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RELAXATION OSCILLATIONS IN VOLTAGE-REGULATOR TUBES

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ABSTRACT: Gas-filled voltage-regulator tubes are subject to relaxation oscillations when operated in parallel with a condenser. These oscillations have been investigated and a qualitative description of their mechanism is presented. It was found that the voltage across the tube as a function of current has a minimum, and that if the current through the tube is greater than that at the voltage minimum, then relaxation oscillations do not occur. It was also found that a 100 ohm resistance in series with a VR105 tube reduces the tube current required to prevent oscillations. Sinusoidal oscillations were observed. The equivalent inductance of a VR105 was observed to increase with decreasing tube current and decreasing frequency.

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The work here reported was performed under Task NOL-Re2d-71-1-53. This report describes studies of relaxation oscillations in gas filled voltage-regulator tubes. Though the explanations are qualitative and the results based on empirical data, it is felt that they will be useful to those in the electronic field. The conclusions drawn and modifications of circuits suggested are based on current information; they may be modified as a result of future work.

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INTRODUCTION

Reference (a) describes an adiabatic compressor to obtain P-V-T data at high temperatures and pressures. The pressure gage to be used with the compressor is described in reference (b). The electronic circuits for use with the pressure gage and associated instrumentation will be described in a forthcoming report. In these circuits several voltage-regulator tubes were used and these tubes occasionally exhibited relaxation oscillations. These oscillations rendered the tubes useless as voltage regulators, and could not be tolerated. Consequently, a study was made of the oscillations, their mechanism and possible means of their prevention.

Gas filled VR (voltage regulator) tubes, such as the VR105 or the VR150 are used mainly for two purposes, voltage reference and voltage regulation. As a voltage reference, the VR tube is operated at nearly constant current. The tube under such operating conditions is subject to instantaneous fluctuations of voltage and slow drifts with time which have been investigated and reported in some detail, reference (c). As a voltage regulator, the tube is in parallel with the load, and operates with fluctuating current. It is well known that a condenser placed in parallel with a VR tube will improve its regulation, especially at higher frequencies. It is also equally well known that such a condenser often causes relaxation oscillations, rendering the tube useless as a regulator. A search in the literature revealed no information concerning the mechanism of such oscillations and what can be done to prevent them. It is the purpose of this paper to give a simple qualitative explanation of why such oscillations occur, and how they may be prevented.

Mechanics of Oscillation

Figure 1 shows the regulator circuit with the condenser C in parallel with the VR tube. The current equation at the plate junction is

$$i_2 = i_1 - i_3, \tag{1}$$

and in terms of the voltage across the condenser,

$$i_2 = C \frac{dE}{dt} \tag{2}$$

where E is the voltage across the VR tube and condenser. With the tube conducting and in equilibrium - that is, constant current through and constant voltage across the tube -

$$\frac{dE}{dt} = 0 \tag{3}$$

and

$$i_1 = i_3. \tag{4}$$

In Figure 2(a) is shown the current-voltage characteristic of a VR tube. The current-voltage characteristics of VR tubes will be discussed below, but for the present assume the characteristic of Figure 2(a). Note that the voltage scale does not begin at zero, but is expanded to show details of the characteristic. Also shown is the load line for the circuit, which is determined by the equation

$$i_1 = \frac{E_{bb} - E}{R}, \qquad (5)$$

where R and E_{bb} are shown in Figure 1. The intersection of the load line and the VR tube characteristic determines the stable operating point of the tube, for it is there that equation (4) is satisfied.

Consider now the path of the point (E, i_3) when E_{bb} is first applied. The VR tube does not conduct. The current through R charges the condenser and increases the voltage E across both the tube and condenser. This is indicated on the current-voltage plot, Figure 2(c), by the path AB, along which the current through the tube is zero. At B the striking potential of the tube is reached, and the tube begins to conduct. The current immediately jumps from zero to the value corresponding to the striking voltage; that is, to the value at C. The tube current is then greater than i_1, the current through R, so the condenser begins to discharge. The (E, i_3) point then continues down the tube characteristic until the load line is reached at D. At D the point stops because $i_1 = i_3$ and so, $(dE/dt) = 0$. It should be noted that as long as the point (E, i_3) is on the tube characteristic to the right of the load line, then i_3 is greater than i_1 and the condenser voltage is decreasing, for from equations (1) and (2),

