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PHOTOELECTRIC CELLS

THEIR PROPERTIES, USE, AND APPLICATIONS

BY

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AND

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PREFACE

APART from other considerations, the technical advances since this book was first written would have necessitated a complete reconstruction. Five years ago the thin film cathode, the rectifier cell, the electrometer valve, and the thyratron were all new or unknown. But the development of the literature is even more important. There was then no modern English book on the theory of photoelectricity, and none at all on its applications. Now we have Hughes and Du Bridge's most excellent treatise on theory; for methods of use, Zworykin and Wilson's book, and Anderson's valuable Report on the discussion at the Physical and Optical Societies; for applications, Walker and Lance's book, and numberless articles in technical and popular journals. The gap that we attempted to fill no longer exists.

Accordingly we have written a new book, with a new purpose, addressed to a much more highly instructed public. In our first edition, though recognizing that experiment is a science as well as an art, we treated principles as subsidiary to practice. We propose now to reverse the emphasis. For with the growth of the art and the increase of the alternatives available, an appreciation of principles becomes even more important if the best alternative is to be selected. Moreover, the interest of the principles themselves increases with their scope. Our book is addressed to those who desire to understand rather than merely to follow accepted procedure. With this object in view, we have greatly increased the first section of the book, and included not only rectifier cells (of course, they would have to appear on any interpretation of our title), but also conductivity cells, whose use is now very limited. At the same time we have omitted all account of the vast group of applications whose importance is mainly derivative, and have discussed much more fully those that introduce or illustrate important principles.

But while so much is changed, much remains the same. Not of the matter—though the curious will find most of the old Chapters V, VI, VII, and X embodied in the new

Chapters III, VII, and IX—but of the spirit. We still make no attempt to conceal where our own knowledge and interest lie, although in so doing we can hardly hope to cover exactly the ground that any of our readers would desire; and we still employ "references" (now rather more abundant) not to support our assertions, but to indicate where further information can be found on matters that we have treated inadequately.

As before, one of us has to thank the Director of the Wembley Laboratories (Mr. C. C. Paterson) for leave to write on his official work; and both of us to thank all the members of the staff for their constant and indispensable help; more particularly our thanks are due to Miss M. K. Freeth and Mr. C. H. Simms. Messrs. J. Guild and T. Smith have been kind enough to purge Chapter XIII of many of its original errors; of course, they are not responsible for those that remain.

NOTE

1. We have deliberately ignored the distinction between E (E.M.F.) and V (P.D.), for we do not believe that it can be maintained without violating even more definite conventions, such as E (or e) for grid voltage. We use E throughout.

2. The statement "x decreases with y" is usually ambiguous, and even "x increases with y." We always use *with* when dx/dy is positive, and *against* when dx/dy is negative. (See e.g. page 105.)

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PHOTOELECTRIC CELLS

PART I

PROPERTIES OF PHOTOELECTRIC CELLS

CHAPTER I

THEORY OF PHOTOELECTRICITY

The Fundamental Rules. All actions of light on material bodies are ultimately electrical, and all instruments for detecting or measuring light might be properly termed photoelectric cells; it would be quite reasonable to include under this term photographic plates, thermopiles, and even our eyes. Actually it is confined to instruments in which the effect of light is to produce or to change an electric current that can be detected by instruments outside the device itself. But this distinction is of practical rather than of theoretical importance. A complete theory of photoelectric cells in the narrower sense would necessarily be a theory of all interactions between light and matter. Any attempt to expound it would lead us into very deep waters. For it is now clear that the fundamental properties of light and matter cannot be visualized or described by means of analogies with mechanical models. They can be described adequately only by mathematical equations, of which the individual symbols in isolation mean nothing at all; a meaning can be attached only to certain combinations or functions of them. Nevertheless, explanation, in the sense of nineteenth-century science, is not completely excluded. Certain rules can be laid down that all physical systems obey; these rules, though sometimes unfamiliar, are easily intelligible; and they permit us to predict the behaviour of systems by means of common sense and without elaborate calculation,

in much the same ways as the models of the older theories. It is only when we try to find principles embracing all these rules, and connecting them with each other, that we have to depart altogether from the realm of common sense and visualized explanation.

In this chapter we shall examine the chief rules that determine the behaviour of the principal types of photoelectric cells. They will be stated baldly and without any attempt to justify them. If they seem strange, that strangeness must be accepted as part of the universe to which we belong; if anyone asks why light and matter interact according to these rules, the only sensible answer is that by light and matter we mean simply those things that do interact according to them.

Quantity of Light. The first set of rules concern the properties of light, of which textbooks on optics treat. They are not at all strange, but are so familiar that most of them need not be stated. But it will be convenient to set forth briefly, and in a form appropriate to our special purpose, those rules involved in definitions of the "quantity" and the "quality" of light.

The quantity of light can be measured by the energy that it carries or, more accurately, by its power, that is to say, the rate at which it conveys energy across a surface that it traverses. It can thus be expressed in watts. This method of measurement alone is possible when the light lies outside the visible spectrum. But when the light is visible, its quantity is often measured by its "luminous flux," expressed in lumens; this quantity depends on the effect of the light on a human eye and cannot be measured apart from visual judgments.

Laws involving the quantity, but not the quality, of the light are true, whether quantity is measured in watts or lumens. Thus if a surface of effective area S is exposed, in a non-absorbing medium and in the absence of other reflectors or refractors, at a distance r from a source whose dimensions are small compared with r, then the quantity of light L falling on the surface varies directly as S and inversely as the square of r, whether L is measured in watts or lumens, so that we can write

$$L = C \,.\, S/r^2 \quad . \quad . \quad . \quad (1)$$

If the source radiates equally in all directions, $4\pi C$ in (1) is the total number of watts or lumens that it radiates. If, like most sources, it does not radiate equally, (1) must be applied only so long as r is always measured in the same direction. If L is in lumens, C is equal to the candle-power of the source in the direction of r.

When there is no obstruction between source and receiving surface, S, the effective area, is the area projected on a plane perpendicular to r. If there is an intervening diaphragm (such as the window of a cell), then S and r must, of course, refer to the diaphragm. If a simple lens is interposed, S and r may be taken roughly to refer to the lens.

When light is parallel—a condition never realized perfectly with laboratory sources—the quantity received by a surface on which all of it falls is, of course, independent both of the area and position of the surface. When light is perfectly diffused—a condition more nearly attainable in practice—the quantity received is proportional to the area of the surface, so that

$$L = I \,.\, S \quad . \quad . \quad . \quad . \quad (2)$$

In this case I is almost always expressed in units related to lumens and not to watts. L will be lumens if S is in square feet and I in foot-candles, or if S is in square metres and I in lux (or metre-candles), or if S is in square centimetres and I in phots.

The quantity of light received by a surface from several sources is generally the sum of the quantities that it would receive from each, if the remainder were absent. This proposition enables us to determine, for example, the light received from a source, the dimensions of which are not small compared with its distance from the surface.

Quality of the Light. Next we must define quality. When light is perfectly homogeneous and cannot be resolved into different qualities (or colours) by refraction, diffraction, or passage through filters, then it has a single wavelength λ, and its quality is best described by this wavelength. (Wavelength will always mean wavelength in vacuo, so that $1/\lambda$ is the wave-number and c/λ is the frequency, when c is velocity of light.) When light is not homogeneous, the quality can be described by a function $F(\lambda)$, which is such that $A \,.\, F(\lambda)d\lambda$

is the quantity (measured in watts, not in lumens) of that part whose wavelength lies between λ and $\lambda + d\lambda$. A is a constant determining the quantity, not the quality, of the radiation, and is conveniently chosen so that

$$\int_0^\infty A \,.\, F(\lambda)\, d\lambda = 1\,;$$

$F(\lambda)\, d\lambda$ is then the proportion of the radiation having wavelength λ to $\lambda + d\lambda$.

In the important class of sources known as "thermal radiators," which includes the filaments of incandescent lamps, the quality, and the form of $F(\lambda)$, depend entirely on the temperature T of the source, so that the quality can be described by a single function $F(\lambda, T)$ applicable to all temperatures. In a special sub-class of thermal radiators, known as black or complete radiators, to which most others approach somewhat nearly, $F(\lambda, T)$ has a special form, called Planck's function, which is

$$P(\lambda, T) = A \,.\, \lambda^{-5}\ [\text{exp.}\ (C_2/\lambda T) - 1]^{-1} \quad . \qquad . \quad (3)$$

For our purpose it is convenient to transform this equation slightly. If λ_m is the value of λ at which P is a maximum, $\lambda_m T$ is the same for all values of T. If P_m is this maximum value of P,

$$P/P_m = B \,.\, (\lambda T)^{-5}.\ [\text{exp.}\ (C_2/\lambda T) - 1]^{-1} \qquad . \quad (4)$$

and is thus a function of λT only. Accordingly one curve will express in relative measure how the quantity of radiation varies both with λ and with T; it is shown in Fig. 1. Here the values of λT are marked along the top of the diagram, the corresponding values of λ for three selected values of T along the lower. With these lower scales, the curve shows the way in which the quantity of radiation varies with wavelength at any given temperature, the maximum quantity at any wavelength at that temperature being always unity. The second curve in Fig. 1 gives the values of

$$Q = C \int_0^\lambda P/P_m \,.\, d(\lambda T) \qquad . \qquad . \quad (5)$$

C being chosen so that $Q = 1$ when $\lambda T = \infty$. Thus with

the lower scales, Q gives the fraction of the total radiation from a source at temperature T which lies in wavelengths less than λ; this total radiation is proportional to T^4. These two curves (or the tables from which they are plotted) give all the information about complete radiation that is required in the succeeding chapters.

Practical thermal radiators are not strictly complete radiators, and the quality of their radiation at temperature T is not quite accurately described by $P(\lambda, T)$. But they approach complete radiators so nearly that, when they are at T, the quality of the radiation from them (but not the quantity) is identical within the visible range with that of a complete radiator at some slightly different (usually higher) temperature T', and is therefore given by $P(\lambda, T')$. The colour of the light from the incomplete radiator at T is then the same as that of the complete radiator at T'; T' is called the "colour temperature" of the radiator, and describes fully the quality of the radiator in the visible range. This method is very convenient for describing the quality of the radiation from incandescent lamps; but it cannot be applied to other sources, such as discharge lamps or sunlight (at the bottom of the atmosphere); the form of $F(\lambda, T)$ for them is not the same as $P(\lambda, T)$ for any value of T.

The quality of light can also be described by means of the relation between the lumens and the watts. Luminous flux is a measure of power to produce illumination that the eye can appreciate; it is determined by comparing the apparent brightness of surfaces. Two differently coloured surfaces may appear equally bright, and two beams of light may therefore carry the same lumens, although they carry different watts. It is found that the ratio of the lumens to the watts (or the lumens per watt) of homogeneous light is determined entirely by its wavelength and not by its intensity. (That is an experimental fact that might not have been true; indeed, it is not exactly true for very feeble light.) Accordingly we can draw once and for all a curve showing the relation between lumens per watt and wavelength; this curve is given in Fig. 2 and is known as the "visibility curve," an inappropriate name that has led to some confusion. Strictly, the visibility curve is different for different eyes, even when colour-blind persons are excluded;

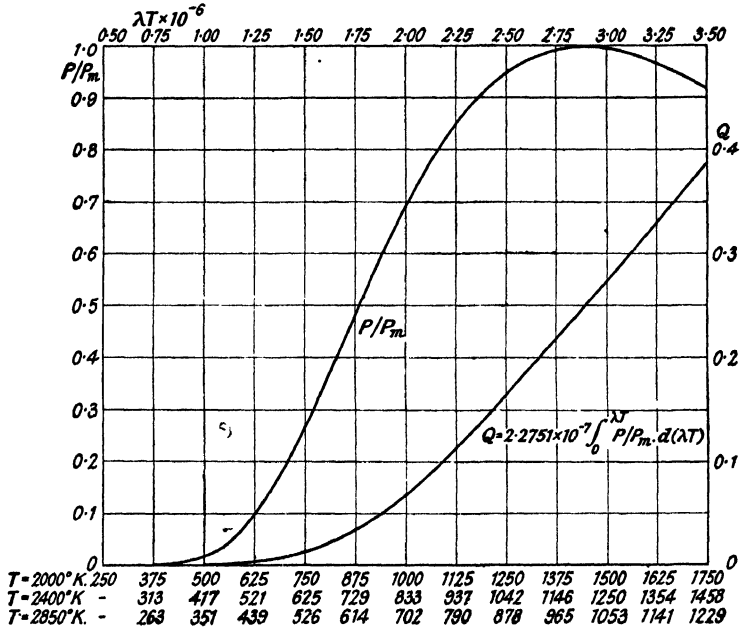


FIG. 1. PROPERTIES OF THERMAL RADIATION

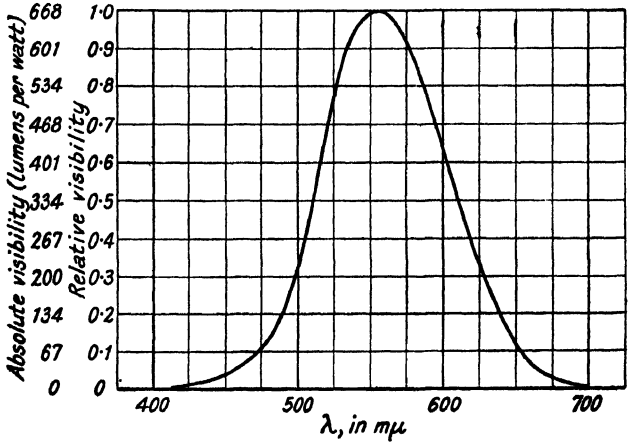


FIG. 2. THE VISIBILITY CURVE

but the variations between normal persons is small, and a standard curve, the mean of many observations, has been adopted by international convention.

When the light is not homogeneous, V, the visibility or lumens per watt, is determined by the form of $F(\lambda)$. Indeed, if the visibility curve is represented by $v(\lambda)$, V is always given by

$$V = \frac{\int_0^\infty v(\lambda)F(\lambda)d\lambda}{\int_0^\infty F(\lambda)d\lambda} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Accordingly the quality of heterogeneous light can be described by a single "visibility" V, just as it can by the single "colour temperature" T'. But a difference between the two methods of description is to be observed. Not all light has a colour temperature, but, if light has one, the colour temperature fixes its quality, at least within the visible range; on the other hand, all visible light has a visibility, but it does not fix the quality uniquely; the same visibility may correspond to very different $F(\lambda)$'s. The ranges in which the two methods of description are useful are practically the same, namely, that of incandescent lamps. And here they are closely related, so that a curve (Fig. 3) can be given showing the relation between colour temperature T' and lumens per watt, or visibility, V.*

Light and Electrons. We now pass to rules governing the interaction of light and electrons, which to-day are hardly less familiar. A charged particle, and particularly an electron forming part of a material body, when exposed to light, has a definite chance of acquiring energy from the light. The chance depends on the forces between the particle and other particles, and vanishes when the particle is completely free and exposed to no forces. The way in which

* If $F(\lambda)$ for all incandescent bodies were identical with $P(\lambda_1 T')$ for *all* values of λ, the relation would be unique; but since it is identical only in and near the visible spectrum, we have strictly to distinguish between V for a complete radiator and V for any given material, such as tungsten, at the same colour temperature. Fortunately the difference is not material for our purpose. (See footnote to p. 45.) Fig. 3 refers actually to a complete radiator.

the chance depends on the forces is extremely complicated, and no attempt will be made to describe it generally; but some particular rules will appear later. The chance is also proportional to the intensity of the light, i.e. the quantity

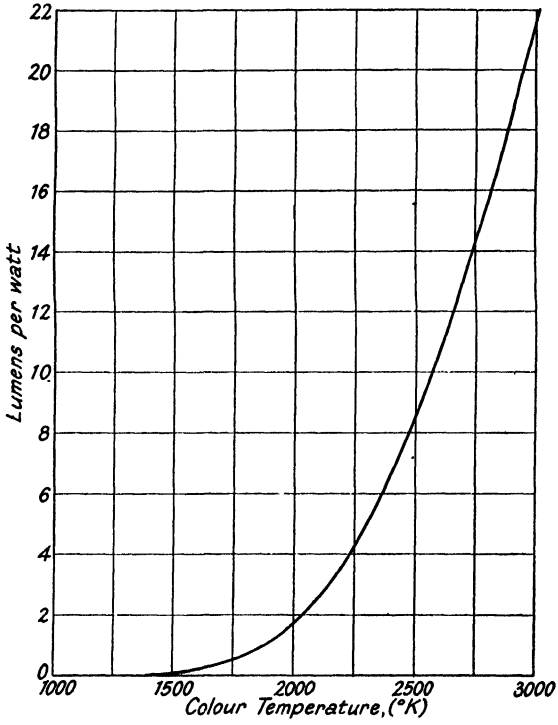


FIG. 3. VISIBILITY AND COLOUR TEMPERATURE

falling on unit area perpendicular to its direction. Since the intensity of two independent beams, acting together, is the sum of the intensities of the individual beams, an alternative, and perhaps better, way of expressing the same rule is that the chance of a particle acquiring energy from one beam of light is unaffected by the presence of another independent beam.

If a particle acquires energy at all, the amount that it acquires is independent of everything whatsoever, except the wavelength of the light. There is a very simple relation

between the wavelength and the "quantum energy," E, that is to say, the energy that a particle takes from the light if it takes any at all. It is

$$E\lambda = \frac{1234}{\lambda} \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Here the unit of λ is 1 mμ = 10^{-7} cm. The visible spectrum lies roughly between 760 mμ (extreme red) and 400 mμ (extreme violet). The unit of E is 1 electron-volt, which is the energy that a particle carrying the electronic charge acquires in falling through a potential difference of 1 volt. Electronic energies will always be expressed in this unit (1 electron-volt = $1{\cdot}6 \times 10^{-12}$ erg). It will be observed that the quantum energy of visible light lies in the range 1·5 to 3 volts.

Electron States. Lastly, we want rules about the behaviour of electrons; these rules are probably less familiar to those who have not followed recent developments of theory. An electron forming part of a material body, or otherwise in interaction with other charged particles, can exist only in one of a number of "states," each of which is characterized by a different energy. Not more than two electrons can ever be in one state. The number of states, which is usually finite, and their energy are determined by the number and distribution of the charged particles with which the electron is in interaction. We shall proceed to describe the states appertaining to various media.

First a few words on the method of description. We shall consider a slab of the medium; Figs. 4–10 represent a section through the slab, x being the distance from the left-hand face. The line representing this face serves also as an axis of ordinates along which is measured the energy E of the various states. If the slab is homogeneous and equipotential, the states are the same throughout it; the states are therefore represented by a series of horizontal lines, each denoting a different energy.

There is always a lowest state, represented by the axis of x; it is that of an electron at rest and possessing only potential energy. The axis of x represents therefore the potential of the medium, which can always be taken as zero,

so long as we are considering a single equipotential medium. Since an electron carries a negative charge, its potential energy is greater when it is in the medium of which the potential is more negative. According to the ordinary convention, a negative potential is lower than a positive; but (in this chapter only) we shall reverse this convention, and

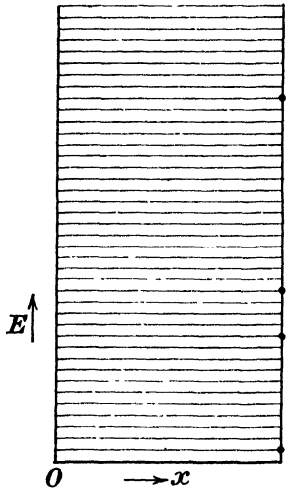


FIG. 4. STATES OF A VACUUM

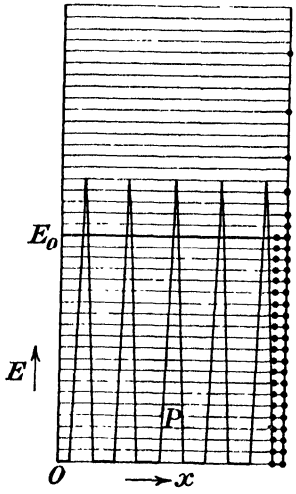


FIG. 5. STATES OF A METAL

represent negative potentials, at which an electron has a greater energy, by lines *above* that of zero potential.

The States of Various Media. Our first medium is an equipotential vacuum, contained in a flat metal box (Fig. 4). The lowest state is the potential energy of an electron at rest. Electrons in motion have also kinetic energy and their states are therefore higher. A single electron in a vacuum can have any kinetic energy whatever. Consequently the space above the horizontal axis is completely filled with horizontal lines, representing the states; they are shown as discrete in the figure merely because it is impossible to show them as continuous. The introduction into the vacuum of a few electrons—so few that they do not appreciably alter the field in the vacuum—does not alter the states; the electrons simply occupy a few of the states, as shown by the dots on the right vertical. The limitation of the number of

electrons that can occupy the same state makes no difference; for there is an infinite number of states within any finite energy range.

Next we take a slab of metal (Fig. 5). This is made up of a large number of positively charged atomic nuclei with a number of electrons sufficient to neutralize their charge. Since the charges are carried by discrete particles, the potential is not strictly uniform throughout the slab; the state in which an electron has only potential energy is not a straight line, but wavy, the trough of each line representing the position of a positive nucleus. But the states of moving electrons are still horizontal straight lines so long as the distribution of the atoms is perfectly regular. If we still divide its energy into potential and kinetic, we must allow that an electron may have negative kinetic energy, because it may have an energy less than that corresponding to its potential (e.g. at P). That conclusion, though surprising, must be accepted; it turns out later to be important. But for the moment another consequence of the atomic structure is more important.

The states are no longer continuous; the number of them lying below any limit, such as E_0, is no longer infinite but is proportional to the number of atoms in the metal. The representation of them by separate lines now really indicates the truth. Since only two electrons can occupy a state, and the number of electrons is a multiple of the number of atoms, the occupied states must form a band of considerable width. In a metal at the absolute zero of temperature all the states up to a finite limit E_0 (an energy of the order of 10 electron-volts) are occupied and none of the states above that limit. But when the metal is at any higher temperature, a small fraction of the electrons have heat energy and lie in states above E_0; the distribution will then be of the kind indicated by the dots on the right vertical, the number of occupied states decreasing rapidly with increasing distance above E_0.

Next we take a slab of a non-metal or insulator (Fig. 6). Now the states, still discrete, do not form a continuous band; there are gaps, as shown, in which there are no states at all. At absolute zero, a certain number of the lower bands are completely occupied; but the upper bands are all quite

empty. The division between occupied and unoccupied states will usually coincide with a gap, because both the number of states in a band and the number of electrons available to occupy them are proportional to the number of atoms. If the insulator is only just above absolute zero, the upper bands will remain practically empty, because an

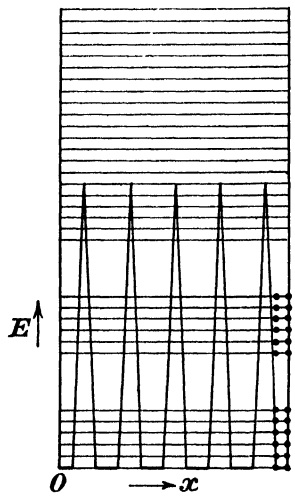


FIG. 6. STATES OF AN INSULATOR

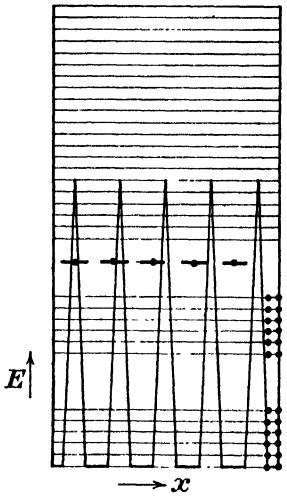


FIG. 7. STATES OF A SEMI-CONDUCTOR

electron cannot cross from a lower to an upper band unless it acquires heat energy as great as the width of the gap, which is of the order of 2 electron-volts; and the chance of its acquiring so much energy is very small. Many electrons will not appear in the upper bands until the mean thermal energy of an electron is of the order of 2 electron-volts, corresponding to a temperature of about 8000° K.

Lastly, we take a slab of a "semi-conductor," a class of bodies only recently distinguished clearly, of which cuprous oxide and selenium are typical examples. Their characteristic feature is that their conductivity, which is electronic and not electrolytic, is due to the presence of impurities and increases rapidly with the temperature. The electronic states in the pure substance are those of an insulator, but the

impurities provide localized states, not extending throughout the slab, which lie in a gap between occupied and unoccupied bands of the pure substance; these states are occupied. The condition at low temperature is therefore that shown in Fig. 7; at rather higher temperatures the electrons from the localized impurity states can reach the unoccupied band and at much higher temperatures those from the occupied band can reach it.

Conductors and Insulators. In this last case, some connection between electronic states and chemical constitution is evident; it is not so evident in the preceding cases. The reader may well inquire why metals should have the states of Fig. 5, while non-metals, such as sulphur, have those of Fig. 6. Theory is not yet sufficiently advanced to answer this question fully, and a partial answer would not help our present inquiry. But it is quite easy to explain the connection between electronic states and conduction, and to show why the states of Fig. 5 must lead to conductivity and those of Fig. 6 to insulation.

If a state extends as a truly straight horizontal line through the slab, an electron in that state can pass freely from one end to the other; there is no "resistance," that is to say, no degradation of energy attending its motion. In a vacuum the states are truly straight lines, and an electron moves perfectly freely; if it has any velocity at all, it will pass from one face of the slab to the other even if there is no potential difference; a vacuum is a perfect conductor. The limitation of current is not due to resistance, involving degradation of energy; it is merely an expression of the paucity of electrons. But in no solid are the states truly straight lines. The lattice arrangement of the atoms is not perfectly regular, owing to thermal motions of the atoms. Accordingly the states in Figs. 4, 5, 6, and 7 should really be shown with little kinks in them, which prevent free motion; an electron cannot move along its state unless by moving it can acquire sufficient energy to allow it to rise to the top of a kink.

But now let us apply a potential difference to the faces of the slab of metal (Fig. 8). If we make the left side positive, so that electrons tend to move from right to left, all the states will then slope downwards in that direction. (For

simplicity here and later, the waves in the potential energy state are omitted.) An electron can now move to the left with constant total energy, but gaining kinetic at the expense of potential energy, by passing to the next higher state, as indicated by the horizontal dotted line, so long as that next higher state is not full; and it will so move, because all systems try to convert kinetic into potential energy. The electrons below E_0 cannot move, because the states immediately above them are full; but the electrons at or above E_0 can move, because most of the higher states are not full. Owing to the irregularities of the lattice, mentioned before, it will not continually gain kinetic energy by passing to higher and higher states; at some points it will lose the energy it has acquired (as shown by drops in the dotted line) and fall back to its original state with the original kinetic but lower potential energy. This loss of energy represents the resistance of the conductor; it increases with temperature, because the irregularities of the lattice increase. But by continually rising to higher and falling to lower states, the electron will move through the slab and provide conduction. A band of unoccupied states therefore provides "running states" for an electron, in which it can move through the medium under an electron field.

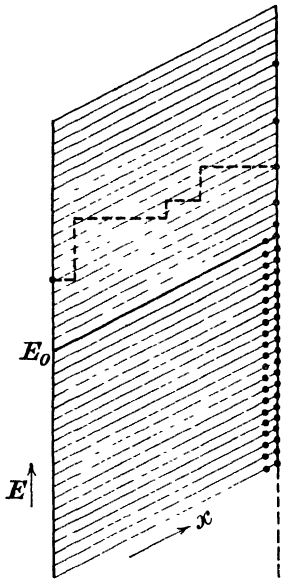


FIG. 8. STATES OF A CONDUCTOR IN ELECTRIC FIELD

But if we apply a potential to the insulating slab of Fig. 6, tilting the states downwards, the same process cannot occur. For now no electron has immediately above it a state that is not full; all the states in the bands are full and between the bands there are no states. There are no running states and there is no conduction.

In the semi-conductor (Fig. 7) there would also be no conduction at zero temperature, for the impurity states,

even if they are not completely occupied, are localized at isolated points and do not provide a path through the substances. Conduction arises only when electrons from the impurity (or lower continuous) states acquire enough thermal energy to pass into the higher band of unoccupied states; there they can conduct as in a metal. Conduction in a semi-conductor is the same process as in a metal; the only difference is that, while in a metal there are always abundant electrons in the states that have unoccupied states immediately above them, in a semi-conductor there are few electrons in these states, since electrons reach them only by acquiring heat-energy in the impurity states. In a metal, current is limited by resistance, representing the energy losses of the abundant conduction electrons; in a semi-conductor much more by the paucity of conduction electrons. When the temperature rises, the resistance of the metal increases, because the irregularities in the lattice become greater; the resistance of the semi-conductor decreases, because the number of conduction electrons increases.

The Inner Photoelectric Effect. What has all this to do with photoelectricity? Simply this. An electron can take up energy from light only if the quantum energy of that light is the difference between the energy of its state and that of some higher unoccupied state at the same point in the material; for the quantum energy is the only amount of energy it can receive from the light, and it cannot receive that energy from any source unless the appropriate higher state is waiting to receive it. If it does take up the quantum energy, it will, of course, pass to that higher state.

If an electron in the interior of the substance is raised by the light from a state in a fully-occupied band or from an impurity state to a state in an unoccupied band, which can therefore serve as a running state, the immediate effect of the light will be an increase in the conductivity of the substance. If the substance is a metal, running states are available immediately above the top full states, so that any light that is absorbed at all must produce some increase in conductivity; but since the number of electrons already in running states at ordinary temperatures is already large, the increase is inappreciable. In insulators and semi-conductors, on the other hand, no electron can receive energy unless the

quantum energy is greater than the gap between the full band or the impurity states and the unoccupied band; no effect will be produced unless the wavelength of the light is small enough to provide this quantum energy. However, if it is small enough, the increase in conductivity due to the increased number of electrons in running states will be appreciable. This increase of conductivity is called the inner photoelectric effect and gives rise to one class of photoelectric cells, namely, conductivity cells.

However, a permanent current will not result from the conductivity when the substance is placed under an electric field, unless the electrons can leave the positive boundary when they reach it and unless their place can be taken by electrons entering at the negative boundary. Moreover, the loss of electrons from the full bands or impurity states produces changes in the states, and alters the chance of further electrons reaching running states. In consequence the primary effect of light, just considered, is complicated and overshadowed by much more complicated secondary effects. These will be left for consideration until conductivity cells are considered; but it may be said at once that they cannot be wholly explained with our present knowledge.

The Outer Photoelectric Effect. We have now to consider an electron so near the boundary of the substance that, if it moves at all towards the boundary, it must cross it. A boundary is represented on our scheme by a change in potential energy and in the distribution of states; for these are the things that distinguish one medium from another.

There is always an increase of potential in passing from a solid to the vacuum surrounding it. That may seem rather puzzling; if the solid is uncharged (as we are assuming), surely its potential is the same as that of its surroundings! But we must remember that the solid is uncharged only as a whole; the number of positive and negative charges it contains is equal, but, owing to atomic structure, they are not distributed with perfect uniformity. Even in the interior of the metal, the potential is not strictly constant, as already explained; still less is it constant near the surface; the surface always occurs at the top of a wave in the lowest state. In other words, an electron tending to leave the mixture of positive atoms and electrons is subject to forces

dragging it back, just as is an electron tending to leave a single atom. These forces, and therefore the increase of potential at the surface, depend in a very complicated manner on the atomic constitution of the solid.

The boundary between a metal and a vacuum may then be represented on our scheme by Fig. 9; the value of E_1, the rise of potential at the boundary, is a characteristic of the particular metal. The potential of the vacuum is so much higher than even the state E_0 of the metal that, although E_0 is some 10 volts above the lowest state of the metals, it is still well below the lowest state of the vacuum. Electrons in E_0 or in any lower state cannot therefore pass into the vacuum, because there are no states on the same level to receive them there. Only those in the state E_1 or above it can escape. Electrons can attain E_1 in virtue of the heat energy of the metal, and the number in that state will increase very rapidly with the temperature. The escape of electrons that have attained E_1 by this means appears as the thermionic emission from hot metals. But electrons in a state E can also reach E_1 by absorbing energy $E_1 - E$ from light; the escape of these electrons, carrying a current through the vacuum, is called the photoelectric emission or sometimes the outer photoelectric effect.

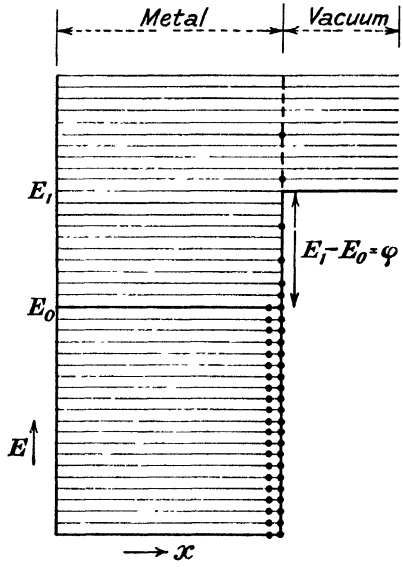


FIG. 9. BOUNDARY BETWEEN METAL AND VACUUM

On these facts the great class of emission cells depends; further details and some complications will again be left until we deal with them.

The Boundary Effect. The laws of the third great class are not so simple. Cells of this class consist essentially of a

semi-conductor in close, but not too close, contact with a metal. They are therefore represented in our scheme by Fig. 10, a thin slab of vacuum intervening between the two solids. Quantities referring to the metal and the semi-conductor are distinguished by the suffixes m and s. Note for future reference that $(E_1)_s$ is drawn greater than $(E_1)_m$.

Much of our discussion has been based on the principle that an electron cannot pass through a space which does not contain a state of the appropriate energy. But, as was hinted above (page 11), this principle is not universally true. A more accurate statement would be that the chance of an electron passing through a space containing no appropriate state into a state on the far side, ready to receive it, decreases very rapidly with the width of the space. If the width is many times the diameter of a molecule, the chance is practically nil; but if it is comparable with molecular diameters, the chance may be quite appreciable. If the width is constant, the chance decreases with increase of depth at which it has to pass below the next higher state in the vacant space; but even if this next higher state is the potential energy of the space, the chance is still finite although in passing through the space the electron has negative kinetic energy. A less paradoxical form of this statement is that, in these circumstances, the division of energy into potential and kinetic is meaningless.

Accordingly in Fig. 10, although almost all the electrons in both metal and semi-conductor are in states below the potential of the vacuum, they will be able to pass through the potential "hump," which represents the vacuous layer, so long as it is narrow and there are states on the far side waiting to receive them. If no potential difference is applied between the two bodies, they will assume a "contact" potential difference such that the number of electrons passing in one direction through the hump equals the number passing in the other, so that no resultant current flows. This condition is attained, as can be shown by detailed calculation, when E_0 for the metal lies nearly half-way between the impurity state E_i of the semi-conductor and the next higher unoccupied state E_f. Electrons in E_f or higher states can travel through the hump, for there are states on the other side to receive them; those below cannot.

For the impurity states, being localized, do not permit the travel of electrons along them; consequently electrons from metal states below E_f find no states or only full states waiting for them on the far side, while the only electrons in the semi-conductor below E_f and able to travel, namely,

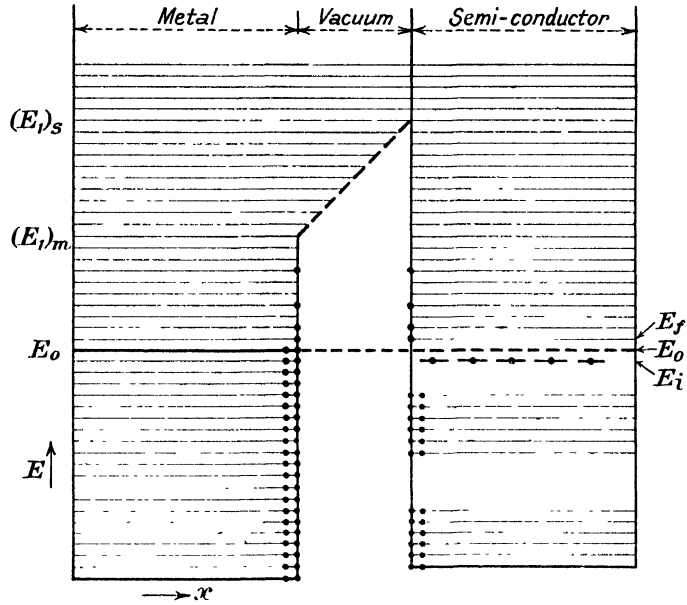


FIG. 10. BOUNDARY BETWEEN METAL AND SEMI-CONDUCTOR

those in the lower full states, find only full states on the far side.

Now suppose that a potential difference is applied between the two bodies. First let it be in the direction to drive electrons from left to right, which means that the states in the semi-conductor are lowered. More electrons will flow from the metal, because now E_f comes opposite lower states of the metal which contain more electrons. Next let it be in the direction to drive electrons from right to left, which means that the states in the semi-conductor are raised. No more electrons flow from the semi-conductor, because the number of these is limited by the number above E_f, not by the absence of states on the far side to receive them,

and the number above E_f is not changed. Accordingly more current will flow if the potential difference is in one direction than in the other, the contact will act as a rectifier passing electrons only from metal to semi-conductor.

This account is not complete. We should really take into account the effect of the potential difference on the form of the potential hump through which the electrons pass; this form affects considerably the chance of an electron passing through it (see page 32). For this reason rectification by the contact depends on the width of the hump and vanishes if it is too small, as well as if it is too large. But we only need a general explanation of the fact that rectification may occur at such a contact.

The effect of light on either metal or semi-conductor in Fig. 10 will be, as before, to raise electrons into higher states and, in particular, into those above E_f, where they can pass from one to the other. Since E_0 in the metal, which contains plentiful electrons, is above E_i, which is the highest state in the semi-conductor that can send electrons into E_f, it would seem to follow that, if both metal and semi-conductor are equally illuminated, more electrons would be raised to E_f on the metal than on the semi-conductor side, so that the electrons carrying the photoelectric current would flow from the former to the latter. As a matter of fact, they flow in the other direction, from semi-conductor to metal. The reason is probably this. The chance that an electron will take up energy from light depends on its condition; the chance is greater if the electron is localized or "bound" than if it is free (see page 7). The electrons in the impurity states, being bound, take up energy much more readily than the free electrons in the metal, and therefore, although they require more energy, they arrive at E_f more frequently, so long as the quantum energy is great enough to transfer them there at all. But now a new difficulty appears. This explanation would suggest that, if the metal and semi-conductor were widely separated and each acted separately as the cathode of a cell of the second class (depending on the outer photoelectric effect), the semi-conductor ought to give a greater emission than the metal. Actually for light in easily accessible regions of the spectrum, this is not true; the semi-conductor gives no emission in

regions where the metal gives considerable emission. However, this becomes intelligible if we remember that $(E_1)_s$ is much greater than $(E_1)_m$. When the bodies are widely separated, electrons cannot emerge until they acquire the energy E_1; accordingly there will be a region of the spectrum in which the quantum energy is great enough to give the electrons from the metal the energy necessary to emerge, but not the electrons from the semi-conductor. If the wave-length is decreased and the quantum energy decreased past this region, so that electrons from both can receive the necessary energy, then the semi-conductor ought to show a greater outer photoelectric effect than the metal. But that will happen only in a part of the far ultra-violet that is difficult of access.

It cannot be pretended that this theory of the matter is yet established; but no facts inconsistent with it are known. Until it is disproved and replaced by a better, it will serve to explain the salient properties of the third great class of photoelectric cells, rectifier cells. It shows why substances that display no outer photoelectric effect may yet show a boundary effect which must consist essentially in the loss of electrons, and why this boundary effect is so intimately connected with rectification.

Electrons as Waves. Those who already know something of modern theory, but not enough to make them skip this chapter entirely, will realize that our exposition is incomplete. They will know that, while in one of their aspects electrons are particles, in another they are waves; we have said nothing about the wave aspect. The reason is that the questions that are answerable if we regard the problem from one aspect are unanswerable if we regard it from the other; and that the questions that concern us most nearly are answerable from the particle aspect. Thus if we had adopted the wave aspect, we might have justified our evasion (except in Fig. 8) of a question that will occur to many readers, namely, how the electrons are distributed in space through a material body; for, if electrons are waves, every electron is everywhere; it extends throughout the whole region to which its state extends. But, on the other hand, we could not have spoken of the passage of an electron across a boundary.

All this is very confusing; and no explanation can make it less so; it is merely an expression of the ultimate fact that no single mechanical model is adequate. If we adopt a model, we must resolutely refrain from asking questions not arising directly out of the features of our model. But the position is not quite so confusing as it was when (according to Bragg's famous joke) the particle theory was true on Mondays, Wednesdays, and Fridays, and the wave theory on Tuesdays, Thursdays, and Saturdays, for we can now distinguish between the two classes of question. Particles are appropriate to events; waves to probabilities. In other words, if on Wednesday we are inquiring about Tuesday, we must use the particle theory; if we are inquiring about Thursday, the wave theory. With that hint we must proceed to matters more obviously within our scope.

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2. For the electronic theory of solids, see Hughes and Du Bridge's *Photoelectric Phenomena* (McGraw-Hill Publishing Co., 1932), especially Chap. VI; and J. Frenkel, *Wave Mechanics* (Oxford Univ. Press). For the theory of semi-conductors, see R. H. Fowler, *Phys. Zeit. d. Sowjietunion* 3, p. 507, 1933.

CHAPTER II

THE VACUUM EMISSION CELL

The Vacuum Cell. An emission photoelectric cell is one dependent on the "outer" photoelectric effect (see page 17). It consists essentially of a cathode from which the electrons are emitted and an anode to which they pass across a vacuous space. Three commercial types of such cells are shown diagrammatically in Fig. 11. In *A* and *B* the cathode is a plate in the centre of the vacuous enclosure; the anode in *A* is a gauze on the walls through which light can pass, and in *B* a simple rod. In *C* the cathode is a layer on the walls, pierced by a window for the admission of light, and the anode is a rod in the centre. The reasons for these differences will appear gradually. Construction *B* is adopted in gas-filled cells, described in Chapter III, rather than for vacuum cells, but is inserted here for convenience; in that chapter, *A* will be termed a *plane* cell, *C* a *spherical* cell.

If the ideal conditions assumed in Chapter I obtained, all the electrons emitted would pass to the anode so long as it was more positive than the space immediately outside the cathode. If it were negative to the cathode, only those electrons would reach it which left the cathode with a kinetic energy greater than that necessary to overcome the opposing potential difference. Accordingly the relation between current and anode voltage (the cathode potential being taken as zero) would be that shown in curve *x* of Fig. 12. The sloping part of the curve would cover a range of potential equal to the quantum energy *E*; for the fastest electrons cannot have more than that energy, the slowest cannot have less than no energy; the flat part, or "saturation current," would measure exactly the rate at which electrons were emitted. The actual characteristic of a vacuum cell is somewhat similar to curve *x*, but the range covered by the steep slope is much greater than the quantum energy and the curve never becomes really flat at high voltages; *a* and *b* in Fig. 12 show actual curves.

The reason is twofold. Cathodes are never perfectly

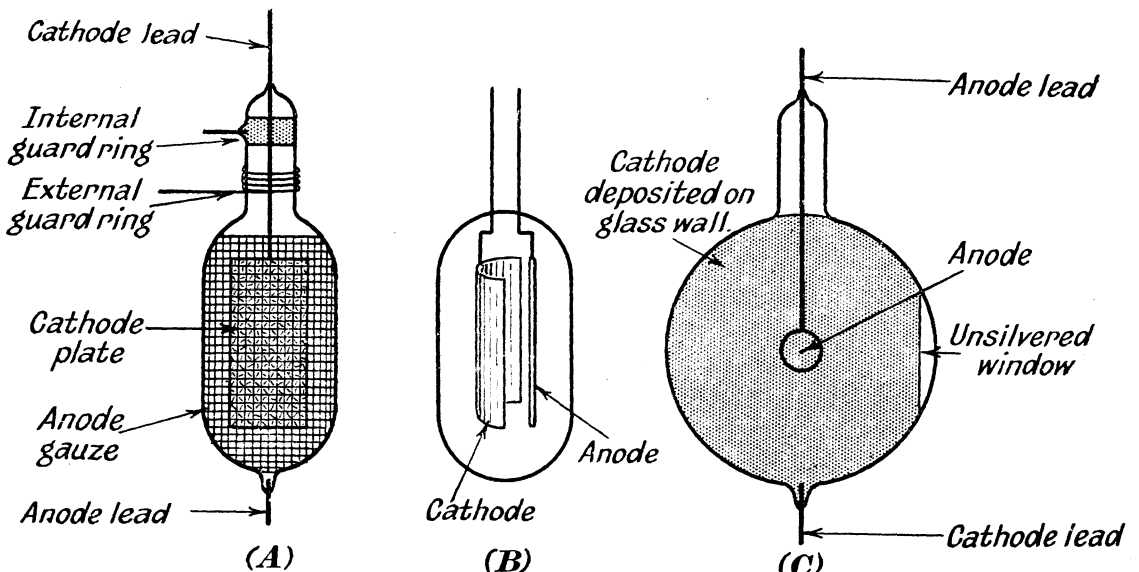


FIG. 11. TYPICAL EMISSION CELLS

smooth plane or convex surfaces; electrons leaving one part may strike another unless the field is strong enough to drag them immediately to the anode. Again, the emission of electrons is not wholly independent of the external electric field; we need not discuss the reason in detail, but it may be observed that "space charge," so important in thermionic valves, plays practically no part in photoelectric cells, because the currents are so much smaller. For both reasons

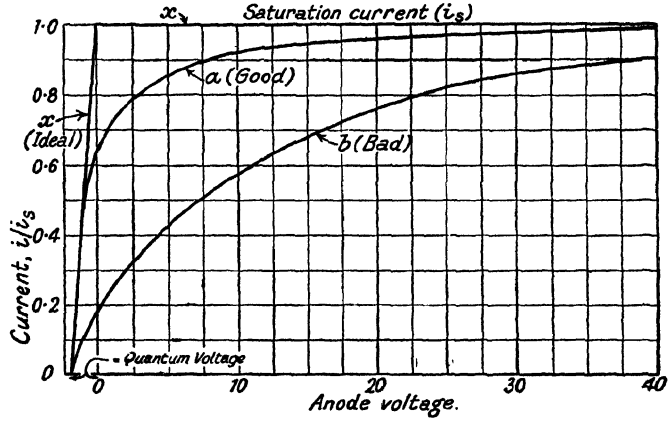


FIG. 12. CHARACTERISTICS OF VACUUM CELL

a cell will approach the ideal more nearly the less concave is the cathode and the more completely it is surrounded by the anode. This is one ground for preferring type *A* in Fig. 11 for vacuum cells, if the slight obstruction of the light by the anode is not a serious objection. Curve *a* in Fig. 12 refers to a good cell of this type; curve *b* to an unfavourable specimen of type *C*. However, the difference is not so important as might appear at first sight. In any vacuum cell there is some voltage beyond which it may be assumed for any given purpose that the current is independent of the voltage and proportional to the emission; there will be an effective "saturation voltage" at which the cell will always be used. Curves of type *a* are preferable, because this voltage is comparatively low, even when the purpose demands that the effective saturation current should approximate closely to the ideal saturation current.

The current in a vacuum cell is therefore determined almost entirely by the emission, and the most important facts about it are those concerning the variation of the emission with the quantity and quality of the light. These facts are much more complex than is suggested by the simple theory of Chapter I, and most of the rest of this chapter will be concerned with them.

Photoelectric Emission. The variation with quantity is very simple, at least in ideal circumstances, and follows directly from the simple theory. Since the chance of an electron taking energy from light of given quality is proportional to its quantity, and since it must take energy in order to emerge and share in the current, the current is proportional to the quantity. How far and why there are departures from this simple relation in circumstances that are not ideal will concern us later (pp. 50, 197). It is convenient therefore, to state all further facts in terms of the ratio of the current to the quantity; this ratio will be termed the *emission*. When the light is homogeneous of a single wavelength λ, the emission will be denoted by σ_λ and will be measured in amperes per watt. (In some older works the emission is expressed in coulombs per calorie; 1 coulomb per calorie = 0·24 A/watt.) When the light is "white," the emission will be denoted by Σ and measured in microamperes per lumen.

