RCA MANUFACTURING COMPANY, INC.

A RADIO CORPORATION OF AMERICA SUBSIDIARY

Harrison, New Jersey

RCA RADIOTRON
DIVISION

APPLICATION NOTE No. 84
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APPLICATION NOTE
ON
THE OPERATION OF PHOTOTUBES

The behavior of a phototube for given operating conditions can be predicted from the anode characteristics of the tube. These characteristics, which correspond to the plate family of an amplifier tube, show the relation between anode current and anode voltage for different values of light input. It is the purpose of this Note to show how the anode characteristics of a phototube can be used to predict performance under given operating conditions.

The solid-line curves of Fig. 1 are the anode characteristics of a typical vacuum phototube having a caesium-oxide coated cathode. When a small amount of inert gas, such as argon, is admitted to the tube, the anode characteristics of the phototube change to those shown by the dashed-line curves of Fig. 1. The dashed-line curves are typical of gas phototubes. These two sets of curves will be used in this Note to illustrate the performance of gas and vacuum phototubes.

Steady-Light Operation

Fig. 2A is a typical phototube circuit in which the output voltage appears across resistor R_L. When light falls on the cathode of the phototube, a current flows through R_L and the phototube; at any instant, the sum of the voltage drops across R_L and the phototube equals E, the applied voltage. Hence, the voltage across R_L and the voltage across the phototube for any value of light input can be determined by the intersection of a load line and the anode characteristic of interest. For example, when R_L = 10 megohms, E = 90 volts, and F = 0.04 lumen, the voltage across R_L is 25 volts for the gas phototube and 8 volts for the vacuum phototube. When R_L = 45 megohms, the output voltage is 56 volts for the gas type and 37 volts for the vacuum type. Hence, as R_L is increased, the output voltage of the vacuum type approaches that of the gas type. The effect of load resistance on output voltage for a given value of light input is shown in Fig. 3.

The circuit of Fig. 2A is suitable for applications in which the d-c output voltage feeds a voltage amplifier which, in turn, actuates a relay. For this type of application, the gas phototube is more sensitive than the vacuum type with the same B-supply voltage and load. However, the sensitivity of gas phototubes changes with age, applied voltage, and values of light input. Because of these factors, circuits for gas phototubes should not be critical to reasonable changes in sensitivity. In some applications, these changes in sensitivity can be compensated by an adjustment of the gain following the phototube. In the event that readjustment of the gain is not desirable, a vacuum phototube used with sufficient amplification to give the desired overall sensitivity will prove more stable.

Modulated-Light Operation

Many phototube circuits depend on modulated light for their operation. In a sound-motion-picture projector, for example, the amplifier following the phototube responds only to the modulated component of light input. In such applications, the criteria for sensitivity are not the same as those for steady-light operation.

In circuits which depend on steady-light input for operation, phototube sensitivity is simply $S = I_a/F$, where I_a is the anode current in microamperes and F is the light flux in lumens received by the cathode. In circuits which depend on modulated-light input for operation, phototube sensitivity is defined as

$$S_d = \frac{dI_a}{dF}$$

S is the static sensitivity and S_d is the variational sensitivity of the phototube. Variational sensitivity is analogous to the transconductance (g_m) of an amplifier tube. Because the output of the phototube usually feeds a voltage-operated amplifier, it is important to know the voltage sensitivity of the phototube and its associated circuit. Voltage sensitivity (S_v) in this Note is defined as the ratio of the alternating voltage output to the alternating light-flux input. In symbols,

$$S_v = \frac{dE_a}{dF}$$

where E_a is the output voltage in volts. Now, the action of the circuit of Fig. 2A is analogous to that of an amplifier tube: the cathode is a source of electrons and the anode collects these electrons; the varying light input on the cathode is analogous to an alternating voltage applied to the grid of an amplifier tube. Therefore, the alternating output voltage of a phototube is

$$dE_a = dF \cdot S_d \frac{r_p R_L}{r_p + R_L}$$

where r_p is the variational resistance in ohms of the phototube and is equal to the slope (dE/dI) of the anode characteristic at the operating point. Since voltage sensitivity is the output voltage per unit of light-flux input,

$$S_v = S_d \frac{r_p R_L}{r_p + R_L}$$

The physical interpretation of this last equation is important. The internal resistance of the phototube shunts the load resistance R_L; the change in current due to a change in light flux causes a voltage drop across the parallel combination of r_p and R_L. Thus, the output voltage may be low, even though S_d is high, because the internal resistance of the phototube reduces the generated voltage.