$$\frac{dE}{dt} = -\frac{i_3 - i_1}{C} \qquad (6)$$

Consider now the locus of the point (E, i_3) when E_{bb} is first applied for the case of Figure 2(c). Here the tube characteristic is the same, but the load line now intersects it on the low current side of minimum. When E_{bb} is first applied, the path and operation are the same as in Figure 2(b) from A to B and from B to C. The point does not traverse the path from C to D, however, for when the minimum (point F) is reached, the slope of the tube characteristic is zero, which requires that $(dE/dt) = 0$, and if the current i_3 decreased still further, then (dE/dt) would have to become positive. This cannot occur, for to the right of D the tube current, i_3, is greater than i_1, and by equation (6) (dE/dt) must be negative. Since the voltage E cannot increase along the path from F to D, the tube characteristic cannot be followed, and the tube ceases to conduct. In terms of current, along the characteristic from F to D by equation (2) the condenser current i_2 would have to be positive at the same time that i_3 is greater than i_1; this is clearly a violation of equation (1) and again shows that the tube cannot follow this part of the characteristic. Thus the path taken in this case is from F to G rather than from F to D. From G the point moves toward B and the cycle is repeated, with relaxation oscillations resulting.

The above discussion of relaxation oscillations explains the mechanism of their generation. With this mechanism in mind it is possible to develop schemes to prevent the oscillation. The most direct procedure is to arrange R and/or E_{bb} so that the intersection D occurs on the high-current side of the minimum F. Also a VR tube might be picked with a minimum at a lower current. It is also possible to place a resistance in series with the tube and shift the point F of the series combination to a lower current, see Figure 3.

The above explanation implies that the existence of the oscillations does not depend on the size of the capacity C, which is not the case. This results from the idealized tube characteristics of Figure 2.

Current-Voltage Characteristics of VR Tubes

The experimental current-voltage characteristics of ten tubes (VR105) are shown in Figure 4. These characteristics were obtained with the circuit of Figure 5. The plate of the VR tube was coupled to the y-axis dc amplifier through a 10 μf condenser. The input resistance of the amplifier was two megohms, which with the coupling condenser C gave an input time constant of 20 seconds. The voltage across the resistance R_1 in series with the VR tube was proportional to the current through the tube and was the input to the x-axis dc amplifiers. As the current through the tube was varied, the voltage change across the tube as a function of current appeared on the scope. The current was changed by manual rotation of the potentiometer; the sweep from 5 to 30 milliamperes and back took about one second.

From the curves of Figure 4 several interesting properties of VR tubes are apparent.

(a) The characteristics of VR tubes vary greatly from tube to tube.

(b) The current-voltage characteristic of a VR tube depends in a remarkable manner on the direction of change of the current. The direction that the current is changing is indicated by the arrow in Figure 4.

(c) The curve for decreasing current is smoother and has fewer abrupt changes than for increasing current. In the above relaxation oscillation discussion, only the curve for decreasing current is important. The decreasing current curves of Figure 4 agree qualitatively with the curve assumed in Figure 2.

(d) Above a certain current, depending on the tube, the curves for increasing and decreasing current are nearly coincident and fairly smooth. In this region, not only should relaxation oscillations be absent, but the tube should be less inclined toward instantaneous fluctuations.

An idea of the day to day changes in VR tube characteristics can be seen from Figure 6, in which the characteristics for tube number 9 that were obtained on different days are compared.

The tube characteristics depend not only on the direction the tube current is changing, but also on the rate at which it is changing. In

Figure 7 the tube characteristics of tube number 9 is shown for several cycling rates. For each cycle the current increases from 5 to 30 milliamperes linearly in one-half cycle, and decreases linearly in the other half. This was achieved by placing a pentode in series with the VR tube and controlling the pentode with a triangular wave. The triangular wave was obtained by integrating a balanced square wave.

