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Auteur(s)	**Laboratoire d'essais mécaniques physiques chimiques et de machines du Conservatoire national des Arts et Métiers**
Titre	**Publication : Laboratoire d'essais**
Adresse	**Paris : Conservatoire national des arts et métiers, 193.-195.**
Nombre de volumes	**125**
Cote	**CNAM-BIB P 1329-B et P 1329-C**
Sujet(s)	**Conservatoire national des arts et métiers (France)** **Génie industriel -- 20e siècle**
Note	**La collection comporte des lacunes : n°24; n°58; n°63; n°67; n°76-n°77**
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	N°36 (1938)
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	N°38 (1938)
	N°39 (1938)
	N°40 (1939)
	N°41 (1939)
	N°42 (1939)
VOLUME TÉLÉCHARGÉ	N°43 (1939)
	N°44 (1939)
	N°45 (1938)
	N°46 (1940)
	N°47 (1940)
	N°48 (1940)
	N°49 (1940)
	N°50 (1940)
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	N° 152 (1951)
	N° 153 (1952)
	N° 154 (1952)
	N° 155 (1952)

NOTICE DU VOLUME TÉLÉCHARGÉ	
Auteur(s) volume	**Laboratoire d'essais mécaniques physiques chimiques et de machines du Conservatoire national des Arts et Métiers**
Titre	**Publication : Laboratoire d'essais**
Volume	N°43 (1939)
Adresse	**Paris : Conservatoire national des arts et métiers, 1939**
Collation	**1 vol. (p. [163-184]) : ill. ; 25 cm**
Nombre de vues	**26**
Cote	**CNAM-BIB P 1329-B (19)**
Sujet(s)	**Conservatoire national des arts et métiers (France) Génie industriel -- 20e siècle**
Thématique(s)	**Histoire du Cnam**
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Langue	**Anglais Français**
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RÉPUBLIQUE FRANÇAISE

LABORATOIRE D'ESSAIS

STUDIES IN PHOTOELECTRIC PHOTOMETRY

A PHOTOEMISSIVE CELL SPECIALLY DESIGNED FOR HIGH PRECISION MEASUREMENTS

par G. A. Boutry et P. Gillod

PUBLICATION N° 43

(Extrait de " Philosophical Magazine " Ser. 7 - vol XXVIII - P. 163 - Août 1939)

From the PHILOSOPHICAL MAGAZINE, Ser. 7, vol. xxviii. p. 163.
August 1939.

Studies in Photoelectric Photometry.
A Photoemissive Cell specially designed for High Precision Measurements.

By G. A. BOUTRY and P. GILLOD.
Laboratoire d'Essais, Paris.

§ 1. *Introduction.*

IT has been evident for some time that the electric response of commercial photoemissive cells † was not strictly proportional to the amount of light incident on the cell cathode. Generally speaking, a departure from proportionality of the order of 1 per cent. often appears when the illumination of the cathode is increased from 1 to 10 ‡. The examination of the cell shape, design, and method of preparation will not always enable the observer to form any conclusion as to whether the cell response is or is not " proportional "—even the sign of the departure from proportionality being imprevisible. In fact, we are to-day, as regards the making and use of photoemissive cells, in very much the same position as physicists were, when, some fifteen years ago, they wanted thermionic triodes capable of giving fair performance in short-wave work. This particular difficulty was easily solved in time by a patient study of the design of the valves. The opinion of the present writers being that a similar process applied to photoelectric cells would yield similar results, their first study carried along these lines is recorded here.

§ 2. *Causes of an Imperfectly Proportional Response.*

We have no reason to doubt the fundamental law of photoelectricity, which stipulates strict proportionality between the number of light quanta incident on a photoemissive cathode and the number of photoelectrons released, *i. e.*, the electric charge which may appear in the circuit. If, in spite of this, the law of proportionality does not hold for most photoemissive cells, the design of the cell and the way it is used must yield the explanation.

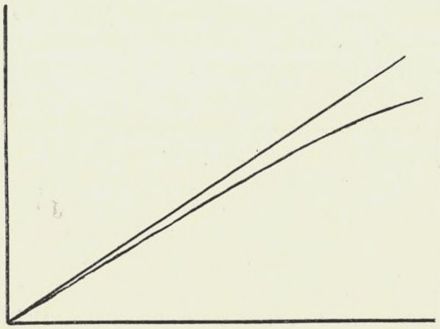
† For the meaning of symbols and denominations used in this paper see G. A. Boutry, 'Photoelectricity' (Phys. Soc. Progress Reports, vol. iii. 1936).

‡ Preston and McDermott, Proc. Phys. Soc. xlvi. p. 256 (1934).

Most photoemissive cells now in use may be described as follows : a cathode of silvered glass (part of the wall of the cell) or metal, coated with the photosensitive deposit and of any shape (spherical, cylindrical, plane, v-shaped . . .) ; an anode generally of very small surface (wire, rod, spiral, grid . . .), generally coated with the same deposit ; the distance anode-cathode varies within large limits ; the shape and size of the bulb may be anything. During the last ten years we have used in our laboratory more than fifty cells of really strikingly different design and shape ; an easy construction seems very often to have been the only guide.

(1) There is evidently no reason, in such cells, why all the electrons liberated by the light incident on the cathode should fall on the anode, except when very high p.d.'s are used. In fact, " saturation " occurs

Fig. 1.



only for p.d.'s ranging from 25 to 200 volts, according to type (the theoretical saturation p.d., it will be remembered, should be equal to the Volta p.d. between cathode and anode, never more than 4 volts and generally much less). Now, the vacuum in the cell is never perfect, so that ionization by collision will occur in the residual atmosphere, under the influence of these high electrical fields. Such ionization will give a response curve $i=f(\phi)$, such as that of fig. 1.

(2) In most photoemissive cells, the anode surface being very small, it follows that, as soon as the number of photoelectrons liberated by light ceases to be negligible, a space-charge is built-up, the concentration of which may be important in the neighbourhood of the anode. This, again, growing with the luminous flux used, will alter the response of the cell, the effect being in opposition with tha of the above factor ; the response curve, in that case, would be like that given in fig. 2.

