PHOTOTUBES

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Edited by
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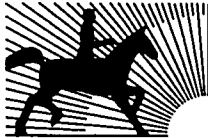
PREFACE

The photoelectric effect is an important concept. Information dealing with phototubes and their relevant amplifiers and circuitry touch upon problems in optics, phototube electronics and amplification. Phototubes, in conjunction with other physical equipment, perform a host of useful services in the electronics industry. Variations in circuit design permit the development of many varied applications which stem from fundamental phototube characteristics.

This book has been organized to help the student understand the more important topics basic to each of the subject fields which relate to phototubes. The material presented goes beyond the basic ideas which have been presented in another volume.* Thus, specific attention has been given to the beginnings of photoelectricity; the early practical photosensitive devices; the empirical laws of photoelectricity; data relating to the radiation spectrum; the intensity-wavelength curves; the basic concept of the quantum theory; photometric standards; luminous intensity and flux; illuminance; the inverse square law; Lambert's law; the Einstein photoelectric equation; threshold frequency and wavelength; illustrative problems using the photoelectric equations; color sensitivity of photomaterials; phototube sensitivity rating; layer emissivity; composite layer phototubes; phototube structure; considerations involving physical structure; direction characteristics; electrode termination; element spacing; the cesium oxide phototube; phototubes for ultraviolet; the relationship of Lambert's law to electron emission; electrostatic field within the phototube; current-voltage relationship and load lines as pertaining to the vacuum phototube; current-light flux relationships; ratings

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*Mark, David, *Basics of Phototubes and Photocells*, New York, John F. Rider Publisher, Inc.,

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and characteristics of vacuum phototubes; secondary emission; gas-filled phototubes; the mechanical behavior of gases; gas amplification ratio; ratings of gas-filled phototubes; nonlinearity of response; multiplier phototube principles; multiplier phototube ratings; essentials of phototube amplifiers; application objectives; phototube relay operation; phototube instrumentation; signal reproduction, and photoelectric servomechanisms.

A minimum of mathematical treatment has been employed, except where an adequate number of problem solutions pertaining to the formulas presented helps to clarify an understanding of pertinent fundamental calculations in phototube circuitry. The analyses presented are sufficiently extensive to permit the interested technician, practicing engineer or advanced student to develop a full comprehension of the important facets of such theory.

Grateful acknowledgment is made to the staff of the New York Institute of Technology for its assistance in the preparation of the manuscript of this book.

New York, New York   A. S.
August, 1959

CONTENTS

FUNDAMENTAL CONSIDERATIONS IN PHOTOELECTRICITY

1. Complements of the Study of Phototubes

The phototube, as an instrument of modern electronics, cannot be properly studied in isolation but must be linked from the start with other physical equipment. Similarly, although the phototube itself may be described in terms of pure electronics, its theory of operation and application to the service of mankind can be adequately comprehended only by studying physical phenomena other than photoelectricity at the same time.

A phototube operates by virtue of radiation falling on a sensitive surface; thus, an understanding of phototube action must entail an understanding of the laws of radiation, optics, and photometry, together with the units of measure now used in these fields.

A phototube is seldom used to activate a relay or other transducer directly. This at once demands a thorough understanding of d-c and a-c amplifiers normally employed as phototube follow-up equipment.

Finally, as a result of the dual nature of the photoelectric effect, i.e., the combination of radiation and electronic action, a comprehensive grasp of the subject cannot be obtained unless one considers modern radiation theory.

All of these associated studies are included in this book. Ordinarily, the phase of optics involving radiation laws, luminance,

illuminance, luminous flux, luminous intensity, and similar facets of the subject is a source of confusion to electronics specialists meeting these subjects for the first time. For this reason, we shall treat them with adequate detail to assure full understanding.

In addition, a sufficient amount of material dealing with phototube amplifiers and their relevant circuitry will also be discussed so that the reader will be able to handle problems involving all three phases of the field: *optics, phototube electronics,* and *amplification.*

2. The Beginnings of Photoelectricity

It is generally agreed that photoelectricity as a subject for investigation began with an accidental discovery made by Heinrich Hertz in 1887. Having successfully demonstrated the effect of one oscillatory spark circuit upon another not directly connected to the first,

ULTRAVIOLET
FROM ARC

POLISHED
ZINC
SPHERE

INSULATING
STAND

GOLD LEAF
ELECTROSCOPE
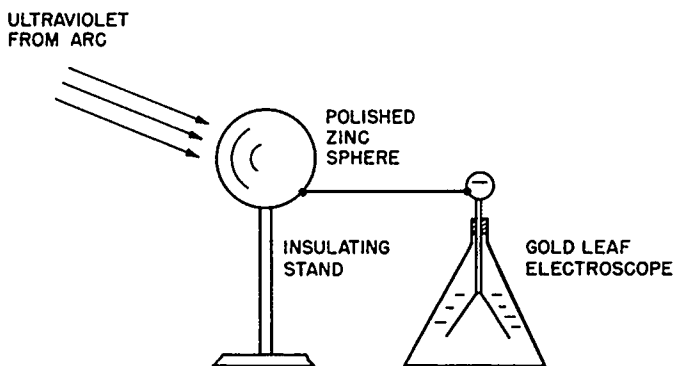
Fig. 1. The Hallwachs apparatus for demonstrating the loss of negative electricity under the action of ultraviolet radiation.

Hertz also noted that ultraviolet light from the first gap made the sparks jump more freely across the second. He further demonstrated that any source of ultraviolet light had the same effect and that the passage of sparks across the gap was encouraged most when the radiation fell upon the negative terminal. This last fact, of such importance to photoelectric theory, was corroborated by Wiedemann and Ebert in 1889.

Late in 1888, Wilhelm Hallwachs succeeded in divorcing the photoelectric effect from the oscillatory discharge effect, demonstrat-

ing that these phenomena were not inseparable. By irradiating a polished zinc sphere connected to a gold-leaf electroscope with the light from a carbon arc lamp, he was able to discharge the leaves when they were initially negatively charged (Fig. 1). Further research revealed that ultraviolet radiation could remove, or cause to be removed, negative electricity from various charged bodies and that the negative electricity moved off along any electrostatic lines that
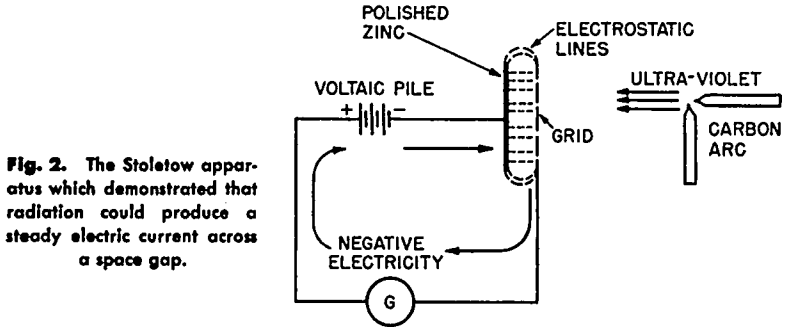
Fig. 2. The Stoletow apparatus which demonstrated that radiation could produce a steady electric current across a space gap.

happened to be present. This phenomenon, now known to be the emission of electrons under the influence of radiation, was originally called the *Hallwachs effect*.

In the same year, Stoletow published in the *Journal de Physique* an account of an experiment which approached modern photoelectric techniques. A coarse metallic mesh grid was placed between a highly polished pure zinc plate and a source of ultraviolet light. Connected in series between the plate and the grid was a source of emf and a high-resistance galvanometer (Fig. 2). As the plate was irradiated through the grid, the galvanometer indicated a small but steady current flowing in such a direction that the results of previous investigators were confirmed. Negative electricity appeared to leave the zinc plate under the action of the radiation, and to move to the positive grid along electrostatic lines of force.

3. The First Practical Photosensitive Devices

The most important advances in the study of photoelectric action and the development of practical photosensitive devices is attributed to the team of Julius Elster and Hans Geitel. From the observations

that aluminum, magnesium, and zinc were the most sensitive photo-materials, they became convinced that other metals with even greater electropositive characteristics* would be even more responsive to radiant energy. Unfortunately, highly electropositive alkali metals such as potassium and sodium are quite unstable in air so that they cannot be used in their pure form as photoelectric elements. Elster and Geitel discovered, however, that by amalgamating sodium and potassium with mercury they could form a photosensitive electrode that was considerably more effective than zinc or other metals previously tried.

Two important discoveries emerged from the preliminary work of these investigators: (1) amalgamated alkali metals made very sensitive photoelectrodes, and (2) these electrodes responded to visible light as well as ultraviolet. This last contribution forms the basis of modern light-activated devices of all types.

Elster and Geitel continued their work on photoelectric materials until at least 1912. They showed that hydride crystals of the alkali metals exhibited even greater sensitivities than the amalgams used in their earlier experiments. Finally, by passing a glow discharge through hydrogen gas enclosed in an alkali cell, they were able to convert the original hydride into a colloidal chemical configuration which displayed a photosensitivity two whole orders of magnitude greater than their original amalgams. Modern photoemissive cathodes are similar in many respects to the Elster and Geitel hydrogenated surfaces. These original cells have come to be recognized as the first practical photosensitive devices that were designed and constructed.

4. Empirical Laws of Photoelectricity

In some of their intermediate experimental work, Elster and Geitel had shown that the carrier of photoelectric currents was a negatively charged body emitted from the cathode. In a sense, this was an extension of the discovery by Hertz that the *negative* electrode of his spark gap was the one affected by radiation. The two co-workers never succeeded in determining whether this negatively

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* An electropositive element stands high in the electromotive chemical series. Aluminum and magnesium are among the most electropositive metals, surpassed only by the alkali metals such as sodium and potassium.

charged body was a negative atom or the pure negative entity dis-
covered by J. J. Thomson and later called the *electron*. In 1900,
the question was settled by Paulus Lenard who demonstrated that
the photoelectric current carrier was identical with Thomson's
cathode-ray particle, the electron. Later, Alberti in 1912 proved
beyond any doubt that the two particles were identical both in
charge and mass by means of a series of very exact measurements.

As the work of the early experimenters was gradually refined by
later investigators, two significant laws of photoelectricity gradually
emerged from the empirical results. The first law is neither startling
nor unexpected: *The number of electrons per unit time emitted
from a photosensitive surface is directly proportional to the intensity
of the incident radiation.* Careful measurement has shown this law
to be valid over extremely wide ranges of light intensity.

The second law of photoelectricity contains some rather surpris-
ing implications: *The maximum energy of electrons from a given
photoemitter is not affected by the intensity of the incident radia-
tion but depends entirely upon the frequency of the radiation.* It
became evident early in the investigation of these laws that the
maximum electron energy was strictly proportional to the frequency
of the incident light. The implications contained in this law may
be summarized thus:

(a) When a photosensitive surface is irradiated by a beam con-
taining many light frequencies, the electrons emitted from the sur-
face may possess various velocities.

(b) The highest-velocity electrons are those released by the radi-
ant energy having the highest frequency.

(c) The highest velocity attained by emitted electrons is not in
the least influenced by the radiant intensity. In other words, if a
feeble source of ultraviolet light succeeds at all in knocking elec-
trons out of a sensitive surface, these electrons will move off with
just as much speed as they would if the same surface were illumi-
nated by an extremely powerful beam of ultraviolet of the same
frequency as the first. This is an unexpected result. If light is merely
a wave phenomenon, there is absolutely no reason for the effects
described by the second law of photoelectricity. High-frequency
waves such as those in the ultraviolet portion of the spectrum should
not, according to the wave theory, possess any more energy than low-
frequency waves of the same absolute intensity. How then can the
high-frequency radiation impart greater energy to photoelectrons?

This question and others of similar nature will be answered in the next chapter with the help of Einstein's photoelectric equation and Planck's quantum theory.

5. The Radiation Spectrum

A thorough understanding of phototubes must be based upon an equally thorough comprehension of the nature and characteristics of radiation. Let us review the radiation spectrum over the limits that are applicable to the study of photoelectricity.

The ultraviolet portion of the spectrum is arbitrarily assumed to start at a wavelength of approximately 1.3×10^{-6} centimeters.* This figure was originally derived from a determination made by Millikan and Bowen in 1924 with a spark-spectrograph which they used to detect radiation having the characteristics of ultraviolet down to a wavelength of 1.36×10^{-6} cm. There is actually no sharp line of demarcation between the extremes of the visible spectrum and the beginnings of either the ultraviolet or infrared regions. For convenience, however, it is assumed that the average person, or "standard observer," is limited in vision between 4000 Å and 7500 Å as shown in Fig. 3.

Photoelectric devices capable of responding to wavelengths well into both the infrared and ultraviolet regions, as well as those in the visible spectrum, are now commercially available. Thus, both these invisible regions must be included in what we call *the photoelectric spectrum.*

Wavelengths shorter than the shortest ultraviolet fall into the soft x-ray domain; similarly, wavelengths longer than the extreme infrared are classified as radio waves. Since photoelectric effects are normally not in evidence in these domains, they are not included in the photoelectric spectrum.

6. The Dilemma of the Intensity-Wavelength Curves

Most of the studies in radiation have been made in terms of the emissivity of a *blackbody.* A blackbody is defined as a perfect ab-

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* Wavelengths are customarily expressed in centimeters (cm), Angstroms where $1Å = 10^{-8}$ cm, and millimicrons where $1 m\mu = 10^{-7}$ cm. Thus 1.3×10^{-6} cm = 130 Å = 13 mμ.
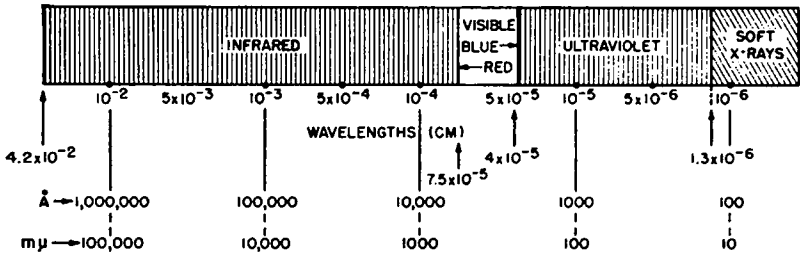
Fig. 3. The photoelectric spectrum.

sorber or radiator. It is an object which is able to absorb or emit equally well all frequencies of radiation. The closest approach to a perfect blackbody is obtained experimentally in the form of a hollow cavity with nonreflecting walls having a very tiny aperture in one wall. Thus, any radiation that finds its way through the aperture has virtually zero statistical chance of finding its way out again and is, therefore, completely absorbed. Similarly, radiation originating inside the cavity and passing out through the aperture will appear as though it is coming from a perfect blackbody in which there is no frequency discrimination.

As a blackbody is heated to progressively higher temperatures, it first begins to radiate wavelengths in the infrared, then in the visible red, orange, yellow, green, blue, and finally violet. Before the turn of the twentieth century, it had already been established that, for each discrete temperature of the blackbody, there is one particular frequency for which the radiation intensity is a maximum. For example, a blackbody heated to 3000° Kelvin emits all frequencies corresponding to a wavelength range from about 3000 Å to well above 25,000 Å. The peak intensity occurs at about 9200 Å, however. This is well within the infrared (see Fig. 3). On the other hand, when the temperature reaches 4000°K, the intensity peaks at approximately 7000 Å. Since this is in the visible region of the spectrum (red), the blackbody becomes. visible as a dully glowing red object. To make the blackbody attain a white heat (really blue heat), it is necessary to raise its temperature to nearly 7000°K. The curve in Fig. 4 shows how the wavelength of maximum intensity shifts toward the shorter waves as the temperature of the radiator is increased. It was quickly realized that a good insight into the true nature of radiation could be obtained if an equation that fitted the contours of the curve (Fig. 4) were developed.

An accurate equation was published by Wien in 1894; it is stated as:

$$\lambda_m = C/T \qquad\qquad (1)$$

in which λ_m is the wavelength of maximum emission, T is the absolute temperature, and C is a constant, later evaluated as 0.289 cm degrees. Although this equation, known as *Wien's displacement law*, gave the true relationship between wavelength (and frequency) of
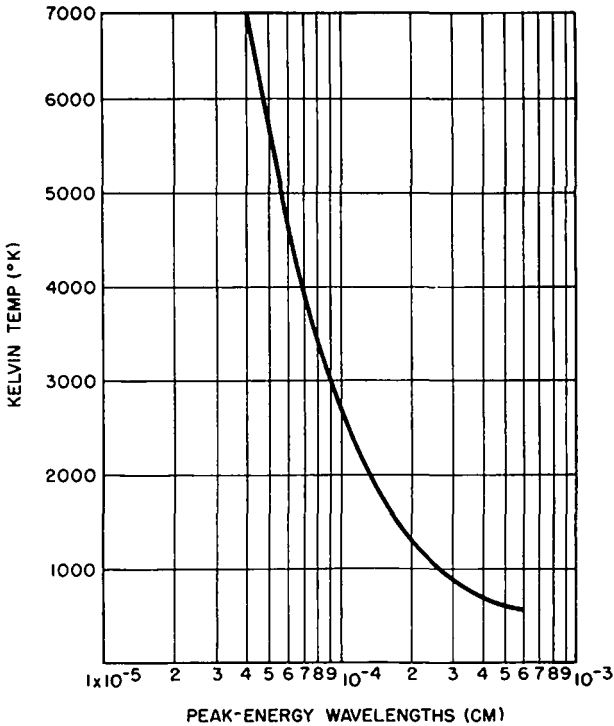
Fig. 4. Spectral shift of peak energies with temperature of blackbody.

maximum emission, it could not explain the spectral distribution of energy radiated by a blackbody at various temperatures. These distribution curves are given in Fig. 5.

In 1896, Wien published an equation that fitted the distributions shown in Fig. 5 nicely for the high frequencies but failed to do so for the lows; very shortly after, Rayleigh proposed an equation that
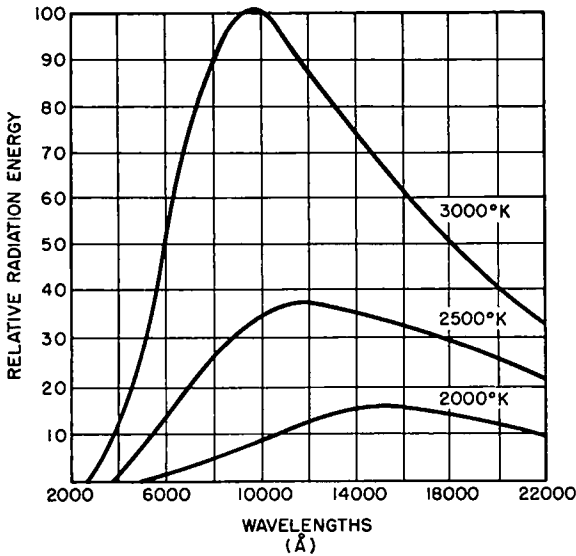
Fig. 5. Spectral distribution curves of blackbody radiation at various temperatures.

agreed with curves for the low frequencies but failed for the highs. Both theoretical approaches were founded on classical radiation laws and classical Newtonian mechanics. It appeared, therefore, that a re-evaluation of the basic concepts had become necessary. The effective solution of this dilemma took place shortly thereafter (1900) in the form of Max Planck's quantum theory.

7. Basic Concept of the Quantum Theory

The failure of the wave theory of radiation to account for the spectral distribution curves led to a revolutionary proposal by Planck. If it is assumed as a starting premise that radiant energy does not flow from a hot body in a continuous stream but rather in discrete packets of energy having certain wavelike characteristics, then it is possible to derive an equation on theoretically logical grounds which fits the distribution curves exactly all along their lengths and for all temperatures. The energy parcels, originally called *quanta* by Planck, are now known as *photons*, particularly when they enter into considerations involving the visible spectrum. Planck showed that the energy of a quantum or photon can be ex-

pressed as the product of the frequency attributed to the "particle" and a constant. In equation form:

$$E = h\upsilon* \tag{2}$$

In this expression, if υ is measured in cps and E is stated in joules, then the value of the constant h (now called Planck's constant) is 6.62×10^{-34} joule/sec. A radiating body can emit 1, 2, 3, or any integral number of quanta, but it cannot emit any fractional number. In normal large-scale emissions, as from bright luminous sources of light, the number of quanta given off is so great that the emission of any single one cannot be detected as a distinct event. Hence, such a process is effectively one of continuous radiation in agreement with the normal experimental observations.

The significance of Planck's work extends beyond the immediate solution of the blackbody radiation problem. His contribution provides a completely new orientation to the concepts of the transmission of radiant energy. This new approach has led to a vast body of information and to the development of physical laws during the last 50 years; in fact, the quantum theory is worthy of being called the forerunner of modern physics. The quantum theory provides the groundwork for a realistic and precise explanation of the laws of photoelectricity. This explanation will be discussed in detail in Chapter 2.