But there is still some ambiguity. Of the light incident on the cathode, some is always reflected, and this reflected light can clearly play no part in producing a photoelectric current. Ought, therefore, the quantity of light to be taken as that incident on the cathode or as that absorbed in it? This question was hotly debated at one time, and great importance was attached to cells in which all the light was absorbed at the cathode and none reflected from it. Such cells can be made from those of the kind shown in Fig. 11(c) by decreasing the size of the window relative to the area of the cathode on the walls, until light entering at the window is all absorbed after many reflections at the cathode, and only an infinitesimal portion can emerge again. But the current in such cells, though, of course, a little greater than that produced by the same light in open cells, such as Figs. 11(A) or 11(B), does not obey materially different laws. It

doubtless would do so if most of the light absorbed at the cathode were utilized in giving energy to electrons that have a large chance of emergence. Actually most of it is absorbed at points so deep in the cathode that electrons acquiring energy there have no chance of reaching the surface, because they lose energy in passing through the metal. Accordingly there is no theoretical reason to consider absorbed rather than incident quantity of light; the latter is much more convenient experimentally; we shall therefore always take quantity of light to mean quantity incident on a cathode of such a shape that none of the reflected light strikes the cathode again.

Strictly, we ought to take into account the angle of incidence of the light on the cathode and its plane of polarization; for both these may affect the emission, especially when it is referred to incident and not to absorbed light. In fact, angle of incidence and polarization ought to have been included with wavelength as "qualities" of the light. They are of considerable theoretical importance, and will be discussed briefly below; but the theory is of little practical importance, because actual cathodes are not usually optically smooth. When a surface is rough or matt, there is no single angle of incidence, and, even if the light is polarized, there is no single angle between the planes of polarization and incidence; whatever the nominal angle and plane of incidence, the actual angles do not vary greatly, unless the angle of incidence is very great. When the contrary is not stated, it will be assumed hereafter that the incidence on the average surface of the cathode is normal: the state of polarization is then immaterial. The effect of large angles of incidence is mentioned in Chapter XII, where alone it is relevant.

Emission and Wavelength. We have now to consider the relation between emission and the quality of the light. Here we enter on great complications. In Fig. 13 the emission (in units that will be explained presently) is plotted against the wavelength of the incident light for two different cathodes, A and B. The features common to the two curves follow from the simple theory of Chapter I. As the wavelength is decreased (and the quantum energy increased) from the right, no emission appears until a "threshold," different

for A and B, is reached. The threshold represents the condition at which the electrons with the greatest energy, namely, those in E_0, just acquire the energy E_1 with which they can emerge. The energy that they must receive is therefore $E_1 - E_0$, which is the work function φ, so important in thermionics. Hence the wavelength λ_0 of the threshold ought to be related to φ by the equation $\varphi = 1234/\lambda_0$. Actually the threshold is not perfectly sharp, because there are always a few electrons at ordinary temperatures with an energy above

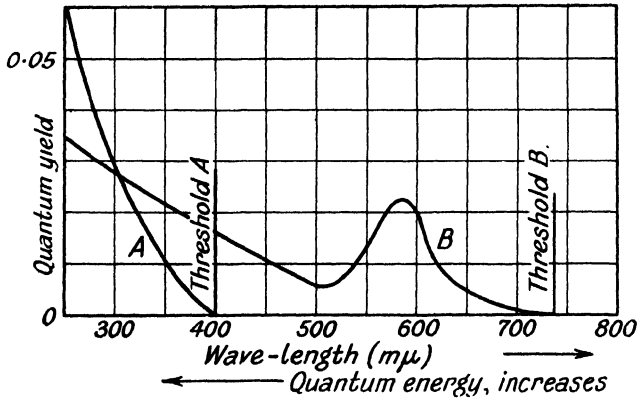


FIG. 13

E_0, and therefore requiring rather less energy than this; λ_0 cannot therefore be determined accurately by mere experiment. Some very pretty calculations by Fowler, based on the general theory of Chapter I, have recently enabled λ_0 to be determined accurately, so that it can be shown to agree exactly with φ determined from thermionic measurements; proof of the theory is thereby obtained. But though the facts connected with the threshold are of great theoretical importance, and have therefore received much attention, they are of little practical importance. For the emission is never large enough to be practically useful until the wavelength is much less than λ_0; and—contrary to what was thought at one time—the useful emission at these shorter wavelengths is not always closely connected with the threshold.

After the threshold is passed, the emission rises rapidly

on both curves. This rise is due, in part at least, to the quantum energy becoming large enough to eject electrons lying in the full states below E_0. Our theory shows that this rise cannot continue indefinitely; for an absolute limit must be reached when all the energy of the light is given to electrons that actually emerge. This limit σ_{max} is easily calculated. The emergence of an electron requires the subtraction of the quantum energy from the light; this is $1234/\lambda$ electron-volts or $(1{\cdot}96 \times 10^{-9})/\lambda$ ergs. One watt of light, conveying 10^7 ergs per second to the cathode, cannot therefore cause the emergence of more than $5{\cdot}11 \times 10^{15}\lambda$ electrons per second, which would provide a photoelectric current of $8{\cdot}1 \times 10^{-4}\lambda$ A. Consequently, we have

$$\sigma_{max} = 8{\cdot}1 \times 10^{-4}\lambda \text{ (A/watt)} \quad . \quad . \quad . \quad (8)$$

The ordinates of Fig. 12 are the values of $\sigma_\lambda/\sigma_{max}$, the ratio of the actual emission to the maximum theoretically possible at each wavelength, which may be called the "quantum yield."

It will be seen that the rise of emission with decreasing wavelength ceases in curve B long before this ratio approaches 1; the curve reaches a maximum when it is only 0·02, falls to a minimum, and then rises again. Curve A, on the other hand, rises steadily to the end of the diagram. Of course, this may be because the diagram is not carried far enough, and that if it were prolonged into the far ultra-violet (where experiments are not easy), A also would show a maximum. This is probably true; yet there is probably a real difference between the forms of the two curves: their immense difference for practical purposes does not arise simply from the easier access of the visible spectrum to our experiments.

For the two forms of curve are closely associated with two kinds of cathode surface. A cathode consisting of a metal with its surface carefully freed from adsorbed gas, and from all the other impurities that attach themselves so readily to metals, usually (if not always) has an emission curve of the form A, having its threshold in the ultra-violet or well towards the blue end of the visible and having no maximum in the accessible region. But if the surface of the same metal is contaminated accidentally or, better still, intentionally, then form B usually appears. The threshold is

much farther towards the red and a maximum of emission appears in the visible (and often in the near ultra-violet as well). The emission curve is determined by the surface of the cathode at least as much as by the bulk properties of the metal of which it is composed. This is a fact of the very highest importance for the photoelectric cells we are considering.

Selective Emission. Emission in the neighbourhood of the maximum of curve *B* is called *selective*; emission on curve *A* or elsewhere on curve *B* is called *normal*. These terms come from a time when it was thought that the hump in curve *B* was something abnormally superimposed on a curve *A*, which represented the ordinary variation of emission with wavelength. This view is now known to be too simple; but nevertheless it is still useful to inquire how any selectivity in emission can arise so that light of a particular wavelength can produce more emission than light of neighbouring wavelengths on either side of it (the quantum yield being always far less than 1); and why selectivity should be so affected by surface conditions.

Three suggestions can be made: (1) Light of the particular wavelength can act more effectively upon the electrons; (2) the electrons can be particularly ready to take up energy from this light; (3) electrons that have taken up energy from this light are particularly capable of emergence. Probably all these suggestions are true to some extent, and the exact part played by each of the three factors is still uncertain; we will therefore consider them in turn.

1. There is one fact greatly in favour of this suggestion. When the emission is normal, it is almost independent of the plane of polarization of the incident light; if there is any variation with the polarization, it is due to a difference in the amount of light absorbed; the emission referred to absorbed light is independent of the polarization. But when the emission is selective, it is often (not always) greater when the light is polarized and incident so that the electric vector of the light has a component perpendicular to the surface of the cathode. (The electric vector of light is parallel to the short diagonal of a Nicol prism which transmits it.) This is comprehensible; for electrons acquiring energy from the light will tend to move in the direction of the electric field

in the light; if that direction is perpendicular to the surface they will emerge more easily. It is not quite so easily comprehensible why the plane of polarization should not affect the normal emission; but if we admit that the electric field in the light may determine emission, a theory, due chiefly to Ives, can give some account of the effect of surface impurities in selective emission. According to Ives, the distribution of the electric field in the light near the surface of the cathode, from which the electrons come, is determined by the optical properties of the bulk metal; the surface film is too thin to affect it greatly; it is merely immersed in the field determined by the metal below. Now the reflection of the light by the metal produces standing waves just above its surface; if the wavelength and the angle of incidence of the light are such that the region occupied by the film lies in a "loop" of these waves, where the field is large, the emission will be much greater than if it lies in a "node," where the field is small. The thickness of the film, the angle of incidence, and the wavelength of the light must therefore be related in a suitable manner if selective emission is to occur.

This theory explains fairly well the variation of the emission with the angle of incidence at some cathodes; it is doubtless part of the whole truth; but it does not seem competent to explain all the very complicated facts, and, in particular, the exact variation of emission with wavelength.

2. It has been noted before that the chance of an electron taking energy from light depends on the manner and extent to which it is "bound." A perfectly free electron, subject to no forces, could never take energy. The factor determining the chance depends on the relation between these forces and the wavelength of the light; the chance is a maximum when the frequency of vibration of the electron, determined by the forces, is equal to the frequency of the light determined by its wavelength, as is expressed by the classical conception of "resonance." Now the forces acting on an electron when it is near the surface are much greater than those acting on it when it is in the interior; and they vary with the nature of the surface. It is comprehensible therefore that the electrons which take up energy, and

therefore emerge, should be mainly those near the surface, that their number should be affected greatly by the nature of the surface, and that there should be a particular wavelength of the light for which the number is a maximum. But here again theory is not sufficiently advanced to make quantitative predictions, and it is therefore impossible to say what part of the selective emission is due to this cause.

3. According to the theory of Chapter I, an electron will emerge if, and only if, it acquires an energy greater than E_1, which is the rise of potential in passing from the metal to the vacuum. This rise was pictured as a sudden discontinuous jump; but this picture is doubtless too simple, especially when the surface of the metal is coated with foreign materials. Between the interior of the metal, where the potential is low, and the vacuum, in which it is high, there is doubtless an intermediate region of finite width, in which the potential may vary in a complicated manner; it may even have maxima and minima, and be fitly pictured by a series of peaks and valleys. Now we have noted already that the chance of an electron passing through a region where it has "negative kinetic energy," and where there are no electron states, depends on the way the potential, representing the lowest state, varies through this region. In fact, if there is a potential valley between two peaks, the chance of an electron getting through is a maximum if its kinetic energy is related in a particular manner to the breadth of this valley. In terms of the "wave-theory of the electron" (an account of which lies outside our province), the condition is that the wavelength of the electron, which depends on its speed, should be a sub-multiple of the breadth, so that the electron can form standing waves in the valley. Accordingly it is quite conceivable that electrons starting off with a particular speed may have a greater chance of passing through the potential jump at the surface than electrons with either greater or less speed. Since the kinetic energy an electron acquires is determined by the wavelength of the light, this means that electrons absorbing energy from light of a particular wavelength may have a greater chance of emerging from the cathode than those absorbing it from light of any other wavelength. That would clearly explain selective emission.

Again, these considerations, as they stand, are doubtless too simple to explain all the facts. It is unjustifiable to separate so completely emergence from the metal and travel through the metal. But there can be little doubt that the enormous effect of minute changes in the surface layer must be attributed, in part at least, to changes in the distribution of potential in the region through which the electrons have to pass on their emergence.

The Facts of Emission. The object of the previous section is not so much to present an intelligible theory of emission, as to indicate how complicated any complete theory must be, and thus to prepare the reader to realize that the facts are equally complicated. The emission of most of the cathodes used in practice is determined mainly by the surface layers; these layers are very difficult to control. Cathodes prepared by ostensibly the same process may differ greatly in emission, and the emission of a single cathode may be altered greatly by the circumstances of its use. That fact must dominate all intelligent use of emission cells, and makes it impossible to give precise data in any simple form. Nevertheless the variations in the emission of a single cathode or among cathodes professedly similar is not so great as to obscure differences between those professedly different. For each kind of cathode there is a norm about which actual cathodes vary and, for those cathodes which have been more completely studied, it is possible to give some idea of the probable extent of the variations.

The cathodes used in practice fall into three classes: (*a*) plain metals; (*b*) sensitized metals; and (*c*) thin films.

Plain Metals. Plain metals are metals as they exist in vessels exhausted by standard vacuum technique, including neither extreme measures to remove the last traces of adsorbed gas nor treatment directed to produce adsorbed films. The metals that have been used most frequently are sodium, cadmium, and zinc; but many others, including calcium, barium, cerium, uranium, thorium, magnesium, and silver have been recommended for various purposes. Most of these metals have no emission in visible light, and can be used only in the ultra-violet (U.V.). The practically important part of the U.V. is the "near" U.V. from 400 mμ to 250 mμ; here lie the therapeutic radiation of interest in medicine,

the absorption band of ozone of interest in geophysics, and the strong mercury spectrum line at 254 mμ; data for plain

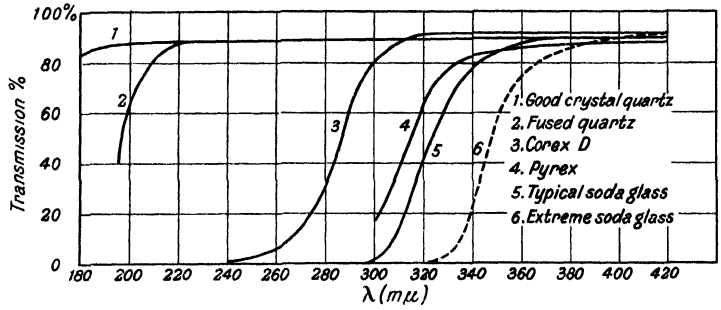


FIG. 14. TRANSMISSION OF GLASSES

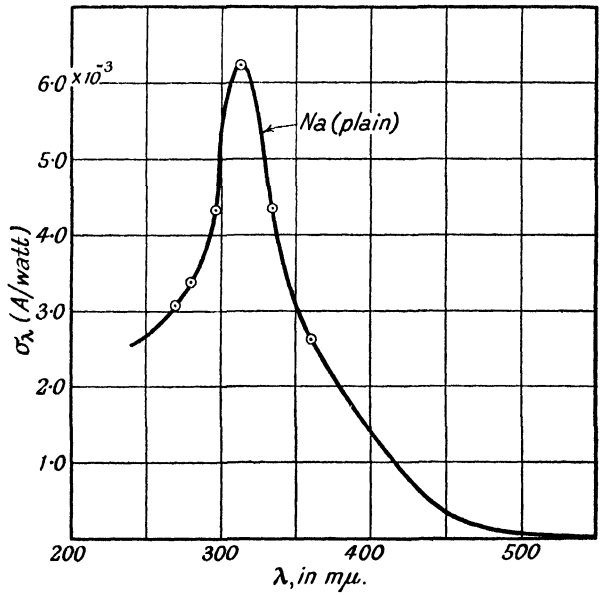


FIG. 15. EMISSION OF SODIUM

metals are required chiefly in this region. Ordinary glass begins to absorb strongly about 330 mμ, and accordingly cells for this region must have bulbs, or at least windows, of quartz or special glass. Very thin windows of ordinary

glass have also been used, the glass being in the form of a bulb sucked into the cell, so that it will withstand atmospheric pressure. Fig. 14 is appropriate here, showing the transmission of a layer 1 mm. thick of various materials that may be used for such cells.

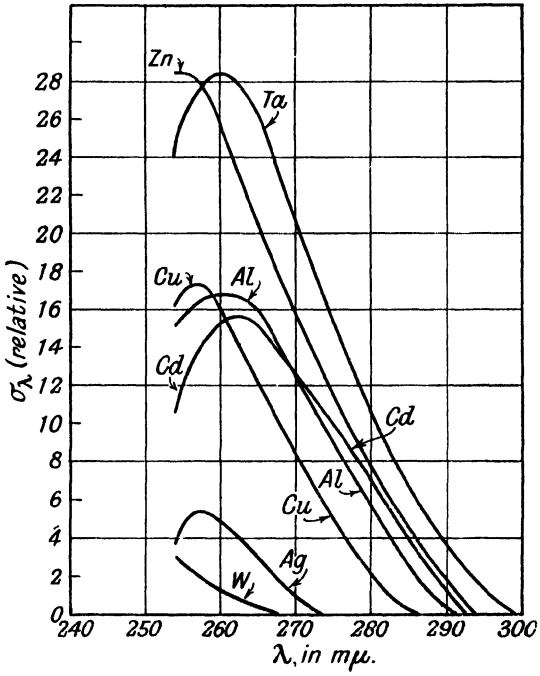


FIG. 16. EMISSION OF PLAIN METALS

The data available concerning the emission of these cathodes are extremely scanty. There are abundant measurements of the variation of σ_λ with λ for some of them, especially Cd. But observers hardly ever give absolute values in amperes per watt. The reason doubtless is that the power of U.V. radiation is so small and related in so complicated a manner to the nature of and power expended in the source, that it is difficult to measure and impossible to estimate. Absolute values, if given, would therefore have little direct practical value. But they would enable a comparison to be

made between different metals measured by different observers or even by the same observer on different occasions. At present even this comparison cannot be made; there is often no evidence even to show which of two metals has the greater emission at a given wavelength.

Sodium is the only metal for which absolute values are available, concerning which several observers agree approximately. σ_λ for this metal is given in Fig. 15. Figs. 16, 17,

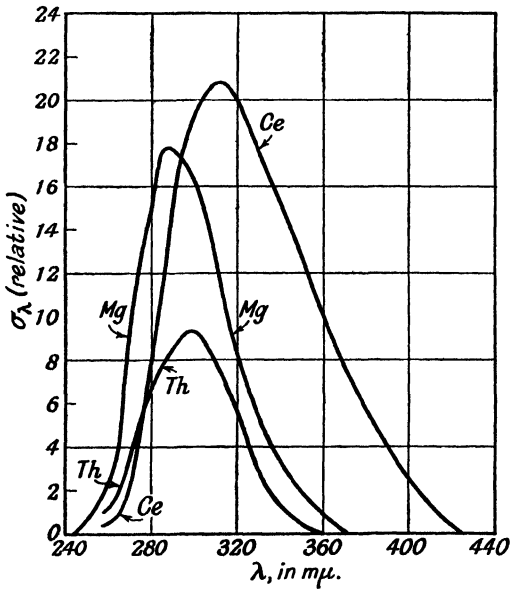


FIG. 17. EMISSION OF PLAIN METALS

and 18 are based on the most extensive series of measurements by the same observers yet published (4); but only relative values are given. In none of these figures is a correction made for absorption by the glass, and since the thickness of the glass is not given, it cannot be applied. In Fig. 16 the glass was very thin and probably does not affect the values at $\lambda > 270$; but the fall at $\lambda < 270$ is probably due in part to the glass. In Figs. 17 and 18 the glass was thicker, probably about 1 mm., and certainly affects the response at small values of λ. There is no means of comparing metals

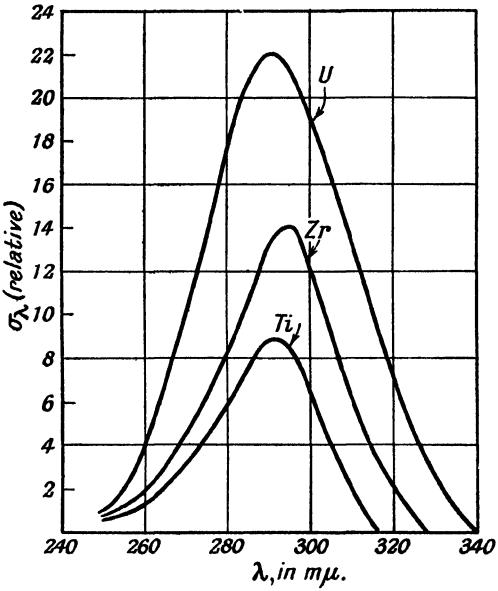


FIG. 18. EMISSION OF PLAIN METALS

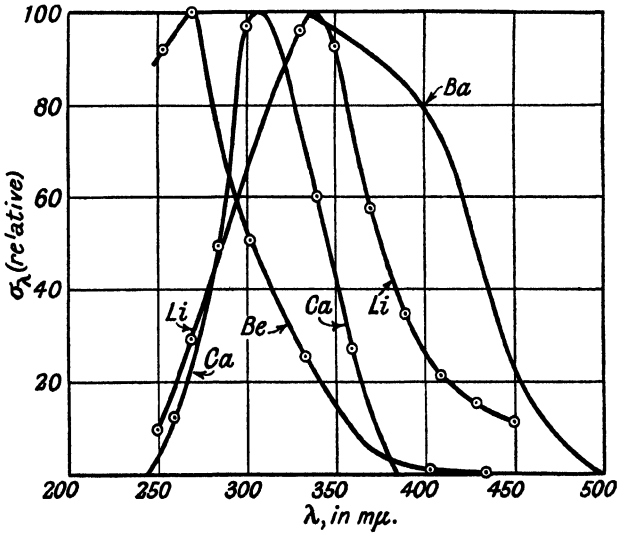


FIG. 19. EMISSION OF PLAIN METALS

in different figures. In Fig. 19 curves are given for Ca, Ba, Li, and Be, the maximum σ_λ being put equal to 100 in each case; this maximum as given by one observer is 52×10^{-4} A/watt for Li and $3{\cdot}6 \times 10^{-4}$ A/watt for Be.

From the data given one important generalization emerges. Among metals showing no selective emission in the region in question, the curves are roughly parallel and do not cross each other; the metal giving the highest emission at any wavelength is therefore that with the longer threshold λ_0. If the metals were perfectly clean, it would therefore be possible to determine the photoelectric properties from thermionic data which fix the work-potential and even from general electrochemical properties which follow it closely; for it is certain that in clean metals the predicted relation between threshold and work-function holds. But in practical cells, metals are not perfectly clean and conclusions from thermionic data may be misleading. The generalization does not hold when selective emission appears; thus, Mg is more sensitive than Cd to $\lambda = 330$ mμ, but less sensitive to $\lambda = 254$ mμ.

The discrepancies between different observers are doubtless due to variations in the surface conditions; it is uncertain how far the data given are truly representative, since they seem to have been obtained for unusually clean surfaces. But the variation due to surface conditions is certainly less for plain metals than for other classes of cathode, if reasonable precautions are taken in their preparation; it is least for the least electropositive metals. In particular plain metals are more stable, and their emission does not vary greatly with exposure to light or to the discharge in a gas-filled cell.

Sensitized Metals. If only plain metals were available, work with visible light would demand the use of metals with the largest λ_0, which are generally those most electropositive, such as the alkali metals potassium, rubidium, and caesium. But it is precisely these metals that are most susceptible to the process of sensitization, which moves the threshold still farther to the red and leads to selective emission in the visible region. Indeed, as has been suggested already, it is very doubtful whether any truly unsensitized metal displays selective emission in any region accessible to

experiment; the selective emission shown in Figs. 17, 18, and 19 is probably due to an unintentional sensitization which cannot be avoided even if the metal is nominally plain. Accordingly these metals are nearly always used in the sensitized (or thin film) condition. Trustworthy data concerning their unsensitized emission are not available; this is why they are omitted from the previous section. Sensitization appears to decrease the emission in the near U.V.; the reason why the metals used in the visible are not so well suited as those of the previous section in this region is probably the difficulty of obtaining them sufficiently clean.

There are two main processes of sensitization. The first was discovered more than thirty years ago by Elster and Geitel, and was used in all emission cells adapted for the visible spectrum for some twenty years. It consists in making the metal the cathode of a glow discharge in hydrogen. It is accompanied by a change in the appearance of the surface; thus the white metallic potassium becomes matt and assumes a characteristic blue-green colour. The second process, developed during the last four years by Olpin and his associates, consists in exposing the metal (usually sodium, but sometimes potassium) for a short time to the action of vapours containing oxygen and/or sulphur. Sulphur vapour, sulphur dioxide, and many dyes containing these two elements have been used. The nature of sensitization is not fully understood; but there is reason to believe that it depends on the formation of compounds of the metals and the subsequent deposition on them of a thin film of the uncombined metal. If so, the distinction between sensitized and thin film cathodes is merely one of practice and not of theory.

Fig. 20 gives normal value of σ_λ in the visible region for the alkali metals sensitized by the Elster-Geitel process. It must be understood that the values obtained vary from cell to cell; the position of the maxima is much more constant than the values of σ_λ at these maxima. Cathodes prepared by the Elster-Geitel process will be generally denoted by K–H, etc.; but in the figure they are denoted by the simple name of the sensitized metal, as they always were before cathodes of more modern type were known. Fig. 21 gives Olpin's values for some of the more useful cathodes prepared by his process. Potassium sensitized by the

Elster-Geitel process, now represented by K–H, is included again in order to extend the curve to shorter wavelengths;

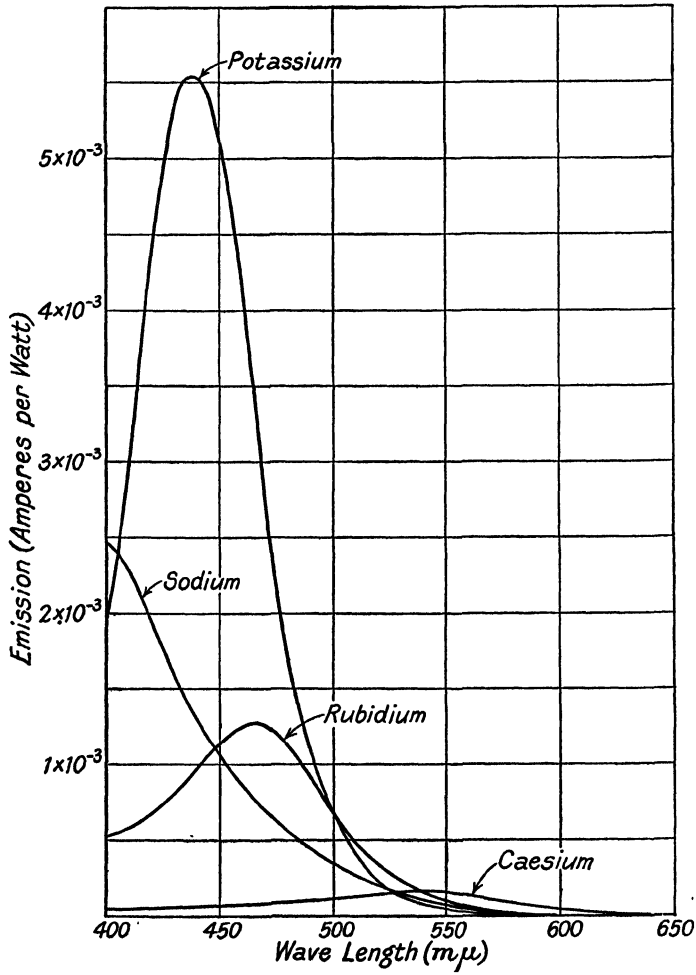


FIG. 20. EMISSION OF SENSITIZED ALKALI METALS

the two curves given for K–H in Figs. 20 and 21 do not coincide; the difference between them illustrates well the variation that may be expected between cathodes of this type

professedly similar. Olpin gives other curves produced by varying the process of the sensitization. If the cathodes could be reproduced accurately, the variation of the emission with the sensitizing agent would be very convenient; for it would enable a cathode to be produced having a maximum at almost any desired point in the visible spectrum. But it seems that this process of sensitization is subject to at least as great inconsistency as the other, and that the differences between cathodes produced by different processes is liable to be obscured by differences between cathodes produced by the same process.

Thin Films. It has long been known that if the cathode of a cell contains potassium, or other alkali metal, the anode, though consisting of a metal having no emission in the visible region, acquires an emission not much less than that of the cathode; its emission is due to the condensation on its surface of a very thin film of alkali metal derived from vapour supplied by the cathode. The properties of these thin films, which are never more than a few atoms thick and are too thin to be seen, were first investigated by Ives, who used perfectly clean metals elaborately freed from surface impurities. He found that as the thickness of the sensitive metal (e.g. potassium) on an insensitive metal (e.g. platinum) increases from zero, the threshold, starting from the position characteristic of the insensitive metal, moves towards the red, until it is actually farther to the red than that of the sensitive metal; thereafter it moves to the blue, until finally, when the layer becomes very thick, it naturally becomes the same as that of the sensitive metal in bulk. In white light the emission of the thin film of sensitive metal on insensitive metal may be much greater than that of the sensitive metal in bulk.

Emission curves of some thin films of this nature are shown in Fig. 22. The curves are normal in the visible region. The only cathode of this nature used in practice is that of caesium on magnesium; it is denoted by Cs–Mg.

The later work of Campbell and Koller, working independently of each other and of Ives, showed that cathodes still more sensitive to red and to white light could be produced by depositing thin films of the alkali metals, not on clean metals, but on their oxides, preferably mixed with

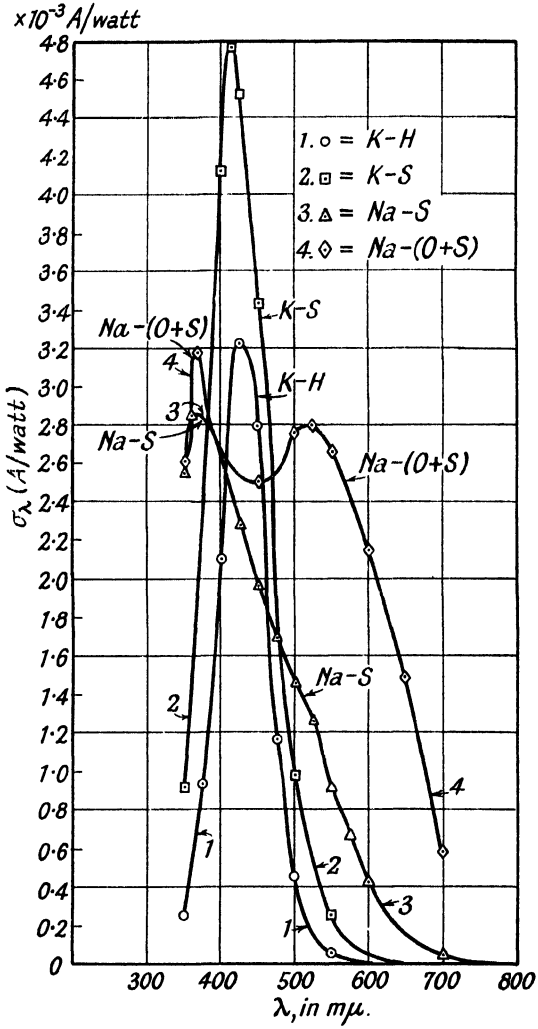


FIG. 21. EMISSION OF SENSITIZED ALKALI METALS

insensitive metals. The process they developed consists in oxidizing a surface of copper or silver and then heating it to about 200° C. in the vapour of caesium, rubidium, or potassium. The alkali metal vapour reacts with the copper or silver oxide, forming a complex of copper or silver with the oxide of the alkali metal; a layer of alkali metal, probably only about one atom thick, is left on the complex when

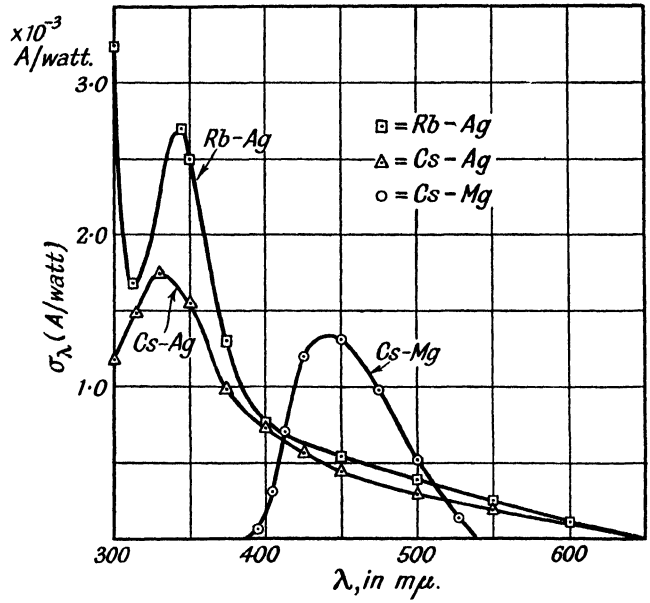


FIG. 22. EMISSION OF THIN FILMS ON PURE METALS

the excess is driven off by continuing the heating after the supply of alkali metal is stopped. The result is conveniently represented by the symbol X–O–M, where X is the alkali metal and M the insensitive metal (usually copper or silver).

Similar cathodes have been obtained by de Boer and Teves, who deposited thin layers of alkali metals on other salts, such as calcium fluoride; their studies and those of others who have investigated variants of the original procedure have thrown much light on the theory of the process. But manufacture seems still to follow that procedure with only slight modification. Cells produced by it are now used

almost exclusively when sensitivity to white light or red or infra-red light is required; they are therefore more important commercially than any others. More than 90 per cent of all the emission cells sold have cathodes represented by Cs–O–Ag.

Fig. 23 gives curves for K–O–Ag, Rb–O–Ag, Cs–O–Ag

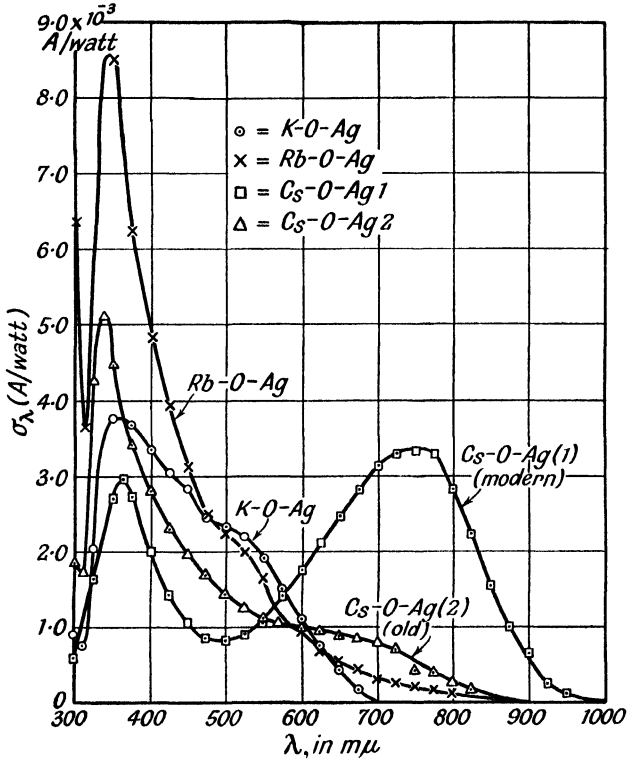


FIG. 23. EMISSION OF THIN FILMS ON OXIDES (PRACTICAL)

representing good commercial practice. The two curves for Cs–O–Ag represent extremes obtainable by variation in procedure; that marked (1) represents best modern practice, and is referred to when Cs–O–Ag is mentioned below; K–O–Cu, which is also used, does not differ very greatly from K–O–Ag. Sometimes cells appear with much greater emissions, especially for long wavelengths. They can be obtained

more regularly by a modification of the process due to Asao, in which a thin layer of silver is deposited on the X–O–Ag cathode after its formation; but they can also be obtained occasionally without it. Fig. 24 gives the emissions of these exceptional cathodes (which may be represented by X–Ag–O–Ag); it shows an ideal to which practice may hope some day to attain regularly. Rb is now below both Cs and K; this is probably merely because the ideal has not been as nearly attained with this metal, which has been less investigated.

Emission in White Light. The sources to which cells are most often exposed are tungsten incandescent lamps; the emission that is of greatest importance is Σ, which will be expressed in μA/lumen, for light from such a source. If T' is the colour temperature of the source, it follows from our definitions that Σ is given by

$$\Sigma = \frac{\int_0^\infty \sigma_\lambda P(\lambda, T')d\lambda}{\int_0^\infty \sigma_\lambda P(\lambda, T')d\lambda} \quad . \quad . \quad . \quad (9)$$

It can therefore be calculated from data already given.* But, of course, it is much more easily measured directly; actually the absolute values of σ_λ in Figs. 20–24 are calculated from the values of Σ given below in heavy type.

When one value of Σ is given, it represents the results of some particular experimenter, and no opinion is expressed how far it is typical. A range in brackets is the range of good commercial practice, excluding those exceptionally sensitive cells that fill the manufacturer at once with hope

* Here an annoying complication enters, arising from the difference between $F(\lambda)$ for tungsten and $P(\lambda, T')$ outside the visible spectrum. (See footnote, p. 7.) In our calculations we have always started from a value given for Σ under light from tungsten at some specified colour temperature. For convenience we have assumed thereafter that tungsten is a complete radiator. No error is introduced thereby except possibly for cathodes having emission at $\lambda > 1000$. But anyone who wishes to check our calculations must either make the same assumption or work throughout with true temperatures and the true $F(\lambda)$ for tungsten; they must not use $P(\lambda, T')$ and the true lumens/watt for tungsten at colour temperature T'. But in view of the general uncertainty of the data, any discrepancy arising from this cause is quite unimportant.

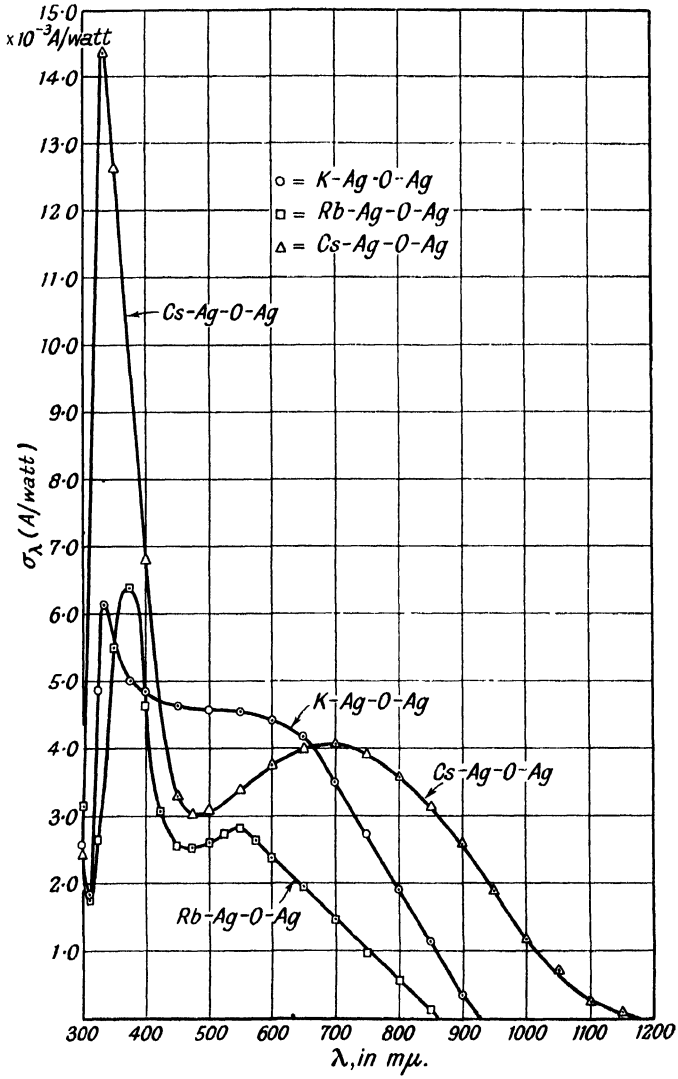


FIG. 24. EMISSION OF THIN FILMS ON OXIDES (IDEAL)

and despair, and also all those that ought to be regarded as definitely defective.

Σ is a function of T' and means nothing until T' is given. The reprehensible habit of stating Σ without T' is not yet wholly abandoned; when it is adopted, it may be assumed that the value of T' actually used is one unduly favourable to the cells for which Σ is given. When a cell is sensitive to the infra-red, Σ can be made as large as is desired by choosing T' low enough. A standard value $T' = 2848°$ K. is likely to be adopted shortly for specifications. Σ is given in Table I for this temperature and also for a lower temperature of 2400° K.; the difference indicates roughly how Σ varies with T'. The range of T' in practice is from 2400° K. (vacuum lamp) to 3000° K. (high-power projection lamp).

It is *not* possible to calculate the amount of light given by a lamp illuminating a cell from the watts and the value of T' for the lamp, using the relation of Fig. 3 between T' and L/W. For (1) the relation of Fig. 3 does not apply accurately to a tungsten radiator, as explained in the footnote; (2) the watts of the lamp are the total watts consumed, and these are always more than the watts radiated, which is the W of Fig. 3. But values of lumens per watt that can be used in such calculations are given in the last row of Table I under the heading L/W'; they give the number of lumens

TABLE I

Cathode	($T' = 2848°$ K.) μA/Lumen	($T' = 2400°$ K.) μA/Lumen
Na	**0·4** (0·2–0·5)	**0·2** (0·1–0·25)
Na–H	(0·5–1·0)	(0·25–0·5)
K–H	**1·04** (0·7–1·8)	**0·85** (0·5–1·5)
K–S	**1·8**	**1·3**
Na–S	**2·7**	**2·2**
Na–(O + S)	**7·5**	**7·6**
Cs–Mg	**2·1**	**1·9**
K–O–Ag	**4·45** (1–4·5)	**4·00** (1–4)
K–Ag–O–Ag	**28**	**37**
Rb–O–Ag	**5·4** (4–15)	**6·0** (4–15)
Rb–Ag–O–Ag	**12·2**	**15·0**
Cs–O–Ag	**23** (8–35)	**35** (11–50)
Cs–Ag–O–Ag	**47**	**73**
L/W' for commercial lamp	13 Lumen/watt	7 Lumen/watt

of light at colour temperature T' emitted by a normal commercial lamp, run at that colour temperature, for each watt of electrical energy consumed.

A single example will suffice to show how the table may be used to estimate roughly the photoelectric current to be expected from a given optical arrangement. A 60-watt gas-filled incandescent lamp sends light through a hole 1 cm. in diameter at a distance of 20 cm. The colour temperature may be taken as 2700° K. Assuming uniform radiation from the lamp and an efficiency of 12 lumens per watt, the lumens passing through the window are (see (1), page 2) $(12 \times 60)/4\pi \times \pi/4 \times 1/20^2 = 0{\cdot}11$ lumen. If a Cs–O–Ag cathode receives the light, giving 20 μA/lumen for light with $T' = 2700$, the resulting current will be of the order of 2μA.

The data concerning the emission of cells under daylight, another important source of white light, are very discrepant. The reason is probably that, even when the colour of daylight is constant, there may be great variation in its content of radiation outside the visible region to which cells are sensitive. It is useless therefore to do more than to point out that daylight generally resembles light of very high colour temperature; in Table 1 emissions tend to become more nearly equal as T' increases; the difference between the various cathodes is therefore markedly less in daylight than in artificial light.

Instability of Emission. The earliest workers with emission cells found that their photoelectric currents fell off gradually; they therefore spoke of *fatigue*. It is now known that most of this change was not a direct effect of the passage of a photoelectric current; it was not even an indirect effect, but was due to oxidation of the cathode by the air. Since all modern cathodes are enclosed in sealed vessels, that source of change has been completely abolished. The changes that still persist are often indirect effects of light; but since they can be produced independently of any photoelectric current, the term fatigue is misleading and ought to be abandoned. Instability is a better term.

The chief sources of instability are changes in the cathode due to change of temperature or to bombardment by positive ions, and to changes in the field due to charges on the walls of the cell. They are connected with the incidence of light

and the passage of a photoelectric current, because light is usually accompanied by heat, and because a photoelectric current may generate positive ions (see Chapter III). So long as the constitution of a cathode is unchanged, its emission is independent of temperature within wide limits, except in the neighbourhood of the threshold (see page 28); but change of temperature may alter its constitution by causing the evaporation or deposition of surface films. Positive ion bombardment may produce the same effects as rise of temperature, and other effects as well.

It is to be expected therefore that those cathodes should be least stable whose emission depends most intimately on the presence of volatile surface layers. And that is the fact. Plain metals are relatively stable. They have not perhaps been subjected to such careful scrutiny as other cathodes, but there is no evidence of any instability in well-constructed cells with plain metal cathodes, either during use or during long periods of storage or even under the influence of a glow discharge in a gas-filled cell.

Metals sensitized by the Elster-Geitel process are very unstable. First, they are subject to chemical change. The alkali metal absorbs hydrogen on its surface during sensitization; this hydrogen tends to diffuse into the unchanged potassium below. In a badly prepared cell, the hydrogen may diffuse away entirely, leaving the surface bright once more; and, though this should not happen in a well-prepared cell, progressive change in sensitivity, usually a loss, is apt to occur over long periods. Second, heating of the cathode causes the alkali metal to distil to the cooler parts of the cell and produces an irreversible change in its sensitivity. Cooling of the cathode, less usual, may cause the reverse change, but not a restoration of the original sensitivity. Such changes of temperature of the cathode relative to the rest of the cell are most likely to occur when the cathode is supported in the centre and is therefore highly insulated. On this ground, type *A* of Fig. 11 is less well suited for accurate work than type *C*. But a third source of instability, closely connected with the second, reverses the position. It has been noted already that all surfaces in a cell containing an alkali metal are covered with a thin film of it, which is capable of acting as a cathode. In type *C*

there is such a film on the bare glass with which the cathode is in contact and which is fully exposed to the light; but the film, being of very high resistance, is incompletely connected to the cathode. The effective area of the cathode depends on this high resistance, which is variable. For this reason (which usually outweighs the other), type *A* is preferable; for here all the large area of bare glass necessarily exposed to light tends to assume the potential of the anode; the cathode area is completely determinate. Lastly, the sensitivity of the cathode is markedly increased by the positive bombardment to which it is subjected in a gas-filled cell, and gradually decreases again when the bombardment ceases. Since the vigour of the bombardment depends on the photoelectric current, the emission takes a long time to assume a steady value when the light is changed. The most reproducible state of the cathode and the highest emission is obtained by exposing the cathode to a glow discharge for a few seconds; the higher values of the emission given in Table I refer to this state. Long-continued vigorous bombardment produces irreversible changes, which are probably due to the heat developed.

No evidence is available concerning the stability of cells sensitized by Olpin's process; but they probably resemble Elster-Geitel cells.

Thin film cathodes are also subject to all these sources of instability, except possibly the first. The cathodes with the highest emission are the least stable; for they contain the highly volatile caesium. The second source is very troublesome; for cells undergo irregular changes of emission (presumably associated with variation of atmospheric temperature) when they are put aside, and always undergo a rapid change in the few first minutes of use if the incident light carries any heat. The third source is also troublesome; in cells of type *C* (Fig. 11) it is not unusual to find that the emission from the apparently bare glass is of the same order as that from the supposed cathode. The effect of positive bombardment is usually an initial increase of emission followed by a decrease to below the original value. Long-continued bombardment always produces permanent damage.

Lastly, a characteristic of some cathodes that produces effects similar to instability should be noted. Though the

photoelectric emission of a cathode is independent of the temperature, the thermionic emission varies very rapidly with it. At the temperature at which cells are used, the thermionic emission from most cathodes is too small to be detected; but it can be detected from cathodes with very large λ_0, and especially from Cs–O–Ag. In cells with these cathodes the thermionic emission may become comparable with the photoelectric when the incident light is less than 10^{-6} lumen; since it varies very rapidly (though perfectly regularly) with the temperature, it is seriously disturbing where such very feeble lights are concerned.

REFERENCES

Since this chapter was written, an extremely valuable summary, covering the whole of its field, has appeared from G. Dejardin, *Rev. Gen. d'Elec.* 34, pp. 515, 555, 591, 629, 1933. It contains fuller references than are given here.

1. For characteristic of vacuum cells, see G. Dejardin, *loc. cit.*, p. 515, *et seq.*

2. For theory of threshold, see R. H. Fowler, *Phys. Rev.* 38, p. 45, 1931; L. A. DuBridge, *Phys. Rev.* 39, p. 108, 1932; also Hughes and DuBridge (*loc. cit.*), p. 241.

3. For general theory of selective and normal emission, see Hughes and DuBridge (*loc. cit.*). For the three particular theories mentioned, see—

(*a*) H. E. Ives and H. B. Briggs, *Phys. Rev.* 40, p. 802, 1932; H. E. Ives and T. C. Fry, *Journ. Opt. Soc. Amer.* 23, p. 73, 1933.