Relaxation Oscillation Tests

The circuit of Figure 8 was used in the relaxation oscillation tests. With the plate supply "on" the tube current was decreased by increasing the series resistance, until relaxation oscillations began. The tube current (strictly speaking, the average tube current) was then increased until the oscillations ceased. For still higher currents, within the normal operating range of the tube, the circuit was stable. The currents at which the oscillations ceased for several values of capacity are listed in Table I. A comparison of Table I and Figure 4 reveals that the relaxation oscillations always cease for currents at or on the low current side of the minimum. Thus for a given VR tube one may make certain that the tube will not oscillate by passing through it a current greater than that at the minimum of the current-voltage characteristics. This is the equivalent of arranging that the intersection D, Figure 2, occur on the high-current side of the minimum F, as was previously discussed.

In Figure 3 it is shown that the minimum in the tube characteristics may be shifted to lower current values by insertion of a series resistance and considering the characteristics of the combination. The tube characteristics show slopes below the minimum which can be compensated to about five milliamperes with a resistance of 50 to 100 ohms. Exact compensation is not feasible because of the variability of the tube characteristics. The data of Table II were obtained in the same manner as those of Table I, but with the resistance R_1 in series with the tube as in Figure 3(a). From these data it is apparent that R_1, in shifting the minimum to the left, does reduce the current through the tube required to prevent relaxation oscillations.

A comparison of Table I with Table II ($R_1 = 0$) indicates how well these measurements agree from day to day.

The experimental current-voltage locus was observed on a cathode-ray oscilloscope and differed in some respects from the curve GBCFG of Figure 2(c). Along the path GB the current was not quite zero. A dark current of a few microamperes was flowing. This current was very small at G increasing approximately linearly with voltage to about 50 microamperes at B. The curve from B to C was not horizontal but, due to inertial effects within the tube, was concave downward. Also, the tube did not abruptly cease conducting at F, but due to the availability of ions and the sluggishness of the tube the locus left the tube characteristic between F and D to reach the zero-current axis a fraction of a volt above G. This behavior does, however, approximate the qualitative picture quite well.

Sinusoidal Oscillations

From Figure 4 it is seen that the VR tubes have a region of negative resistance as indicated by the negative slope of the tube characteristics. With such a negative resistance element there is the possibility of sinusoidal oscillations, and during the above tests such oscillations were often observed. No detailed study was made of these oscillations, but the following facts were noted:

(a) Occurrence. Oscillations did not occur for all tubes under the test conditions, and for a given tube would not occur for all values of parallel capacities. For a given current and capacity, however, the tube, if it did oscillate in this manner, would cease if the current were changed a fraction of a milliampere. With this current change, either relaxation oscillations would begin (with a decrease of current) or the sinusoidal oscillations would stop (current increase). There was one unusual case, however, for which oscillations were stable over a current range of 2 milliamperes. Sinusoidal oscillations were usually observed in one of two ways:

(1) With relaxation oscillations occurring the current would be increased, and, as indicated above, the relaxation oscillations would cease, but the tube would then continue to oscillate sinusoidally. These oscillations were not the same frequency as the relaxation oscillations.

(2) When the tube operation was stable and the current was being reduced to start relaxation oscillations, then sinusoidal oscillations often would occur. In many cases, however, for which stable sinusoidal oscillations did not occur, such oscillations of increasing amplitude were observed. After a few cycles of these oscillations -- of the order of 5 to 50 cycles -- the relaxation oscillations would begin. This was observed to occur in at least one-half of the cases. Thus, if a VR tube circuit, when operating, suddenly begins relaxation oscillations, it is probable that the relaxation oscillation was initiated by a sinusoidal oscillation. If this sinusoidal oscillation could be prevented, then the likelihood of relaxation oscillations should be reduced.

(b) Amplitude. Whereas the amplitude of the relaxation oscillations were of the order of 10 volts, the amplitude of the sinusoidal oscillations were usually one volt or less.

(c) Frequency. The oscillation frequency depends on the capacity in parallel with the tube and the current through the tube. With a capacity of 80 μf the frequency varied from 17 cycles per second at 6 milliamperes to 58 cycles per second at 22 milliamperes. For 4 μf, the frequency varied from 90 cycles per second at 8 milliamperes to 175 at 11 milliamperes. In general the frequency increased with increasing current and decreasing capacity.