8. Photometric Standards

The science of *photometry,*with which phototubes are inextricably connected, involves four basic measurements for which standards are required. Since light has been shown to be as much a form of energy as heat or electricity, the units used to measure it must take cognizance of its energy characteristics. The four measurements are: (1) The light-giving *power* of a source. Power is defined, as always, as energy per unit time. (2) The amount of *illumination* on a given surface. This is a function of the power of the source and the distance between the illuminated surface and the source. (3) The amount of light *reflected* back from the illuminated surface. (4)

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* The symbol υ is pronounced "noo" and has been universally adopted to designate frequency in cps in connection with the equations relating to the quantum theory and photoelectricity.
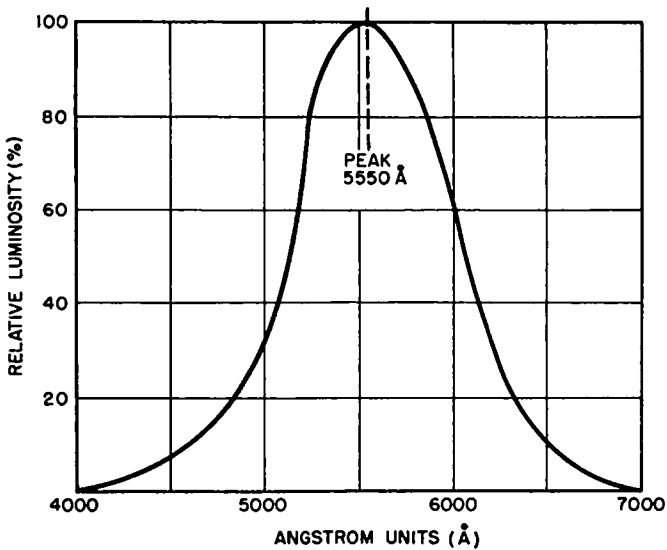
Fig. 6. The response of the human eye to visible light of different wavelengths.

Measurements of (1), (2), and (3) based upon the separate colors that may happen to be of interest.

It is apparent from this outline that photometry must be insepar-ably connected with the behavior of the human eye. Since the eye is capable of differentiating between various wavelengths of light (color) and between varying degrees of brightness, both of these factors must enter into specific photometric measurements. The eye responds unequally to visible light of different colors even though the source for each of them has the same power. Figure 6 illustrates the *average* response accepted by modern photometrists. The nor-mal human eye is most sensitive in the yellow-green portion of the spectrum (about 5500 Å). On each side of this wavelength, the relative luminosity for equal sources falls off rapidly as shown in the figure.

9. Luminous Intensity

If one lamp gives more visible light than another, we say that the lamps differ in luminous intensity. The unit of luminous in-tensity is the *international candle*. Originally, the standard candle

was made of spermacetti, a derivative of whale sperm oil, to definite
dimensions, and burned at a definite rate. Modern standards are
far more precise than this: the standard source now used consists of
platinum kept at its melting temperature of about 1773°C in a
specially designed container. One-sixtieth of a square centimeter of
area of this standard source is said to have a luminous intensity of 1
international candle. Hence, one square centimeter of the standard
source has a luminous intensity of 60 international candles, provided
that the observer is in a position to view the luminous area at a
right angle.

The luminous intensity of any source depends upon the point of
view. For instance, when viewed from the base end, an incandescent
lamp has much less output than when viewed from the top. Thus,
the statement that a given source has a luminous intensity of 100
candles implies that this intensity is obtained in one specific direc-
tion but not necessarily in all directions. This is an important con-
cept in the application of phototubes.

10. Luminous Flux

Luminous flux is a measure of the rate at which light energy flows
out of a luminous source. To define it most simply, let us imagine
a point source having a luminous intensity of one standard candle
placed at the center of a sphere with a radius of 1 foot (Fig. 7). If
we assume the source to radiate equally well in all directions and
then mark out an area on the surface of the sphere of exactly 1
square foot, then the luminous flux arriving on this area is said to
be 1 lumen. The area of a geometric sphere is given as:

$$A = 4 \pi r^2 \tag{3}$$

where r is the radius of the sphere. The area of our 1-foot sphere is,
therefore, 4π ft². Since every square foot of the surface receives 1
lumen of flux, this means that a standard candle must emit a total
of 4π lu. If a point source has a luminous intensity of I candles, the
amount of luminous flux in lumens is, therefore:

$$Flux = 4 \pi I \text{ (lu)} \tag{4}$$

Example: If a 100-watt tungsten lamp had a uniform luminous
intensity of 130 candles in all directions, the luminous flux from it
would be $4 \pi \times 130 = 1630$ lu. The relationship between luminous

intensity and luminous flux may also be stated in a manner that defines the power of a standard candle. A point source emitting light equally in all directions is said to have a luminous intensity of 1 *candlepower* if it emits a total luminous flux of 4 π lu.

11.   Illuminance

Illuminance is an extremely important concept in photometry since it describes the amount of light that reaches the surface or object to be illuminated. It may be rigorously defined as the amount of luminous flux falling on a unit area of the surface. Re-

Fig. 7. A standard candle at the center of a sphere of 1-foot radius sends 1 lumen of luminous flux against each square foot of area on the sphere.
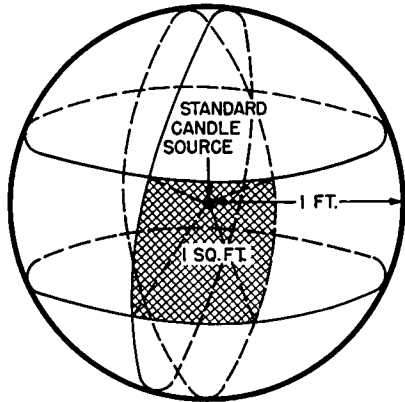
lating this definition to the sphere of Fig. 7, we see that: (a) the luminous flux against each square foot of area is one lumen so that (b) the *illuminance* on the inside surface of the sphere is 1 lumen per square foot.

If the sphere in question had a radius of 1 meter and the area being considered were 1 square meter, then the luminous flux through this area would again be 1 lumen and the illuminance would be 1 lumen per square meter. One of the older units of illuminance (or *illumination* as it was first called) is the *foot-candle*. This unit is defined as follows: one foot-candle is the illumination on a surface every part of which is 1 foot from a standard candle source. This is exactly the equivalent of a standard candle inside a sphere of 1 foot radius since every point on such a sphere is 1

foot from the source. Since the illuminance on the inside of such a sphere is 1 lumen per square foot,

$$1 \text{ foot-candle} = 1 \text{ lumen per square foot} \qquad (5)$$

Despite the fact that many technical authors consider the foot-candle an obsolete unit, it is still present in modern phototube literature. The relationship given in equation (5) ties the foot-candle in with more recent terminology and is worth remembering.
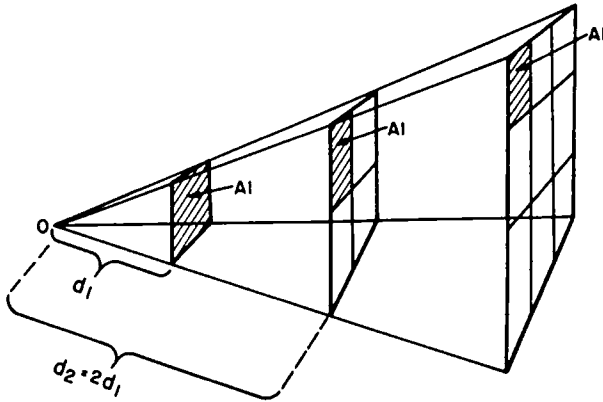
Fig. 8. Light moving away from its source spreads out to cover increasing areas as the distance increases.

It should also be mentioned here that, when the sphere radius and the surface are measured in meters, the unit for illuminance is given the name *lux*. Thus,

$$1 \text{ lux} = 1 \text{ lumen per square meter} \qquad (6)$$

12. The Inverse Square Law

When luminous flux travels outward from a source in free space, its ability to produce illuminance decreases as the distance from the source increases. This occurs because the light spreads out, covering increasingly greater areas with each unit of distance away from the source (Fig. 8). This causes it to thin out as paint does when used to cover greater areas. Analysis of the geometry of Fig. 8 demonstrates that the area increases fourfold when the distance is merely

doubled, it increases to 9 times its initial size when the distance is tripled, and so on. Extending this, we can show that the quantity of light falling on or passing through a surface of fixed size is inversely proportional to the square of the distance between source and illuminated surface. Since the total illuminance is also directly proportional to the candlepower of the source, we have the basic photometer equation:

$$\text{Illuminance} = \frac{\text{candlepower}}{d^2} \qquad (7)$$

As we shall see in Chapter 6, one of the important applications of phototubes is that of the *comparator*. This is a photoelectric device that enables the operator to compare two sources at two different distances in such a manner as to make their respective illuminances on the phototubes equal (Fig. 9). For example, consider a strong

Fig. 9. Photoelectric comparator used as a photometer to obtain equal illuminance from two different sources.
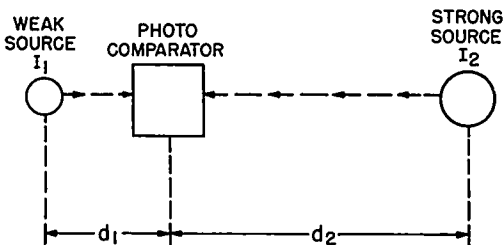
source I_2 and a weak source I_1 placed so as to make the comparator read equal illuminances. The two separate ratios of candlepower to distance squared may be equated so that:

$$\frac{I_1}{d_1^2} = \frac{I_2}{d_2^2} \qquad (8)$$

This is the basic photometer equation. If one of the two sources has a known luminous intensity, then the luminous intensity of the other may be quickly found by establishing equality of illuminance and measuring the two distances from the photometer head.

Problem 1. Equality of illuminance is obtained by comparing a primary standard having an emission aperture of 1 cm² with an unknown lamp. The primary standard and unknown are located respectively 15 cm and 35 cm from the photometer head.

Solution. As we have noted in Section 9, the luminous intensity of 1 cm² of a

standard source is 60 international candles or 60 candlepower. Hence, we can substitute directly in equation (8) as follows:

$$\frac{60}{(15)^2} = \frac{I_2}{(35)^2}$$

$$I_2 = \frac{60 \times (35)^2}{(15)^2}$$

$$I_2 = 326 \text{ candlepower}$$

13. Lambert's Law

The inverse square law was derived on the basis of a point source of light. In phototube work, the light source is often an extended one such as the open sky or a large subject to be photographed. We cannot assume that all sources will emit light equally in all direc-
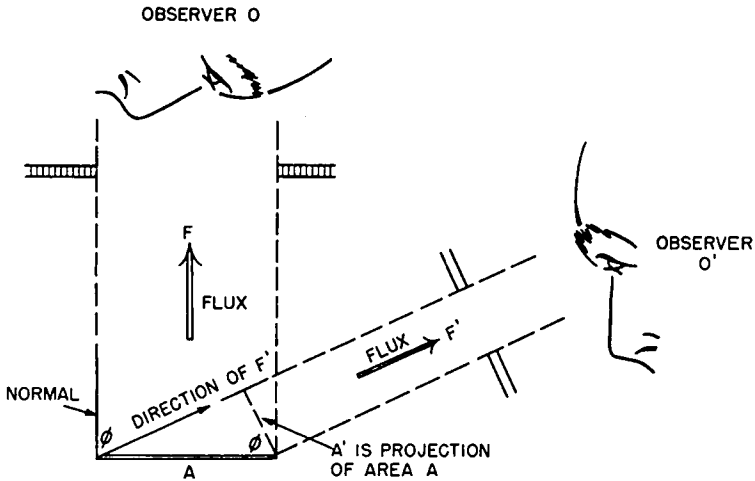
Fig. 10. Illustrating the significance of Lambert's law.

tions; similarly, when speaking of extended sources having large areas, we cannot take it for granted that the intensity of light flux emitted from the surface is the same regardless of direction.

An ideal diffusing surface* follows a law first derived by J. H. Lambert (1728 - 1777); *the intensity of the luminous flux coming from an extended source is proportional to the cosine of the angle*

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* Such an ideal surface is approached by fresh snow in bright sunlight.

the direction of emission makes with the normal to the surface (Fig. 10). The law probably first suggested itself from the following observations: if a luminous flat plate having an area A is viewed from afar, its apparent candlepower (or *brightness*) is greatest when it is broadside to the line of sight. As it is rotated, its brightness diminishes until it becomes virtually zero when viewed end on. When the observer approaches the plate more closely, he finds that loss of brightness is due to the smaller angle subtended by the surface in his eye; that is, the cross-sectional area of the beam coming from the surface is smaller. When sufficiently close, or when the area is large compared to the distance of the surface from the observer, the plate has the same apparent brightness regardless of the direction from which it is viewed. Since brightness is defined as quantity of light emitted perpendicular to the surface per unit area of surface, and since the brightness appears the same to the observer at 0 and 0', then we can equate as follows:

$$\frac{F}{A} = \frac{F'}{A'} \tag{9}$$

or

$$\frac{F'}{F} = \frac{A'}{A} \tag{10}$$

but $A'/A = \cos \phi$ so that we may write:

$$F' = F \cos \phi \tag{11}$$

This, of course, is Lambert's law: The energy emitted from a surface in any direction (F) is proportional to the cosine that angle makes with the normal to the surface.

This explains why the moon, which emits light to our eyes from various angles depending upon whether we are looking at its equatorial belt or at its poles, appears as a uniformly illuminated *flat* disc or why a white-hot cylinder gives the impression of being a flat strip. From a practical point of view, it also explains why a photographer may take an exposure reading of a uniformly illuminated subject from one angle, then shift his camera to another angle without repeating the meter reading.

14. Review Questions

   1. Describe the method used by Wilhelm Hallwachs to show that it was possible to obtain photoelectric effects without the use of oscillatory discharge circuits.

2. Why are alkali metals such as potassium and sodium so difficult to use in photoelectric sensors?

3. Explain why the empirical law of photoelectricity in which it is shown that intensity has no effect upon the energy of emitted electrons was instrumental in invalidating the wave theory of light.

4. Express 5.55×10^{-5} cm in Angstrom units; in millimicrons. Change 1500 A into meters, centimeters, microns, and millimicrons.

5. Using Wien's displacement law, calculate the wavelength of maximum emission for a blackbody heated to 5000°K.

6. Describe qualitatively how Planck's quantum theory differs from the wave theory of radiation.

7. What is the candlepower of a standard platinum source when the viewing window is 1.7 cm²?

8. Prove, with the aid of diagrams, that a standard candle source emits 12.57 lu.

9. Using the definitions of the foot-candle and the lumen, show that 10 foot-candles is the equivalent of 10 lu/ft².

10. A 32-candlepower headlight lamp is placed 3 feet from a photometer. At what distance from the photometer would you place a 50-candlepower lamp to obtain the same illuminance?

Chapter 2

PHOTOEMISSIVITY THEORY

15. The Fundamental Photoemissive Experiment

When Albert Einstein, in 1905, published his theoretically derived photoelectric equation, it was little suspected that it heralded the ultimate triumph of the quantum theory of Max Planck. Today the quantum theory is universally accepted by physicists and chemists alike. It must be remembered, however, that the theory was in its infancy when it was first proposed to explain the spectral distribution curves of blackbody radiation (Section 7, Chapter 1). Its success in this respect was little short of phenomenal, yet the quantum theory needed Einstein's application to photoelectricity to achieve an unshakable position.

To appreciate more fully the significance and strength of Einstein's theoretical approach, we will consider in detail a basic experiment in photoelectricity that points out the inadequacy of classical theory and calls for a revision of the old wave theory concepts.

A photoemissive surface is enclosed together with a collecting electrode in an evacuated envelope (Fig. 11). Radiation of intensity I and frequency v falls on the emissive surface causing the ejection of one or more electrons having a charge e. If no external potential is applied $(V = 0)$, a small photocurrent flows through ammeter A as evidence of the emission of electrons from the photosensitive surface. These electrons possess a range of initial velocities, but when the right negative potential is applied between the collector and the emitting surface, even the fastest moving electrons will be prevented

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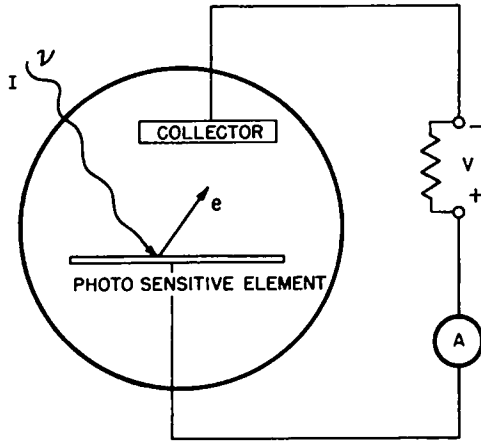
Fig. 11.   The fundamental photoelectric experiment.

from reaching the collector. We shall refer to this potential as the *stopping potential* V_s. As the applied potential V is permitted to move in a positive direction, the photocurrent increases until saturation occurs. With light intensity I as a parameter, the curves given in Fig. 12 are obtained.

It is noticed immediately that the same stopping potential V_s serves for any light intensity. In other words, regardless of the strength of the light source, electrons may be stopped from reaching the collector by the same stopping voltage. *This means that the maximum velocity achieved by any electron is independent of the strength of the light incident upon the photosurface.*

The experiment is now continued by varying the frequency of the incident light and measuring the stopping potential with frequency as a parameter and intensity constant. This gives the curve shown in Fig. 13. It is seen from these curves that the stopping potential must be made increasingly negative as the frequency of the incident light increases. *Interpreted physically, this means that the velocity of the fastest moving photoelectrons must increase as the frequency increases, necessitating a more negative value of V_s to stop them.*

16.   Failure of Classical Theory

If we now attempt to explain these experimental results on the basis of purely classical theory, we find that we encounter an impasse almost immediately.

The only equation offered by classical theory in which electron velocity as opposed to stopping potential are equated is given by:

$$\tfrac{1}{2}mv_m^2 = eV_s \qquad (12)$$

in which m is the mass of an electron, v_m is the velocity of the fastest moving photoelectrons, and e is the charge of an electron. This equation is easily derived verbally: the kinetic energy of a moving electron (or any moving mass) is $\tfrac{1}{2}mv^2$ so that the left-hand term of equation (12) gives the energy of the electrons having the maximum velocity. To stop these electrons from reaching the collector, the electric field must do an amount of work equivalent to the energy of the electrons. The product eV_s is a statement of the work needed to stop one fast electron before it arrives at the collector.*

Since electrons are emitted as a result of the absorption of energy from the incident light, it would seem that a more intense light
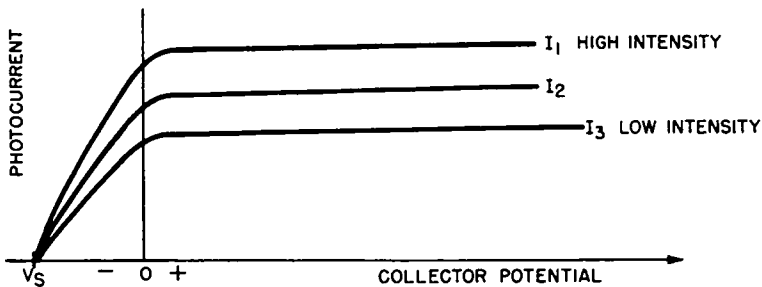
Fig. 12. Variation of photocurrent with collector voltage, light intensity as a parameter. The light frequency is constant.

would liberate higher speed electrons; since our experiment demonstrates that V_s, and hence v_m, are independent of the light intensity [from equation (12)], the wave theory contains nothing that can correlate the experimental findings with the prediction.

The second result is even more difficult to explain. Since higher frequencies of incident light call for greater stopping potentials (Fig. 13), it is evident that electrons released by higher frequencies have a higher velocity, hence greater energy, than those ejected by the light of lower frequency. Nowhere in the classical theory is there any evidence that this should be so. Actually, the wave theory

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* Since potential = energy/charge, then energy = potential × charge. For a derivation of this definition see *Electrostatics*, John F. Rider Publisher, Inc., 1958.

of radiation contains no aspect that even remotely links light energy to frequency.