(3) Both these influences will co-exist in most photocells, so that a balance may sometimes be obtained. It is clear that the laws followed by the two phenomena being different, a perfect compensation will normally exist only for one or a few points of the response curve, which will assume some such shape as that represented in fig. 3. As a matter of fact, numerous measurements have shown us that such types of response are quite often met with in practice.

Fig. 2.

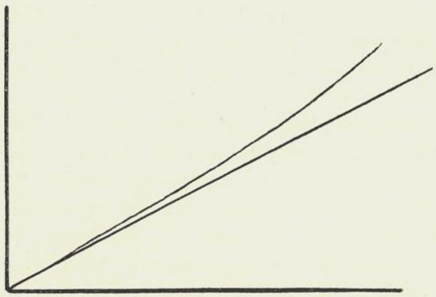
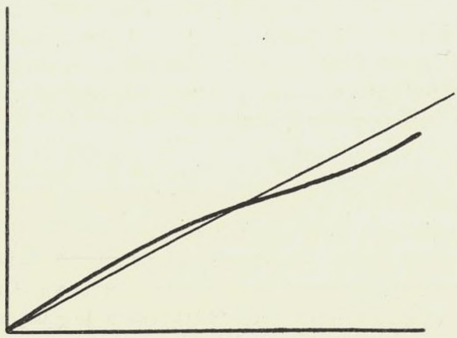


Fig. 3.



(4) The influence of surface charges on the walls of the cell should also be considered ; this may be twofold. It is a well-known fact that, owing to the high vapour tension of the alkaline metals, the walls of any photoelectric cell become coated, on the inside, with a thin transparent metallic film. This may not be continuous, and in any case its electrical resistance is extremely high. The cell being submitted to relatively high tension, the walls will gather slowly charges which may shift and

dissipate equally slowly ; one of the disturbing results is that the properties of a given cell may fluctuate, particularly at the beginning of a series of measurements ; this is an effect entirely different from the " ageing " produced by the evolution with time of the cathodic photoemissive layer.

Another effect of this metallic coating of the walls of the cell will be an increase of the " dark " current. Again the response curve of the cell may be affected ; as soon as light is turned on the cathode it is also diffused on the walls of the cell, creating a new distribution of surface charges, and altering the apparent " dark-resistance."

All this explains why a photoemissive cell giving an accurately proportional response over a large register of luminous flux variation is seldom met with : such a cell seems to be the product of chance rather than purpose.

It will be seen, however, that most of the causes of non-proportionality roughly described in the present section would disappear or become greatly reduced in importance if two principal conditions were satisfied : (*a*) the photoelectronic paths should not be distorted by any exterior influence such as that of stray charges on the walls of the cell ; (*b*) the p.d. necessary to reach saturation should be made as small as possible. It is clear that each of these two conditions is related to the other : condition (*a*) will be satisfied by using electric screening, while condition (*b*) involves using an anode working after the fashion of a Faraday cylinder—which comes to practically the same thing. It is also evident that each of these main conditions involves many secondary consequences : for instance, it is not necessary to stipulate that the density of disturbing space charges should be reduced as much as possible : the fulfilment of condition (*b*) is only possible if that is so.

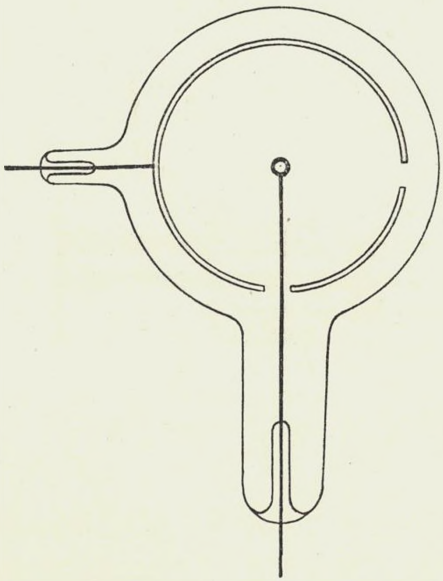
§ 3. *Design of a Cell giving Proportional Response.*

Cells were made and used more than thirty years ago which fulfilled moderately well the above conditions ; their only drawback was, and is, that it is not possible to get a large photoelectric yield from them ; we allude to cells of the type known as central cathode cells, with which many determinations of the energy distribution of photoelectrons have been carried out. In these cells, the anode is a sphere made of an electrically conducting material which completely surrounds a point-like cathode (fig. 4), two small holes being provided, one for the admission of light, and one for the exit of the cathode lead. The results given by such cells are classical ; saturation is obtained for a p.d. difference very close to the theoretical value, on condition that the illumination be small enough not to create an appreciable space charge in the vicinity of the small cathode. This practically forbids such a design in modern technique.

Moreover, the large anode generally gives an important "negative" current which reduces the sensitivity *.

Now, conditions (*a*) and (*b*) would also hold in a cell having infinite parallel plane electrodes; it is not impossible to build cells working nearly in the same way as this ideal type: finite plane parallel electrodes with guard-rings will meet the case. But a cell built in such a way must have at least one transparent electrode for the admission of light. It is a cell of such a type that will now be described † (fig. 5).

Fig. 4.



