THE PHOTRONIC PHOTOELECTRIC CELL

MONOGRAPH B-8

WESTON
ELECTRICAL INSTRUMENT
CORPORATION
NEWARK ··· NEW JERSEY

The
PHOTRONIC
Photoelectric Cell

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WITH EXPERIMENTS

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Weston Electrical Instrument Corporation
Newark, New Jersey

FOREWORD

THE science of photoelectricity, dealing with electrical effects dependent upon light is of rapidly increasing importance today.

The idea of harnessing the sun's power has always intrigued Man. In his quest of this goal many phenomena of large significance were uncovered. As always, their value was not appreciated; in the search for imposing results the minor profitable details were forgotten.

At length we are beginning to realize the worth of what we already have. Some day we may harness the sun. However, we have come to see the folly of meanwhile neglecting what lies in our hands.

Photoelectricity, embracing a wide range in theory, has, for our present purposes, been narrowed to the use of Photoelectric Cells. These cells allow us to draw upon the energy of the sun and other light sources to provide comforts and conveniences in our every-day life. In industry they have become indispensable controls.

Photoelectric Cells give us fire-alarms for safety, talking-movies for enjoyment, industrial assistance to lighten work. They keep the beacons flashing in our lighthouses. They make possible the radio transmission of pictures of far-off happenings. They light the fields for our airliners. They are extremely valuable and the technical student, tomorrow's engineer, dare not ignore the study of them.

This booklet has been prepared to impress students with the importance of this all-pervading art of Photoelectricity, and to render some tangible service to those engaged in teaching Science.

PHOTRONIC Photoelectric cells have been the fundamental contribution of Weston engineers to this art. The PHOTRONIC cell is a "dry" type cell converting light energy into electrical energy.

This monograph draws upon Weston's wide experience gained in developing and applying this cell for the accurate measuring, control and use of light in industry. Therefore Weston feels that the information here given, while not offered as a text or complete course of study in Photoelectricity or Photo Cells, nevertheless will be helpful in arousing student interest in such an important field.

A general knowledge of physical optics and some laboratory work is presupposed. The experiments given are designed to show the application of theory to everyday engineering problems.

Chapter I

HISTORICAL

"Electric Eyes" or Photoelectric Cells, as we have them today are the result of nearly one hundred years casual and deliberate investigation. Reported isolated discoveries by various men goaded the curiosity of others and led to real scientific investigation. The resulting accumulated knowledge gave us our present cells.

Photoelectricity manifests itself in three general ways, known as the photo-voltaic, photo-conductive and photo-emissive effects. The historical development of these effects is the story of Photoelectricity up to the present.

The Photo-Voltaic Effect

The photo-voltaic effect is, strictly speaking, the generation of voltage in a liquid type of cell through the action of light. The term has, however, been applied to many types of cell, even to the dry type referred to later.

Edmund Becquerel, a French scientist, first recorded an observation of this effect in 1839. While studying primary voltaic cells he discovered that the output of his cells increased when sunlight was allowed to fall on one of the platinum electrodes.

Further, Becquerel's curiosity prompted him to vary the color of the light which reached the electrode. He accomplished this by means of a prism and found that green light gave the highest voltage.

Apparently he did not realize the possibilities that lay in his discoveries and contented himself with merely recording the unusual things he had found.

Commercially, no liquid type cell employing the photo-voltaic effect appeared on the market until quite recently. In 1930 a liquid cell with two copper-oxide electrodes was brought out. The cell was housed in a bakelite container having a glass window to admit light. When one of the electrodes was illuminated, voltage generation resulted.

Upon standing, the usefulness of the cell was limited by the formation of destructive gases, although no galvanic action was supposed to occur.

The Photo-Conductive Effect

When light falls on certain materials it changes their resistance to the passage of electrical currents.

This photo-conductive effect was first observed by Willoughby Smith, in 1873. Smith, a telegraph electrician in the Azores at the time, in testing his lines with selenium resistors, found puzzling differences in his results.

Upon investigation he found the discrepancies to lie in the fact that these selenium resistors changed their electrical resistance characteristics when light reached them.

Evidently Smith was struck by his discovery for, in recording it for the Society of Telegraph Engineers, he said: "By the aid of the telephone I have heard a ray of light fall on a bar of metal!"

Other investigators began looking into the peculiar light-properties of selenium and, in 1873, M. L. Sale published an article in the magazine "Nature" on the "Action of Light on the Electrical Resistance of Selenium."

Sale found that the wavelength, or color, of light played a part in the phenomena and that red had the greatest effect upon this particular material. He found that selenium was electrically sluggish, that it did not respond over-promptly to fresh stimulations. He also noted effects due to temperature changes.

Lord Rosse, another Englishman, in 1874 investigated the selenium cell from the viewpoint of its use as a thermopile. His work in this regard was not successful however.

The early investigators missed one point completely. They always visualized a new source of power and bent their efforts toward greater and greater output. They completely overlooked the value of photoelectric cells as instruments for controlling ever-so-many processes and devices.

The photo-conductive property of selenium is employed commercially today. One type of cell consists of a glass disc, about ¾ inch in diameter, upon one surface of which there are fine lines of platinum film, separated, condenser-like, by intervening lines of selenium film.

Alternate lines of the platinum grid are joined together to make each of the two cell-electrodes. So long as no light falls on the selenium, it acts as a high resistance separator. When it is illuminated, however, its resistance is reduced, allowing current to flow between the platinum conducting films.

Selenium is affected by moisture. Therefore this type of cell is enclosed in an especially designed glass capsule which is translucent, thereby allowing light to reach the sensitive material.

Although this type of cell is a great improvement over earlier forms, it still has serious limitations.

Most important, probably, is the fact that it is not self-generating, that is it requires an outside source of electrical potential for operation. When this is considered in conjunction with the fact that selenium, as used in such a cell, is merely a relatively-high resistance material, it can be readily seen that some current will flow even when the cell is kept darkened.

Of next importance is the cell's instability. It is not constant or permanent in performance, it does not always have the same conductivity under the same light conditions. Its characteristics alter with age. Temperature changes affect it markedly. All but relatively-low light intensities damage it. And it has the aggravating habit of being relatively slow to follow changes in light intensity.