(*b*) I. Tamm and S. Schubin, *Zeit. f. Phys.* 68, p. 97, 1931; J. Frenkel, *Phys. Rev.* 38, p. 309, 1931.

(*c*) N. R. Campbell, *Photoelectric Cells and Their Applications* (Ed. J. S. Anderson, Physical and Optical Societies, 1930), p. 10; R. H. Fowler, *Proc. Roy. Soc. A.* 128, p. 123, 1930.

4. Data for plain metals are mainly derived from H. C. Rentschler, *Rev. Sci. Inst.* 3, p. 794, 1932. The curves for Na and Li come from H. de Lazlo, *Photoelectric Cells and Their Applications*, p. 222; and *Phil. Mag.* 13, p. 1171, 1932. The values for Na are in rough accord with H. Krefft and M. Pirani, *Zeit. f. Techn. Phys.* 14, p. 393, 1933, and with Olpin (below). The difficulty of reconciling the work of different observers and of giving absolute values may be gathered by comparing H. de Lazlo (*loc. cit.*) with G. Dejardin and R. Schweigler, *Comptes Rendus* 196, p. 1585, 1933; and with H. Bomke, *Ann. d. Phys.* 10, p. 579, 1931. For σ_{254} with Mg, De Lazlo gives 1330×10^{-5}, Dejardin and Schweigler give $4{\cdot}0$–$7{\cdot}9 \times 10^{-5} A$/watt. Again, while σ_{254} of Cd is generally thought to be greater than σ_{254} for Mg, Bomke gives $1{\cdot}7 \times 10^{-8}$ A/watt for Cd; but there may be a clerical error here, since his Fig. 8 and Table I do not agree. In

view of this hopeless confusion, we are unwilling to express any opinion.

5. Data for K–H from our own measurements (given in previous editions). Fig. 21 from A. R. Olpin, *Phys. Rev.* 36, p. 251, 1930. The theory of sensitization by hydrogen seems to be cleared up by P. J. Lukirsky, *Phys. Zeit. Sowjietunion* 4, p. 212, 1933. For other work on sensitization by oxygen, etc., see P. Selenyi, *Photoelectric Cells and Their Applications*, p. 39; W. Kluge, *Zeit. f. Phys.* 67, p. 497, 1931.

6. Data for Cs–Mg from V. Zworykin and E. D. Wilson, *Journ. Opt. Soc. Amer.* 19, p. 81, 1929. Other data for thin film from S. Asao, *Physics* 2, p. 12, 1932. See also W. Kluge, *Phys. Zeit.* 34, p. 115, 1933. T. W. Case, *Photoelectric Cells and Their Applications*, p. 49, gives data for a barium cell, which is doubtless thin film. These have not been included, although there is no reason to doubt them, because the cells have not come into general use.

For films on salts other than oxides, see J. H. Boer and M. C. Teves, *Zeit. f. Phys.* 65, p. 489, 1930.

For the theory of X–O–M cathodes, Hughes and DuBridge (*loc. cit.*), pp. 171–178, together with J. H. de Boer and M. C. Teves, *Zeit. f. Phys.* 83, p. 521, 1933, will serve as an introduction. For methods of making these and other cells, see references to Chapter X.

7. More data concerning the variation of Σ with T' are to be found in P. Selenyi (*loc. cit.*) under (5), and L. R. Koller, *Rev. Sci. Inst.* 3, p. 760, 1932.

8. For thermionic emission from Cs–O–Ag, see L. R. Koller, Phys. Rev. 33, p. 1082, 1929; N. R. Campbell, *Phil. Mag.* 12, p. 173, 1931.

CHAPTER III

THE GAS-FILLED CELL

Ionization by Collision. In a gas-filled cell the primary current, carried by the electrons emerging from the cathode under the influence of light, is magnified by causing them to ionize by collision some of the molecules of a gas through which they pass on their way to the anode. The ratio in which the current is increased by the presence of gas in the cell is now usually called the *gas amplification* factor or simply the *gas-factor*. In previous editions of this book, the term *magnification* was used, but it will now be abandoned. The gas used for this purpose is always one of the rare gases; for these exert no chemical action on the cathode, even when it consists of one of the highly reactive alkali metals; all other gases would change the photoelectric emission of such cathodes by mere contact with them. Of the rare gases, argon (usually containing a little nitrogen) is much the most widely used; its use will be implied when the contrary is not stated.

The collision between a slowly moving electron and a molecule of a gas is similar to that between elastic or partially elastic bodies; the electron may give some of its kinetic energy to the molecule, but the colliding bodies separate essentially unchanged. If, however, the electron is moving fast enough, the molecule may be broken by the collision; an electron may be detached from it, leaving a remainder which is a positively charged ion. The energy required to detach an electron from a molecule, or to *ionize* it, is a definite property of the molecule; when measured in electron volts, it is called the *ionization potential* of the gas; for all gases it lies between 10 and 25; for argon it is about 16. An electron cannot ionize unless it possesses a kinetic energy greater than the ionization potential; if it has a greater energy, it will ionize if it makes a very direct impact, but not if the impact is glancing; if it ionizes the molecule, it loses energy equal to the ionization potential. An electron that initially possesses an energy equal to n times the ionization potential can thus ionize n molecules, if it makes a

sufficient number of collisions of the right kind in passing through a gas. The ionization potential will be denoted by η.

When ionization has occurred, two electrons are present in the gas in place of one, namely, the original, primary electron, and the secondary electron ejected from the molecule. If the gas is placed in an electric field, both electrons will move to the anode, while the positive ion moves to the cathode. The anode receives a negative charge equal to twice that on an electron; the cathode receives an equal and opposite charge, represented by the charge on the primary electron that it loses and that on the positive ion that it gains. If each electron ionizes n times in passing through the gas, the current through it should be $(n + 1)$ times that carried by the primary electrons. Actually this is not quite true generally, because an electron may disappear again before it reaches the anode by encounter with a positive ion, produced by some other electron; it may *recombine* with this ion and form a neutral molecule again. But we shall leave recombination out of account through most of our discussion.

So far we have left out of consideration the source of the energy of the ionizing electron. If the quantum energy of the radiation is sufficient, electrons liberated by the photoelectric effect may start from the cathode with an energy many times the ionization potential of the gas into which they emerge; if they make sufficient collisions, each may produce many ions; and, so long as the electric field is great enough to drag the ions and electrons to the electrodes, the primary current may be magnified many times. This state of affairs, in which the magnification is independent within wide limits of the voltage between anode and cathode, is found in the ionization chambers used for measuring X-rays, of which the quantum energy is several thousand volts; such chambers are essentially gas-filled photoelectric cells. But this term is usually restricted to devices for detecting light in the visible and nearer ultra-violet region of the spectrum, where the quantum energy is less than the ionization potential of any gas, and no primary electron can ionize on its own account. In such cells ionization by collision is induced by causing the primary electrons to pass through a strong electric field, and thus to acquire the requisite energy.

Gas Factor—Pressure and Voltage. In order to investigate this process, something must be known about collisions that do not result in ionization. We shall assume that an electron loses all its energy when it collides and fails to ionize; the assumption is not correct, but it leads to nearly the right result. Accordingly, if the electrons are to acquire the energy necessary to ionize by travelling through the gas in an electric field, they must acquire it between successive collisions. If the electrodes are planes between which is a distance d and a difference of potential E, and if λ is the free path of the electrons between collisions, the energy acquired during the free path is $E\lambda/d$; in order that there may be ionization, $E\lambda/d$ must be greater than η. If all free paths were equal the further investigation would be very simple; n, the number of collisions, would be given by

$$n = d/\lambda \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

n', the number of ionizing collisions would be n or zero, according as $E\lambda/d >$ or $< \eta$. At each ionizing collision the number of electrons travelling to the anode is doubled; consequently, if N_0 start from the cathode, N would arrive at the anode, where

$$N = N_0 \cdot 2^{n'} \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

N/N_0 is the gas factor; it increases rapidly with n'.

Actually λ is not the same for all collisions, but varies fortuitously about a mean. This mean λ in any given gas is inversely proportional to the density or, if the temperature is constant, to the pressure p. Hence we may write

$$p\lambda = \lambda_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

When the variation of λ is taken into account, we have in place of (11)

$$N = N_0 \cdot e^{n'} \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

where $e = 2{\cdot}713$. The proportion of collisions at which ionization occurs is still determined by the value of $E\lambda/d$, so that we may write

$$n'/n = f(E\lambda_0/pd) \quad . \quad . \quad . \quad . \quad . \quad (14)$$

the function f increases with the argument $E\lambda_0/pd$.

n is still given by (10), so that

$$n' = \frac{pd}{\lambda_0} f(E\lambda_0/pd) \quad . \quad . \quad . \quad . \quad . \quad (15)$$

From (13) and (15) n', and therefore the gas factor, increases with E if pd is constant. If E is constant, there is a value of pd for which n' is a maximum; this maximum increases with E. If pd is less than the value corresponding to the maximum, n' falls off because the total number of collisions is too small; if it is greater, n' falls off because the proportion of collisions resulting in ionization is too small. The value of pd for maximum n' is determined, as in the simple theory, by $E\lambda_0/\eta$, and is actually of the same order of magnitude as that quantity. For example, in argon at room temperature λ_0 is about 0·045 (when p is in mm.), and η is about 16 volts; consequently, if the plane electrodes are 1 cm. apart, and E is 200 volts, the optimum value of p should be about $200 \times 0{\cdot}045/16$, or about $\frac{1}{2}$ mm.

(15) is still true if the electrodes are not parallel planes, so long as geometrical similarity is preserved when d is changed, though the function f will be different. Thus, with another f, (15) would be true if the electrodes were concentric spheres with a constant ratio between their diameters, and d were the diameter of either of them; for instance, it would still be true that variations of p and d do not change n' so long as pd is constant. But this would not necessarily be true if the diameter of one of the spheres were constant, while d, the diameter of the other, varied. Again, λ_0, and η (which is involved in the function f) depend on the nature of the gas; (15) tells us nothing of how n' varies from one gas to another, unless the forms of f for the two gases are specified. Nevertheless, though the range of (15) is limited, it is useful in tracing the rather complicated variations of n' with all the possibly variable factors.

It is especially useful when only p and E vary. Fig. 25 shows some illustrations based on actual measurements for this case; the cell is spherical with a diameter of 6 cm. and has a small central anode; the active metal is sensitized potassium, and the gas argon. N/N_0 is plotted against E for various values of p; the curves are the *voltage characteristics* of the cell at different pressures of gas, for an illumination which would give a saturation current represented by 1. As the theory predicts, each curve rises continually with E; but the curves cross each other and, as E increases, the gas factor at higher pressures increases relatively to that

at lower pressures. Thus at $E = 100$ volts, $p = 0{\cdot}08$ mm. gives higher gas factor than $p = 2{\cdot}3$ mm.; but at $E = 140$ volts, $p = 2{\cdot}3$ mm. is better.

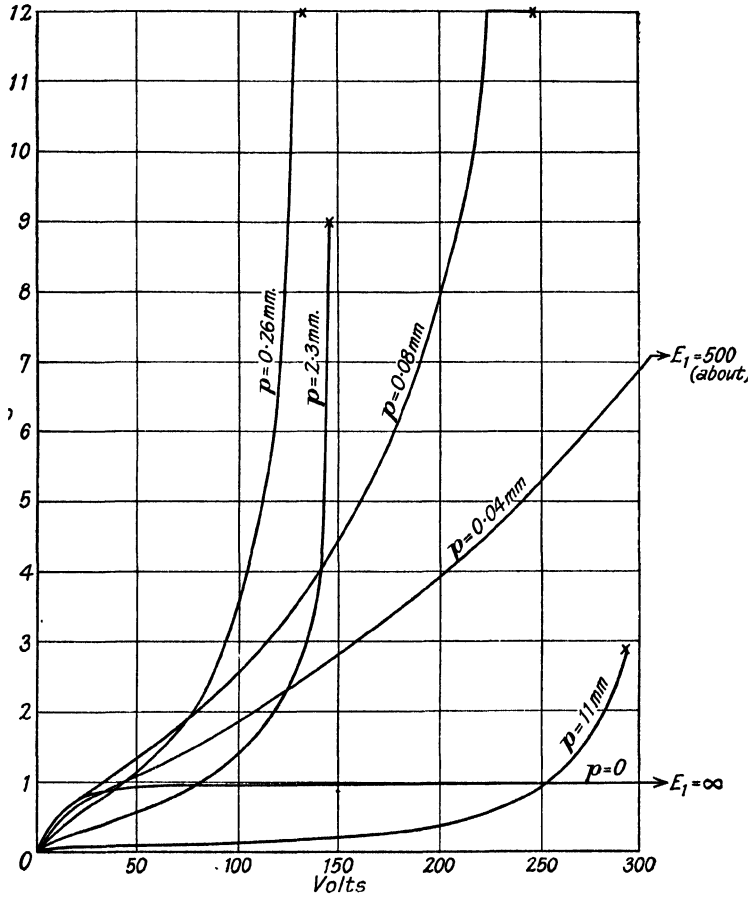


FIG. 25. RELATION BETWEEN GAS FACTOR AND VOLTAGE AT VARIOUS GAS PRESSURES

The Glow Discharge. But now we have to deal with an important consideration outside this simple theory, which affects very greatly conclusions about the optimum pressure. According to (15) and (13), the gas factor ought to

increase indefinitely with E, and any gas factors, however large, ought to be attainable if sufficiently large potentials are available. Actually a limit is set to E by the influence of the positive ions, which have been left wholly out of account. They affect the current in two ways. First they cause the liberation of electrons from the cathode independently of the photoelectric emission; second, their presence in the neighbourhood of the cathode increases the electric field there, by reason of the charge that they carry. (The electrons similarly increase the field in the neighbourhood of the anode, but their influence is less important.) These two effects are closely related. It is still doubtful exactly how the positive ions liberate electrons at the cathode, whether by direct impact or by some indirect process; but it is certain that they do liberate them, and that the liberation is connected with the increased field due to the positive "space charge"; the greater the number of positive ions arriving at the cathode, the greater is the chance that each of them will liberate an electron additional to those liberated by the light. Accordingly, when once the action of the positive ions starts, it is cumulative and reinforces itself. As E is increased, and with it the number of positive ions, a stage is reached at which the current increases much more rapidly than it would according to (15); and, finally, a second stage in which the positive ions, produced by the collisions of the primary photoelectrically liberated electrons, in their turn, produce at the cathode secondary electrons as numerous as the primaries. When this second stage is reached, the current will continue to flow even when the light is turned off, for the liberation of the primaries is no longer necessary to its continuance; its magnitude will be determined not by the supply of electrons from the cathode, but by the disappearance of electrons and positive ions by recombination in the gas and at the walls of the vessel.

This condition is accompanied by a visible glow in the gas; it represents the *glow discharge*, which can be started in any gas at low pressure (such as that in a neon glow lamp) by the application of a sufficient field. When it occurs, the current through the cell no longer varies (or varies considerably) with the illumination; the cell is no longer a photoelectric cell. The highest potential that can be applied

usefully to a photoelectric cell is the *glow potential*, E_1, at which the glow starts and the current, increasing suddenly, becomes independent of the illumination; the useful part of the characteristic terminates at this point.

In Fig. 25 these terminations are marked by crosses ($\times$) when they lie within the limit of the diagram; when they do not, the voltage E_1 at which they occur is marked by a cross joined to the curve by an arrow. It will be seen that E_1 varies with the pressure; the manner of its variation is shown in Fig. 26, which refers to the same cell. In a cell of any other form, the curve would be very similar; it always has a flat minimum and a very rapid rise at lower pressures. The minimum value of E_1 depends both upon the nature of the gas and of the cathode, but is very nearly independent of the arrangement of the electrodes.

The existence of the glow potential complicates greatly the choice of the optimum pressure for a given E, for which n' is a maximum. The choice indicated by (15) is valid only if at the pressure so indicated E is less than E_1. Thus, in Fig. 25, if the curves continued indefinitely on the course indicated by (15), $p = 2{\cdot}3$ would be preferable to $p = 0{\cdot}08$ at all values of E above that at which the curves cross. Actually the characteristic for $p = 2{\cdot}3$ terminates at its glow potential at $E = 145$; for higher values it does not exist for photoelectric purposes, and, therefore, $p = 0{\cdot}08$ becomes preferable once more, and when E is 215 gives a gas factor higher than any which can be obtained with $p = 2{\cdot}3$.

Some other facts about the glow potential may be recorded here for future reference. If the glow discharge is started by raising E above E_1, and E is then reduced, the glow discharge does not stop when E_1 is reached again; the change is not completely reversible. In order to stop the glow, E has to be reduced to a considerably lower value E_2, the *stopping potential*. E_2 varies with the gas and the cathode and the pressure in much the same way as E_1, having a minimum at about the same pressure. Again, E_1 and E_2 are not perfectly constant; E_1 is usually higher when the cell has stood for some time without a discharge passing than it is just after a discharge has passed; but even if an attempt is made to reproduce the condition of the cell by

a series of discharges before measurements are made, appreciable variations will be found on different occasions. E_2 is less variable than E_1, but is still not absolutely constant.

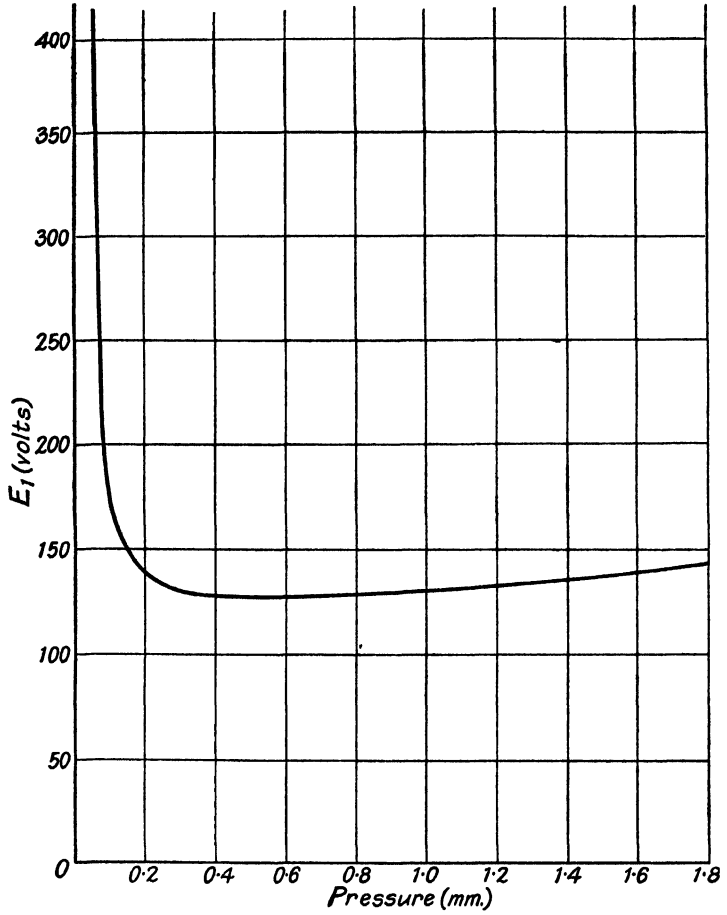


FIG. 26. VARIATION OF GLOW POTENTIAL WITH GAS PRESSURE

These variations in E_1, E_2, and in the part of the characteristic immediately below E_1 are due to changes in the condition of the cathode, and are associated with variations in the photoelectric sensitivity, which were discussed

in Chapter II (page 49); but they are not sufficient to affect the general truth of the statements made here.

Finally, the preceding paragraphs have implied that, in the absence of light, there is no current through the gas in a gas-filled cell at any voltage below the glow potential. This is, unfortunately, not strictly true. Even in the complete absence of light and of measurable thermionic emission (see page 51), there is usually a small "dark current" at voltages just below the glow potential, which is very troublesome when small amounts of light have to be measured. Its origin is obscure and its amount very variable. (See further, page 174.)

Change of the Gas Factor with Illumination. So far it has been assumed tacitly that the characteristic of the cell, and the gas factor N/N_0 obtained at any pressure and potential, are independent of the illumination. This assumption is not true; the true facts are shown in Fig. 27, which refers to a cell in which the anode and cathode are nearly parallel planes and not to the spherical cell of Fig. 25. The general nature of the changes introduced by varying the illumination are the same in all types of cell; but they are easier to investigate completely in the plane cell.

In Fig. 27 the various curves are voltage characteristics similar to those of Fig. 25; but for convenience the ordinates represent the logarithms of the current i, not the current simply. Each curve refers to a different illumination, L, the relative value of which is marked against it. If the characteristic were independent of the illumination, the ratio of the currents for two values of L, or the difference in log i, would be the same at all values of E; the curves would be equi-distant through their course, and would differ only in being displaced parallel to the axis of log i; they would all terminate at the same E_1, that is to say, on the same vertical line. Actually, they are equi-distant only in the lower part of their course, most of which is omitted from the diagram because it is uninteresting; the characteristic is independent of the illumination only if E is greatly below the glow potential.

At the larger values of E, varying illumination produces changes of two kinds. The first, important at the lower illuminations, is a decrease of the glow potential with

increasing illumination. The terminations of the curves lie on a regular curve (the thick line) which cuts off the curve earlier the greater the illumination. Since the curves become steeper as they proceed, this means that the maximum gas factor obtainable and the steepness of the curve just

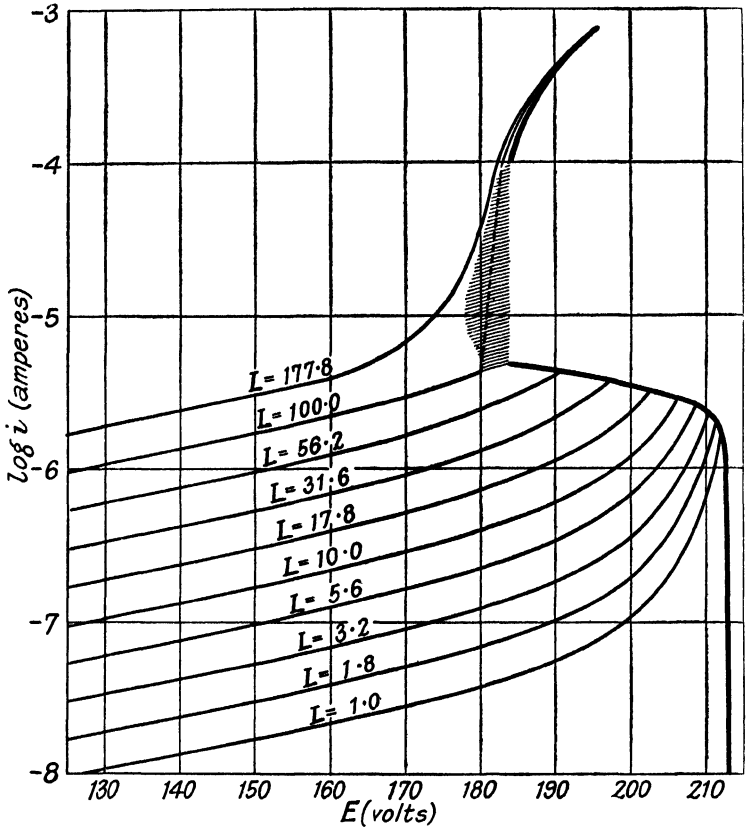


FIG. 27. VOLTAGE CHARACTERISTICS AT VARIOUS ILLUMINATIONS

before it terminates are less the greater the illumination. Although a greater current N is always obtainable from a greater emission N_0, the maximum ratio N/N_0 decreases as the illumination increases. Our knowledge of the exact circumstances that determine the glow potential is not complete enough for a detailed explanation of these changes to

be given. But the cause must doubtless be sought in the action of the positive ions at the cathode. Since their effect is cumulative and not merely proportional to their number, the current must cease to be simply proportional to the illumination at potentials so high that their action is important.

The second change appears at the higher illuminations. The thick line, which represents how E_1 varies with the illumination, ends on the left; but there is a least value below which E_1 cannot fall, however great is the illumination. This minimum E_1 is actually E_2, the *stopping potential*; E_2 is independent of the illumination; the termination of the thick line means that the glow cannot ever start at a potential less than that at which it would stop in the unilluminated cell. If the illumination is so great that, before E_2 is reached, the current flowing through the cell is already comparable with that carried by the glow discharge, then it is not to be expected that the attainment of potentials at which the glow would start at lower illuminations should produce the sudden increase of current characteristic of the starting of the glow. For such high illuminations there is no glow potential or stopping potential in the usual sense; there is gradual transition from the conditions of no glow to those of the glow; as the potential is increased, a stage is reached at which the current does not fall to zero, or even decrease appreciably, when the light is removed; the cell is now insensitive to light, and the passage to the glow discharge is complete. This stage is indicated in Fig. 27 by the point at which the characteristic merges into the upper thick line, which represents the relation between voltage and current in the glow discharge.

The two thick lines form together a "limiting curve" which divides the area of the diagram into two parts, that to the left, which represents combinations of voltage and current that can exist if the illumination is appropriate, and that to the right, which represents combinations that cannot exist at all. When a characteristic meets any point of the limiting curve, the cell changes from a state sensitive to light to a state insensitive; the lower part of the limiting curve represents unstable states and, when a characteristic meets this part, the cell immediately flies over to the

upper part which represents the stable glow discharge. The characteristics fall into two classes according as they terminate on the upper or lower part of the limiting curve, and there is a critical illumination which divides the two classes. Actually, the critical illumination cannot be determined precisely, because in this neighbourhood measurements are irregular; in the area shaded in the figure no consistent measurements at all can be made, but comparatively narrow limits between which it must lie can be found. There is no indication of any part of the limiting curve between the two portions shown.

The illumination affects the characteristic in two other ways of minor importance, which are not shown in Fig. 27. At very large illuminations the space charge due to the photoelectrically liberated electrons has the same effect as in the vacuum cell (page 25), but more markedly; the characteristic rises less steeply at very low voltages. Again, the wavelength of the light is said to have some influence; but there is a difference between different observers concerning the magnitude and even the sign of the influence. Our own experiments disclose no effect of the frequency comparable with that of the intensity of the illumination; and since illuminations of the same intensity but different frequencies have seldom to be compared, any variations in the characteristic due to change in frequency will usually be masked completely by variations due to change in intensity.

Again an influence of the distribution of the light might be anticipated. If the light is concentrated on one small part of the surface and the rest is dark, it might be expected that this part alone would be effective, and that the shape of the characteristic would be that appropriate to high illuminations; while if the same light is spread uniformly over the whole surface, the form would be that appropriate to low illuminations. But this expectation is falsified; in cells of normal construction the form of the characteristic is determined almost entirely by the total light entering the cell, whether it is concentrated or diffused; if there is any effect of distribution, it is masked by changes due to the lack of uniformity of the sensitive surface (page 33). The reason is that the variations in the form of the characteristic are

due to the actions of the positive ions. The positive ions do not return to the part of the cathode whence came the electrons that produced them, but are distributed almost uniformly, even if the source of the electrons is concentrated in one spot. The distribution of the light does not determine the distribution of the positive ions or, therefore, the form of the characteristic. On the other hand, in very large cells with light distributed very unequally, some effect of the distribution may be appreciable.

Particular Cells. Nothing has been said so far in this chapter about the nature of the cathode. According to the original theory of Townsend, on which our discussion has been based, this should be immaterial, until the voltage applied becomes very near the glow potential; the main part of the voltage characteristic should be determined wholly by the geometrical form of the electrodes and the nature and pressure of the gas. But the facts fail entirely to accord with this expectation, as is shown in Fig. 28, where the characteristics are given of two cells, both with electrodes of the same form, filled with argon to the same pressure and with the same primary photoelectric emission, but one having an Elster-Geitel cathode of sensitized potassium, the other a thin film Cs–O–Ag cathode. The same emission corresponds, of course, to a much smaller amount of light received by the cell with the latter cathode. The characteristic with the latter cathode is steeper throughout and terminates at a much lower glow potential.

The difference is due to the much greater number of secondary electrons emitted from the thin film cathode when the ionization of the gas is the same. The result in practice is that a cell with a thin film cathode cannot be used except with quite moderate gas factors—10 is about the limit; gas factors of 50 or more, possible with the less sensitive potassium cathode, are out of the question; even if they are ideally obtainable, the characteristic is so steep that they are useless. Accordingly, in gas-filled cells, the gain in sensitivity arising from the substitution of a thin film for a potassium cathode is much less than in vacuum cells. But at the same time the complications that we have been discussing vanish; gas-filled cells with very sensitive cathodes can only be used in the region where the gas factor

is nearly constant and the current very nearly proportional to the light.

The facts displayed in Fig. 27 are therefore much less important than they were a few years ago, when only cathodes of the old type were available. Nevertheless, since the older cathodes are still sometimes used, a little more

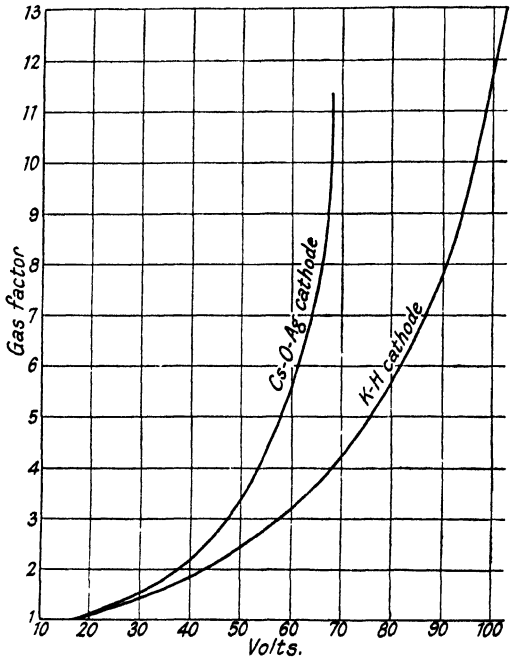


FIG. 28. CHARACTERISTICS OF SIMILAR GAS-FILLED CELLS HAVING DIFFERENT CATHODES

must be said about them. Though the facts are qualitatively true of all cells, they vary quantitatively with the form of the electrodes. The chief types to be distinguished are those in which cathode and anode are of about the same size (e.g. type *A*, Fig. 11), and those in which the cathode is much larger than the anode (e.g. type *B* and *C*, Fig. 11). Fig. 27 refers to the former type; in the latter type the difference between the glow and stopping potentials is much greater, and so is the interval between the upper and lower

parts of the limiting curve; the approximately horizontal part of the lower limiting curve covers a much larger voltage range and the upper curve is outside the range of practically useful illuminations. The practical result is that the type with small anode is preferable for small illuminations; but if the illumination is so large that the upper limiting curve is attainable in the type with equal anode and cathode that type can give a much larger gas factor.

A form of cell introduced by Dunoyer needs special mention here. It is hemispherical, the cathode lying on the curved surface, while the flat surface is almost plane and of bare glass with a rod anode close to it. The charges developed on the plane glass surface near the anode affect the characteristic greatly. The lower and upper parts of the limiting curve are no longer separated by a region of instability; even at moderate illuminations, stable gas factors of several hundred can be obtained by applying potentials exceeding the nominal glow potential. The relation between current and illumination in this region is not even approximately linear, and its use is therefore not suitable for any kind of measurement; but if the illumination is of a suitable strength and the largest possible response to it is desired, these cells may be useful. However, they have not come into general use.

The Gas-filled Cell in Practice. The facts have been expressed so far in a way that brings out the principles underlying them. For practical purposes, it is sometimes better to express them in another way. In Fig. 29 the currents through the cell to which Fig. 27 refers are plotted against the primary photoelectric emission. The abscissae are thus proportional to the quantity of light entering the cell, and the ratio of the ordinates to the abscissae is the gas factor; when the curves are straight lines, the gas factor is constant and the current is proportional to the light. The different curves refer to the voltages on the cell marked against them; they terminate (if at all) on the dotted line, which represents in another form the lower part of the limiting curve of Fig. 27. The numerals marked against the terminations are the maximum gas factors.

The curves illustrate again some facts already noted. If it is necessary that the current should be proportional to

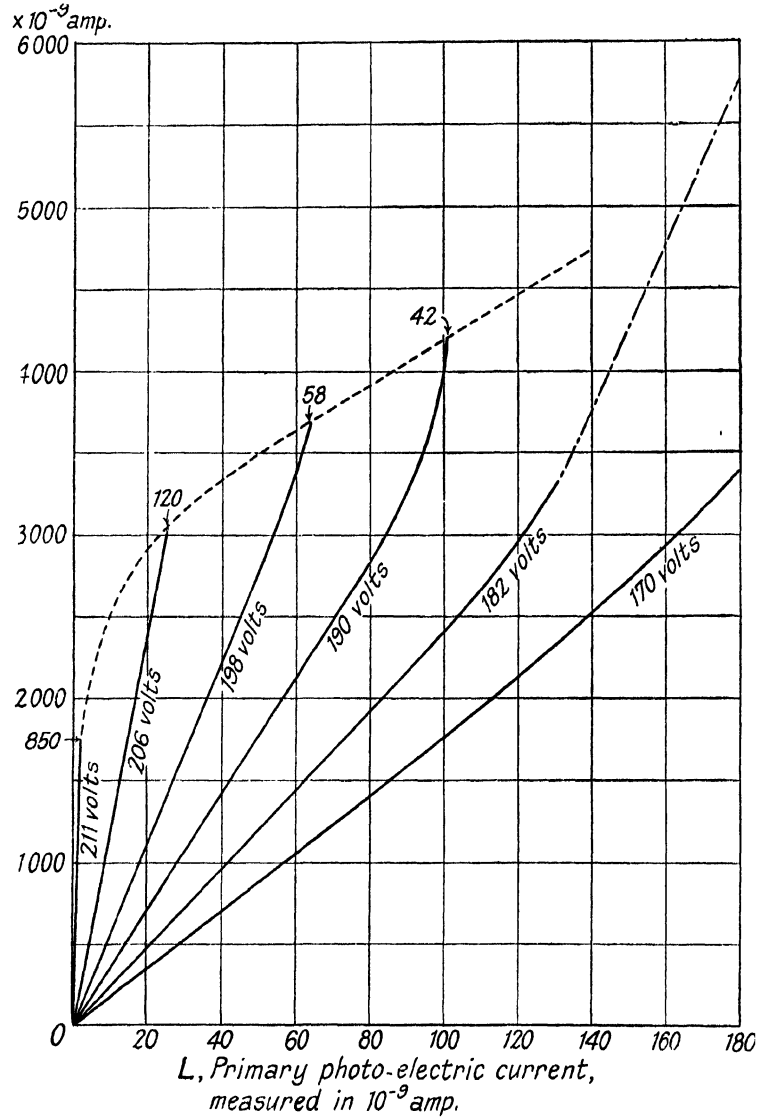


FIG 29. VARIATION OF CURRENT WITH ILLUMINATION AT VARIOUS VOLTAGES

the light, only the straight part of the curves of Fig. 27 must be used; either feeble lights must be used or, with stronger lights, low voltages. The limit at which marked deviation from proportionality occurs is fixed by the current rather than by the light; for all lights it lies between 2 and 3 microamps. Again, if proportionality is not demanded, and the object is to obtain the greatest current from a given light, the maximum current, limited by the glow potential, does not increase nearly so rapidly as the light; over most of the range of Fig. 29 the maximum gas factor attainable increases as the light decreases, and the maximum current is more nearly independent of the light than proportional to it.

The Characteristic Conductivity. Further, we have assumed that the voltage across the cell, when once adjusted, remains independent of the current passing through it. This assumption is never accurately true. For there is always some resistance in the circuit exterior to the cell; if a constant voltage is applied to the circuit as a whole, that applied to the cell will fall as the voltage drop in the exterior resistance increases with the current. If the exterior resistance is merely that required to protect the cell from damage, i.e. about 10,000 ohms, the variation of the voltage across the cell with the current will be generally inappreciable; but in certain methods of using cells much larger resistances than this are employed, and their effect is very important.

If the illumination of the cell is constant and the voltage across it is varied, a small change in voltage dE will produce a proportional small change in current di. Accordingly, for small changes of voltage the cell behaves as if it were an ohmic conductor with resistance $r = \frac{dE}{di}$, and conductivity $\Gamma = \frac{di}{dE}$. When the illumination varies, but the voltage about which the small changes occur is constant, Γ is proportional to i; hence if we write

$$\gamma = \Gamma/i = \frac{1}{i} \cdot \frac{di}{dE} \quad . \quad . \quad . \quad (16)$$

γ (which is called the characteristic conductivity) is nearly independent of the illumination, and a function only of the voltage; it is the relative increase in gas factor due to

an increase of 1 volt in the voltage, so that if the current through the cell increases by x per cent when the voltage is increased by 1 volt, then $\gamma = x/100$.

Because of the characteristic conductivity, the current is not proportional to the illumination when there is much exterior resistance, even if the cell works on a part of the characteristic where there would be proportionality if the applied voltage were constant. Let i_0 be the illumination, measured by the primary photoelectric current, g the gas factor at the voltage E, R the exterior resistance. Then i, the current in the circuit, is given by

$$i = i_0 g(1 - \gamma R i) \quad . \quad . \quad . \quad (17)$$

If we are measuring the current by the voltage drop e in the exterior resistance, then the appropriate formula is

$$e = i_0 g R(1 - \gamma e) \quad . \quad . \quad . \quad (18)$$

In each case the expression in brackets is a correcting factor determined by the characteristic conductivity of the cell. Some idea of its magnitude should be given. If the cell is working on a part of its characteristic far from the glow potential, γ will be of the order of 0·02; if it is working near the glow potential it may be as high as 0·1. Accordingly, if an error of 1 per cent is important, the drop across the exterior resistance must not exceed 0·5 volt in the first case, or 0·1 volt in the second. If the exterior resistance is only 10,000 ohms, the error will not enter until the current is 10μA. In a vacuum cell γ need not be greater than 0·001, and the effect of the characteristic conductivity is always negligible.

γ (which in this connection is usually termed the *slope* of the characteristic) determines in other ways the largest gas factor that can be used; for, when it is large, the steep part of the characteristic is being approached and the complications that we have considered before are likely to enter. The question arises therefore how the highest permissible gas factor and anode voltage are to be determined in any particular instance. Rules for adjusting the voltage to give the utmost sensitivity were given in previous editions, but they will be omitted here. The maker of a cell now usually indicates the best voltage; when he does not, or the circumstances are exceptional, the principles that have been discussed must be invoked.

Time-lag. The interval between the incidence of light on the cathode of an emission cell and the emergence of the corresponding quota of electrons is certainly less than 10^{-8} sec.; there are theoretical grounds for believing that it is literally immeasurable. That does not mean that from a vacuum cell the current reproduces accurately the variations of the light, however rapid they may be; for, in order to produce a current or any external effect, the electrons have to cross the space between the electrodes and then charge to a finite potential difference the condenser formed by the two electrodes of the cell and by any conductors connected to them. The time required for crossing never exceeds 10^{-6} sec. in practical conditions; any apparent *time-lag* in response is due wholly to presence of the condenser and can be reduced without limit by reducing its capacity.

On the other hand, in a gas-filled cell there may be a true lag of current behind light; when the cell is exposed to rapidly varying light the current does not reproduce accurately the variations. This lag is of the greatest importance in the use of cells for picture-telegraphy, for the reproduction of talking films, and, above all, for television. Here it appears in the guise of an effective sensitivity, decreasing as the frequency of the light variations is increased, which is usually displayed by *frequency response* curves. These are taken by interrupting the light incident on the cell by a rotating disc pierced with holes, the holes being formed so that the light varies harmonically about its mean with frequency n; i_n, the amplitude of the alternating component of the photoelectric current, is measured after amplification by a valve voltmeter. If there were no time-lag, i_n would be the same at all frequencies, so long as the amount of light and the sensitivity of the cell were unaltered. Actually i_n decreases against n in gas-filled cells; the change can be shown, independently of the amount of the light and the sensitivity of the cell, by plotting i_n/i_0 against n, where i_0 is the value of i_n for very low frequencies.

Typical frequency response curves obtained in this manner are shown in Figs. 30 and 31. Fig. 30 refers to the same cell (of the type of No. 2 in Fig. 31) with different anode voltages and therefore different gas factors G. It shows how much greater is the fall in sensitivity at the higher gas

factors. For the same light, i_n is always greater at the larger gas factor; but the gain in sensitivity due to the gas factor (that is to say, the effective gas factor) is reduced at the higher frequencies in the ratio i_n/i_0. At higher frequencies than those shown, the gain due to gas-filling becomes almost negligible.

Fig. 31 shows how greatly the fall in sensitivity due to

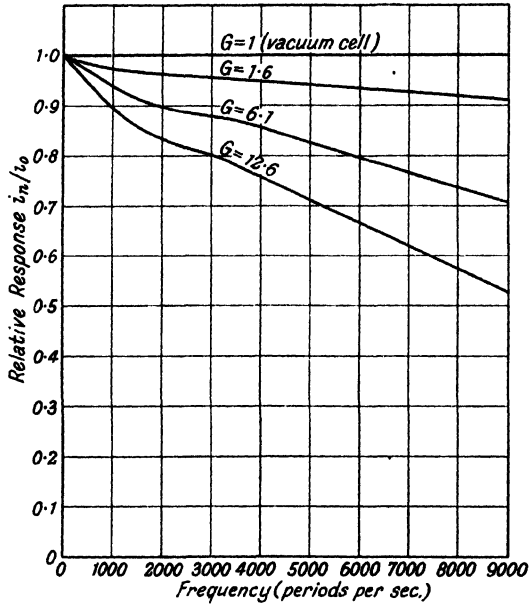


FIG. 30. FREQUENCY RESPONSE CURVES

time-lag may vary from cell to cell. The cells are here tested at the gas factors at which they would probably be used; it will be seen at once that reduction to the same gas factor would exaggerate rather than remove the differences. Curve (1), showing small time-lag, refers to a cell with K–H cathode-on-wall (type *C*, Fig. 11) and argon filling; curve (2) to a cell with Cs–O–Ag cathode-in-centre (type *B*, Fig. 11) filled with argon; curve (3) to a cell with Cs–O–Ag cathode-on-wall filled with helium. The curves illustrate the general rule that, at the same gas factor, the time-lag is greater with cathodes of greater emission to light of long

wavelength and with helium as compared with argon as the filling gas. It appears also that the geometrical form of the cell has some effect; the time-lag is smaller in the smaller cell, and is generally less with cathode-in-the-centre than with cathode-on-wall.

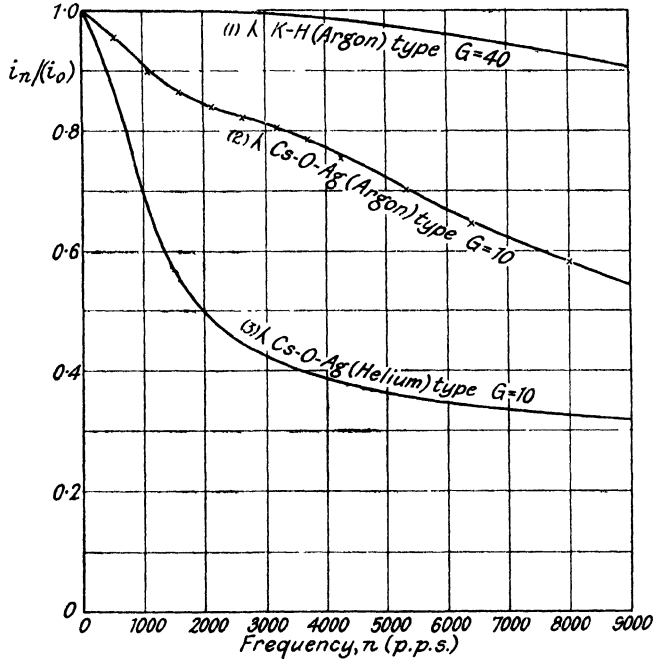


FIG. 31. TIME LAG IN VARIOUS EMISSION CELLS

The precise nature and cause of this time-lag is still uncertain. One way to investigate it is to throw light suddenly on the cell, maintain it constant until the current reaches a steady value and then turn it off suddenly, following the changes of the current meanwhile, for instance, with an oscillograph. In Fig. 32 the course of the light changes is shown by the dotted line, that of the current by the full line. The current rises suddenly to the value OP, increases gradually in a finite time t to the value O_1Q (which is the steady current corresponding to the steady light), falls suddenly to O_1R when the light is turned off and then gradually

decays to zero. The *effective time-lag*, that is to say, the extent to which time-lag distorts the ideal relation between light and current, is roughly measured by the ratio of the area PNQ to the area $ONQO_1$. It thus increases both with the ratio PN/ON and with the time OO_1, that is to say, both with the fraction of the current subject to lag and with the lag to which it is subject.

The gradual rise from OP to O_1Q is exactly similar to the gradual fall from QR to zero, so that the area PNQ is exactly equal to the area RO_1X. Consequently the total quantity of electricity passing through the cell is the same

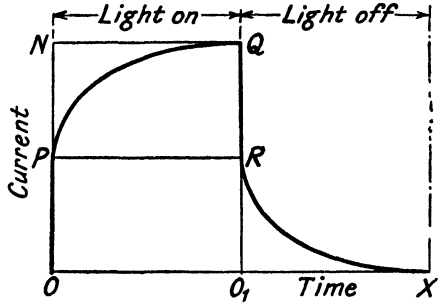


FIG. 32. TIME LAG IN GAS-FILLED EMISSION CELL

as would have passed if there had been no lag at starting and stopping, and if the current had followed the course $ONQO_1$. This is very important; for it implies that the mean current from the cell is independent of the frequency of interruption of the light. If light is thrown on a cell through holes in a rotating disc and the current measured by a sluggish galvanometer, then the steady reading of the galvanometer is completely independent of the speed of rotation of the disc. Again, it appears that the increase in time-lag when the voltage on the cell and therefore the gas factor are increased, as shown in Fig. 30, is not due entirely to an increase in the fraction of the current subject to time-lag, i.e. to an increase in PN/ON; some at least of it is due to increase in the lag OO_1.

The simplest explanation of these facts is that the lag represents the time required for the positive ions to reach their final destination at the cathode. The positive ions

move much more slowly than the electrons in a given electric field; owing merely to its greater mass an argon atom takes 270 times as long as an electron to travel a corresponding distance in a vacuum; in a gas the difference is still greater owing to its greater size and more frequent collisions with molecules. Accordingly, though the time that the current takes to cross the cell may be inappreciable when it is carried by electrons, it may be appreciable when the current is carried by positive ions. The greater effective time-lag with thin-film cathodes would then be due to the greater importance of secondary emission at the cathode. A secondary electron is not emitted until the positive ion arrives at the cathode; it then starts and may produce more positive ions which have to reach the cathode and may excite further secondary electrons—and so on. The current may not be finally steady until positive ions have traversed the cell several times.

There must be some time-lag arising in this way, and perhaps it is a large fraction of the whole in cells which show comparatively little lag when the light is varied with low frequencies. But it can hardly explain a large lag at frequencies below 1,000 p.p.s., such as some thin-film cells display; nor can it explain why the lag in helium should be greater than that in argon; for the helium ions move faster than the argon ions. This difference between helium and argon is generally (and doubtless rightly) attributed to the greater facility with which *metastable atoms* form in helium. A metastable atom is one in which an electron has been displaced by a collision (or by radiation) without being ejected; it is uncharged and can exist for a long time without change; but if it comes near the cathode it will return to the normal state by giving up its excess energy, acquired at the collision, to an electron of the metal, which may then emerge. The presence of such metastable atoms, unaffected by the field, but diffusing to the cathode at which they produce secondary emission, clearly explain the existence of a time-lag. Nevertheless it is still difficult to understand all the quantitative relations that have been discovered and, in particular, the increase of the lag (as distinct from the proportion of the current affected by lag) with increase of voltage.

Other causes of time-lag have been suggested; for

instance, an actual delay in the discharge of an ion when it arrives at the cathode or a delay between collision and ionization (especially by positive ions). But there seems no positive evidence in their favour. Some theories proposed are inconsistent with the facts recorded under (2) above; if the total quantity of electricity that passes is independent of the frequency of interruption of the light, there can be no interaction between the effects of light incident at different times; the time-lag must arise in the process following the emission of a single electron, not from the interaction of different primary electrons or of their products. However, more work is needed; the subject has not received the attention that its theoretical interest and practical importance demand.

