User's Manual

PHOTOMULTIPLIER

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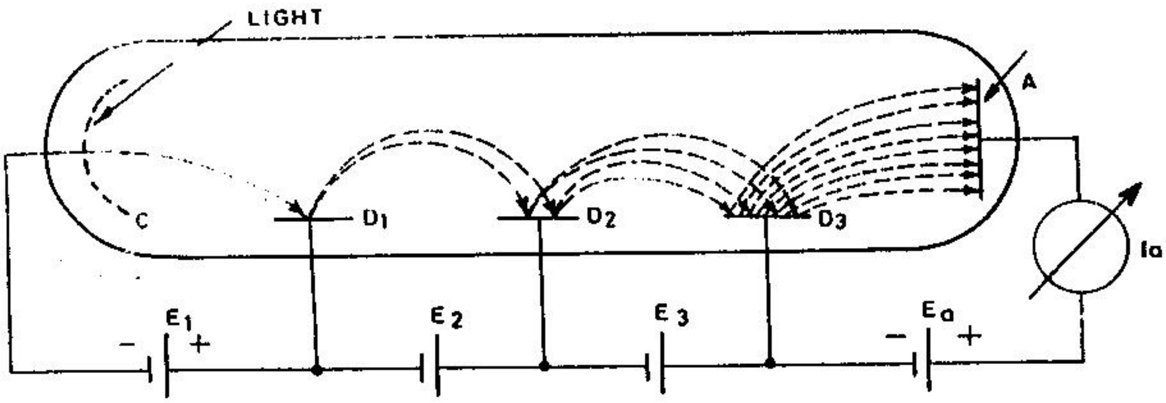


FIG (5-1) 1 PHOTOMULTIPLIER, SCHEMATIC DIAGRAM.

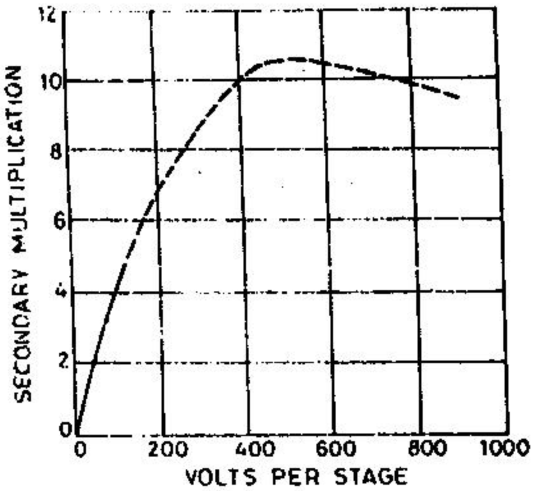


FIG. (5-1) 2 GAIN PER STAGE OF A PHOTOMULTIPLIER (typical for RCA 931 A AND 1P 21 - type dynode surfaces) (from R.F. POST NUCLEONICS 10 46 (MAY 1952) by permission).

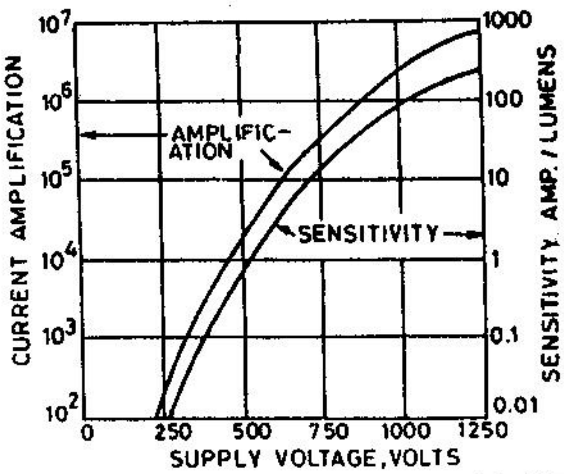


FIG. (5-1) 3 OVER-ALL AMPLIFICATION AND SENSITIVITY OF A PHOTOMULTIPLIER VOLTAGE PER STAGE = 1/10 OF SUPPLY VOLTAGE (from RCA TUBE MANUAL TUBE 1P 21; by permission)

