Publications, 1931 - 1940

1937

The Strobotron—II

Practical use of this new cold-cathode tube, described in the February issue, depends on a knowledge of the grid voltages and currents required to start the gas-discharge. Herewith are the starting characteristics

By A. B. WHITE
W. B. NOTTINGHAM
H. E. EDGERTON
K. J. GERMESHAUSEN
Massachusetts Institute of Technology
Cambridge, Massachusetts

THE strobotron, developed principally by Germeshausen,[1] has been applied by Germeshausen and Edgerton[2] in a number of circuits, the best-known of which is the "Strobotac"—a small stroboscope manufactured by the General Radio Company for use as a tachometer. Here the tube is used as an instantaneous light source. In combination with a simple pool-type mercury arc, the strobotron may be used as a controlled arc rectifier capable of handling hundreds of amperes. An example of such an application for the accurate control of a standard small power resistance welder has been described by Gray and Nottingham.[3] Since there are many other possible uses of the strobotron, it seems worth while to present a fairly comprehensive discussion of its starting characteristics.

The strobotron is a gas-filled (neon) tube with a caesium-coated cold cathode. The two grids serve as auxiliary electrodes for starting purposes and for electrostatic shields. Throughout the discussion below, all potentials will be referred to the cathode as zero unless otherwise specified. The discharge is initiated by starting a glow between two elements. For example, if the plate is 300 volts positive, and the inner grid (g_1) is zero, a discharge from cathode to plate may be created by raising the outer grid (g_2) potential to about +100 volts. This starts a glow between grids with the inner one as a "momentary cathode," following which, a discharge develops from cathode to anode if the glow between grids is sufficiently intense. With the same plate potential (300 volts positive) a discharge may also result if the outer grid (g_2) is made about 110 volts negative, in which case a glow first starts between the two grids with the outer one as the "momentary cathode." In either of the above cases the current carried by the glow discharge between the grids must exceed a certain magnitude in order to form a true plasma and give rise to a complete breakdown from the cathode to the anode.

These characteristics of the strobotron are summarized by Table I and Fig. 2. The information presented in Table I can best be understood by the graphical representation of Fig. 2. In this figure the outer-grid (g_2) potential referred to the cathode as zero is plotted as the abscissa, and the inner-grid potential as the ordinate. The six solid lines of this figure may be placed independent of anode potential, while the location of the dashed line depends upon anode voltage. The area inside the figure represents the range of outer- and inner-grid potentials for which the strobotron will remain nonconducting. The boundary line defines critical values of potential for which a discharge will develop.

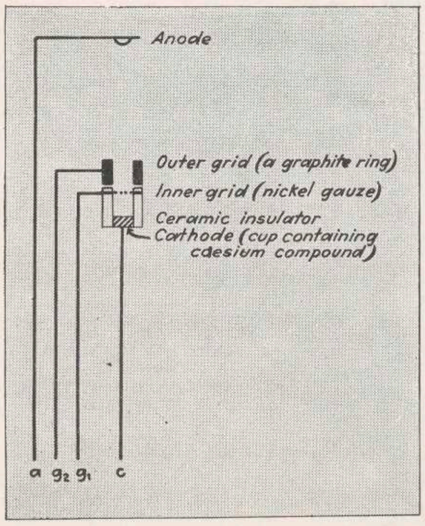

Fig. 1—Diagram showing relation of strobotron elements

In order to clarify the connection between Table I and Fig. 2, let us consider in detail the conditions represented along each line of the figure. Along the line *a-b*, which is drawn at an angle of 45 degrees with the horizontal, the outer grid (g_2) is everywhere positive a constant amount with respect to the inner grid (g_1). A point located just to the left of line *a-b* corresponds to a potential less than that required to initiate a glow discharge between these grids. If we attempt to set the actual potentials of the grids to correspond to a point on the right of line *a-b*, then a glow discharge will start and the current carried by this discharge will become very large unless limited by resistances in the associated circuit. In case the resistance in this circuit is so high that the grid current has too small a value (a milliampere or or less, depending on the anode-to-cathode voltage as shown by Fig. 5), a complete breakdown may not take place. This point will be expanded in discussing Fig. 6.