Photo-Emissive Effect

Photo-emission, as the name implies, is the release of electrically charged particles, electrons, from certain substances when light falls upon them.

Commercially this photo-emissive effect has become one of the most important manifestations of photoelectricity. Our present-day movies depend almost entirely for their sound reproduction upon cells built on this principle.

In photo-emissive cells the electrodes are separated by a high-resistance path consisting of an air gap, inert gases or merely a vacuum. The ejected electrons bridge this gap between the light-sensitive cathode and the receiving anode, by the aid of an applied potential.

Heinrich Hertz, in 1887 first discovered that illuminated substances shot off such carriers of electricity. While studying inductive currents he noticed that the sparks in secondary-circuit gaps increased when they were exposed to light from spark gaps in the primary circuit.

By shielding the induced spark with opaque substances, he proved that the effect was due to the influence of light. But, even glass screens caused the sparks to die. Thus Hertz correctly concluded that, not visible light, but ultra-violet light, which does not penetrate glass, was the agent affecting his electrodes.

Hallwacks, in the following year, found confirmation of this discovery and, because of the work he did in this field, became generally known as the discoverer of the photo-emissive or "Hallwacks effect."

This German scientist found that charged zinc plates lost their charges when exposed to ultra-violet light coming from arc lamps. Electroscopes connected to such plates showed that this light, invisible to our eyes, had caused electricity to be dissipated.

Hertz's increased spark length, and Hallwack's discharged plates involved the flow of very little photoelectricity. The effects needed much enlarging before approaching anything like practical use. Also, the necessity for an ultra-violet source was an added hardship.

However, in 1889, Elster and Geitel investigated the light-sensitive qualities of the alkali metals, principally sodium and potassium. These metals were found to give much stronger currents. Most important, however, they reacted to ordinary visible light.

Elster and Geitel were on the way to a commercially practical article. Further investigation disclosed that these alkali metals worked much better when dissolved in mercury so as to make amalgams. Still better results were obtained when the electrodes were acted upon in a vacuum or in the presence of inert gases.

Naturally, vacuum or gas-filled cells meant containers. Glass receptacles solved the problem, although glass could not have been used if the alkali metals did not have that important property of responding to visible light.

Other workers undertook the job of perfecting this type cell and brought it to its present state. Despite much development, certain inherent inconvenient features remain, however.

The distance between the electrodes, small as it may be made, is still a difficult path for the emitted electrons to travel. Consequently, external operating voltages are required to attract them toward the anode. Even at that, the resulting generated current is so small that vacuum tubes must be employed to amplify it.

Emissive type photoelectric cells now on the market are similar in appearance to present-day glass radio vacuum tubes. Caesium compounds have generally replaced the other alkali metals and, except for one small section to admit light, the inner surface of the tube is entirely coated with this light-sensitive material. The externally-charged anode stands in the center of the tube and attracts electrons from all sides.

Some newer cells have the photo-sensitive material held upon a semicircular plate instead of being deposited upon the glass of the container. The operating principles are the same, however.

This type of cell is particularly adapted for reproducing sound recorded on talking picture film. The cells must be placed near the amplifier to prevent large leakage losses occurring in long conducting leads.

Barrier-Layer Cells

The type cell almost universally used today for other than sound reproduction is the barrier-layer cell. The name comes from a supposed layer of some sort, within the cell, which acts as a barrier or stop, making conduction possible in one general direction only.

The barrier-layer cell is sometimes classed among the photo-voltaic, but its action seems to indicate that it belongs more to the photo-emissive type. These cells use no liquids, are not fragile, have a permanency denied other types, and require no vacuum tube amplification.

Adams and Day, in 1876, found that a selenium rod, joined to platinum electrodes, produced small self-generated currents when either of the platinum-selenium junctions was exposed to light.

Fritts, in 1883, went a step farther. He deposited a layer of selenium on metal supporting discs. On top of the sandwiched selenium he placed translucent gold leaf. This device also generated small electrical currents when light fell upon it.

Grondahl, in 1926, used the same principle except that he substituted the copper oxide of his rectifiers for the selenium of Fritts. The first copper oxide cell of commercial possibilities was produced by Lange, in Germany, during 1930.

Lamb and Bartlett, two Weston engineers, were the first to produce barrier-layer cells with apparently permanent characteristics. Their cell, known as the PHOTRONIC photoelectric cell, consists of a metal supporting disc upon which is deposited a layer of photo-sensitive material. Upon this is placed a special kind of metallic grid, acting at once as electrode and collector for the current set up by the electrons freed from the light-sensitive material. Light reaches this material through the grid itself.

This direct conversion of light energy into electric energy of usable strength marks an important milestone along the path toward tapping the large reservoirs of power that lie in the sun, etc. Whether the future shall justify the visions of early investigators, remains to be seen. By taking advantage of what little knowledge we thus far have, however, the beam of light has been pressed into the service of Man.

Fig. 1. The PHOTRONIC Cell and its component parts

Chapter II

LIGHT UNITS

There are units and terms requiring definition if the phenomena and devices associated with the use and measurement of light are to be discussed intelligently. Therefore, before considering the action of PHOTRONIC cells, we shall review the language employed in connection with them.

Radiation

Radiation is the transmission of energy through space by electromagnetic waves.

Sunlight, even though streaming in through cold window-glass, on winter days, if allowed to strike the hand, gives a sensation of warmth. The sun is sending out energy in every direction, and a part of this, having definite wavelengths, furnishes most of what we feel as heat.

Part of the emitted energy produces in the eye the sensation of light. And there is still other energy reaching us which we can neither feel nor see, and can detect only by special methods.

Fundamentally all this energy is alike, differing only in wavelength or vibration frequency. Nature, however, has attuned our senses to only certain of these wavelength bands. That particular band producing the sensation of light shall be one of our principal concerns in connection with PHOTRONIC cells.

Radiation is brought about in various ways. In the sun gases are heated to incandescence; in the familiar light bulb radiation is caused by similarly heating the filament through the agency of electric current. The reddish light from neon-lamp advertising signs is radiated energy due to the effect of potential on the imprisoned gases. Radiation may result from chemical action. And it may be caused by the very action of light itself.