(d) VR tube inductance. Because of the inertial effects of the gas within the tube, the equivalent circuit of a VR tube includes an inductive component. It is the inductance of the tube resonating with the parallel capacity that determines the frequency of the sinusoidal oscillations. This inductance was determined from the frequencies measured and the known capacities. It was found to be a function of both the current through the tube and the frequency of oscillation. At 20 milliamperes it varies from 0.06 henry at 200 cycles per second to 0.14 henry at 50 cycles per second. At 5 milliamperes the inductance varied from 0.76 henry at 90 cycles per second to 1.5 henry at 15 cycles per second. Thus over the range of these data the inductance decreases with increasing tube current and with increasing frequency.

As pointed out above none of the tubes would oscillate sinusoidally for all values of capacity, and some would not oscillate for any value of capacity used. Consequently no one tube would sustain oscillations at a sufficient number of frequencies, of parallel capacities, or of currents to allow the above observations to be made. The observations were made by considering the information obtained from all the tubes. They agree qualitatively with those reported by Kirkpatrick for the measured inductance of a single VR tube over a range of currents and frequencies.

Conclusions

Relaxation oscillations in VR tube are to be expected if the tube is shunted by a condenser and the load line intersects the tube characteristic curve on the low current side of the minimum. The oscillations can be prevented by arranging for the intersection to occur to the right of the minimum. This can be done by decreasing the resistance R, Figure 1, and moving the load line so the intersection occurs at sufficiently high current, or it can be done by placing a resistance in series with the tube to move the minimum to the low current side of the intersection. Sinusoidal oscillations will sometimes occur in a circuit where a VR tube is shunted by a condenser, but increasing the tube current one milliampere or so will usually stop them; decreasing the current would probably bring on relaxation oscillations. The equivalent inductance of a VR tube decreases with increasing tube current and with increasing frequency.

Table I

Current through VR tubes required to stop relaxation oscillations for various values of parallel capacity C

VR Tube Number	Parallel Capacity C 1 μf	4 μf	10 μf	30 μf	80 μf
1	4 ma	10 ma	14 ma	12 ma	12 ma
2	4	4	4	4	4
3	4	6	8	13	18
4	6	7	7	7	8
5	6	5	4	2	2
6	8	6	7	5	8
7	6	14	14	14	20
8	3	13	14	14	21
9	6	14	12	14	15
10	6	14	13	20	22

Table 11

Current through VR tubes required to stop relaxation oscillations for various values of parallel capacity C and series resistance R_1

VR Tube Number	R_1 Ohms	Parallel Capacity, C 1 μf	4 μf	10 μf	30 μf	80 μf
1	0	4 ma	12 ma	16 ma	20 ma	22 ma
	50	4	8	10	9	9
	100	3	6	8	6	6
2	0	2	4	4	3	4
	50	2	3	3	2	3
	100	2	4	2	2	3
3	0	3	6	11	20	22
	50	2	4	6	7	10
	100	2	3	4	4	6
4	0	6	9	7	7	7
	50	5	6	6	6	7
	100	4	5	4	4	4
5	0	5	6	4	3	3
	50	4	4	3	2	3
	100	4	4	2	2	3
6	0	6	6	6	4	4
	50	5	4	4	4	4
	100	4	4	4	4	4
7	0	4	16	18	18	22
	50	4	10	10	10	11
	100	4	6	6	6	6
8	0	2	13	14	16	18
	50	2	6	7	8	8
	100	2	4	4	4	5
9	0	5	12	12	14	16
	50	4	10	8	8	9
	100	4	5	6	6	6
10	0	6	14	13	20	22
	50	5	9	11	12	14
	100	5	8	8	8	7

