

THE IMAGE ICONOSCOPE, A CAMERA TUBE FOR TELEVISION

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The oldest television camera tube, the iconoscope, is now used only for transmitting still pictures (e.g. the signal picture of a certain station) and film pictures. Further development of camera tubes in Europe has followed a course different from that in America. In the U.S.A. the image orthicon has become predominant, whilst in Europe the image iconoscope is widely used. Of the latter there are British and French versions and also one that has been developed in the Philips Laboratory at Eindhoven (Netherlands). This Philips image iconoscope is described here and compared with other camera tubes.

The object of television is to transmit moving pictures via electrical means. This is achieved by "measuring" in succession the brightness of the very large number of picture elements into which the picture to be transmitted is imagined as being divided. This measuring consists in the conversion of the brightnesses into corresponding fluctuations of an electric current which in some way or other govern the signal transmitted.

To be reproduced with a satisfactory definition a picture has to be divided into some hundreds of thousands of elements; let us say, for the sake of convenience, that there are 400,000. Just as in cinema projection, to keep the picture free of flicker the number of pictures produced per second has to be greater than a certain minimum; in Europe the picture-repetition rate is mostly 25 complete pictures per second.

Hence the time available for measuring the brightness of one picture element is only $\frac{1}{400,000 \times 25}$ sec $\approx 10^{-7}$ sec. Already in 1908 — when 10^7 picture elements per second was beyond the wildest dreams and one had in mind a number something like 160,000 — Campbell Swinton realized that it would be imperative to have a practically inertialess electronic apparatus¹).

To explain what is meant by this, let us describe the so-called flying-spot method frequently used for televising film pictures.

On the fluorescent screen of a cathode-ray tube (fig. 1) a raster of lines is scanned. A lens L_1 focuses this raster on the film picture to be transmitted, and another lens L_2 projects the transmitted light onto a photo-electric cell (a multiplier tube). The latter produces a current varying in strength according to the density of the successively illuminated

picture elements on the film. The fluctuating current forms a signal with which the intensity of the electron beam in a cathode-ray tube (picture tube) at the receiving end is modulated. This beam is synchronized with that at the transmitting end. Thus the televised film picture is reproduced on the screen of the picture tube.

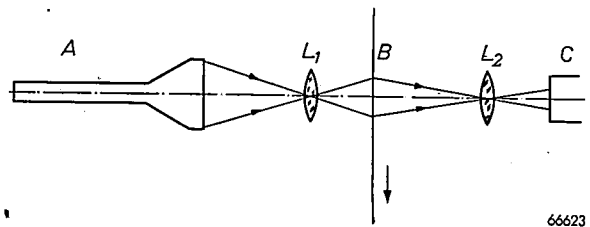


Fig. 1. Flying-spot method for televising film pictures. A cathode-ray tube with fluorescent screen on which a raster of lines is scanned. The lens L_1 projects this raster onto the film picture B and the transmitted light is concentrated by the lens L_2 in the multiplier tube C.

In principle it is possible to televise any scene in a similar way, by projecting a raster of light onto the scene and picking up the scattered light in a photocell. Practice shows, however, that in such a case the photo-electric currents are so small as to be "drowned" in the statistical noise of the photo-electrons, which noise creates at the receiving end the impression of the scene having been televised during a snowstorm! This poor result is due to the fact that only a very small part of the light scattered by the scene in all directions can be picked up in the photocell, such being contrary to the case with the film picture, where practically all the transmitted light can be collected in the photocell.

Fundamental failings of this otherwise fairly simple method are that the fluorescent spot is a weak source of light and that each picture element is illuminated for only 10^{-7} sec, so that one has to manage with the naturally limited amount of light thereby obtained.

¹) A. A. Campbell Swinton, Distant electric vision, Nature 78, 151, 18th June 1908, where a remarkable outline is given of the principles of present-day television.

However, another method can be imagined, whereby the scene is illuminated continuously, while for each picture element in succession in the space of time of 10^{-7} sec a signal is transmitted which corresponds to an illumination that was present during the whole of the time ($1/25$ th sec) available per picture. This idea is to be found materialized in all present-day television camera tubes (with the exception of the tubes used for transmitting film pictures according to the method outlined above). With this method there is a continuous accumulation of charge during a frame period, and thus these tubes have come to be known as "storage tubes".