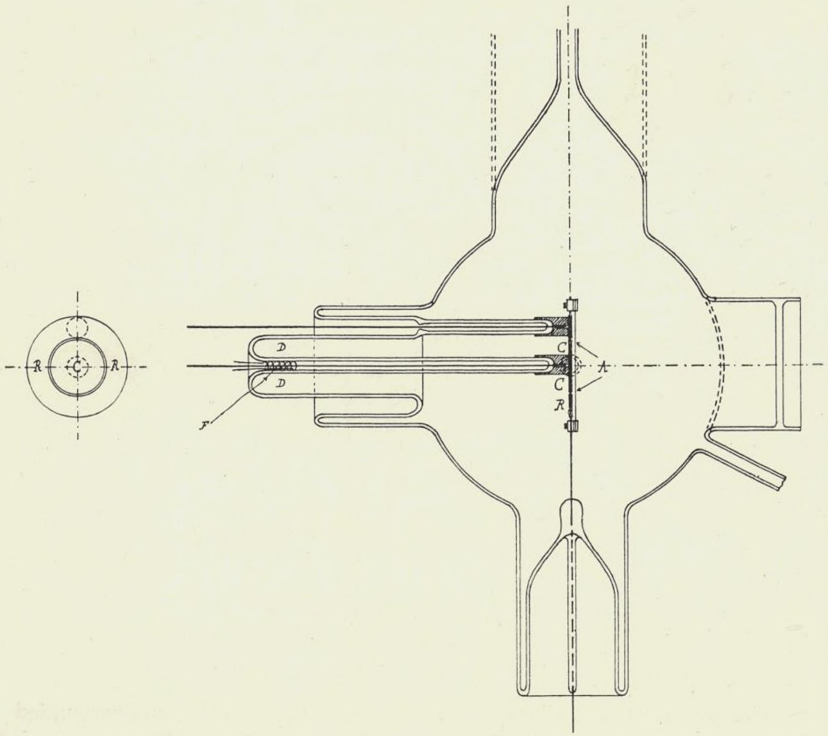
The cathode C is a disk, cut in a plane sheet of silver and surrounded by a guard-ring R, cut into the same material, whose width is approximately equal to the diameter of the cathode. Both these electrodes, during the making of the cell, were oxidized and coated with a thin layer of cæsium. The cathode and guard-ring leads are insulated from

* Hughes and du Bridge, 'Photoelectric Phenomena,' pp. 115–120: New York, 1932. Boutry, 'Les Phénomènes Photoélectriques et leurs Applications,' i. pp. 47–49: Paris, 1936.

† The first cell of this type, imagined by one of the authors (G. A. B.) in 1934, was only built in 1936, with the very able help of M. P. Cherdakoff; numerous technical difficulties explain this delay.

each other and from the anode lead. Precautions were taken in the making of the cell to have this insulation as good as possible. It will be seen from fig. 5 that the electric path along the walls of the cell connecting any one of the three electrodes to the others is quite long; moreover, the tube D containing the cathode lead could be heated to

Fig. 5.



250° with a small electric coil F without danger to the cell. Such a precaution, however, seems superfluous.

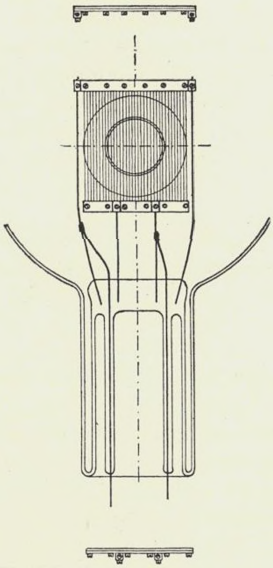
The design of the anode A is somewhat complicated, and is shown in detail in fig. 6. It is not a metallic plate, but a grid of parallel vertical tungsten wires of very small diameter (18 μ). The distance separating each wire from its neighbour varies with the cells from 0·25 to 1 mm. These wires are held at the top and bottom by two nickel bars insulated from each other: this arrangement permits the heating of the wires

by passing a current through them; the purpose of this will be examined in section 6. Anode and cathode were mounted parallel to each other, the distance between them being about 2 mm.

The bulb of the cell may have any dimension or shape; for ease of preparation and security, the bulbs used were large pyrex balls of about 12 cm. diameter. A plane glass window would be a useful adjunct.

The above description speaks for itself. At a small distance from the wires, the electric field between anode and cathode has the same distribution as between infinite plane parallel electrodes, provided the guard-

Fig. 6.



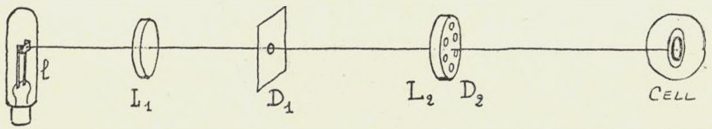
ring and the cathode are kept at the same potential. Again, if the guard-ring and the *anode* are kept at the same potential, the cell should behave as if its cathode was completely surrounded by its anode (Faraday cylinder type). In both cases saturation should be obtained near the theoretical Volta contact potential difference, and proportionality of response for the cathodic current should hold over large intervals, *whether the guard-ring be illuminated or not*: one sees that such a cell may be tried and used in many ways. The sensitivity should be of the same order as that of commercial vacuum cells now in use; an additional advantage being that no perfect vacuum should be necessary, as no ionization by collision can occur.

The only drawback to this encouraging theoretical picture is that the anode is not really a plate; though its apparent surface, as regards potential distribution in the field, is the same as that of the cathode and guard-ring, this does not hold near the wires, where the space charge is not negligible and still causes local distortion of the field; this effect will be investigated in section 6.

§ 4. *Testing the Cells.*

When testing a cell for proportional response, many methods may be—have been—employed. These fall into two classes: in the first, the luminous flux, originally ϕ, is adjusted, by means of neutral filters or wedges, polarizers, etc. . . . to a lower value, $K\phi$ or ϕ^n, the factors K and n being accurately known from previous calibration; in the second, two or more fluxes, ϕ_1, ϕ_2, . . . ϕ_n, unknown, fall first one after the other on the cell; after which, the sums $\phi_1+\phi_2$, $\phi_1+\phi_2+\phi_3$ . . . are turned on, and the responses measured. No calibration is needed in the last case; it is only necessary that ϕ_1, ϕ_2 . . . ϕ_n remain constant throughout the

Fig. 7.



test. Preston & McDermott * and Fleury † have used methods of this kind.

The method here described belongs to the same class: the source of light was a tungsten ribbon lamp fed by a large battery. Tension and intensity were permanently controlled with a potentiometer and kept constant throughout a series of measurements, the variation being less than 1 part in 50,000. The rate of cooling of the lamp was kept as constant as possible (protecting funnels, doors and windows blocked, movement of operators avoided in the room, etc. . . .). One hour after the lighting of the lamp, its emission was thus kept constant with an accuracy of at least 1 part into 10,000.