At the intersection of lines *a-b* and *b-c* of Fig. 2 the process of initiating the discharge changes from that of a glow between grids to a

Reprinted from ELECTRONICS, March, 1937

glow between the cathode and the outer grid (g_2). The critical potential for this process is $v_{2c} \cong 175$ volts.

TABLE I

Approximate Initial Glow Potentials

Positive Electrode	Negative Electrode	Critical Potential Diff.		Expected Variations in Volts	
		Desig.	Volts		
g_2	g_1	v_{21}	96	+15	-5
g_1	g_2	v_{12}	100	+50	-30
Anode	g_2	v_{a2}	500	+50	-100
Cathode	g_1	v_{c1}	130	+15	-10
g_2	Cathode	v_{2c}	175	+25	-15
g_1	Cathode	v_{1c}	130	+10	-10
Cathode	g_2	v_{c2}	200	+40	-60
Anode	g_1	v_{a1}	600	+50	-40

If the circuit is properly arranged it is possible to instigate a complete breakdown with the minimum of control-grid current (approximately 2 x 10^{-9} amp) by crossing the line *b-c* near the point *c*. Further details are given below.

The line *c-d* is the boundary determined by the critical potential $v_{1c} \cong 130$ volts with the initial glow forming between the inner grid (g_1) and the cathode. The diagonal *d-e* again represents the locus of points of constant difference in grid potential $v_{12} \cong 110$ volts, and for this the outer grid is the "momentary cathode."

The construction involved in the location of the dashed line *e-f* is more complicated. This corresponds to a breakdown between the outer grid (g_2) as "momentary cathode" and the anode. For a particular value of anode potential we locate the line by subtracting the critical glow potential $V_{a2} \cong 500$ volts from the anode potential (V_a). In symbols we have

$$V_a - V_{a2} = V_2$$

Thus if V_a is 325 volts and V_{a2} is 500 volts, we have $V_2 = -175$ volts. Since V_{a2} is a constant of the tube, we see that V_2 or the location of the dashed line *e-f* will shift linearly with the anode voltage.

An analogous equation, namely, $V_a - V_{a1} = V_1$, may have to be used to locate the lower boundary of the region of nonconduction when an anode voltage V_a greater than the critical voltage difference ($V_{a1} - V_{c1}$) is used with strobotrons which happen to have critical potentials such that $V_{a2} + V_{21} > V_{a1}$.

Figure 3 represents an experimental determination of the "characteristic loop" for a particular strobotron, showing how corners are rounded off and that the observed diagonal lines are not strictly 45-degree lines, but deviate very slightly. These minor differences from the idealized diagram of Fig. 2 are unimportant.

In the following paragraphs on grid-current characteristics it will be shown that as the potential difference between two elements of the tube is increased, the current flow is very small (about 10^{-7} amperes or less) until the critical potential difference is reached. A complete characteristic shows that oscillations begin at this point and the average potential drop between elements *decreases*. The potentials recorded in Table I and Fig. 2 show the critical values in volts which must be exceeded in order to initiate the discharge. It is important to realize that these values do not represent the actual potential across the two elements which is observed after the glow has been started and its intensity increased enough to cause a complete breakdown in the tube. In