The oldest form of storage tube is the iconoscope, designed by Zworykin (1933), which will presently be dealt with. In the main this article will be devoted to a modern camera tube named the image iconoscope. Some other types will be mentioned in passing.

Classification of modern camera tubes

In the most important camera tubes of modern design there is a plate ("target" or "mosaic") on which is projected an electrical image, consisting of a two-dimensional pattern of electric potentials corresponding in amplitude and position to the luminance in the optical image of the scene to be transmitted. This electrical image is scanned point by point by a focused beam of electrons (the scanning beam), the potentials being thereby reduced to a certain "stabilizing potential" which in some way or other produces an electric signal.

The target is, of course, made of an insulating material, e.g. mica. When an electron beam is directed upon it the rule is that for every surface element, in the stable state, on an average just as many electrons have to be emitted as impinge upon it. This number of electrons may be zero or greater than zero, and it is these two possibilities which, as will be seen, form the basis for the classification of camera tubes into two groups.

Behaviour of an insulator when bombarded with electrons

Let us consider the following case. A beam of electrons (the primary electrons) is focused upon an insulating plate set up in vacuo. In the vicinity of the plate is an electrode, the collector, which has an adjustable positive potential V_{coll} .

When the primary electrons impinge upon a surface element of the plate they release secondary electrons from the material. The secondary-emission

coefficient δ , i.e. the average number of secondary electrons released by one primary electron, depends upon the material and the velocity (thus the energy) of the primary electrons at the plate. If V_{coll} is so high that the collector attracts all the secondary electrons towards it then the variation of δ as a function of the energy V_{pr} (expressed in electronvolts) of the primary electrons is as represented in fig. 2. In the case of most materials there are two values for V_{pr} where $\delta = 1$; the smaller of the two is denoted by V_1 , the larger by V_2 . For mica, for instance, these material constants are in the order of 10 volts and some thousands of volts respectively.

As already stated, there are two possible stable states of the surface element, one where no electrons strike or leave the surface, and one where per second a certain number of electrons (> 0) impinge upon it and just as many leave it. Which of these two states will be obtained depends upon the value of V_{pr} . If V_{pr} is less than V_1 , and consequently δ is smaller than 1, the number of primary electrons striking the surface element per second will be greater than the number of secondary electrons released from it. Thus the potential of the element drops; only when it has reached zero (the cathode potential) — no primary electrons at all then reach the plate — is one of the two stable states of equilibrium obtained.

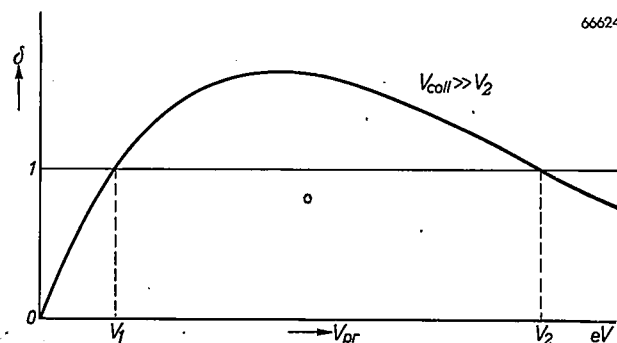


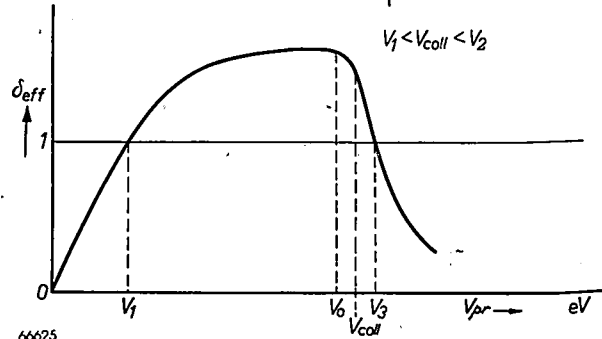
Fig. 2. Secondary-emission coefficient δ of an insulator, as a function of the energy V_{pr} of the primary electrons. At two values of V_{pr} (V_1 and V_2) δ is equal to 1.