The adding device is shown on fig. 7. The lens L_1 gives a good image of the central part of the ribbon covering the hole bored in diaphragm D_1. The lens L_2 gives in the plane of the cell's cathode a circular image of D_1, uniformly illuminated and of variable size (l, L_1 and D_1; L_2 are mounted on two slides on a photometer bench). A diaphragm D_2, in which circular holes of nearly equal areas are bored, is kept in front of lens L_2, whose

* Preston and McDermott, *loc. cit. supra.*

† Fleury, *Comptes Rendus*, cxcix. p. 195 (1934).

components are well enough corrected to give no sensible displacement of image, however situated the holes used are. The quantity of light passing through hole No. 1, ϕ, being taken as unity, the quantity of light issuing from holes Nos. 2, 3, . . . n, ϕ_2, ϕ_3, . . . ϕ_n can be written $1+\epsilon_2$, $1+\epsilon_3$, . . . $1+\epsilon_n$, where ϵ_2, ϵ_3, . . . ϵ_n are small enough for a direct comparison of ϕ_1, ϕ_2, . . . ϕ_n by means of the cell to be legitimate, even if the response of the cell used be not strictly proportional; if ϵ_2, ϵ_3 . . . ϵ_n are of the first order, the errors involved will be of the second. The relative values of ϕ_1, ϕ_2, . . . ϕ_n being thus determined, the sum $\phi_1+\phi_2$, $\phi_1+\phi_2+\phi_3$ . . . , $\phi_1+\phi_2$ . . .$+\phi_n$ are then measured and compared to their theoretical values.

There are obvious limitations to the number of holes; but, if a monochromatic light filter is used, or if there is no objection to a change in the spectral distribution of the light used (that is to say, if the cell shows no departure from proportionality specifically dependent on the colour of the light used) the range of measurements can be increased by adjusting the intensity of the source l: after a set of measurements, ϕ_1, $\phi_1+\phi_2$ . . . , $\Sigma=\phi_1+\phi_2+$. . .ϕ_n having been measured, the current feeding the lamp is adjusted till the quantity of light passing through the first hole $\phi'_1=\Sigma$. In this step by step way, measurements have been made for values of the luminous flux ranging from 1 to 30 arbitrary units. As well as can be estimated without any absolute measurements, the range 0·002 to 0·06 lumen has thus been covered.

The photoelectric currents were measured with a potentiometer, a Lindemann electrometer being employed as null indicator (fig. 8). The circuit is very nearly that described in 1932 by P. Fleury *.

The current to be measured, i, flows through the high resistance ρ and thence to earth through part of the potentiometric coils r, r'. Through the constant resistance $r+r'$ also flows a constant current j; the photocurrent i always has a negligible value as compared to j, which is of the order of a few milliampères, that is to say about $10^5\,i$.

The electrometer needle can be electrically connected either to the earth T or to point K (cathode) through the key L; let us suppose that there is no deflexion when this is done: this means that the coils r have been so adjusted that the fall of potential rj exactly compensates that, ρi, due to the photocurrent flowing in ρ; then

$$i=j\,.\,\frac{r}{\rho}.$$

It will be seen that throughout the work, the cell can be kept under a constant p.d. v_0 given by battery B_1, whatever the values of ρ and i may be: a very troublesome correction is thus avoided.

* Fleury, *Revue d'Optique*, xi. p. 385 (1932).

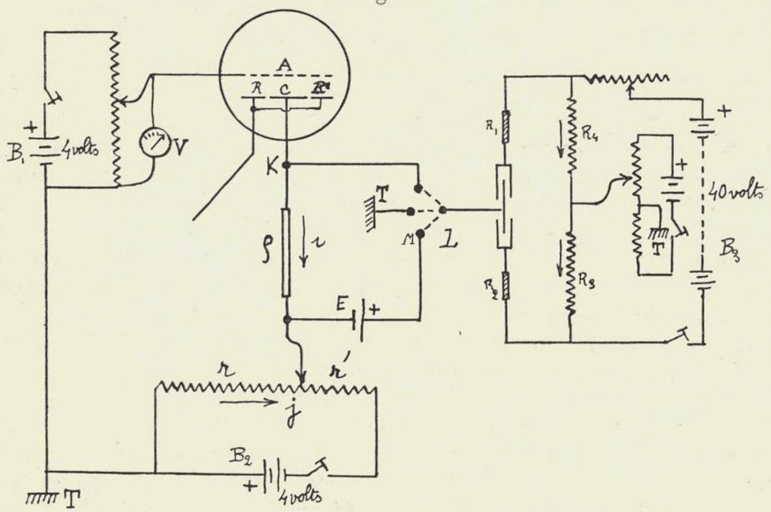
For the measurement of j, a standard cell E and a third position of the key L are provided; when the key is shifted to M, and the potentiometric coils adjusted in such a way (r_m, r'_m) that there is no deflexion of the needle, then

$$r_m \cdot j = e,$$

where e is the known e.m.f. of the Weston standard cell.

During the measurements, the guard-ring R was also kept at a constant potential, either that of the earth or that of the cell's anode. It will be seen from fig. 8 that only the current flowing to the cathode was measured. In other sets of measurements, however, both current

Fig. 8.



flowing to the guard-ring and to the cathode were measured. *No tension on the cell greater than 4 volts was used.*

The potentials of the electrometer quadrants were adjusted through a potentiometric arrangement R_3R_4. The whole apparatus was properly screened and in the insulation fused silica was used throughout. Very stable results and comfortable operation were thus obtained. The limit of sensitivity of the apparatus was somewhat below 10^{-12} amp. The general accuracy of one set of measurements was seldom worse than 1 in 1000, as will be seen below.

§ 5. *Results : Response of the Cells to Light.*

Measurements were carried on from June, 1937, to June, 1938, on a series of six cells of the same type; sets made in which the light used was

filtered through a Corning monochromatic red glass (No. 246); in other sets the total radiation of the lamp was used. Some examples of the results obtained are given here.

Cell No. 11.—" Red " Light.