17. The Einstein Photoelectric Equation

Four years after Planck proposed his quantum hypothesis, Einstein applied it to the photoelectric effect with complete success. Taking each quantum (photon) of radiant energy falling on the photosensitive surface as having an energy content of h υ, he approached the problem in an entirely new way. He recognized that some energy is needed to cause an electron to leave the surface, otherwise, emission would go on constantly under all conditions; this energy of release is generally referred to as the *work function* (ϕ), and differs for various materials. Obviously, the ejection of an electron can take place only if hυ is greater than ϕ. Furthermore, if hυ does exceed ϕ, the electron will be left with some excess energy that must appear in kinetic form. This consideration permits us to write the equation:

$$\text{K.E.}_1 = h\upsilon - \phi \tag{13}$$

Some electrons released by the light energy must actually require more energy than that needed merely to overcome the work function since there must be some that come from under the surface. Extra energy input will be needed to bring them up to the plane of emission. Hence, K.E.$_1$ must represent the *maximum* excess of kinetic energy that could possibly be expected, and must apply to the fastest moving electrons emitted from the photosurface. This at once iden-
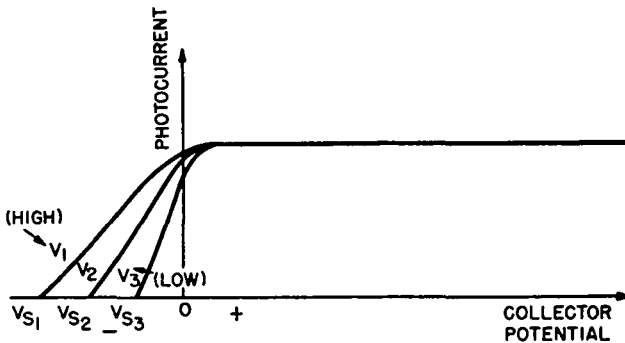

Fig. 13. Stopping potential as measured with frequency as a parameter and light intensity constant.
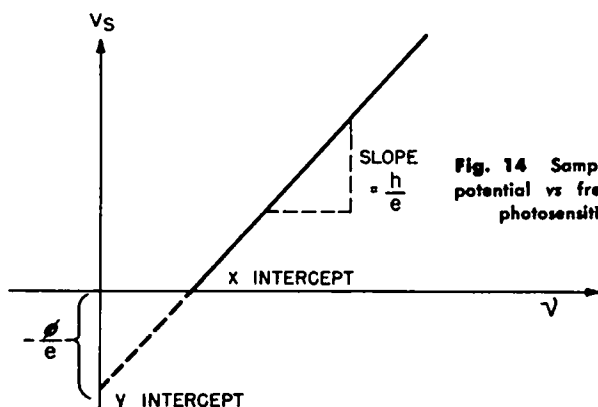
Fig. 14 Sample plot of stopping potential vs frequency for one photosensitive material.

tifies it with the $\frac{1}{2}mv_m^2$ factor of equation (12). Equating (12) and (13) gives us:

$$\tfrac{1}{2}mv_m^2 = eV_s = h\upsilon - \phi \tag{14}$$

Equation (14) fits the experimental facts described previously. The maximum energy of the expelled electrons is a linear function of the frequency and is quite independent of the light intensity. The latter conclusion is justified because intensity does not appear in the energy equation.

A conclusive experiment performed by Millikan in 1915-1916 verified this equation in all details. With ingeniously designed equipment, Millikan determined the stopping potential V_s for many different frequencies of incident radiation on various photosensitive materials. In every case, when V_s was plotted against frequency, a straight line was obtained. It will be easier to understand the significance of this plot if equation (14) is solved for V_s thus:

$$eV_s = h\upsilon - \phi$$

or

$$V_s = \frac{h\upsilon}{e} - \frac{\phi}{e} \tag{15}$$

In general form this is the equation of a straight line,* h/e is the slope, and $-\phi/e$ is the y intercept (Fig. 14). The form of Millikan's

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* The equation of a straight line is $y = mx + b$ in which m is the slope of the line and b is the y intercept. Thus, in this equation h/e is the slope and ϕ/e is the y intercept.

results permits the slope to be measured from the experiments, thus obtaining an experimental value for h/e. This agrees very closely with the ratio obtained by substituting Planck's constant h, obtained from the blackbody distribution curves for the numerator, and the previously determined charge on the electron e for the denominator. Furthermore, the value of ϕ obtained by Millikan by measurement of the y intercepts of his curves again gives close agreement with the value of the work function for the same materials obtained by thermionic emission methods.

18. Threshold Frequency and Wavelength

Since a linear relationship exists between photoelectron kinetic energy and frequency, one might well ask what minimum frequency will still dislodge electrons from the surface of a material having a work function ϕ. This is easily determined by setting the velocity of the emitted electron equal to zero — this, of course, means zero energy — and solving equation (14) as follows:

$$\tfrac{1}{2}mv_m^2 = h\upsilon - \phi$$

if the electron velocity is zero, then

$$\phi = h\upsilon \tag{16}$$

Thus, there must be a certain minimum frequency, called the *threshold frequency* (υ_0), below which no radiation can liberate an electron. In this case we set $h\upsilon_0 = \phi$ and resubstitute in equation (14) to obtain:

$$\tfrac{1}{2}mv_m^2 = h\upsilon - h\upsilon_0$$

or

$$\tfrac{1}{2}mv_m^2 = h(\upsilon - \upsilon_0) \tag{17}$$

Using equation (14) once again and substituting eV_s for $\tfrac{1}{2}mv_m^2$, we can write:

$$eV_s = h(\upsilon - \upsilon_0) \tag{18}$$

which may then be solved for the threshold frequency:

$$\upsilon_0 = \upsilon - \frac{eV_s}{h} \tag{19}$$

Thus, having experimentally determined the stopping potential V_s for a given material at a frequency v and knowing the values of electron charge e and Planck's constant h, the minimum or threshold frequency v_0 can be calculated.

This constant has been calculated and experimentally verified for numerous photoelectric materials with excellent agreement between results obtained by both methods. For example, if a photosensitive material is to respond over the visible spectrum, say, from 4000 to 8000 Å, the work function at its surface must be 1.55 electron volts (ev) or less.* To illustrate: sodium has a work function of 1.82 ev, hence responds only to the higher frequencies in the visible spectrum, its threshold frequency being in the vicinity 6800 Å. Cesium, on the other hand, with a work function of only 1.36 ev is photosensitive over the entire visible spectrum plus some of the infrared.

Much of the research carried on today in this field has a two-pronged objective: (1) to develop photosensitive materials with as low a threshold frequency as possible and (2) to discover means by which the photoelectron yield can be brought as near to 100%, i.e., one photoelectron for every incident photon, as nature will permit.

19. Using Photoelectric Equations

The following four problems illustrate the use of the photoelectric equation.

Problem 2. Find the maximum kinetic energy of the photoelectrons in an emission process in which a stopping potential of 8 volts is required. (The charge on an electron may be taken to be 1.6×10^{-19} coulombs).

Solution. Use equation (14).

$$\text{Max. K.E.} = eV_s = (1.6 \times 10^{-19} \text{ coul}) \ (8 \text{ volts})$$

$$= 12.8 \times 10^{-19} \text{ coul volts or joules}$$

Problem 3. What will be the maximum speed of the electrons emitted in the preceding problem?

Solution. The mass of an electron is approximately 9.1×10^{-31} kgm, the maximum velocity is: (from $E = \frac{1}{2}mv^2$)

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* An electron volt (ev) is a unit of energy *not* potential. It is the energy acquired by an electron that is moved under the action of electric forces through a potential difference of 1 volt. The ev is numerically equal to 1.6×10^{-19} joule.

$$v = \sqrt{\frac{KE}{2m}}$$

$$v = \sqrt{\frac{12.8 \times 10^{-19}}{2 \times 9.1 \times 10^{-31}}}$$

$$v = .84 \times 10^6 \text{ meters/sec}$$

Problem 4. What is the threshold frequency for sodium with a work function (ϕ) of 1.8 ev?

Solution. At the threshold frequency, $h v_o = \phi$ or $v_o = \phi/h$. Thus

$$v_o = \frac{(1.8)\ (1.6 \times 10^{-19})\ \text{joule}}{6.62 \times 10^{-34}\ \text{joule/sec}}$$

$$v_o = 4.4 \times 10^{14}\ \text{sec}^{-1}\ \text{(cps)}$$

Problem 5. At what speed will the highest-speed electron be emitted if the wavelength of the incident light is 5000 Å?

Solution. The frequency corresponding to a λ of 5000 Å is first determined:

$$v = c/\lambda = \frac{3 \times 10^8\ \text{m/sec}}{5 \times 10^{-7}\ \text{m}} = 6 \times 10^{14}\ \text{cps}$$

From equation (14):

$$v = \sqrt{\frac{2hv - 2\phi}{m}} = \sqrt{\frac{2\ (6.62 \times 10^{-34} \times 6 \times 10^{14} - 1.8 \times 1.6 \times 10^{-19})}{9.1 \times 10^{-31}}}$$

$$v = \sqrt{\frac{2\ (1.09 \times 10^{-19})\ \text{joule}}{9.1 \times 10^{-31}\ \text{kgm}}}$$

$$v = 4.9 \times 10^5\ \text{m/sec}$$

20. Color Sensitivity of Photomaterials

Assuming equal values of light flux, various photosensitive materials display varying response to radiation of different wavelengths. For example, the alkali metals (lithium, sodium, and potassium) all begin to show usable sensitivity before the radiation reaches ultraviolet frequencies, i.e., in the visible portion of the spectrum, while a copper oxide surface is responsive to nothing below the ultraviolet. Rubidium, on the other hand, reaches peak emission at about 4800 Å, while cesium peaks at approximately 5600 Å, both well inside the visible range.

The relative response of a photosensitive surface to light of various wavelengths is known as its *spectral sensitivity*.* Modern photo-

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* Spectral sensitivity is synonymous with color sensitivity, response range, and sensitivity range.
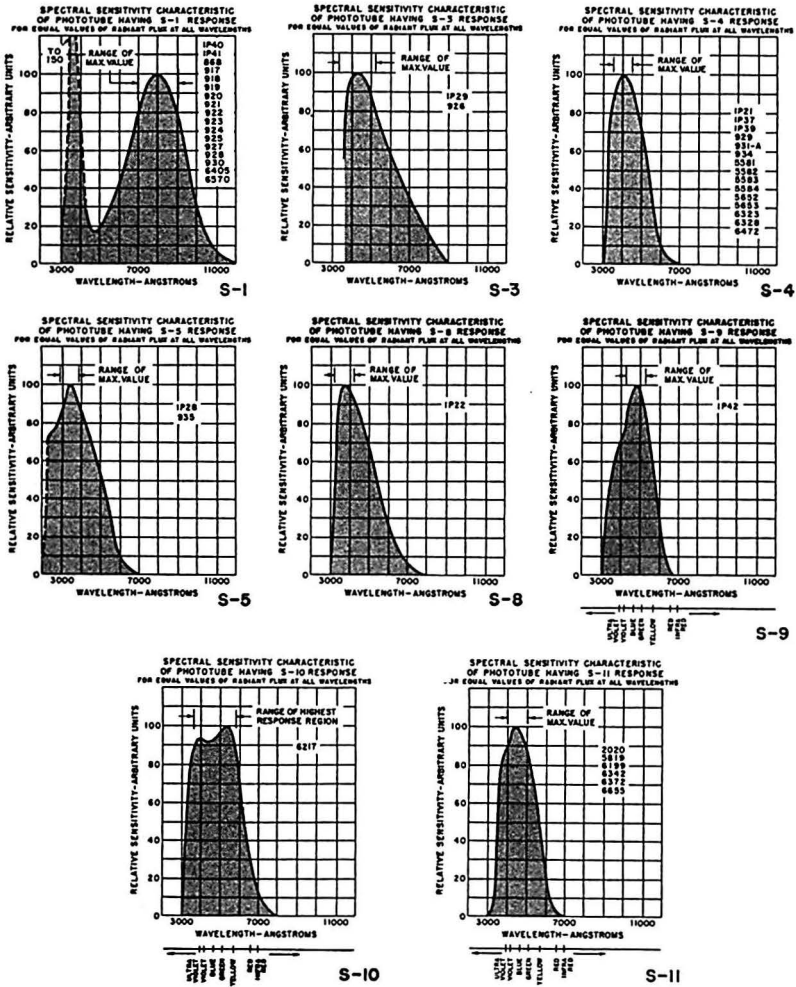
Fig. 15. Response curves for modern phototube surfaces.

tubes may be obtained with eight different surfaces having various spectral sensitivities (Fig. 15). The S-3 surface has a response closest to that of the human eye. The S-4 surface is very sensitive to blue and blue-green radiation but displays a negligible response to radiation at the red end of the visible spectrum. The S-5 and S-6 types show high sensitivity only in the ultraviolet region.

21.   The Phototube Sensitivity Rating

The *sensitivity* of a phototube is a factor that describes the anode
current output of the tube for a given amount of light flux incident
on the cathode. It is most commonly given in terms of microamperes
per lumen with a light source having a color temperature of 2870°
Kelvin. The need for a specific source is apparent when one consid-
ers that phototubes respond differently to different wavelengths and
that a comparison can only be made between sensitivities when the
emission color is kept constant.

Two different kinds of sensitivities are generally stated for com-
mercial phototubes: *static* sensitivity and *dynamic* sensitivity. These
will be discussed fully in Chapter 4 and are mentioned here merely
to indicate that surfaces having different color sensitivities also dis-
play varying absolute sensitivities to standard 2870°K sources. For
example, the S-1 surface is rated at 20 μa/lu, the S-3 surface at 6.5
μa/lu, and the S-4 surface at 45 μa/lu. It is also interesting to note
that the S-4 surface is the most sensitive type available today; using
daylight as illumination, the sensitivity of phototubes using S-4 coat-
ings is as high as 120 μa/lu.

22.   Layer Emissivity

Stated broadly, the work function of any photosensitive materials
must depend to a large degree upon the atomic electrostatic forces
acting near, or directly on, the top surface of the cathode. With this
in mind, it is only one step to the speculation that improvements in
performance might be realized by combining different materials at
the emissive surface. Early work in photoelectricity was naturally
based upon solid emitters having the same composition below the
surface as they had at the surface. It was soon realized, however, that
substantial increases in sensitivity might be possible if the arrange-
ment of the outer atomic layers could be properly changed.

Experimental and theoretical studies have consistently shown that
the work function of photocathodes can be reduced by depositing
monatomic layers of the sensitive material on some other base sub-
stance. In this respect, the action is quite analogous to thermionic
emission where the emissivity of a hot tungsten wire can be increased
190,000 times merely by diffusing a monatomic layer of thorium to
the tungsten surface. In this connection, the study of layer emissivity

was encouraged by the fact that the work function of all materials studied by thermionic methods corresponded very closely with the work function measured under conditions of photoemissivity. By 1948, very convincing demonstrations had been presented by workers like Ives and Campbell that the greatest photosensitivity could be obtained with monatomic depositions of substances like rubidium and cesium on other metals of considerably less activity. The final foundation for modern supersensitive phototubes can probably be attributed to Koller who developed the forerunner of today's cesium phototubes.

23. Composite Layer Phototubes

The phototubes now being adopted as standard in industry have *composite emissive surfaces.* These are the results of countless experiments in layer emissivity coupled with much theoretical and mathematical research. For example, Koller's phototube used a cathode consisting of a base layer of silver, followed by a layer of cesium oxide, and topped by a monatomic deposit of pure cesium. Details of modern phototube construction are discussed in Chapter 3, but facts that apply to the more standard types of cathode surfaces are presented in Table 1.

TABLE I

POPULAR PHOTOTUBE CATHODES

Surface Type	Base Metal	Intermediate Layer	Monatomic Layer	Frequency Range of Maximum Value
S-1	silver	cesium oxide	cesium	7000 - 9000 Å
S-3	silver	rubidium oxide	rubidium	3300 - 5200 Å
S-4	nickel	cesium oxide	antimony + cesium	3500 - 4500 Å

24. Review Questions

1. Explain why Einstein's photoelectric equation accounts for the observed results in experiments relating maximum photoelectron energy to frequency of incident radiation.

2. What is meant by *stopping potential?* In what way (s) did experiments on stopping potential play a part in the development of modern photoelectric theory?

3. What is meant by work function? Is a large or small work function desirable in photocathodes? Explain.

4. What is threshold frequency? Why is threshold frequency an important factor in the design of a phototube?

5. Find the threshold frequency of cesium which has a work function of 1.36 ev.

6. What will be the velocity of the highest-speed electron emitted as a result of irradiation by ultraviolet having a wavelength of 3000 Å?

7. Define spectral sensitivity of phototubes and give two synonyms in current use.

8. Explain the rating 65 μa/lu at 2870°K excitation.

9. Why does an S-4 coating display a greater sensitivity (120 μa/lu) when irradiated with daylight than it does when excited by a standard color source?

10. What is meant by layer emissivity? By composite layers? Give some examples of the latter.

Chapter 3

THE STRUCTURE OF PHOTOTUBES

25. The Glass Envelope

Since all emission-type phototubes contain elements that operate either in a vacuum or under controlled gas pressure, a sealed glass enclosure is needed around them. The exciting radiation must pass through the envelope with as little absorption as possible, making it necessary to select the enclosure material with care and judgment.

When a phototube is designed to respond to the light in the visible spectrum, ordinary *lime glass* is satisfactory provided that the tube is small enough. Lime glass is not particularly strong mechanically so that it is generally not used when the physical size of the phototube exceeds more than an inch or two in maximum radius or axial length. Lime glass is well suited for envelope fabrication because it is soft, easily worked, and lends itself readily to the making of glass-to-metal seals.

Ordinary glass becomes more or less opaque when the radiation wavelength drops to 3000 Å or below. Since photocathodes have been developed to respond to this region of the ultraviolet, devices for measuring these wavelengths photoelectrically are possible provided that an envelope other than glass is used. Although fused quartz has been employed in ultraviolet phototube housings, a special hard glass known as *Corex* is now almost universally used. Corex, manufactured by the *Corning Glass Works*, New York, has a mean coefficient of expansion between 0° and 350°C of 3.8×10^{-6} cm/cm/°C and is rather difficult to work since it softens at 804°C as compared with 696°C for lime glass.

When certain industrial phototubes of large size are manufactured, they are enclosed in a bulb of *Pyrex* glass. This glass, a borosilicate compound, has a somewhat smaller coefficient of expansion than Corex (3.2×10^{-6} cm/cm/°C and a slightly higher softening temperature (812°C). Its low coefficient of expansion makes it suitable for large bulbs that might undergo alternate heating and cooling in the process of manufacture; the low coefficient minimizes the danger of cracking due to thermal expansion strain.

26. Connecting Leads

Electrical conductors must be led into the glass enclosure for contact with the electrodes, of course. This must be done without endangering the internal vacuum. The chief problem is that of the differential in expansion coefficient between the glass bulb and the feeder wire. Ideally, the glass and wire lead should have identical coefficients of expansion; in practice, this identity is approached as closely as possible.

Platinum wire, once necessary for wire seal purposes, is no longer used because of its cost, and has been replaced by *Dumet* metal whose coefficient is very close to that of lime glass. (Lime glass — 9.5×10^{-6} cm/cm/°C, Dumet — 9×10^{-6} cm/cm/°C). Dumet metal is a composite material consisting of a core of nickel-iron alloy on which a layer of copper is plated.

Corex and Pyrex bulbs, because of the unusually low coefficients of expansion involved, cannot be fed by Dumet wire seals. For these, tungsten is usually used despite the fact that it is quite brittle and expensive. The coefficient of expansion of tungsten is 4.5×10^{-6} cm/cm/°C — a considerably higher figure than either Pyrex or Corex. Satisfactory seals can be maintained only if the range of temperature can be kept relatively small, possibly from room temperature (20°C) up to about 150°C.

27. Electrode Arrangements

Most of the applications in which phototubes are used require that the emitting surface (cathode) receive as much light as possible. In general, this necessitates making the cathode itself the large element so as to expose as much of the photosensitive surface to the incident radiation as conditions permit. To avoid the shading effect

that might be caused by a large anode, the latter is generally fashioned into a rod coaxial with the cylindrical cathode or a wire ring mounted above the cathode. Such phototubes are called *central-anode* types (Fig. 16). Although the best sensitivity is obtained by using a large cathode and a central anode, the small size of the anode demands a relatively high voltage to achieve saturation, to collect all the electrons available with a reasonably large incident flux.

Some attempts have been made to market phototubes built along the general lines of thermionic types. In these, a small central cathode is almost completely surrounded by the anode, a small part of the latter being left open to admit the radiation. Although these have been useful in certain types of laboratory work, they have not found commercial favor since they do not have sensitivities that approach the central-anode structure. On the other hand, the large surface of the anode makes it possible to realize saturation with only a volt or two on this element. This has been advantageous in applications involving circuits that use low-voltage power sources such as batteries.

28. Considerations Involving Physical Structure

In general, more phototubes are fabricated in tubulated glass envelopes than in any other way. This design permits the insertion of a large cylindrical cathode without waste of space. In other respects, phototubes differ from each other in socket-type, cathode and anode placement, electrode terminations, presence or absence of gas in the envelope, and directional characteristics.