Secondary Emission Cells. Finally, mention must be made of a proposal for obtaining some of the advantages of gas-filling without its disadvantages. Secondary electrical emission is produced, not only by the impact of positive ions, but also by the impact of electrons. When electrons bombard a metal surface (which need not be of low work-function, but may be an ordinary metal such as nickel), the number of secondary electrons emitted may be three or four times as great as the number of primaries. This fact is of great importance in thermionic valves. Suppose, then, that we cause the photoelectric electrons to bombard a metal surface with an appropriate velocity, which will correspond to a few hundred volts; and that we measure the secondary electrons emitted. Then we shall obtain a magnification of the primary current, similar to that produced by a gas factor. It will be smaller; but the current should be always proportional to the light and free from time-lag. The method has not yet been fully proved, but has to be borne in mind.

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2. For effect of cathode on characteristic, see K. H. Kingdon and H. E. Thomson, *Physics* 1, p. 343, 1931.

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CHAPTER IV

RECTIFIER CELLS

Fundamental Properties. According to the theory of Chapter I, there is an essential similarity between rectifier and emission cells. In both cases the effect of the light is to cause electrons to cross a boundary at a rate which, for light of given quality, is proportional to the intensity of the light. The only difference is that in the emission cell the electrons, having crossed the boundary, cannot return across it under the action of an electric field, while in the rectifier cell they can return; in the emission cells the boundary is a complete insulator, in the rectifier cell it is a conductor. It appears therefore that, for many purposes, it should be possible to represent a rectifier cell as an emission cell P, shunted by a conductor of finite resistance R (Fig. 33), and to express its properties in terms of the properties of the equivalent emission cell and of the value of R.

This is indeed the fact; our discussion will be based on this equivalence. But first the introduction of the external circuit of resistance r containing the indicating instrument G requires some consideration. For the cell consists of a boundary between two different materials, the semi-conductor (S) and the metal (M); if these are joined by an external circuit, there must be somewhere in it another boundary between S and M across which the current flows in the opposite direction. If the two boundaries were similar and were equally illuminated, each would counteract the effect of the other and no resultant photoelectric current would flow. This difficulty might be avoided by illuminating only one boundary; but that is not the solution adopted in practice. We have called rectifier cells by that name, because they are also rectifiers. A circuit with two similar boundaries can never rectify; rectification is essentially a property of circuits containing two dissimilar boundaries.

Our theory indicates how boundaries may be dissimilar; they may differ in the width of the gap separating S and M. It has already been recorded that this width influences the

degree of rectification; and it is not difficult to see that, if the width vanishes entirely and nothing intervenes between S and M, the boundary can have none of the properties we discussed. In the absence of light and potential difference, the potentials of S and M always have to set themselves so that states of the same energy on either side of the boundary contain equal numbers of electrons, so that the flow in both directions is the same. If there is no gap and therefore no obstacle to electrons passing across the boundary, nothing can disturb this equality; any cause tending to disturb it will immediately be neutralized by the movement of electrons. Rectification and also a photoelectric effect demand

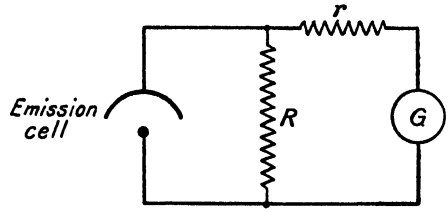


FIG. 33. EQUIVALENT OF RECTIFIER CELL

that the resistance R in Fig. 33 should be finite and not zero. It is not quite so easy to see why rectification should vanish at the other extreme when the gap is very wide; but a full calculation shows that it should do so; however, although rectification may vanish, the photoelectric effect may remain.

There should therefore be found experimentally three classes of boundary—

(1) Those which neither rectify nor give a photoelectric effect;

(2) Those which do both; and

(3) Those which give a photoelectric effect, but do not rectify.

Classes (1) and (2) certainly exist, and will be termed respectively inactive and active boundaries; class (3) probably exists, but it is not practically important at present; for our purpose it may be included in class (2). These classes differ according to the presence or absence of what Schottky, before the theory was fully understood, appropriately called a "Sperrschicht" ("blocking-layer"); in Germany, rectifier

cells are called Sperrschicht cells, and the term would be appropriate here if it were more translatable.

Construction of Rectifier Cells. If active boundaries had no properties but rectification, it would be impossible to decide definitely which were active and which inactive; we could only say that of the two boundaries of a rectifying circuit, one must be active and the other inactive. But the photoelectric property, combined with subsidiary evidence, enables us to decide. It is known that the boundary between a semi-conductor and a metal simply pressed on its surface is always inactive. On the other hand, there are at least two ways of obtaining active boundaries.

One was discovered by Grondahl in 1920 and is applicable when the semi-conductor is cuprous oxide (Cu_2O). At first, only the rectifying properties of the boundary were known; the photoelectric properties were described by Grondahl and Geiger in 1927, and independently by Lange in 1930. This method is employed in making the well-known Westinghouse "metal-plate" rectifiers, of which the cuprous oxide rectifier cell is a simple development. It consists in forming a layer of cuprous oxide on the surface of a copper plate by heating it in air at about 1040° C. and subsequently annealing it at about 600° C. The active boundary is then formed between the parent copper and the overlying oxide; an inactive boundary is formed by pressing a metal plate (usually lead in a rectifier) on the surface of the oxide.

The second method investigated, but perhaps not discovered by, Waibel and Schottky consists in depositing a metal (usually gold or platinum) layer on a semi-conductor by "sputtering" from the cathode of a discharge through a gas at low pressure. It is applicable to either cuprous oxide or selenium. The inactive electrode is then a metal plate supporting the semi-conductor and giving it mechanical strength. Deposition of a metal layer by condensation of the vapour evaporated from a heated metal does not usually, if ever, give an active boundary when cuprous oxide is used; the metal must be sputtered. But other methods of forming the layer can apparently be used with selenium.

These facts and particularly the last, would be difficult to explain if the boundary layer separating S and M were indeed a vacuum or layer of gas, as supposed in Chapter I.

For it would seem that intimate contact, an infinitely thin layer, and therefore an inactive boundary should be produced by the methods that actually produce an active boundary, rather than by the simple pressing into contact which actually produces an inactive boundary. But the layer is almost certainly not a vacuum or layer of gas; it is a layer of the material of which the semi-conductor is composed, chemically pure and therefore devoid of impurity states. Such a material has practically no electrons in its free states; it will be exactly equivalent to a vacuum in respect of the qualities relevant to our discussion on page 18; the only difference from a vacuum lies in the possession of a band of full states, lying at a considerable distance below the free states, which plays no part in rectification or the photo-electric effect.

The methods that actually produce active boundaries are likely to lead to the formation of a layer of pure material. For the impurity that confers the impurity states on cuprous oxide is almost certainly oxygen; the conductivity of this substance is closely related to its content of excess oxygen. In the first method this excess is removed from the boundary by combination with the parent copper; in the second it is removed by the discharge that deposits the metal; for such discharges are known to act chemically as reducing agents. It is not so certain what is the impurity that makes selenium a semi-conductor; but if, as is probable, it is any oxidizing impurity, it will behave like the oxygen in cuprous oxide.

If this view of the boundary layer is correct, it appears that not every semi-conductor need be capable of providing rectifiers and rectifier cells. A further condition is that the impurity must be easily removable from its surface layers. Perhaps this is why cuprous oxide and selenium are the only semi-conductors that have come into general use; but the reason may be that the field has been insufficiently explored.

In order that a rectifier should act as a rectifier cell, light must be able to reach the active boundary between S and M; it can do so only by passing through either S or M. If the active boundary is made by the first method, the construction shown in Fig. 34 is adopted; M_2, the metal at

the inactive boundary, is a grid or a plate with a single hole in it; the light passes through the hole and through S to M_1, liberating electrons at the active boundary there. Since the photoelectrons liberated travel from S to M_1, they travel in the same direction as the light in such cells, which are

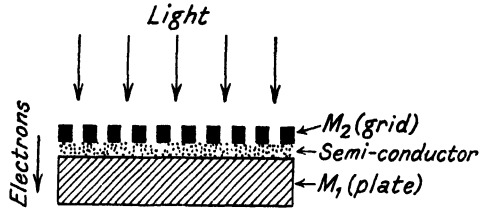


FIG. 34. DIAGRAM OF BACK-WALL CELL

called *back-wall* (*hinterwand*). If the active boundary is made by the second method, the layer of deposited metal is made so thin as to be transparent; the light then travels

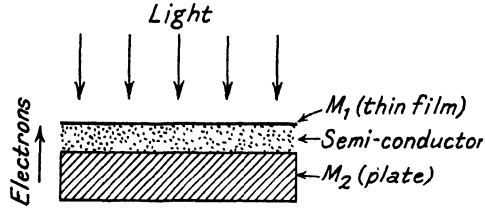


FIG. 35. DIAGRAM OF FRONT-WALL CELL

from M_1 to S across the active boundary (Fig. 35); its subsequent course is unimportant. In such cells, the photoelectrons travel against the light; the cells are called *front-wall* (*vorderwand*).

Properties of Rectifier Cells (i and L). We now proceed to consider those properties of rectifier cells that determine their use in practice; we shall state them in terms of the equivalent circuit of Fig. 33.

In dealing with emission cells, we started with the relation between i and E, the applied voltage. In rectifier cells the E.M.F. in the external circuit is almost always zero; the occasional departures from this practice will concern us later; at present we shall assume that it is zero. We may

then proceed at once to the variation of the current i with the quantity of incident light L, which in a given cell may be measured by the illumination.

If the resistance R in the equivalent circuit of Fig. 33 were constant, this property would be very simple. The current in the external circuit i would be a constant fraction of the photoelectric current flowing across the boundary; it would be proportional to the light. But R is not constant

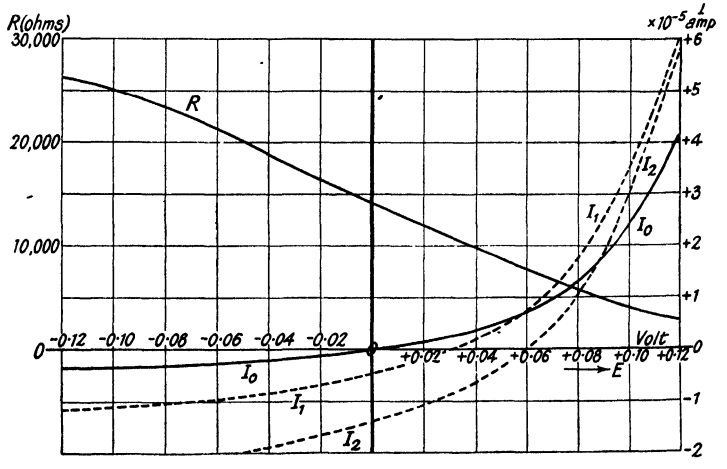


FIG. 36. CHARACTERISTICS OF RECTIFIER CELL

if the cell is a rectifier; for rectification implies that R varies with the potential across the boundary and with current flowing through the cell.

The usual method of expressing the properties of a rectifier is shown in Fig. 36. Here the curves marked I give the relation between current I through the rectifier (ordinates on right-hand scale) and E, the E.M.F. in a resistanceless external circuit; they are typical of a "metal-plate" rectifier of the type we are considering. The curve R gives the relation between resistance (ordinates on left-hand scale) and voltage; the resistance is defined as E/I. The full curve refers to a rectifier cell in the dark; the dotted curves show how the characteristics are changed by the photoelectric current that flows when the cell is illuminated.

It may seem at first sight that we should obtain the

information we want, if we plotted R against I rather than E, identified I with the photoelectric current, and applied the corresponding value of R to the equivalent circuit of Fig. 33. But the matter is much more complicated. The primary photoelectric current flows from S to M_1, which is

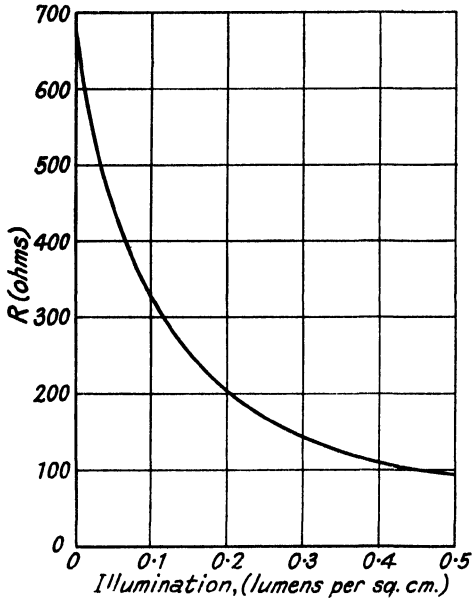


FIG. 37. VARIATION OF RESISTANCE WITH ILLUMINATION IN RECTIFIER CELL

the direction of negative I in Fig. 36; the current in the external circuit continues in the direction from OI_1 to OI_2, and this is the direction of a "reverse" rectifier current. If the resistance of the external circuit is not zero, a potential differential is established across the boundary and a return current flows in the direction of positive I; the relevant value of R is the value corresponding to this return current, which is not equal to i, the current in the external circuit, but is the difference between i and the primary current, which is not directly measurable. Accordingly, Fig. 36 does not provide a convenient way of deriving the relation we seek. Nevertheless it prepares us for a feature of the relation,

expressed in a more convenient way. Since R decreases against E and I in the relevant positive half of Fig. 36, we shall not be surprised to find that the R in Fig. 33 decreases against the light incident on the cell. And, in fact, we find that it does so decrease. Fig. 37 shows how the resistance

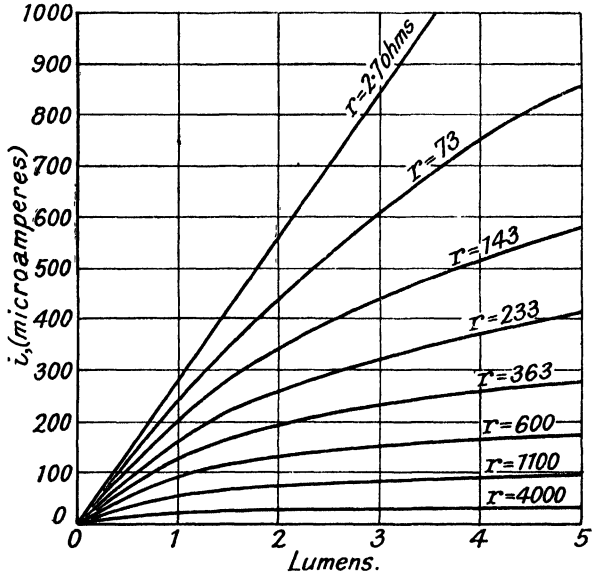


FIG. 38. CURRENT AND ILLUMINATION IN RECTIFIER CELL FOR VARIOUS VALUES OF EXTERNAL RESISTANCE r

R_0, measured for $E = O$, varies with the illumination in a particular cell.

Now, since, in Fig. 33,

$$i = I \,.\, R/(R + r) \quad . \quad . \quad . \quad . \quad . \quad (20)$$

where i is the measured current and I the primary current proportional to the light; and since R decreases against I, i will increase less rapidly than the light, the departure from linearity increasing with R/r. In Fig. 38, i is plotted against the illumination L for different values of the external circuit r, the cell being that of Fig. 37. It will be seen that i is proportional to L over a large range of illumination only if r is so small that it is always small compared with R. If r is comparable with R, i is proportional to L only at small

illuminations, and the ratio of i to L decreases against r. If the sensitivity of the indicating instrument were independent of its resistance, it would be desirable to use one of the least possible resistance; and, conversely, if I were independent of the cell, it would be desirable to use a cell with the greatest possible resistance.

R_0 depends partly on the semi-conductor. It is generally larger for selenium cells (which may have $R_0 = 10{,}000$ ohms for an area of 5 sq. cm.) than in cuprous oxide cells (in which R_0 is seldom more than 1000 for the same area). It is, of course, roughly inversely proportional to the area; thereby a new consideration enters. In emission cells, if the quantity of the light and the nature of the cathode are constant, the area of the cathode and distribution of the light are immaterial. This is not so in rectifier cells. If the illuminated area is fixed, it is best to choose a cell having exactly that area, for any dark portion merely acts as a shunt. If the quantity of light is fixed and the illuminated area can be varied (e.g. by a lens), it is preferable to use a small cell and concentrate the light on it, if the largest value of i is required; for the decrease in R due to the stronger illumination is more than offset by the smaller R_0. If, on the other hand, proportionality of i to L is required, it may be desirable to spread the light evenly over the largest possible area so as to reduce the intensity at any point.

We have so far supposed that the photoelectric effect is measured by the current flowing in an external circuit. It might also be measured by the potential difference e established between S and M on open circuit, an electrostatic or compensating potentiometric method being used. In an emission cell ($R = \infty$ in Fig. 33), the equilibrium value of e is independent of the quantity of the light; it is determined by the velocity of the electrons leaving the cathode and depends only on the wavelength of the light and the contact potential between cathode and anode. If R were finite and independent of the light, e would increase at first with L, but the same limit would be approached under sufficiently intense illumination. But actually R depends on L; e may then be determined by different considerations, namely, a balance between increase of primary current with L and decrease of R against L. The relation between e and L is

therefore very complex, involving the quality of the light. Since e is also less easily measured than i, methods involving e are not likely to be of practical importance. It may be recorded, however, that a formula

$$e = e_0 \cdot \frac{L}{L + a} \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

has been found to hold over a considerable range; e_0 and a are independent of the quantity of the light, but may vary with its quality.

Properties of Rectifier Cells (I and λ). The second important property is the variation of the current with the quality of the light. The current now will always mean the primary current I, which can be measured directly by making r sufficiently small compared with R. This property is best expressed by the quantities of Chapter II as the emission of the equivalent vacuum cell in Fig. 33. The facts are simpler than those of Chapter II, because the number of types of cell at present in use is much less than the number of emission cathodes, and because cells professedly the same are actually more uniform; but there are still very material differences between professedly similar cells. Fig. 39 shows σ_λ for typical cuprous oxide front and back wall cells and selenium cells, which are always front wall cells; the corresponding values of Σ for $T'' = 2848°$ K. and 2400° K. are given on the diagram. The difference between the front and back wall cells arises mainly, if not entirely, from the absorption of the light in passing through the cuprous oxide

It should be mentioned that there is some evidence that the effects of independent beams of light of different quality are not strictly additive. If this suspicion is confirmed—and it is so far only a suspicion—the discrepancy must be attributed to the changes produced in the remaining electronic states by the ejection of an electron from one of them —an effect quite conceivable when the sparsely distributed impurity states are concerned. The practical result would be that the mean emission Σ would not be related to σ_λ by any simple formula such as (9) on page 45. Since the absolute values of σ_λ in Fig. 39 are calculated from the absolute values of Σ by that formula, there may possibly be error from this source.

Again, some cuprous oxide cells, illuminated by red light, have been found to give currents in the wrong direction, i.e. carried by electrons flowing from M_1 to S, while the current under white or blue light is in the right direction. This discrepancy is probably due to the fact that the boundary between S and M_2, as well as that between S and M_1, is an active boundary, so that the cells are partially back-wall

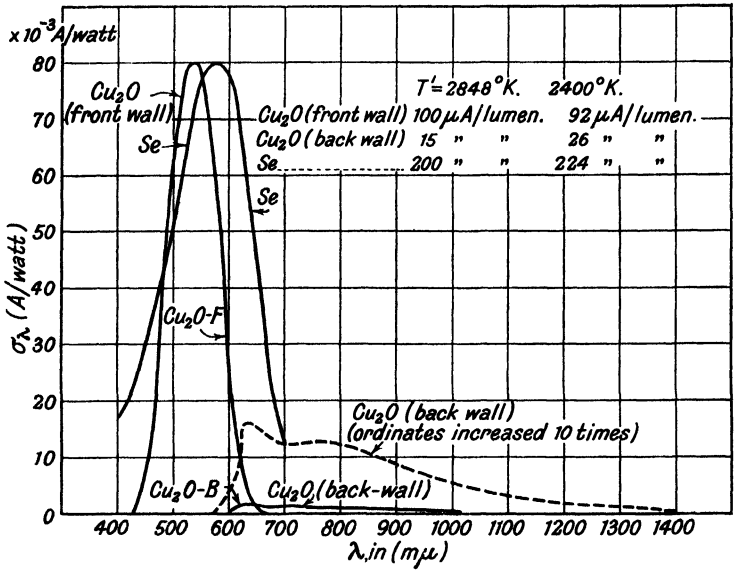


FIG. 39. EMISSION OF RECTIFIER CELLS

and partially front-wall. Such cells are anomalous and are to be avoided.

Properties of Rectifier Cells (Miscellaneous). In a vacuum emission cell the photoelectric current is almost completely independent of temperature T. In a rectifier cell R decreases rapidly with increase of T, as theory predicts. If r is not very small compared with R, i should decrease against T on this account. But I may increase with T. Our simple theory indicates no such change, except in the neighbourhood of the threshold (see page 28); but a change in the impurity states might produce it. If it exists, i might increase with T when r is small, owing to increase of I, and

decrease against T when r is large, owing to decrease of R. The facts are uncertain, since the experiments of different observers show apparent discrepancies, which may be largely due to a failure to state the value of r/R. Most (but not all) observers agree that in cuprous oxide cells, i decreases against T at a rate of the order of 1 per cent per degree C near room temperature; some find that in selenium cells i is almost independent of T or increases at the rate of about 0·2 per cent per degree. At the temperature of liquid air R becomes practically infinite and the properties of a rectifier cell almost identical with those of an emission cell, but I is apparently much less than at room temperatures.

There are similar discrepancies about the stability of rectifier cells. Some maintain that the current under constant illumination is constant indefinitely, others that it decreases gradually. It is not clear whether the decrease observed is permanent or is reversed when the light is removed. A gradual change in the cell for long periods after its preparation is to be expected; for rectifiers are known to show such an "ageing." In view of these uncertainties, the reader can only be recommended to examine the facts for himself, if they are relevant, with the actual cell he proposes to use; irregularities are certainly less when methods of measurement are used which eliminate the effects of changes in R. (See p. 170.)

True "time-lag" is completely absent in the rectifier cell, as in the vacuum emission cell, if the external E.M.F. is zero; I is determined completely by the instantaneous value of the light. But the cells possess a very considerable electrostatic capacity, which is that of the condenser formed by S and M_1, separated by the boundary layer which is not more than 10^{-6} cm. thick. It should be represented in the equivalent circuit of Fig. 1 as a condenser C, in parallel to R, with a capacity of the order of 0·1 μF per square centimetre of cell area. But the presence of this condenser cannot produce an enormous apparent time-lag, as it might in vacuum cells if r were large, because R is never greater than a few thousand ohms. Even if C is 1 μF, the time constant $2\pi RC$ of the circuit will not exceed 0·01 sec.; accordingly, even apparent time-lag is negligible for many purposes.

Lastly, a word is required on the application of an

external E.M.F. to rectifier cells. Greater sensitivity, i.e. a greater change of current due to the incidence of a given quantity of light, can undoubtedly be obtained by the use of such an E.M.F.; but it is partly due to the change of resistance of the semi-conductor, not to a boundary effect. Rectifier cells used in this way resemble conductivity cells, with all their advantages and disadvantages, and so belong to the next chapter. The nature of the change produced by light in these conditions will appear from an examination of the three characteristics of Fig. 36; the magnitude, and even the sign of the change of current, depends on the E.M.F. applied; the relation between light and change of current is very complicated. It is doubtful whether the increased sensitivity is ever worth the difficulties arising from these complications.

Photo-voltaic Cells. The first photoelectric effect to be discovered, prior even to the photo-conductivity of selenium, was the Becquerel effect. It consists of a change of the E.M.F. in a voltaic cell when one electrode is illuminated. There are apparently two separate effects of this kind. One is associated with particular electrolytes, especially organic dyes, and arises from the illumination of the liquid near the electrode; it is probably similar in principle to photo-conductivity. The other is associated with particular electrodes, and arises from the illumination of the electrode-electrolyte boundary; it is almost certainly a boundary effect, precisely similar to that we have just been considering, the electrolyte playing the part of the metal M_1.

Cells utilizing this effect have been sold recently under the trade name "Arcturus." They seem to consist essentially of an active electrode of copper coated with cuprous oxide, immersed in a solution of sodium sulphate (or other simple neutral salt), and surrounded by an inactive electrode of copper. If rectifier cells had not appeared, they would probably have been very important in practice; for they give photoelectric currents, requiring no external E.M.F., larger even than those of rectifier cells. But they suffer from many of the defects of the conductivity cells we are about to consider. The current is never accurately proportional to the light; they are unstable and are apt to deteriorate even when not used, and they are affected by a time-lag, which

may be merely "apparent" and due to capacity, but is not the less prominent in practice. For these defects their greater sensitivity is hardly a compensation; moreover, their sensitivity is not equal to that of conductivity cells. They are falling out of use as rectifier cells become better known. Accordingly we do not propose to discuss them; for we do not know of any purpose for which they are preferable to all of the three classes to which our attention is confined.

REFERENCES

1. The development of the theory of these cells may be traced in: W. Schottky, *Phys. Zeit.* 31, p. 913, 1930; 32, p. 853, 1931, and F. Waibel and W. Schottky, *Phys. Zeit.* 32, p. 833, 1931; 33, p. 583, 1932; W. Jusé, *Nature*, 132, p. 242, 1933; H. Teichmann, *Roy. Soc. Proc.* 139, p. 105, 1933.

2. The history of the Cu_2O rectifier and cell is given by L. O. Grondhal, *Rev. of Modern Physics* 5, p. 141, 1933. The independent discovery by Lange in Brit. Pat. 360391, and B. Lange, *Phys. Zeit.* 31, p. 139, 1930. The selenium rectifier cell seems to have been first described by L. Bergmann, *Phys. Zeit.* 32, p. 286, 1931. A new type of rectifier cell, not yet in general use, is described by C. G. Fink and Alpern, *Trans. Amer. Electrochem. Soc.* 62, p. 369, 1933.

3. The data given in the text are derived from L. Bergmann (*loc. cit.*) and *Zeit. f. Techn. Phys.* 14, p. 157, 1933; A. Dressler, *Licht u. Lämpe* 21, pp. 35 and 211, 1932; B. Lange, *Phys. Zeit.* 32, p. 850, 1931; *Naturwissenschaft* 19, p. 527, 1931; A. Goldmann and M. Lukasiewitch, *Phys. Zeit.* 34, p. 66, 1933 (measuring e not i); H. Teichmann, *Zeit. f. Phys.* 67, p. 192, 1931, and L. Dubar, *Comptes Rendus* 193, p. 659, 1931 (temp. effect). The effect of the plane of polarization of the light is described by L. Bergmann, *Phys. Zeit.* 33, p. 17, 1932.

4. For use of rectifier cells with external E.M.F., see A. Dressler, *Licht. u. Lämpe*, 21, p. 35, 1932; F. Waibel and W. Schottky, *Phys. Zeit.* 33, p. 583, 1932.

5. For Becquerel effect, see Hughes and du Bridge (*loc. cit.*), Chapter IX; also F. Waibel, *Zeit. f. Phys.* 76, p. 281, 1932. For Arcturus cells, see commercial literature issued by the makers.

CHAPTER V

CONDUCTIVITY CELLS

Primary and Secondary Current. The difference between a conductivity cell and a rectifier cell is primarily one of boundary conditions. In Chapter I we supposed that in a rectifier cell the electrons raised to higher states by the light were all so near the boundary that they could reach it without material loss of energy; but if they were produced farther from the boundary, nothing would be changed, so long as the states into which they were raised were running states, and a small field were applied to provide the energy lost in passing along a running state. If the boundary conditions were the same, a thick slab of semi-conductor placed in an electric field and illuminated at the middle would act exactly like a rectifier cell made of the same semi-conductor. But if the boundary is such that the electrons cannot cross it, they will accumulate there, setting up a field opposing the applied field and ultimately preventing further flow.

This condition of affairs was first detected clearly by Gudden and Pohl in zinc blende and in rock-salt coloured by X-rays, both of which are semi-conductors. A brief flash of light produces a momentary *primary current*, and results in the appearance at the surface in contact with the electrode of a charge, proportional to the intensity of the light and to the time for which it has acted, and independent of the electric field, so long as it is above some limit. But a further continuation of the light does not result in an asymptotic rise of the charge to a maximum and the cessation of all current. A *secondary current* continues to flow however long the light acts, much less simply related to the intensity of the light and the strength of the field.

The continued secondary current is evidence that the electrons are escaping from the semi-conductor at the positive electrode and entering it from the negative. They can do so only because the field created by their accumulation at the boundary has changed completely the distribution of states there. Further, their loss from the relatively small

number of impurity states in the interior, leaving positive charges behind, changes these states. Lastly, the positive charges may move to the negative boundary and produce yet further changes of the states there. Since the properties of a material are determined by its electronic states, the original semi-conductor has ceased to exist; it is replaced by a new and different substance. The final steady value of the current is determined by the conductivity of this new substance, which may be very different from that of the old. The part played by these various changes cannot be distinguished clearly in the present state of our knowledge, and it is impossible to predict the properties of the new substance; but there is no doubt that this account of the secondary current is qualitatively correct, although it may not be entirely complete.

In some substances, such as rock-salt and even cuprous oxide, the changes are comparatively small, and the primary and secondary currents can be distinguished. In others, such as selenium, the changes are enormous and, even in the shortest measurable initial period, the primary current is wholly masked by the secondary. It is the large secondary currents that make these substances useful for conductivity cells. Hence a complete theory of the conductivity cell cannot be given; but it is useful to regard it as analogous to a photographic plate rather than to an emission or rectifier cell. The changes on which its use depends are not a direct effect of the light; they are due to a transformation of the nature of the material consequent on a "development" of the primary effects of light by sources of energy (the chemical developer in one case, the field in the other) independent of the light. In one case as in the other this process of development occupies an appreciable time.

And now we will leave theory completely on one side and state those properties of conductivity cells relevant to their use. It is evidence of the complexity of the changes that, though conductivity cells have been studied for a much longer period than any other type, much less trustworthy quantitative information is available. All that we give has been selected from published work; we have used our own knowledge only where it is necessary to decide between conflicting statements.

Construction of Conductivity Cells. Modern conductivity cells usually have the form shown in Fig. 40. A glass plate is coated with a thin film of metal (usually gold), which is then divided by a zigzag line so as to form two interlacing grids, which are connected to terminals. A thin film of semi-conductor is then deposited over the whole; the conductivity measured is therefore across the width of the zigzag line. The plate is enclosed in an evacuated vessel to preserve it from chemical attack by the air. Selenium in the grey modification is the usual material; but alloys of selenium and tellurium have also been used, as well as a thallous oxysulphide ("thalofide" cell). The thalofide material is sensitive to light of long wavelength; the alloys are useful chiefly because they permit some adjustment of the region of maximum sensitivity. Where the contrary is not stated, we refer primarily to selenium; but in most respects all these materials are qualitatively the same.

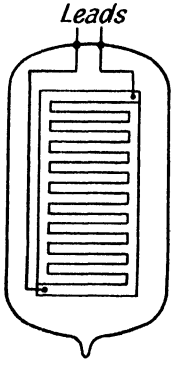


FIG. 40

Since a semi-conductor owes its properties to impurity states, the performance of the cell depends greatly on the exact method of preparation. The impurity is probably oxygen. The procedure adopted always includes a carefully adjusted heat-treatment; it is usually a trade secret and, even when it is described in detail, attempts to follow the description seldom give the expected result. The thalofide substance seems to be particularly capricious; this is probably why it is seldom employed.

Commercial cells are usually designed for use at some voltage between 100 and 250, and have a resistance (for selenium) between 5 and 100 megohms. Thalofide cells may have a resistance as high as 1,000 megohms.

Current and Voltage. Even in the dark conductivity cells do not obey Ohm's Law exactly. The current at constant voltage generally increases somewhat with lapse of time since its application; when the voltage is changed the current increases more rapidly than the voltage. These departures from Ohm's Law may be due, at least in part, to increase of temperature due to the passage of the current.

But if the voltage prescribed by the maker is applied for a few minutes before measurements are taken, Ohm's Law is nearly true for any probable departures from it; similar cells may therefore be compensated for change of voltage by connection in a Wheatstone Bridge. The voltage should not be reversed for any length of time; the maker usually gives the direction in which it is to be applied. Evidence concerning the effects of an A.C. voltage is conflicting; but some makers offer A.C. cells.

These statements apply primarily to the relation in the dark. Data concerning the relation when the cell is illuminated are scarce; but it is probable that the changes of current with voltage are still qualitatively the same.

Current and Temperature. According to theory, the conductivity of a semi-conductor, and therefore the current through it at constant voltage, should increase rapidly with rise of temperature, following the law $R \exp. \left(-\frac{b}{T}\right)$, where b is in the region of 10^4. The facts confirm expectation, at least approximately; the dark current increases about 2 per cent per 1° C. temperature rise at room temperatures. The current when illuminated changes in the same sense, but less rapidly. It follows that the increase in current produced by light decreases as the temperature rises; in some cells at least (data are scanty) the decrease of the effect of light at room temperature is about $\frac{1}{2}$ per cent per 1° C. rise. This relation is said to hold even down to liquid air temperature, where the dark conductivity is almost *nil*, but light produces a greater change in current than at room temperatures. It would appear desirable therefore to use conductivity cells at as low a temperature as possible, at least if time-lag is of no importance.

Current and Time. We have already noted that the development of the secondary current from the primary current takes a finite time. Accordingly, when light is thrown on the cell or cut off, the current will vary in some such way as that shown in Fig. 41. The form of the rise and fall of current consequent on a change of light varies greatly in the measurements of different observers, and so does the time, denoted by t_0, required for the current to reach a steady value. (The current approaches its final value asymptotically

and t_0 cannot be defined very precisely; we take it to be the period after which a further change of 1 per cent does not occur in further period t_0.) The efforts of manufacturers of cells have been devoted lately to producing cells in which t_0, the *time-lag*, is as small as possible; and they appear to have been successful. For, while a few years ago t_0 in the best cells was to be measured in minutes, its value for the cells lately described by Metcalf, to which Fig. 42 refers, is

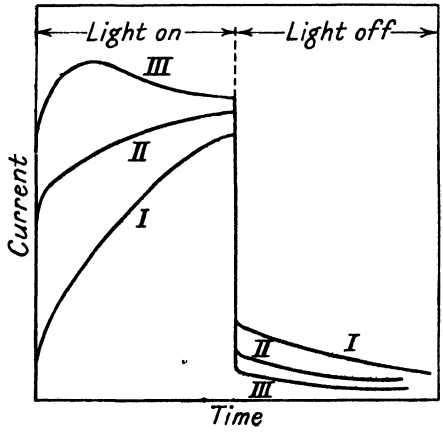


FIG. 41. TIME-LAG IN CONDUCTIVITY CELL

only about 0·1 sec. But a word of warning should be given; t_0 appears to depend greatly on the exact conditions, and we have not always been able to confirm the value claimed by makers for their cells. A long t_0 is usually associated with a general instability, so that, even if time is allowed for the current to become steady, the same value of the current does not always correspond to the same value of the light, if the previous variation of the light differs considerably; the response is a complicated function of past history.

But, even if t_0 is as low as 0·1 sec., the time lag will affect greatly the response of the cell to rapidly varying light; frequency response curves similar to those discussed on pages 71 to 74 are important, i_n being again the amplitude of the A.C. component of the current produced when light varying with frequency n is incident on the cell.

Curves for selenium cells of various types have been given by several observers; it is remarkable that they agree much more closely than the differences in t_0 would suggest. This is not incomprehensible; for when the frequency is more than 100 p.p.s., the output is determined by a stage in the development of secondary from primary current that is hardly accessible to direct observation. Fig. 42 shows the frequency response curve of a selenium cell given by Metcalf (with whose results Schoenwald and others agree closely); it is expressed in the same manner as in Figs. 30, 31, except that the standard 100 per cent response is taken to be that

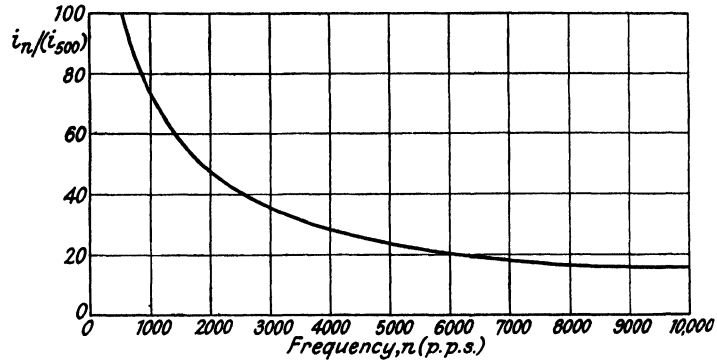


FIG. 42. FREQUENCY RESPONSE OF SELENIUM CONDUCTIVITY CELL

at 500 p.p.s. and not that at very low frequencies; this change is necessary because the curve is so steep and not flat at low frequencies. It will be seen that the decrease of effective sensitivity against frequency is more rapid than in even the worst gas-filled emission cell.

Current and Quantity of Light. It is evident that if any relation between current and quantity of light is to be obtained, the time for which the light acts must be defined. The only statement that seems independent of this time is that the current increases less rapidly than the quantity of light; and even when two observers have professed to define the time in the same way, their results seldom agree in more than this. Either cells differ greatly among themselves or the relation is very sensitive to the definition of the time

or to other conditions of use. In either case, any precise relation can be valid only over so narrow a range that it is of no general interest; all attempts to state a general relation with a few adjustable constants are doomed to failure.

Accordingly we shall give only two curves. The first (Fig. 43A) is due to Metcalf, and shows the relation between the increase in current when a steady illumination is maintained for so long that further changes with time are inappreciable. The light is that from a tungsten filament at 2870° K. The sensitivity, i.e. the ratio of change of current

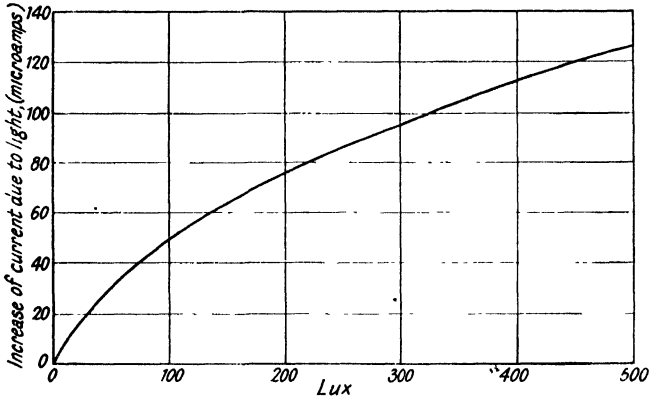


FIG. 43A. RELATION BETWEEN LIGHT AND STEADY CURRENT FOR CONDUCTIVITY CELL

to change of illumination, is greatest when the illumination is small; the tangent at the origin gives 0·75 μA/lux. The area of the cell was probably about 6 cm.^{2}; consequently the sensitivity is about 1200 μA/lumen, very much greater than the sensitivity of any emission or rectifier cell. But this comparison is not strictly legitimate. The response of a conductivity cell is determined by illumination and not by quantity of light. With a given quantity of light, the response is greatest when it is evenly spread over the cell and when the cell is small; other things being equal, the sensitivity in lumens is inversely proportional to the area of the cell. These are important points to remember in practice.

The sensitivity as defined here is roughly proportional to the applied voltage; but a voltage higher than that assigned

by the maker (in our example, 100 volts) should never be applied; and there is seldom reason to apply a lower voltage. Sensitivities considerably greater than that given have been claimed by other makers; but some at least of them have been attained by sacrificing stability or increasing time-lag. The effective sensitivity for practical use increases somewhat with the resistance in the dark and with the ratio of the change of current produced by light to the current in

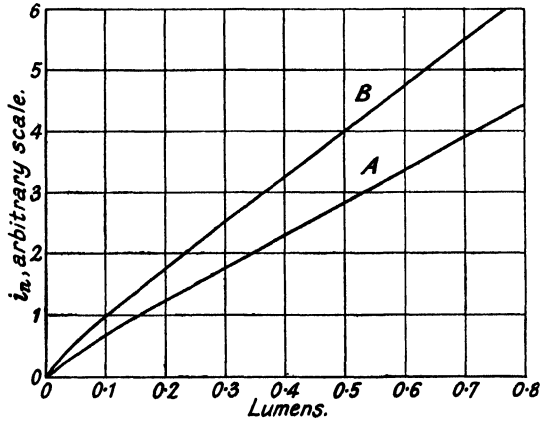


FIG. 43B. VARIATION OF CURRENT WITH INTERMITTENT ILLUMINATION IN CONDUCTIVITY CELL

the absence of light. The total change in the resistance of the cell of Fig. 43A produced by a very great amount of light is approximately from 6 to 0·75 megohms. A change of 2 per cent in the conductivity, and of 0·32 μA in the current, such as is due to a change of 1° C. in temperature, is produced by 3×10^{-4} lumens; so that if light of less amount than this is to be detected, care must be taken to keep the temperature constant.

The second result (Fig. 43B) is due to Schoenwald and gives (in arbitrary units) i_n, the alternating component of the current due to illumination interrupted (or rather varied harmonically between zero and a maximum) at a frequency of 1500 p.p.s. Curve *A* refers to this intermittent illumination alone; curve *B* to the superposition on it of a constant illumination of 0·4 lumen, only the alternating component

still being measured. The response, i_n, is now much more nearly proportional to the illumination, but the sensitivity measured by the slope of the straight portion is much less. Schoenwald's cell was not very sensitive; absolute values of i_n in μA/L are not given by other workers and cannot be obtained by extrapolation to zero frequency because the curve is so steep. Accordingly it is not certain how the sensitivity to rapidly varying light compares with the sensitivity to steady light; but it appears likely that the sensitivity in the neighbourhood of 10,000 p.p.s. is of the order of 100 μA/L (and indeed less than this) when the sensitivity

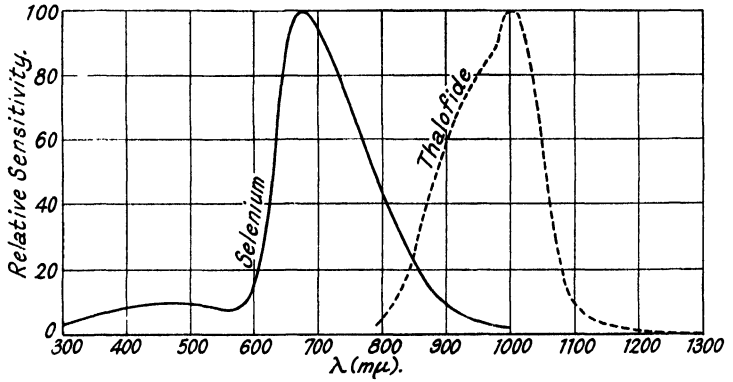


FIG. 44. WAVELENGTH SENSITIVITY CURVES FOR CONDUCTIVITY CELLS

for steady light exceeds 1000 μA/L. This great decrease of sensitivity is, of course, another aspect of the frequency-response curve (Fig. 42).

Current and Quality of Light. We now require information similar to that contained in the emission curves of Chapter II. Since the response, however measured, is not really proportional to the light, it is impossible to separate entirely quality from quantity. But if a very small light is used or an alternating light not too small, there is approximate proportionality; we can measure sensitivity as before by the change of the current produced by steady light, or by the amplitude of the component produced by intermittent light, always of the same energy but different wavelength. There is no evidence how far the sensitivities

measured by these two methods are similar in their variation with wavelength; but since the results obtained by different workers by different methods do not differ very greatly, it may be assumed that they agree nearly. Any difference is likely to be obscured by differences between individual cells, which are probably nearly as large with conductivity as with emission cells. Fig. 44 gives a typical result for (*a*) a selenium cell and (*b*) a thalofide cell. The very marked maximum is found by all observers; its position on the wavelength scale is very variable, but it always lies well on the red side of the maximum of the visibility curve. Conductivity cells are therefore much more "red-sensitive" than the eye and definitely sensitive to the invisible infra-red; to short wavelengths they are comparatively insensitive. These are the chief facts of practical importance.

Other Conductivity Cells. It must be insisted again that photo-conductivity is not a property peculiar to selenium, tellurium, and the thalofide substance. Many other materials display it; but, though they may have various advantages over selenium, they lack the advantage that alone makes conductivity cells practically interesting, namely, sensitivity. At one time it seemed that silver chloride might be used ([4]), but to-day the only likely alternatives to selenium cells are rectifier cells used with an E.M.F. in the external circuit. Claims have been advanced that greatly increased photoelectric currents can be obtained by this means without a sacrifice of linearity of response and freedom from time-lag; but they do not seem to be substantiated; rectifier cells used as conductivity cells appear to have all the drawbacks of other conductivity cells, and are superior to them only in so far that, owing to their construction, they are adapted for use with lower voltages. We shall therefore content ourselves with references to an account of their use in this manner ([5]).

REFERENCES

1. For a general account of photo-conductivity, see Hughes and DuBridge (*loc. cit.*), Chapter VIII.

2. No mention is made in this book of the Dember "Crystal effect," because it is so far of purely theoretical interest. (See e.g. H. Dember, *Phys. Zeit.* 33, p. 207, 1932.)

3. The data are mainly taken from G. F. Metcalf, *Electronics*; B. Schönwald, *Ann. d. Phys.* 15, p. 395, 1932. (See also F. Schröter and F. Michelssen, *Photoelectric Cells and Their Applications* (*cit. ante*), p. 208, and G. B. Barnard's book, *The Selenium Cell* (Constable) is a mine of facts; but the ore and the dross are still unseparated. For the thalofide cell, see R. Sewig, *Zeit. f. Techn. Phys.* 11, p. 269, 1930.

4. For photo-conductivity of AgCl, see F. C. Toy and G. B. Harrison, *Proc. Roy. Soc. A.* 127, p. 631, 1930.

5. For rectifier cells used as photo-conductivity cells, see Reference (4) to Chapter IV.

PART II

THE USE OF PHOTOELECTRIC CELLS

CHAPTER VI

SOME GENERAL PRINCIPLES

Detection, Comparison, and Measurement. The objects and methods of using photoelectric cells are many and various. But there are certain elements common to all of them. It will save time if we begin with some very general considerations, although they may seem at first sight too abstract for a practical handbook.

In every application we are concerned with variations in some ultimate cause L, which is related to variations in some immediate effect y through the action of the photoelectric cell and its subsidiary apparatus. Thus L may be the luminous flux from a lamp, y the position of a spot on a galvanometer scale; or L the reflecting power of some object scanned in television, y the brightness of a neon tube; or L the colour of an indicator in volumetric analysis, and y the note in a telephone; and so on. By studying the possible forms of the relation between L and y we can classify the objects of various applications and the methods available to attain them, and can establish criteria to decide how far each class of method is suitable for each class of object.

We begin with objects. These we may classify as detection, comparison, and measurement. Our object is detection, if we merely wish to distinguish whether L lies within or without certain limits; it is comparison, if we wish to decide whether one L is the same as some other L; it is measurement, if we wish to distinguish every L from every other different L, and to assign numerals to represent the differences. Achievement of these three objects imposes conditions of progressively increasing stringency on the relation between L and y. If the object is detection, it is sufficient that every y corresponding to an L within the limits is distinguishable from every y corresponding to an L without

them. If it is comparison, it is necessary further that no two L's should correspond to the same y, but it is not necessary that no two y's should correspond to the same L. Measurement consists in measuring y and making use of a numerical law between L and y; then the relation between L and y must be expressible mathematically by an analytic function or graphically by a smooth curve, and (in practice) the function or the curve must have one of a few simple forms.

The recognition of these differences is important, because greater stringency in one direction often necessitates less stringency in another, or at least some loss of convenience. If our object is measurement, we cannot expect the latitude of choice possible in detection; if, on the other hand, we merely want to detect, it is unwise to hamper ourselves by the limitations required for measurement.

But though the three operations are distinct, both comparison and detection can lead to measurement. Thus, if we have at hand a sufficiently large collection of systems of which the L's have already been measured, we can measure any other system by comparing it with the standard systems and deciding which of them has the same L. Again, detection can usually be associated with control; y can consist in the operation of some mechanism which is started or stopped according as L falls within or without the limits. The mechanism can then often be arranged to alter L so that it falls at the boundary of limits, to measure it by the amount of alteration required, and to record the measurement. Many problems of measurement are thus really problems of comparison or of detection; more than a superficial analysis is required to classify them. We shall often use the term measurement, for the sake of brevity, to include both comparison and detection when no confusion is likely to arise; but we hope to preserve the distinction whenever it is material.

Sensitivity, Accuracy, and Precision. We now turn from objects to methods. These are distinguished by the nature of their y's, and of the intermediaries connecting them with L. But before we discuss this aspect, let us consider some desirable qualities of methods.