Flux.	Photocurrents measured.	Flux.	Photocurrents.	
			Measured.	Computed, admitting proportional response.
ϕ_1	438	$\phi_1+\phi_2$	883	884
ϕ_2	446	$\phi_1+\phi_2+\phi_3$	1331	1333
ϕ_3	449	$\phi_1+\phi_2+\phi_3+\phi_4$	1748	1749
ϕ_4	416			

Cell No. 13.—" White " Light.

Flux.	Photocurrents measured.	Flux.	Photocurrents.	
			Measured.	Computed, admitting proportional response.
ϕ_1	166_2			
ϕ_2	169_4	$\phi_1+\phi_2 = \Sigma_1$	335_5	335_6
ϕ_3	182_4	$\phi_1+\phi_2+\phi_3 = \Sigma_2$	519_0	518_5
ϕ_4	179_0	$\phi_1+\phi_2+\phi_3+\phi_4=\Sigma_3$	698_0	697_5
$\Sigma_2=\phi_5$	519_5			
ϕ_6	560_5	$\phi_5+\phi_6 = \Sigma_4$	1080_5	1080_0
$\Sigma_4=\phi_7$	1080_5			
ϕ_8	1154	$\phi_7+\phi_8 = \Sigma_5$	2239_5	2234_5
$\Sigma_5=\phi_9$	2239			
ϕ_{10}	2038	$\phi_9+\phi_{10}$	4277	4277

Cell No. 14.—" White " Light.

Flux.	Photocurrents measured.	Flux.	Photocurrents.	
			Measured.	Computed, admitting proportional response.
ϕ_1	285_0			
ϕ_2	276_0	$\phi_3+\phi_4$	601_0	601_5.
ϕ_3	300_5	$\phi_2+\phi_3+\phi_4=\Sigma$	875_5	877_5
ϕ_4	301_0	$\phi_1+\phi_2+\phi_3+\phi_4$	1164_5	1162_5
$\Sigma=\phi_5$	875_5			
ϕ_6	812_0	$\phi_5+\phi_6$	1687_0	1687_5

Other numerical examples would be tedious. The results can be summed up very simply : with none of the cells could any systematic departure from proportionality of response greater than the incertitude involved by measurement be found. This holds whether the guard-ring was illuminated or not, and whether its potential was that of the anode or that of the cathode, the only condition to be fulfilled being evidently that the distribution of light and electric conditions should remain the same during one complete set of measurements.

None of the cells, during all the time they were in use, gave any dark-current that could be detected. Heating the cathode stem proved unnecessary. This, of course, is due to the extremely low values of the potential differences used on the cells. Partly for the same reason, and partly because of the screening, no " fatigue " and no " shift " were seen during the measurements, the photocurrent keeping very constant indeed, in spite of the fact that caesium layers are generally of poor stability.

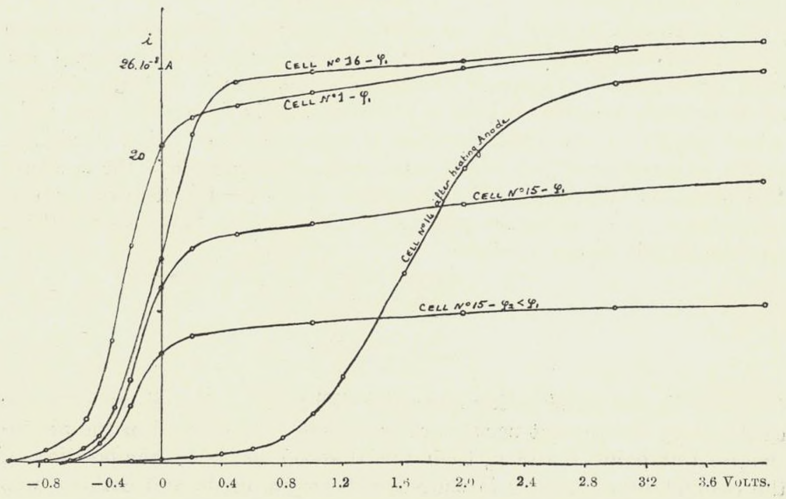
§ 6. *Results.—Space-charge, Negative Currents and the Shape of the Current.—Potential Characteristics.*

From the fact that the law of proportionality holds for these cells whether the guard-ring is illuminated or not, and whether the guard-ring is connected to the anode or to the cathode, one should not imply that the properties of the cells are the same in all these cases. On the

contrary, the shape of the characteristic curves $1=f(V)$ is largely dependent upon these conditions.

1. *Space Charge.*—Let us begin with the simplest case : the whole surface of the cathode and guard-ring is uniformly illuminated and both these electrodes are earthed or connected to one terminal of the battery (fig. 8). Some of the response curves for constant illumination $i=f$ (V) obtained in this case are given on fig. 9, which shows immediately that, as foretold, the cell yields a photocurrent even for retarding potentials, and saturation is obtained for a very small accelerating potential difference, in the present case about 1 volt. This value has no connexion

Fig. 9.



with the theoretical Volta potential difference between tungsten and caesium : in the three cells to which fig. 9 is related, anode and cathode had both been coated with a caesium layer; the Volta potential difference between the surfaces thus obtained, much smaller than that between Tu and Cs, could not be foretold, and is probably slightly different from one cell to another. This difficulty prevented a systematic investigation of the influence of the geometrical characteristics of the cells on their properties ; six cells had been built with different values of the distances between anode and cathode and of the distances between the anode wires. Unhappily, the variations adopted were too small, and the effect produced was of the same order of magnitude as that due to the shift in Volta potential difference from one cell to another, so that, apart from

the fact that the greater the number of the anode wire the smaller the saturation potential difference, no very clear results were obtained.

Heating the anode wires before using the cells evaporated the caesium layer and greatly increased the saturation potential, as appears also in fig. 9 : the anode of cell 14 in this figure had been heated just before measuring the response curve $i=f(\mathrm{V})$ shown on this figure, and the saturation potential difference became of the order of 4 volts, which is reasonably near the value of the Volta potential difference between tungsten and caesium ($3\pm0{\cdot}6$ volt). Fig. 9 shows further that no complete saturation really occurs. The response curve $i=f(\mathrm{V})$ is never quite flat ; nor is it quite straight ; on a smaller scale, we meet here the same defect as in commercial cells. The cause also is the same : the space charge, though greatly reduced, is not negligible.