Mounting Methods: Phototubes are designed to plug into a radio-type socket or to be mounted in a cartridge holder. Among the socket mounting phototubes we find the type 927 which is supported by a special, small 3-pin socket; the 868, 918, 920 types, etc., which plug into standard medium 4-pin bases in which both anode and cathode terminate at the socket pins; the 917, 919 types, etc., which mount in the same type of 4-pin socket but in which one of the electrodes is connected to a top cap on the glass envelope; the 925, 929, and 930 types which utilize standard small octal sockets as their means of support; and the 921, 922 types, etc., which are held in special cartridge clips. Finally, some phototubes such as the 924 type are designed to be screwed into a mazda-type base. The choice of mounting style depends upon the physical needs of the individual
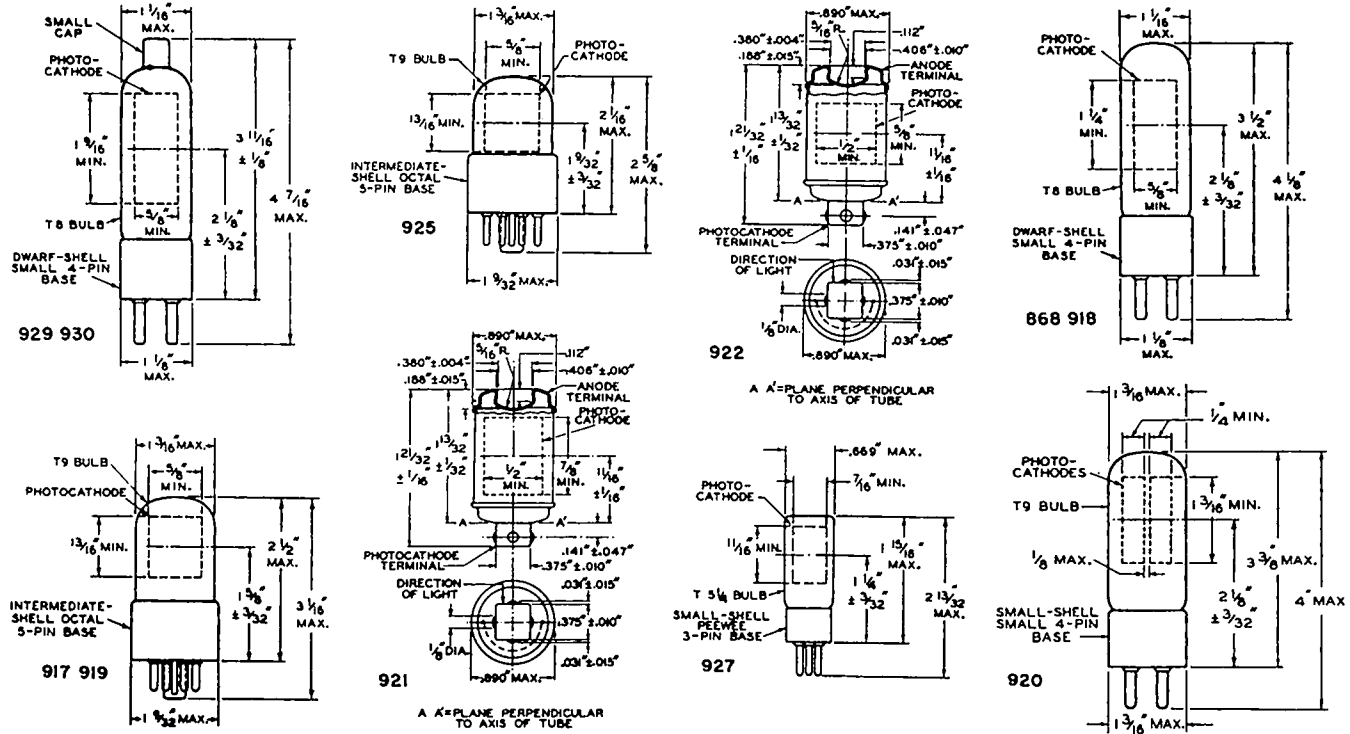
Fig. 16. Representative central-anode phototubes. RCA.

application, amount of available space in relation to the direction of incident light, and so forth.

Direction Characteristics: When the cathode is set upright in the cylindrical type of envelope, the phototube is then sensitive to light reaching it through the side of the structure (929, 917, 927, 925 types). In others, the cathode is a cup-shaped structure, and the anode is a ring having the same diameter as the cathode mounted immediately above it. Such tubes (1P41 type) are called end-type or head-on operation. For systems in which the light may be incident on the phototube from any direction — sides or top — the cathode is perforated and completely cylindrical. Light can then strike one portion of the inside surface by entering through the holes on the opposite side (Fig. 16, 928 type).

Electrode Terminations: The problem of electrical leakage between the two electrodes of a phototube may become a serious factor in circuits where the illumination is feeble, and where very high sensitivity is required. At best, the photocurrent is seldom more than a few microamperes under these extreme conditions. If a leakage path between anode and cathode exists, the leakage current may very well exceed the photocurrent, resulting in a masking of the photoelectric reaction. The simplest solution to the leakage problem is to locate the cathode and anode connections at opposite ends of the glass envelope, one at a socket terminations and the other at an end cap. In the type 917 the anode is brought out to an end cap, while in the type 919 the cathode connects to the end cap and the anode to a socket pin. In all other respects, these two phototubes are identical.

Presence or Absence of Gas: As discussed in Chapters 4 and 5, this physical difference is an extremely important one. The inclusion of controlled quantities of certain gases contributes heavily to the high sensitivities of many types of phototubes. The presence of gas also alters the phototube characteristics in other ways to be discussed later. At present the commonest gases in phototubes, either in the pure or mixed form, are argon, neon, xenon, and krypton — all members of the *rare* gas family. These gases are completely inert so that there is no danger of chemical combination occurring between them and the active materials in the phototube.

Element Spacing; Interelectrode Capacitance: Certain photoelectric systems in which fluctuating light is used to excite the phototube (sound-on-film, modulated-light long-distance relays, etc.) call for

very low input capacitances of the phototube. This is necessary to maintain a flat frequency response, particularly in sound-recording on film. This requires careful spacing of the elements. Although interelectrode capacitances in phototubes are not generally very high, they may become significant in special applications as described. The range of values runs from a low of about 0.5 μμf in the cartridge type (922 type) up to approximately 3.0 μμf in the 928 and similar tubes.

29.   Fabrication of the Cesium Oxide Phototube

All other types of emissive phototubes are slowly being displaced by the cesium oxide type because of its excellent sensitivity to the longer wavelengths (especially those from ordinary tungsten incandescent lamps). One typical method of assembly is described here.

A semicylindrical sheet of copper is first plated with a very thin layer of pure silver and mounted on a glass stem. A coaxial anode wire of nickel-plated copper is then mounted on the same glass assembly with Dumet or tungsten leads brought out for later connection. At the top of the anode a cup-like piece of nickel is welded in place and filled with a measured quantity of cesium dichromate and silicon. The elements are then sealed in the glass envelope and the air exhausted from it.

The entire assembly is then subjected to a baking process for a short period. When cool, a small quantity of oxygen is admitted into the enclosure and a glow discharge started between the anode and cathode, causing the surface of the silver to oxidize. The oxygen is removed by pumps and the pellet heated by an induction method until it explodes, liberating cesium vapor into the envelope. The baking continues causing the cesium to combine with the silver oxide, forming a relatively thick layer of cesium oxide (Cs_2O) on the cathode surface. The baking process is finished when the entire surface of the cathode has turned cream color. At this point, the photosensitivity is still quite low.

Pure argon is then introduced into the housing and a second glow discharge established between the anode and cathode. As the discharge proceeds, the sensitivity rises to its final value. By controlling the various phases of the entire process carefully, it is possible to obtain several different kinds of spectral sensitivity (Fig. 17). Curve A shows that cesium oxide surfaces may display unusually good
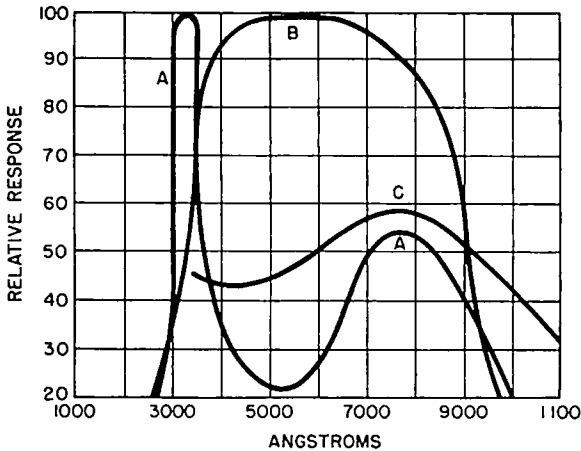
A-ONE POSSIBLE SPECTRAL RESPONSE.

B-SPECTRAL RESPONSE EQUIVALENT TO HUMAN
EYE ALSO POSSIBLE BY CONTROLLING PROCESS.

C-HEAVY SENSITIVITY TO INFRARED   OBTAINED
BY USING VERY PURE MATERIALS &
CONTROLLED BAKING.

Fig. 17.   Spectral responses obtainable with cesium oxide (Cs₂O) cells by varying manufacturing procedure.

sensitivity in the near ultraviolet despite the fact that these curves were drawn for a lime-glass enclosure. By proper treatment, the cesium oxide cell can be given a spectral sensitivity pattern very similar to that of the human eye (curve B). When the materials are made very pure, and the baking process carefully controlled, a cesium oxide cell becomes quite sensitive in the infrared portion of the spectrum (curve C).

30.   Phototubes for the Ultraviolet

Studies in the measurement and control of ultraviolet radiation have taken on greater importance than ever before. The use of ultraviolet lamps for the treatment of certain skin conditions has been often effective; the unquestionable therapeutic value of ultraviolet treatments for the prevention and cure of rickets has made a complete investigation mandatory, and much work has been done in this field. It has been firmly established that the antirachitic thera-

peutic range is a short one, extending only from about 2800 Å to 3200 Å. It is also known that the average human skin is rapidly reddened by wavelengths between 2900 and 3050 Å, also in the ultraviolet region. Phototubes that respond to ultraviolet radiation, therefore, are of great value because they permit direct and exact measurement of the intensity of the rays and a controlled check on the possible damage to the human organism that might result from an overdosage.

Although the cesium oxide phototube may be extremely sensitive far into the ultraviolet if enclosed in a material such as quartz, many other types of phototubes have appeared in recent literature. One important reason for continued research in specific ultraviolet-sensitive materials is cesium oxide's high sensitivity to visible and infrared radiation. Thus, carefully designed filters must be utilized to cut out all but the ultraviolet when precise measurements are carried on. In addition, the fact that pure metallic cathodes display emissive qualities when irradiated by ultraviolet permits construction of competent phototubes for the short waves without the use of complicated manufacturing procedures.

Various pure metals have been investigated as possible cathodes for the ultraviolet. Among these are lithium, cadmium, uranium, thorium, cerium, zirconium, titanium, and zinc. Some notable advances in the field had been reported as far back as 1930. In modern photoelectricity, however, one seldom hears of further experiments along this line. Current trends indicate the use of an increasing number of combinations of alkali metals such as cesium and rubidium, and others like antimony, for specific ranges in the near, medium, and far ultraviolet. As has been mentioned, the S-5 type of surface has excellent sensitivity in and around 3000 Å even in a lime-glass bulb. When enclosed in Corex D glass or quartz, the range of this surface may be extended as far down as 2300 Å with good sensitivity.

31. Review Questions

1. Why is lime glass used in the envelopes of most phototubes?
2. What are the characteristics of quartz that make it desirable for use in certain types of phototubes?
3. What characteristics are required of connecting leads which are used to join the electrodes in an envelope to the outside via a fused section of glass? Why?
4. What is the advantage of the central-anode type of phototube structure? The central-cathode type?

5. Give an example of an application in which omnidirectional characteristics of the phototube would be desirable. Where would a phototube having a unidirectional characteristic be utilized?

6. Explain why electrical leakage between the elements of a phototube causes a reduction in the sensitivity of the system to slight variations in light flux.

7. How does the interelectrode capacitance of a phototube used in reproduction of sound-on-film affect the performance of the system? Explain.

8. Describe a typical process for the manufacture of cesium oxide phototubes.

9. State one possible application for a phototube having the spectral response characteristic of curve A in Fig. 17. Repeat for the other curves in this figure.

10. Cesium oxide tubes are sensitive into the far ultraviolet when enclosed in suitable material. Why has so much research been carried on to find a pure cathode metal if the cesium oxide type is satisfactory?

Chapter 4

THE VACUUM PHOTOTUBE

32. Electron Emission and Lambert's Law

Lambert's law of reflection from diffusing surfaces was discussed in Section 13. Its significance in this discussion was based upon considerations involving both luminous and illuminated sources. The application of Lambert's law does not stop here, however; it was shown that electrons released from a photosensitive surface also display a distribution pattern that adheres quite closely to Lambert's law.* Thus, with light incident on a small emitting surface (see Fig. 18), electrons are ejected symmetrically around the normal to the surface, the numbers of electrons being proportional to the cosine of the angle between the direction of emission and the normal. If each of the arrows in the figure is taken as a vector whose length represents relative number of emitted electrons compared to the maximum number along the normal, then these vectors represent the relative distribution of emitted electrons along the lines shown. Suppose, for example, that 10^8 electrons are emitted along the normal with a given intensity of incident light. Then a total of 0.94 $\times$ 10^8 electrons would be released along a line that makes an angle of 20° with the normal, 0.77 $\times$ 10^8 electrons along the 40° line, and so on.

The cosine characteristic of photoelectron emission — an emission characteristic that is valid for *any* angle of incident light, it must be

* Ives, Olpin, and Jonsrud, "The Distribution of Photoelectrons From Alkali Metal Surfaces," *Physical Review*, Vol. 32, page 57, 1928.

NORMAL
0°

20°   20°

40°   40°

60°   60°

80°   80°

0°   0°

SMALL EMITTING
SURFACE

LIGHT INCIDENT AT
ANY ANGLE FROM
ABOVE
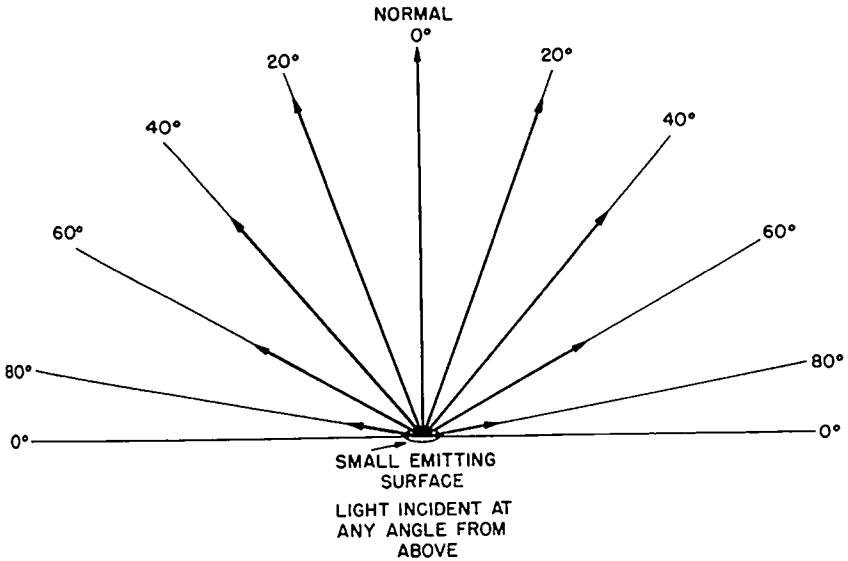
Fig. 18.   Light incident from above at any angle causes the emission of electrons from a small photosensitive surface in accordance with the cosine law.

remembered — explains two important facets of modern central-anode phototube construction. By placing the anode at the center of a semicylindrical cathode, more electrons will leave the cathode going directly toward the anode than in any other direction. This assumes that there is no potential difference applied to the two elements. As soon as a voltage does exist, the electrons will be displaced from any path they may happen to take toward an electrostatic line of force. These lines are normal to the cathode as a result of the geometry of the system.

Thus, under the restrictions imposed by central-anode construction, the largest possible number of electrons leave the cathode in the proper direction, requiring therefore a field of minimum strength to produce saturation. This may be summarized as follows: the Lambert distribution encourages normal emission from the cathode; the geometry of central-anode construction calls for normal emission if the anode is to receive all of the emitted electrons; the electrostatic field in the tube makes the natural forced paths of the electrons radial in direction. The combination of all these factors results in the greatest anode current possible for a given voltage and a given luminous flux on the cathode (Fig. 19). The path followed by any
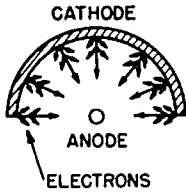
CATHODE

PHOTO-ELECTRON EMISSION AS A RESULT OF LAMBERT'S LAW, ZERO POTENTIAL BETWEEN ANODE AND CATHODE.
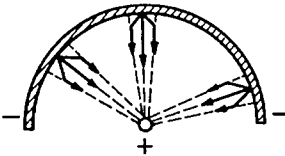
ANODE

ELECTRONS

WITH POTENTIAL APPLIED, ALL ELECTRONS TEND TO TRACK WITH ELECTROSTATIC LINES (DASHED LINES). GREATER NORMAL EMISSION TO START WITH CALLS FOR LESSER FIELD INTENSITY TO REALIZE SATURATION.

Fig. 19. Central-anode construction encourages maximum anode current for fixed conditions of voltage and light intensity.

particular electron is determined by its initial direction of ejection from the cathode, its emission velocity, and the intensity of the electrostatic field produced by the electrode voltages. Therefore, central-anode design conforms with the Lambert distribution, making possible larger anode currents with smaller electrode voltages than with any other geometrical arrangement.

33. More About the Electrostatic Field

The ratio of electrical energy to charge defines the concept of *electric potential.** That is:

$$V = W/q \qquad (20)$$

in which V is the electric potential, W is the energy consumed in moving the particle from one position to another against a resisting force, and q is the charge of the particle. It is from this concept that the definition of the *volt* is obtained: one volt of potential difference exists between two points if one joule of work must be done (or one joule of energy must be used) to move one coulomb of charge

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* See *Electrostatics*, page 19, New York, John F. Rider Publisher, Inc., 1958.

from one point to the other. Thus, solving equation (20) for energy we can write:

$$W = V q \qquad (21)$$

or when the charged body is an electron having a charge e:

$$W = V e \qquad (22)$$

In the case of photoelectrons, the total work required to move a single particle from the cathode to the anode after emission is, therefore, V e regardless of the shape or distribution of the electrostatic lines of force. On the other hand, the actual kinetic energy developed by each of these electrons may be described as:

$$K.E. = \tfrac{1}{2} m v^2 \qquad (23)$$

where m is the mass of the electron and v is the velocity attained at the instant of impact at the anode. Thus, the expressions contained in equations (22) and (23) may be equated since, from the law of conservation of energy, the work W done on an electron is converted into kinetic energy.

$$V e = \tfrac{1}{2} m v^2 \qquad (24)$$

It might also be pointed out at this time that for an electron that leaves the cathode with an initial velocity v_o, the total kinetic energy of this particle at the anode must be $\tfrac{1}{2} m v^2 + \tfrac{1}{2} m v_o^2$. Under these conditions the actual final velocity of the electron is, therefore, given by the expression:

$$v_t = \sqrt{v_o^2 + v^2} \qquad (25)$$

In equations (23) and (24), energy is given in joules if V is in volts, e in coulombs, m in kilograms, and v in meters per second. In dealing with electrons in motion, however, it is convenient to express energy in terms of electron volts. An electron that has accelerated through a potential of one volt has increased its energy content by one electron volt.

To determine the relation between joules and electron volts, consider equation (22). Here W is in joules and V in volts while e is in coulombs. Hence:

$$1 \text{ joule} = 1 \text{ volt} \times 1.6 \times 10^{-19} \text{ coul}$$

the charge on the electron being 1.6×10^{-19} coul. A volt, according to definition, is one joule per coulomb. Thus, the work done in

moving an electron through a potential difference of 1 volt is:

$$W = 1 \text{ joule/coul} \times 1.6 \times 10^{-19} \text{ coul}$$

or

$$W = 1.6 \times 10^{-19} \text{ joules}$$

Therefore 1 electron volt is the equivalent of 1.6×10^{-19} joules.

Problem 6. A photoelectron is emitted from a cylindrical cathode with an initial energy of 10 electron volts, its motion being normal to the cathode. The anode is 10 cm away from the cathode and has a positive potential of 1000 volts with respect to the cathode. Find (a) the kinetic energy upon impact at the cathode, and (b) the initial velocity of the electron as it leaves the cathode.

Solution. (a) Combining equations (23) and (24) we may write:

$$\text{(total) K.E.} = V e + \frac{1}{2} m v_o^2 \qquad (26)$$

in which the second term on the right side is the initial K.E. of the electron. Since $V e$ is in joules and since one electron volt $= 1.6 \times 10^{-19}$ joules, we may rewrite this equation for energy in electron volts thus:

$$\text{K.E. (in ev)} = V + \frac{1}{2} m v_o^2 \qquad (27)$$

Hence the K.E. of impact is:

$$\text{K.E.} = 1000 + 10 = 1010 \text{ e v}$$

(b) From equation (26)

$$\frac{1}{2} m v^2 = \text{K.E.} - V e \qquad (28)$$

K.E. is the final kinetic energy while $V e$ is the kinetic energy gained in transit [see equation (24)], so that K.E. $- V e$ is the initial kinetic energy or $(K.E.)_o$. Thus:

$$\frac{1}{2} m v^2 = (K.E.)_o \qquad (29)$$

and

$$v = \sqrt{\frac{2 \ (K.E.)_o}{m}}$$

$$v = \sqrt{\frac{2 \times 10 \times 1.6 \times 10^{-19}}{9.1 \times 10^{-31}}} \quad \begin{array}{l} \text{(joules)} \\ \text{(electron mass in kg)} \end{array}$$

$$v = 1.87 \times 10^6 \text{ m/sec}$$

34. Current-Voltage Relation

Despite the possible retarding contact potentials which may exist between a pair of dissimilar metals such as the anode and cathode of a phototube, a small number of photoelectrons may reach the anode

if the frequency of the incident radiation is high enough, even with zero applied voltage. As the anode is made increasingly positive with respect to the cathode, more and more of the slower electrons manage to reach the anode. It is found that all the electrons ejected from the cathode for a given frequency of incident light will finally reach the anode, provided the applied voltage is raised sufficiently. When this point is reached the tube is said to be saturated.