The electromagnetic spectrum, that is the entire gamut of electromagnetic waves, runs from the smallest possible to the longest conceivable wavelengths. By various means waves have been measured as short as .00005 millimicrons, .00005 of the millionth part of a millimeter! And some have been found 20,000 meters long!

In the field Man has thus far explored, are such things as Cosmic Rays, Gamma Rays, X Rays, Ultra-violet Rays, Visible or Light Waves, Infra-red Rays, Hertzian Waves, and Radio Waves. Essentially they are all alike; the only differences are their wave lengths and the corresponding rapidity at which they dance in space. The shorter they are, the faster they vibrate, because they all travel through space at the same speed.

For the present we are principally concerned with Visible Radiation or Light. As was said, a certain section of the electromagnetic spectrum sends out waves which have the faculty of producing in the eye sensations of light and color. This section of the large spectrum is called the Visible Spectrum.

Particular attention should be paid to terms here given so that, by clearly understanding the distinctions, similar-sounding phrases will not be confused. Wherever the words "visible" or "luminous" are used, it must be borne in mind that the energy spoken of is merely one kind of radiant energy, one little band of wavelengths having a specific physiological effect on the normal human eye.

Radiant Flux

Flux means flow, and radiant flux means the rate at which radiant energy is transmitted. This energy is usually measured in microwatts or ergs per second. We receive, or a source emits, certain quantities of energy in definite units of time.

Light

But a pitiably small fraction of all the radiated energy reaching us comes as light. We see only those waves lying in a band roughly between 400 and 700 millimicrons wavelength, less than one octave in the vast scale of all the electro-magnetic spectrum.

Radiant energy just lower than 400 millimicrons length is invisible ultra-violet, the rays which cause sunburn. Immediately above the 700 millimicron waves are the equally invisible infra-red in which most heat resides. Often the term "light" is attached to these, but it is merely a stretch of the term, and does not indicate that they are visible.

Color

Color is the sensation produced within the eye by waves from different parts of the visible portion of the electromagnetic spectrum.

This introduces another consideration to be noted carefully: Our eyes do not see all colors with equal ease. If we have a blue, a red and a yellow light, each of which is sending out into space equal quantities of radiant energy, our eyes will see the yellow much better than the other two. In other words, more Luminous Flux flows from the yellow source than from an equal-energized red or blue.

Visibility Curve

The Visibility Curve is shown in Figure 2. This is an experimental curve, worked out over a number of years by skilled observers and adopted officially as indicating the spectral sensitivity of the average human eye. It shows the relative quantities of Luminous Flux reaching the eye from equal-energized waves within the visible spectrum.

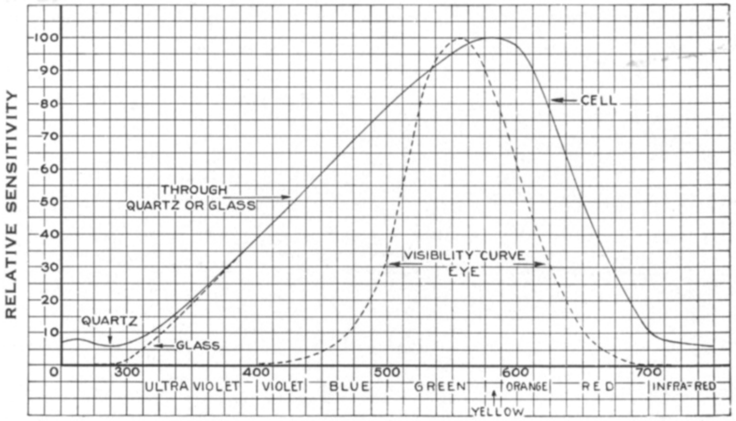

Fig. 2. Spectral Sensitivity of the PHOTRONIC Cell

A glance at the curve will show that a monochromatic blue light, a blue light of one wavelength at 475 millimicrons, furnishes our eyes with only 11% as much luminous flux as a yellow-green light of 555 millimicrons wavelength. Energies being equal, we see yellow-green best, and that is why the Illumination Engineers are experimenting with those yellow sodium-lamps on our highways.

Color Temperature

Color temperature is a term often used and almost as often leading to misunderstanding. A body may have a color temperature of 3,000° K and yet be as cold as ice. For example, the blue sky of outer space, which we know to be bitterly cold, may have a color temperature as high as 25,000° K.

Color temperature bears no relation whatsoever to the temperature of the light giving source. To say that the sky has a color temperature of 25,000° K means that, for us to get a color like that of the sky, it would be necessary to heat a complete radiator up to 25,000° K. A complete radiator is "a perfect black body" such as is approached by the interior of a closed furnace viewed through a tiny hole.

Color temperature is usually given in degrees Kelvin, which is a temperature scale based on absolute zero (about —274° C.) but whose degrees are otherwise equivalent to the regular centigrade scale degrees.

Spectral Distribution of Radiation from Light Sources

Figure 3 illustrates the spectral distribution of radiant flux from sources of various color temperatures but which emit equal quantities of luminous flux. That is, the curve shows how much radiant flux is given out at each wavelength by these sources, each of which furnishes the eye with the same amount of light or visible energy.

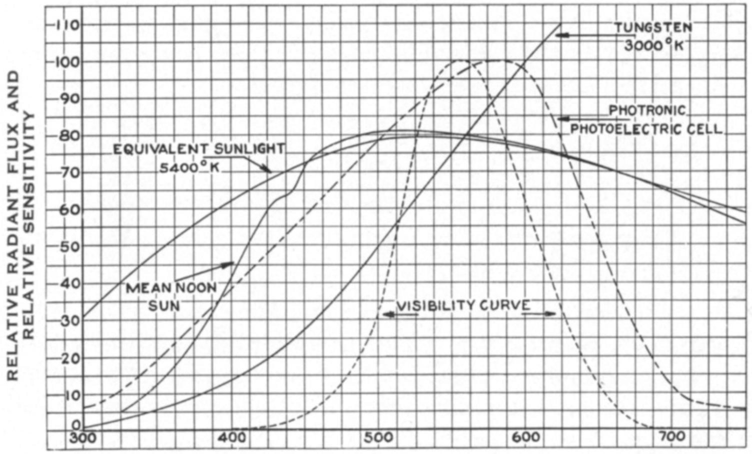

Fig. 3. Spectral energy distribution of Radiation from various sources having the same visual intensity and the spectral sensitivity of the PHOTRONIC Photoelectric Cell

The visibility curve of the eye has been added to this graph to make it clearer. The sensitivity curve of the PHOTRONIC cell has also been added, and indicates just how the cell "sees" the energy given out by the sources. Observe how closely the PHOTRONIC cell approaches the human eye in "seeing" quality, that is in the color it "sees" most readily. Note also how much more it "sees" than the eye.