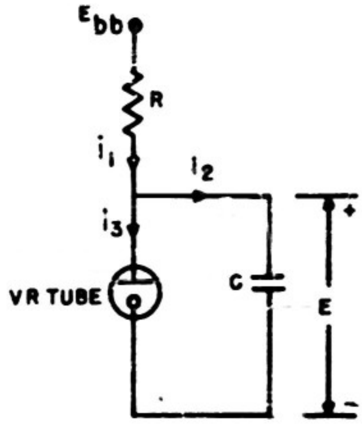

Figure 1 - Voltage-regulator tube with parallel condenser

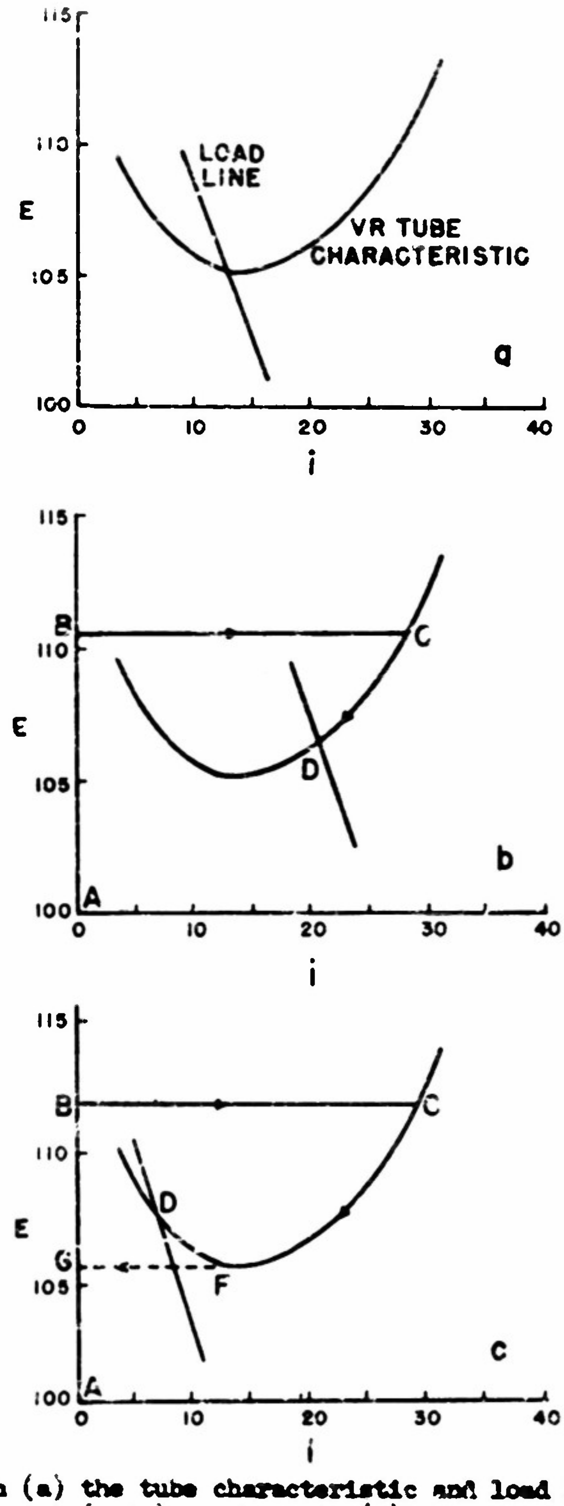

Figure 2 - In (a) the tube characteristic and load line are shown. The path of the point (E, i_2) is shown in (b) for the case of the intersection D on the high-current side of the tube-characteristic minimum, and in (c) for D on the low current side. E is in volts and i in milliamperes.