The internal resistance of a vacuum phototube is very high, while that of a gas phototube is low over a large portion of its operating range. The value of r_p at a point on any anode characteristic can be determined by measuring the slope at the point of interest. S_d is constant for vacuum phototubes over their operating range, but is not constant for gas phototubes. For this reason, it is desirable to calculate the performance of phototubes by graphical methods. However, it should be noted that for vacuum phototubes the output voltage can be calculated with fair accuracy by the relation

$$E_a = F\, S_d\, R_L$$

where F is the alternating component of the light input in lumens and E_a is the alternating voltage output in volts.

Consider the typical phototube circuit of Fig. 2B. The load is R_L for steady-light input and is the parallel combination of R_L and R_g for alternating-light input, provided the reactance of C is negligible at the lowest frequency of interest. To predict the operation of the phototube when the light input is modulated, draw the load line R_L from the B-supply voltage, as shown in Fig. 1. For a steady-light input of 0.06 lumen, the operating point is O for the vacuum-type phototube and is O' for the gas-type phototube.

A convenient value of R_L = 10 megohms is assumed. When $R_g = R_L$ and the amplitude of the sinusoidal light input is constant, load lines AB and A'B' represent the operating lines for the vacuum and gas phototubes, respectively. Now, when the steady-light input is modulated 66-2/3%, for example, the peak value of light input is 0.1 lumen and the minimum value is 0.02 lumen; the corresponding changes in voltage across R_g are (67.5 - 51) = 16.5 volts for the gas phototube and (82 - 74) = 8 volts for the vacuum type. These values are the total changes in output voltage; the peak values of the fundamental components are approximately half these values.

For a sinusoidal variation in light input, the distortion is negligible for the vacuum phototube and is appreciable for the gas phototube.

the second-harmonic distortion may be calculated from the relation

$$\text{Per Cent Second Harmonic} = \frac{(I_{max} + I_{min} - 2\ I_o)}{2(I_{max} - I_{min})} \times 100$$

where I_{max} and I_{min} are the maximum and minimum instantaneous values of current, respectively, and I_o is the current at the operating point. Substituting the values obtained from Fig. 1 for the gas phototube, we have

$$\text{Per Cent Second Harmonic} = \frac{4.6 + 1.3 - (2 \times 3.2)}{2(4.6 - 1.3)} \times 100 = -7.5\% \text{ (approx.)}$$

The sign of a harmonic indicates its phase; the negative sign in this example signifies that the average value of the anode current is less with modulation than without modulation. This simple analysis shows that for chosen values of R_L, R_g, and E, and with the same B-supply voltage, the gas-type phototube furnishes about twice as much output as the vacuum type; however, the output of the gas type may contain too much distortion for some purposes.

A comparison of the anode characteristics of the two types of phototubes shows that for very large values of load resistances corresponding to the light flux on the cathode, the performance of both types is identical, because the sensitivity of the gas phototube approaches that of the vacuum phototube at low values of anode voltage. When R_g is infinite, the calculations for output voltage and distortion are made along the load line corresponding only to R_L.

The recommended maximum anode voltage for a gas phototube is 90 volts. When the anode voltage rises above 90 volts, a glow discharge takes place and the active emitting surface of the cathode sputters off. Thus, the peak value of the maximum alternating output voltage from a gas phototube is limited to a little less than 90/2, or 45 volts.

The recommended maximum d-c anode-supply voltage for a vacuum phototube is 500 volts. In order to obtain the maximum voltage output from a vacuum phototube supplied with modulated light, it is necessary to adjust the anode voltage under static conditions to a value approximately one-half of the maximum d-c supply voltage. This adjustment permits the modulated voltage output to have a peak value of nearly 250 volts.

From this discussion, it is seen that when the respective maximum anode voltages are applied to each type of phototube, and when the value of the load on the vacuum phototube is increased until the minimum instantaneous anode voltage (E_{min}) is the same for both types, the voltage sensitivity of the vacuum phototube can be much higher than that of the gas type. In the limiting case when maximum output voltage is obtained from each type for the same value of light input, the voltage sensitivity of the vacuum phototube is approximately 250/90, or 2.7 times that of the gas phototube.

The static and variational sensitivities of gas phototubes vary with age, temperature, light-flux, and anode voltage. In applications where changes in sensitivity necessitate readjustments of circuit conditions, consideration should be given to the use of vacuum phototubes. It is easy to compensate for the comparatively low gain of vacuum phototubes under certain operating conditions by increasing the gain of the succeeding amplifier.

A good frequency characteristic is desirable in many cases. When a vacuum phototube is used, the anode-cathode capacitance of the phototube and the equivalent shunt capacitance of the associated circuit determine the high-frequency response characteristic. When a gas phototube is used, the time necessary to deionize the gas is also a factor in determining high-frequency response. The relative magnitudes of the effects of capacitance and gas on high-frequency response depend on the physical placement of the components and their electrical characteristics.