This curve applies when the collector potential is high compared with V_2 .

Let us now consider the case where V_{pr} lies somewhere between V_1 and V_2 . Then δ is greater than 1, the number of secondary electrons released from the surface per second is greater than the number of primary electrons impinging upon it, and the potential of the surface rises until at V_2 a stable state is reached.

The supposition that all the secondary electrons pass over to the collector only holds if V_{coll} is much higher than V_2 . If that is the case then, upon

gradually reducing V_{coll} , the shape of the curve does not change at first until V_{coll} approaches V_2 . This is explained by the fact that when the surface element has a potential higher than that of the collector the released secondary electrons have to overcome an electric field before reaching the collector. Whether they succeed in doing so, or whether they fall back



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Fig. 3. Effective secondary-emission coefficient δ_{eff} of an insulator, as a function of the energy V_{pr} of the primary electrons when the collector potential V_{coll} is smaller than V_2 (cf fig. 2). $\delta_{eff} = 1$ at $V_{pr} = V_1$ and at $V_{pr} = V_3$, the latter value being a few volts higher than V_{coll} . To the left of V_0 (slightly lower than V_{coll}) the curve is identical to that in fig. 2.

upon the target, depends entirely upon their energy and the geometry of the set-up. The potential of the surface will be stabilized at a value V_3 , where the current intensity of the secondary electrons actually reaching the collector (i_{coll}) is equal to the current intensity i_{pr} of the primary beam. The ratio i_{coll}/i_{pr} may be called the effective secondary-emission coefficient, δ_{eff} . For $V_{pr} < V_3$ (but $> V_1$) δ_{eff} is greater than unity, and for $V_{pr} > V_3$ the effective secondary-emission coefficient δ_{eff} is less than unity. As a rule V_3 is slightly higher than V_{coll} (fig. 3); in contrast with V_1 and V_2 , V_3 is therefore not a material constant.

Thus it is seen that when bombarded with slow electrons ($V_{pr} < V_1$) the surface potential becomes stabilized at zero, and when bombarded with electrons of high velocity it becomes stabilized at the value V_2 (provided $V_{coll} > V_2$) or at V_3 ($\approx V_{coll} < V_2$). For the target of a camera tube however no use is made of the value V_2 , for practical reasons; it is strongly influenced by the condition of the surface and thus is too variable from point to point.

It is according to these possibilities that camera tubes are classified as:

- 1) low velocity tubes, where the target is stabilized at cathode potential (on that account they are also referred to as "cathode potential stabilized tubes", or for short "CPS tubes"), and
- 2) high velocity tubes, where the target is stabilized at the potential $V_3 \approx V_{coll}$ (e.g. 1000 V).

Among the first belongs the image orthicon,

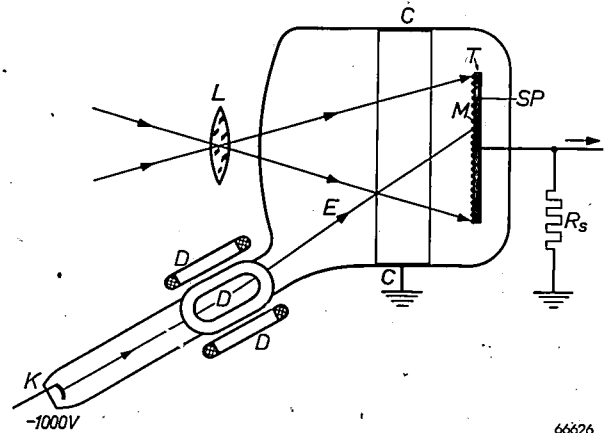
which is the type of tube mainly used in the U.S.A., while belonging to the second group are the iconoscope and the image iconoscope, the latter often being given preference in European television circles. One of the reasons for this preference is related to the large number of lines adopted on the West-European continent (625, and in France 819): with a high electron velocity it is easier to satisfy the high requirements for the the focusing of the scanning beam which are demanded for the definition required for such a large number of lines.