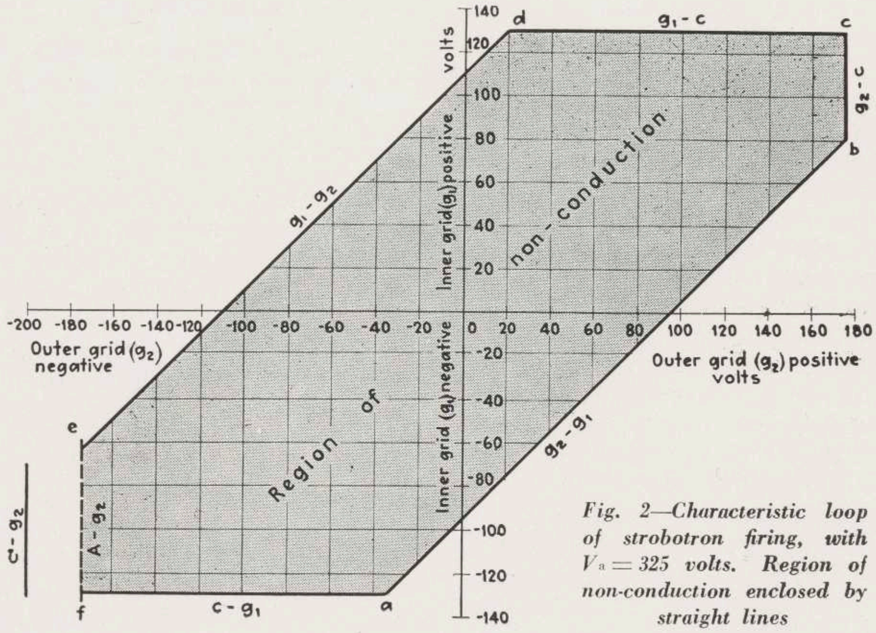

Fig. 2—Characteristic loop of strobotron firing, with $V_a = 325$ volts. Region of non-conduction enclosed by straight lines

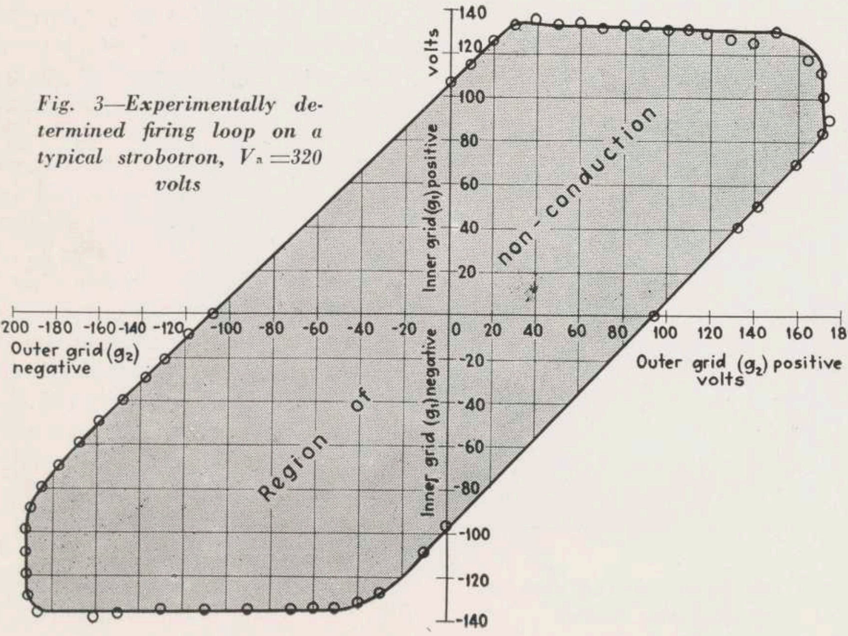

Fig. 3—Experimentally determined firing loop on a typical strobotron, $V_a = 320$ volts