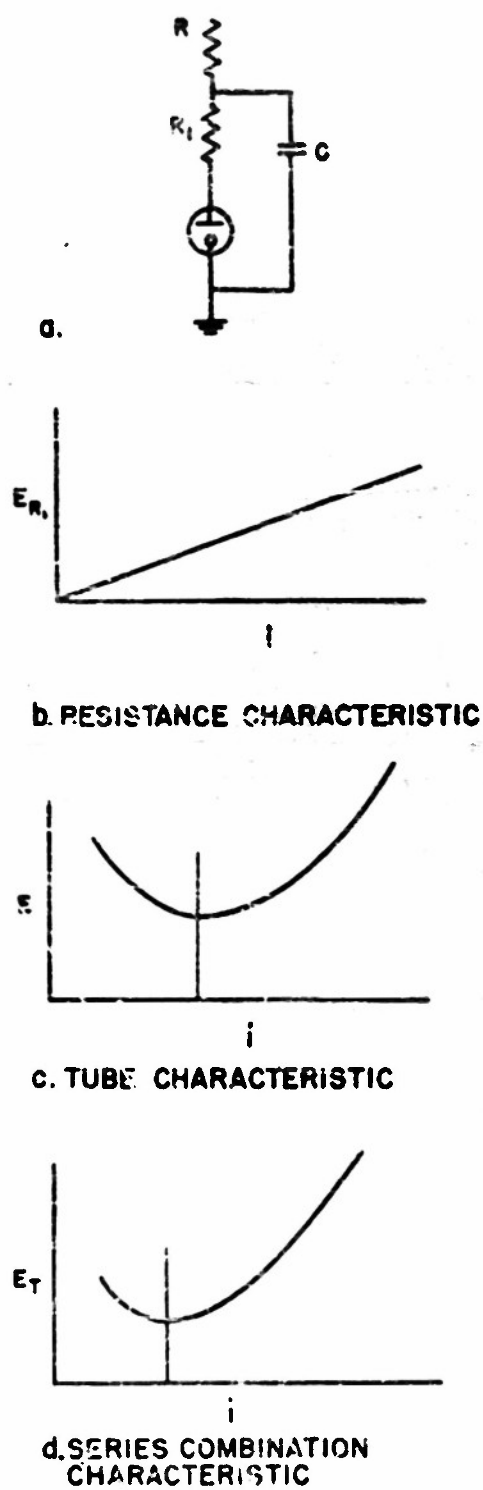

Figure 3 - In (a) the resistance R_1 is placed in series with the VR tube of the regulator circuit. The characteristics of the resistance (b) and tube (c) in series add to give the combined characteristic (d). The minimum of the series combination occurs at a lower current than does that of the tube alone.