In this article exclusively high velocity tubes will be dealt with, though at the end some comparisons will be made with the image orthicon.

The iconoscope

The iconoscope is the camera tube which at the time gave such an impetus to television²⁾. It is schematically represented in fig. 4, while in fig. 5 a photograph is given of the Philips iconoscope, type 5852.

A lens (objective) projects an image of the scene onto a target of thin mica coated on the front with a mosaic of minute, mutually insulated, photo-sensitive elements. On the reverse side is a coating of metal, called the signal plate, forming the output



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Fig. 4. Iconoscope. L a lens projecting the scene on the mosaic M of the target T . SP signal plate, R_s load resistor, C collector, K cathode, D deflection coils, E scanning beam. The (electrostatic) focusing is not shown.

electrode and externally connected to earth via a resistor. A ring-shaped coating of metal on the inside of the envelope serves as collector and is connected to earth direct.

In an arm of the envelope is an electron gun supplying a beam of electrons which is focused on the target plate. The cathode is at a potential of, say, -1000 V with respect to earth. The beam is made

²⁾ See, e.g., Philips techn. Rev. 1, 18-19, 1936.

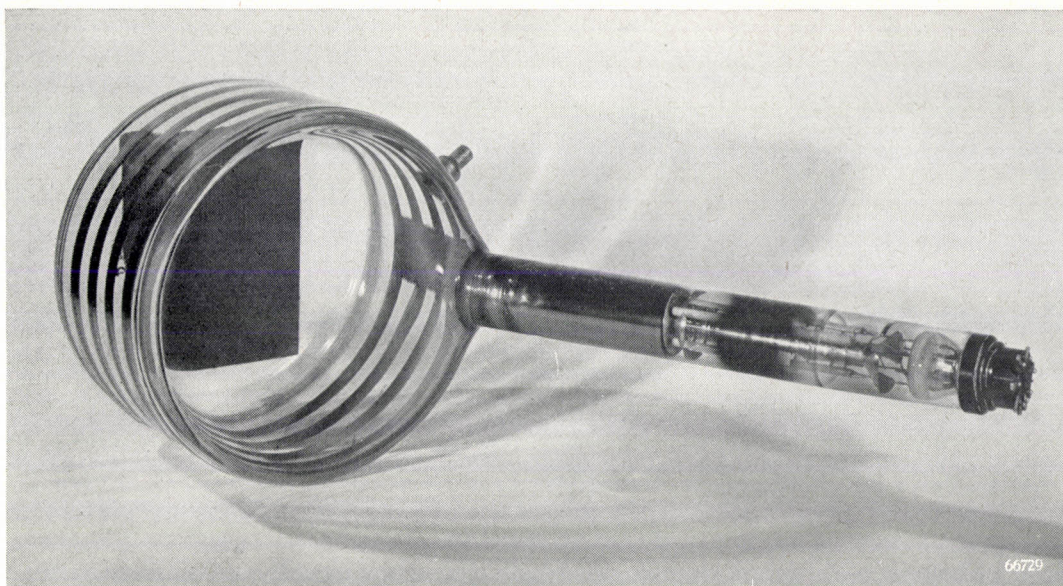


Fig. 5. The Philips iconoscope, type 5852.

to scan the mosaic continuously by means of two pairs of deflection coils. Thus a picture element is formed by the small area of the surface of the mosaic struck by the beam; although this is very small it covers a large number of photo-electric elements.

The action of the iconoscope is sometimes explained in the following (inadequate) way. The incident light causes the photo-electric elements of the mosaic to emit photo-electrons, which are taken up by the collector. Thus a positive electrical image is formed on the mosaic. The photo-electric elements together with the target form as many minute capacitors. As the scanning beam moves across the mosaic the group of capacitors belonging to a certain picture element are discharged. Through the resistor via which the signal plate is earthed there then flows a small current corresponding in intensity to the charge of the picture element, thus corresponding to the local luminance of the optical picture. Thus in the scanning of the electrical image a series of current impulses are generated which together form the video current.