Several factors contribute to the magnitude of the saturation voltage. First there is the size of the anode itself; this element, usually a thin rod-like structure, cannot produce a strong electrostatic field in its immediate vicinity because of its small size. Many electrons fly past the anode without striking it as they would do if the anode were larger. On the other hand, increasing the area of this electrode would cause cathode shading, and all the available light would not reach the cathode due to the shadow cast by the anode.

A second factor is space charge. A phototube requires a transparent window; glass and quartz are both good insulators; hence, many electrons that miss the cathode deposit on the insulating walls of the tube and produce an electrostatic field that acts to oppose the emission of cathode electrons. Such space charge necessitates a larger voltage than would otherwise be required to cause saturation.

Finally, the presence of even small amounts of residual gas exerts a definite effect upon the value of the saturation voltage. This matter will be treated in detail in the next chapter. In most phototube applications, operation at saturation is a decided advantage since it permits the applied voltage to vary appreciably without affecting the phototube current for a given light flux.

In Fig. 20, the current-voltage curve for a typical vacuum phototube is given. Between the origin of the curve and point A, the phototube acts as a linear circuit element, the current from cathode to anode increasing in direct proportion to the increment of applied voltage. Between A and B, the transition to the saturated condition occurs while full saturation exists between points B and C.

35. The Use of the Load Line

The curve of Fig. 20 clearly shows that a phototube is essentially a high-impedance device. Even with a high anode voltage, say 140 volts, the tube current is only a little over 22 $\mu a/lu$ of flux. This order of current is not satisfactory for relay operation. Microam-

meters, though reliable in this range, are expensive and undesirably delicate. This suggests amplification which, in turn, necessitates using the load line for designing amplifiers having the required characteristics.

The fundamental amplifier input circuit for a vacuum phototube is given in the insert in Fig. 21. The source of anode potential is connected in series with the phototube and the load resistor r. The voltage drop across r is then used as grid input to a triode or pentode voltage amplifier. For the moment, we shall consider the amplifier a d-c amplifier although the same input circuit may be used
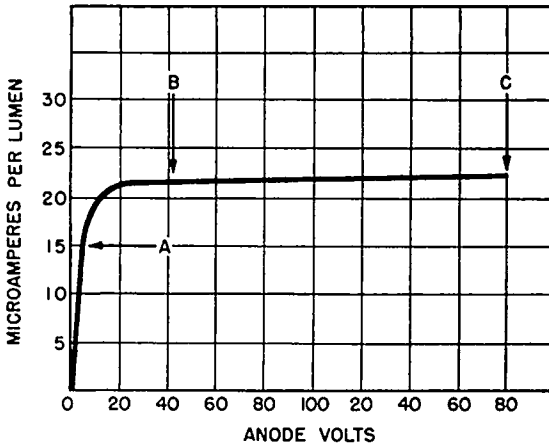
Fig. 20. Current-voltage relation of a typical vacuum phototube.

for amplification of fluctuating phototube currents such as would be encountered in sound-on-film reproducing systems. Since the phototube is a high-impedance device, a large value of r is necessary to obtain a practical voltage drop as grid input to the tube, even when the light intensity is relatively large. Let us assume that we wish to draw the load lines for a supply voltage of 250 volts and load resistors of 1 megohm, 10 megohms, and 25 megohms.

The procedure is similar to that used for load lines drawn into average anode characteristic curves of amplifier tubes. The steps involved may be given as follows:

(1) All load lines terminate on the x axis at the supply voltage (point O), regardless of the value of r. Assume that the anode current I_a is zero when the phototube is in complete darkness. Under

those conditions the anode voltage is equal to the supply voltage. This is obtained from the familiar relation:

$$E_a = E_{bb} - I_a \, r \qquad (30)$$

when $I_a = 0$, $E_a = E_{bb}$.

(2) To determine the second point for a given load line, assume *any* voltage distribution between the phototube and the load, and then evaluate the anode current that must flow for this distribution. Start with the 25-megohm load resistor, and assume that light conditions are such as produce a 160-volt drop across the tube. This leaves $250 - 160 = 90$ volts across r. Hence, the current flowing in the anode circuit through r is:

$$I_a = 90/25 \times 10^6 \text{ amperes}$$

$$= 3.6 \ \mu a$$

This coordinate is then entered on the graph (point A, Fig. 21) and the load line drawn between 250 volts on the x axis and point A. The line may be extended upward as far as desired.
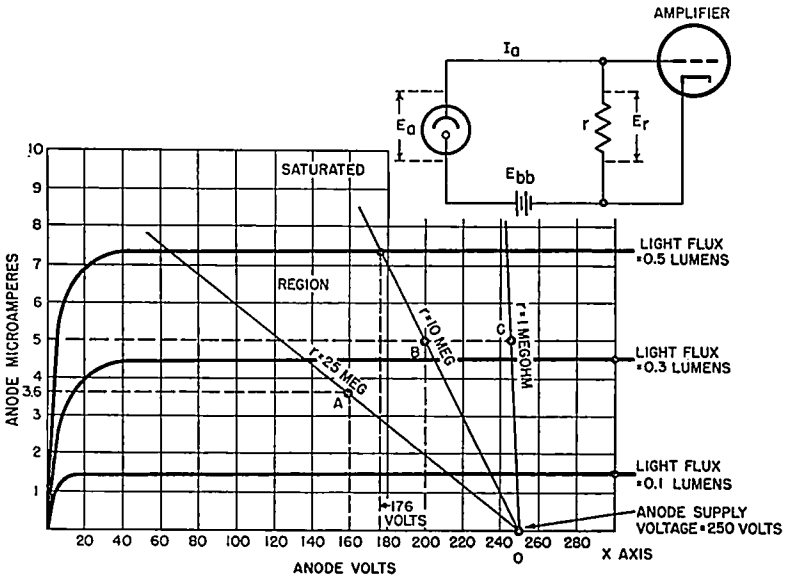
Fig. 21. Basic amplifier input circuit. Load lines for three different load resistors r with anode supply voltage of 250 volts.

The 10-megohm load line is found in a similar manner. Some caution must be exercised in selecting the assumed voltage distribution to avoid unreasonably large current values. One would not expect the voltage drop across the load resistor to be nearly as great when it is 10 megohms as when it was 25 megohms. Thus, we might obtain the second terminal of this load line by assuming a drop of, say, 50 volts across r and 200 volts across the tube. For this condition:

$$I_a = 50/10^7$$

$$I_a = 5 \; \mu a$$

so that point B is entered on the graph at 5 μa on the 200-volt ordinate.

When the load line is only 1 megohm, the drop across r will be very small when the illumination is low. We might assume a 5-volt drop across r so that:

$$I_a = 5/10^6$$

$$I_a = 5 \; \mu a$$

when the anode voltage is 245 volts. Thus, the coordinates of point C are 245 volts and 5 microamperes and provide us with the third load line.

Phototube load lines are used in much the same way as those drawn into vacuum tube curves. For example, suppose we wanted to know what voltage drop would develop across r (value 10 megohms) when the light flux is 0.5 lu. All we need do is note the intersection of the 0.5-lu curve and the 10-megohm load line and read off the load drop directly from the projection of this intersection on the x axis. In this example, we see that the 10-megohm load line intersects the 0.5-lu curve at a tube drop of 176 volts. The drop across r is, therefore, 250 − 176 = 74 volts.

Problem 7.   The phototube of Fig. 21 is equipped with a 25-megohm resistor as a load. Find the voltage across the load (E_r) when the light flux is 0.3 lu and the supply voltage is 250 volts.

Solution.   The 25-megohm load line intersects the 0.3-lu curve at a tube drop of 138 volts. The potential that will appear across r is, therefore, $E_r = 250 − 138 = 112$ volts.

Thus load lines are extremely useful for predicting anode currents for various light values, as well as output or load voltage available as either a positive or negative potential for application to the grid

of an amplifier. The polarities shown in the insert of Fig. 21 will apply a positive voltage to the grid with respect to cathode; a reversal of the grid-cathode connections will produce a negative grid voltage.

Problem 8. A circuit like that shown in the insert of Fig. 21 is set up using a 6J5 triode amplifier. The triode has a fixed bias of −6 volts. In order to place a relay in the triode plate circuit, the bias must be reduced to −1 volt. The phototube load resistor is 10 megohms. Will the relay trigger with a luminous flux of 0.1 lu on the phototube?

Solution. To reduce the grid voltage of the triode from −6 to −1 volt, a positive potential of +5 volts must develop across r as a result of phototube current. Following the 10-megohm load line, we find that a 5-volt drop will occur across r when the anode current is about 0.5 μa. At this point, the tube drop will be 245 volts. An anode current of this value will flow in this tube when the light value is approximately 0.05 lu. Hence, a flux of 0.1 lu will certainly trigger the relay.

36. Current- Light Flux Relation

The quantity of electrons emitted from a sensitive surface should vary in direct proportion to the intensity of the radiation incident upon the surface. A very well-evacuated phototube does display this characteristic to a great extent. For example, if the current-light flux relationship of the phototube discussed in the previous section (type 925) is plotted at a relatively high anode voltage (e.g., 180 volts) the curve of Fig. 22 is obtained. The need for a relatively high anode voltage is apparent from the curves in Fig. 21. Since phototubes are always operated in the saturation region in practice, the anode voltage must be made high enough to insure that saturation occurs. It is also evident from the linearity of the current-voltage curves that the current-light flux relationship would be very nearly the same for any anode potential between approximately 50 volts and 250 volts.

The linear performance of a good vacuum photocell is of great advantage in many applications. For instance, a foot-candle meter or other photometer can be calibrated with a perfectly linear scale. Rough calibrations of photometers can be accomplished by taking only two convenient check points. For precise photometry, however, a complete examination of current *vs* illumination is recommended since any given photometer may develop nonlinearity either in manufacture or during use. The causes of such nonlinearity are residual gas in the phototube, variable leakage resistances outside
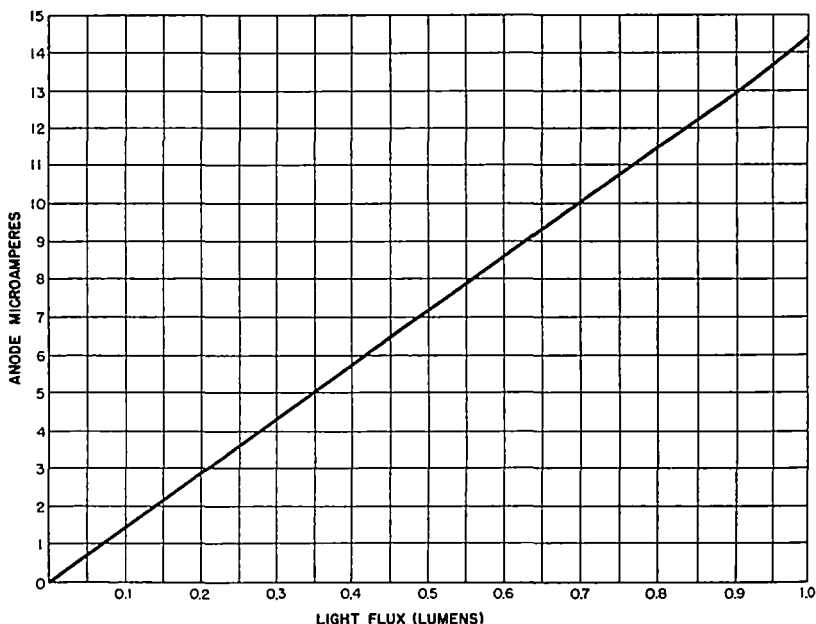
Fig. 22. Current-light flux relationship in a type 925 phototube for a fixed anode voltage of 180 volts.

the tube either along its envelope or through component supports such as terminal strips, etc., and undissipated space charge.

Problem 9. A direct reading photometer is to be constructed using a type 925 phototube with 200 volts on its anode. What range microammeter should be used if the largest anticipated light flux is to be 0.6 lu?

Solution. From the curve of Fig. 22, it is seen that a light flux of 0.6 lu will cause a current of 8.7 μa to flow in an external circuit of zero resistance. The true external circuit in this case, however, consists of a microammeter and a source of potential, both of which have finite resistances. We might first compute the static resistance of the phototube from the data given. That is:

$$R = \frac{200}{8.7 \times 10^{-6}} = 23 \times 10^{6} \text{ ohms} = 23 \text{ megohms}$$

Normal D'Arsonval microammeters seldom have coil resistances greater than 100 ohms; a reasonably good power supply has an output impedance of about the same order. Hence, the total external resistance of the circuit is only 200 ohms which represents an error of roughly 0.001 %. This is completely inconsequential, of course. Since microammeter scales are generally purchasable from stock in steps of 5 μa, a 0 to 10-μa movement would be satisfactory for this photometer.

37. Ratings and Characteristics of Vacuum Phototubes

Like their thermionic counterparts, vacuum phototubes are given definite ratings to assist the designer in selecting the right unit for his particular application; to enable him to predict its performance before construction of a prototype; and to help him avoid operating the tube in excess of its maximum ratings. For example, the type 925, in a current catalog, is given the ratings shown in Table II.

Let us examine each of these ratings and characteristics in turn.

Description: Vacuum phototubes are manufactured with varying bulb dimensions. Always included in any table of ratings will be found a reference to an outline drawing from which the maximum bulb and socket dimensions of the phototube may be read at a glance; in addition, such an outline drawing generally conveys information relative to mounting methods (see Section 28). The outline drawing for the type 925 is given in Fig. 23.

Spectral Response: The reader should refer back to Fig. 15 at this point. The S-1 curve, it will be recalled, has a double peak, the
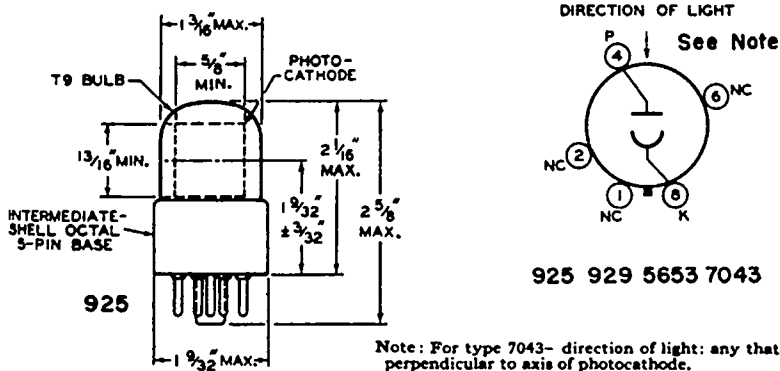
Fig. 23. Outline drawing for the type 925 vacuum phototube. RCA.

one having the greater value being the peak at the blue end of the spectrum. A statement concerning surface is very important to the prospective user since it tells him the nature of the source of light he will need to get the most out of the tube. Conversely, if his light source is already selected, it enables him to choose the phototube best suited to it.

TABLE II
RATINGS FOR A TYPE 925 PHOTOTUBE

RCA Type	Description	Out-line	Spec-tral Re-sponse	Wave-length of Max. Spectral Response angstroms	Maximum Ratings *					Characteristics		
					Anode Supply Voltage dc or peak ac volts	Average Cathode-Current Density μa/sq.in.	Average Cathode Current μa	Ambient Temper-ature °C	Anode Voltage dc volts	SENSITIVITY		Max. Anode Dark Current at 25°C μa
										Radiant μa/μwatt	Luminous μa/lumen	
925	Short-bulb type. For relay applications.	23	S-1	8000	250	30	5	100	250	0.0018	20	0.0125
926	Cartridge type. For colorimetric applications.	27	S-3	4200	500	30	5	100	250	0.0018	6.5	0.005
929	For light-measuring and relay applications.	19	S-4	4000	250	25	5	75	250	0.045	45	0.0125
934	For sound and facsimile equipment.	24	S-4	4000	250	30	4	75	250	0.030	30	0.005
935	For ultraviolet measurement applications.	10	S-5	3400	250	30	10	75	250	0.043	35	0.0005
5652	Composite anode - cathode type with balancing capacitance. For facsimile service.	21	S-4	4000	250	30★	4★	75	250	0.045	45	0.01
5653	For relay applications.	19	S-4	4000	250	25	5	75	250	0.02-0.1	20-100	0.25
6570	For industrial applications critical as to microphonics and sensitivity gradient.	8	S-1	8000	500	25	5	100	250	0.0027	30	0.013
7043	Non-directional type. For sound reproduction.	17	S-4	4000	250	25	5	75	250	0.045	45	0.0125

● Averaged over any interval of 30 seconds maximum.

* Absolute values.

★ For either electrode.

□ At wavelength of maximum spectral response for each type.

‡ On basis of tungsten-filament light source operated at 2870° K.

Note 2: Direction of light is into concave side cathode.

Note 3: For type 7043– direction of light: any that is perpendicular to axis of photocathode.

Wavelength of Maximum Spectral Response: This information is offered as a kind of short cut for the reader. Without looking at the curve, he knows the wavelength to which the phototubes is most sensitive, in this case 8000 Å. This means that the 925 is not particularly well adapted for use with incandescent lights whose radiation is principally in the red and yellow portions of the spectrum.

Maximum Anode Supply Voltage, Dc or Peak Ac: Since phototubes may be used either with d-c power supplies or a-c sources, under no conditions is this voltage to exceed 250 volts for this tube. Excessive voltage may result in excessive anode current or a glow discharge if residual gas is present. In either case, the tube is likely to be damaged.

Maximum Average Cathode-Current Density: This figure is given as an averaged one over 30 seconds of current-flow time as a maximum. Thus, the cathode surface of the 925 is limited to 30 μa per square inch for a 30-second maximum time. This states implicitly that the tube may be damaged if the current density is greater than this for 30 seconds or less or if this particular current density flows for more than 30 seconds steadily. The measurements in Fig. 23 indicate that the cathode area of the 925 is very close to 0.5 in.^{2} Thus, the maximum current density for this cathode $0.5 \times 30 = 15$ μa for the entire surface. Remember that, however tiny this current may appear to be, it cannot flow for more than 30 seconds without danger to the phototube.

Maximum Average Cathode Current: For continuous use, the 925 may run an anode current of 5 μa. This is approximately one-third of the value given for the 30-second interval.

Maximum Ambient Temperature: Most phototubes will continue to operate without changes in characteristics up to 75 or 100°C. Beyond this point, they must be operated at reduced anode voltages and currents. If the temperature rises to unreasonable figures, there is danger that the cathode may release adsorbed gas with its attendant danger of greatly changed tube characteristics and the possibility of the initiation of a glow discharge.

Radiant Sensitivity: Radiant flux embodies the concept of physical power rather than energy; that is, the notion of time must enter into a description of the luminosity of any source. For this reason, the basic measure of luminosity is the joule/second or the *watt.* Historically, the standard candle was the first unit to be defined and the lumen was secondary. More recently, when the lumen

was redefined in terms of power and relative luminosity, an attempt was made to maintain the best possible agreement between the old definition of the lumen based on the standard candle and the new definition based on the number of lumens in one watt of radiant power. The number 680 is now accepted so that:

$$1 \text{ lu} = 1/680 \text{ watt of radiation of wavelength}$$

$$5.55 \times 10^{-7} \text{ m} \quad (5550 \text{ Å})$$

Thus, 680 lu of this wavelength equal 1 watt of radiant power. Note that 5550 Å is the wavelength of light to which the average human eye is most sensitive.

For radiation of 1-watt power but in some wavelength other than 5550Å, the lumen value or luminous flux (F) is given by:

$$F = 680 \times \text{relative Y} \quad (\text{lu}) \tag{31}$$

The term "relative Y" represents the relative ordinate on the response curve for the human eye (Fig. 6) applying to the wavelength in question.

Consider the rating of 0.0018 µa/µw at 8000 Å for the type 925. Since this wavelength is beyond the range of visibility, conversion to sensitivity in terms of microamperes per lumen is impossible in this case. Hence, the sensitivity of the 925 is specifically in the ultraviolet with respect to this rating. For a tube (such as the 926) with a maximum response at 4200 Å, the conversion from radiant sensitivity to luminous sensitivity at this wavelength would appear as follows:

Radiant sensitivity = 0.0018 µa/µw = 1.8 µa/mw (at 4200 Å)

Lumens = 680 × 0.03 (relative Y at this wavelength is 0.03 on the curve of Fig. 6)

Luminous sensitivity = 680 × 0.03 × 1.8 = 36.7 µa/lu at 4200 Å

Luminous Sensitivity: This rating is based upon strictly visual effects. A light source operating at 2870°K is used as a standard. Such a source emits visible light of virtually all wavelengths as is characteristic of a white-hot tungsten filament. When a total luminous flux of one lumen falls on the cathode of a 925 type (anode voltage = 250 volts), the anode current is approximately 20 µa. This should be compared with the curve of Fig. 22 where the anode current is approximately 15 µa for 1 lumen of flux. Note that this is due to the fact that the coordinates for this curve were obtained on the basis of an anode voltage of only 180 volts, and that no specific color temperature is given so that we cannot be certain of the

standardness of the source. It should now be evident that consider-
able rigor is necessary in defining photometric ratings and curves if
they are to have any real technological value.