To study this further, the problem of potential distribution between plane-parallel electrodes, when the cathode is emitting electrons, has been investigated. Langmuir's classical calculation is of little aid here as the working hypotheses used in it do not hold in the present case : the initial energy of the photoelectrons is very far from being negligible, and is, as a matter of fact, of the same order of magnitude as the accelerating potential difference used ; the value of the electric field on or near the cathode, too, cannot be taken as 0. Using only Poisson's condition and the kinetic energy theorem,

$$\frac{d^2\mathrm{V}}{dx^2}=\frac{4\pi j}{v},$$

$$v^2-{v_0}^2=-\frac{2e}{m}\mathrm{V}$$

(where V is the accelerating potential difference, x the distance of the electrodes, j the current per square centimeter, v the speed of the photoelectrons at point x, and v_0 their initial speed for $x=0$), the position of the equipotential surfaces in the space between anode and cathode was calculated. The following equation was obtained :

$$\left[\mathrm{K}-\frac{2m}{e}4\pi j\sqrt{{v_0}^2-\frac{2e}{m}\mathrm{V}}\right]^{\frac{1}{2}}\cdot\left\{\frac{1}{6}\left[\mathrm{K}-\frac{2m}{e}4\pi j\sqrt{{v_0}^2-\frac{2e}{m}\mathrm{V}}\right]+\mathrm{L}\right\}$$
$$+\mathrm{M}=\pm\frac{m}{e}(4\pi j)^2x,$$

in which K, L, M, are constants, determined by the limiting conditions

$$\text{cathode : } \mathrm{V}=0 \quad \frac{d^2\mathrm{V}}{dx^2}=4\pi\frac{j}{v_0},$$

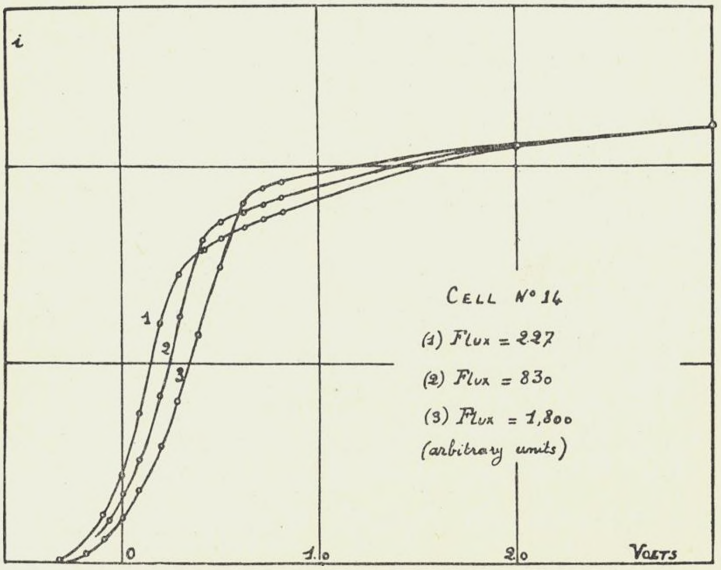
$$\text{anode : } \quad \mathrm{V}=\mathrm{V}m\ *,$$

their numerical values in specified conditions being easily computed.

* For details, see appendix (p. 182).

From this equation, it was ascertained that, for initial energies ranging from 0 to 4 volts, and for saturation currents not greater than 10^{-7} amp./cm.^{2}, the distortion of the field was just detectable, the displacement of equipotential surfaces never being greater than 0·5 per cent. But it must be remembered that the anode is not really a plane surface, and that the total projected surface of the wires that compose it is of the

Fig. 10.



order of 1/100 of the surface of the cathode. As K in the working conditions of the cell is always great compared with

$$\frac{2m}{e}4\pi j\sqrt{v_0^2-\frac{2e}{m}\mathrm{V}},$$

the distortion of the field is not multiplied by 100, but in the neighbourhood of the anode it ceases to be negligible, so that measurable retardations of saturation should occur even when $j<10^{-7}$ amp. The best way to show this is, having drawn curves $i=f(\mathrm{V})$ for increasing illuminations of the cell cathode, to compute from these results the first derivative

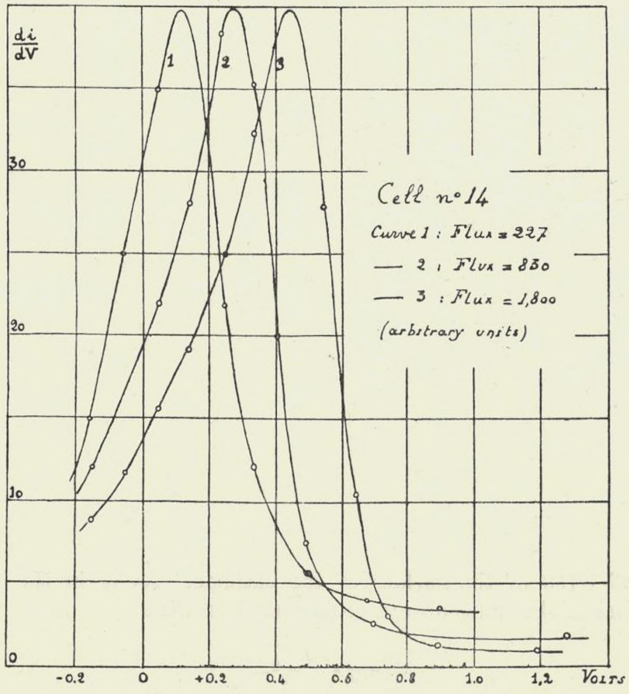
$$\frac{di}{d\mathrm{V}}=e\frac{d\mathrm{N}}{d\mathrm{V}}.$$

If there is no space-charge retardation effect, $\frac{dN}{dV}$ is the normal energy distribution function of the photoelectrons, and the curves

$$\frac{di}{dV} = f(V)$$

should all coincide. If, on the other hand, the preceding remarks hold true, a shift of these curves with growing illumination should appear,

Fig. 11.