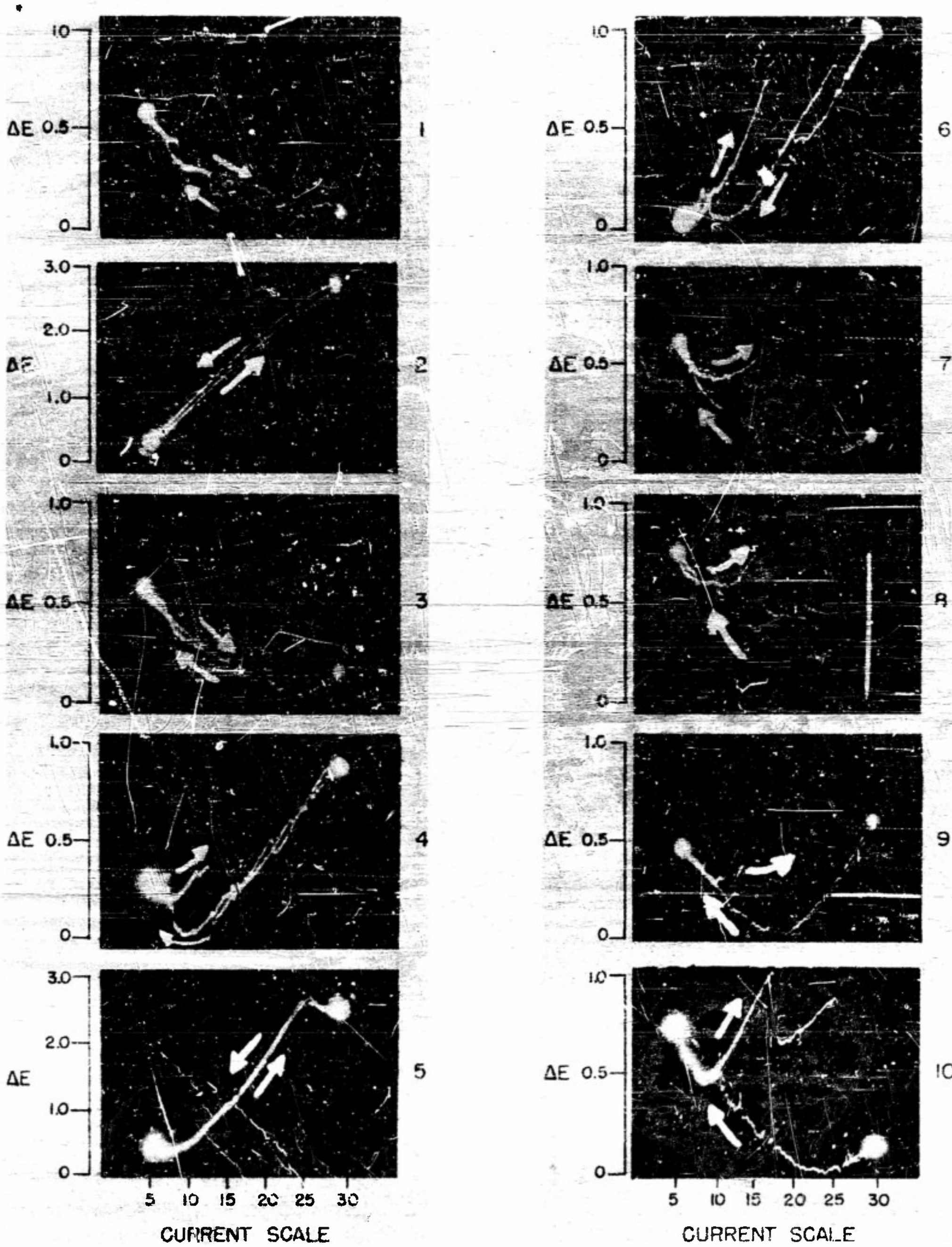

Figure 4 - Current-voltage characteristics for ten VR105 voltage-regulator tubes. The arrows indicate the direction of current change. The voltage ΔE is in volts and the current i is in milliamperes. Note that the voltage scale is not the same in all cases. These tubes were taken from those at hand in the laboratory. No effort was made to obtain a representative sampling from various manufacturers and for different operating voltages.

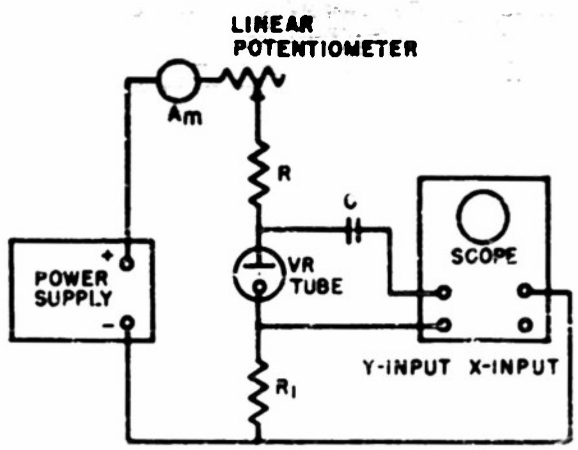

Figure 5 - Circuit used to determine the current-voltage characteristics of voltage-regulator tubes

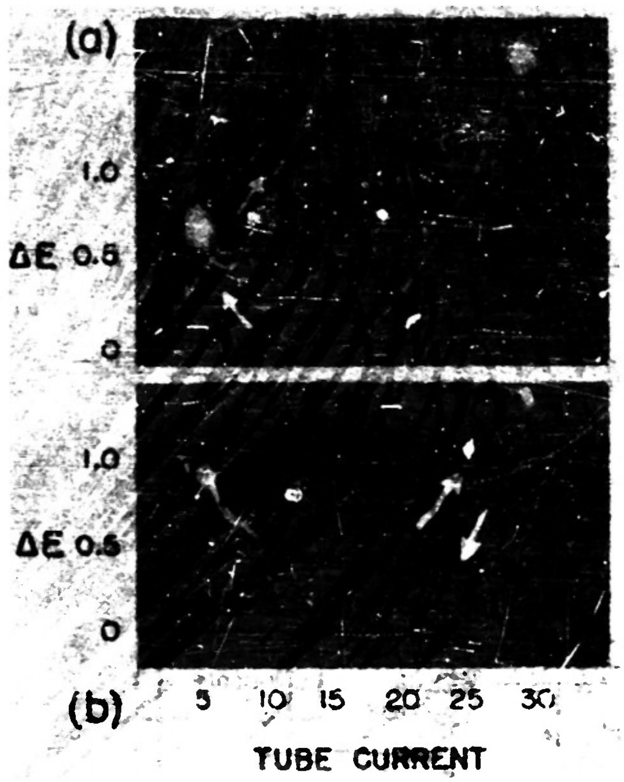

Figure 6 - Tube characteristics of VR tube number 9. Record (b) was obtained a day later than record (a). Increasing-current characteristics similar to that of record (a) were also observed at the time record (b) was made. The characteristic curve for Figure 4 was made two weeks later. The arrows indicate the direction of current change. ΔE is in volts and the tube current in milliamperes.