PHOTOMULTIPLIER

GENERAL

A schematic diagram of a photomultiplier is shown in Fig. (5-1)1. Light strikes a photocathode C and liberates electrons; the electrons are accelerated by a voltage E_1 and focused upon an electrode, the dynode D_1, where each incident electron causes the emission of several secondary electrons. The same process is repeated at the dynodes D_2, D_3,....... The electrons from the last dynode stage are collected by a positive anode A, and the current I_a is measured. If the gain of each stage (the number of electrons formed by secondary emission for each primary electron) is g and if n dynode stages are used, the total amplification is

$$A = g^n$$

The value of g varies with the voltage between successive dynodes and with the surface composition and the geometry of the dynodes from 0.5 to about 10.

The focusing of the electrons from one stage to the next can be accomplished with magnetic or electrostatic electron- optical systems. Recent constrictions use electrostatic focusing systems almost exclusively.

The gain and the sensitivity of photomultipliers vary with the voltages applied to the dynode stages. A typical characteristic for a single stage showing the gain per stage over a wide range of applied voltages is shown in Fig. (5-1)2, for continuous operation only the part indicated by a solid line is used. In this range, the characteristic can be expressed analytically, according to Larson and Salinger, by

$$g = k\sqrt{E_{st}}$$

Where k is a constant and E_{st} is the voltage applied to the stage. A characteristic showing the over-all current amplification of a photomultiplier as a function of the applied voltage is shown in fig. (5-1)3.

The amplification can be controlled, within wide limits, by changing the supply voltage applied to the photomultiplier.

INPUT CHARACTERISTICS

The spectral sensitivities of photomultiplier tubes are determined by the characteristics of their cathodes and are similar to those described in Fig. (5-1)4. The sensitivity of the