Anode Dark Current: A small but very real anode current flows
in even the best vacuum phototube in complete darkness. This is
due to the release of some high-velocity electrons from the photo-
cathode under the influence of only the electrostatic field set up by
the anode supply potential. Its magnitude is a function of many
things: surface type, surface area, amount of residual gas, electrode
position, etc. At this point, its significance may be somewhat ob-
scure, but when the dark current of vacuum tubes is compared with
that of gas-filled types later in this book, its importance will be clari-
fied.

38. Secondary Emission

It was mentioned in Section 27 that experimental phototubes
based on a central-cathode type of construction somewhat like ther-
mionic tubes are capable of reaching saturation with only a volt or
two of potential difference between the two electrodes. In such a
tube, photoelectrons literally have no place to go other than to the
large surrounding anode. With the anode more positive than the
cathode by only one volt, all emitted electrons would ultimately
arrive there. However, such tubes are not used because their sensi-
tivities are very much lower than the central-anode type.

A central anode, being a slender rod with little surface, must be
made more positive to achieve saturation. This positive potential —
varying from about 8 to 20 volts depending on tube type — is respon-
sible for a relatively large acceleration of electrons leaving the cath-
ode. Thus, the speed of all the electrons that ultimately reach the
anode is comparatively high. For those electrons that leave the
cathode at a high *initial* speed, the final velocity of impact will be
great enough to dislodge other electrons from the material of the
anode itself. Such newly released particles represent a fresh supply
of current carriers capable of increasing the anode current. This
phenomenon, as in thermionic tubes, is called *secondary emission.*
Although anode secondary emission is of no value in ordinary two-
electrode vacuum phototubes, it plays an important part in the
functioning of multiplier phototubes. These will be discussed at
length in Chapter 5.

39. Review Questions

1. Explain carefully the relationship between Lambert's cosine law and the de-
   sign of modern phototubes.
2. Define the volt in terms of the work required to move a given charge between
   two points having a given potential difference.
3. Derive the expression $v = \sqrt{2Ve/m}$ where v is the velocity of an electron
   having a charge e and a mass m, and V is the potential acting on the particle.
4. Prove that one electron volt is the equivalent of 1.6×10^{-19} joules.
5. Define saturation in a phototube. Why is it advantageous to operate a photo-
   tube in a measuring or relay circuit at saturation at all times?
6. Using the graph of Fig. 21 (or a duplicate of it), draw in the load line for a
   5-megohm load and a supply potential of 180 volts. Using this load line, de-
   termine the voltage developed across the load resistor for a luminous flux of
   0.5 lu.
7. Why is a linear current-light flux relation in a phototube desirable? For
   what kinds of applications would a severely nonlinear characteristic be in-
   tolerable?
8. Explain what is meant by the rating *maximum average current density*.
9. What is the difference between the radiant sensitivity of a phototube and the
   luminous sensitivity of the same tube?
10. Why is it desirable to have as low an anode dark current in a phototube relay
    circuit as possible?

Chapter 5

GAS-FILLED PHOTOTUBES

40. Mechanical Behavior of Gases

The study of general gas laws, i.e., principles that explain observed mechanical phenomena in gases and predict the behavior of gases under specific conditions, encompasses a large slice of the field of physics. In this section we shall want to touch briefly only on those phases of gas behavior that are related to the effects produced by electricity.

The mechanics of confined gases depend upon the thermal motion of gas molecules. According to the kinetic theory, the molecules of any gas at any temperature other than absolute zero (0°K or —273°C) are in constant, random, translatory motion. At room temperature, molecular speeds may reach two or three miles per second. Due to the relative crowding of the molecules of gas held at approximately atmospheric pressure, each one suffers innumerable collisions each second with its neighbors and the walls of the confining vessel. The pressure exerted by a confined gas on the sides of its container results directly from the impact of the moving molecules on these surfaces.

The researches of men like Boyle, Charles, Gay-Lussac, and Avogadro can be succinctly summarized in a single expression known as the *general gas law*. Equation (32) presents this law in its expanded form:

$$pV = RT = \frac{2}{3} N (\frac{1}{2}mv^2) \qquad (32)$$

where

  p = gas pressure. Using the mks system, this would be meas-
      ured in newtons/meter^2
  V = volume (m^3)
  R = the universal gas constant, 8.314 joules per mole of gas
      per °K
  T = absolute temperature in °K
  N = number of molecules in the sample of gas
  m = mass of an individual gas molecule
  v = average velocity of individual molecules

From the first two terms in equation (32) we may deduce that:

(a) The volume of a gas held at constant pressure is directly pro-
portional to the absolute temperature since $V = RT/p$. With p a
constant, then the ratio R/p may be replaced by k so that $V = kT$,
an expression of direct proportionality.

(b) The volume of a gas held at constant temperature is inversely
proportional to the pressure on the gas, or $V = k'/p$ by the same
reasoning as above.

(c) Finally, the pressure exerted by a confined gas of constant
volume is directly proportional to the absolute temperature, or
$p = k''T$.

In addition, using the left- and right-hand terms of equation (32),
we can deduce that the pressure per unit volume of any gas is a
function of the number of molecules contained in that unit volume
and the average kinetic energy of the molecules since

$$p = \frac{2}{3} \, n \left(\frac{1}{2}mv^2\right) \tag{33}$$

in which p is pressure, n is the number of molecules in the unit
volume (i.e., N/V), and ($\frac{1}{2}mv^2$) is the average kinetic energy.

We do not need to explore the general gas law further than this.
We shall draw on these facts where necessary in the work that follows.

41. Ionization and Mean Free Path

The average distance that a molecule travels between successive
collisions with other molecules is called the *mean free path*. In
electronic equipment, such as phototubes containing gas, the *elec-
tronic* mean free path is the average distance that an electron travels

between collisions with gas molecules. It may be shown that the mean free path of an electron in a gas is inversely proportional to the product of the cross-sectional area of the gas molecule involved (e.g., neon, argon, etc.) and the number of molecules per unit volume that are present. In other words, the mean free path is longer when the gas molecules are physically smaller and when fewer of them are present.*

Electrons liberated from a photocathode travel toward the anode with an acceleration that depends upon the difference of potential between the two elements. If any given electron attains sufficient velocity, its kinetic energy may become great enough to enable it to dislodge an orbital electron from a gas atom with which it collides. Thus, the likelihood of this event occurring in a specific instance depends upon two factors: (a) the accelerating potential and (b) the length of the mean free path. The connection of (b) with the final kinetic energy of the electron derives from a consideration of Newton's second law of motion.

$$ft = mv \tag{34}$$

where f = force, t = time that force is applied, m = mass of body to which force is applied, and v = final velocity of body. Thus:

$$v = \frac{ft}{m} \tag{35}$$

from which it is evident that the velocity of the electron is directly proportional to the time of application of the force. If the mean free path is too short, the force may not be applied for a long enough period to permit the electron to reach dislodging velocity.

Assuming a high enough accelerating potential and a sufficiently long mean free path, a given electron will release an electron from a gas atom with which it collides. Both electrons will then accelerate further toward the anode. Since each of these can liberate an additional electron by further collision, the dislodging process can proceed at a geometric rate (i.e., 2, 4, 8, 16, 32 . . . . . 2^n), causing a tremendous increase in anode current. At the same time, atoms that have lost electrons in the collision avalanche become positively charged ions and move back to the cathode; this reverse motion of

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* The actual equation is mfp = 1/4 $\sqrt{2aN}$ in which a is the molecular cross-sectional area and N is the number of molecules per cubic meter. Here the mfp is measured in meters.

positive charges amounts to a further increase of anode current. Finally, many slow-moving electrons attach themselves to neutral atoms forming negative ions that also are attracted to the anode, thus producing still more anode current.

It has been pointed out that the incidence of ionization in any particular gas is a function of accelerating potential and mean-free-path length. We must also realize that whether or not a gas ionizes in an electron collision depends also upon the nature of the gas.
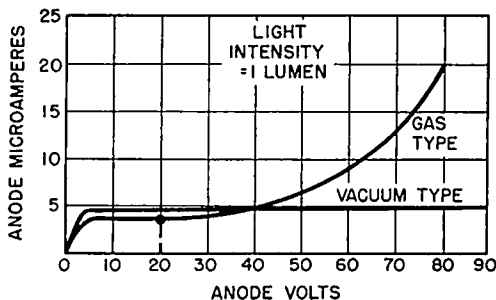
Fig. 24. Comparison of current-voltage curves of a vacuum and gas phototube. The intensity of the incident light is the same for both phototubes.

Some gases hold on to their orbital electrons with more tenacity than others, requiring a higher impact energy before an electron can be liberated. This characteristic is described in terms of *ionization potential* defined as follows: Ionization potential is the potential through which an electron must fall in order to acquire enough energy barely to release an electron from an atom upon impact. The ionization potentials of the rare gases that have been used in gas tubes are:

> Neon = 21.5 volts   Argon = 15.1 volts
> Krypton = 13.3 volts   Xenon = 11.5 volts.

42. Gas Pressure in Phototubes

We might now question whether there is some optimum pressure for filling the glass housing of a phototube to produce the greatest amount of ionization for a given accelerating potential. It would seem likely that an optimum pressure exists for the following reasons: If the pressure is too high, the volume will contain very many gas molecules so that a large number of electron-molecule collisions

will occur before the electron has gathered sufficient kinetic energy to dislodge orbital electrons; if the pressure is too low, many photo-electrons will be able to reach the anode without colliding with any gas molecules at all.

According to investigations reported in various scientific publications, pressures of the order of 0.2 to 0.5 mm appear to give the best results with most of the common gases. The increased current yield under these conditions improves the sensitivity of the phototube by a factor of 9 or 10 times.

43. Gas Amplification Ratio

The contribution of the current carriers produced by ionization to the total anode current results in a greater change of anode current per lumen of incident light than is obtainable in a vacuum phototube. This increase in sensitivity is called the *gas amplification ratio* (or factor), and may be defined as the ratio of the change in anode current per lumen of incident light at maximum anode voltage to the change of anode current per lumen at anode voltages below the ionization potential. This definition will be clarified by an examination of Fig. 24 and the accompanying text. For anode potentials between zero and 20 volts, both tubes behave in much the same fashion, saturation is reached at about 5 volts between anode and cathode. As ionization begins, however, the gas-tube current surges upward with each additional volt applied to the anode.

Assume for the moment that both tubes are in complete darkness. As we showed in Section 37, the current in the vacuum tube would be of the order of 0.01 μa. Although the dark current of an equivalent gas type would be about 10 times greater than this (to be discussed later), both these currents may be considered negligible on the scale of coordinates used in Fig. 24. Thus, for the tubes shown in this drawing, a light flux of 1 lumen on the vacuum tube causes an increase of anode current of 5 μa (anode potential = 80 volts), while the same increase of flux produces a current of 20 μa in the gas tube. For this theoretical case, the gas amplification ratio is 20/5 = 4.

44. Gas Amplification of a Type 930 Gas Tube

For a better understanding of gas amplification, we might study the average anode characteristics of the type 930 gas phototube as
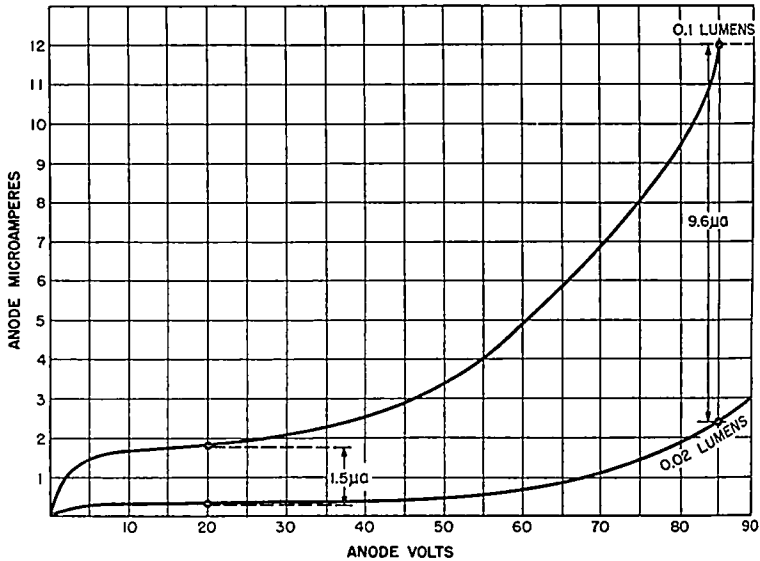
Fig. 25. Average anode characteristics for a small gas-filled phototube. (Types 930, 921, and 923.)

given in Fig. 25. These curves apply as well to the types 921 and 923. Two curves are given. The lower curve traces the plate-current rise in the tube as the anode voltage is increased from zero to 85 or 90 volts with an incident flux of 0.02 lu; the upper curve repeats for the performance of the tube when the incident flux is 0.1 lu.

At an anode potential of approximately 20 volts, i.e., before ionization begins, a change of 0.08 lu results in an increase of 1.5 μa of anode current. When the anode voltage is raised to 85 volts, the same increase in luminous flux gives rise to a current increment of 9.6 microamperes. The gas amplification ratio is, therefore:

$$\text{Gas amp. ratio} = \frac{9.6}{1.5} = 6.4$$

Any attempt to raise the gas amplification ratio by further increase of anode potential may give rise to a self-sustaining glow discharge in which all the gas molecules are ionized.* Because of the large number of massive positive ions that form when this occurs, there is

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* For a discussion of glow discharge and cathode sputtering, see Schure, A., *Gas Tubes*, New York, John F. Rider Publisher, Inc., 1958.

serious danger of ruining the tube due to cathode sputtering. For this reason, the maximum anode potential permitted on most small gas-filled phototubes does not exceed 90 volts.

45. Ratings of Gas-filled Phototubes

In general, the ratings of gas-filled phototubes are similar to those given for vacuum types with the exceptions discussed below. A comparison chart for the gas-filled 930 and the comparable vacuum tube (925) shows the difference at a glance.

TABLE III

COMPARISON BETWEEN GAS-FILLED AND VACUUM PHOTOTUBE

	Type 925	Type 930
Spectral response	S-1	S-1
Wavelength of maximum response (Å)	8000	8000
Max. anode supply voltage, d-c or peak a-c volts	250	90
Average cathode-current density, μa/in².	30	30
Average cathode current (μa)	5	3
Ambient temperature, max. (°C)	100	100
Radiant sensitivity with anode supply = max. in μa/μw	0.0018	0.012
Max. anode dark current at 25°C with max. anode voltage (μa)	0.0125	0.1

The important differences are apparent. The gas tube must not be operated with more than 90 anode volts as compared with the 250 volts permitted for the vacuum tube. This may at times be an annoying restriction requiring careful precautions to avoid overvoltage. The average cathode current is somewhat less for the gas tube than for the vacuum type. The gas-filled tube has a much higher radiant sensitivity than the vacuum tube due to its gas amplification ratio. The dark current in the gas type is likewise greater; this characteristic, among others, makes a gas tube unsuited for
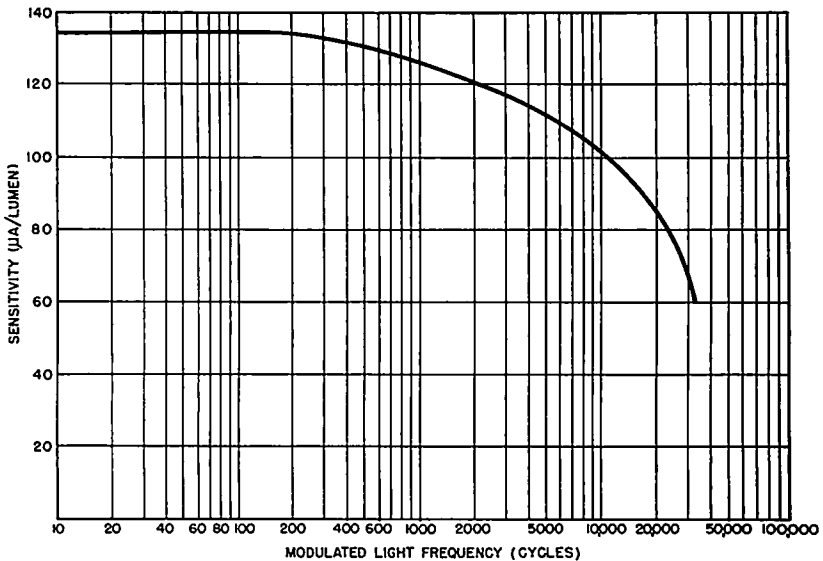
Fig. 26. Average sensitivity characteristic of a type 930 gas-filled phototube.

photoelectric instrumentation intended for use under low-intensity illumination conditions.

Luminous sensitivity ratings have been omitted from Table III. This subject is of sufficient importance to warrant a brief separate discussion.

Phototubes may be rated in terms of either *static* or *dynamic* sensitivity. Static sensitivity may be defined as the ratio of d-c anode current to the incident luminous flux of constant value. When phototubes are used with modulated light sources as in sound-on-film projection or long-distance modulated light relays, the sensitivity may be defined as the ratio of the alternating component of the anode current to the alternating component of the incident luminous flux. This dynamic sensitivity characteristic is the same as the static characteristic for vacuum phototubes *but not for gas-filled types.* For this reason, the luminous sensitivity of the gas tube must be either a set of figures for various frequencies or a graph that shows the variation of dynamic sensitivity with *frequency.*

For a gas-filled phototube, the sensitivity falls off with increasing frequency of modulation or interruption of the light from the source. The average sensitivity for various frequencies for a type 930 gas tube is given in Fig. 26.

The explanation of the shape of this curve is found to lie in the finite time required for photoelectrons to build up to the steady-state value of the amplified current in the phototube. Many workers are under the impression that this build-up time is due to the slow motion of collision-generated ions in the gas; this has been shown to be untrue. Despite the relative massiveness of these ions and their slower acceleration in the electric field in the tube, their transit times are measured in microseconds. Hence, they could not possibly account for the drop-off of output at the higher frequencies in the order of 10,000 cycles.* It has been found that the more important limitation on flat response is caused by the slow diffusion of so-called "metastable," electrically neutral atoms that drift toward the cathode. Upon impact, these atoms give rise to additional electron emission. Since this emission accounts for much of the steady-state anode current, the delay described is sufficient to cause the loss of amplification encountered in gas tubes.

If the manufacturer of the gas phototube does not provide an amplification response curve such as that of Fig. 26, he will probably supply specific information for definite frequencies. Thus, for the type 930:

TABLE IV

TYPICAL GAS PHOTOTUBE AMPLIFICATION FACTOR

Max. Gas Amplification Factor	Luminous Sensitivity $\mu a/lu$, source $2870°K$		
	0 cps	5000 cps	10,000 cps
10	135	111	101

46. Nonlinearity of Response

Figure 27 compares the anode current-illumination characteristics of two phototubes that are identical in structure except that one is a vacuum and the other a gas-filled type. The rapid anode current rise of the gas tube is quite evident, but a departure from linearity

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* For an account of these measurements, see Skellet, A. M., *J. Appl. Phys.*, vol. 9, 1938.

also begins to be displayed at higher illumination levels. The anode current increases at a faster pace than the illumination for anode voltages that are greater than the ionization value for the gas. This nonlinearity makes gas tubes unsuited for instruments but has little effect when they are used in relay and sound reproduction applications.

47. Multiplier Phototube Principles

A multiplier phototube does not contain gas but is included here because it has something in common with gas tubes: inherent amplification of phototube current. Instead of utilizing additional elec-
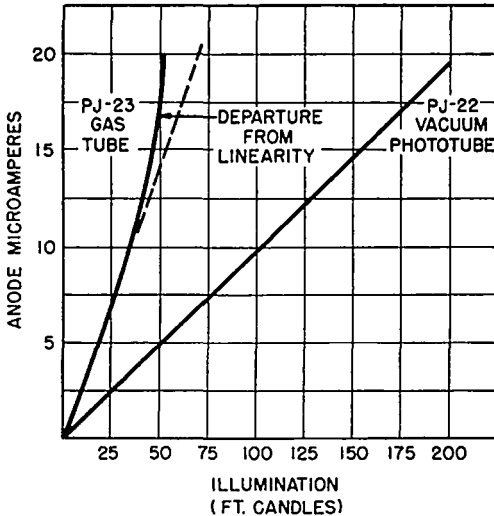
Fig. 27. Comparison of the current-illumination curves of vacuum and gas-filled phototubes. The tubes are identical except for the atmosphere in the envelope.

trons and ions for amplification, the multiplier phototube makes use of electrons produced by secondary emission.