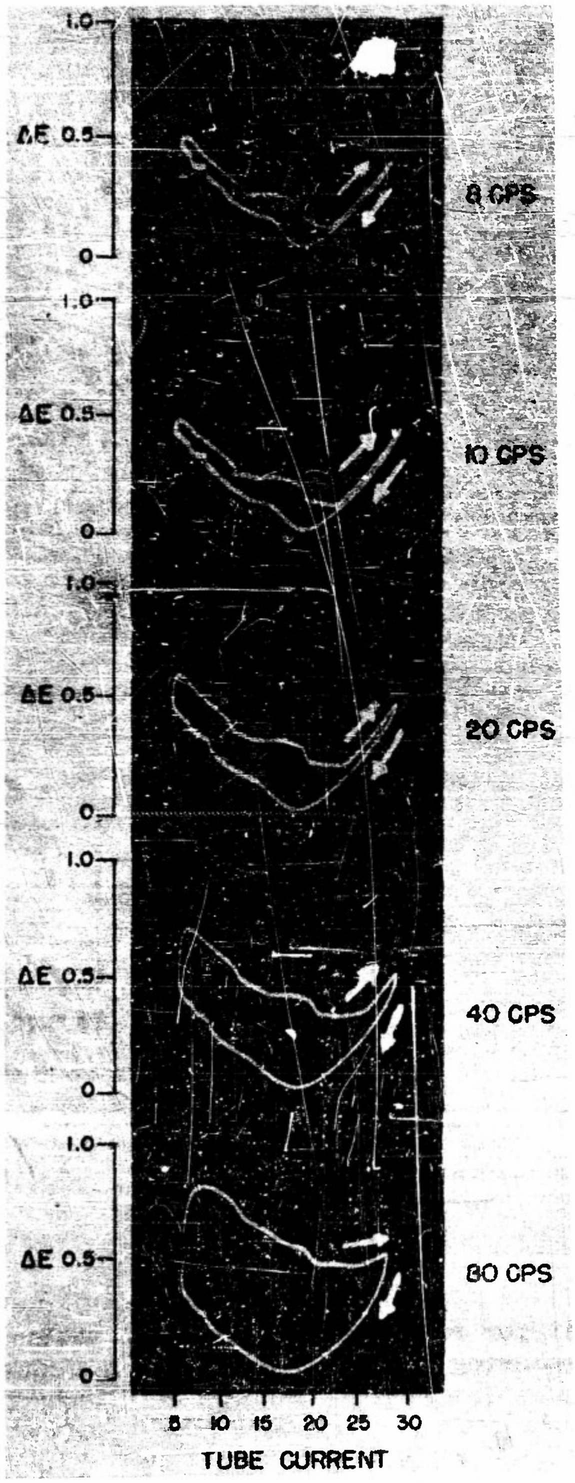

Figure 7 - Voltage-regulator tube number 9 current-voltage characteristic for several cycling rates. The arrows indicate the direction of current change.

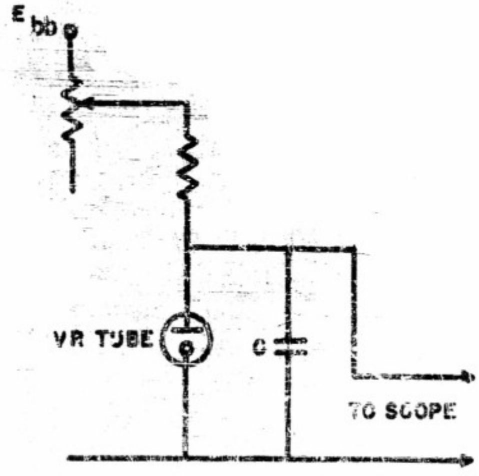

Figure 8 - Circuit for relaxation-oscillation tests. The milliampere meter used for measuring the tube current is not shown.

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(c) Kirkpatrick, G. M., "Characteristics of Certain Voltage-Regulator Tubes", Proc. I.R.E., 35, pp. 485-489, (1947).