Whether the object be measurement, comparison, or

detection, an important quality of the method is *sensitivity*. This word is often used loosely with many slightly different meanings; when a precise and definite conception is required it is better to use the *sensitivity limit*. (It is unfortunate that the smaller sensitivity limit corresponds to the greater sensitivity in the ordinary sense; but this anomaly is unavoidable except at the expense of verbal clumsiness, and, once it is observed, need cause no confusion.) The sensitivity limit (ΔL) of a method of detection is the least difference between two L's lying on opposite sides of the limit of detection; of a method of comparison, the least difference between two L's that can be judged different; of a method of measurement, the least difference between two L's to which different numerical values are assigned. The conception may be usefully extended also to the y's, and to any magnitudes intermediate between L and y in the chain of cause and effect. Thus the sensitivity limit (Δy) of y is the least difference between two y's that can be directly distinguished; and if y is the scale reading of a galvanometer actuated by the currents through the cell due to its illumination, Δi is the least difference between two currents that the galvanometer will distinguish.

The sensitivity limit is closely connected with *accidental error*, and usually arises from the failure of the same y always to correspond to the same L. Although the connection does not amount to identity, it will be unnecessary for us to distinguish between them. However, the connection has a consequence that we must notice carefully. If the same y always corresponded to the same L, it would follow that $\Delta L = dL/dy \cdot \Delta y$, where dL/dy would be fixed by the average relation between L and y. But since different y's may correspond to the same L, dL/dy is not determinate, and the true ΔL may differ widely from that calculated from Δy. We shall distinguish these respectively as the *effective* and the *ideal* sensitivity limits. The distinction is very important; for while the ideal sensitivity limit of L decreases with dy/dL, the effective limit sometimes decreases against dy/dL.

Another important quantity is *accuracy*. Though accidental error prevents a relation between L and y from being valid in each instance, it permits a statistical relation such

as is embodied in a numerical law. Many methods of measurement and some of comparison involve the assumption that some particular numerical law, or other statistical law, is true; for instance, that y is proportional to L. If this assumption is not true, the method is inaccurate and affected by *systematic error*, which can sometimes be measured by the departures from the law; it will then be represented by E_L or E_y. In principle, accuracy and sensitivity are quite independent, but unfortunately they are often mutually antagonistic.

Precision is the resultant of sensitivity and accuracy. A method is precise when both the sensitivity limit and systematic error lie below some assigned limit.

Sensitivity limits and error usually depend on and increase with L and y; but the relative sensitivity limit or error, i.e. $\Delta L/L$, E_y/y, etc., often decrease against L and y.

These considerations have a special application to *null methods*, in which some form of compensation is introduced, so that a value of L which would otherwise correspond to a large y corresponds to $y = 0$. Their primary advantage is sensitivity; Δy is usually least when $y = 0$. Thus if a current which would throw the galvanometer spot off the scale is compensated, a smaller shunt can be employed. If the method is one of pure comparison by substitution, and the equality of the two L's is observed by replacing one by the other, the gain in sensitivity need be accompanied by no loss of accuracy. But sometimes the compensating means is used for measurement, L being measured by the amount of compensation required to bring y to zero. In that case the accuracy depends on the nature of the compensation, and the use of compensation may or may not increase precision. This is sometimes overlooked, because in the most familiar instance of compensation, namely, the Wheatstone bridge, compensation does increase accuracy as well as sensitivity; it so happens that the law that corresponding arms are proportional is more nearly true than the law that the deflection is proportional to the conductivity. But this is a fortunate chance, quite unconnected with the general properties of null methods.

Measurement by compensation is most likely to be accurate when the introduction of compensation leaves the apparatus

symmetrical; compensation that introduces asymmetry seldom leads to precision, however much it may increase sensitivity. Even when there is no measurement in our sense, but only comparison by substitution, some advantage in accuracy may lie with the more symmetrical compensation.

Compensation and Substitution. Let us now proceed to particulars. In the remainder of this part L will generally be a photoelectric current; we shall be primarily concerned with methods of measuring such a current, though in Chapter IX we shall deal with some other quantities associated

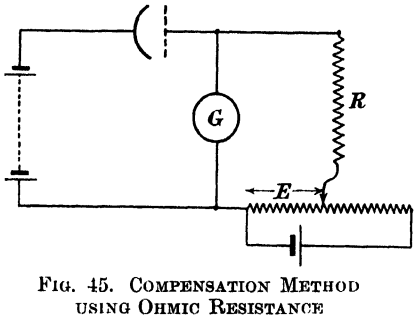


FIG. 45. COMPENSATION METHOD USING OHMIC RESISTANCE

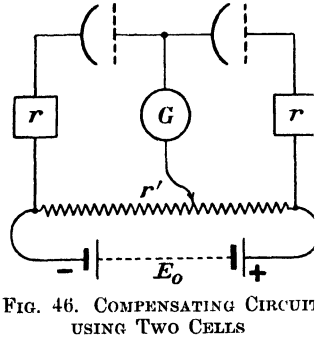


FIG. 46. COMPENSATING CIRCUIT USING TWO CELLS

with the incidence of light on a photoelectric cell. The connection between the photoelectric current and the properties that it is used to measure will be the subject of Part III. There are certain devices that can be associated with all methods; these must receive attention first.

Some of them are concerned with compensation in null methods. Fig. 45 shows, applied to an emission cell, the standard method of compensating any current flowing through an indicating instrument G by means of an equal and opposite current supplied from a battery E through an ohmic resistance R. An alternative method of compensation is shown in Fig. 46 when the compensating current is derived from another photoelectric cell suitably illuminated. One or other of these two methods, or some simple variant, is employed in almost all photoelectric null methods.

Our general discussion indicates that the second method is preferable, as being more symmetrical. And this is generally the fact. If both cells can be illuminated by the same

source of light, it has the very important advantage of making the condition of balance independent of variations in the source, a frequent cause of accidental error; but, of course, both cells must then respond in the same way to the variations. It may also make the balance independent of variations in the battery E_0 or other source of supply. This advantage is most marked with conductivity cells; for Fig. 46 then becomes a Wheatstone bridge. It is absent with rectifier cells, which have no supply, and not very important with vacuum emission cells, which are almost independent of the supply voltage. (But here variation of the movable contact on the potentiometer resistance r' sometimes gives a useful fine adjustment, since the currents in the cells vary very slowly with its position if they are nearly saturated.) It would be valuable with gas-filled cells, if a pair having the same characteristic could be used; but actually characteristics are so little uniform that the variations in the supply are not easily balanced out by this method. Lastly, it has the advantage with vacuum cells, and even with gas-filled cells which are of very high equivalent resistance, of involving little loss of sensitivity; in Fig. 45 G is reduced in effective sensitivity by being shunted by R, which it may be inconvenient to make as large as the cell resistance.

On the other hand, the method of Fig. 45 has one advantage, namely, that the compensating current, and thus the current it compensates, can be measured absolutely in terms of E and R. This advantage is likely to be greatest when the cell is one giving a current proportional to light, so that the compensating current measures the light without any calibration.

Measurement by comparison, involving the substitution of an unknown light (or current) by a known equal light, is also of great importance in photoelectric work. In the form that is being ever more widely used it is known as the *alternating light method*. Two beams of light are thrown in rapid alternation on the same cell; if they are not equal, there is an alternating component in the resulting current; this alternating component is separated from the steady mean current by means of transformers or condensers and detected by a suitable instrument. Since equality of the beams is indicated by the vanishing of an A.C., the method is a

null method not involving compensation. But it is sometimes advantageous to use it in conjunction with compensation; the steady current from the unknown light being compensated approximately at least, by one of the methods already mentioned.

The merit of this method arises from the ease with which small A.C. currents and voltages of any frequency above 50 p.p.s. are amplified by thermionic valves. Further, if the frequency of the alternation is carefully controlled, the A.C. component of the photoelectric current can be readily separated from spurious currents by means of electric filters or their equivalent tuned to that frequency (but see page 153). For the detecting instrument, a vibration galvanometer is highly suitable; or the A.C. component may be rectified and detected by a D.C. instrument. Both of these plans have the disadvantage that the sign of the unbalance cannot be distinguished, so that it is not immediately clear in which direction the known light has to be changed to produce a balance. This objection can be overcome by passing the A.C. component, usually after amplification and separation from the steady component, through a commutator to a D.C. instrument, the commutator being run in synchronism with the alternations of light. The direction of deflection will then change with the sign of the unbalance. It is not easy to construct a commutator that does not introduce the accidental error that the method is designed to avoid: though the difficulty has been successfully overcome by several workers, it is generally better to avoid it, if possible, by subsidiary devices for detecting the sign.

If sensitivity is to be obtained, the A.C. component must really vanish when the lights are equal; this demands that one is thrown on the cell exactly as the other is thrown off, so that the total light incident is constant. Any departure from this ideal will introduce an A.C. component of double frequency, which may in principle be removed, but in practice is better avoided. The standard method of achieving this is shown in Fig. 47. The two optical systems, S and S', which are to illuminate the cell alternately, are made mirror images of each other in the plane AB (Fig. 47*a*). In this plane is placed a rotating disc (Fig. 47*b*), having clear sectors and mirror sectors of equal size. The cell is placed at C; it

receives light from S, or S', according as a clear or mirror sector is at AB; if S and S' are true mirror images and (strictly) if the transmission coefficient of the clear sector is equal to the reflection coefficient of the mirror sector, there can be no change of total light. Other methods can, of course, be used; but this is certainly the best.

The ease of detecting an A.C. current has led to the use of modifications of this method that are not substitution methods. Thus, in the compensation method of Fig. 46, the lights to be compared can be directed alternately on the two cells. It has even been proposed to apply it to Fig. 45,

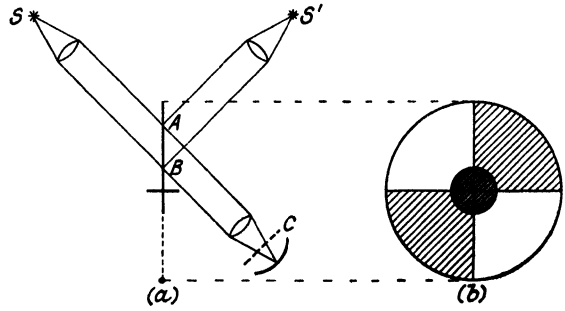


FIG. 47

either by alternating the light on the cell and compensating it from a source of A.C. voltage replacing E, or even by supplying the cell constantly illuminated with A.C. voltage. These methods may have the merit of instrumental simplicity, but they can have no other merit. The last is essentially inaccurate unless the voltage-current characteristic of the cell is linear over the range of A.C. applied; this condition is never really fulfilled in emission cells, to which the method has been applied. On the other hand, when conductivity cells are placed in a Wheatstone bridge, there is much to be said for feeding the bridge with A.C. if valve amplification is to be applied.

Lastly, it may be noted that, even in a direct reading method, there may be advantage in replacing a D.C. by an A.C. photoelectric current, if it is to be amplified. The light may be interrupted; or the cell fed from an A.C. supply; or the current interrupted by a mechanical switch. The

first method is often employed in detection, and is very suitable when artificial light (which can be interrupted) has to be distinguished from stray daylight. The second is employed in television, the A.C. being of the frequency of the carrier that is to be modulated. The third has been employed, somewhat heroically, in especially difficult circumstances ([3]).

REFERENCES

1. For general theory of measurement, see N. R. Campbell, *Measurement and Calculation* (Longmans, Green & Co., London, 1928).

2. For alternating light method, see C. H. Sharp, *Photoelectric Cells and Their Applications* (*cit. ante*), p. 110; and G. & B. Dobson and D. S. Perfect, *Photoelectric Cells and Their Applications*, p. 79.

3. W. R. G. Atkins and H. H. Poole, *Photoelectric Cells and Their Applications*, p. 132.

CHAPTER VII

CURRENT MEASUREMENT

Electrolytic Methods. A current may be measured electromagnetically, electrostatically, or electrolytically. The last procedure, in which the current is passed through an electrolytic cell and the quantity of electricity that has passed determined from the quantity of some (usually cathode) product, is not much used; but where a very variable current has to be integrated over a long period, as in the measurement of daylight, it has some applications. Attention may be drawn to Wilson's ingenious, but neglected, micro-coulombmeter [1].

Electromagnetic Methods

System	Resistance (Ohms)	Period (Secs.)	(μA for Full Scale)
Pointer—			
Unipivot	1,000	4	24
Double-pivoted	20	4	125
			(Deflection in mm. for 1 μA)
Moving Coil, Reflecting—			
General use	400	4	800
Especially ballistic	2,800	22	12,000
Moving Magnet, Reflecting—			
Paschen	3,000	6	130,000
Vibration	1,400	Vibration period 0·01	60
Einthoven String—			
Extreme sensitivity	4,000		60,000

Electromagnetic measurement may also be treated briefly, not because it is limited in range—it is used much more frequently than any other—but because it is so familiar. Nobody needs to have explained to him the operation of a micro-ammeter, galvanometer, or electromagnetic relay. All that need be given is some information concerning the performance of representative members of the various classes of instrument.

The most important characteristics of a galvanometer are (*a*) the resistance; (*b*) the period required to take up a steady reading; and (*c*) the sensitivity. (*a*) is not of great importance with emission or conductivity cells, for their resistance is always large compared with that of the measuring instrument; but it is important with rectifier cells. The table on page 112 shows some typical instruments [2]—

In relays the important characteristics are (*a*) the resistance; (*b*) the working current required to operate the relay; and (*c*) the controlled current which the contacts can carry under a voltage of about 100. The following values are typical—

Relay	Resistance (Ohms)	Working Current	Controlled Current
Very sensitive, slow working	500	0·01 mA	50 mA
Telephone relay, quick working	2,000	1·5 mA	200 mA
Telephone relay, quick working	500	6 mA	200 mA

Attention should be drawn to the ballistic use of electromagnetic instruments for measuring quantity of electricity, for this use has been unduly neglected. A ballistic galvanometer may replace an electrometer in the constant time method of page 116, and is not much less sensitive [3]; it may also serve as a tuned circuit in valve amplification (see page 135).

Electrostatic Methods—General Theory. In electrostatic methods a potential difference is measured by means of the force acting on a charged body placed in a field arising from

it. If an unlimited current is available to maintain the potential difference, they are much less sensitive than electromagnetic methods of measuring potential difference. But if the current is limited, because current is really the quantity to be measured, they may be much more sensitive; for the measurement does not demand in principle the passage of any finite current. In practice, however, some current is always demanded for the maintenance of a potential difference, because insulation is never perfect; the sensitivity of electrostatic methods is always limited by the perfection of

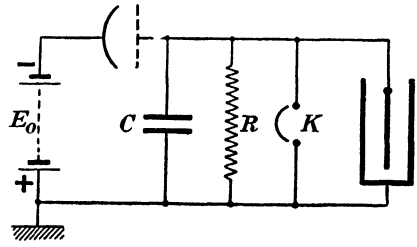


FIG. 48. MEASUREMENT OF PHOTOELECTRIC CURRENT BY MEANS OF AN ELECTROMETER

the insulation. This is most important; it shows at once why electrostatic methods are valuable only with emission cells, which alone possess a sufficiently high internal resistance.

Any instrument for measuring a potential difference electrostatically will be called an electrometer. In the older electrometers the charged body on which the force is measured was a delicately suspended material body, e.g. a gold leaf. It seems possible to-day that they will finally be replaced by the thermionic valve electrometer, in which the charged body is an electron in free space. But many essential principles will remain unchanged by the replacement. Our discussion will therefore be based on the older type of electrometer, and we shall use terms and symbols in the diagrams suggested by the oldest type of all, the gold-leaf electroscope; thus we shall distinguish the *leaf*, an insulated conductor of variable potential, from the *case* maintained at a fixed potential. But we shall be careful not to assume without notice that the leaf is the body on which the forces

are measured, for that assumption is untrue of many of the older as well as of the newer electrometers.

Fig. 48 shows the essential parts of any arrangement for measuring photoelectric currents by means of an electrometer. The anode of the cell is here shown connected to the leaf; nothing would be altered if the cathode were connected to the leaf and at the same time the battery E_0 were reversed. When the switch K is opened, the conductor, consisting of one electrode of the cell, the leaf of the electrometer, one plate of the condenser (if any) and the connections between them, receives the photoelectric current i flowing through the cell; if C is the capacity of this conductor relative to the remainder of the apparatus, the potential E, indicated by the electrometer, begins to rise at a rate given by

$$C\frac{dE}{dt} = i \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$$

so that

$$E = \frac{it}{C} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

But as soon as E becomes finite, part of the current flows away through the resistance, and we have

$$C\frac{dE}{dt} = i - \frac{E}{R} \quad . \quad . \quad . \quad . \quad . \quad (25)$$

so that

$$E = Ri\,(1 - e^{-\frac{t}{t_0}}) \quad . \quad . \quad . \quad . \quad . \quad (26)$$

where $t_0 = RC$.

In the final state all the current flows away through the resistance, and E assumes the steady value

$$E = Ri \quad . \quad . \quad . \quad . \quad . \quad . \quad (27)$$

E in (27) is the greatest reading of the electrometer that the current i can produce, and the ideal sensitivity limit of the apparatus is, therefore, $\Delta i = \Delta E/R$, where ΔE is the smallest change of potential the electrometer will show. R is greatest when it represents nothing but the unavoidable leak of the most perfect insulation that can be used to support the insulated electrodes; it may then be as great as 10^{15} ohms. ΔE need not be greater than 0·001 volt, so that Δi may be as low as 10^{-18} amp. A gas-filled cell may give as

much as 10^{-4} A./lumen, so that 10^{-14} lumen, or the light received on 1 sq. cm. from a candle 100 km. distant, might be detected. But such sensitivity is not really practicable; for the deflection corresponding to E in (27) would not be attained until after a time much greater than t_o; C will not be less than 5 $\mu\mu$F, and therefore t_o not less than $10^{15} \times 5 \times 10^{-12}$ sec. $= 1\frac{1}{2}$ hours. This calculation is given merely to indicate the order of the magnitudes with which we may be concerned here; we will now turn to the conditions of practical use.

Rate of Deflection Methods. The most usual direct-reading methods of electrometer measurement are based on (24). For an absolute measurement, the three magnitudes E, C, t must be determined; but in relative measurements, two of them may be constant and the third determined. In the *constant voltage* method, E and C are constant, and the time required for the current to charge the electrometer to a fixed potential is determined; i is inversely proportional to this time. In the *constant time* method, C and t are constant, and the potential attained in a fixed time is determined; i is proportional to this potential.

Both methods have their virtues and defects. The constant voltage method requires no calibration of the scale of the electrometer, which is often not even approximately linear; the calibrated instrument is a stop watch or chronograph. On the other hand, the constant time method is suitable for automatic registration; for a mechanism can easily be devised to allow the current to flow for a fixed time, and then record the reading of the electrometer. The constant voltage method cannot be used if the electrometer has appreciable inertia, so that the reading does not correspond to the simultaneous voltage; in the constant time method, the instrument can be allowed to come to rest before the reading is taken.

In the constant time method there is no limitation, in principle, to the sensitivity other than that which has been noted already; for, according to (26), i is always proportional to E, for a given t, however large t may be. On the other hand, the sensitivity of the constant voltage method is limited by accuracy; for (24) is not valid, and i is not inversely proportional to t, unless t is small compared with t_0. The limitation thus imposed is the more serious the greater

the difference between the currents to be compared. With sufficient approximation we have

$$\frac{i_1}{i_2} = \frac{t_2}{t_1}\left(1 - \frac{E}{2R}\,\frac{i_1 - i_2}{i_1 i_2}\right) \quad . \quad . \quad . \quad . \quad (28)$$

The expression in brackets must not differ from 1 by more than the permissible error; that is to say, if an accuracy of x per cent is required, it must not differ by more than $x/100$. As representing rather unfavourable conditions, we may take $E = 1$ volt, $R = 10^{14}$ ohms (for our previous value of 10^{15} ohms is not easy to attain); if currents in the ratio of 10 to 1 are to be measured with an accuracy of 1 per cent, the smallest of them must then not be less than 5×10^{-13} amp. It is to be observed that the capacity does not affect this limit; it is important that the capacity should be small, only if a limit to t is set by the speed of measurement demanded and not by its accuracy. In our example, accuracy rather than speed will be the determining factor; for, even if C is as large as 100 $\mu\mu$F—it is not likely to be so large—t for the smallest currents is only 200 sec. In fact, it is probable that C would be deliberately increased by the insertion of a condenser in order to make the time for the largest currents conveniently long.

But though the constant time method is preferable in this respect to the constant voltage method, in another respect it is inferior. We have supposed so far that the current to be measured is strictly constant, and does not vary during the measurement; this assumption will fail if the current is not saturated, for the voltage across the cell falls as that across the electrometer rises. This is a very serious source of error in the constant time method when gas-filled cells are used; for in such cells used at a moderate gas factor the current will change at least 2 per cent for a change in voltage of 1 volt, and, if they are used near the limits fixed by the glow potential, it may change 10 per cent. The constant voltage method is free from this defect, if (as is usual) the measurement of current is only a means to the measurement of illumination. For since the same range of voltage is covered in each observation, t will still be inversely proportional to the illumination, if at any constant voltage the current is proportional to the illumination. To prove

this we may use the conception of the characteristic conductivity of the cell (see page 70), and substitute $1/\gamma i$ (for R in (26)), so that

$$E = \frac{1}{\gamma}\left(1 - e^{-\frac{\gamma i t}{c}}\right) \quad . \quad . \quad . \quad . \quad . \quad (29)$$

i enters only in the combination it.

From (29) we may derive also a formula, similar to (28), for the error incurred by the use of the constant time method; it is

$$\frac{i_1}{i_2} = \frac{E_1}{E_2}[1 + \tfrac{1}{2}\gamma(E_1 - E_2)] \quad . \quad . \quad . \quad (30)$$

The *relative* error thus depends on the difference between the *absolute* values of the extreme voltages observed. For 1 per cent accuracy, this difference must not exceed 1 volt if $\gamma = 0{\cdot}02$, nor 0·2 volt if $\gamma = 0{\cdot}1$. There is no limit in either direction to the magnitude of the currents, so long as the fixed time and the capacity are chosen so as to reduce the extreme voltages observed within these limits; since an increase of capacity will always result in a reduction of the voltages, no difficulty need ever be experienced in fulfilling the condition; on the other hand, an electrometer with a low sensitivity limit for voltage may be required in order that voltages within the narrow range imposed by accuracy may be distinguished.

Steady Deflection Method. A third possible direct-reading method is based on (27); the switch is kept open until a constant reading of the electrometer is attained; this reading is proportional to the current. This may be regarded as a variant of the constant time method in which the time chosen is long compared with t_0, so that its exact value is immaterial. It is essential that the resistance R should be constant; the insulation leak is never very constant; for this reason, and also in order that the time required for an observation may be kept within reasonable limits, it is necessary to insert an artificial leak of resistance R_0, small compared with the insulation resistance R and in parallel with it. The sensitivity is necessarily reduced greatly. If a reading is not to occupy more than 1 minute, t_0 must not be

more than 12 seconds, if 1 per cent accuracy is sought; consequently, if C is as low at 20 $\mu\mu$F, R must not be more than 6×10^{11} ohms, and the sensitivity limit for current will not be much less than 10^{-14} amp. This is certainly greater than the sensitivity limit attainable in the measurement of small currents by either of the other methods.

Null Methods. The precision of all these direct-reading methods of measurement is small, being limited partly by sensitivity and partly by accuracy; it is not easy to avoid uncertainties of 1 per cent. In comparison, their precision is somewhat greater because accuracy is no longer essential, and with carefully-designed apparatus currents differing by only 0·1 per cent may be distinguished. On the other hand, most of the difficulties that we have been discussing disappear if null methods are used. Either of the two methods described on pages 107, 108 may be adopted. The leads to G in Figs. 45 and 46, are represented by the leads to the leaf and earthing switch and to the case; a balance is attained when the electrometer does not begin to charge up if the switch is opened.

When compensation is by means of an ohmic resistance R_0, the sensitivity limit for current is $\Delta E/R'$ where $1/R' = 1/R_0 + 1/R$; in order that there may be no sacrifice of sensitivity, R_0 must not be small compared with R. The objections to a large value of R_0 in the steady deflection method, which is closely similar, are no longer serious, because there is no need to wait until the deflection becomes steady before taking a reading. But, actually, resistances greater than 10^{12} ohms (which is much less than the insulation resistance should be) are not often employed, because it is difficult to obtain such resistances obeying Ohm's Law. The method is valuable when currents of the order of 10^{-12} amp. or more have to be measured, but is not to be recommended for very small currents. The second of the two methods, namely, compensation by the current from another photoelectric cell subject to a controlled illumination, is entirely suitable, even for the smallest currents. But there may be some difficulty about calibration when the absolute magnitude of the current has to be known.

The best method in these circumstances is usually one not mentioned in the preceding chapter, because it is

suitable only in conjunction with an electrometer. This is compensation by electrostatic induction (Fig. 49). As the insulated electrode charges up with the current through the cell, its potential is reduced to zero by inducing on it an equal and opposite charge through the condenser C_0, of which one plate is connected to the leaf, by raising the potential E_c of the other plate by means of a potentiometer. (C is now the unavoidable capacity of the leaf, and its connections; R is the insulation resistance.) In this procedure the switch is opened when $E_c = 0$; the light is then thrown on the cell by means of a shutter for a period t. During this period the electrometer is kept near zero by

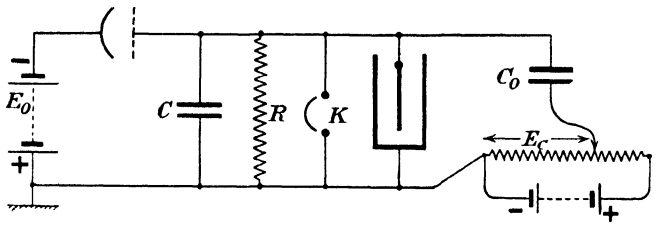


FIG. 49. COMPENSATION BY ELECTROSTATIC INDUCTION

means of the potentiometer, in order to reduce insulation leaks to a minimum. After the shutter is closed again, it is adjusted accurately to zero. If E_c is the final reading, $i = E_c C_0/t$. The only calibration required is a measurement of the capacity C_0, which is permanently stable if the condenser is properly made; the same condenser can be used in different experiments. If small currents are to be measured, C_0 should be small compared with C, in order that the speed of the measurements should not be reduced, and a wide range obtained by using large values of E_c. This is an admirable method; the necessity of turning the light on for accurately-timed intervals is not an objection (4).

Vacuum and Gas-filled Cells. In both of the last two methods of compensation, the ideal sensitivity limit of current is the maximum obtainable, $\Delta E/R$ or, as it is more conveniently expressed for our present purpose, $\Delta E.\Gamma$, where $\Gamma = 1/R$ is the conductance of the insulation. But it is most important to observe that Γ includes the conductance of the cell when it is passing the current i that is being

measured. In fact, if Γ' is the pure insulation leak, $\Gamma = \Gamma' + \gamma i$. Incomplete saturation will not affect the accuracy of null methods, as it does that of direct-reading methods, but it will affect the sensitivity. Now γ is much greater for gas-filled cells than for vacuum cells; it appears at once that, if i is sufficiently great, Γ will be greater for the former than for the latter, and that a lower sensitivity limit and a greater sensitivity will be obtained with the vacuum cell. Moreover, we must remember that for the same illumination i is greater for the gas-filled cell; but, on the other hand, since relative sensitivity for illumination is important rather than absolute sensitivity for current, a larger sensitivity limit will be tolerable. We must inquire more closely.

Let us measure illumination L, in micro-amperes, by the saturated current it produces in a vacuum cell, and suppose that, with any given voltage applied to the gas-filled cell, i is proportional to L. Then we may write

$$i = mL \qquad . \quad . \quad . \quad . \quad . \quad . \quad (31)$$

where m is 1 for the vacuum cell and equal to the gas factor in a gas-filled cell. The quantity which is to be made as small as possible is $\Delta L/L$, the relative sensitivity for illumination. When the cell and the voltage at which it is to be used are fixed, we have

$$\frac{\Delta L}{L} = \frac{\Delta i}{i} = \frac{\Delta E.\Gamma}{i} = \Delta E\left(\frac{\Gamma'}{mL} + \gamma\right) . \qquad . \quad (32)$$

There is no reason why Γ' should vary with the type of cell. Let us now assume $\Gamma' = 10^{-14}$ mho, and the following values for m and γ, which are favourable to the gas-filled cell.

Vacuum cell . . .	$m = 1$	$\gamma = 0{\cdot}001$
Gas-filled cell . . .	$m = 50$	$\gamma = 0{\cdot}05$

Then it appears that the vacuum cell is more sensitive unless L is less than $0{\cdot}2 \times 10^{-6}$ μA, which is an illumination less than is likely to occur in any of the more usual applications, except stellar photometry. In the photometry of lamps and the measurement of absorption in the visible spectrum, to which compensation methods have been often applied, L is more likely to be of the order of 10^{-3} or even 10^{-2}.

Perhaps this is not quite the whole story. The speed of

observation is greater if gas-filled cells and larger currents are used; speed increases regularity, since irregular changes in the electrometer zero are less important, and thus increases the effective, as distinct from ideal, sensitivity. But this ideally greater speed will not be effective if L is greater than 10^{-5} μA; for a current of that magnitude charges a capacity of 50 $\mu\mu$F. to 0·1 volt in $\frac{1}{2}$ sec., which is less than the period required for an observation. On the other hand, vacuum cells have advantages of their own that have not been taken into account. They are much more regular in their action, their sensitivity is more independent of their previous history, and, since their current is nearly saturated, constancy of the battery potential E_0 is less important. These features tend to make the effective approach the ideal sensitivity. In short, vacuum cells should be regarded as normally most suitable for null methods using an electrometer; there may be circumstances, such as imperfect insulation or very small illuminations, in which gas-filled cells have the advantage, but they should not be used unless there is definite positive evidence that these circumstances have arisen.

One further remark should be made in order to avoid misunderstanding. Since the greater current sensitivity of gas-filled cells does not make them preferable to vacuum cells, it might be concluded rashly that variations of current sensitivity in cells of the same class are unimportant. But in our comparison we have supposed that the photoelectric emission is the same in the vacuum and gas-filled cell; increased current sensitivity arising from increase in the emission is always desirable.

Electrometers. We will now proceed to experimental details which, though far less important than they were, still cannot be ignored entirely in any practical work on photoelectricity. We will start with electrometers.

The first class is that in which the leaf, which is charged by the current, is the body moved by the electrical forces. In the oldest sub-class, no subsidiary potentials are employed; Phillips' ticking electroscope is the sole remaining representative, and is still useful when very rough measurements are sufficient and simplicity is the primary consideration.

It is essentially a diverging leaf electroscope, in which the leaf, when it attains a certain divergence, touches the case, is discharged, and collapses. In order that the leaf may not stick when it touches, it is best made of a carbon filament attached to an insulated fixed plate by a gold-leaf hinge, while the part of the case that it touches is the end of a carbon rod carried on a screw by means of which its distance from the plate can be varied (see Fig. 50). If the screw is

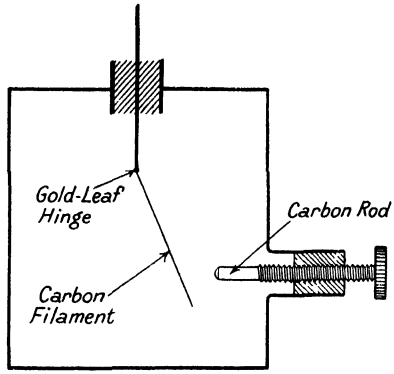


FIG. 50. "TICKING ELECTROSCOPE"

set so that the leaf touches it when its potential is E (about 50 volts), the leaf will "tick" (i.e. diverge and collapse) n times per second, where $n = i/EC$ and C is the capacity; in practice n should not be more than 2. The method, being a modification of the constant voltage method, is applicable even to gas-filled cells, although much of their advantage is lost, because the voltage across the cell drops E volts during the observation. The instrument cannot be trusted for a relative precision better than 10 per cent.

In the newer sub-class, subsidiary potentials are employed. Of these, the Lindemann and Wulf electrometers are the best known examples. The Lindemann is generally preferred by those who buy an instrument; for details, reference may be made to the descriptive pamphlet of the Cambridge Instrument Co. But those who want to make their own instrument should approximate more nearly to the Wulf; accordingly our description of the type will be

based on it, though much of what follows is equally applicable to the Lindemann.

In the arrangement shown in Fig. 51, a very light conductor lies between two plates P maintained at equal and opposite potentials from earth or, more accurately, from the potential of L when the earthing switch is closed. The equilibrium of L is unstable in respect of the electrostatic forces from the plates, and, if these acted alone, L would fly to one

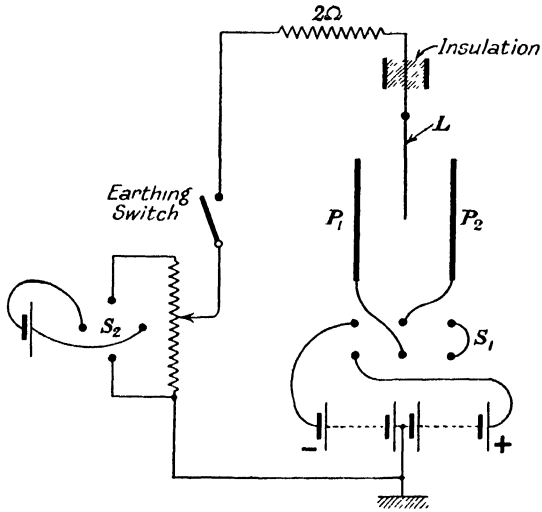


FIG. 51. TYPICAL ELECTROMETER CIRCUIT

plate or the other; stability is given by the weight of L, and sometimes by elastic forces due to a spring attached to its lower end. The two sets of forces are nearly balanced, leaving a slight margin of stability; the less this margin the greater the sensitivity. But the balance never extends equally over the whole space between the ends; if there are no elastic forces, instability will enter when the deflection is too large. The deflection of L is not proportional to its potential above earth except over a small central range. It may be observed either through a microscope or preferably by projection on a screen. Since many experimenters are not as familiar with projection as with galvanometer spots, it may be recorded that an image magnified at least

20 times and visible from a distance, without shading, in a well-lighted room can be obtained with a microscope objective of 1 in. focus, if a 24-watt motor-car headlight with a condensing lens 3 in. in diameter is used as illuminant.

In the professionally made instrument, L is a silvered quartz fibre, but the amateur will be wise to avoid quartz fibres, unless he has previous experience of them; for though they are probably more sensitive than any other form of leaf, the formation of a permanent conducting layer and the mounting of the fibre are very difficult. Gold-leaf is an alternative, but is not pleasant to observe; a carbon filament (still obtainable from lamp makers), hung by a gold-leaf hinge, is preferable, and not very difficult to make; Wollaston wire involves an appreciable sacrifice of sensitivity. A good substitute proposed recently is a straight, fine wire supported at its *lower* end, so long that the gravitational and elastic forces nearly neutralize each other, and the wire nearly, but not quite, bends over under its own weight; a plane loop or hairpin is still better because it will deflect only in one plane. Tungsten is probably the most suitable metal for the wire, but others might serve. The defect of this device is that the instrument is very sensitive to changes of level.

The case of the electroscope should be made as small as possible, and should be lagged thermally, for convection currents disturb the leaf. The distance between the plates should be roughly adjustable; the position of the support of the leaf L relative to the plates should be finely adjustable. The potentials of the plates will be of the order of $\pm$ 50 volts; it is not essential that the potential of the plates should be precisely equal. A grid leak of 2 megohms should be placed between the leaf and the key (as shown) to protect the leaf if it touches a plate. In adjusting, the plates should first be placed far apart and the leaf moved until, when the potential is applied to them, the leaf does not move; for this purpose the switch S_1 is useful. The sensitivity is then tested by applying about $\frac{1}{2}$ volt to the leaf by switch S_2. If it is not sufficient, the plates should be brought nearer and the adjustment repeated. The greatest practicable sensitivity is reached when the potential of $\frac{1}{2}$ volt throws the leaf beyond the range of stability, so that

it flies over to one plate. A large distance between the plates and a high potential gives rather greater sensitivity than a small distance and a small potential; but there is a considerable range in which distance and potential may be adjusted to each other to give the same sensitivity.

A voltage sensitivity limit of 0·01 volt may be obtained easily with these instruments, the time of the (completely damped) swing of the leaf being less than 1 second. The capacity will be about 10 $\mu\mu$F.

The second class of electrometer, descended from the Thomson quadrant, is that in which the moving body is not the leaf (in our sense), but is maintained at a constant potential. The Compton electrometer is the modern representative; again reference is made to the descriptive pamphlet of the Cambridge Instrument Co. A voltage sensitivity limit of less than 0·001 volt is easily attained, the period of swing being 9 seconds and the capacity about 10 $\mu\mu$F.

The long period makes the constant voltage method impossible, and the constant time method very tedious and somewhat inaccurate; for the effective capacity of the electrometer varies with the deflection and, if E is variable in (24), C cannot be assumed constant. The usual substitutes for these methods, when an electrometer with considerable inertia is used, are the rate of deflection and the ballistic methods. In the first the switch is opened, and the spot allowed time to take up a constant velocity along the scale; this velocity is taken to be proportional to the rate at which the electrometer receives charge, i.e. $\frac{dE}{dt}$. In the second, the switch is opened for a constant time and the maximum deflection of the spot taken as proportional to the charge acquired; in both cases the factor of proportionality is determined empirically. It can be shown that if certain assumptions about the behaviour of the electrometer are true, either of these methods is legitimate; actually they are not true, and neither method is accurate, unless the assumption of proportionality is abandoned and a detailed calibration undertaken.

On the other hand, the long period is no objection for the steady deflection method; for here it is usually less than

the period required for the final value of the potential to be reached. Since here nothing but voltage sensitivity is required, the quadrant electrometer is clearly preferable to the leaf electrometer. Its value in null methods depends somewhat on the temperament of the operator. A naturally slow worker will not be made slower by the extra time that is necessary to decide in which direction the instrument is tending to deflect, and he will be able to make use of its higher ideal sensitivity; a quick and probably impatient observer will do better with the speedier though ultimately less sensitive instrument; for it must be remembered that irregularities are likely to enter if the time occupied in setting a balance is prolonged.

For the most sensitive work, which hardly falls within our scope, mention may be made of the Hoffmann "duant" electrometer, in which there is only a single pair of "quadrants" above which moves a light suspended "needle" forming a sector of a circle ([5]). It is designed so that the destabilizing electric forces very nearly balance the stabilizing forces. It is certainly the most sensitive instrument known for measuring charge (with the exception of the suspended drops of Millikan and Ehrenhaft); its peculiar properties make it misleading to assign to it a definite capacity and voltage sensitivity, but it has a sensitivity limit for charge of the order of 10^{-16} coulomb, which would be attained by electrometers of other types only if they combined a capacity of 10 $\mu\mu$F. with a voltage sensitivity limit of 10^{-5} volts.

The thermionic valve electrometer, which falls in this class, will be discussed in the next chapter.

Insulation. Insulation is one of the main problems of electrometer technique. The supports of the insulated system connected to the leaf must not only have a very high resistance, but must also be free from electric hysteresis and the tendency to acquire surface charges. The materials generally used in instrument making and electrical engineering—ebonite, rubber, silk, and so on—are quite unsuitable for such supports, though, of course, they may be used where they serve merely to prevent short circuits of batteries. There are only four solids worthy of consideration, amber, sulphur, quartz, and certain waxes or cements; and of these the last two are included with hesitation. Amber is almost universally

employed in Germany; if the right material can be obtained and the technique of working it mastered, it is the best of all. Sulphur is as good an insulator, but its mechanical properties are less suitable. It should be cast in place from a temperature just above its melting-point; since it contracts greatly on solidifying, the parts that it separates should be provided with keys, so that the sulphur cannot slip at its boundaries. Just after solidification sulphur is soft, and can be cut with a sharp tool; later it becomes hard and brittle; but its surface—and insulation leaks are due almost entirely to surface conduction—can be readily cleaned by scraping. Quartz is much stronger than amber or sulphur, and is sometimes convenient in the form of rod or tube; but not all specimens are trustworthy, and we should always prefer amber or sulphur; it must be cleaned by heating to redness and kept clean thereafter.

Of the waxes, we can recommend "Bank of England" red sealing-wax (but not other varieties) and the German black Picein; probably others are equally satisfactory, but we speak of what we know. They are useful for coating other materials, and, in particular, glass. The weakest link in the chain of insulation is (or ought to be) the wall of the photoelectric cell, where the lead emerges; for here glass must be used. The borosilicate glasses, rich in silica (e.g. Pyrex), are much better insulators than soft soda glass; they are preferable for other reasons as a material for cells, but they are improved by a coating of one of these waxes. The waxes should never be heated in the flame, but rubbed on the glass when it is just hot enough to make them run easily.

The smallest possible volume of insulation should be used and mechanical strain avoided, because it develops piezoelectric charges. The insulation is best tested by charging up the insulated system, and observing the fall of its potential. The time required to fall to $1/e$ of the initial value is t_0 of page 115; it should never be less than 15 minutes.

Shields and Switches. The whole of the insulated system must be enclosed in an earthed metallic case of the smallest possible volume. Leads should be carried through tubes and supported by insulation at the ends only. It is sometimes recommended that the tubes and the lead should be of the same material, in order that voltaic E.M.F.'s may be avoided;

but this is not necessary if the insulation is good. If the insulated system tends to charge up when it is not connected to the cell, either the insulation is bad or the shielding is insufficient, or some part is not efficiently connected to earth or other fixed potential. A "zero leak" arising outside the cell should never be tolerated. Earthed guard rings should be inserted whenever the insulated electrode is in solid connection with any conductor not at earth potential.

Since some observers still seem to regard "dark current" as an inevitable evil in photoelectric work, it may be well to insist once more that there are only two causes of it that cannot be avoided by proper design of the apparatus. The first is the thermionic current (see page 51); this can be distinguished because it is saturated in vacuum cells and changes in magnitude when the field is reversed. The second is the corona current, which only occurs very near the glow potential of a gas-filled cell and increases very rapidly with the voltage. Other "dark currents" can always be eliminated by the use of guard-rings and by proper shielding; no cell should be used for sensitive and accurate work without an internal guard ring. Of course, guard rings will not prevent leakage to earth; but they will prevent dark current.

The leads to the cell, electrometer, condenser, and any other connected parts are best brought independently to a central box containing the earthing switch. The earthing contacts should be of gold or other unoxidizable material; the make and break should not involve scraping, and should not place great strain on the insulation; if these precautions are neglected a troublesome jump of the electrometer will occur when the switch is opened. If the shielding is adequate, it is not essential that the "earth" should really be earthed; the "earth" can be any conductor to which all the "earthed" parts are solidly connected.

Condensers. The condenser used for the compensation method of page 120 must have air (or vacuum) as its dielectric; and so must any condensers that may be introduced (as is sometimes convenient) to diminish the rate of change of potential, if accuracy is required. All solid dielectrics show appreciable hysteresis, which is fatal. Fig. 52 shows a good construction for the compensating condenser, having a

capacity of about 6 $\mu\mu$F.; this capacity should be small compared with that of the rest of the system in order that the whole capacity should not be increased. An important element is the flange shielding the insulated electrode from the surface of that part of the insulation which is exposed to the applied field.

Resistances. Satisfactory high resistances for the steady deflection method or the ohmic resistance compensation method used to present a difficult problem, but now are commercial articles. Up to 10 megohms or even more, grid leaks, in series if necessary, will serve; beyond this special

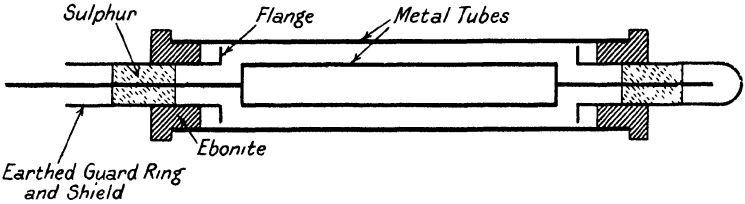


FIG. 52. CONDENSER FOR USE IN COMPENSATION METHOD
Not to scale—about half full size

resistances are available ([6]). For those who wish to make their own, three methods are available—

1. Streaks of carbon in some form on ebonite or other insulator, or lines of indian ink ruled on paper. The latest form is quartz rod smoked in a flame; our limited experience with it is wholly favourable.

2. Metal films sputtered or evaporated on glass or quartz surfaces.

3. Mixtures of alcohol and benzene or toluene, possibly with the addition of other ingredients; 10 per cent alcohol and 90 per cent benzene gives about the required conductivity.

All these conductors obey Ohm's Law, but none is very constant in resistance. Of conductors not obeying Ohm's Law, none but the Koch device (see page 182) needs mention; with so many good resistors available, it is foolish to-day to put up with a bad one. Nobody really seems to have succeeded in using resistances of more than 10^{13} ohms; 10^{12} is probably sufficient for any but quite exceptional purposes.

REFERENCES

1. For electrolytic measurement, see C. T. R. Wilson, *Proc. Camb. Phil. Soc.* 19, p. 345, 1930; W. R. G. Atkins and H. H. Poole, *Sci. Proc. Roy. Dublin Soc.* 19, p. 159, 1929.

2. The Cambridge Instrument Co.'s catalogue is of most value; the instruments given have been taken from it, but, of course, similar instruments are made by others.

3. For use of ballistic galvanometer, see E. B. Moss, *Proc. Phys. Soc.* 43, p. 254, 1931.

4. For a well-designed measuring system, see E. B. Moss, *Photo-electric Cells and Their Applications* (*cit. ante*), p. 71.

5. For Hoffmann electrometer, see G. Hoffmann, *Ann. d. Phys.* 52, p. 665, 1917.

6. High resistances.

(*a*) Commercial resistances are offered by Shallcross Manufacturing Co., 700 Parker Avenue, Collingdale, Pa., U.S.A.

(*b*) For carbon resistances, see G. W. Stewart, *Phys. Rev.* 26, p. 302, 1908; H. E. Ives, *Astrophys. Journ.* 39, p. 428, 1914; A. K. Brewer, *Rev. Sci. Inst.* 1, p. 325, 1930; H. C. Reutschler and D. E. Henry, *Rev. Sci. Inst.* 3, p. 91, 1932.

(*c*) For metal films, see E. Perucca, *Comptes Rendus* 189, p. 527, 1929; F. Kruger, *Zeit. f. Techn. Phys.* 10, p. 428, 1929; F. Joliot, *Comptes Rendus* 190, p. 627, 1930; L. C. Van Atta, *Rev. Sci. Inst.* 1, p. 687, 1930.

(*d*) For liquid resistances, see N. R. Campbell, *Phil. Mag.* 23, p. 668, 1912; A. Gyemant, *Wiss-Veröff. d. Siemens Konzern* 6, p. 58, 1928; and 7, p. 134, 1928.

CHAPTER VIII

VALVE AMPLIFICATION

Valves as Electrometers. Any thermionic triode can be regarded as an electrometer of the second class (page 126). The grid is the "leaf," the cathode the case, the electrons emitted from the cathode are the needle; their motion under the potential difference E_g applied between leaf and case is observed, not mechanically, but by the change in the anode current i_a; this difference does not make most of the last chapter any less relevant. Let us start, then, by studying valve amplification from this point of view.

The ideal sensitivity limit of a triode electrometer is $\Delta E_g = \Delta i_a/M$, where M is the mutual conductance, di_a/dE_g and Δi_a is the least perceptible change of anode current. If a null method is used (see below) and the change of anode current read on a sensitive galvanometer, Δi_a may easily be as small as 10^{-9} A.; M may be at least 10^{-3} (1 mA per volt); so that ΔE_g may be as small as 10^{-6} volt; a valve electrometer is ideally much more sensitive to potential difference than any other.

But for photoelectric work current sensitivity, not voltage sensitivity, is required; this is, as we have seen, limited by the insulation resistance R. In ordinary valves R is not much greater than 10^9 ohms, which is much less than that of ordinary electrometers. Accordingly, until a few years ago, valves were less sensitive than electrometers for measuring small currents. But a careful study of the source of grid leakage by Metcalf and Thompson [1] has entirely changed the position. The leakage is partly due to faulty solid insulation, which can be greatly reduced by suitable construction, involving a grid lead brought out far from the remaining leads. But it is also due to an internal grid current i_g flowing across the "vacuum." This current, which we shall consider more closely later, is mainly due to the presence of positive ions formed by ionization of the residual gas by the electrons; it can be abolished almost completely by using an anode voltage so low (e.g. 6 volts) that the

electrons never gain the energy required for ionization (page 53).