Although the intensities of radiating sources on the graph have been chosen because they emit equal amounts of luminous flux, note what a small part of the total radiated energy this is. The energy represented as outside the visibility curve is in the ultra-violet and infra-red regions, into which our eyes cannot penetrate.

Candle-Power

The International Candle is the measuring stick used for comparing the light intensity from luminous sources. It is the light intensity from a candle or lamp of defined type, rate of burning, etc., adopted as a standard. Just what these specific requirements are, need not concern us here, so long as we fully understand that a 32 candle-power lamp means one that gives an intensity 32 times that of the standard International Candle, and so on for any other value of candle-power.

Besides the International Candle there is the Hefner Candle, the intensity of another standard "candle" which, when made according to definite rules, has an intensity equal to 0.9 International Candle. This "candle" used in Germany and some other European countries is really a lamp burning amyl acetate as fuel.

The Lumen

The lumen is the unit of luminous flux radiated, and combines the idea of area with intensity. It represents the light on a certain area when illuminated by a source of a certain intensity.

The connection between the lumen and the candle is this: If we have a uniform point source, with an intensity of one candle-power, at the center of a sphere whose radius is one foot, then the luminous flux which falls on one square foot of the sphere's surface is called one lumen.

Since the surface of a sphere, in square feet, is equal to 4π times the radius in feet, it naturally follows that the surface of our unit sphere contains 4π square feet. Since each square foot represents one lumen, the one candle-power source at the center furnishes 4π lumens in all.

Another way of defining the lumen is to say that it is the luminous flux emitted in a unit solid angle from a uniform point source of 1 candle-power. Of course, this does not mean that a lumen must always be associated with a particular area or solid angle. Naturally, it may be concentrated upon a small area or spread out over a large one.

Illumination

Illumination is the measure of the density of luminous flux per unit area. It is, let us say, the number of the above-described lumens which fall on one square foot of surface as the result of the light from any source.

If we were measuring the illumination on the surface of our unit sphere, we would say that the illumination was equal to one lumen

per square foot. If we place a two candle-power source within the sphere, then the surface would have an illumination of two lumens per square foot.

The measure of the illumination is independent of the character and color of the surface upon which it falls; it represents simply how much light is reaching an object. Therefore illumination must not be confused with brightness, which will be defined later.

A white surface may appear very bright to our eyes in spite of the fact that it is receiving no greater illumination than a black surface right beside it. The black absorbs the light, the white reflects it; but each one receives exactly the same amount.

The Foot-Candle

In measuring illumination, we might say that a surface received so many lumens per square foot. And we do say just that. A more common unit of illumination, however, is the foot-candle. On a surface at right angles to the direction of the light, this is equal to the illumination received at a distance of one foot from a source having an intensity of one candle-power. In other words, in the unit sphere of which we spoke, we would say that the surface illumination was either one lumen per square foot or, simpler, one foot-candle.

The following values are representative of good lighting practise:

0-3 foot-candles—aisles, stairways, passageways, etc.
3-10 foot-candles—locker rooms, elevators, power plants, etc.
10-20 foot-candles—classrooms, general offices, etc.
20-50 foot-candles—fine office work, drafting rooms, etc.
50-100 foot-candles—fine manufacture and inspection.

The Lux

The lux is merely another unit of illumination and is used mostly in Europe. It is based on the metric system and represents the illumination on the surface of a sphere such as we have described, except that the radius is one meter instead of one foot and the surface area, of course, is in square meters. The light source at the center is still one candle-power.

The lux is equivalent to one meter-candle, and just as the total amount of light received by a square foot of surface, illuminated to an intensity of one foot-candle is a lumen, so too, the amount of light received by a square meter, illuminated to one lux is also a lumen. One foot-candle or lumen per square foot is equivalent to 10.764 lux or 11.96 Hefner lux.

Inverse-Square Law

The intensity of illumination produced by a point source of light varies inversely as the square of the distance from the source. For example, let us suppose an intensity of 5 foot-candles at a distance of 10 feet from a source. If we move our lighted object to 20 feet, we shall have multiplied the distance by two and naturally diminished the light intensity on that object. However, the light will not be ½ its former intensity but ½ squared, or ¼ and our resulting light intensity will be ¼ of 5 or 1.25 foot-candles.

Cosine Law

The Cosine Law has to do with the effect of light rays striking a surface at an angle instead of perpendicularly. When light strikes at an angle, the illumination is less than it would be at right angles because the same energy is spread over a larger area and is equal to the illumination value in the "normal" position multiplied by the Cosine of the angle between this "normal" and the new "angle of incidence"

In calculating illumination we can combine the Inverse-Square and Cosine laws as follows:

$$\text{Illumination} = \left(\frac{\text{c. p.}}{D^2}\right) \cos \theta$$

In this formula "c. p." means candle-power, "d" distance to the source, and "θ" the angle of incidence.

Brightness

Brightness considers the area, color and other characteristics of a luminous surface, whether it be a primary source such as the filament of a standard lamp or a secondary source such as the reflecting surface of a wall or of the sky, etc.

Brightness is expressed in candles per unit area and means that a certain area, as a primary or secondary source of light, is equivalent in a definite direction to a certain number of ideal candles. A brightness of 10 candles per square foot indicates that the light-giving source, for every square foot of its surface, is giving out as much light in a given direction as 10 point-source candles.