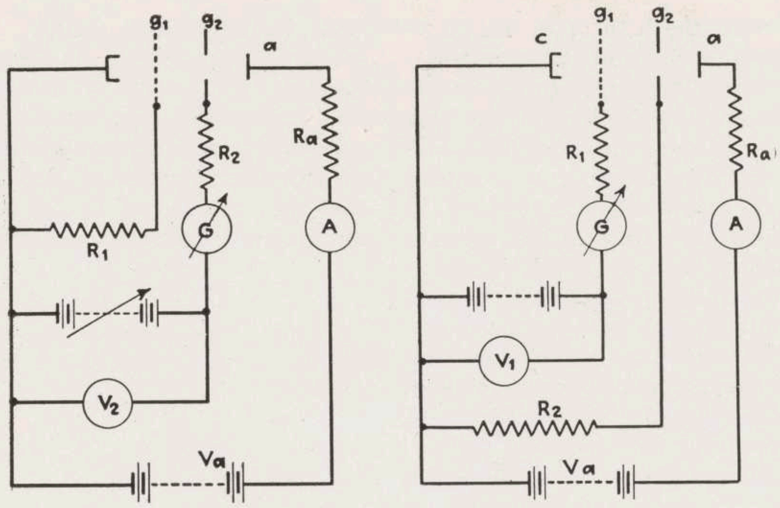

Fig. 4—Circuits for determining grid current, (left) in outer grid and (right) in inner grid

terms of the discussion to follow, the critical potentials of Table I correspond to the point *B* of Fig. 6.

Grid-Current Characteristics

The grid-current characteristic of a strobotron is difficult to determine with accuracy, since the current is not a strictly reproducible function of the voltage. This must be expected, since cold-emission effects are undoubtedly dependent on the surface conditions on the electrodes, and these change as a result of the ion bombardment taking place each time the tube is "fired." These changes alter the critical voltage by only one or two volts in most cases. The problem of observing the grid-current characteristic just before the tube is fired is difficult, since over certain ranges of current the glow discharge is inherently not stable and oscillations result which cannot be eliminated no matter how high the resistance in the external circuit. Because of these complications the important end results are presented in Table II and no attempt has been made to prepare detailed curves showing the grid current as a function of the voltage over the entire range. Two of the circuits used for studying the grid currents at the moment of "firing" are shown in Fig. 4. The circuit illustrated at the left was used to determine the grid current and potential required to cause a complete breakdown in the tube when the outer grid (g_2) was made positive or negative. The grid current thus obtained was found to be a function of the anode potential and is shown in Fig. 5. The true grid voltages were found by measuring the meter voltage V_2 and subtracting from that the IR drop through resistance R_2.

Table II should be very useful in connection with the design of circuits using strobotrons, since it is essential to consider the grid current which must be supplied in order to accomplish a complete breakdown between the cathode and the anode. Fortunately it is not necessary to deliver the current for more than a few microseconds, and the use of a condenser which may be charged by a small current often makes perfectly satisfactory operation possible.

One of the important features of the double-grid strobotron is that it can be used so advantageously in circuits for which the simultaneous action of two different potentials is required for operation. This property was utilized by Gray and Nottingham[3] in the welder control by putting a 60-cycle peaked wave on the inner grid and a contact control on the outer grid. For all such applications the boundary shown in Fig. 2 must be crossed somewhere on the 45-degree lines, i.e., either *a-b* or *d-e*. The grid-current data presented in Table II show that smaller currents are required for crossing *a-b* than for crossing *d-e*, and furthermore we have found that boundary line *a-b* is definitely more reproducible than the *d-e* boundary.

TABLE II

Minimum * Glow Current in Amperes For Strobotron Breakdown

Boundry Crossing	Anode Voltage 125	300	400	Current in
a-b	10^{-3}	1.5×10^{-5}	10^{-5}	g_1 or g_2
*b-c***	10^{-8}	5×10^{-9}	2×10^{-9}	g_2
c-d	5×10^{-3}	6×10^{-6}	4×10^{-6}	g_1
d-e	7×10^{-3}	3×10^{-4}	1.2×10^{-4}	g_1 or g
e-f	5×10^{-7}	6×10^{-8}	5×10^{-8}	g_2
f-a	5×10^{-4}	1.5×10^{-4}	3×10^{-9}	g_1

* In all cases the condenser method of "firing" permits operation with a control current less than 10^{-7} ampere.

** These data for trigger method of operation with 20,000 ohms or less in the inner-grid (g_1) circuit.

This is brought out by the column of "expected variations" in Table I.