Special electrometer valves are now made in which these principles are applied. The first of them was the American FP-54, but similar valves are now made by all the chief makers. The doubts expressed in previous editions of this work concerning the utility of valves for the amplification of very small currents are now removed. The very low anode voltage reduces M to about 0·08 mA./V; on the other hand, R can be as great as 10^{-15} ohms and the ideal current sensitivity limit can be as low as 10^{-20} A. The grid capacity is less than 2 $\mu\mu$F.

External Irregularities. Nevertheless, a distinction has still to be made between ideal and effective sensitivity. The anode current corresponding to $E_g = 0$ is never perfectly steady; at high sensitivities the galvanometer in the anode circuit has a steady drift on which are superimposed irregular variations. Some of these are of extraneous origin, and are due to the valve being a very sensitive "detector" of high-frequency disturbances. They can be removed by enclosing the apparatus completely in a conducting shield, preferably earthed; but the enclosure must be complete, and, in the last resort, must contain the whole apparatus, including the batteries, and the source of light. Some experimenters, finding practically no benefit from partial enclosure or from placing large condensers across all leads, have rashly concluded that the irregularities that troubled them were not of external origin. But in the matter of shielding, it is the last step that counts; the final sealing of some crack that looks too small to be noticed, or the substitution of a soldered for a less perfect connection, will often make the whole difference between success and failure.

In addition to those disturbances removable by shielding, there are others removable by enclosing the valve, together with the cell, in a vacuum. Their origin is not quite certain; it may be irregular surface leakage or, more probably, ions arriving from the atmosphere; but it is certainly necessary to remove them by this means, if precision is required.

Another source of irregularity lies in the batteries supplying the cathode filament, the grid bias, and the anode current. If sound batteries are used, the irregularity consists

mainly in a steady drift, which is not always objectionable; but any trouble from this source can be eliminated by suitable methods of compensating the anode current for $E_g = 0$, which is necessary in any case if a sensitive galvanometer is to be used. The principle of symmetry suggests that compensation should be by another similar valve, and many bridge circuits employing this method have been described. But experience with them shows that it is very difficult to obtain two valves really similar, even by selection from a large number. Accordingly, modern practice tends away

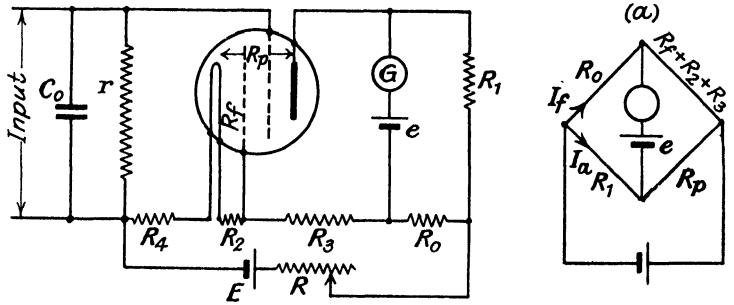


FIG. 53. COMPENSATION BY OHMIC RESISTANCE

from this procedure and towards compensation by an ohmic resistance in a manner essentially similar to that of Fig. 45. A circuit proposed for this purpose by Soller is shown in Fig. 53; further developments are described in the references.

A single battery, whose effective E.M.F. E_b is variable by R, supplies both the anode voltage E_a and the filament current I_f; I_f flowing through R_4 provides the negative grid bias, and flowing through R_2 provides positive bias for a space-charge grid. (Not all electrometer triodes have space-charge grids.) If the valve behaved as an ohmic resistance and if the battery e in the galvanometer circuit were omitted, the arrangement would be the Wheatstone bridge shown in Fig. 53*a*, and the balance would be independent of E_b. But the valve is not an ohmic resistance and the balance varies with E_b; Soller therefore ingeniously introduces e in the galvanometer circuit, which also makes the balance vary with E_b, and arranges matters so that the two

variations are equal and opposite. The conditions to be fulfilled are

$$E_a - e = I_f(R_f + R_2 + R_3) \quad . \quad . \quad . \quad (33)$$
$$R_0 \, . \, I_f - e = I_a R_1 \quad . \quad . \quad . \quad . \quad . \quad (34)$$

together with the equations resulting from differentiating (33) and (34) by E_b. If the valve is to be run at prescribed I_a, I_f, E_a, and grid biases, only three quantities remain for adjustment, R_0, R_1, R_3, since e is fixed by being the E.M.F. of some cell. Accordingly, it is not possible in principle always to secure adjustment. But actually sufficient adjustment can be secured, especially if the characteristics of the

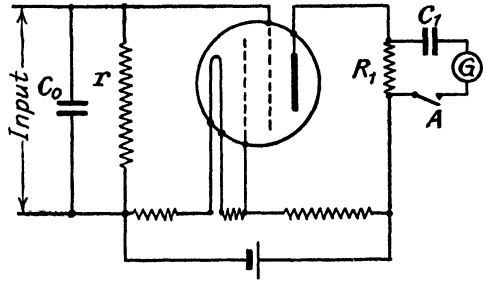


FIG. 54. BALLISTIC USE OF GALVANOMETER

valve are suitable, for it is not necessary to run the valve at exactly the prescribed values. The best procedure is to assume the prescribed values and from them determine R_2, R_4, and then R_3 according to (33). Then choose R_1 so as to be about equal to the galvanometer resistance, and set E_b so that I_a is right. Now balance by means of R_0 and try whether the balance is independent of a small change of R. If it is not, R_1, E_b, or both should be altered; after a few trials the direction of the change of balance due to a small change in R will indicate the direction in which an alteration should be made. The whole process is not nearly as difficult as it sounds; if there is any real trouble it probably lies in an unsuitable valve.

Another very simple method, suitable in some circumstances, is shown in Fig. 54. Here the galvanometer is used ballistically. With the cell dark, the galvanometer will remain at zero, even though there be "dark current" in the

cell and even though the anode current is changing, so long as the change is so slow that it is inappreciable during t_0, the period of swing of the galvanometer. If light is now thrown on the cell and maintained for a time at least equal to t_0, the change in the anode current δi_a will send a quantity of electricity $R_1C_1 \cdot \delta i_a$ through the galvanometer. In principle this may be made as large as desired by increasing C_1. Some limitations, however, must be noticed. Neither rC_0 nor R_1C_1 must be large compared with t_0. R_1C_1 usually presents no difficulty; for the value of C_1 that gives a sensitivity as great as that limited by other irregularities (say, 10 μF.) is consistent with this condition. But it may be difficult to make rC_0 small enough; for C_0 is the irreducible capacity of cell and valve (say, 5 $\mu\mu$F.), and reduction of r decreases sensitivity. It may, however, prove possible to overcome this difficulty by breaking the galvanometer circuit at A, while the photoelectric current i charges C_0 up to the final potential i/r, and then discharging C_1 through the galvanometer. This method is not yet fully established, but is promising.

Internal Irregularities. Other irregularities are due to instability of the thermionic emission of the cathode which (like photoelectric emission) is very sensitive to anything that may alter its surface. They are most noticeable when the valve is first brought into action or its circumstances otherwise changed. It should be a strict rule to make switching on the filament the last operation in starting up, and switching it off the first in shutting down; preferably the apparatus should be run continuously without either operation. But even when these precautions are observed, rapid changes in either direction persist. They could probably be reduced by using "bright emitter" cathodes of pure tungsten, but this is undesirable on other grounds.

Moreover, if they were eliminated, sources of irregularity would remain which are unavoidable even in principle. One of them lies in what used to be called *Schweidler's fluctuations*, and is now usually called the *shot effect*. Electrons emerge from a thermionic cathode as bullets from a squad firing individually, and not as bullets from a machine gun. If, on the average, over a long period, N emerge per second, the number emerging in any finite period t will be

not Nt, but $Nt + n$, where n is completely irregular apart from two conditions affecting its average taken over a large number of periods t. They are

$$\left.\begin{aligned} &(1)\ \overline{n} = 0 \\ &(2)\ \overline{n^2} = Nt \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (35)$$

The same will be true if N is not the number of electrons emerging from the cathode, but that arriving at the grid. If the grid circuit is a capacity C shunted by a resistance R, the period t over which the valve averages the current is effectively $\frac{1}{2}RC$*. Accordingly, the change on the grid will fluctuate about its mean value over a range which corresponds to an excess or defect of $\sqrt{(\frac{1}{2}NRC)}$ electrons. If $i_g = N\varepsilon$ is the current carried by the electrons, a simple calculation will show that this fluctuation of the charge on the grid is equivalent to a fluctuation δi in any current that the valve is used to measure, where

$$\delta i = \sqrt{(\varepsilon i_g / 2RC)} \quad . \quad . \quad . \quad . \quad . \quad (36)$$

Now in the most perfect valve i_g is probably of the order of 10^{-15}A; the grid takes up a steady potential only because this current arriving at the grid is neutralized by other currents leaving it; these other currents have their own fluctuations; if these are taken into account the 2 in (36) ought to be omitted. Accordingly we conclude that, since RC will never be much greater than 100 sec., the grid current of 10^{-15}A. must involve a fluctuation in any current measured of about $1{\cdot}3 \times 10^{-18}$A.; and that the sensitivity limit cannot be much less than this (which corresponds to about 8 electrons per second).

* Reams of complicated mathematics have been devoted to calculating the effective value of t of various circuits. But all the results so far obtained could have been reached in a few lines from a simple and ancient proposition. It is this. Suppose that the arrival of a single electron (or other elementary event) causes the indicating instrument to vary from its mean position by an amount θ, and ultimately to return it; let the value of θ at all times after the arrival of this isolated electron be $\theta = f(t)$. Then the R.M.S. fluctuation of the instrument, when N electrons are arriving per second, is given by

$$\overline{\theta}^2 = N \int_0^\infty f^2(t)dt$$

So the integral measures the effective t, apart from a factor determined by the mean sensitivity of the instrument.

There are other equally fundamental sources of inevitable fluctuations, subject to the same general theory, such as those that arise from thermal motions of the electrons. But the fluctuations due to them are somewhat less. The calculation that has just been given leads to a sensitivity limit which accords well with that actually found in practice; it may be concluded, therefore, that this limit really represents the smallest that can ever be attained with existing valves. Nor can much be hoped from improvement in valves, for even if grid current could be abolished, thermal fluctuations, not much less, would remain. Moreover, there are the fluctuations in the photoelectric current i itself, which is subject to precisely the same laws; i can never be measured with a relative sensitivity limit less than that given by

$$\Delta i/i = \sqrt{(e/2iRC)} \quad . \quad . \quad . \quad . \quad . \quad (37)$$

The conclusion is therefore this we have attained. The effective sensitivity limit of the valve electrometer can be made as low as 10^{-17}A., by precautions that are perfectly practicable. For currents much smaller than 10^{-15}A., the valve electrometer is not suitable; claims to have measured currents of 10^{-17}A. with an error of a few per cent need substantiation. It is doubtful whether any more sensitive instrument of any other kind has actually been developed that is available in any but exceptional circumstances. Finally, it may be observed that no increase of sensitivity would result from using several stages of amplification, for the sensitivity of the anode galvanometer is never a limiting factor. However, multi-stage amplifiers are sometimes used, when an insensitive indicating instrument is desired. They must be direct coupled and have independent batteries, or their equivalent, whose variations are amplified together with the current to be measured. Those who are not confident in their experimental skill should be cautious in attempting them ([4]).

An ingenious arrangement, called the Mekapion, may be mentioned here, for it is the analogue of the Phillips' ticking electroscope. It was primarily designed for measuring currents in an X-ray chamber; but it has been used with U.V. photoelectric cells, and might be used with any cells, if convenience is the prime consideration ([5]).

Valves as Relays. A relay is a device by which a small amount of power controls a very much larger amount of power. Relays are generally used for mere detection, as distinct from comparison or measurement, so that it is only necessary that any power on the input side exceeding some limit should liberate power on the output side exceeding some much higher limit. In what follows it will be assumed, unless the contrary is stated, that no more is demanded, though often some chosen relation between input and output is actually achieved. It was, of course, the use of valves as relays that brought fulfilment to the dreams of many early inventors, and enabled automatic control by photoelectric cells to replace visual control in many industrial operations.

The use of a valve as a relay does not differ in principle from its use as an electrometer. But since the anode circuit is required to provide some considerable power, relatively high anode voltage must be used, and there will be appreciable internal grid conductivity due to positive ionization; since ordinary valves are convenient, there will be considerable insulation leak. On the other hand, the conditions are far less exacting, for comparatively large photoelectric currents i are usually available, and no accuracy is demanded. If i exceeds 1 μA., it will be large compared with i_g, the grid current, and will provide all the grid potential that is needed if it is passed through a resistance R of 10^7 ohms, which should be smaller than that of the insulation leak. In these circumstances, the appropriate circuit is very obvious (Fig. 55). The same high-tension supply is conveniently used for the anodes of both cell and valve; the grid bias is adjusted so that the anode current is too small to operate the apparatus G (which is usually an electromagnetic relay) when the cell is dark, and rises sufficiently to operate it when the light falls on the cell. The cell is shown as an emission cell, but it can also be a conductivity cell. (A rectifier cell is not suitable on account of its low internal resistance.) If it is the latter, the greatest sensitivity is obtained if R is equal to the cell resistance; but since a large grid bias is then required, and since the greatest sensitivity is seldom necessary, a much smaller R is generally used. It is to be observed that, in this arrangement, the incidence of light

increases the anode current; a circuit in which it decreases the anode current will be given later (Fig. 57).

But, though this circuit is applicable to the great majority of problems, we shall do well to study the effect of grid conductivity when the photoelectric current is no longer large enough to swamp it. We may take the current amplification $A = di_a/di$ at constant E_a to be the quantity that should be a maximum. For though it does not strictly measure the power amplification, owing to the drop of voltage in the

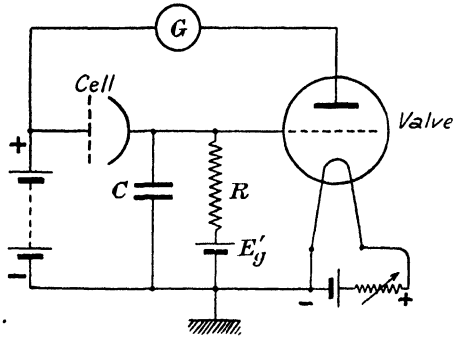


FIG. 55. VALVE AMPLIFICATION

impedance G, the difference between power and current amplification is not serious for our purpose. Now

$$A = M\frac{dE_g}{di}$$

But

$$E_g = E_{g0} + i/(\Gamma + \Gamma_g) \quad . \quad . \quad . \quad . \quad (38)$$

where E_{g0} is the grid bias, Γ the conductivity of the grid leak, R Γ_g the internal grid conductivity of the valve. Hence

$$A = M/(\Gamma + \Gamma_g) \quad . \quad . \quad . \quad . \quad . \quad (39)$$

Fig. 56 shows part of the characteristics of a typical power valve suitable for use as a relay; i_a, i_g (on two scales), and Γ_g are plotted against E_g. M is constant and therefore A a maximum where $(\Gamma + \Gamma_g)$ is a minimum. If Γ were zero and there were no grid leak, the grid bias could not be applied and, when the cell was dark, E_g would necessarily

assume the value corresponding to $i_g = 0$. But this is not the value for minimum Γ_g. Accordingly to make $(\Gamma + \Gamma_g)$ a minimum it is better to make Γ of the same order as the

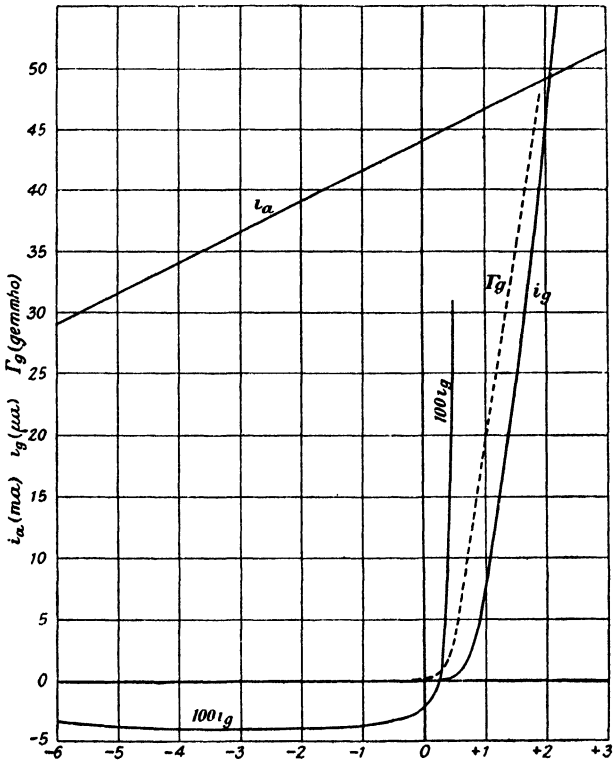


FIG. 56. VALVE CHARACTERISTICS

insulation leak of the valve and apply a negative grid bias so as to make Γ_g zero.

This conclusion, to which any one familiar with valves would be led by common sense, is valid only so long as the photoelectric current and the change of grid voltage are so small that Γ_g may be regarded as constant. It is then immaterial in which direction i flows in R and whether the photoelectric current imposes a positive or a negative potential on the grid. In practice, this condition is not

likely to be fulfilled, because the resulting change of anode current would be insufficient to operate the detecting apparatus in the anode circuit. The more probable condition is that i will be greater than the maximum negative i_g (i.e. the "backlash"), which is about 0·04 μA. at $E_g = -3$ volts. There is now an advantage in making Γ as small as possible, and in connecting the anode of the cell to the grid, rather than the cathode, so that the photoelectric current injects electrons into the grid and makes it negative. For when $i = 0$, the grid potential E_g will be that corresponding to $i_g = 0$, i.e. + 0·2 volt. If i is 0·05 μA. and takes electrons from the grid, charging it positively, electrons will flow in from the cathode; E_g will rise to about 0·3 volt and i_a change by only about 1 mA. But if i is 0·05 μA. again and charges the grid negatively, the electrons injected cannot escape and the positive ions are too few to neutralize them. The grid potential will be carried past $E_g = -3$ and will fall until the voltage across the cell is insufficient to maintain i; if the voltage applied to the cell is sufficient, E_g will fall so far that the anode current will fall from 44 mA. to zero. When light ceases to act, and i falls to zero, the anode current would remain zero, if the insulation were perfect; but with an actual valve the charge on the grid leaks away and after a few seconds the original condition is restored.

Here we have an extraordinarily powerful method of detection. It is also extremely simple when the circuit can be fed from mains giving a potential E_0 of 200 volts or more, and there is no objection to wasting the power required to heat the filament of the valve directly from the mains (Fig. 57). The resistances r_+ and r_- are chosen so that $E_0/(r_+ + r_-)$ is equal to the filament current i_f (the resistance of the filament can usually be neglected), and so that $i_f r_+$ is equal to the appropriate anode voltage; $i_f r_-$ will then be the voltage applied to the cell, and will be great enough, when applied to the grid, to reduce i_a to zero. When no light falls on the cell, i_a will assume the value corresponding to $i_g = 0$; with a "power valve" this will be more than 10 mA.; i_g will be about 10^{-3} μA., and any illumination giving an i greater than this will reduce i_a to zero. The effective current amplification will thus be of the order of one million. The same circuit can, of course, be used with independent

supplies to the valve filament, valve anode, and cell cathode.

The same circuit may be used even if the supply from the mains is alternating current, not direct current. For when the direction of the supply voltage is opposite to that shown in Fig. 57, the valve will pass no current since the anode is negative. The cell may pass a small positive charge to the grid, because the anode has usually some photoelectric emission; but if this emission is very much smaller than that of the cathode (as it usually is), the positive charge

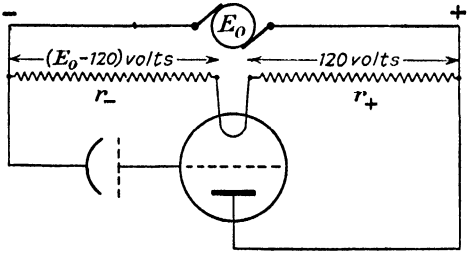


FIG. 57. AMPLIFYING CIRCUIT FOR USE OFF SUPPLY MAINS

received by the grid in this phase will not be enough to neutralize the negative charge received during the opposite phase; when the anode of the valve becomes positive once more, the grid will still be negative. On the other hand, during the change of the valve anode from positive to negative, a positive charge will be induced on the grid; but the resulting rise of potential may be abolished by connecting a condenser of about 0·0005 μF. between the grid and earth. With this addition, the circuit will operate as before and pass current only when the cell is dark; but this current will be smaller, because the anode is positive for only half of the period, and the response will be rather slower, because a larger capacity has to be charged or discharged when the change between light and darkness occurs. It is not strictly necessary now that the cell cathode and valve anode should be connected to points on the resistance on opposite sides of the valve filament; but, of course, the potential across the cell must never be allowed to rise to the glow potential, if a gas-filled cell is used.

The circuit of Fig. 57 can, of course, still be used when the photoelectric currents are large compared with the grid current. A grid leak of the order of 10^7 ohms may then be connected between the grid and a point on the cathode circuit providing the necessary bias; the delay in the return of the system when the light ceases to act is thereby greatly reduced and the operation generally rendered more regular. In fact, the circuit now becomes similar to that of Fig. 55, except that light now stops the anode current and darkness starts it. Fig. 58 shows the circuit as adapted to conductivity cells, for which it is very suitable. S_1, S_2 are two similar cells; the effects of temperature are thereby reduced, since both S_1 and S_2 change in the same sense; the current may be started by light falling on S_2 and stopped by light falling on S_1, the grid bias being suitably adjusted in each case by the ratio r_-/r_+.

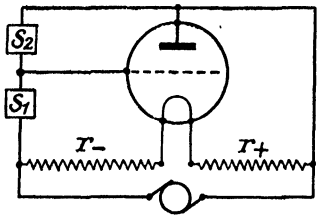


FIG. 58

Thyratrons as Relays. The "hard" valves that we have been considering, though still more widely used than any others as relays, are not now always the most suitable for that purpose. On every ground but expense, gas-filled triodes or *thyratrons* are often preferable. (They are also called gas-filled relays and grid-glow tubes.) These, like ordinary valves, have a cathode, an anode, and a control grid; but the space surrounding them, instead of being highly evacuated, is filled with mercury vapour generated from a small quantity of the metal in the envelope. The presence of this vapour alters the characteristic profoundly. So long as the grid potential lies below (i.e. is more negative than) a certain critical potential E_{g0}, the current in the anode circuit amounts at most to a few micro-amperes. But when it rises above E_{g0}, a glow discharge starts; the anode-cathode potential drops to a fixed value of about 12 volts, so that the anode current is determined almost wholly by the external circuit; and the grid loses control, so that if its potential is reduced again below E_{g0}, the current in the anode circuit continues unchanged. E_{g0} becomes more negative as E_a, the E.M.F.

in the anode circuit, increases. The grid current at potentials below E_{g0} is not much greater than that in ordinary valves at negative grid potentials; but it depends on the temperature and vapour pressure of the mercury and is therefore variable. Accordingly gas-filled triodes are entirely unsuited to the measurement of small photoelectric currents; but so long as these currents are not much less than 1 μA. and exceed the maximum grid current for potentials below E_{g0}, their operation as relays is almost independent of this variability. When the discharge starts, the grid current is large, but its value is then immaterial, since the discharge is independent of the grid potential. A limit to the anode current that can be carried by the discharge is set by the risk of damaging the cathode; in the smallest and most popular type (e.g. Osram G.T.1) the limit is about 0·6A., and is thus much greater than the anode current in the valves we have been considering. This is, of course, the great advantage of gas-filled triodes; they can be used to operate directly a heavy current contactor or other apparatus requiring considerable amounts of power (even as much as 1 kW.), which would demand the use of an intermediate relay if vacuum valves were used.

The simplest circuits employing gas-filled triodes are again those of Figs. 55 and 57, a grid leak being used in the latter; the photoelectric current is passed through the grid leak and carries the grid potential from below E_{g0} to above E_{g0} when it starts (Fig. 55) or when it stops (Fig. 57). In neither case does the anode current stop when the original light is restored. If the relay is to be self-restoring on a D.C. supply, an automatic switch must be provided in the anode circuit, which breaks it momentarily after its work is done and then makes it again; if the grid potential has meanwhile fallen below E_{g0}, the anode current will not start again.

But gas-filled triodes are best adapted to an A.C. supply. Then the anode current is automatically extinguished each time the anode potential becomes negative, or rather each time it falls below E_{a0}, the limit of about 12 volts that obtains while the discharge is passing. The anode current will then flow for about half of every cycle, so long as the grid potential is kept above E_{g0} and will cease within half a cycle of its falling below E_{g0}. Further, it is possible to vary

the mean anode current by varying the fraction of this half-cycle for which the discharge lasts. For this purpose we use the change of E_{g0} with E_a. If the grid potential is kept above the value of E_{g0} for E_{a0}, then the discharge will start as soon as E_a attains this value; if it is kept below E_{g0} for the maximum E_a, the discharge will never start at all; if it is kept just above E_{g0} for maximum E_a, the discharge will not start till E_a attains its maximum and will then continue till E_a falls to E_{a0}. Remembering that the actual anode current, i_a, is determined by the external circuit and not by the triode, as long as the discharge passes at all, we see that, by variation of the grid potential by means of the photoelectric currents, we can give the mean anode current the value 0 or any value between about $\frac{1}{4}i_a$ and about $\frac{1}{2}i_a$; we cannot obtain values between 0 and $\frac{1}{4}i_a$, because no steady grid potential can cause the discharge to start after E_a has passed its maximum and begun to fall.

But if we supply an alternating grid potential of the same frequency as the anode potential, but variable in phase with respect to it, we can give the mean anode current any value between 0 and $\frac{1}{2}i_a$. For we can apply a steady grid bias equal to E_{g0} for E_{a0}. If grid and anode potentials are in exactly the same phase, E_g will then rise above E_{g0} at the moment when E_a becomes positive, and the discharge will flow for the full half-cycle of positive E_a. If they are in exactly opposite phase, and the amplitude of E_g is greater than the difference between E_{g0} for E_{a0} and for maximum E_a, E_g will be below E_{g0} for the entire half-cycle in which E_a is positive; the discharge will never start. If E_g lags slightly behind E_a, E_g will rise above E_{g0} slightly after the start of the positive half-cycle of E_a; if it lags nearly 180° behind, E_g will rise above E_{g0} only just before the end of that half-cycle. The exact relations are somewhat complicated because E_{a0} is not zero and because E_{g0} varies with E_a, but enough has probably been said to show that by this means the mean anode current can be varied continuously between 0 and $\frac{1}{2}i_a$ by variation of the phase difference between E_g and E_a.

The circuit most generally used for introducing an adjustable phase-difference between E_g and E_a is shown in Fig. 59(A). The resistance R is trying to keep E_g and E_a in phase;

the capacity C is trying to keep them in opposite phases, since it is fed from the other end of the transformer. R will win if it is very small; C if it is very great. According to the simple theory that omits all complications, E_g will lag behind E_a by an angle α given by

$$\tan \alpha/2 = 2\pi nCR$$

The lag will be the greater, and the mean anode current the smaller, the greater is R. If R is a conductivity cell,

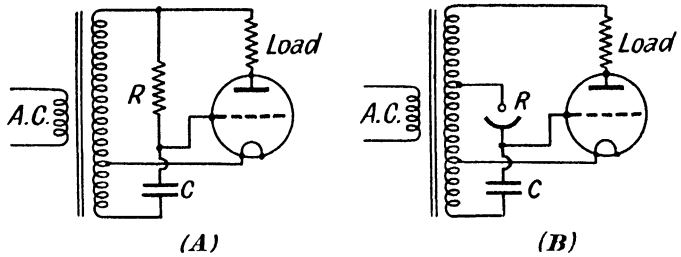


FIG. 59. THYRATRON CIRCUITS

the incidence of light on it, which decreases the resistance, will increase the anode current; the triode will act roughly as an amplifier. R can also be an emission cell as shown in Fig. 59 (B); for though it is then difficult to say to what ohmic resistance it will be equivalent, it will always be equivalent to some resistance which decreases against the light, so long as C and n are unaltered. It would lead us too far to consider in detail the theory of this use of photoelectric cells, which is complicated and never complete. It will suffice to say that with normal emission cells and a supply at 50 p.p.s., the appropriate value of C is of the order of 500 $\mu\mu$F. The optimum value must always be determined by trial; but it is not critical. Lastly, it should be observed that if the positions of C and R (or the equivalent emission cell) are interchanged in Fig. 59, E_g will lead E_a, if the cell passes any current; accordingly there will be no intermediate stage between the full current $\frac{1}{2}i_a$, when the cell is dark, and no current, when it is highly illuminated.

When gas-filled triodes are thus used to vary a large current continuously in accordance with light, they cease to be mere instruments of detection and become in principle

instruments of measurement. It is well therefore to insist once more that they are essentially inaccurate and are not suitable for measurement in any of the narrower senses of the word. Thus they have been used very conveniently to make a motor run faster or slower as a lamp is brought towards or away from a cell; but their use for such purposes does not imply that they could be used, even with the most careful adjustment, to measure the luminous flux from the lamp with a precision sufficient for even the least exacting demands.

Combinations of Cells and Valves. From time to time proposals are made to combine a photoelectric cell and a thermionic valve in the same envelope, usually by making the photoelectric cathode the control grid of the valve. The object is to avoid the insulation leak and the additional capacity attendant on connecting the cathode to the grid outside the cell. But the advantages gained thereby have not proved in practice sufficient to counterbalance the disadvantages; the combination of cell and valve is likely to be inefficient both as a valve and as a cell. A similar proposal that may be mentioned here, although it belongs more properly to the next section, is to construct a gas-filled cell itself as a triode. A grid is introduced between the cathode and anode; alternating voltage applied to this grid causes a periodic emission of electrons from the cathode, which is amplified by gaseous ionization between grid and anode. An alternating output is thereby obtained, which is further amplified by thermionic valves more easily than the usual D.C. output. But this proposal again has not so far been found to present any practical advantages outweighing the drawbacks ([7]).

Valves as Amplifiers. Amplification in the general sense is involved in the use of valves either as electrometers or as relays; but we use the term here to denote the production of a larger current which follows as faithfully as possible the variations of a smaller current. Such amplification is not necessarily involved in the uses we have considered so far, though it may actually be attained when the photoelectric current is small; it is difficult to attain so long as the currents to be amplified are direct, or rather (since the distinction between D.C. and A.C. is one of degree rather than of

kind) so long as the changes in the currents are so slow that the valve may change appreciably during their occurrence. But if the changes are of audio-frequency, the highly developed technique for which valves are primarily designed can be applied; several stages of amplification coupled by condensers or transformers can be used, transmitting only those variations that are to be amplified, and large amplifications can be obtained without the distortion almost inevitable if it is attempted in a single stage.

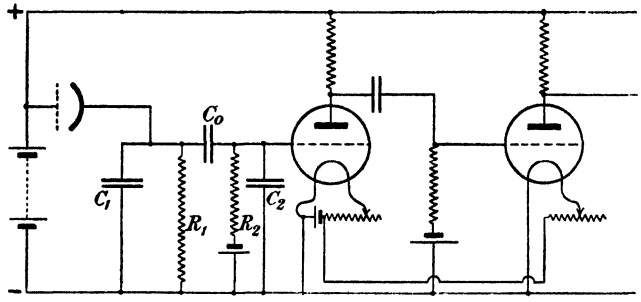


FIG. 60. AMPLIFICATION OF RAPIDLY VARYING PHOTOELECTRIC CURRENTS

The principles involved are too well known to need statement here. We shall consider only matters that are peculiar to the amplification of photoelectric currents; these concern only the input to the first stage, and arise because the circuit is usually of much higher impedance than the input circuit in (e.g.) radio reception. The first two stages of a typical resistance-capacity-coupled amplifier for photoelectric work are shown in Fig. 60.

Our attention is required only for the parts marked C_0, C_1, C_2, R_1, R_2.

At the start let us suppose that C_0 is infinite and C_2 zero. C_1 is the capacity to earth of the electrode of the cell and its connection to the valve. (This electrode is shown as the cathode; it may equally be the anode; indeed it is usually preferably the anode, because the anode, being smaller, has a smaller capacity to earth.) If the current were constant or if C_1 were zero, all the photoelectric current would pass through R_1 and the amplitude E_0 of the voltage across R_1 would be i_0R_1, where i_0 is the amplitude of the current. But

if the current is alternating and C_1 finite, some of the current passes through it; E_0 which determines the output is given by

$$E_0 = i_0 R_1 / \sqrt{(1 + 4\pi^2 n^2 C_1^2 R_1^2)} \quad . \quad . \quad . \quad (41)$$

The second term under the root involves n and therefore implies distorted amplification, unless the input is a pure sine-wave; distortion becomes serious when this term becomes comparable with the first. Moreover, even if distortion does not matter, little is gained by increasing R_1 beyond this point, for after it E_0 increases very slowly with R_1. Thus if R_1 is made so great that the second term amounts to 0·4, the second harmonic is reduced relatively to the first in the ratio 1 to 1·9, a very serious distortion; but a further increase of R_1 can at most increase E_0 in the ratio of 1·6 to 1. This value of R may therefore be taken as the maximum permissible and useful; if small distortions are important, still smaller values must be used. The following table gives this value of R in megohms for various values of n and C—

VALUES OF R FOR CONSTANT DISTORTION

n (p.p.s.)	C_1($\mu\mu$F.)				
	10	100	1,000	10,000	100,000
100	100	10	1	0·1	0·01
1,000.	10	1	0·1	0·01	0·001
10,000.	1	0·1	0·01	0·001	0·0001
100,000.	0·1	0·01	0·001	0·0001	0·00001

The entries in the table also give the relative values of the maximum output for a given distortion obtainable from a given photoelectric current for prescribed values of n and C, i.e. the relative sensitivities of the amplifier. It appears at once how extremely important it is to reduce C_1 to the lowest possible limit when high frequencies are to be amplified. If an emission cell is used, C_1 need not be much more than 10 $\mu\mu$F.; in a rectifier cell it is usually more than 100,000 $\mu\mu$F.; hence even if the rectifier cell gives 100 times as much current, it will be 100 times less sensitive at any frequency for the same distortion.

It remains to consider C_0, C_2, R_2. C_2 is the capacity of the grid of the valve to all the other electrodes and is usually about 5 $\mu\mu$F.; it is not merely the grid-anode capacity, and is greater, not less, than normal in a screen-grid valve. In order that there may be no distortion, C_2 and R_2 must be related as C_1 and R_1; in addition, R_2 must be so small that variations of the valve grid current do not cause variations in the voltage across it comparable with the voltage to be amplified. On the other hand, in order to avoid both distortion and loss of sensitivity, C_0 and R_2 must be so large that C_0R_2 is large compared with $1/n$; but C_0 must not be larger than necessary; since it is impossible in practice to increase the coupling capacity C_0 without at the same time increasing the capacities C_1, C_2 which it couples. The choice is therefore very complex and, except at very low frequencies, it is difficult to fulfil all the conditions perfectly at the same time; thus it is usually impossible to produce a first stage in a photoelectric amplifier which gives the same amplification within 25 per cent over the whole audio-frequency range of 50 to 10,000 except at some considerable sacrifice of sensitivity. But as a reasonable compromise the following values may be suggested, the cell being a gas-filled cell of modern form and the first valve a low-power high-frequency triode

$R_1 = \frac{1}{4}$ megohm, $R_2 = 2$ megohms, $C_0 = 0{\cdot}01$ μF., C_1 and C_2 the unavoidable capacities of cell and valve.

When true amplification is required, it is usual, therefore, to adopt one of two courses. The first is to admit distortion in the first stage and to correct it by opposite distortion introduced in later stages. Of course, perfect correction can never be attained, but very large distortions can be corrected approximately. It is even possible thus to obtain good reproduction of music from talking films by means of conductivity cells, which themselves give enormous distortion owing to their frequency-response curves. This plan of producing distortion and then correcting it offends the purists, but it undoubtedly works—at least to the degree of accuracy demanded by the ear, which is not a very exacting instrument. The methods by which the compensating distortions are produced lie beyond our province; they involve, of course, the introduction of subsidiary reactance

at some points and are familiar to all accustomed to work of this kind. The second plan is deliberately to sacrifice sensitivity in the first stage, to make it a mere coupling stage between a high impedance input and a normally low impedance output, and to make up the lost sensitivity by the addition of more stages. This plan used to be common in talking-film sound-heads, when less efficient cells were available; it is less often employed to-day, for multiplication of stages in itself involves some distortion.

A lower limit to the photoelectric input that can be amplified up to any desired energy is set by the irregularities of the first valve, discussed earlier in this chapter; unless the input exceeds considerably the "noise level" determined by these irregularities, nothing approaching true amplification can be achieved. It is likely that valves with specially low noise level will soon be introduced, and will improve the A.C. amplification of small currents as much as "electrometer" valves have improved D.C. amplification. But with existing valves it is not possible to amplify truly an input voltage of less than 0·1 volt or to detect an A.C. input of much less than 0·001 volt. The conditions are the more favourable the higher the frequency of the input, for the noise consists chiefly of low-frequency components ($n < 1{,}000$ p.p.s.), which can be separated from higher-frequency components by rough "high pass" filters, of which a small capacity in the condenser coupling is the simplest example ([8]).

Rectifier Cells in Amplification. The foregoing discussion has implicitly assumed the use of emission cells. Conductivity cells need no special treatment, for they make conditions approximate more nearly to those of an ordinary radio-receiving set. Rectifier cells suffer, as usual, from inability to provide the voltage necessary for grid control. But when the current is A.C., it is natural to inquire whether this defect cannot be overcome by passing the cell current through the primary of a step-up transformer and connecting the grid circuit to the secondary. That is certainly possible; but, if we remember that the whole of the energy must come from the cell itself, we shall see that the plan has its limitations. On the secondary side for efficient amplification, the voltage exceeds 0·1 volt and the current must be greater than 0·01 μA., which is about the grid current of the

valve. Hence, if I is the current on the primary side, R the internal resistance of the cell, a the step-up ratio, we must have

$$I > 0{\cdot}01\ a(\mu\text{A.});\ IRa > 0{\cdot}1\ (\text{volt}) \quad . \quad . \quad (42)$$

If R is 1,000 ohms, these conditions cannot be fulfilled unless I is at least 1 μA. Moreover, we have neglected all impedances except R. The frequency must be less than 1,000 p.p.s., because at that frequency the admittance of the capacity of the cell becomes serious. The input inductance of the transformer must be much less than R, because otherwise the transformer will receive no energy; and yet the ratio of reactance to resistance must be very large, and the coupling must be close, the transformation ratio large. A few simple calculations will show that these conditions are not easily satisfied with either air-cored or iron-cored transformers. That is why the use of transformers with rectifier cells has often been proposed, but seldom (never, so far as we know) practised.

Generation of Alternating Light. The lowest detectable A.C. input is decidedly lower than the lowest detectable D.C. input, unless electrometer valves are used and the energy output is very small. Hence amplifiers are often used for detection, even when the primary purpose does not necessarily concern rapidly varying light. Methods for converting a normally D.C. photoelectric current into A.C. have been discussed in Chapter VI. But here a word of warning should be added. It is desirable that the A.C. should have a very constant frequency in order that sharply-tuned receivers may be used for its detection and extraneous disturbances eliminated; the necessary tuning can, of course, be incorporated in the amplifiers. Now that a very constant frequency can be obtained from A.C. mains, and synchronous motors for clocks are readily available, it is natural to use this frequency for this purpose; and it will often serve admirably, although the constancy over periods of a few minutes is notably less than that suggested by the accuracy of the clocks, which average the frequency over long periods. But a difficulty arises from disturbances, having the same frequency, due to the stray field of the mains and the leads connected to them; very perfect shielding is

required to eliminate them. The difficulty can sometimes be overcome by deriving the A.C. frequency of the photoelectric current from a rotating member-driver of the synchronous motor through gearing having a ratio not very different from 1. Thus if a 50-cycle motor drives an interrupting disc through 50–53 gearing, the lowest harmonics of the two frequencies which approach within 2 per cent of each other are the 14th of one and the 13th of the other. Sharp tuning will then eliminate all the lower and stronger harmonics.

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3. For theory of fluctuations, see N. R. Campbell, *Proc. Camb. Phil. Soc.* 15, pp. 117, 310, 513, 1910; W. Schottky, *Phys. Rev.* 28, p. 74, 1926. For summary of theory, see E. B. Moullin and H. B. M. Ellis, *Proc. Inst. Elec. Eng.* (in Press). For the facts relevant here, see B. A. Kingsbury, *Phys. Rev.* 38, p. 1458, 1931; L. R. Hafstad, *Phys. Rev.* 44, p. 201, 1933; F. V. Orban, *Zeit. f. Techn. Phys.* 14, p. 137, 1933.

4. For an example of a multi-stage D.C. amplifier, see H. Krefft and M. Pirani, *Zeit. f. Techn. Phys.* 14, p. 393, 1933.

5. The Mekapion is described by E. J. H. Roth, *Brit. Journ. Radiology* 3, p. 155, 1930.

6. For thyratrons, see W. B. Nottingham, *Journ. Franklin Inst.* 211, p. 271, 1931; S. K. Lewer and C. R. Dunham, *The G.E.C. Journal* 3, p. 131, 1932.

7. Combinations of cells and valves are the subject of many patents, e.g. Brit. Pat. 296411, see also W. K. Zworykin, *Phys. Rev.* 25, p. 247, 1925.

Triode cells are also discussed mainly in patents, e.g. 279068, 279937.

8. For investigation of noise in valves, see G. F. Metcalf and T. M. Dickinson, *Physics* 3, p. 11, 1932.

CHAPTER IX

SPECIAL METHODS

The Geiger Counter. Here we shall consider a few ways of using photoelectric (chiefly emission) cells that do not fall conveniently within the previous chapters.

One method is to use a Geiger counter, which is in principle a gas-filled cell filled to an unusually high pressure and sometimes provided with an anode with a special surface treatment. If the pressure and the electrodes and the voltage between them are properly adjusted, no current passes so long as no ions are formed in the gas; but, when an ionizing particle enters the chamber and produces ions, a momentary pulse of current passes through it and then ceases; the number of particles entering can then be counted either by observing an instrument in circuit or (after amplification) automatically. The reason why the current, which is of the nature of a glow discharge, should cease when the ionization ceases has never been explained quite satisfactorily; but the discussion of "intermittent currents" below throws some light on it. This counter is an indispensable instrument in modern work on radio activity; here the ionizing particles are usually produced outside the chamber and penetrate a thin window. For photoelectric work they must be produced within the chamber and the light must enter the window.

This method has been studied so recently and so completely by Locher (1) that no details need be given here. It is certainly the most sensitive method of measuring a photoelectric emission, for we have clearly reached the limit when we detect each emergent electron separately. For some scientific purposes it may prove very valuable. But when the emission is merely a means to the detection or measurement of light, and especially white or red light, the position is not quite so simple. For it would probably be difficult to produce cathodes of the highest emission within the counter; it might be preferable to use a higher emission and a less sensitive method of detecting it.

The remaining methods all depend on the glow and/or

stopping potentials of an electric discharge. One of the simplest is to use the starting (or glow potential) of a gas-filled cell to measure the light incident on it. For, as Fig. 27 shows, the glow potential depends on this light. The method has some advantages for the automatic recording of (e.g.) daylight. A simple mechanism raises the potential, and a relay operated by the discharge marks the value at which the glow occurs. But the method is inaccurate, because the glow potential under a constant illumination is not constant and is apt to rise continuously as the cathode is damaged by the bombardment of positive ions.

Another method is to use a "flashing" discharge tube, usually filled with neon, the operation of which is now generally understood and is described incidentally in the next section. If a photoelectric cell is substituted for the large resistance through which the condenser is charged, the rate of charge, and therefore the number of flashes in a given time, increases with the light incident upon it. This method has been employed to measure a photoelectric current on board ship, where many kinds of indicating instruments are impossible (2); but it cannot be very accurate, since the glow and stopping potentials of the discharge are not constant; moreover, it requires very perfect insulation. Since both galvanometers and electrometers independent of gravity are now available, the method is not of very general interest.

Intermittent Currents. The last method, to which considerable space was devoted in earlier editions, may be regarded as a combination of these last two methods, a gas-filled cell being used as its own "flashing tube." It has not proved as important as was expected, largely because of new alternative methods. Nevertheless, our parental interest prevents us from dismissing it in a few words. It depends on the use of a thermionic diode as a "current limiter." If the voltage across such a diode is sufficiently large and the thermionic emission from the cathode sufficiently small, the current through it is determined entirely by that emission and is independent of the external circuit; it can be controlled by the current heating the cathode.

Suppose, then, that such a thermionic current-limiter is placed in series with a gas-filled photoelectric cell, as shown

in Fig. 61, that a large potential E_0 is applied to the circuit, and that the filament current of the limiter is adjusted so that the saturated current is i. Then, if there is a point with an ordinate i on the voltage characteristic of the cell for the particular illumination to which it is subjected, a steady current i will flow through the cell; the voltage

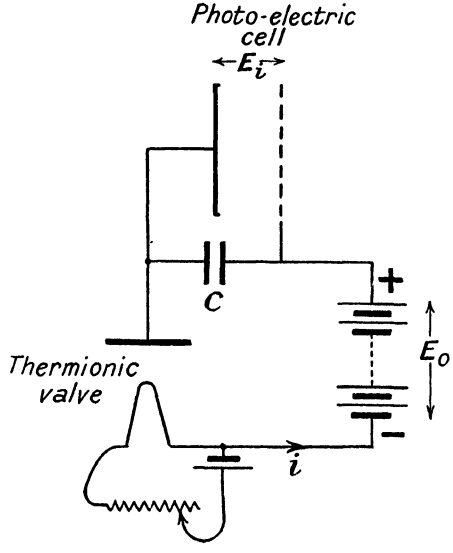


FIG. 61. USE OF A CURRENT-LIMITER

across it will take up the value E_i, corresponding to i, on the characteristic; and the balance of the voltage, $E_0 - E_i$, will be taken up by the current-limiter. (We see now what is meant by a "large" potential E_0; it must be such that $E_0 - E_i$ is always sufficient to saturate the current-limiter.) But there may be no point with an ordinate i on the characteristic of the cell; for the greatest value of i on the characteristic is that corresponding to E_1, the glow potential; this we shall call i_1. i_1 increases with the illumination, and can always be made less than i by decreasing the illumination. What will happen when $i > i_1$, and there is no voltage which can send steadily through the cell the current that the limiter permits to pass?

The answer is that an intermittent current will flow, of

which the mean value is i. There is always a capacity C (Fig. 61) in parallel with the cell, even if no condenser is added; for the electrodes of the cell form a condenser. When the current i is switched on, C will begin to charge up, and will continue to charge up till the voltage across the cell reaches E_1. Then a glow discharge will pass through the cell carrying a current i_1' which is very much greater than i_1. If (as we shall suppose at present) i lies between i_1 and i_1', C now begins to discharge, because the current i_1' flowing out of it through the cell is greater than the current i flowing into it from the current-limiter. The current will continue until the voltage across the cell falls to the stopping potential E_2, and the current to some value i_2' corresponding to this potential in the glow discharge. If (as we shall assume) i_2', as well as i_1', is greater than i, the glow discharge must now cease, for the current passed by the limiter cannot maintain it; when it ceases, the current falls to i_2, the value corresponding to E_2 on the voltage characteristic of the cell; since i_2 is less than i_1 and, therefore, less than i, C begins to charge up once more and the cycle is repeated.