Naturally, brightness can be measured in other units too, such as lumens per square centimeter (lamberts) or candles per square centimeter, etc. If brightness is expressed in candles per square centimeter, it may be reduced to lamberts by multiplying by π (3.1416) These are in different systems and the multiplier π is significant of the difference.

As was said, illumination did not consider the character of the surface in any way. In brightness this does play an important part since the reflecting power of a wall, for instance, determines what sort of a secondary source of light that wall will be for our eyes. A surface that had no reflecting power would have absolutely no brightness, it could not act as a source of light to illuminate something else—no matter how much illumination the surface itself was receiving.

The Lambert

The Lambert is a unit of brightness frequently used, and represents the average brightness of any surface emitting or reflecting one lumen per square centimeter. It is also defined as the uniform brightness of a perfectly diffusing surface emitting or reflecting one lumen per square centimeter.

Brightness and Illumination

For a perfectly diffusing surface, brightness is related to the illumination producing it as follows:

$$B = \frac{ER}{\pi}$$

Here B is brightness in candles per square foot; E is illumination in foot-candles; R is the reflecting power or ratio of total light reflected to light received by the surface under consideration. If E is in lux, then B will be in candles per square meter.

Chapter III

FUNDAMENTAL CONCEPTS

PHOTRONIC cells, in a sense, have an action similar to that of thermionic vacuum tubes. Not that their physical appearance and electrical characteristics are alike, but, merely, that they resemble one another in the liberation of electrons.

From the vacuum tube's heated cathode, electrons boil off into space. Between this cathode and the anode they are faced with a high-resistance path and, unless the anode is charged with positive electricity from outside, these negative particles of electricity cannot complete the circuit but are lost in returning to the cathode.

PHOTRONIC cells need no heat for the liberation of electrons. Photons, "bullets of light" striking the cell's sensitized surface knock off electrons directly. The distance from the anode to the supporting back plate of the cell, which acts as cathode, is a matter of a fraction of a millimeter. Compared with the vacuum tube path, the one in the PHOTRONIC cell is comparatively of low resistance. Consequently the electrons have no difficulty negotiating it without the application of external potentials.

This explanation of the cell's action appears very simple. It is hardly necessary to remark that the thing is a bit more complicated. We shall, however, consider only the larger aspects here; for more detailed theoretical information the reader is referred to the literature concerning cells of this type.

Permanence

Any photocell, to be really useful, must retain its characteristics, it must continue to deliver the same amount of current every time it is affected by equal quantities of light, and it must do this over a reasonable life-span.

In the past, lack of permanence has been a bugbear in using photoelectric cells. The older cells, when exposed to, let us say, 50 foot-candles of light, would give so many microamperes one time and a different number the next. Also their average output would continue to deteriorate and, sometimes, in a month or two would be permanently lowered by considerable percentages.

PHOTRONIC cells, however, apparently operate without chemical or physical changes within their makeup. The materials play a role similar to catalysts in chemistry in that they generate electricity by light without using up their own substance. This "electronic" action would seem to be amply demonstrated by the data following.

At the Weston Plant, some of these cells—properly protected of course—are so arranged as to receive the full light of day. With the first peep of dawn they start to deliver current, the amount of which increases until maximum light has been reached. Then, as the day begins to wane, the light grows less and less and the cells deliver current proportionately until darkness. They rest during the night and then start their cycle all over again with the coming of a new day.

At times, when the sunlight shines full upon them, they deliver as much as 10 milliamperes each. Yet, after some 500 days of test, these cells are still doing their job satisfactorily!

Naturally such permanence is the reward only of proper handling. The cell's top surface, which acts as collector for the generated current, must not be scratched or in any part destroyed. Temperatures higher than 50° C. (122° F.) or burns from currents due to externally applied potentials may easily ruin the cell or at least alter the amount of current delivered. Currents of any magnitude possible by self-generation, however, do no harm.

In PHOTRONIC cells the light-sensitive material itself is at least temporarily deranged by moisture. Further than that, moisture, by setting up electrolytic currents between the various metallic parts of the cell assembly (external contact rings, etc.) and the metallic base and top of the cell itself, does permanent chemical damage.

In normal use none of these agents of destruction should be permitted. Where surrounding temperatures are high these must not be allowed to reach the cell. External voltages must be kept away. Where dampness or chemical vapor exists the cells must be housed in containers that protect them thoroughly.

Current Output

From tests under best practical approach to ideal zero-resistance external circuits, PHOTRONIC cells generate current directly in proportion to the light reaching them. Their response is linear, i. e., 100 foot-candles generates 100 times as much as one foot-candle. The curve labeled 3 ohms, in Figure 4, illustrates this.

Although the curve is drawn only to 240 foot-candles, tests with low-resistance circuits show the same linear characteristic for intensities up to those of direct sunlight (10,000 to 15,000 f. c.)

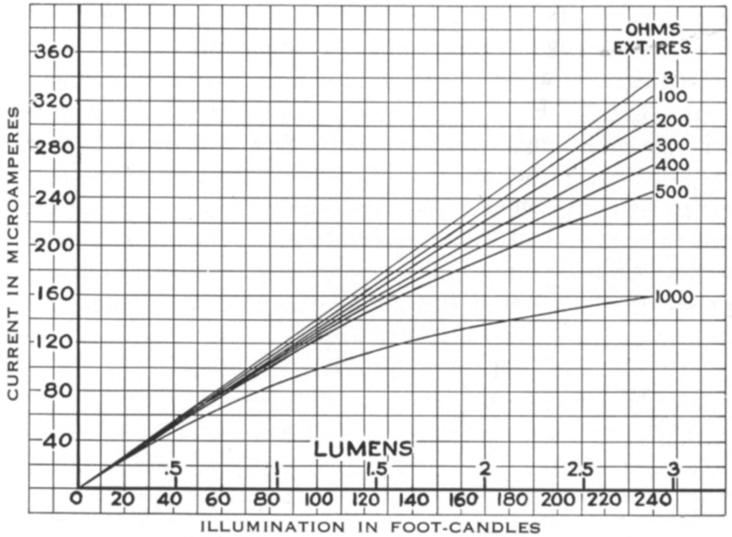

Fig. 4. Effect of External Resistance on Current Output of the PHOTRONIC Cell [Tungsten lamp at 3,000° K.]