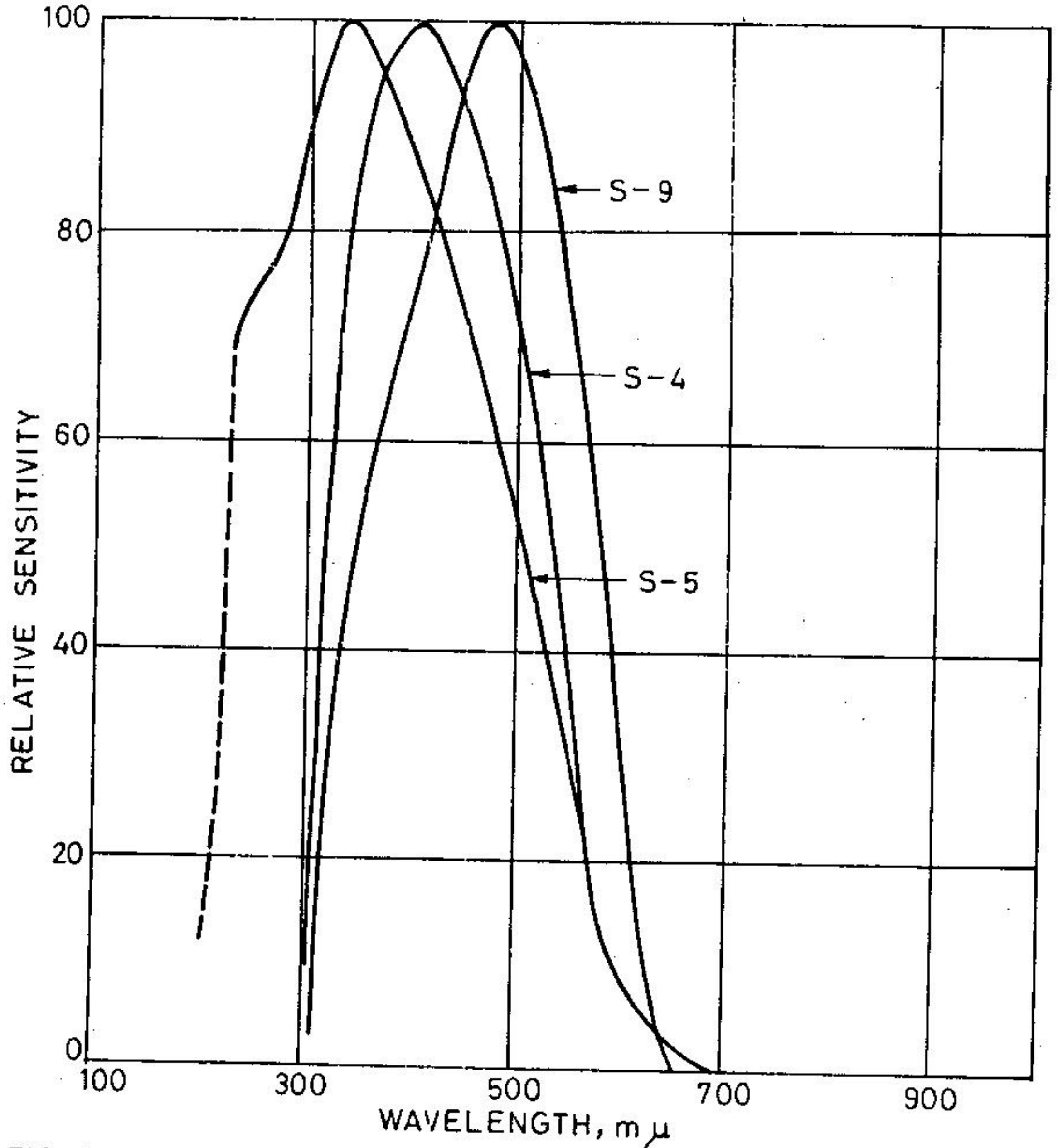


FIG. (5-1) 4 RELATIVE SENSITIVITY OF DIFFERENT COMMERCIAL PHOTOCATHODES (from RCA TUBE MANUAL; by permission).

photocathodes in photomultipliers is, in general, of the order of 60 μA/lumen. The light intensity level for which a photomultiplier is suitable determined primarily by the method of operation of the photomultiplier. The lower limit is set by a dark current and by noise. At high levels of illumination, the useful range of a photomultiplier is limited by fatigue and life time considerations.

An exposure to light in excess of the specified level can cause a reversible and, under extreme conditions, irreversible reduction of the sensitivity (fatigue). The fatigue effect can be caused, even without the application of a voltage to the photomultiplier, by an attachment of electronegative gases that remain in the tube after pumping. With voltage applied to the photomultiplier, the impact of positive ions tends to deteriorate the cathode surface or the dynode surfaces. Also, the exposure to high levels of illumination causes electrons to be emitted from the cathode at a high rate. These electrons are not replenished fast enough from internal layers, and a number of positive ions remain unneutralized. The result is decrease of sensitivity and may be a shift of spectral distribution, in particular a reduction of the photoelectric threshold to shorter wavelengths. Frequently, the photocathode recovers after a period of idleness (several minutes to hours) in darkness at room temperature; recovery may also be achieved by short heating or by irradiation with rod or infrared light of wavelength longer than the threshold wavelength. A fatigue effect also occurs at the last dynode stage or stages under the influence of high current. If the continuous anode current is less than 1 mA, the tube usually recovers after storing in darkness for a day. At higher currents, the sensitivity can be irreversibly lost.

OUTPUT CHARACTERISTICS

For continuous operation and if longtime stability is required, the output current should be limited to a value of 10^{-5} to 10^{-4} A. Much higher currents can be used for pulsed operation.

The output impedance is essentially that of the load resistor in the anode circuit; it is, in general, in the MΩ range.

The output from a photomultiplier is a linear function of the incident light. The deviations from linearity are about 3% or a variation of the light flux between 10^{-9} and 10^{-3} lumen.

The response time of a photomultiplier is, in general, shorter than 10^{-8} sec.