The process may be illustrated by extending the voltage characteristic of the cell. Hitherto this has been confined to potentials less than E_1, so that the current is controlled by the illumination. But there is also a definite relation between current and voltage when the potential exceeds E_1 and the glow discharge is passing; this relation, which is represented by the upper part of the limiting curve in Fig. 27, is another part of the characteristic. These two parts are usually distinguished as the Townsend and the glow characteristics; Fig. 62, which is a reproduction of part of Fig. 27, shows the glow characteristic and the Townsend characteristics for a large and a small illumination in a plane cell. The current i determined by the current-limiter may be represented by a straight line XX. If this cuts either the Townsend characteristic or the glow characteristic a constant current flows through the cell; but if it lies between them, as shown, a constant current cannot flow; the cycle just described will occur; the point representative of the state of the cell will pass up the Townsend characteristic to A_1 or A_2 (according to the illumination), jump across to B_1 or B_2, travel down the glow characteristic to C, and jump back

to the Townsend characteristic at D_1 or D_2. The condition that the current shall be continuous is that XX lies above

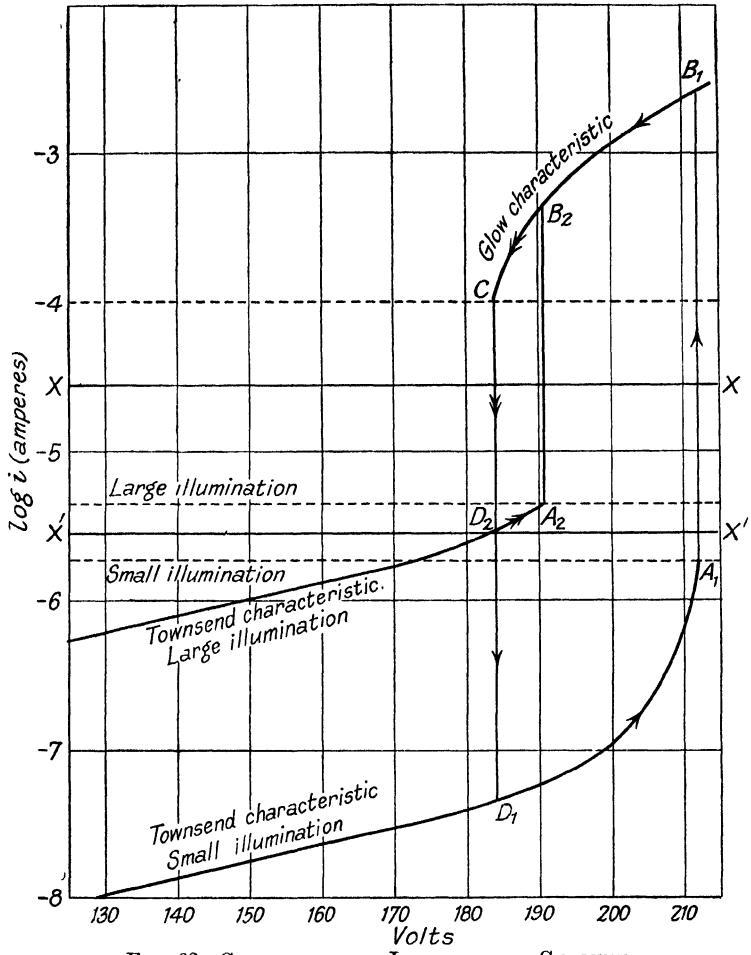


FIG. 62. CONDITIONS FOR INTERMITTENT CURRENT

the upper or below the lower dotted line, this latter varying with the illumination; the condition that the current shall be intermittent is that it lies between them.

The Critical Illumination. Intermittent discharges of this kind can be made to occur in any discharge tube by placing

a condenser across its terminals and limiting the current in the exterior circuit. They have been closely studied in neon lamps, and put to a variety of practical uses. The difference between the "flashing" neon lamp and the gas-filled photoelectric cell in this matter is that the cell possesses a definite Townsend characteristic, variable with the illumination. As the illumination increases, the whole characteristic rises and the distance between the horizontal lines diminishes. If then the current-limiter is set so that XX lies between these lines at a small, but not at a large, illumination (e.g. so that it lies at $X'X'$), increase of the illumination on the cell will make the lower line rise above XX, which will then cut the Townsend characteristic. This means that i can be set so that the current through the cell is intermittent if the illumination is small, but becomes continuous if the illumination is sufficiently great. The change from an intermittent to a continuous current can easily be detected, e.g. by means of a telephone placed in the circuit; the intermittent current will give rise to a series of clicks, but when the current becomes continuous there will be silence.

In the use of this method we have to know the relation between L, the illumination of the cell, and the critical value of i at which the change between a continuous and an intermittent current occurs. According to the simple theory of the matter that has just been expounded, this value is i_1, the current at the glow potential E_1. But the relation between this i_1 and L is given by the dotted curve in Fig. 29; if the simple theory were true, the same curve ought to represent the relation we seek between L and the critical value of i. This curve is reproduced dotted in Fig. 63, which shows also the relation determined experimentally for the same cell. The two curves are very different. In the experimental curve there are no values of i at all corresponding to illuminations below one limit or above another limit, while between these limits there are in general two values of i corresponding to the same L. Let us examine the meaning and cause of these discrepancies, and inquire what elements have to be added to the theory to explain them.

For this purpose it will be convenient to invert the relation in our minds and consider the critical illumination L that is required to make a given current i change from

intermittent to continuous, rather than the critical current at which the change occurs for a given illumination; that is to say, according to the ordinary convention, Fig. 63 must be turned through a right angle, so that i is the abscissa and L the ordinate. We start then with small values of i. Here there is no critical illumination; for, even when the cell is

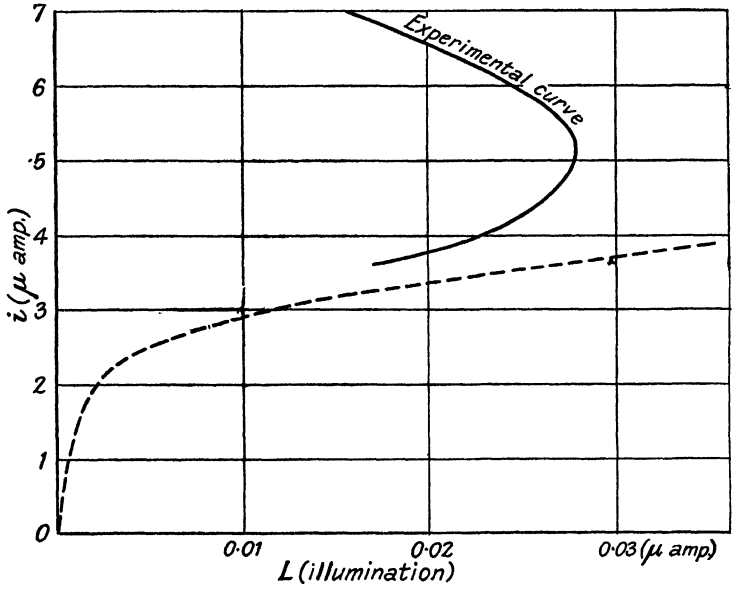


FIG. 63. RELATION BETWEEN CURRENT AND CRITICAL ILLUMINATION IN A PLANE CELL

dark and, according to Fig. 29, $i_1 = 0$, the current through the cell is continuous and not intermittent. The reason for this discrepancy lies in our neglect of the corona discharge, which gives rise to the dark current. If the conditions are those supposed to prevail in Fig. 29, and the resistance in the exterior circuit is small, this current is so small as to be inappreciable on the scale of that diagram. But the greatest current that the corona discharge can carry increases with the exterior resistance—the theory of the matter is so obscure that no reason for this increase can be given—and when the very large resistance represented by the current-limiter is present, it rises to much higher values. The

current is continuous even when there is no light; there is no critical illumination, and the curve of Fig. 63 does not start until i exceeds i_c, the greatest current that the corona discharge can carry.

A further complication, not shown in Fig. 63, enters for the same reason; i_c depends on the capacity in parallel with the cell, decreasing as the capacity increases up to a certain limit. Accordingly, the point at which the curve of Fig. 63 starts and its initial course are influenced by the capacity C. The value of C in Fig. 63 is supposed to be the least that reduces i_c to its minimum; this is about 100 $\mu\mu$F.; if C were reduced, the curve would not start until a still higher value of i was reached.

When light is thrown on the cell, the photoelectric current is added to that carried by the corona discharge. Possibly there is some interaction, so that the total current is not exactly the sum of those which would flow in the absence of one or the other; but this possibility may be neglected. Accordingly, once the curve starts, it follows roughly the course of the curve of Fig. 29; L rises with i, but the value of i corresponding to any L is greater than in Fig. 29 because i includes a larger corona discharge.

If, however, i is increased still further, an entirely new departure from the simple theory appears. A maximum of the critical illumination is reached, and thereafter L decreases as i increases. This is because i_2', the current at which the glow discharge stops is not, as we have assumed, independent of L; as L is increased, i_2' decreases, though the decrease is not easily detected except when the current in the exterior circuit is limited. Increase of L in Fig. 62 not merely raises the lower dotted line, it also lowers the upper dotted line; the current may become continuous, not because the lower line rises above XX, but because the upper line falls below it. The maximum critical illumination occurs at the value of i, such that XX is at the level where the lower and upper lines meet as the illumination is increased. For small values of i the critical illumination is that at which the lower line reaches XX; this illumination increases as XX is raised. For large values of i, it is that at which the upper line reaches XX; this illumination decreases as XX is raised. The curve of Fig. 63 finally terminates, as explained before,

when i is so great that XX reaches the upper line of Fig. 62 even when there is no illumination, so that the glow discharge can pass even when the cell is dark.

Figs. 62 and 63 refer to a plane cell. If we substitute a spherical cell, the general nature of the relations is really unaltered; but once more there is a change of degree which appears experimentally as a change of kind. In the first place i_c is very much smaller, and the curve of Fig. 63 therefore extends to very much smaller currents and critical illuminations. Fig. 64 gives the corresponding curve for a spherical cell, the part shown being that for currents so small that the corresponding part does not exist at all in a plane cell; we shall see later that this is the part important experimentally. (Here, again, L is measured by the saturated current which the illumination would give if the cell were evacuated.) However, there is still a small corona discharge and a minimum i_c below which the curve does not exist at all, but it is so small that it is not visible at all on the scale of Fig. 64; moreover, this value, and the form of the early part of the curve, varies with the capacity C in the manner already explained.

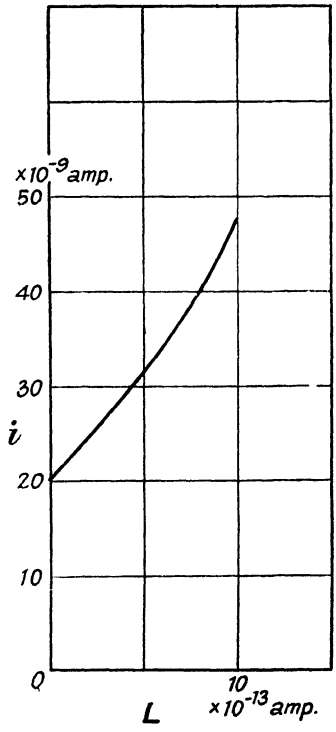


FIG. 64 RELATION BETWEEN CURRENT AND CRITICAL ILLUMINATION IN SPHERICAL CELL

In the second place, there is no definite maximum critical illumination. If it existed, it would be expected at a much higher value than in the plane cell, because the upper dotted line of Fig. 62 lies at much higher currents. Actually, the critical illumination increases continually with i until values

much greater than those of Fig. 63 are attained, and the curve finally terminates before the upper dotted line is reached, because the changes become irregular and irreversible; the current can be changed from intermittent to continuous by increasing the light sufficiently, but it does not become intermittent again when the light is turned off. The same thing happens to a minor degree in the plane cell on the upper branch of the curve of Fig. 63. But these matters are of no consequence for the purpose, because the illuminations at which they occur are beyond the practical range; for all important illuminations L increases regularly with i in the spherical cell.

The Period of Intermittence. So far we have only distinguished intermittent from continuous current, and have said nothing of the frequency of intermittence or the period of the cycle. This period is made up of two parts. During the first, C is charged up from E_2 to E_1 by the difference between the current i, and the current i', varying with E, which leaks through the cell. Consequently

$$C \cdot \frac{dE}{dt} = i - i' \quad . \quad . \quad . \quad . \quad . \quad (43)$$

so that, if we write $i' = f(E)$, the period τ_1, occupied by this part of the cycle, is given by

$$\tau_1 = C \int_{E_2}^{E_1} \frac{dE}{i - f(E)} \quad . \quad . \quad . \quad . \quad . \quad (44)$$

In the second part of the cycle, the condenser C discharges; if the current flowing through the cell is now $i_1' = f_1(E)$, the period is similarly

$$\tau_2 = C \int_{E_1}^{E_2} \frac{dE}{f_1(E) - i} \quad . \quad . \quad . \quad . \quad (45)$$

The complete period is $\tau = \tau_1 + \tau_2$, but $f_1(E)$ is always much greater than $f(E)$, and, though $f(E)$ is less than i, $f_1(E)$ is much greater when i is small. Then τ_2 will be very small compared with τ_1, and we may identify τ with τ_1.

If the simple theory of page 158 were true, $f(E)$ would be zero when the cell is dark, and we should have

$$\tau = \frac{C(E_1 - E_2)}{i} \quad . \quad . \quad . \quad . \quad . \quad (46)$$

Actually this is not true, because $f(E)$ rises to i_c even when the cell is dark. This does not affect the conclusion that τ increases with C and decreases with i; but τ calculated from (46) will be less than the actual value. The effect of illumination is to increase $f(E)$, but to decrease E_1; these effects

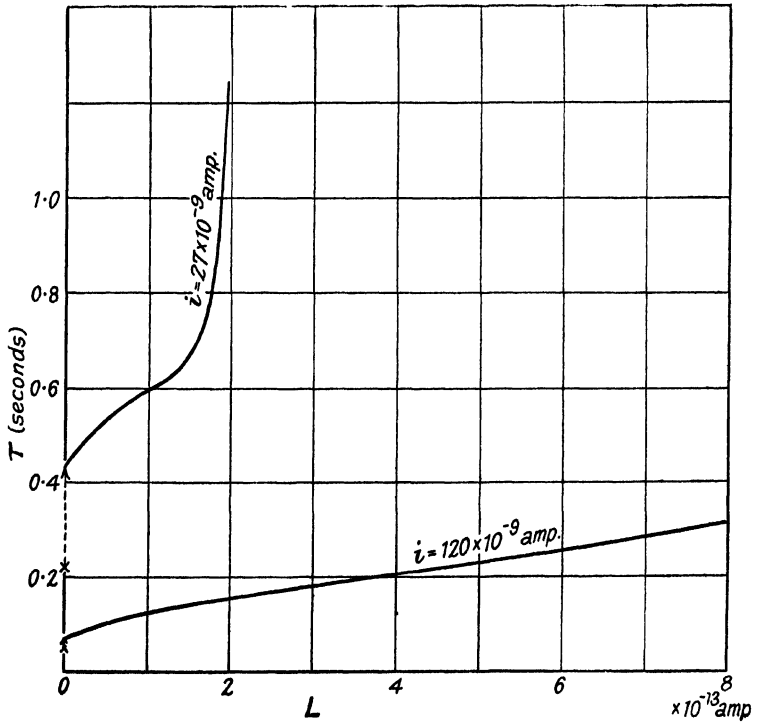


FIG. 65. VARIATION WITH ILLUMINATION OF PERIOD OF INTERMITTENT DISCHARGE IN SPHERICAL CELL

work in opposite directions, but actually, for small currents and illuminations, the second is the greater and τ is increased by illumination, becoming infinite when the critical illumination is attained and the intermittence ceases. Fig. 65 shows the relation between τ and L in the spherical cell to which Fig. 64 refers for two values of i; it should be observed that τ varies much more rapidly with L when i is small. The capacity C was here 100 $\mu\mu$F.; the value of τ indicated by (46) is marked by a cross on the axis of τ.

In the plane cell the corresponding curve would not start at all until L attained much larger values, and the greatest value of τ would be much less. But the relations for the plane cell are more interesting when i is large, corresponding to a point on the upper branch of the curve of Fig. 63. Here the first of the two effects of the light becomes more important; increasing illumination reduces so greatly the difference of potential $(E_1 - E_2)$ through which C is charged and discharged that it decreases the whole period τ; light makes the frequency of intermittence greater, and, when the critical illumination is reached, the intermittence vanishes because its frequency has become infinite and its period zero. The process is too complicated to be treated theoretically, but the facts are perfectly plain; when i is small, the period of intermittence increases, and the frequency decreases, with illumination; when it is large, the period decreases and the frequency increases. Between these two ranges there is one in which the period is almost independent of the illumination, and when the critical illumination is reached, the intermittence ceases without any marked change in frequency. There are the same three ranges in the spherical cell; but for the reason already explained only the first is important.

Use of Intermittent Currents. The most likely use of the facts we have been considering is in the comparison of small quantities of light of the order of 10^{-6} lumens. Two quantities of light are equal, if they give the same period τ for the same current i through the current-limiter. The method has the advantage of not requiring a constant H.T. supply—rectified A.C. from the mains can be used—and very simple observing apparatus, namely, a telephone, which may be at a great distance from the cell. But a constant supply is needed for the filament of the current-limiter and well-constructed rheostats for varying it. There is no trouble from interference by H.F. disturbances. A spherical cell has to be used and carefully selected, for apparently similar cells differ greatly in corona current; a sensitized potassium cathode is best in spite of its low emission; thin film cathodes give much less regular glow potentials. Insulation is important, especially in the condenser C_1, which must be variable; a glass tube coated outside with tin-foil and filled with a variable quantity of mercury is suitable. The telephone can be

connected to the secondary of a transformer, the primary of which is placed between the anode of the cell and H.T. +; it must not be put in the earthed return of the H.T. supply, for the discharge does not pass through it there. Any receiving valve will serve as a current-limiter, but one with a "bright-emitting" cathode is best.

A plane cell can be used to detect illumination of the order of 0·1 lumen, a relay being operated by the cessation of the intermittent current, amplified by valves. This method has the advantage attaching to the amplification of A.C. rather than D.C. current, and was treated at some length in previous editions. But since it has been displaced by the methods of detection described in the previous chapter, nothing more need be said of it here. However, it may yet find a use for special purposes.

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2. For Neon tube current meter, see J. H. J. and H. H. Poole, *Photoelectric Cells and Their Applications* (*cit. ante*), p. 142.

PART III

SOME APPLICATIONS OF PHOTOELECTRIC CELLS

CHAPTER X

GENERAL CONSIDERATIONS

Choice of Cell—The Type. In every application a choice has to be made between the three types of photoelectric cells. The facts on which the choice should be based have been set forth already; but it may be well to collect and summarize them here.

There is probably no function that can be performed by one type of cell that cannot be performed by any other in principle, that is to say, with sufficiently elaborate apparatus, and in sufficiently favourable conditions. But there is a very clear distinction between the function to which the various types are *well* adapted.

Conductivity cells are suitable only if (1) voltages as high as 100 are available; (2) accuracy is not required; and (3) the detection of very rapid light fluctuations of frequency $> 10{,}000$ p.p.s. is not required. If these conditions are fulfilled, they have an advantage over rectifier cells in the power that they can control in response to a small amount of light, over the best emission cells in price, and over all gas-filled emission cells in less sensitivity to voltage variation. They have a bad reputation for reliability, and are said to fail inexplicably and without warning. But this reputation is, in part at least, a relic of their past history; we know of no real evidence that it applies to modern cells; but our experience is not sufficient for us to dismiss it as wholly undeserved.

The field specially appropriate to their use is mechanisms required merely to detect light, and worked off a mains supply. The reasons why they are not universal in this very important field are not primarily technical. The chief of

them are a distrust created by claims made for advantages in other fields for which they are not suitable, and the greater familiarity of other types arising from their use in these other fields. Conductivity cells are entirely unsuited for measurement.

Rectifier cells have the advantages over the other types that they require no electrical supply, and that they are small, robust, and cheap. They are much more accurate than conductivity cells, but less accurate than vacuum emission cells used properly. They are less sensitive than conductivity cells, but much more sensitive than vacuum emission cells, if the quantity of light is not so small that the current requires an electrometer for its measurement. They are slightly superior to gas-filled cells in sensitivity and similar in accuracy. The current from them cannot be amplified easily by thermionic valves; they can therefore control an appreciable amount of power only by the use of delicate electro-mechanical relays, operating with a current of a few microamperes; at present, such relays are more expensive and less convenient and reliable than valves; but the position may change, since there is now a demand for such relays. They are unsuitable for measuring fluctuations in light with a frequency above 1,000 p.p.s.

The field specially appropriate to rectifier cells is the measurement of moderate quantities of light with an accuracy of not more than 1 per cent. This field includes the photometry of lamps with a precision at least equal to that of the eye, the measurement of illumination both indoors and outdoors, and the measurement of transmission (in the very general sense of Chapter XI). They are also suitable for detection where no considerable amount of power is required, as in galvanometer relays. In all this field, which covers most of the laboratory uses of cells, rectifier cells have no serious rivals.

It should be pointed out that the accuracy of which rectifier cells are capable varies more with the conditions of measurement than in other cells. If a direct reading method is required, accuracy demands that either the galvanometer should have a resistance very small compared with the internal resistance or that the incident light should be so small as to cause no appreciable change in that resistance.

This latter condition makes it possible to use them for spectrophotometric work if a galvanometer with a sensitivity limit of 10^{-11} A. is used, even if it has a resistance of several hundred ohms. But it is worth while to point out that by the use of the null method of Fig. 45 (without an E.M.F. in the cell circuit), all inaccuracy arising from the internal resistance can be abolished, for when a balance is attained there is no potential difference across the cell. If a measuring instrument (which may be of any resistance) is placed in the lead from the compensating potentiometer, it will then read the primary current I of Chapter IV, so that some at least of the advantages of a direct reading method are obtained; its reading will be larger than if the same instrument were placed directly in series with the cell; it will be proportional to the light (4) and will not vary rapidly with the temperature. The sole remaining effect of the internal resistance is then to reduce the sensitivity of the circuit; it is no use placing an instrument of very high resistance and sensitivity at G. This method ought to be adopted whenever simplicity of apparatus is not the primary consideration.

Gas-filled emission cells have no single quality in which they excel all others; but they often provide an excellent compromise between the qualities in which other types excel. They combine high sensitivity with considerable accuracy, maintained at all but the highest frequencies of fluctuation, and they can control large amounts of power. The chief disadvantages peculiar to them are their variability with anode voltage and their liability to damage from the passage of a glow discharge; other qualities they share with vacuum emission cells. It must be remembered (see page 65) that the maximum gas factor decreases in general against the emission of the cathode, so that much more is gained by the gas-filling of cells with the less sensitive cathodes. Further, it is useless to use a gas-filled cell at a voltage appreciably below that for which it is designed, for then it will have little more sensitivity than a vacuum cell combined with most of the disadvantages of a gas-filled cell.

There are two fields in which gas-filled emission cells are at present supreme. One is the reproduction of talking films and picture telegraphy; here their high sensitivity and

relatively good frequency-response give them the advantage. They are commercially the most important type of cell, because more cells are made for talking films than for all other purposes put together. Of the other, astronomical photometry is typical; here the very highest sensitivity is required, combined with an accuracy which, though not absolutely high (say, 2 per cent), is high enough to put conductivity cells out of court. There is no immediate prospect of their being displaced in either of these fields, but their position in the second is stronger than that in the first. They are also widely used in mechanisms controlled by the simple detection of light; but it is not at all clear that they are really superior here to conductivity cells or even vacuum emission cells.

As against the other types, *vacuum emission cells* have the merits of accuracy and perfection of frequency response, and the demerit of insensitivity. In the narrow, but important, field of precise measurement, they are indispensable; in television, involving frequencies of 100,000 p.p.s. and upwards, they will probably displace the gas-filled cells that are more widely used at present; in all other fields their insensitivity is generally held to be offset by no countervailing advantage. We have never shared this opinion. In many uses a minimum sensitivity is required, but any excess over this minimum is unimportant. Thus in laboratory uses, so long as the current is large enough to be measured on a reflecting galvanometer, very little is gained by increasing it so that it can be read on a pointer instrument; when valve amplification is used, little is gained by increasing the output of the cell beyond the point where it is large compared with the "noise level" of the first valve. If a vacuum cell has the minimum sensitivity, more is usually lost than gained by substituting a gas-filled cell; there is no field in which either accuracy or independence of applied voltage is really unimportant. Reference must be made again to the future possibilities of the secondary emission cell (page 76).

If vacuum cells could be made regularly with the sensitivity that they sometimes attain (say, 50 μA./L.), they would possess the minimum sensitivity for all the chief purposes (including talking films) for which gas-filled cells are now

generally used. Such cells might be more expensive than gas-filled cells, but they would have an infinitely long life unless broken by maltreatment; and it is worth remembering that the cost of a cell is seldom a large part of the cost of the apparatus with which it is associated.

Conductivity and Rectifier Cells. When the type has been chosen with reference to these considerations, there still remains a choice within the type.

The qualities in which every maker of conductivity cells claims that his cells are superior to all others are permanence and freedom from time-lag. We have no evidence on which to adjudicate between these claims, and can merely record that many of the makes we have examined would serve the purposes to which cells of this type are specially appropriate, and that none are as free from time-lag as even the very worst emission gas-filled cells. Selenium cells are still used much more widely than either thalofide or selenium-tellurium alloys. For work in the infra-red thalofide is certainly superior; but, so far as we can ascertain, these cells are not made on any large scale.

In rectifier cells the front-wall type seems definitely superior to the back-wall, which is now almost obsolete. The choice then remains at present between cuprous oxide and selenium as the semi-conductor. The Se type seems to be rather more sensitive to white light; it has a higher internal resistance R and therefore permits the use of measuring instruments of higher resistance; it is therefore superior for general use. On the other hand, the Cu_2O type has an emission curve more similar to the visibility curve and therefore has some advantage in photometry, but the similarity is not so close as to avoid the need for "correction" in comparing sources of widely different colour (see page 199). However, the difference between the two types and others which may shortly come on the market is not very great.

Emission Cells. Here the cathode is the primary consideration. For white light the Cs–O–Ag is usually preferable, because of its high emission. But it is not suitable when constancy over long periods is required, for it seems to be more liable to spontaneous changes than less sensitive cathodes. Again, the comparatively large thermionic emission makes it unsuitable for a light of less than 10^{-6} lumen.

It is unfortunate that it should fail just when high sensitivity is most desirable, and proposals have been made to abolish the thermionic emission, when very feeble light is to be measured, by cooling the cell to $-60°$ C. (or lower); the temperature need not be constant and the method is doubtless practicable, but it is not likely to be used except when the apparatus is already very elaborate, as in astronomical photometry.

When the Cs–O–Ag cathode is precluded for these reasons, there is much to be said for the K–O–Ag cathode, which, though less sensitive, is very stable and has an almost inappreciable thermionic emission. Moreover, its emission, though far from uniform throughout the visible spectrum, is probably more uniform than that of any other; it is therefore useful for spectrophotometric work in the visible region. Again, K–O–Ag is preferable to Cs–O–Ag when regions of the visible spectrum are to be isolated by means of filters, for it is difficult to find filters which absorb the near infra-red to which Cs–O–Ag is so sensitive; for example, the Wratten "monochromatic" filters are hardly distinguished by Cs–O–Ag, since they all transmit in the infra-red.

With sunlight or starlight, which is much bluer than our standard "white light," K–H and Na–H increase in sensitivity relative to the thin film cathodes. Once universal, they are still used more than any other in astronomy, where gas-filled cells are essential; we are not sure that K–O–Ag has been tried sufficiently to establish its inferiority. K–H, and probably Na–H, are rather unstable in vacuum cells; but "plain" K, though relatively insensitive, appears to be remarkably stable and to retain its emission unchanged for years. It has been used in the measurement of daylight as a standard, against which other cells can be calibrated.

When a limited region of the spectrum is to be used, the best cathode is usually that having a maximum in this region; but the possibility of modifying the emission by filters ought to be borne in mind; emission curves ought to be studied in conjunction with transmission curves of filters (1). Further, it should be remembered that radiation can be measured by subtraction as well as addition; a filter absorbing selectively in the required region in conjunction with a relatively non-selective cell enables the

light in this region to be measured by means of the change consequent on its introduction. Cathodes sensitized by Olpin's method seem to offer great possibilities for selective work; but they have not appeared on the market, and little information is available about their behaviour in practice. The peak in the ultra-violet of the X–O–Ag cathodes, shown in Figs. 23 and 24, is not of much practical use, because such cells are so sensitive to traces of light of longer wavelength.

A special case of selective work is the measurement of ultra-violet light for medical and physiological purposes. Here cadmium is still employed more than any other cathode, together with sodium when sensitivity to visible light is not an objection. But the facts set forth in Chapter II suggest that uranium and possibly other metals might be preferable. No cathode has an emission curve coinciding even approximately with the "erythema," or any other biological, curve; and filters are always necessary if the biological effect is to be measured accurately. A possibility that has to be borne in mind is to cause the primary light of short wavelength to excite fluorescence in a suitable substance, and to use a photoelectric cell to measure the secondary fluorescent light of longer wavelength. This method has not yet been fully explored (2).

In gas-filled cells the ideal sensitivity is determined by the product emission × maximum gas factor. The two factors in general vary against each other, but the cell with the higher emission is the more sensitive. But in respect of qualities other than sensitivity, the low emission cathodes are preferable. They are more stable and give a better frequency response. The effective sensitivity to very feeble light ($< 10^{-8}$ lumen), such as is used in astronomical work, is often limited by the dark current, which arises not only from thermionic emission, but also from a feeble discharge at high gas factors even when there is no cathodic emission. Its nature is not understood and it is very variable even among cells of apparently similar construction; some sodium cells (but not all) are remarkably free from it, and are therefore used by astronomers in spite of the low emission. Insufficient attention seems to have been paid to the possibility of eliminating dark current by compensation and

other null methods; they may be incapable of the infinite ideal sensitivity of the "charging-up" methods of pages 116 and 118, but their effective sensitivity may be as great.

In selecting the form of the cell, the main choice is between cathode-in-the-centre (types *A* and *B* of Fig. 11) and cathode-on-wall. The former gives greater accuracy, especially in vacuum cells, for the reasons given on page 49; type *A* should be used. In gas-filled cells for high sensitivity, cathode-on-wall is preferable, especially with cathodes of low emission; but the range over which current is proportional to light is not so great as in type *A* of Fig. 11, and the frequency response is generally worse than that of either type *A* or *B*. Large cells are preferable to small cells in everything except frequency response.

Argon is generally used as the gas; it has been stated that krypton and xenon are preferable, both as regards maximum gas factor and frequency response, but we have no evidence in favour of the assertion. The maximum gas factor, which is limited by the slope (page 70), increases against the gas pressure, but so does the anode voltage required. The pressure chosen is usually a compromise between the desire of the maker for a low gas pressure and the desire of the user for a low anode voltage. But little is ever gained by using anode voltages greater than 200. Anode voltages for a given slope are lower if krypton or xenon is used, and higher if neon or helium is used.

The Making of Photoelectric Cells. We have excluded from this book all account of how to make a photoelectric cell of any type, because we believe that the making of cells is best left to professionals. Even if a cell is required of some special type, not available commercially, it is better for those who have not great experience to seek the aid of those who have, rather than to attempt manufacture for themselves. The reason is not that professional makers are possessed of jealously guarded secrets that they are unwilling to publish, but that the making of cells is still as much an art as a science, involving a personal skill that is uncommunicable in writing.

Problems of Detection. We have explained in our Preface that we do not propose to consider in detail most of the applications of photoelectric cells, but to confine ourselves

to those that raise questions of principle not discussed adequately elsewhere. We thus omit entirely one class of immense importance, namely, that which includes talking-film reproduction, picture-telegraphy, and television. We should like to be able to omit entirely another, namely, that which includes their manifold uses in mechanical engineering. But the nonsense that is still talked, even in technical journals, about the "marvels of the electric eye" compels us to a brief comment.

An eye and a photoelectric cell have only one power in common, namely, that of distinguishing light from darkness. The characteristic function of the eye in distinguishing form and colour is not possessed by a single cell at all; on the other hand, the cell has a much greater power of recognizing definite amounts of light and rapid variations of light. Accordingly it does not follow that any operation, normally performed visually, can be performed automatically by any practicably simple photoelectric apparatus; or that the only operations that photoelectric apparatus can perform are those now performed visually. Much more careful analysis of the essentials of a problem is required before it can be decided whether a photoelectric solution is practicable or superior to any other.

Most of the applications in this group are simple detection; the only function of the cell is to work a relay when the amount of light falling on it passes through some limit. The range in which detection is possible and the means of achieving it are now well understood and standardized; no ingenuity in this part of the apparatus is required. But ingenuity or, better still, a sound knowledge of the principles of engineering and of the purpose to which the detection is to be applied—these are needed. If both in the design and the advertisement of such applications less attention were paid to the photoelectric part of the apparatus and more to the remainder, the desirable state would be reached much more rapidly, in which the ordinary engineer would regard photoelectric cells as one of the normal tools of his trade.

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1. For filters, see Kodak catalogue of Wratten gelatine filters; Corning Glass Works and Jena (Schott) Glass Works, catalogues of

glass filters. See also H. Krefft and M. Pirani, *Zeit. f. Techn. Phys.* 14, p. 393, 1933.

2. P. Dubouloz, *Rev. d'Opt.* 12, p. 114, 1933.

3. Generally see R. Fleischer, and H. Teichmann, *Lichtelektrische Zelle und ihre Zerstellung* (Steinkopf Dresden); G. Dejardin, *Rev. d'Opt.* 9, p. 337, 1930.

For Olpin sensitization, see references to Chapter II.

For manufacture of X–O–M cathodes, in addition to references in Chapter II, see R. Sewig, *Zeit. f. Phys.* 76, p. 91, and 77, p. 420, 1932; also C. H. Prescott, Junr., and M. J. Kelly, *Bell-System. Tech. J.* 11, p. 334, 1932.

The many patents on this subject (Class 40 of the British classification) are likely to confuse rather than to instruct those not already well-informed.

4. This is not strictly true. It would be true if the whole of the series resistance r in Fig. 33 (p. 79) lay outside the cell terminals. Actually a small part of it lies inside, so that the P.D. across the actual cell is not zero when the P.D. across the terminals is zero. This makes it almost impossible ever to measure truly the primary current I.

CHAPTER XI

ABSORPTION

Absorption and Transmission. By *absorption* we mean here any action of a material body on light whereby the quantity of that light received by some surface differs according as the light is or is not incident on the body. (Strictly perhaps we ought to say quantity or quality; but there is no important case in which quality is changed without concurrent change of quantity.) Absorption thus includes reflection, both specular and diffuse, as well as polarization and scattering. The common feature of all these actions, which leads us to group them together, is that with each of them is associated a property of the material body, and usually of the light as well, which is measured by means of the ratio of the quantities of light in two beams, both proceeding from the same source. The problem that we are going to consider in this chapter is how such a ratio may be measured by photoelectric methods. The ratio we shall call the *transmission* of the body; the ambiguity between a ratio and its reciprocal will be resolved by choosing for the transmission that ratio which is less than 1. Transmission thus includes the transmission coefficient as ordinarily defined, the reflection coefficient, the scattering power; it is simply related to the rotary power for polarized light, and some other magnitudes of less importance (2).

We shall assume throughout that the transmission is independent of the intensity of the light incident on the body. This assumption is always true of the magnitudes enumerated; for in those comparatively rare cases in which it is apparently untrue, the light is always said to change the properties of the body, so that it remains true of a body in any defined state. On the other hand, the transmission may depend greatly on the quality of the light, including its angle of incidence and state of polarization.

Although we propose to group many different magnitudes under the common name transmission, it must not be supposed that it does not matter which of them is being measured. In measuring the "density" of a photographic film,

which scatters as well as absorbs the light incident on it, it is very important to decide whether the incident light (which forms one beam) is to be parallel or diffused, and whether the emergent light (which forms the other) in the first alternative is to include that scattered. Similarly, in measuring the reflection coefficient of an imperfectly matt surface, it is important to decide whether specularly reflected light is to be included. But these decisions are common to all methods of measuring transmission. They concern the definition of the two beams, not the measurement of their ratio, with which alone we are concerned.

On the other hand, we cannot neglect entirely the change of the quality of the light that often accompanies transmission. For such a change may introduce a difference between the transmission measured photoelectrically and that measured visually or photographically, unless the emission curve of the cell is identical with the visibility curve or the sensitivity curve of the photographic plate. If the visual transmission is the magnitude that we really want to measure (as in determining the whiteness of a surface) or the photographic transmission (as in determining the printing value of a negative), then only two alternatives are open if the difference between photoelectric and other methods cannot be neglected. One is to use a cell, or a combination of cell and filters, whose emission curve is of the desired form; the other is to resort to spectrophotometry. Something will be said of the first in Chapter XII; the second will be treated in Chapter XIII; but it may be recorded here that photoelectric methods are little suited to such problems unless great precision is sought even at the expense of instrumental elaboration.

However, when visual and photoelectric transmissions differ, they may be means to the same end and therefore equivalent. Thus if the real problem is to measure the concentration of a dye in a solution, photoelectric transmission will serve our purpose as well as visual, whatever cell is used; for, if either is proportional to concentration, so is the other, and both vary in the same way with the thickness. Again, even when visual transmission is our primary concern, photoelectric transmission may be a desirable means for measuring it; for slight differences in transmission within

the visible spectrum may be accompanied by much larger differences in the ultra-violet or infra-red to which the cell is sensitive. Indeed, one of the commonest errors in adapting photoelectric methods to problems to which visual methods have been applied hitherto is a failure to analyse the problem sufficiently at the outset, and to turn to advantage what may appear at first sight the disadvantage of the differing properties of the eye and the cell. It is hardly ever right to take a visual method and to translate it directly into a photoelectric method by simple substitution of cell for eye.

Direct-reading Methods. The simplest method of measuring transmission photoelectrically is to throw on a cell the two beams of light, whose ratio is to be determined, and to measure the resulting currents. In order that this method should be accurate, three conditions must be fulfilled.

1. The cell must be placed in the two beams where they have the same cross-section; for, since the sensitivity of a cell is never uniform over its surface, equal currents do not necessarily correspond to equal intensities of the beams, unless they fall on the same part of its surface. This condition cannot be fulfilled if absorption is accompanied by scattering, and one of the two beams to be measured is the whole of the scattered beam. When it cannot be fulfilled for this reason, the usual procedure is to compare, not the original and the scattered beam, but the beam scattered from the test surface and that scattered from some surface, giving the same scattering, of which the transmission is known, the incident light being the same in both cases. Thus the transmission of matt surfaces is always measured by comparison with a standard matt surface of magnesium oxide or carbonate of which the transmission is known or assumed to be unity. When this method is not available, some method of integrating the light over the section of the scattered beam must be used, unless the scattering is so small that the lack of uniformity of the cell surface can be neglected. The discussion of this problem is beyond our province, for it arises in all methods of measuring transmission.

2. If the transmission is to be identified with the ratio of the currents, the apparatus must be *linear*, that is to say,

the current must be proportional to the light. This condition is not so difficult to fulfil as is sometimes believed (see page 197); it may be noted here that the measurement of transmission itself provides a test of linearity; for the ratio determined will vary with the quantity of the light unless the apparatus is linear; this test ought always to be applied before any method of measuring transmission is accepted. The quantity of the light must be varied for the purpose of the test without varying its quality. The best way to do this is to insert blackened wire gauze in the path of the light; a stop before a lens will serve if the optical system is sufficiently achromatic; other methods are available in special cases. When the test fails, a possible change in the quality of the light should always be one of the first objects of suspicion; stray light is also a probable culprit.

If the apparatus is not linear, it is possible in principle to calibrate the apparatus so as to obtain a relation between light and current; but this is seldom desirable. A better plan is to substitute comparison for measurement, to introduce into the unabsorbed beam an object of known adjustable absorption, and to vary its absorption until the current is the same as that produced by the absorbed beam. This method of substitution is often associated with the null methods that we shall consider presently; indeed, it often makes direct and null methods barely distinguishable. But it can be used with advantage when the method is clearly not null, e.g. when the current is read on a galvanometer without compensation or on a valve voltmeter subject to the drift to which all such voltmeters are liable. If the substitution of the known for the unknown absorber and *vice versa* can be made rapidly, trouble from drift can be eliminated, and very precise measurements made with feeble lights with very simple apparatus for measuring the current. This method has been unduly neglected.

3. The source of light must be constant. It is clearly impossible to measure both the original and absorbed beam at the same time; there must therefore be no change of the original beam during the period occupied by successive measurements. In all but work of the highest precision, there is no difficulty in fulfilling this condition if the source is run from batteries; a motor-car headlight lamp is

usually suitable; but it is impossible to run the lamp from the mains, if a precision of even 2 per cent is required.

If a variable source must be used, the only direct reading method is that of the Koch resistance. It is almost obsolete now, but still deserves brief mention. In this method the current from the measuring cell, on which the beam to be measured falls, passes through a second "resistance" cell illuminated by a constant fraction of the light from the same source. The resistance of this cell will not be ohmic; but, if the cell is linear, its voltage characteristic may be taken to be $i = S \cdot f(E)$, where S is the momentary intensity of the source. If the measuring cell is also linear, the currents to be measured will be $i_1 = a_1 \cdot S$ and $i_2 = a_2 \cdot S$, where a_1/a_2 is the transmission. If E_1, E_2 are the voltages across the resistance cell for the two currents, we shall have $a_1/a_2 = f(E_1)/f(E_2)$, independently of S. If, further, a_2 is constant, a_1 is a function of E_1 which can be established by calibration. One objection to the method is the difficulty of obtaining resistance cells with smooth and nearly linear functions $f(E)$; another is that the simplicity that should be the chief advantage of a direct reading method is sacrificed, and that the additional complexity would usually be better devoted to producing a constant source of light.

Many of the limitations discussed affect null methods as well, and are therefore not objections to direct measurement. Direct methods are usually best if high precision is not required and if sufficient light is available; it is always better, if possible, to increase the amount of light rather than the sensitivity of the measurement. Rectifier cells are best, used so that variation of their internal resistance is negligible; that is to say, either a low resistance instrument must be used, or the compensation method of page 170.

Null Methods. In null methods of measuring absorption, the light to be measured is usually compensated by an auxiliary beam from the same source. Fluctuations of the source can thus be wholly or partially eliminated, while the superior sensitivity generally characteristic of null methods can be obtained.

The variation of the auxiliary beam in order to produce compensation is produced by an adjustable absorber (denoted by Z), whose transmission need not be known. In

order that fluctuations of the source should be wholly eliminated, the current in both cells must vary in the same way with the light; since the quality of the light usually varies with its quantity, this means that the two cells must have the same emission curve. This condition is impossible to fulfil exactly; constancy of the source is still required for high precision, except when monochromatic light is used and the quality cannot vary. Further, both cells must be approximately linear, for it is equally impossible to obtain

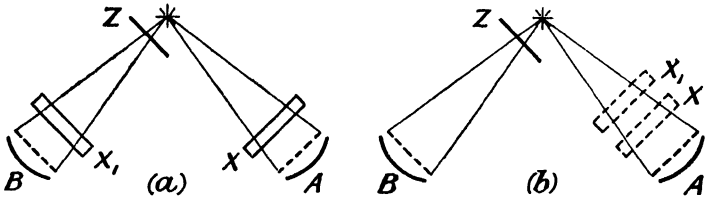


FIG. 66. NULL METHODS

two cells with the same considerable departure from linearity. It will be assumed that the transmission to be measured is the transmission coefficient without scattering of a transparent body X. If it is not, it will usually be difficult to compensate with the same beam both the original and absorbed beams; the device, already mentioned, will have to be adopted in which the original beam is replaced by a beam received after incidence on a body of the same kind with known transmission, preferably 1.

We also require an absorber X_1 whose transmission is adjustable and known. There are, then, two variants of the method (Fig. 66, (*a*), (*b*)). In one, X_1 is introduced before the compensating cell B, while X is introduced before the main cell A; in the other, X_1 is substituted for X before A. In the first method, Z is used to produce a balance with X absent and the original beam on A; in the second method, with X in place and the absorbed beam on A. The transmission is, of course, the transmission coefficient of X_1, when it is so adjusted that balance is restored once more after the introduction of X in the first case and its removal in the second. If X and X_1 are absorbers of the same kind, symmetry is a reason for preferring the method of direct substitution; but if they are not, this reason fails and there seems to be

no other. For the conditions, such as similarity of the two cells, which are obviously desirable if X and X_1 are before different cells, are no less actually desirable when they are before the same cell. The first variant is usually the more convenient mechanically. The auxiliary absorber Z is always one of the variable absorbers to be considered later, but it need not be calibrated. It is possible, but seldom desirable, to use X_1 itself as the auxiliary absorber Z, so that the two balances correspond to different transmissions of X_1, whose ratio is the transmission to be measured. In designing apparatus, time spent in considering which of these variants (and of some obvious minor alternatives) is best adapted to the problem in hand will never be wasted.

The light from the source is best divided into the two beams, falling on A and B, by means of a partially reflecting and partially transmitting plate. Beams proceeding from the source in different directions (as suggested in Fig. 66) may also be used; there is, then, greater symmetry of the optical paths, but less certainty that the two beams will vary together with variations in the source. If the method is to be one of true compensation, the balance must be effected by the means shown in principle in Fig. 46; it is equally applicable to either emission or rectifier cells. But there are very great advantages in the alternating light method of page 108, especially if the light is feeble and emission cells are used, for then valve amplification can be employed. However, it should be observed that the method is not strictly one of compensation; variations in the source during the period of alternation are not eliminated; these may be appreciable if the source is a discharge lamp or an incandescent lamp fed by A.C., but hardly if it is an incandescent lamp fed by D.C.

If the alternating light method is used, the second cell may be, and usually should be, abolished; the two beams, which in Fig. 66 fall on separate cells, may be directed by mirrors to fall on the same cell; no assumption about the transmissions of the two halves of the optical system is involved, except that their ratio remains constant during any measurement. A still further simplification is to abolish the second beam entirely, and to make the method one of

pure substitution in which X and X_1 are rapidly interchanged in a single beam. In principle we are then back where we started; the only difference of this proposal from the direct reading method of substitution is that we determine the identity of the two currents in a single operation, instead of observing each individually and noting that they are the same. But if the direct reading method is not suitable, the use of the compensating beam is usually advantageous, for unless X and X_1 are of the same kind (and sometimes even if they are), it is difficult to interchange them at a high speed in a manner that gives a sharp minimum of the A.C. output when they are equal. When the compensating beam is used, the advantage of rapid and smooth interchange of the beams compared can be combined with the advantage of a leisurely interchange and accurate adjustment of X and X_1.

Adjustable Absorbers. All but the simplest of these methods we have discussed require an adjustable absorber X_1, of which the transmission in our general sense can be varied at will. The available alternatives fall into two classes, according as (*a*) they do not, (*b*) they do, require calibration. In class (*a*) come—

1. The inverse square law.
2. The glass reflecting plate.
3. The laws of absorbing solutions.
4. The Nicol prism.
5. The sector disc.

(1) The inverse square law is never practicable, unless possibly for calibration. In compensation methods, using two beams from the same source, it requires movement of the cell, and in all it involves a change in the distribution of the light.

(2) The reflecting plate comes doubtfully within this class, for the theoretical relation between angle of incidence and coefficient of reflection holds only so long as the surface is optically clean; moreover, the output of a cell is determined to some extent by the polarization of the light.

(3) De Beer's Law that the absorption coefficient of a solution is proportional to the concentration of the solute has been proved true for certain wide classes of solute.

Since concentration cannot be easily varied reversibly, and since the proportion of light absorbed by a given thickness of solution varies exponentially with the coefficient, it is not a convenient law for most purposes; but it has obvious uses when the object of determining transmission is to measure concentration. The law relating thickness and transmission of a single medium has been used, and special glass cells of accurately adjustable thicknesses are made for using it. But the exponential form of the law is again inconvenient; it makes the accuracy very different at different parts of the scale. However, when concentration is the ultimate quantity, it is often convenient to compensate changes of concentration by opposite changes of thickness; but it is often doubtful whether the law that, for a given transmission, thickness is inversely proportional to concentration is valid over a wide range in actual conditions.

(4) The Nicol prism has been used in very accurate work; we have no experience of it, but it clearly will serve the purpose admirably in suitable conditions; the limited aperture of all but very expensive prisms is an obstacle for some purposes. It is not available in the ultra-violet.

(5) The sector disc is free from all objections in principle. It requires the truth of the analogy of Talbot's Law (i.e. that the time-average of the current electricity passing through the cell is determined by the time average of the incident lumens, not by their distribution in time); but this law is always true for any cells likely to be used on other grounds. It is rather slow in operation, for, except in devices that have not yet fully proved their worth, the rotation has to be stopped in order that the angle of the sector may be adjusted; that is not serious in standardizing work. It cannot be used with an alternating light method in which the A.C. component of the current is detected, unless the frequency of its rotation is very great compared with that of the alternations—a condition that can seldom be fulfilled. It has the advantage of being available and equally suitable for light of all wavelengths.