This linear relation, of course, has to do with generation within the cell and, strictly, can hold as to external delivery only where the external resistance is zero. While this is impossible, it is nevertheless practically accomplished by using rather low resistances in the external circuits. The deviation from this linear condition caused by higher resistances is shown by the other curves in Figure 4.

Cell Resistance

Explanation of these deviations lies in the makeup of the cell itself. While radiant flux, within the sensitivity limits of the cell, generates current in proportion to its quantity, the current cannot all escape into the external circuit on account of a resistance return path existing within the cell.

The important feature of this internal resistance is that, contrary to usual expectations, it is in parallel with the external circuit resistance rather than in series with it. Therefore the division of generated current between internal and external paths depends upon the laws relating to parallel circuits. The rather startling, but entirely correct, corollary to this is that cells with highest internal resistances furnish the greatest percentage of their generated current to the external circuit.

If the resistance of this internal conducting path were constant under all conditions, computing expected external currents would be a simple matter. It is not fixed, however, but depends upon the light intensity and the "leakage" or internal current itself.

When the cell is dark no current is being generated and the internal resistance has a certain definite ohmic value. As soon as light falls on the cell, this resistance changes, decreasing as the light intensity increases. As soon as light falls on the cell, current also begins to flow through the internal structure, and this too causes a change in the resistance, which again decreases as the leakage current increases. When the cell is connected to an external circuit the resistance of this circuit naturally modifies the flow of current through the cell and thus influences these internal resistance changes.

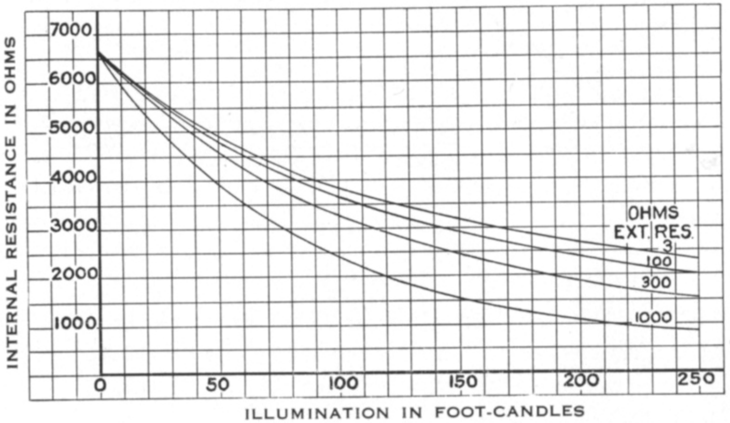

Fig. 5. Internal resistance under varying conditions of illumination and external resistance of the PHOTRONIC Cell [Tungsten lamp at 3,000° K.]

The curves of Figure 5 give a picture of these phenomena, showing how light and external resistance control the internal resistance of the typical cell.

The formula relating currents and resistances is as follows.

$$I = \frac{E\, i_0\, r}{R + r}$$

Here I = external circuit current
E = illumination reaching cell
i_0 = total current generated within the cell per unit illumination—practically equivalent to the current flowing per unit light intensity in an external circuit of negligible resistance
r = internal resistance of cell for illumination E and external resistance R
R = external resistance
i_0 = internal cell-current

The equivalent circuit is shown in the following diagram.

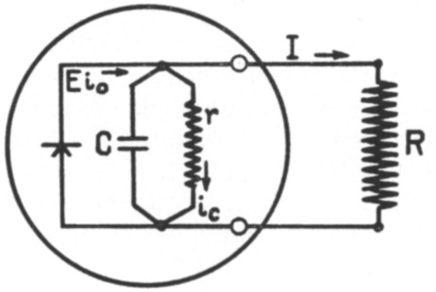

Fig. 6. Equivalent circuit diagram

In the circuit diagram, Fig. 6, there is represented a condenser C. This indicates a capacitance effect manifested within the cell when currents are generated by pulsating light. When the light intensity is constant this does not enter. Where it is present, it is in parallel with the cell internal resistance.

Voltage Output

PHOTRONIC cells are generally used as current sources rather than for their voltage output, since current is the fundamental characteristic and furnishes the more usable feature.

The voltage, like the internal resistance, is not a linear function of light intensity. Doubling the light intensity does not mean that the generated voltage will be doubled. For low intensities, however, where the generated e.m.f. is about 7 milli-volts per foot-candle, the relationship is practically linear.

When it is desired to use a PHOTRONIC cell as a source of constant voltage, the current of the cell, rather than the directly-generated voltage, is usually employed. This is done by connecting a low resistance resistor in series with the cell. Since, naturally, the resistance of the resistor is fixed and the current, generated by the cell, flowing through it is steady, therefore the IR, or voltage drop across it remains a constant quantity and may be used as a steady voltage source.

Figure 7 shows how the voltage output of typical cells varies with the light intensity. These determinations were made by potentiometric methods, employing an opposition e.m.f. sufficient to reduce the external current to zero.

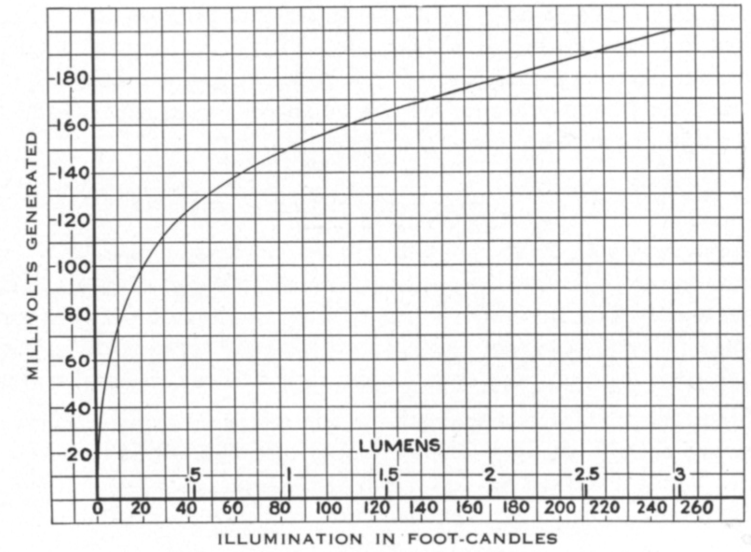

Fig. 7. Voltage output of the PHOTRONIC Cell
[Tungsten lamp at 3,000° K.]