Before discussing the other details of Table II, it will be necessary to consider certain facts brought out by the determination of the current flowing between adjacent elements as a function of the voltage between them. For example, the inner grid (g_1) and the cathode were connected together while the outer grid (g_2) and the anode were connected and made positive with respect to the other two elements. The current observed to flow is shown in Fig. 6.

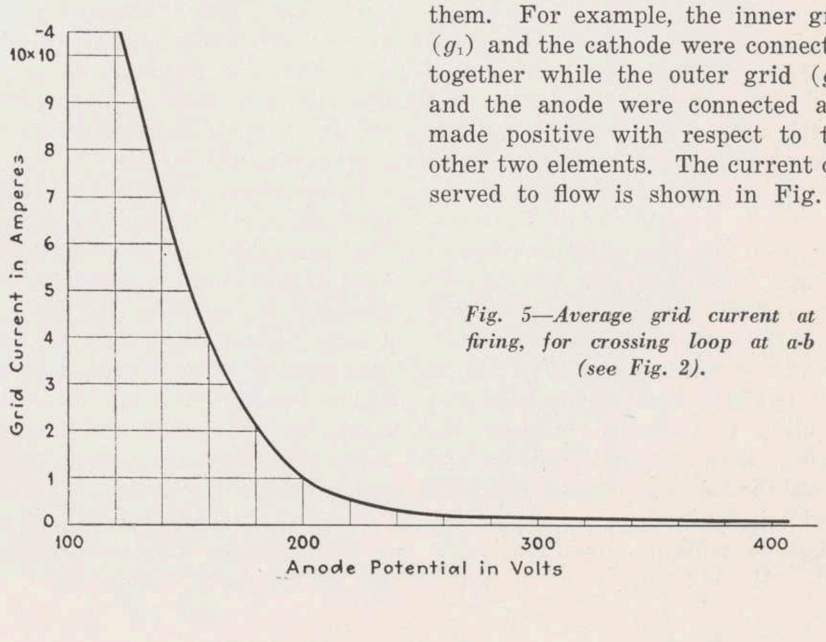

Fig. 5—Average grid current at firing, for crossing loop at a-b (see Fig. 2).

Starting at very low voltages, the currents are small (less than a microampere) and increase very gradually over the range *AB*. At *B* oscillations set in, resulting in a definite decrease in the average value of the potential drop over the tube, while the average value of the current increases. A plot of the average curve would lead one to think that the characteristic curve should have been stabilized by the resistance *R* used in the circuit, but the fact that different "average" curves were obtained for different resistances showed at once that oscillations were present and these were observed with a cathode-ray tube. As the current was increased, the oscillation ceased and a more or less regular curve was obtained. Curves of this kind were determined for each pair of elements. Since these current-vs-voltage curves were taken under conditions which clearly did not represent typical operating conditions, it was considered worth while to compare the observed currents and voltages at the time of "firing" with those of the two element characteristics. For example, with 150 volts on the anode and with the inner grid (g_1) at zero, the grid current in the g_2 circuit at the instant of complete discharge was observed to be 4.5×10^{-4} amperes, and the corresponding voltage was 78 volts. This point is shown by a circle next to the curve of Fig. 6.

In order to initiate a discharge between any two elements the point of maximum voltage, point *B* of Fig. 6, must first be exceeded. It is for this reason that the critical potentials presented in Table I correspond to this point and not to the actual grid potential impressed on the grid at the instant of "firing." If a line is drawn through the point *B* with a slope of $-1/R$, where *R* is the resistance in the grid circuit, the intersection of this line with the current-voltage curve will give the current and voltage immediately after the glow discharge to this grid is initiated, as shown by point C of Fig. 6. In case this current is less than that required to cause a complete discharge between the cathode and anode, the tube does not become fully conducting.