In class (*b*) the chief members are—

1. Stops and shutters.
2. Absorbing wedges.

3. Blackened gauze.
4. Varying voltage on lamp or cell.

(1) Stops and shutters are excellent if they can be placed in the optical path so that they do not vary the distribution of light over the cell. If this important condition can be fulfilled, they should always be preferred.

(2) Wedges fulfil this condition more easily; but they are never completely non-selective in their transmission.

(3) Blackened gauze is quite non-selective and does not alter the distribution of the light, but it is incapable of continuous variation.

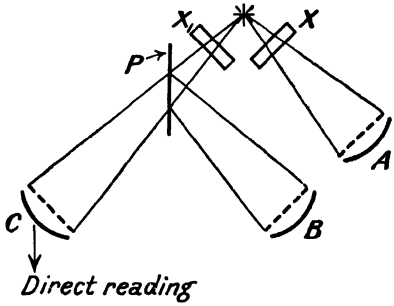


FIG. 67

(4) Variation of voltage is not suitable for precise work, but it is sometimes useful in rough work and as a fine adjustment to other absorbers, e.g. blackened gauze. If vacuum emission cells are used according to Fig. 46, change of r gives a very delicate and sufficiently stable adjustment.

All this is obvious. The only matter that has really to be discussed is whether there is any advantage in using an absorber of class (*b*) which has to be calibrated; and, if so, how best the calibration is performed. The experience of all workers in this field has lately tended so clearly in the same direction that a partial answer can be given with some confidence. All precise absolute measurements of transmission are referred either to direct measurement of the two beams or to the sector disc; but neither of these methods is widely employed in routine measurements; shutters or wedges are used to transfer the ultimate calibration to the routine apparatus. The main reason is that the alternating light method, employing substitution, is usually the most convenient on account of its sensitivity; even when plenty of light is available at the source, it is convenient to be able to lose most of it in an elaborate optical train. The absorber used in the actual measurements is calibrated in special

experiments using much more light. At present the sector disc is more often used in this calibration than direct measurement; but as confidence in the linearity of suitable apparatus grows, the position may be reversed.

It is possible ([4]) to conduct the calibration at the same time as the measurement, by a modification of Fig. 66 (*a*), shown in Fig. 67. A reflecting plate, P, placed between X_1 and B, sends only a small constant fraction of the transmitted light to B and sends most of it to a direct measuring apparatus C; the light received by B (and therefore by A when the apparatus is balanced) is then proportional to the direct reading. Doubts of the precision of this plan may be entertained; but it must be remembered that precision of apparatus for measuring transmission can be, and always should be, established by the test of independence of the intensity of the source.

REFERENCES

1. For general discussion, see K. S. Gibson, *Photoelectric Cells and their Applications* (*cit. ante*), p. 157. This deals professedly with spectro-photometry, but most is of a more general application.

2. Photoelectric polarimetry is such a special case of the measurement of "transmission" that it has been omitted from the text. But it has been much studied. Much of the earlier work was done by v. Halban; recent work has been done by G. Bruhat and A. Guinier, *Revue d'optique* 12, pp. 1 and 397, 1933.

3. The most modern well-designed apparatus is that of C. H. Sharp and H. J. Eckweiler, *Journ. Opt. Soc. Amer.* 23, p. 246, 1933.

4. See F. C. Smith and E. R. Holliday, *Optical Soc. Trans.* 33, p. 20, 1924.

CHAPTER XII

PHOTOMETRY

Photoelectric and Visual Photometry. Photoelectric methods are rapidly replacing visual photometry in the rating of lamps. The reason is not as obvious as may appear at first sight. They possess the advantage that they can be used in a well-lit room instead of in a fatiguing semi-darkness, and that their practice requires fewer and less skilled observers; but their adoption is more often urged on the ground of precision. Now the eye is certainly a very unsuitable instrument for measuring radiation; its very virtues and, in particular, its adaptability make it so; an instrument that will work with almost equal precision in illuminations differing in a ratio of 10,000 to 1 is not likely to distinguish easily small differences in illumination. But then lamps have usually no purpose except to promote vision; and it might be argued that a precision exceeding that of vision could not be useful. Though we have spent much time in studying photoelectric photometry, at first and at second hand, we are not quite sure what is the right reply. Perhaps it is that differences between lamps too small to be distinguished visually may develop later in their life into very large differences. However, all this is not strictly relevant to our theme; there is, in fact, a demand for photometry more precise than the eye can attain, and photoelectric methods can meet it. But the demand does not arise unless the lamps themselves are constant to a precision at least as great as that of visual photometry; in the visual range this condition is fulfilled only by electric incandescent lamps, and by some modern discharge lamps that are only now coming into general use; accordingly only incandescent lamps will be considered.

In what follows, we shall consider only matters that are peculiar to photoelectric photometry. Problems shared with visual photometry, such as errors arising from selective absorption by "white" spheres, or imperfect circuits for controlling and measuring the electrical input, will be left

wholly on one side. We are addressing ourselves to a reader familiar with visual photometry, who is thinking of adopting photoelectric methods.

Adaptation of Visual Methods. Visual photometry is based on the law that the brightness of a surface of given quality is determined completely by its illumination, that is to say, by the surface density of luminous flux incident upon it. If, therefore, holes of equal area are pierced in surfaces of the same quality and equal brightness, the amount of light passing through these holes, and incident on any sufficiently large object behind, will be the same. Since all methods of visual photometry depend on adjusting surfaces of the same quality to equal brightness, it might seem that all these methods might be converted directly into corresponding photoelectric methods by replacing the surfaces by holes of equal area and placing photoelectric cells behind them. But the matter is not quite so simple; the complications that have been omitted are most important and require close attention.

First, we must remember that no cell measures visual light accurately, because its emission curve does not coincide with the visibility curve (see page 6); two lights that are equal to the eye will not in general be equal to the cell unless they are of precisely the same quality. Identity of colour is not sufficient, for lights with very different spectra may have the same colour; the relation between the wavelength and the power of the constituent homogeneous radiations must be the same. (Strictly, differences of polarization and angle of incidence ought also to be taken into account; but the former are unimportant, and the latter are dealt with in a manner considered below.) In principle the photoelectric cell ought to be used only to compare lamps giving the same spectra; but in practice this limitation can be removed in two ways. If the range of quality is small, cells, or combinations of cells and filters, can be found which do agree with the eye to the necessary precision within this small range; in this way the whole range of commercial tungsten lamps, from the vacuum lamp of lowest temperature to the gas-filled lamp of highest temperature, can be measured without correction to an accuracy of $\frac{1}{4}$ per cent. Alternatively, the spectrum (or, for incandescent lamps, the

temperature) can be determined independently, and an empirical correction introduced for the difference between the test lamp and the standard to which it is referred.

Next there are complications arising from the lack of uniformity of photoelectric cells. A single eye can view at the same time two surfaces illuminated by different sources, and compare their brightness. But a single cell cannot distinguish light from one source from light from another; to compare different sources in a strictly analogous manner, the lights from them would have to be thrown on two different cells; the emission of these cells will not be exactly the same, and equality of the currents will not indicate equality of the lights. If equality of currents is to indicate equality of light, the lights must be thrown alternately on the same cell; the only visual method that can be adapted immediately to a photoelectric cell is the little used method of flicker.

In several of the more precise methods of photoelectric photometry some modification of this method is used. But almost as important as the difference in the emission of different cells is the difference between different parts of the same cell. Thus, if we are trying to use the inverse square law, we shall set up a cell behind an opening of fixed area in a screen, and vary the distance of the source from this screen until the current through the cell attains some fixed value. But unless the screen is in contact with the cathode, or at least at a distance from it very small compared with the distance of the source (conditions almost impossible to attain in practice), the area of the cathode covered by the light passing through the opening will vary with the distance of the source; if the emission of the cathode is not perfectly uniform over its surface, equality of current will not indicate equality of light coming through the opening. The same difficulty enters if we are using a sphere for measuring total luminous flux. The brightness of the surface of the sphere is independent of the distribution of the flux from the lamp; but if the cathode of the cell is not a portion of the wall of the sphere, but merely placed behind an opening in it, the distribution of the light over it may vary appreciably with the distribution of the flux from the source. Further, it is not certain that, even if the cathode were part of the wall,

the current would be independent of the distribution of flux; for the relation between the angle of incidence of the light and the resulting emission is not the same as that between this angle and the resulting brightness of a perfectly diffusing surface.

Departures from Visual Methods. For these reasons it is impossible to adapt visual methods to photoelectric measurement in the simple manner suggested, except at a sacrifice of the precision that is its main advantage. We must now consider what modifications are necessary and possible. For the present we shall assume that the sources to be compared give light of the same quality, and shall leave to a later stage errors of the first kind that may arise if the quality is different.

Errors arising from differences between two cells are always avoided, as has been suggested, by the use of a single cell and a method which is in principle one of flicker. This in itself means a departure from the best visual methods. Errors arising from the lack of uniformity of a single cathode can be avoided by interposing a perfectly diffusing member between the cell and the aperture illuminated by the source, so that, whatever the distribution of radiation over the aperture, the distribution over the cathode is always the same. A sheet of opal glass suggests itself immediately as the diffusing member, and would be entirely satisfactory if sheets infinitely thin, and yet perfectly diffusing, could be obtained. But since they cannot, the legitimacy of this device for work of the highest precision is doubtful, especially when the inverse square law is to be used. For, when a precision of 1 part in 1,000 is being attempted, an uncertainty of 1 mm. in the distances between the source and the screen may be important; a glass giving approximately perfect diffusion is always more than 1 mm. thick, and the doubt as to which layer of the glass is to be taken as the screen in the estimation of that distance may therefore be serious.

A better method (Fig. 68) is to invert the principle of the Ulbricht sphere, to place the cell in the centre of a white sphere S, and to throw light from the two sources to be compared on apertures A_1, A_2 in this sphere, these apertures being shielded from the cell by the usual screens D_1, D_2.

The cell may also be placed, not in the centre of the sphere, but behind a third aperture in its wall; in this case the three apertures are preferably at the ends of mutually perpendicular radii. This is more convenient, since leads have not to be brought out of the sphere; but the other plan is more perfect if the cell has a plane of symmetry in which the line A_1, A_2 can lie. Among emission cells, type A (Fig. 11) is very suitable, the cathode having two sides. When the light incident on A_1 or A_2 is directional, it is doubtful whether this method is preferable to that of the opal glass, but when the sources to be compared are themselves enclosed in spheres S_1, S_2 (indicated by dotted lines in Fig. 68), then there is no doubt that this method ought to be preferred to any other.

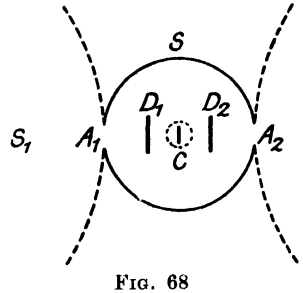


FIG. 68

Any of the methods described in Chapter VI can be used for determining when the currents are the same. The alternating-light method is probably the most satisfactory in principle, the apertures A_1 and A_2 being opened alternately; the mechanical problem of producing the alternations when the apertures are part of the same sphere is not very simple. In addition, there is the difficulty in commutation (see page 109); it cannot be avoided if the two sides of the balance are to be distinguished, as they must be for rapid work. These two difficulties have been overcome, but they probably provide one of the reasons why this method is not growing in favour and, indeed, why the visual method of comparison is losing ground relative to direct reading methods. If it is not adopted, the cell must be connected to some apparatus for indicating a D.C. current (which will probably include an amplifying valve if an emission cell is used); it will first be exposed to the light entering through A_1 and the reading noted, and then to the light entering through A_2, which will be varied till the same reading is reproduced. It is generally advisable to use a null method and to compensate the current due to the light from A_1, so that the reading that has to be reproduced is always zero; the operations involved in a single measurement are longer,

since they involve first adjusting the current to zero under the light from A_1, and then reproducing the reading under the light from A_2; but accuracy is gained. In principle, any type of cell might be used; but in practice the conductivity cell is ruled out (except possibly in the alternating-light method) by the delay in reaching a steady state. The greater effective sensitivity of the emission cell for light of small intensity probably makes it superior when high precision is sought.

Calibration. We have now to consider how the adjustable flux through A_2 is to be produced. Two methods will occur immediately to experts in visual photometry. One is to remove the sphere S_2 and to use the inverse square law. The comparison source L_2 is placed at an adjustable distance r from A_2; the flux entering A_2 will then be proportional to $1/r^2$. But it is very doubtful whether diffusion by the sphere S is complete enough to make this method legitimate; the area of the illuminated patch on the far side of S will vary with r, and with it the proportion of the entering flux which emerges again through A_1 and A_2. It can be recommended only when the candle-power of a source in a single direction is being measured and not its total flux. In this case, the sphere S_1 will also not be present and the source under test L_1 will also illuminate A_1 directly; if the distances of L_1 and L_2 from S are not very different, errors due to imperfect diffusion will tend to compensate each other. But systematic errors can hardly be avoided completely. The truth is that the implicit reliance placed on the inverse square law in visual photometry, and the associated importance attached to the conception of candle-power, are justified only so long as the systematic errors associated with them are concealed by the accidental errors inherent in visual comparisons. The inverse square law may be ideally true, but the conditions necessary for its precise truth are very difficult to attain in practice; when the precision of photoelectric methods is sought, it is better to abandon entirely the use of it and of all its derivatives.

The second method is the rotating sector of variable aperture. This is perfect in principle, for the analogue of Talbot's Law, on which its use depends, is accurately true of any cells suitable for this work. But it is inconvenient

on account of the well-known difficulty of varying the aperture continuously.

The simplest method is to use standard lamps, and a shutter or wedge covering A_2. A comparison lamp, maintained constant, is placed in S_2; the standard lamps are inserted in turn in S_1 and the readings of the shutter noted. But since the calibration is purely empirical, the lamps required must be numerous and must cover the entire range of measurement; it is hardly possible to have enough lamps to detect small irregularities and departures from smoothness in the calibration curve. Moreover, if our aim is to produce apparatus of the utmost precision, it is useless to calibrate it with lamps measured to a less precision, at any rate unless the exact form of the calibration curve is known *a priori*. But how are lamps calibrated with equal precision to be obtained? Not by visual methods. To this it may be replied that the ultimate calibration of a lamp must be visual, since luminous flux has no meaning apart from visual judgments. That is true so far as absolute calibration, in terms of the standard unit of flux is concerned; but it is not true of the relative calibration that alone is required to establish the relative intensities of sources—and this is the problem in which precision is really required.

There is only one method of calibration that solves this problem completely and ensures that the relative calibration is as precise as the errors inherent in the method of measurement permit. It depends on the fact that luminous flux is an "additive" quantity, and that there are linear cells (see page 180), such that the current produced in them by one beam of light is independent of the simultaneous presence of another beam. The essentials of the procedure are as follows. Two lamps are placed in S_1 and a comparison lamp in S_2; the currents through the two lamps are adjusted so that each, acting alone, gives the same current in the cell, indicated by the same reading x_1 of the shutter. The two lamps are now turned on together, each carrying its adjusted current, and the shutter adjusted so that balance is reached at the reading x_2. It is then known that x_2 corresponds to double the flux corresponding to x_1; by seeking a sufficient number of such pairs of readings (x_1, x_2) such that the second corresponds to double the flux of the first,

the complete relative calibration curve can be established. A single point, established by a single source of known absolute flux in S_1, then suffices to give a complete absolute curve.

Modifications of the exact procedure described will be obvious. More than two lamps may be included in S_1, and a set of shutter readings corresponding to fluxes 1, 2, 3 . . . determined in a single experiment. It is convenient for this purpose to have a lamp with (say) six independent filaments in the same bulb; but the necessity for independent supplies (see below) sets a practical limit in this direction. Between the points on the calibration curve thus determined, other points can be interpolated by using sources of lower power, or the same sources run at smaller currents. The extreme of this procedure is to have only two lamps, one of high and one of low power; the low-power lamp is always fed with the same supply; the supply of the high-power lamp is varied. The change in shutter reading due to turning on the low-power lamp then always corresponds to the same increase in flux. This last method is not recommended for the primary calibration, for the errors are large when the curve is built up by small increments; but it is an excellent method of checking the accuracy of a calibration established by other methods; in fact, it provides a test which should always be applied to every calibration curve, by whatever means it was originally obtained, before it is finally accepted as accurate.

It is to be observed that this procedure does *not* involve the assumption that the fluxes sent through A_1 by the two lamps in S_1 are proportional to the total fluxes emitted by the lamps; or that when a balance is attained, the flux entering S_1 through A_1 is equal to that entering through A_2; or that if the two lamps emit the same flux they produce the same current in the cell; or that any pair of lamps concerned give radiations of the same quality. In fact, the only dubitable assumptions made are (1) that the cell and the compensating lamp are steady throughout the calibration; (2) that the flux through A_1 from a lamp in the position of test is proportional to the flux which is to be measured—the assumption on which the use of the Ulbricht sphere rests; and (3) that change of the current produced in the

cell by turning on one of the lamps in S is the same, whether the others are on or off—the assumption of linearity in a rather more general form. If the cells are suitable, (3) will be true, so long as sufficient care is taken of the electrical circuits; it is highly desirable that each lamp should have an entirely independent supply, so that it cannot be affected by switching other lamps off and on. If any two lamps have a common supply, the most painstaking scrutiny of the circuits is required to ensure that they do not affect each other; the neglect of this precaution has led to much trouble. If the conditions are fulfilled, the form of the calibration curve will be unaltered if at some subsequent time the emission of the cell or the flux from the comparison lamp changes; the change will affect all ordinates in the same ratio and can be corrected by the measurement of a single standard lamp placed in S_1. On the other hand, the form of the curve might be changed by a change of the distribution of sensitivity over the cell, or by a change in its spectral sensitivity if the shutter were in any degree selective for colour, as a "grey" wedge might be. But such changes are less probable.

But can really linear cells be obtained of which (3) is strictly true? There has been much argument on this matter, some workers maintaining that they can secure a linearity perfect under the most sensitive tests, others that no cells are perfectly linear. We belong to the former group, and are so sure of our position that we are prepared to regard the latter as simply misled by inadequate experiments. For, unless sensitivity is in doubt (and it is not), experiments in which linearity is apparently attained have greater evidential value than those in which it is not; for apparent, as distinct from true, linearity can only arise from a most improbable mutual compensation of errors. Moreover, none of those who have failed to secure linearity show a proper appreciation of the conditions necessary to secure it, or of the tests necessary to disprove it. But while we regard it as no longer doubtful that linear cells can be obtained, it is, of course, equally certain that some cells are not linear. It may be well to point out therefore that, if non-linear cells are used, calibration is necessarily precarious. For a change in the comparison source or in the light-current relation of the cell may change the form of the calibration curve, so that

complete re-calibration is required, and not merely the re-determination of a single point. On the other hand, the method of calibration described can be applied to non-linear cells if some of the assumptions that were declared not necessary with linear cells are actually true. Thus it can be applied if the two lamps in S_1 give light of the same quality as the source to be tested, and if equality of the currents they produce individually in the cell implies equality of the flux passing through A_1. But it is not worth while to consider in detail the minimum conditions.

Direct-reading Methods. Photometry by the comparison of two fluxes, as suggested by the practice of visual photometry, thus proves very complicated and cannot be made completely satisfactory unless linear cells are available. But, if truly linear cells are available, there is no need for comparison; a flux can be measured directly by the current that it produces, if the current can be measured with sufficient precision. Modern practice therefore is tending to abandon completely methods derived from visual photometry and to resort to direct measurement. The apparatus will then consist of spheres S and S_1 with a common aperture A, and of means for measuring the current through the cell.

However, it is worth noting that one direct reading method does not even require linear cells. It depends upon "bracketing" the test lamp between two standard lamps (or possibly two positions of the comparison lamp) not very different from it. The form of it that has been developed with great care and elaboration employs the constant time method of page 116. A recording quartz-fibre electrometer is alternately earthed and insulated by an automatic mechanism; during the period of insulation, the fibre is momentarily illuminated at accurately-timed intervals, so that the record shows a series of dots, a line through which indicates by its slope the rate at which the charge accumulates. During the succeeding earthed period, the lamp is changed. Successive series of dots thus refer to different lamps; in the interpretation of the record, all that has to be assumed is that the characteristic of the cell remains unchanged during the interval covering the measurement of the test lamp and of the two standards, one greater and one less, by which it is immediately preceded and followed. In order to interpolate

between these standards, it is assumed that over the small range concerned the rate of deflection is proportional to the light. It is unlikely that such a method will ever find a use outside standardizing laboratories of the first class; but it is doubtless capable of very great precision (2).

In all other conditions, linearity must be assumed; it can be established and must be established by the additive method of calibration; the current due to two lamps acting together must always be the sum of the currents due to them acting independently. Accuracy now depends on the apparatus for measuring the current. If a rectifier cell is used, a plain galvanometer will probably suffice, preferably with the compensation arrangement of page 170. The current may then, of course, be read from the potentiometer instead of from a galvanometer through which it passes; a method is not the less "direct-reading" for our present purpose, if the *current* is measured by a null method. A thermostat may be required to keep the temperature of the cell constant. If an emission cell is used, the best method is undoubtedly compensation by a potentiometer applied to an ohmic resistance, an electrometer valve being used as an indicator; this plan has the advantage that the range of the instrument can be altered and changes in the emission of the cell allowed for by alteration of the resistance. The potentiometer can be calibrated in lumens, with several ranges; a standard lamp is inserted in S_1 and the resistance adjusted till the potentiometer reads the right value; it will then read all other values correctly. Metallic film resistances, with wire resistance for fine adjustment, are suitable.

Colour Correction. In this discussion we have been assuming in effect that the sources to be measured all give radiation of the same quality; we have left completely out of account the difference between the emission curve of the cell and the visibility curve. The difficulty arising from this difference in measuring sources of varying quality is undoubtedly the most serious in photoelectric photometry.

If the variation of quality is small, as it is in comparing incandescent lamps of nominally the same voltage and wattage, the difficulty is not serious. Front-wall rectifier cells, and particularly the front-wall cuprous oxide cell, have emission curves so similar to the visibility curve that

the difference may probably be neglected entirely; inaccuracy is masked by lack of precision. The same is probably true of the K–O–Ag emission cell, for though its curve is very different from the visibility curve, having a minimum where the latter has a maximum, the two maxima, one in the red and one in the blue, tend to compensate each other and to give results which, for small variations, agree with those of the eye. For true coincidence of the emission and visibility curves is required only when sources of any quality, however different, have to be measured.

If the variation is somewhat greater—for example, that between high and low temperature incandescent lamps, covering the range from 2360° K. to 2900° K.—some correction will be needed. One plan is to determine (e.g. by the method of page 214) the colour temperature of each lamp, and to apply to the measured flux a correction based on the measurement of standard lamps of known flux and known temperature. Another plan is to make the effective emission curve of the cell agree more nearly with the visibility curve by inserting a selective filter in the path of the light. It is sometimes possible to find really suitable filters. If rectifier cells or thin film emission cells are used, suppression of the sensitivity of the red and infra-red is required; solutions of copper salts, especially cupric chloride, will achieve this. But if a blue sensitive cell is used, e.g. sensitized potassium, the red is completely lacking and no filter can restore it. Moreover, any filter which modifies seriously the emission curve must absorb much light, and may therefore decrease sensitivity for lamps of low power. A better plan is not simply to subtract from the effective light, but to add to it or to combine addition and subtraction. Thus a cell which is too red sensitive may be corrected by combining it with a cell that is too blue sensitive; the combination can be effected by placing both cells behind apertures in the wall of S and connecting them electrically in parallel; or by placing the test lamp in a large central sphere S, and a cell in each of two smaller spheres S_1, S_2 on either side of it. A combination that gives approximately the same results as the eye over the range of incandescent lamps can be formed from a K–O–Ag cell and a KH cell. The proportion of each that is effective in the combination can be adjusted

by a shutter over one of them, which is varied empirically until the desired agreement with a standard calibrated visually is attained. Another method of combining two emissions which diverge in opposite directions from the visibility curve is to cover part, but not all, of a cathode with a filter which over-corrects it. Thus a filter absorbing only 700 mμ and longer wavelengths would over-correct a rectifier or K–O–Ag cell, making it too sensitive to the blue; by adjusting the fraction of the cell covered by such a filter, satisfactory correction over a considerable range of colour temperature can be obtained.

But if the quality is very different, none of these devices are really satisfactory. If there is a marked difference in colour, for example, if a neon lamp has to be compared with a mercury lamp, precision is in any case unattainable; for the visual comparison, on which heterochromatic photometry must ultimately depend, is subject to large errors, arising both from uncertainty of an individual observer and systematic differences between observers. Errors of 10 per cent must be tolerated; but it is difficult to adjust cells by any of the methods described so that even this limit is not exceeded. The situation is even worse if the colour is approximately the same, while the spectrum is very different; for example, in the comparison of a carbon monoxide discharge lamp (which gives approximately white light) with daylight. For here the colour difference is small enough to allow of comparatively precise visual comparisons, while the photoelectric problem is almost as difficult as when great colour differences are present.

With the recent increase in the use of discharge lamps, these problems are becoming important. One solution is to abandon physical methods entirely and to rely wholly on visual observations; and, as has been said already, it is difficult to find a reasonable reply to those who advocate this course, so far as the comparison of lamps of different types is concerned. If only lamps of the same type (e.g. discharge lamps with the same gas filling) are to be compared, it may prove possible to solve the problem by the methods adopted for incandescent lamps; it is not yet known whether the variations of spectrum within a single type are small enough to make this possible. The last solution is to

resort to spectro-photometry (see Chapter XIV), to resolve the light from each differently coloured source into its spectrum and to compare only radiations of the same wavelength; once the distribution of energy flux $F(\lambda)$ is known, the luminous flux is given $\int_0^\infty F(\lambda)V(\lambda)d\lambda$. Now that the visibility curve has been standardized by international agreement, the ultimate adoption of this procedure is inevitable. (So far, only the relative values of $V(\lambda)$ have been fixed; the absolute values are sure to follow, either directly, or by the determination of $F(\lambda)$ for some source of which the flux is standardized.) For it avoids all the uncertainties due to different observers and gives a sound basis for a preference of physical over subjective methods.

Finally, it will doubtless be asked what is the relative precision of visual and photoelectric photometry. This is a vague question, but two answers can be given. In the comparison of incandescent lamps with the highest precision, the inconsistencies arising from uncertainties in visual comparisons, using two observers, are of the same order as those arising from other causes; those arising from photoelectric comparisons by a single observer are negligible compared with those from other causes. In the routine photometry of large numbers of lamps under commercial conditions, inconsistencies of 2 per cent were ignored when the work was visual; with photoelectric methods, inconsistencies of 1 per cent are regarded as demanding inquiry and explanation; at the same time the speed has been more than doubled.

Illumination. Another problem in photometry is the measurement of illumination, that is to say, the lumens per unit area incident on a surface. Precision is here seldom important; errors of 10 per cent are often permissible; on the other hand, the apparatus must be portable. There are two chief sources of error. One is again colour-difference; it is often necessary to compare daylight with artificial light, or direct sunlight with light under trees or below the surface of the sea. The only ways to remove it are those already discussed; but their application is often rendered more difficult by ignorance of what light is truly effective. Thus it is by no means certain that the illumination that

determines visual acuity or absence of fatigue is the same illumination as that which determines subjective brightness, when colour differences are present as extreme as that between daylight and the light from a discharge lamp. Again, it is not known precisely what regions of the spectrum promote the growth of organisms. Even if the effective emission of cells were completely under control, we should not always know what emission curve to use.

The other error arises from the variation of the photo-

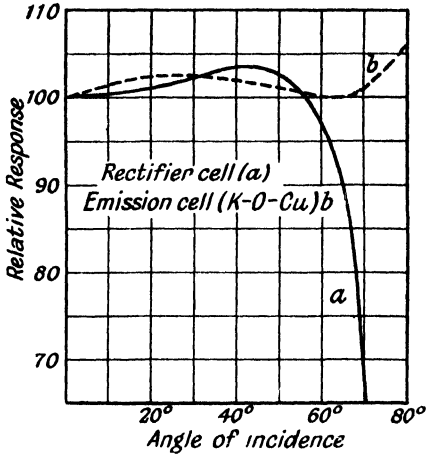


FIG. 69. DEVIATION FROM COSINE LAW

electric current with the angle of incidence of the light, its quantity being always the same. Such variation is often called a failure of the cosine law, because, if it were absent, the current produced by a beam of parallel light, greater in cross-section than the cell, would vary as the cosine of the angle of incidence. This law is not generally true, even if the cell is designed so that light from no direction is actually obstructed. Fig. 69 gives the current produced by the same beam of light at different angles of incidence (*a*) in a rectifier cell; and (*b*) in a specially designed emission cell, with a K–O–Cu cathode which is matt and black. Since the most perfect matt surfaces used in visual photometry show deviation of 2 per cent, curve (*b*) is good enough, but curve (*a*) is not. Unless the distribution of the illumination is known —a condition seldom fulfilled—it is impossible to apply a

correction for an imperfect curve; the only possible course is to diffuse the light before it reaches the cell, so that, whatever the manner of incidence on the surface under test, the angles of incidence on the cell will be the same. Probably the nearest approach to the idea would be to place the cell again in a sphere of which an aperture forms the surface or to use the concentric spheres of opal glass proposed by Bennett ([4]). But both these methods involve a great loss of light, which is serious when the measuring apparatus has to be portable and relatively insensitive. Simpler and less perfect devices are usually employed; but those who have paid most attention to the problem are by no means sure that they have solved it. There is again the difficulty that we are often not sure what we want to measure, and whether illumination defined so as to be independent of the angle of incidence is really the relevant magnitude ([5]).

In these circumstances, all ready-made illumination meters should be regarded with suspicion, and trust placed in their indications only after suitable tests have been made. The best that can be said for many of them is that they are no more inaccurate than the visual instruments they are designed to replace. And this may be good enough, especially in such things as photographic exposure meters; on no other ground can there be justification in using for this purpose a simple rectifier cell that is neither linear nor corrected for colour or temperature, nor subject to the cosine law.

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2. The bracketing method is described by C. Müller, *Zeit. f. Techn. Phys.* 61, p. 227, 1930.

3. For colour correction see the papers mentioned under (1), and J. S. Preston and L. H. McDermott. *Journ. Sci. Inst.* 11, p. 150, 1934.

4. M. G. Bennett, *Proc. Phys. Soc.* 40, p. 316, 1928.

5. For a typical discussion of "effective illumination," see W. R. S. Atkins and H. H. Poole, *Sci. Proc. Roy. Dublin Soc.* 18, p. 277, 1926.

CHAPTER XIII

COLORIMETRY

The Meaning of Colour. Colour is primarily a property of light or of sources of light. The colour of a material not itself a source means the colour of the light transmitted, reflected, or diffused from it when it is illuminated. The colour of this light depends on the colour of the illuminating source; accordingly, the colour of a material means nothing unless the illuminant is specified. At the start we shall consider only the colour of a beam of light. Here brightness or luminosity has to be distinguished from colour; two beams may have the same colour, but different luminosity, or the same luminosity but different colour. Luminosity, apart from colour, can be measured by the methods of Chapter XII. In this chapter we are primarily concerned with colour alone.

The meaning of these terms, colour and luminosity, depends on vision; to a blind man neither can convey anything; to a man with very defective vision the former can convey nothing. All decisions about luminosity and colour must rest ultimately on visual judgments. Nevertheless, they are closely connected with quantity and quality of light, as defined in Chapter I.

If two geometrically similar beams of light have spectral distributions $A_1 . F(\lambda)$ and $A_2 . F(\lambda)$ where F is the same for both, and A_1, A_2 independent of λ, then they have the same colour; if further $A_1 = A_2$, they have the same luminosity. That proposition is strictly true, however abnormal the vision of the observer, so long as he can see at all. The converse of part of this proposition is true; if the F's are the same, equal luminosity implies equal A's. But the converse of the rest is not true; beams of the same colour may have different F's, and equality of A's does not imply equality of luminosity if the F's are different. Moreover, different observers do not agree in selecting the same groups of F's to correspond to the same colour or in judging what beams of different colour are equally bright. Even if this last difficulty could be overcome by specifying a standard observer,

the specification of colour by means of F's would be very inconvenient, for there would be no simple mathematical relation between the F's corresponding to the same colour.

Trichromatic Coefficients. The modern specification of colour by the "colour triangle" or "trichromatic coefficients" depends on quite different propositions. By mixing suitable quantities of the light from three differently coloured sources, preferably red, green, and blue, we can produce light that matches in colour and luminosity light of many different colours. The quantities required to match beams of the same colour but different luminosity stand in the same ratios to each other, so that the colour can be specified by two ratios and the luminosity by one factor. Unfortunately, not all colours can be thus matched, whatever are the three sources. But a combination of light that cannot be thus matched and light from one of the sources can be matched against some combination of the lights from the other two. This is expressed conveniently by saying that all lights can be matched by combining suitable quantities of light from any three sources such that light from one cannot be matched against any combination of light from the other two, if negative, as well as positive, quantities of light are admitted. The quantities of light from one set of three sources required to match a given light are related to those from any other set required to match the same light by linear equations, the constant coefficients of which are determined by the colours of the sources in the two sets. This fact enables us to introduce partly or wholly imaginary sets of sources such that positive quantities of the light from them will match any light; and we may choose these sets so as to fulfil other conditions not directly connected with colour-matching. Observers do not agree wholly in the colour matches described, even if their colour-vision is not markedly abnormal.

These facts are used in the specification of colour, formulated by the Commission Internationale de l'Éclairage (C.I.E.), in the following way. First, the colour vision of a "1931 C.I.E. observer" is specified by means of his visibility curve (page 6) and his colour matches. Then an imaginary set of three sources is defined by means of the quantities of light from these sources required to match light of four specified colours. It is then possible for any observer.

with the standard colour vision to define uniquely the colour and luminosity of any beam of light by assigning values to three variables x, y, z, as the result of colour matches made with suitable apparatus. The colour is defined by the two ratios of x, y, z, so that the colour is always the same if these ratios are the same, and conversely. If a statement of colour alone is concerned, it is usual to choose the absolute values of x, y, z, so that their sum is 1; x, y, z are then called trichromatic coefficients. If luminosity is also required, the absolute values are chosen so that y is proportional to the luminosity, whatever the colour.

We do not imagine for a moment that this summary account will suffice to initiate a novice into the mysteries of trichromatic colour-measurement; we hope, merely, that it tells him enough for our limited purpose. For information concerning the C.I.E. system, he should consult T. Smith and J. Guild, *Trans. Opt. Soc.* 33, pages 73–134, 1931–2. This paper will also give him references to more elementary work; a paper by T. Smith (page 214 of the same volume) is recommended as a theoretical introduction.

Colour and Spectral Distribution. We must now seek a connection between spectral distribution $F(\lambda)$ and trichromatic coefficients x, y, z. A connection can be established if certain very simple assumptions are made. One of these is that luminosity (carefully defined) is additive, so that a beam of light produced by bringing two component beams into coincidence has a luminosity equal to the sum of the luminosities of its components. From these assumptions it follows that, by studying the colour matches of a standard observer, we can define three functions of λ, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$, such that the trichromatic coefficients of light having the spectral distribution $F(\lambda)$ are given by

$$x = 1/R \int_0^\infty \bar{x}(\lambda) F(\lambda) d\lambda$$

$$y = 1/R \int_0^\infty \bar{y}\ \lambda) F(\lambda) d\lambda$$

$$z = 1/R \int_0^\infty \bar{z}(\lambda) F(\lambda) d\lambda$$

where R is the sum of the three integrals. The luminosity of

the light is proportional to y, so long as $F(\lambda)$ refers to geometrically similar beams. $\bar{y}(\lambda)$ is actually the visibility function $v(\lambda)$ with the ordinates reduced so that the maximum ordinate is nearly 1.

$\bar{x}$, $\bar{y}$, $\bar{z}$ have been determined and are given in Table III of Smith and Guild's paper. The problem of determining colour may therefore be reduced to that of determining $F(\lambda)$. This involves no visual judgments and can be achieved by purely "physical" apparatus, including photoelectric cells. All the visual judgments are made once and for all in determining $\bar{x}$, $\bar{y}$, $\bar{z}$.

The measurement of the colour of a material follows very similar lines. Once the illuminant is defined, the colour of a material depends on a spectral distribution function $a(\lambda)$ just as the colour of a light depends on $F(\lambda)$. $a(\lambda)$ is the ratio of the intensity of light of wavelength λ after transmission, reflection or diffusion from the material, to the intensity of the same light before incidence upon it. Functions of λ, $E\bar{x}$, $E\bar{y}$, $E\bar{z}$ can be determined in the same way as the function $\bar{x}$, $\bar{y}$, $\bar{z}$, such that the trichromatic coefficients of the colour of a material characterized by $a(\lambda)$ are given by

$$x = 1/R' \int_0^\infty a(\lambda) \,.\, E\bar{x}d\lambda$$

$$y = 1/R' \int_0^\infty a(\lambda) \,.\, E\bar{y}d\lambda$$

$$z = 1/R' \int_0^\infty a(\lambda) \,.\, E\bar{z}d\lambda$$

where R' is the sum of the three integrals. The determination of colour is thus reduced to the determination of $a(\lambda)$. $E\bar{x}$, $E\bar{y}$, $E\bar{z}$ depend on the illuminant. Tables VI, VII, VIII of Smith and Guild's paper give their values for the three standard illuminants defined by the C.I.E. The specifications of these illuminants, representing roughly domestic artificial light and two kinds of daylight, are given on pages 75 and 76, and their spectral distribution functions $F(\lambda)$ (denoted by E) in Table V; the choice of the illuminant is left to be decided by the purpose of the measurement. It is to be observed that the illuminant chosen need not actually be

used in determining colour by means of $\alpha(\lambda)$; its properties cease to matter once $E\bar{x}$, $E\bar{y}$, $E\bar{z}$ are determined.

Spectro-photometry. $\alpha(\lambda)$ is simply the transmission of the material in the generalized sense of page 178. Accordingly, little more need be said about its measurement. Spectrally-resolved light must, of course, be used. The spectrometer may be placed in the optical train either before or after the light falls on the material; both plans have been used, the preference between them rests on considerations of intensity and of stray light; it is important to remember that stray light of very small or no visual intensity may produce a considerable current in the cell and must be excluded. When colour by reflection is concerned, comparison with a white surface is always employed. The alternating light method is generally preferred nowadays. An elaborate automatic instrument, which not only measures and records $\alpha(\lambda)$, but also calculates the integrals required to derive x, y, z, has been designed by A. C. Hardy ([1]).

In measuring $\alpha(\lambda)$, the spectral distribution of the source need not be known; but in measuring the colour of light by means of $F(\lambda)$, a source of known spectral distribution $F_0(\lambda)$ is required. Light from the known and unknown source is thrown alternately on the slit of the spectrometer, and the ratio of the emergent light of wavelength λ is determined. $F(\lambda)$ is thus determined from the measured ratio $F(\lambda)/F_0(\lambda)$ and the known $F_0(\lambda)$. Here, again, we are concerned with the comparison of the intensities of beams following the same optical path; the problem is therefore closely similar to that of measuring transmission. One of the beams is reduced in intensity in a known ratio until it is equal in intensity to the other; the methods of effecting such reduction have been discussed already. For the known source $F_0(\lambda)$, a tungsten radiator at known colour temperature is usually employed. It is important that the distribution of the energy should not be changed between leaving the source and reaching the slit of the spectrometer. Change may occur owing to absorption in the glass of the lamp or optical system, or by imperfect achromatism of the latter. In work of the highest precision, F_0 is preferably measured at the slit by a thermopile; but then it may sometimes be doubtful whether much is gained by deriving F indirectly through the

ratio F/F_0 by means of the photoelectric cell, for F can also be measured directly by the thermopile. But when the problem is to compare two unknown sources rather than to find F absolutely for either of them, the superior sensitivity of the photoelectric cell usually gives increased precision. But photoelectric methods are certainly not as valuable in determining the colour of light as in determining the colour of a material; so far, however, the latter problem has been much more important.

A third problem, independent of colour, but requiring a similar technique, may be mentioned here. It is that of measuring the emission curve $\sigma(\lambda)$ of a cell. Here, again, spectrally-resolved light must be used; but now the output of the cell $i(\lambda)$ must be actually measured. (Comparison with a cell of known emission curve is conceivable; but cells of reliably constant emission curves are not obtainable and, even if they were, there would be the problem of calibration.) $\sigma(\lambda)$ is then $i(\lambda)/F_0'(\lambda)$, and F_0' is the power of the light emerging from the spectrometer, which is not the same as that entering it. If absolute values are required, $F_0'(\lambda)$ must be measured for each value of λ by means of a thermopile replacing the cell. But if only relative values and no great precision is required, it may be sufficient to assume $F_0(\lambda)$ for the light incident on the spectrometer and calculate the proportion of the light reaching the cell from the dispersion of the spectrometer and any selective absorption in it. $i(\lambda)$ will, of course, be small, and one of the sensitive methods of measurement must be employed.

The advantages most often claimed for colorimetry by photoelectric spectro-photometry are speed and convenience arising from abolition of a skilled observer. As against colour-matching, this advantage may be very great, for colour-matching is worthless unless performed by a highly-trained observer with normal vision. As against visual or photographic spectro-photometry the advantage is more doubtful, but may be appreciable in certain circumstances. But precision has also to be taken into account. Photoelectric methods of determining α and F ought to be more sensitive than visual and more accurate than photographic. It is doubtful whether a superior precision has yet been achieved; but the history of lamp photometry suggests that

it will be achieved if perseverance is worth while. All indirect methods, i.e. those that involve the determination of a and F and the use of the C.I.E. tables, are at present less sensitive generally than direct colour-matching by a skilled observer. He can distinguish some colours to which these methods assign the same trichromatic coefficients and, in the assignment of these coefficients to a given source or material, he can attain sometimes more consistent results by matching against mixtures of three primaries than can be attained by measuring F or a. Even if his vision is not standard, he may avoid all systematic errors, not concealed by accidental errors, by a careful determination of the necessary corrections. If the precision of spectro-photometry could be greatly increased, the position might be reversed; then the indirect method would be more precise than the direct in the same sense as that in which photoelectric methods are more precise than visual in the determination of luminosity. But this sense is necessarily somewhat Pickwickian, for since luminosity and colour have no meaning apart from vision, it would seem that no method can be more precise than vision. Perhaps a better way of expressing the position would be to say that, in these circumstances, the C.I.E. tables would become the definition of a new magnitude to which visual colour is an imperfect approximation. However, one further possibility must be mentioned. The tables derive their significance from certain laws, for instance, the law that colour is completely determined by the relative spectral distribution $F(\lambda)$, and is the same for $A_1 . F(\lambda)$ and for $A_2 . F(\lambda)$. It is conceivable that more precise spectro-photometry might prove some of these laws false. What should we say then? It is wiser to leave that question till it arises.

Alternative Methods. The great complexity of the method of colorimetry sketched in the foregoing sections has naturally encouraged a search for simpler alternatives. All that have been proposed involve the principle of using cells with different emission curves; since such cells can distinguish beams of light of the same luminosity but different colour, it seems plausible to suppose that they might measure colour.

There is one method based on this principle that is theoretically satisfactory; it has been advocated by Bloch (2). It

follows from the principles of trichromatic colorimetry that if it were possible to obtain three cells R, G, B, with suitable emission curves $\sigma_R(\lambda)$, $\sigma_G(\lambda)$, $\sigma_B(\lambda)$, then the trichromatic coefficients x, y, z of any light would be linear functions of the three currents i_R, i_G, i_B, evoked by that light in the three cells; consequently a determination of i_R, i_G, i_B would enable x, y, z to be calculated. There would be a very large number of possible sets σ_R, σ_G, σ_B, all of which would be suitable.* If a set cannot be found among unscreened cells, the emission curve of any cell sensitive throughout the visible spectrum could be modified by three filters so as to produce the required effective emission curves; for in principle a filter can be obtained having any desired relation between transmission and wavelength.

But though this method is theoretically satisfactory, it is impracticable. The emission curves σ_R, σ_G, σ_B would have to be adjusted very precisely. The variation of the emission curves of different cells, and even the variation of the emission curve of the same cell at different times, would make constant adjustment necessary if accuracy were to be attained. If accuracy is abandoned and the method regarded as merely approximate, it merely becomes one variant of a more general method that is better studied from another point of view.

If a selectively absorbing filter is placed in the path of a beam of light, its transmission depends on the spectral distribution of the light. If two beams of light are equally absorbed by *all* filters, then they must have the same spectral distribution, and therefore the same colour; if they are absorbed equally by a series of filters each transmitting a different part of the spectrum, these parts covering together all the spectrum, then they must have nearly the

* One form of the "trichromatic theory of vision" asserts that the eye perceives colour because it is a combination of three receivers having different sensitivity curves; those who hold this theory would therefore maintain that the three cells R, G, B would closely simulate actual vision. The theory is not universally accepted, and it is not our business to express any opinion concerning it. But for fear of misunderstanding we must insist that an opponent of the theory, unless ignorant of practical colorimetry, would not deny the proposition asserted in the text. Though he would hold that the three cells acted in a perfectly different way from the eye, he would not deny that they might be used for the determination of trichromatic coefficients.

same spectral distribution and nearly the same colour. By absorption experiments we can detect similarity of colour which arises from similarity of spectral distribution. Further, we can even measure roughly a difference of colour that is simply connected with a difference of distribution; thus light that is yellower owing to a larger content of spectrum yellow, the remaining distribution being unchanged, will be more absorbed by all filters that absorb spectrum yellow; the ratio of the absorption by a filter which does not transmit spectrum yellow to the absorption of one that does transmit spectrum yellow is therefore, within the range of similar distributions, a measure of yellowness.

This is the principle of the Toussaint colorimeter. If used with discretion, it is undoubtedly capable of giving useful information concerning such variations of colour as are likely to occur in dyeing, and in some other industries; the principle involved is so obvious as to require no further elaboration. But it must never be forgotten that it is incompetent to deal with colours whose similiarity does not depend in a very simple manner on similarity of spectral distribution, unless it is elaborated so as to have become completely equivalent to Bloch's method. Even if the filters approximate closely to a set conferring on the cell the effective emission curves σ_R, σ_G, σ_B mentioned above, it will not be true in general that two beams of light of the same colour have the same transmission in any one of these filters or that the same ratio of the transmission in two of them establishes identity of colour; the identity of colour would be established only when the transmissions in all three filters stood in the same ratio. There is no half-way house between complete measurement of colour by means of trichromatic coefficients and a mere detection of such similarity of colour as arises from similarity of spectral distribution.

In using the principle, the Wratten series of "monochromatic" filters are useful. They are "monochromatic" only in the visible region and all transmit the near infra-red; the cell must therefore not be one (such as a Cs–O–Ag cathode) sensitive to this region. On the other hand, the cell should have an appreciable sensitivity throughout the visible spectrum; among emission cells K–O–Ag is suitable; among

rectifier cells front wall Cu_2O or Se with a greenish filter. It is seldom necessary to use all the six filters incorporated in the Toussaint instrument; if two, or at most three, will not give the information sought, information obtained with more is likely to be misleading; and—once again—any procedure it is proposed to adopt must be checked by expert visual observation before it can be trusted to give any information at all about colour.

It should be clear from this discussion that, instead of filters placed before a single cell, cells of different emission curves may be employed. This plan has been used with success in measuring the colour temperature of incandescent lamps. Suppose cell *R* is more sensitive to the red, cell *B* to the blue. The cells are exposed to a lamp at a standard colour temperature, and the proportion of its light incident on each adjusted so that the currents are equal and the cells balance; if another lamp is substituted, the proportions being unaltered, the balance will be maintained if the colour temperature is the same; but if the temperature is lower and the light redder, cell *R* will give more current than cell *B*; conversely, if the temperature is higher. Owing to the sensitivity of the balance, this method is extremely sensitive and can detect changes in colour temperature much less than those appreciable to the eye; it is used in precision lamp photometry. In this case, and this alone, photoelectric methods have led to increased precision in colorimetry. The method may be conveniently combined with colour correction (see page 200). The difference of the currents from the two cells indicates the colour of the lamp; their sum may indicate the lumens independently of colour differences ([3]).

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