Series and Parallel Operation of Cells

Where it is necessary to have more current than one cell can deliver under given conditions, the current outputs of several cells can be made additive by connecting them in parallel. Since each cell adds resistance to the circuit in about the same proportion as it adds e.m.f., putting cells in series results in practically no increase in total available current.

Parallel connection has another advantage. Due to the fact that, unless illuminated, cell resistances are very high, if one or more cells of a parallel group are not illuminated, practically none of the current generated by the others is lost in the darkened ones. This makes it possible to use cells, thus connected, at different points and still keep the total current proportional to the total light falling on the system. If three cells, in parallel, together furnish 100 microamperes when illuminated by three equal light sources, darkening one of them results in a current loss of practically one-third.

The most advantageous number of cells for parallel use in specific cases is best determined by experiment, since it depends upon the effects from illumination and the characteristics of the indicating instruments.

Although there is no current gain in series connection, still, if connected in this way, the cell voltages are additive. So long as no current is drawn from or passed through the cells, such an arrangement may be used, for example, to provide bias on thermionic tube grids and for other similar purposes.

Temperature Effects

As is shown in curves, Figs. 8 and 9, temperature changes do not affect the total generated current very much although they do have a pronounced effect upon the voltage. Giving thought to this for a moment, it is obvious that a rather steady current, passing through the variable cell resistance as a shunt, produces a variable terminal voltage.

Since the voltage characteristic of the cell is little used, curve 8, showing current changes due to temperature alteration, concerns us most. While it is true that, in general, temperature changes do not normally interfere with the current delivered, still they do have some effect.

This temperature coefficient of delivered current is practically zero for external resistances up to about 200 ohms and for all investigated light intensities. Consequently, whenever large temperature changes are unavoidable, the external resistance should be kept within these limits for least current alteration.

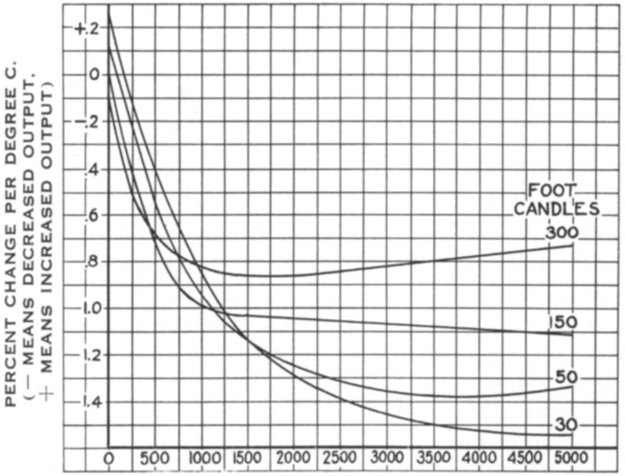

Fig. 8. Effect of Temperature on current output of the PHOTRONIC Cell
[Tungsten lamp at 3,000° K.]

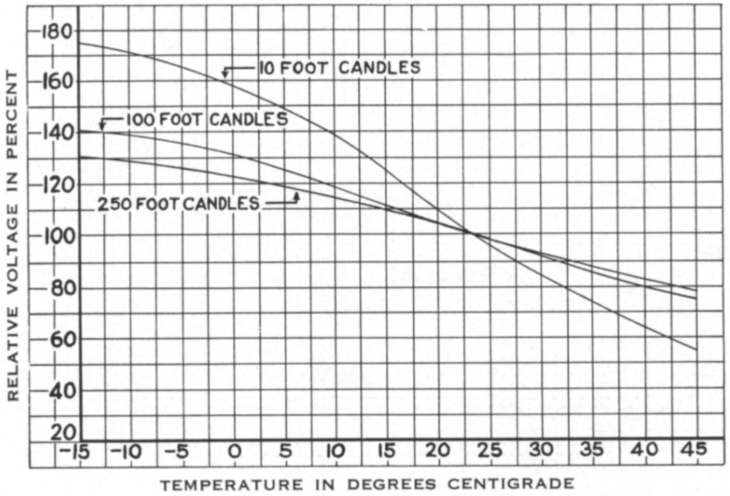

Fig. 9. Effect of Temperature on Voltage output of the PHOTRONIC Cell
[Tungsten lamp at 3,000° K.]

Angle of Incidence

As was pointed out in Chapter 2, under "Cosine Law" the illumination falling on any surface depends not merely upon the light intensity of the source but also upon the angle at which the incident rays strike that surface.

In cells of the PHOTRONIC type there is still another consideration. Generated current depends upon the light effectively absorbed by the cell surface rather than upon the total illumination falling on it. Light which is reflected before reaching the sensitive surface accomplishes absolutely nothing toward current generation.

Therefore the reflecting power of the cell surface must be considered, as must such items as shadow from the rim of an enclosing case and reflection losses due to the glass of protecting windows.

The effect of all these is shown in curve Fig. 10, where the level indicated by relative current 1.0 is the level at which the cell would operate if only the cosine law were acting to diminish the absorbed light.