Undesirable signals can be caused by dark current and noise. Dark current, by itself, does not necessarily introduce an error if corrections for it can be applied. However, the noise component of the dark current is frequently objectionable. The dark current in commercial photomultipliers at room temperature is generally of the order of 10^{-7} A.

The dark current is caused by three phenomena :

(1) Leakage current, predominantly at the inside of the tube and frequently caused by traces of cesium, but also occurring at the outside of the tube and in the tube socket.

(2) Thermionic emission from the photocathode and, to a smaller extent, from the first dynode stages.

(3) Regenerative ionization, i.e., the impact of positive ions upon the cathode, but also the incidence of light from excited gas molecules and from glass fluorescence upon the cathode.

The relative magnitude of these three sources of dark current and their variation with the voltage applied per stage are shown in Fig. (5-1)5.

Thermionic component of the dark current can be reduced by cooling of the tube. Roughly, each 10°C decrease of temperature causes a reduction of the thermionic current to one-half. The thermionic current may also be reduced by reducing the sensitive area of the photo-cathode.

Noise in photomultipliers is of two fold origin; the random variation of the thermionic emission and that of the photo-emission. The rms noise current, measured at the anode, is

$$(I^2)^{1/2} = G\left[2\,e\,Df(i_t + i_p)\right]^{1/2}$$

where G is the amplification (gain) of the photomultiplier tube, e the charge of the electron, f the bandwidth of detecting system, i_t the thermal emission from the cathode (at room temperature of the order of 10^{-14}), and i_p the photocurrent at the cathode. The signal-to-noise ratio is

$$\frac{S}{N} = \left[\frac{i_p^{\,2}}{2\,e\,Df\,(i_t + i_p)}\right]^{1/2} \qquad (1)$$

Engstrom remarks that this equation does not include the noise resulting from thermionic emission from the dynodes, which he estimates to be 3% of that expressed in Eq. (1), nor that associated with random secondary emission, of the order of 15 %.

The most effective means to reduce the noise level in photomultipliers consists in reducing the thermionic emission by operating the tube at low temperature. Reduction of the temperature from room temperature to that of liquid air reduces the noise level by a factor of 100.

The equivalent noise input, i.e., that light intensity at the input of the photomultiplier which furnishes at its output a current equal to the rms noise output over a band width of 1 cycle is, for commercial photomultipliers operated at room temperature, between 5×10^{-13} and 10^{-11} lumen.

Gordon and Hodgson have observed a reduction of the noise level by a factor of 7 in a photomultiplier that was kept in darkness for five weeks. The effect seems to be due to a decay of glass fluorescence.

The movement of the electrons can be strongly influenced by stray electric and magnetic fields. Even the magnetic field of the earth can cause variations of the photomultiplier output. Adequate shielding should be provided where such stray fields cause errors. Stray light entering the tube can cause erratic results.

OPERATION OF PHOTOMULTIPLIERS

Three different methods of operating photomultipliers are generally distinguished :

(i) The light flux falling upon the cathode can be continuous; the output from the photomultiplier is read directly or after d-c amplification. This method is generally applicable when the incident light level is higher than 10^{-8} lumen. At lower levels, the unavoidable drift of d-c amplifiers can cause serious errors.

(ii) The light beam can be periodically interrupted or modulated by alternating current, and the output can be fed into a-c amplifiers, which are inherently more stable. The method has the further advantage that the band width of the output signal detector can be restricted so that the noise level is reduced. The method is in general applicable for light levels as low as 10^{-13} lumen.

(iii) For lower levels the bursts caused by single photoelectrons are observed or counted. This method permits the measurement of smallest light levels down to the order of 2×10^{-16} lumen.