In a typical multiplier arrangement, a conventional cathode emits electrons under excitation from a radiant source, the photoelectrons being collected by a nearby positively charged element called a *dynode.* The primary electrons are given sufficient energy by means of electrostatically induced acceleration to dislodge more secondary electrons from the dynode than there were primary electrons initially. The secondary electrons are then impelled toward another dynode that is still more positive than the first, again causing the

emission of an excess number of new secondary electrons. The impact-secondary-emission-impact sequence may be repeated as many as 14 times (as in the type 6810-A and 7046) with the result that there is a tremendous increase in the total number of electrons that reach the final anode compared to the original number. For example, the
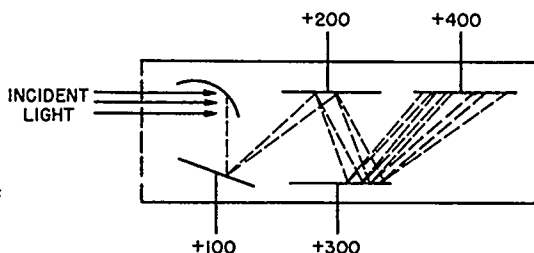
Fig. 28.   Basic action of a multiplier phototube.

6810-A, a 14-dynode multiplier phototube has a current gain of 12.5 × 10⁶. This means that for every initial primary electron, twelve and one-half million electrons (on the average, of course) reach the final anode. This fantastically large increase in current is responsible for the very high sensitivity of the multiplier phototube to low illumination levels.

The basic principle underlying multiplier action is shown in Fig. 28. The tube must be designed so that each successive dynode, at a higher positive potential than the one preceding it, receives most of the secondary electrons from its forerunner. In some tubes, especially those of earlier design, magnetic focusing was used to ensure that the electrons remained in the right path. The present trend, however, is based upon proper shaping of the dynodes and the establishment of electrostatic fields of the proper curvature to accomplish this without the use of externally generated forces.

Current multiplier phototubes run the gamut from 9 dynodes in tubes such as the 1P21 and 1P22, 10 dynodes as in the 2020 and 6342, and 14 stages as in the 6810-A and 7029. Through the series, we find current amplifications ranging from 1.2 × 10⁵ (type 2020 with a total supply voltage of 1250 volts) up to 12.5 × 10⁶ (6810-A). Their applications include: scintillation counters, detection and measurement of ultraviolet radiation of low intensity, automobile headlight control service, detection of alpha particles, color densitometers, spectrometers, flying-spot signal generators, light-operated relays, x-ray exposure control, and facsimile transmission. (See Fig. 29.)

TABLE V

RATINGS FOR MULTIPLIER PHOTOTUBES

RCA Type	Description	Outline	Spectral Response	Wavelength of Max. Spectral Response angstroms	Maximum Ratings *§				Supply Voltage (E) Between Anode and Cathode dc volts	Characteristics				
					SUPPLY VOLTAGE			Average Anode Current● ma.		SENSITIVITY		Current Amplification	Max. Equiv. Anode-Dark-Current Input ϕ lumen	Equiv. Noise Input ϕ lumen
					Ef dc or peak ac volts	Between Anode and Final Dynode dc or peak ac volts	Dynode No.1 dc or peak ac volts			Radiant $\mu a/\mu watt$	Luminous‡ amp/lumen			
1P21	9-stage type for specialized scientific applications involving extremely low light levels.	14	S-4	4000	1250	250	—	0.1	1000	80800	80	2×10^6	5×10^{-10}	5×10^{-13}
1P22	9-stage type having response similar to that of eye. Especially useful in colorimetry.	14	S-8	3650	1250	250	—	1.0	1000	768	1.0	3.3×10^5	3.75×10^{-7}	7.5×10^{-12}
931-A	9-stage type for use in light-operated relays, X-ray exposure control, and facsimile transmission.	14	S-4	4000	1250	250	—	1.0	1000	24000	24	0.8×10^6	2.5×10^{-9}	9.5×10^{-13}
2020	10-stage, head-on, flat-face type similar to 6342 but having low-resistivity photocathode.	5	S-11	4400	1500	250	400▲	2.0	1250 1500	4800 22400	6 28	1.2×10^5 5.6×10^5	2.25×10^{-9} —	7×10^{-12} —

● Averaged over any interval of 30 seconds maximum.

* Absolute values.

f Between anode and cathode.

Note 1: Direction of light is into end of bulb.

§ The maximum ambient-temperature rating of all multiplier types is 75° C except for type 1P22 which is limited to 50° C.

▲ This value is also the max. focusing-electrode voltage.

‡ On basis of tungsten-filament light source operated at 2870° K.

ϕ At 25° C and with supply voltage (E) adjusted to give luminous sensitivity of 20 amperes per lumen, except that for the 1P22 the supply voltage (E) is adjusted to give luminous sensitivity of 0.4 amperes per lumen.

Under conditions of 25° C tube temperature, tungsten-filament light source of 2870° K, and ac amplifier bandwidth of 1 cps.

Fig. 29. Electrode shape and placement in two modern multiplier phototubes. (A) Type 6810. (B) Type 1P21. RCA.

(A) I–14: DYNODES
      15: ANODE

(B)

O= PHOTOCATHODE
IO= ANODE
I–9=DYNODES
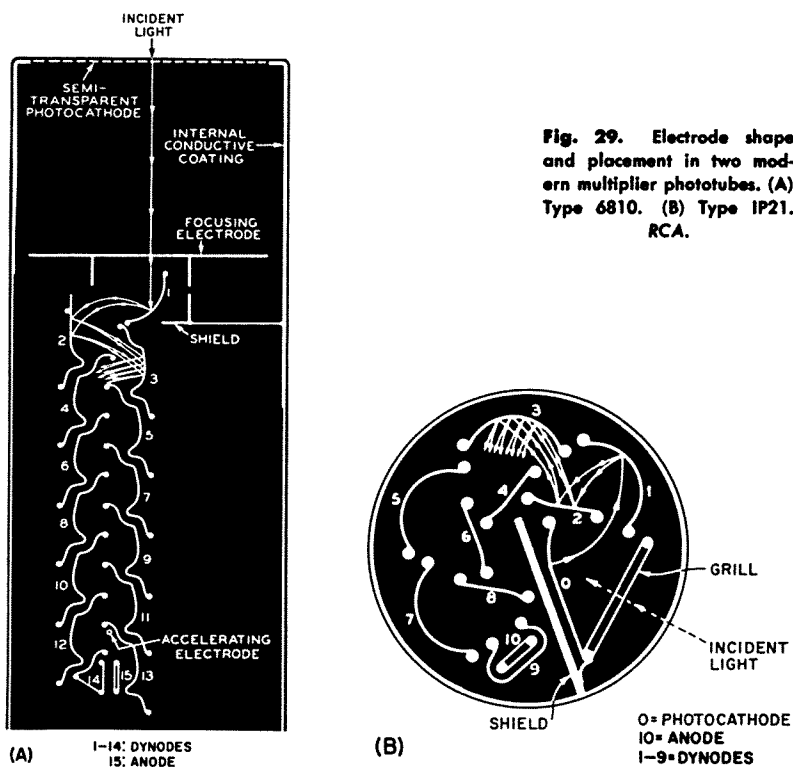
48. Multiplier Phototube Ratings

An examination of a typical set of ratings for a multiplier phototube gives insight into the circuits required as auxiliaries, such as the power supply for the phototube and the amplifier that follows it. Let us use a 931-A as an example. See Table V for its ratings.

49. Review Questions

1. Prove that a statement of Boyle's law for gases is implicit in the general gas law given in equation (32).
2. Why is the concept of mean free path of importance in any discussion of ionization of gases?
3. Both argon and neon are commonly used in the manufacture of gas-filled phototubes. In which type does ionization start at lower anode voltages? Is this an advantage or disadvantage? Why?

4. Explain why gas pressure is a critical factor in the performance of gas photo-tubes.

5. Define gas amplification ratio. Why cannot the gas amplification ratio of a phototube be raised without limit?

6. What may occur if the anode potential of a gas tube is raised too much? Why does this not happen in a vacuum tube?

7. Is a large dark current in a phototube a desirable or undesirable character-istic? Why is the dark current in gas tubes usually greater than in vacuum tubes?

8. Explain the causes for decreasing phototube current output with increasing frequency for gas tubes. Why is this not true of vacuum phototubes?

9. With the aid of diagrams, explain why multiplier phototubes have large current amplifications.

10. Draw the diagram of a power supply that might be used in setting up the voltages required for operating a type 931-A multiplier phototube.

Chapter 6

ESSENTIALS OF PHOTOTUBE AMPLIFIERS

50. Application Objectives

Phototubes are used in literally thousands of industrial devices but, in general, these may be grouped so that any individual function can be cataloged in one of the following:

(1) *Relay operation* as in intrusion alarms, machine safety controls, door openers, counters, etc.

(2) *Instrumentation* as in photometers, exposure meters, colorimeters, densitometers, pyrometers, etc.

(3) *Signal reproduction* as in sound-on-film recording, facsimile transmission, television, communication via light beams, etc.

(4) *Servomechanisms* as in automatic sorting devices, counting and speed controls, crucible heat controls, illumination controls for street and indoor lighting, loom and knitting machine controls, etc.

The functional operations involved in these four groups are: (1) relays — on-off, all-or-nothing action; (2) instrumentation — gradual change of output with equally gradual changes of luminous flux, usually involving some form of d-c amplification; (3) signal reproduction — fluctuating currents, always containing an a-c component, often without a d-c component of any kind; (4) servomechanisms — generally closed-loop systems for industrial control, using either d-c or a-c amplifiers, or both.

In this chapter we shall discuss the four major application groups listed above. Although the emphasis will be placed on general principles, specific circuits will be used as explanatory illustrations. The

reader is reminded that every new application problem introduces needs that normally cannot be met by standard, previously published designs and that limitless combinations and permutations of basic ideas are possible for the solution of an individual design problem.

51. Phototube Relay Operation

Single Vacuum-Tube Amplifier: As we have pointed out previously, the photocurrents in the normal phototube, even with intense illumination, are generally too small to operate even a sensitive type of relay. This calls for amplification of the phototube current to a value great enough to operate a relay. An ordinary power amplifier such as the 6K6 or 6V6 is made to order for this task.

Let us first examine the basic circuit given in Fig. 30. We start with a triode since this lends itself to somewhat easier circuit analysis. Battery E_a provides the potential needed for the anode of the phototube. For a vacuum type, this might be anything up to 250 volts; for a gas type, the limit would be about 90 volts. E_c provides bias for the vacuum triode, while E_{bb} is the normal plate supply for this tube. When light impinges on the cathode of the phototube, anode current flows as indicated by the arrows, and a voltage drop having the polarity shown occurs across the grid resistor, R_g. This drop, being in series-opposing with the bias voltage, cancels some negative bias from E_c, making the triode grid more positive. With circuit constants and illumination properly chosen, the triode plate
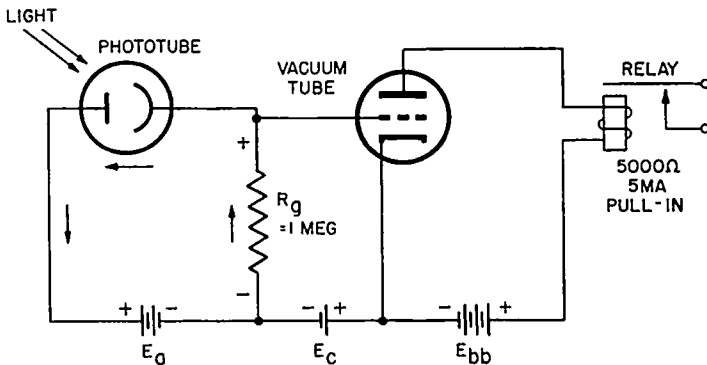
Fig. 30. Basic single-stage triode phototube amplifier.
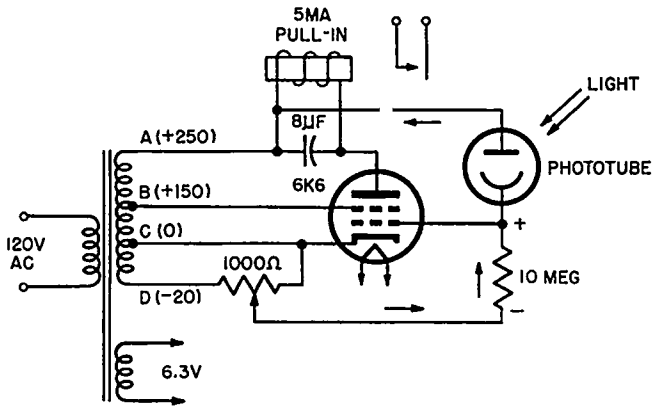
Fig. 31. A practical pentode single-tube phototube amplifier.

current will now rise sufficiently to cause pull-in of the relay arma-
ture. Note that the coil resistance of the relay (5000 ohms in this
example) is large enough to serve as the plate load for the triode.

It is relatively easy to progress from the basic battery-operated
circuit just described to a line-operated, a-c system of practical value,
using a 6K6 pentode as the relay tube (Fig. 31). This particular
circuit, originally designed to protect workers from coming too close
to high-speed gears in a machine, is wired so that the relay drops out
when the light beam is *interrupted*. Since the lower contact of the
relay is used, dropout causes machine turnoff.

The circuit operates as follows: at a given instant in time, the
instantaneous voltages at the secondary taps of the special transfor-
mer have the values and polarities shown. With light shining on the
photocathode, the phototube conducts and causes a voltage drop
across the 10-megohm grid resistor. The polarity of this is such as
to make the grid positive enough with respect to the cathode so that
the plate current of the 6K6 is sufficiently high to energize the relay.
When the beam is interrupted, the phototube current ceases to flow
and the grid returns to whatever negative voltage exists at the wiper
of the 1000-ohm potentiometer.

With this control initially adjusted under dark conditions to bring
about cutoff or near cutoff of the pentode, the relay must then drop
out, shutting off the controlled machine. During normal operation,
the capacitor connected across the relay coil is depended upon to
hold the relay pulled in as the ac reverses during each half cycle.
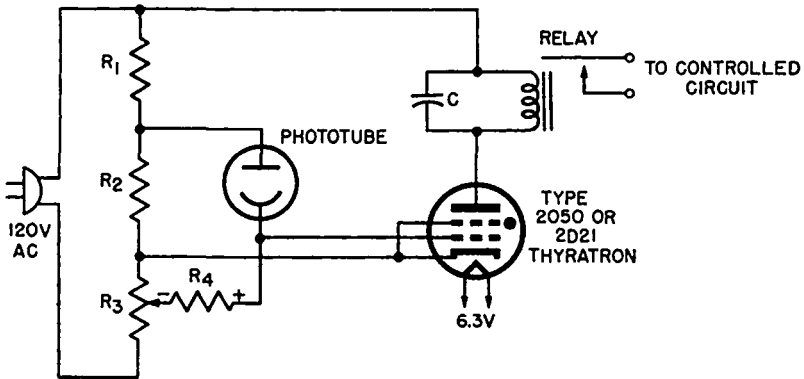
CIRCUIT VALUES

	Gas tube (868, 927, etc.)	*Vacuum tube (925, 917, etc.)*
C	8 µf	8 µf
R₁	10,000 ohms	0 ohms
R₂	9000 ohms	20,000 ohms
R₃	1000 ohms, 1 watt	1000 ohms, 1 watt
R₄	10 megohms	10 megohms
Rᵧ	5000-ohm, 10-ma pull-in	5000-ohm, 10-ma pull-in

Fig. 32. Forward-action thyratron photo-relay circuit. RCA.

Since all plate and anode currents must drop to zero when the upper taps of the transformer are instantaneously negative, the relay would tend to chatter were it not for the presence of the stored energy in the capacitor.

The presence of this capacitor, however, renders the circuit somewhat sluggish in response. A definite interval must elapse between interruption of the beam and relay dropout since the capacitor requires some time to discharge through the relay coil. All single tube a-c relay systems are characterized by this defect. Fast action can be obtained by using two tubes, as we shall demonstrate shortly.

Single Thyratron Amplifier: A small thyratron can be used quite successfully as a phototube trigger device because of its inherent "all-or-nothing" action. Thyratrons are either in a conducting or nonconducting state, depending upon the anode and control grid voltages.* If a thyratron is biased so that its grid is more negative

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* For complete details on thyratron structure and circuit action, see Schure, A., *Gas Tubes*, New York, John F. Rider Publisher, Inc., 1958.
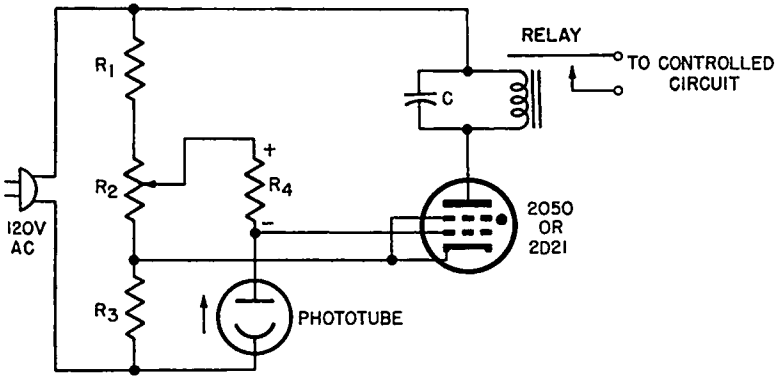
COMPONENT VALUES

	Gas tube	Vacuum tube
C	8 μf	8 μf
R_1	3000 ohms, 2 watts	0 ohms
R_2	2000 ohms, 1 watt	5000 ohms, 5 watts
R_3	1000 ohms, 1 watt	1000 ohms, 1 watt
R_4	10 megohms	10 megohms
R_7	5000 ohms, 10 ma	5000 ohms, 10 ma

Fig. 33.   Inverse-action circuit. RCA.

than the critical potential for the anode voltage being used, the tube behaves as an open circuit and a relay in series with its anode will not be energized. With a phototube as an input device, incident flux can be made to raise the thyratron grid voltage in a positive direction sufficiently to cause the tube to *fire* or conduct. This action is virtually instantaneous, the anode current going from a near-zero value to its maximum in a matter of microseconds when the plate load is purely resistive. The rise time of the anode current is, of course, somewhat greater when a relay coil serves as a load due to the L-R time constant, but this increase is generally of little consequence.

A single thyratron can be used with either a vacuum or gas-filled phototube. The circuit may be arranged to provide either forward action, relay pull-in with increase of light, or inverse action, relay dropout with increase of light (Fig. 32 and Fig. 33).

In the forward-action circuit of Fig. 32, R_3 is adjusted in the absence of light so that the control grid is more negative than the

critical potential. This holds the relay open since the tube is non-conducting for this condition. When light reaches the photocathode, the anode current of the phototube flows through R_4 — a very large resistance — causing a voltage drop as shown in the diagram. The control grid of the thyratron then rises above the critical potential and the thyratron fires, activating the relay. With the interruption of light to the phototube, the control grid returns to its below-critical voltage and the thyratron extinguishes. It might be remarked here that the thyratron stops conducting when the grid goes negative because the *anode supply is ac.* If this potential were dc, the tube would continue to conduct even after the grid voltage was restored to its former negative potential; this is a thyratron characteristic. Since the anode potential passes through zero twice in each a-c cycle in this case, the tube's conduction is stopped by the temporary absence of anode voltage. If, in the meantime, the grid has gone sufficiently negative, conduction will not begin again until the grid is made positive once more.

Inverse action may be obtained by converting the circuit above to that of Fig. 33. In the absence of light the thyratron conducts when R_2 is properly adjusted to maintain the control grid above the critical potential. As light falls on the phototube, the anode current flowing through R_4 causes the grid potential to drop below critical value and the thyratron extinguishes, releasing the relay. Thus, this system brings about relay action when the light is interrupted.

Fast-Acting Relay Circuit: The use of ac calls for a capacitor to be connected across the relay coil to prevent chatter. Due to the L-C circuit formed by this capacitor and the coil, there is an appreciable lag in the response of this relay circuit when the light value changes. Extremely fast action, limited only by the inertia of the relay armature, can be obtained by employing dc and a cathode-follower circuit in which there are no capacitors, hence no time-delay components (Fig. 34). This circuit contains but one control and a rather unique triggering arrangement wherein the relay tube is activated by a change in voltage on its screen grid.

To analyze the circuit, let us start by assuming that the phototube is in darkness and that its anode current is nearly zero. For this condition, the grid of V_1 is at ground potential while the grid of V_2 is at about 9 volts positive with respect to ground. The combined plate currents of V_1 and V_2 flow through the common cathode re-
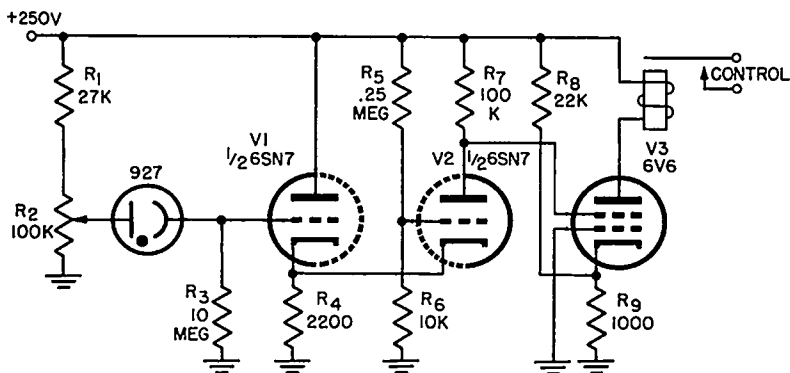
Fig. 34. A high-speed response, cathode-follower phototube relay circuit.

sistor R_4, resulting in approximately cutoff for the cathode-follower (V_1). At the same time, there is enough conduction in V_2 due to the +9 volts on its grid so that its actual plate potential is in the vicinity of +50 volts. Since the screen grid of the relay tube (V_3) is connected to the V_2 plate, this electrode is also at about 50 volts. Resistors R_8 and R_9 furnish the cathode with about 10 volts positive with respect to ground. For these voltages (250 plate, 50 screen, and 10 cathode) the 6V6 is nearly cut off and the relay is unenergized.

