Williams, C. E.: "The Use of Thyratrons for High-Speed Automatic Counting of Physical Phenomena," *Proceedings of the Royal Society*, July 1931, **132.**

(2) Hough, G. H., and Ridler, D. S.: "Multi-Cathode Gas Tube Counters," *Electrical Communication*, September, 1950.

(3) Meek, J. M.: "The Electric Spark in Air," *Journal I.E.E.*, 1942, **89,** Part I, p. 335.

(4) Reeves, A. H.: British Patent No. 639827.

(5) Loeb, L. B.: "The Mechanism of the Electric Spark" (Stanford University Press, 1941).