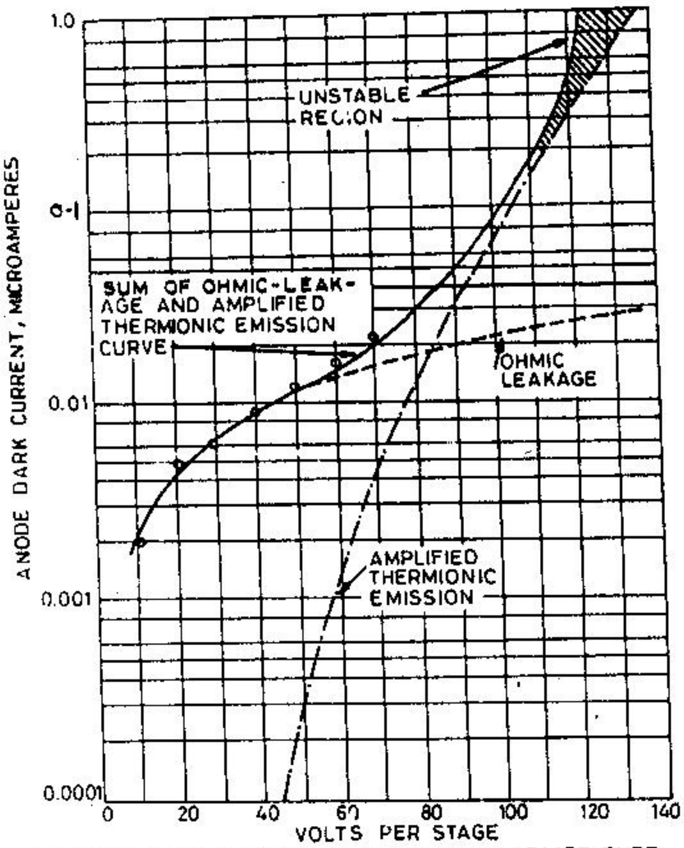


FIG.(5.1)5 DARK CURRENT IN A PHOTOMULTIPLIER TUBE (from R W ENGSTROM Rev. Sci Instr. 37, 430 (1947) by permission).

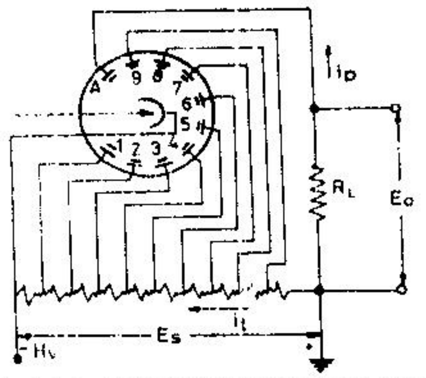


FIG.(5.1)6 PHOTOMULTIPLIER WITH RESISTIVE VOLTAGE DIVIDER: C, CATHODE, A, ANODE, 1 to 9 DYNODES; E_s SUPPLY VOLTAGE, E_o OUTPUT VOLTAGE ACROSS LOAD RESISTOR R_L

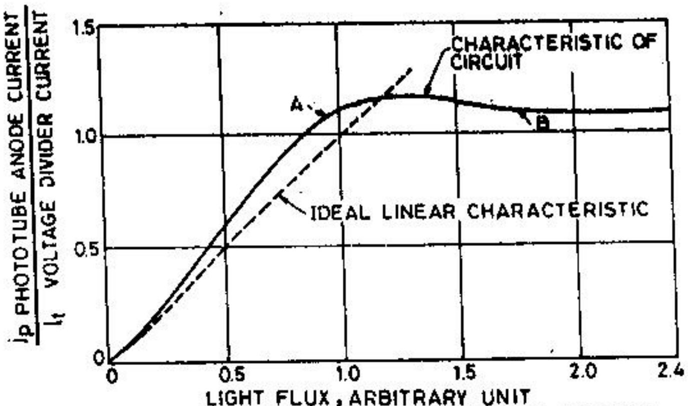


FIG.(5.1)7 RELATIV RESPONSE OF AN R C A 931-A PHOTOMULTIPLIER AS A FUNCTION OF THE LIGHT FLUX IN THE CIRCUIT I_t VOLTAGE DIVIDER CURRENT FOR ZERO LIGHT FLUX (from R.W. Engstrom and E.Fischer Rev. Sci. Instr, 23, 325 (1957) by permission).