Hiss Output

The absolute value of hiss output is in general not as important as the signal-to-hiss ratio. The data in Fig. 4 show the relation between signal-to-hiss ratio and light flux for typical vacuum and gas phototubes. When it is desirable to have a large signal-to-hiss ratio, the use of a vacuum phototube may be preferable.

Determination of Light Flux

The success of any method for predicting the performance of a phototube depends on the accuracy with which the light flux received by the cathode is known. The light flux in lumens on the cathode can be determined when the candlepower of the light source, the distance between light source and cathode, and the area of the light spot on the cathode are known. The light flux, F, in lumens, is

$$F = \frac{(CP)\ A}{144\ R^2}$$

where (CP) is the average candlepower in candles of the light source; A, the area of the light spot on the cathode in square inches; and R the distance in feet between the light source and the phototube. This formula should be used only when R is much greater than the largest dimension of the light source.

In most applications, it is necessary to shield the phototube from extraneous light; a small aperture, about 0.5-inch in diameter, admits the light that actuates the tube. For a light spot of this size, the value of F becomes

$$F = 0.00137\ \frac{(CP)}{R^2}$$

The following table lists the approximate candlepower rating of a number of standard inside-frosted Mazda lamps which are not surrounded by reflecting surfaces.

Watts	Bulb Designation	Initial CP (Approx.)
15	A-17 I.F.	-
25	A-19 I.F.	-
40	A-19 I.F.	34
50	A-19 I.F. (Rough Service)	35
60	A-21 I.F.	60
75	A-21 I.F.	82
100	A-23 I.F.	120
150	A-25 I.F	200

Under "bulb designation," the first letter indicates the shape of the bulb, the following number is the maximum diameter of the bulb in eighths of an inch, and the letters I.F. signify inside frosted.

In the case of automobile headlight lamps, the rated value of candlepower obtains for the direction which is perpendicular to the plane of the filament.

A value of light flux obtained from these data is approximate and should serve only as a guide. Final values of circuit constants should be based on tests with the equipment operating over the expected range of line-voltage variation.

PHOTOTUBE ANODE CHARACTERISTICS

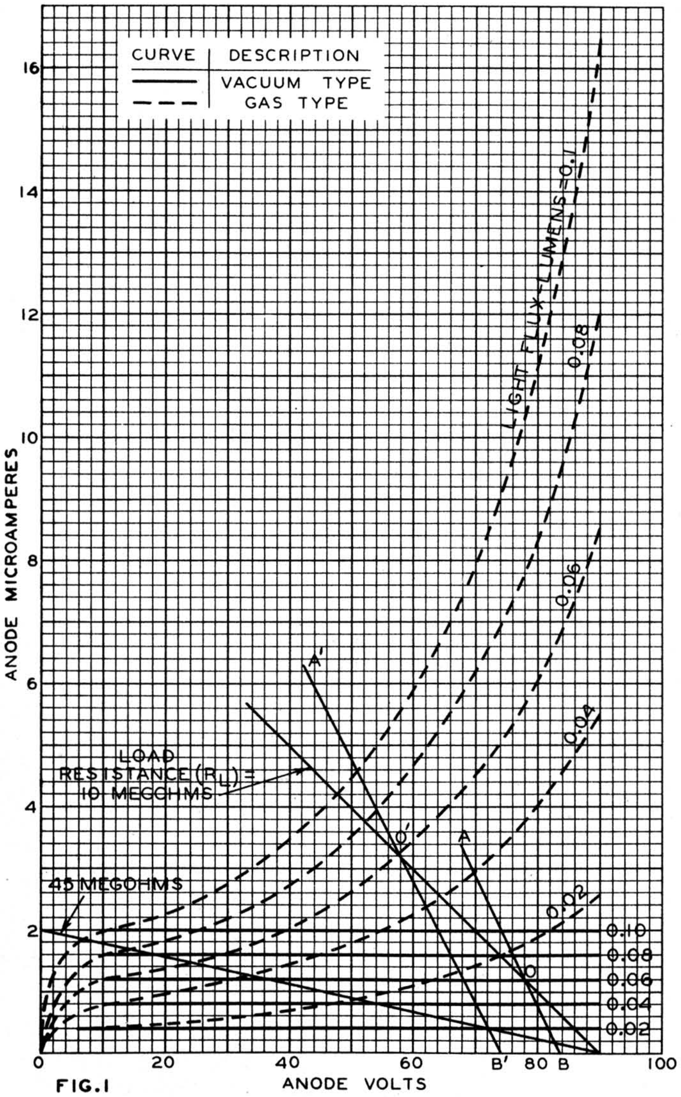

FIG. I

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PHOTOTUBE OPERATING CHARACTERISTICS