Let us redirect our attention to Table II, and notice in particular that with the help of a small condenser (.0005 to .01 μfd.) connected between grid and cathode, or between grids, depending on the type of circuit used, the large instantaneous current required to complete the discharge can be furnished by the condenser, since in this case the "load-line" can be made so nearly vertical through the point "B" that its intersection with the grid-current characteristic curve is well beyond the minimum current required to "fire" the strobotron. The maximum current required from the control circuit corresponds to that at point B, since the condenser is charged up by the control current between consecutive operations of the strobotron.

Another way of operating a strobotron with an exceedingly small current results from crossing the boundary *b-c* near the point *c*. The currents demanded in the outer-grid circuit for this operation never exceed 10^{-8} ampere and in many cases are nearer 10^{-9} ampere. The breakdown here occurs as a two-stage process. When the potential of the inner grid is maintained only three or four volts less than the critical potential $V_{1c} \cong 130$ volts, and the resistance in this circuit is less than 20,000 ohms, it is easy to see that very little current will be required in the outer-grid circuit to initiate the glow by crossing the critical potential V_{2c}. This crossing triggers off the glow between the inner grid and the cathode which in turn brings about the complete breakdown cathode to anode. Either the condenser method or the "trigger action" method of firing should be used whenever it is necessary to control a strobotron with a photoelectric cell or any other high-resistance low-current source.

In designing circuits for strobotron use, it is important to visualize the characteristic loop shown in Figs. 2 and 3, and to remember that starting by crossing the line *a-b* can be accomplished with the least grid current when double grid control is needed. The use of a small condenser to furnish the instantaneous grid current is strongly recommended when the control current is very small. If only single grid control is needed, then the "trigger" method should be used for small currents in the control circuit. Since the initial currents used in the strobotron are the result of field emission, assisted in some cases by the minute room-temperature thermionic or photoelectric emission (assuming that the tube is not in the dark), the starting characteristics are not as reproducible as one would like for operation on a narrow voltage margin. It is therefore necessary to provide for a considerably greater range of operating potentials than is required for the conventional hot-cathode type of grid-controlled gas-discharge tube. The advantage gained in having no "stand-by" power, an instantaneous peak current capacity of a hundred amperes or more, no heating period, and negligible temperature effect, often more than compensates for the wider operating range for which provision must be made.

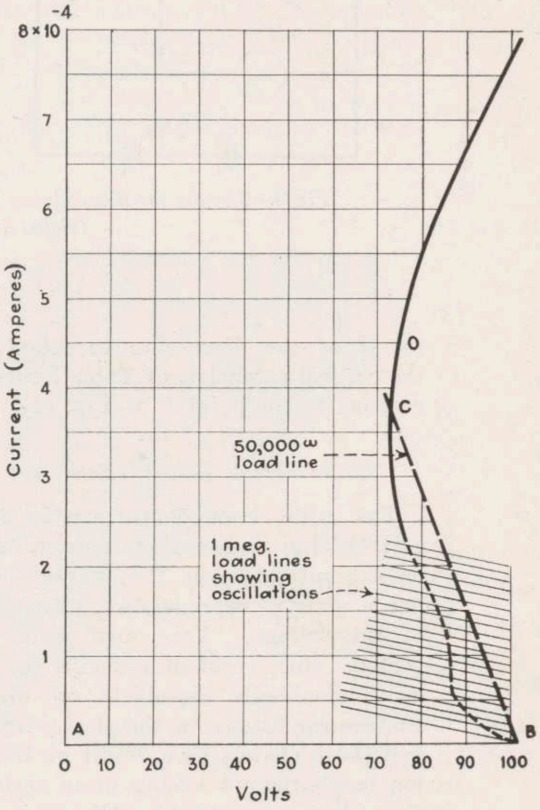

Fig. 6—Current flow between grids as a function of potential difference

1. Germeshausen, K. J. and Edgerton, H. E., *Electrical Engineering* Vol. 55, p. 790, (1936)
2. Germeshausen, K. J. and Edgerton, H. E., *Electronics*, Vol. 10, No. 2, p. 12, February 1937.
3. Gray, T. S. and Nottingham, W. B., Review of Scientific Instruments, (1937).