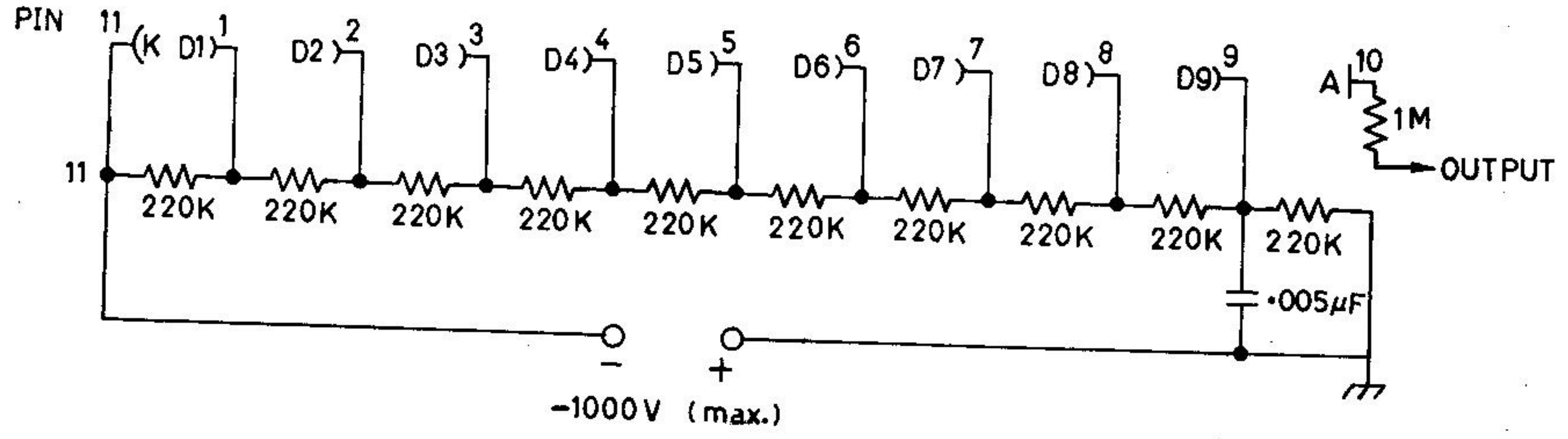
CIRCUITS FOR PHOTOMULTIPLIERS

The simplest circuit to obtain the appropriate voltages for the single stages is a resistive voltage divider, as shown in Fig. (5-1) 6. The operating voltage applied to the voltage divider is of the order of 1 kV; for d-c output, the positive pole is preferably grounded; the partial voltages for the single stages are between 70 and 150 V; the output signal E_O appears across the load resistance R_L and is usually amplified in successive stages. Higher voltages are frequently applied to the initial stage to improve the collection of photoelectrons emitted from the cathode; high collection efficiency (95 to 100%) at this stage is important to improve he signal-to-noise ratio.

The output signal follows a linear function of the incident light flux for small and moderate light levels when the current i_b through the photomultiplier tube is small compared to the current i_t through the resistive network. If the incident light flux increases, the current through the tube increases too, in particular that between the last dynode and the anode. If this current approaches the voltage divider current i_t, the voltage distribution of the voltage-dividing network will be upset; the voltage between the last stages will be diminished, those between the initial stages will be increased (under some conditions to the extent that an internal breakdown occurs). The result may be an increase or decrease of the gain as shown in Fig. (5-1)7.

Since the amplification of photomultiplier tube varies strongly with the supply voltage; operation at constant voltage and the use of stabilized supply sources is required. For instance, a variation of the supply voltage by 1% can cause a variation of the photomultiplier output by as much as 10%.

POSITIVE GROUND



BIASING CIRCUIT FOR
931A, IP_{21} AND IP_{28}

DRG. NO.	CHECKED & APPROVED
SCIENTIFIC EQUIPMENT & SERVICE 16 CIVIL LINES ROORKEE (UP)	