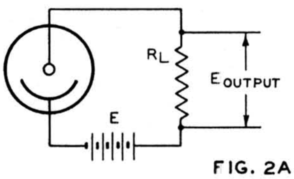

FIG. 2A

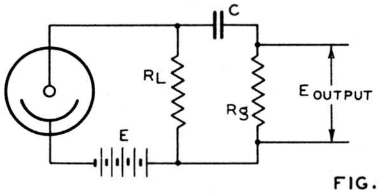

FIG. 2B

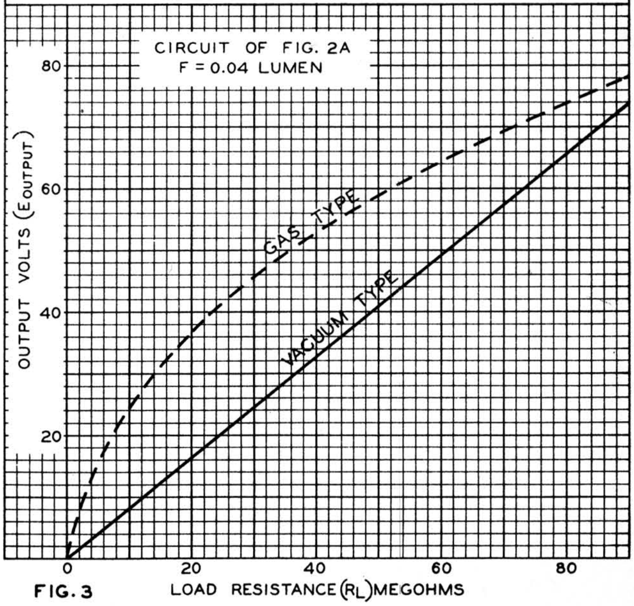

FIG. 3

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SIGNAL-TO-HISS RATIOS OF TYPICAL PHOTOTUBES

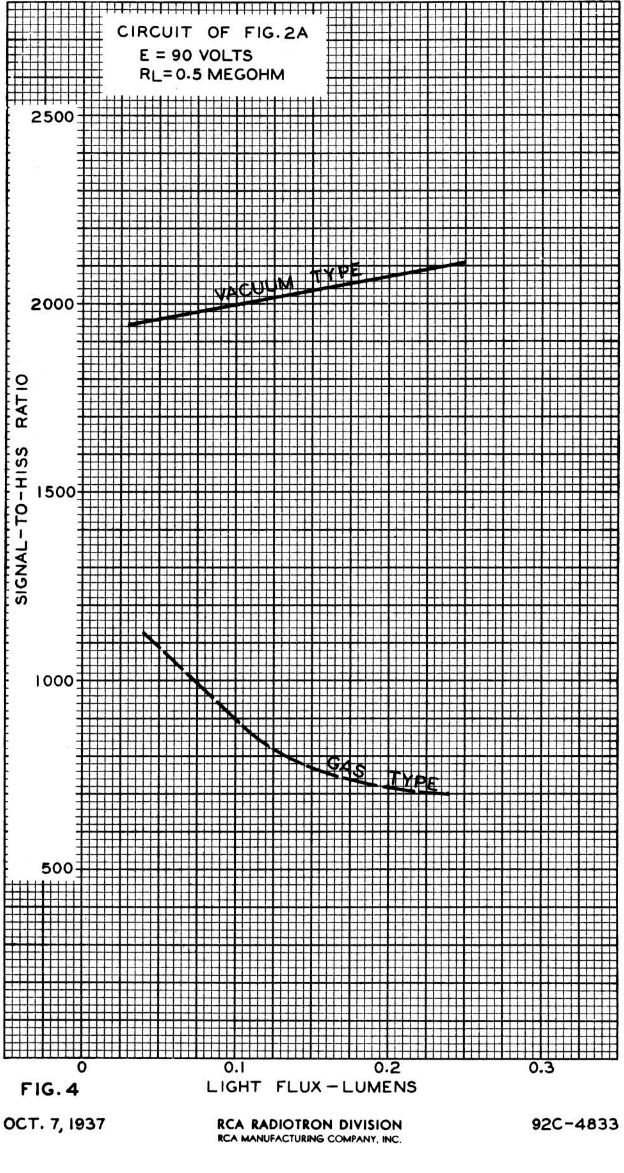

FIG. 4

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