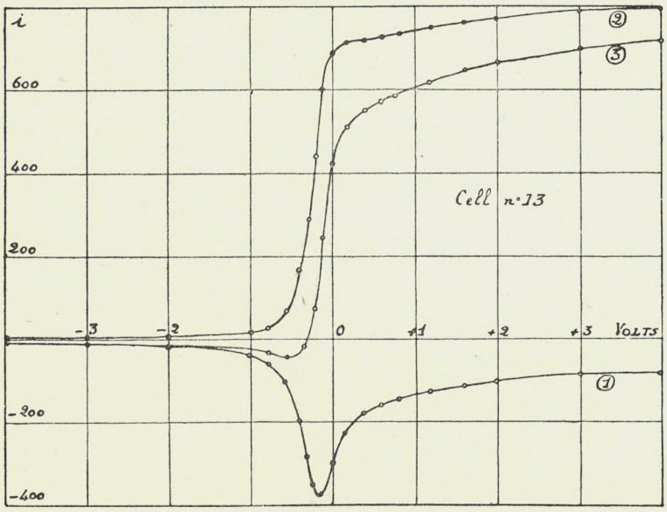
the apparent initial energy of the photoelectrons growing less when their number increases.

This is actually the case. From the reduced characteristic curves $i=f(V)$ of fig. 10, the curves $\frac{di}{dV}=f(V)$ have been computed (cell No. 14 before heating ; fig. 11). The shift in the peak of the curves is here greater than 0·3 volt ; the largest current measured in this experiment

was $5 \cdot 10^{-8}$ amp. : as previously stated, this proved that even in these cells distortion of the field is not absent. Though its effect on the response of the cell to light is not detectable, its influence is felt on the curves $\frac{di}{dV} = f(V)$. Incidentally, this shows with what care experiments on the determination of the energy distribution function of photoelectrons must be conducted, to avoid errors due to this effect.

2. *Negative Currents.*—Fig. 9, giving the shape of the curves $i = f(V)$ for uniform illumination of the whole sensitive surface, is not complete.

Fig. 12.



When increasing negative potential differences are applied to the cell, the current-voltage curves cross the horizontal axis and "tail off," a negative current being measurable even for a retarding potential difference of 4 volts. Curve No. 3 on fig. 12 shows this effect, measured on cell No. 13. These negative currents have two origins : (*a*) one part, i_1 is yielded by the anode, when this bears a caesium layer : it is always less than 1 per cent. of the total; (*b*) the rest, i_2, comes from the illuminated guard-ring, whose photoelectrons may fall on the adjoining cathode *.

* Naturally, electrons coming from the cathode also fall on the guard-ring in comparable numbers. It will be remembered that only the cathodic current is measured and plotted.

When the field h has the direction given in fig. 13, the path of a photo-electron liberated on the surface of the guard-ring may be such as the dotted parabola on fig. 13 ; in that case, the electrons fall on the cathode at a distance x from its starting-point,

$$x = \frac{m}{e}\frac{v^2}{h}\sin^2\alpha.$$

As long as the retarding field h has large values, the value of x remains very small, so that few electrons coming from the guard-ring may fall on the cathode. When h decreases, x increases ; so does the negative

Fig. 13.

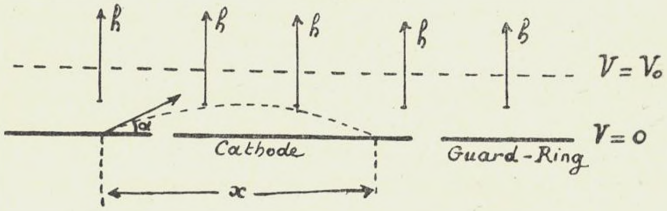
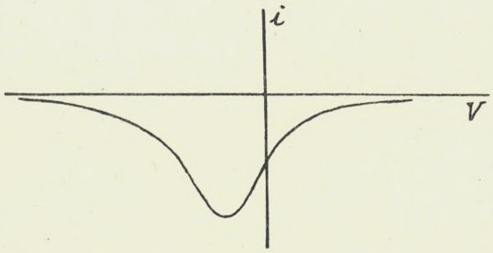


Fig. 14.



current. This should reach a maximum when x takes values of the order of magnitude of the cathode diameter ; from now on, the negative current should diminish and become negligible as soon as the sign of h changes, that is to say, when saturation occurs : the variations of the number of electrons released on the guard-ring and falling on the cathode should vary with the potential difference in the manner illustrated by fig. 14.

Now, such a phenomenon can be isolated and studied alone in a very simple way : by using a suitably shaped diaphragm, the light falling on the cathode may be intercepted, and the guard-ring alone illuminated ; curve I on fig. 13 gives a representation of the cathodic current measured

in this case. It will be easily seen that, for increasing positive potentials, this current decreases much more slowly than in fig. 14 ; the curve is not symmetrical ; we have been unable to demonstrate the reason for this fact, which has been found in all the cells *.

Anyhow, further proof of the origin of this negative current can be obtained by measuring the cathodic current obtained when the cathode alone is illuminated. Curve II on fig. 13 is then obtained. If the small anodic component i_1 be excepted (in all cases i_1 is always too small to be seen on fig. 13), the negative tail of the current potential characteristic has entirely disappeared. The apparent sensitivity is increased. Moreover, the algebric sum of the currents given by the cathode in case I and II for each value of the potential difference, when plotted, fall on curve III with an approximation of 1 in 1000, that of the whole set of measurements. This, though not a proof that no ejected electron is lost or multiplied may be considered as indirect evidence that the cell response to illumination is linear. Needless to say, most of these illuminating phenomena disappear when the guard-ring is electrically connected to the anode. It has been already stated that, in that case also, the response of the cell to illumination was linear, a fact which the reader will probably think now to be self-evident.