When the 927 is illuminated, its anode current drives the grid of V_1 positive causing the cathode follower to rise out of cutoff. This increased current places the common cathode at about 24 volts above ground, causing the second 6SN7 section (V_2) to cut off. As V_2 cuts off, its plate voltage surges up to about 170 volts carrying the screen of V_3 with it. This is enough to make the 6V6 conduct heavily and pull in the plate-circuit relay.

52.   Phototube Instrumentation

All phototube instruments are based upon the conversion of radiant flux (or luminous flux if the user is concerned only with visible light) into an electric current or voltage that can be read on a suitable meter or recorded for future interpretation. A *photometer*, determines luminous flux in illumination units (foot-candles, lumens); a *densitometer* measures the optical transmission of translucent solids, liquids, or gases; a *colorimeter* is used to analyze the color of a
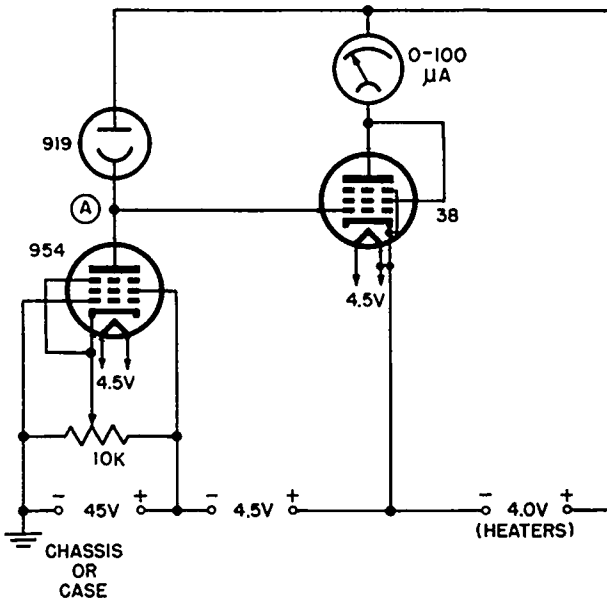
Fig. 35. A highly sensitive photometer that can be used as a densitometer, reflectometer, or colorimeter when supplied with suitable filters.

material to determine the relative percentages of the primary colors it contains;* a *pyrometer* is employed for temperature measurements and is nothing more than a specially adapted colorimeter; and a *goniophotometer* is essentially a special type of reflection-measuring instrument.

The principles underlying photoelectric instruments can be further reduced to two fundamental processes: (1) measurement of current, usually with the aid of d-c amplifiers, although a-c amplifiers are sometimes used, and (2) voltage balance and measurement, generally set up in some form of bridge circuit. The examples that follow illustrate each of these basic approaches.

A Sensitive Photometer: The instrument shown schematically in Fig. 35 will display a full-scale deflection of the indicating instrument for a light intensity change of only 2×10^{-6} lu. This circuit is an illustration of process (1) above in that phototube current is measured with the help of a two-stage d-c amplifier.

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* The primary colors as used in color television are: red, 6710 Å; green, 5050 Å; and blue, 4700 Å.

The 954 pentode vacuum tube acts as a very high load impedance for the 919 vacuum phototube. The potential of point A with respect to ground is determined by the point where the average anode characteristics of the 954 and 919 intersect. As we will show in the discussion of bridge instruments to follow, this arrangement causes a change in potential at point A of several volts when the light intensity changes even slightly. This output voltage is applied to the grid of the 38 output tube whose plate current is indicated on a 100-μa meter.

With the 954 serving as a high grid impedance for the 38, precautions against grid emission and residual gas current are necessary. Grid emission is discouraged by running the heater of the 38 at only 4 volts. Thus the elements of the tube are kept cool enough to prevent the grid from emitting. Heater emission is prevented by keeping the heaters at a positive potential with respect to the plate of the 954 and the grid of the 38. Gas current in the 38 is prevented by using very low electrode voltages so as to minimize any tendency toward gas ionization.

In operation, the 10K cathode resistor of the 954 is adjusted for cut-off bias of the 38 so that the meter reads zero or very close to zero, with the 919 in darkness. When light is incident on the phototube, point A becomes more positive, and the plate current of the 38 is read on the meter.

A Bridge Photometer: The action just described will be clarified by the text that follows and by the accompanying diagrams.

The circuit of Fig. 36 is generally known as a *comparator.* One of the two phototubes is illuminated by a "standard" source of light which is to be compared with an "unknown." The second phototube is illuminated by a comparison source used merely to establish a balance in the meter reading as will be explained in a moment.

In operation, the grid of the 38 is first connected to the cathode and the wiper of potentiometer R_2 adjusted for maximum meter reading (full-scale). This adjustment establishes conditions for maximum possible current in the 38 plate circuit and prevents *pinning* of the needle regardless of how unbalanced the circuit may be during use. The grid-to-cathode short is then removed and R_1 adjusted for half-scale reading with both phototubes in complete darkness.

Next, the phototubes are exposed to the light from the standard and comparison sources whose distances are arranged so that the
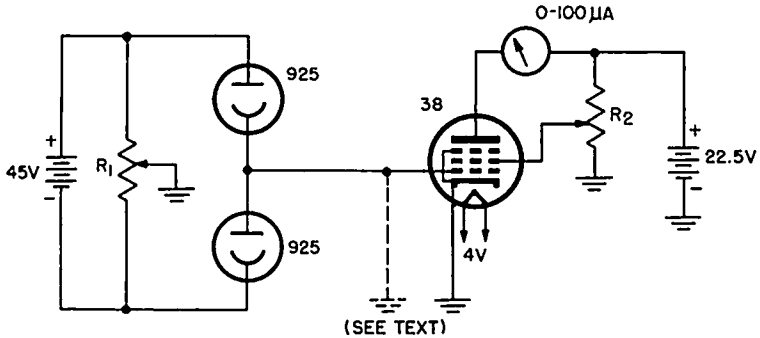
Fig. 36. A photoelectric comparator circuit using a bridge input arrangement.

meter again reads half scale. When the standard is then replaced by the unknown test lamp, the meter reading will be off center by an amount that depends on the difference in intensity between the standard and the unknown. A difference of only 0.05% is sufficient to produce a measurable reading, hence such a circuit is never used to compare lamps or sources of greatly different intensities. Its significant use lies in its ability to detect tiny differences between sources.

Its excellent sensitivity results from the action that takes place relative to the average anode characteristic curve intersection when the light on one of the phototubes is varied. The two halves of R_1,
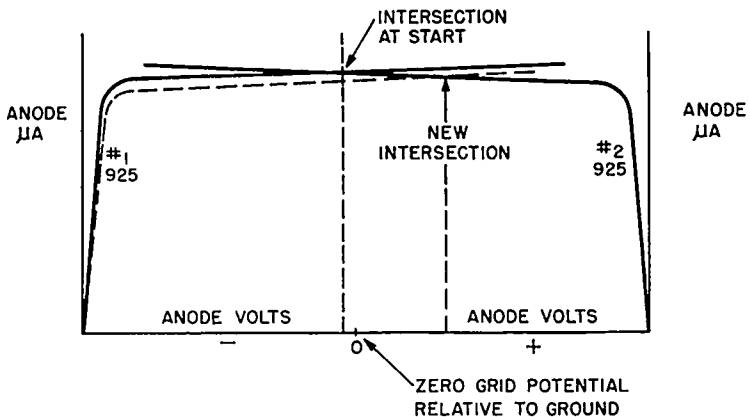
Fig. 37. Average anode characteristics of both 925's plotted on the same axis.

together with the two 925 phototubes form a bridge input circuit, with the grid and cathode of the 38 in the indicator position in the bridge. If both phototubes are identical, if the light on each is the same, and if R_1 is set exactly in the middle of its range, then the potential between grid and cathode is zero and the bridge is balanced. Due to the initial setting of R_2, this condition must result in a full-scale reading of the meter. Since adjustment of R_1, originally made, was such as to cause a half-scale indication, the grid of the 38 must be slightly negative to accomplish this.

Thus the grid voltage on the 38 is a function of the ratios of the voltage drops across both phototubes. When the average anode characteristics of the 925's are drawn, therefore, they must be shown in opposite directions since one phototube is effectively acting as the load for the other. The intersection of the curves, when projected down to the voltage axis, represents the resultant grid voltage. In Fig. 37, we have shown the grid slightly negative according to the half-scale adjustment described previously.

The action with a change in incident light is immediately evident from the curves. Suppose that the luminous flux falling on the #1 phototube (due to the use of a slightly weaker "unknown") falls by a small amount. The resulting anode current (dashed line) is very slightly less than before, but the intersection of the curves, hence the 38 grid potential, shifts a relatively large distance to the right. This, of course, brings about an appreciable increase in the plate circuit meter reading.*

53.   Signal Reproduction — A-C Amplification

Relays and instruments usually involve d-c amplifiers. As an example of another type of application, we consider next the kind of amplifier required for reproducing sound-on-film in the movie projector.

The normal sound track used in most projection systems today is the variable-density type (Fig. 38C), although the variable-area system has been successfully used. As illustrated in the block diagram (Fig. 38D), a small lamp called the *exciter* supplies an unvarying

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* The magnitude of the voltage change has been exaggerated in Fig. 37 for purposes of clarification. Obviously, any real shift as large as this would drive the grid positive and produce a sizable grid current — a highly undesirable situation.

35MM FILM

SPROCKET HOLE

PICTURE

SOUND TRACK

POSITION OF SOUNDTRACK
(A)

HIGH-
AMPLITUDE
LOW-FREQUENCY
SOUND

LOW-
AMPLITUDE
HIGH-FREQUENCY
SOUND

VARIABLE-AREA
SOUND TRACK
(B)

VARIABLE-DENSITY
SOUND TRACK
(C)

PHOTOTUBE

SOUND
SYSTEM
LAMP

OPTICAL
SYSTEM

FILM

AMPLIFIER

LOUDSPEAKER

SOUND REPRODUCTION
(D)
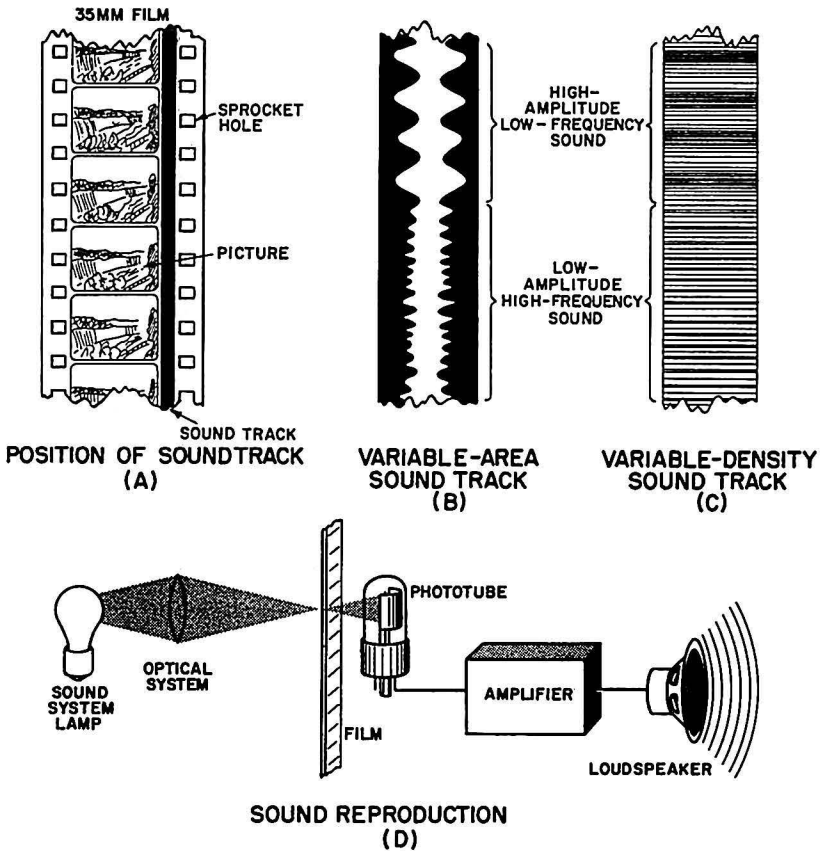
Fig. 38. (A) Position of sound track on motion-picture film. (B) Variable-area sound track. (C) Variable-density sound track. (D) Block diagram of sound-reproduction system.

beam of light through a suitable optical system to the varying density sound track. As the film moves past the beam, the intensity of the illumination falling on the photocell varies in accordance with the original sound used to make the track. The proportional pulsating d-c is then amplified and reproduced as sound by the amplifier and speaker system.

The standard input system to the sound amplifier is shown in Fig. 39. The remainder of the amplifier is quite standard. Every effort is made to maintain high fidelity during the amplification process; hence the amplifier circuit is designed to meet modern hi-fi specifications.

Similar a-c amplifiers are required in the transmission and reception of *facsimile,* a system in which still pictures are photoelectrically scanned at the transmitting end. The varying current thus obtained from the photocell is amplified and used directly for wire transmissions, or is used as a modulating signal for radio transmissions. A synchronized scanning and reproducing system at the receiving end then prints the picture either by photographic or chemical means.

Similar basic principles are used in television. Camera tubes such as the image orthicon and vidicon are not two-element phototubes, of course, and are beyond the scope of this book. Television video amplifiers differ from other a-c types principally in bandwidth since the requirements for high-fidelity reproduction of television pictures are considerably more rigorous in this respect. It is not at all unusual to encounter a camera video amplifier with a bandwidth of 8 to 10 mc. This, of course, is far beyond the bandwidth normally used in sound-on-film and facsimile systems.

54. Photoelectric Servomechanisms

By definition, a servomechanism is an electrical or mechanical system in which automatically reacting devices cause the elements of the system to behave in accordance with previously issued "instructions." Some familiar examples of servomechanisms are: (a) The home thermostat, which accepts instructions in the form of a preset temperature level on a dial and turns the burner on or off to maintain this
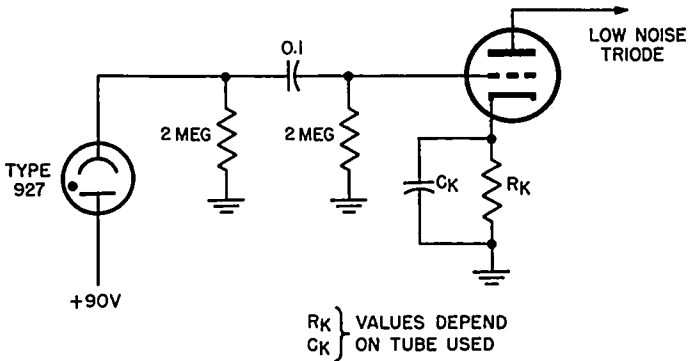
Fig. 39. Standard input system from phototube to first voltage amplifier of sound system.
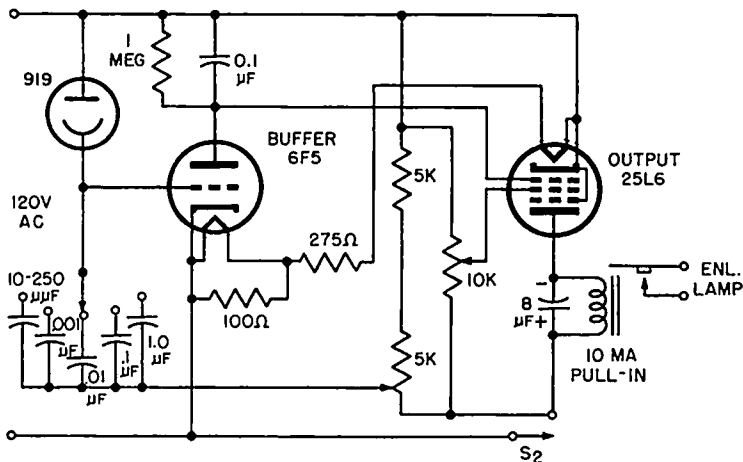
Fig. 40. Schematic diagram of simple photographic enlarging exposure control.

level. (b) The automatic pilot on a ship or plane. Instructions are given in the form of a course (and altitude) setting on appropriate dials; the autopilot observes errors as time proceeds and makes the necessary corrections to maintain the preset course and altitude. (c) Photographic exposure control. In a high-grade commercial system, a phototube evaluates the intensity of light passing through the photographic negative and then automatically adjusts the exposure time for the best print quality. For proper operation, the phototube control must be given "information" relative to the paper speed; as long as one type and grade of paper is employed, the remainder of the process is fully automatic.

A very simple photographic enlarging exposure control is shown in Fig. 40. This circuit measures exposure by detecting the change in potential across a capacitor connected in series with the phototube. This voltage change is proportional to the charge supplied by the phototube which, in turn, depends upon the magnitude and time of flow of the current going into the capacitor. In use, the light reaching the phototube can be reflected from the paper surface or transmitted through a part of the film.

When S_2 is open, the plate and screen of the output tube are at zero potential; the relay is, of course, dropped out for this condition. Due to grid-circuit rectification, the timing capacitor that happens to be switched in the circuit takes on a charge close to that of the

peak a-c line voltage. When S_2 is closed, a major portion of the grid-cathode voltage of the buffer stage is removed, and the voltage applied by the timing capacitor cuts off the plate current of the buffer stage.

At this instant, the voltage drop across the 1-megohm plate resistor becomes zero, bringing the grid of the output tube to the same potential as its cathode. Since closing S_2 also applies plate and screen voltage to this stage, the relay pulls in and turns on the enlarging lamp. The phototube now receives light from the film or paper causing its resistance to decrease. The timing capacitor gradually discharges through the phototube at a rate determined by the amount of light falling on the latter. As this occurs, the plate current of the buffer begins to flow, a voltage drop develops across the plate load resistor (negative at the bottom), and the output-stage plate current begins to drop due to this increasing bias. The exposure interval for a given paper and enlarger lamp intensity must be determined experimentally for the purposes of adjusting the 5000- and 10,000-ohm potentiometers. Some judgment on the operator's part is still required to determine the best setting for the 5000-ohm potentiometer to compensate for differences in film contrast.

55. Review Questions

1. Draw the schematic diagram of a single-pentode phototube relay amplifier. Explain its operation in detail.
2. What are the advantages of using a thyratron rather than a vacuum tube as a relay amplifier? What about the principle of operation of a thyratron gives it this characteristic?
3. Explain why a-c operated, single-tube relay circuits cannot give fast response.
4. Explain the difference between an ordinary current-measuring photometer and the use of a balanced bridge circuit to accomplish the measurement of light values.
5. Describe the steps followed to determine the intensity of an unknown source of light using the comparator method.
6. What characteristics are desirable in an amplifier intended for use with a sound-on-film reproducer?
7. Describe the general arrangement of the phototube, the light source, the sound track, and the amplifier in a motion-picture sound projector.
8. Explain why a bridged phototube arrangement for light measurements is very sensitive, using the interpretation of Fig. 36 to help you.
9. Define a servomechanism. Give several examples of servomechanisms.
10. Explain the operation of the photographic exposure control illustrated in Fig. 40.

APPENDIX I

UNITS AND PHYSICAL CONSTANTS

Quantity to be measured	Units	Conversion factors
Wavelength	Centimeter (cm)	10^{-2} meter
	Angstrom ($\overset{\circ}{A}$)	10^{-8} centimeter
	Millimicrons (mμ)	10^{-7} centimeter
Wien displacement constant	——	c = 0.289 cm°K
Temperature	Degree Kelvin (°K)	0°K = −273°C
	Degree Centigrade (°C)	0°C = 32°K
Frequency (ν)	Cycle per second (cps)	——
Planck's constant	——	h = 6.62 × 10^{-34} joule-seconds
Electrical charge (Q)	Coulomb	——
Mass of electron	——	m = 9.1 × 10^{-31} kgm (kilogram mass)
Energy (E)	Joule	——
Velocity of light	——	c = 3 × 10^8 meters per second
Luminous intensity (candle power)	International candle	——
Luminous flux	Lumen (lu)	1/680 watt
Illuminance	Lumen per square foot	1 lumen per square meter
	Lux	
	Foot-candle	
Potential	Volts	——
Velocity	Meter per second	——
Mass	Kilogram (kgm)	——
Energy	Electron volt	1.6 × 10^{-19} joules
Sensitivity	Microampere per lumen at 2870°K	
Resistance	Ohms	
	Megohms	10^6 ohms
Current	Ampere	
	Microampere	10^{-6} ampere
Current density	Microampere per square inch	——
Pressure	Atmosphere	14.696 lb/in.²
		1033.2 g/cm²
		760 millimeter of mercury

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