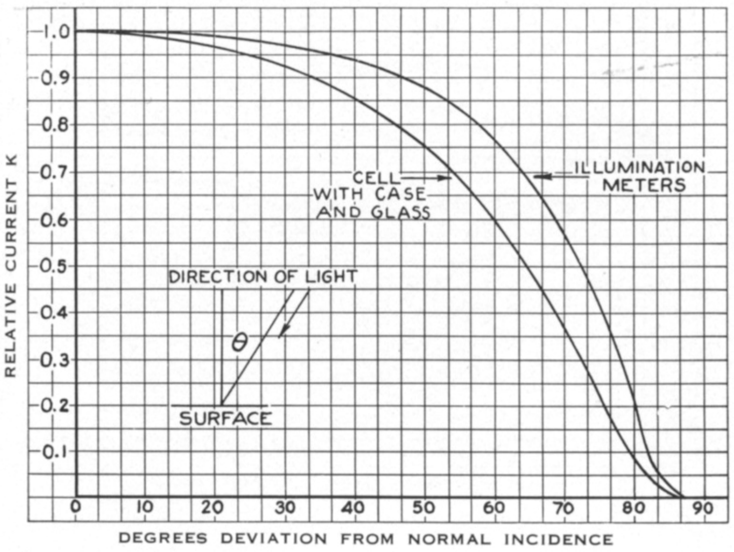

Fig. 10. Effect of Angle of Light Incidence on the PHOTRONIC Cell
[Tungsten lamp at 3,000° K.]

K = relative current output at various angles of incidence, per unit illumination on cell surface, for example, per foot-candle.

NOTE: The "illumination" referred to is the actual value on the cell surface. It was produced by a single luminous source and its value computed by the usual law,

$$\text{illumination} = \frac{cp}{D^2} \cos \Theta$$

where cp = candle power, D the distance to the source, and Θ the angle of incidence.

For *illumination meters,* if E_t is the actual illumination on the surface of the cell, then the indicated value $E_i = KE_t$.

Color or Spectral Sensitivity

Like the human eye, PHOTRONIC cells do not "see" radiated energy of different wavelengths with equal ease. In addition to that, while in general they view things pretty much as does the eye, still they do "see" a wider range than that organ and are affected to a different degree than it by those waves which lie in the visible spectrum.

These differences are more clearly brought out by an inspection of Figure 2, showing the cell sensitivity and eye visibility curves. Remember that all points on these curves represent the effects of equal values of radiated flux.

Looking at the solid curve for the cell, it will be seen that the PHOTRONIC cell is most sensitive to yellow light of 580 millimicrons wavelength. The eye curve shows that member as at its best when viewing yellow-green light of 555 millimicrons wavelength. (Sometimes the term Angstrom Unit is used instead of millimicron. This unit is equivalent to 0.1 millimicron.)

Since PHOTRONIC cells are usually equipped with glass windows for physical protection, the dotted portion has been added to the cell curve, in the ultra-violet region. Ordinary glass absorbs most of the ultra-violet and keeps it from reaching the cell. If cells are to be used for measuring energy in this region quartz windows must be substituted for glass.

Filters

For use under all light conditions, where we want the cell to be affected to the same extent and by the same flux as the eye, we interpose, between the cell and the light source, devices known as filters.

These filters, usually colored glass or layers of dyed gelatin, etc., absorb the radiated energy represented by the area between the visibility curve and the cell sensitivity curve. They are the spectacles which correct the "vision" of the cell and bring its "seeing" power in line with that of the normal eye.

Where an unfiltered cell is calibrated with an instrument such as an illumination meter, the indications are strictly correct only for measuring light sources matching the original standardizing source in light quality. It can readily be seen that sources, radiating light of wavelength bands different than the standard source, will generate currents in the cell which do not correspond.

Fortunately in their relation to the PHOTRONIC cell sensitivity there is a happy accidental equivalence in spectral composition of light emanating from tungsten lamp filaments at 3000° K color temperature and from sunlight. For this reason we are able to calibrate cells in our laboratories by artificial light so that they will correctly indicate visual properties of daylight.

Absolute Spectral Sensitivity

All cells are not affected in exactly the same way by the radiant energy reaching them. Unavoidable variations in manufacturing account for this, much as Nature, in turning out millions of human eyes, does not get them all exactly alike.

For this reason we always speak of the average PHOTRONIC cell. This average cell then, at its maximum sensitivity, 580 millimicrons, is said to produce current, in low resistance circuits, of about 0.046 microampere for each microwatt of radiant flux. In looking at the cell sensitivity curve, this means that the ordinate 100, at 580 millimicrons, corresponds to the above current. Other ordinates indicate proportional values.

For the eye curve, it has been determined experimentally that the 100 mark corresponds in absolute value to 621 lumens per watt, or 0.000621 lumen per microwatt, at maximum eye sensitivity, 555 millimicrons.

Fatigue

Fundamentally, PHOTRONIC cells seem to have no fatigue. There is no current generated when cells are in the dark and, when current is generated by light, this current is not subject to erratic or non-reversible changes.

Practically, however, due to secondary effects, cells exhibit a property which may be termed fatigue. When first exposed to a light source, cells connected to external circuits generate current which gradually grows less over a period of several minutes, until it finally reaches a constant value. For this reason, where relatively high accuracy is desired, the better plan is to wait some few minutes before taking readings.

Cell Responsiveness

When used with instruments or relays, PHOTRONIC cells respond practically instantaneously to changes in light intensity. They follow such changes much more rapidly than the devices used can follow changes in current received from the cell connected to them. Actual tests have shown that cells respond rapidly enough to record the passage of rifle bullets through a beam of light.

Frequency Response

Where intermittent light is used, PHOTRONIC cells respond satisfactorily for constant light modulation up to 60 cycles. The response diminishes as the frequency of these interruptions increases and is approximately inversely proportional to their number. This is due to the shunting effect of a capacitance of the order of 0.5 microfarad in the cell itself.

Taking 60 cycles as 100%, if the beam of light falling on a cell is interrupted 120 times per second the response will be about 58%. At 240 cycles it is 30%; at 1000 cycles about 6.4%.

Comparatively-flat response curves up to 5000 cycles have been attained through use of filters and special coupling transformers. This method, however, reduces the power level of the cell to such an extent that amplification becomes necessary.

PHOTRONIC cells are not suitable where very high frequencies are used as, for example, in connection with talking pictures.

Amplification

Where amplification is desired under constant illumination conditions, a direct current or static amplifier must be used. Since such devices are troublesome to build and operate, a better method is to chop the light falling on the cell by interrupting the beam with a sector disc or some such means, to produce, say, 60 impulses per second. In this way the pulsations cause alternating current to be generated and this can then be increased by any good audio frequency amplifier.