§ 7. *Conclusion.*

The cells whose properties have been described in the present paper were made for a practical purpose : that of finding solutions at the same time simpler and more accurate to the problems of photoelectric photometry and spectrophotometry. The writers hope that, with these cells, it will always be found possible to use the simple direct method of measurement, thus avoiding the complications involved in the null or equal deviation methods. It is expected that a registering spectrophotometer, now being built in the Laboratoire d'Essais, will give an example of such simplification.

Attention must also be drawn to the fact that the cells may be used either with the whole available light concentrated upon a part of the cathode or with constant illumination over the whole surface of cathode and guard-ring ; in the first case, the luminous flux is measured ; in the second, the brightness of a source may be directly determined. It will be seen at once that in many cases this possibility may be useful. As an

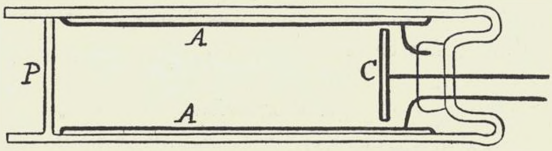
* A possible reason for that is found in the fact that between guard-ring and cathode (both kept at the same potential), there exists a circular region, due to the finite thickness of the electrodes, bounded by an emitting surface of no negligible area, and where the electric field is practically 0, whatever value is given to the anode potential.

example, it is possible to build with such a cell a direct reading optical pyrometer giving high precision.

Owing to the low tensions they employ, the cells are much easier to use than most commercial photoemissive cells. For the same reason, their "noise-level" when used with an amplifier is extremely small, so that—though the designer had not thought of this application—the talking-film industries might find them of use.

The first cells were exceedingly difficult to make: everything was built in a metrological laboratory, without proper equipment. There is no reason now why they could not be made cheap and of small size, particularly if one realizes that the present laboratory design could be greatly simplified without sacrificing any of its qualities. For instance, cells have recently been built in this Laboratory, designed as shown in fig. 15: the anode is a Faraday cylinder A, at the bottom of which is the photosensitive cathode C; the light comes in through a plane glass window P. The properties of such cells, now under investigation, are

Fig. 15.



substantially the same: low saturation potential (*circa* 0·1 volt), strict linearity of response to light, space-charge much smaller than was the case with the first model, so that after saturation, the current-potential characteristics are quite straight and horizontal up to the first excitation potential of the residual gas in the cell. Many other designs giving similar results can be conceived.

Appendix.

The Electric Field between two Plane-Parallel Electrodes, Electrons being present.

As the calculation may be found useful for the study of other problems in electronics, it is given here in full (notations, p. 176).

Starting from the fundamental conditions:

$$\text{I}\begin{cases} \dfrac{d^2\text{V}}{dx^2} = \dfrac{4\pi j}{v}, & \ldots\ldots\ldots\ (1) \\ v^2 - v_0^2 = -\dfrac{2e}{m}\text{V}, & \ldots\ldots\ldots\ (2) \end{cases}$$

and

$$\text{II}\begin{cases}\dfrac{d^2V}{dx^2}=4\pi\dfrac{j}{v}, & \ldots\ldots\ldots (1)\\ mv\dfrac{dv}{dx}=-e\dfrac{dV}{dx}, & \ldots\ldots\ldots (2')\end{cases}$$

one finds

$$\frac{d^2V}{dx^2}=4\pi j\frac{1}{\sqrt{v_0^2-\dfrac{2e}{m}V}}, \quad \ldots\ldots (3)$$

and

$$(4\pi j)^2\frac{m}{e}\left(\frac{d^3V}{dx^3}\right)-\left(\frac{d^2V}{dx^2}\right)^3\cdot\frac{dV}{dx}=0, \quad \ldots\ldots (4)$$

eq. (3) is easily integrated by substituting p for $\dfrac{dV}{dx}$, the resultant equation being

$$\left(\frac{dV}{dx}\right)^2=-\frac{2m}{e}(4\pi j)\sqrt{v_0^2-\frac{2e}{m}V}+K, \quad \ldots\ldots (5)$$

eq. (4), by substituting, $h=\dfrac{dV}{dx}$ and $q=\dfrac{dh}{dx}$, gives, by two successive integrations, the equation

$$\frac{1}{6}\left(\frac{dV}{dx}\right)^3+L\frac{dV}{dx}+M=-(4\pi j)^2\frac{m}{e}x. \quad \ldots\ldots (6)$$

Eliminating $\dfrac{dV}{dx}$ between these two equations, one finds the equation given, p. 176 :

$$\left[K-\frac{2m}{e}\cdot 4\pi j\cdot\sqrt{v_0^2-\frac{2e}{m}V}\right]^{\frac{1}{2}}\left\{\frac{1}{6}\left[K-\frac{2m}{e}\cdot 4\pi j\sqrt{v_0^2-\frac{2e}{m}V}\right]+L\right\}+$$

$$+M=\pm\frac{m}{e}[4\pi j]^2x. \quad \ldots (7)$$

Only one relation between constants K, L, M can be computed by an easy algebric method. On the cathode, we have

$$\frac{d^2V}{dx^2}=4\pi\frac{j}{v_0}; \quad \ldots\ldots\ldots (8)$$

from equation (II.) it can be shown that

$$\frac{d^2V}{dx^2}=\frac{-[4\pi j]^2\dfrac{m}{e}}{\dfrac{1}{2}\left(\dfrac{dV}{dx}\right)^2+L}; \quad \ldots\ldots\ldots (9)$$

eliminating $\left(\frac{dV}{dx}\right)$ between equations (5) and (9) we find

$$K=-2L. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

In the case of $v_0=0$, one more relation can be found by making $x=V=0$; in equation (7), we find

$$M=\frac{1}{3}K^{\frac{3}{2}}.$$

In all cases K is to be calculated numerically for stated values of j, x_0 (distance of electrodes) and V_0. The actual calculation of the location of equipotential surfaces, though not difficult, is slow: the coefficient of x being small, the first member of the equation, which is a sum of three terms all of the same order of magnitude, must be known to within many places of decimals (9 at least for $j=10^{-6}$ amp. and $x=2$ mm.). In contradistinction with the classical hypothesis, the electric field near the cathode is not found to be null.