Actually the position is not so simple as this. Such a description does not take into account the part played by secondary emission³⁾. In point of fact we have here again the case of an insulator bombarded with electrons, where the collector potential is smaller than V_2 (cf. fig. 3). For the moment photo-emission may be left out of consideration by assuming the iconoscope to be in total darkness.

³⁾ V. K. Zworykin, G. A. Morton and L. F. Flory, Proc. Inst. Rad. Engrs **25**, 1071-1092, 1937, and W. Heimann and K. Wemheuer, Z. techn. Phys. **19**, 451-454, 1938.

Not all the secondary electrons reach the collector, firstly because the potential of a bombarded surface element is higher than V_{coll} . If the scanning beam were to be brought to a standstill then, as explained with reference to fig. 3, the element would assume a potential V_3 , for instance, 3 volts higher than V_{coll} . Normally, however, the beam is in motion and "rests" on the surface element for such a short space of time (10^{-7} sec) that although the value actually reached (V_{max} , fig. 6) is a fraction of a volt lower than V_3 , it is still always higher than V_{coll} and thus prevents secondary electrons from reaching the collector. Furthermore, the collector is rather far removed from the target.

The secondary electrons which do not reach the collector fall back on other parts of the mosaic,

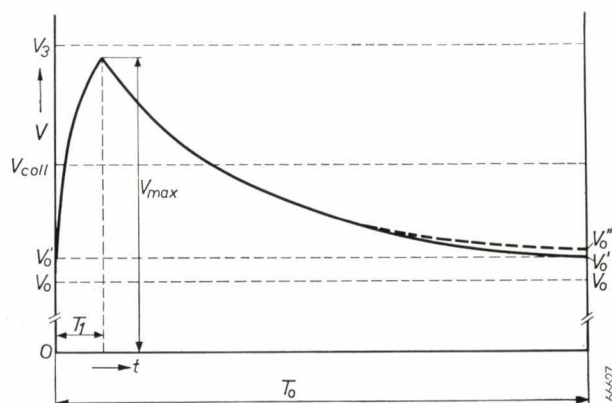


Fig. 6. Curve of the potential V of a picture element on the mosaic of an iconoscope, as a function of the time t . Fully drawn line: mosaic not illuminated; broken line: mosaic illuminated. T_0 = scanning period for the whole image ($1/25$ th sec), T_1 = scanning time for one picture element (10^{-7} sec; in the drawing highly exaggerated). For the meaning of V_{coll} and V_3 see fig. 3, and for V_0 , V_0' , and V_0'' see the text.

which, as we have already seen, are at a slightly higher potential than the collector. This distribution of the secondary electrons is called the redistribution effect, and it is of essential importance for the action of the iconoscope.

After the surface element in question has been scanned, thereby assuming the potential V_{\max} , it will continue to receive secondary electrons originating from other surface elements, until it is scanned by the beam again. Thus its potential V begins to drop (fig. 6) and, if a sufficient length of time were to elapse before the next scanning, would ultimately reach a value V_0 so low that the surface element in question could no longer take up secondary electrons from its surroundings. In practice, however, the surface element is again struck by the beam $1/25$ th sec after the first scanning; the potential it reaches immediately prior to the second scanning is denoted by V_0' (fig. 6).

How is this course of affairs affected when the mosaic is illuminated? An illuminated image element will not emit photo-electrons continuously: from fig. 6 it is seen that during a considerable part of the scanning period the potential V of the element is higher than V_{coll} , and the photo-electrons do not possess sufficient energy to overcome this potential difference. Photo-emission begins, therefore, when — owing to the redistribution effect — the potential V has been sufficiently reduced. Experience teaches even that only during about the last 5% of the scanning period is V low enough for the photo current to reach the point of saturation. Owing to the photo-emission the right-hand part of the V curve of the picture element in question comes to lie somewhat higher (see the broken line in fig. 6), ending with a value $V_0'' > V_0'$, so that in the next scanning the surge from V_0'' to V_{\max} is smaller than that from V_0' to V_{\max} in the case of a non-illuminated element. It is this difference that gives rise to the signal current. (The illumination causes a change also in V_{\max} , but this is small compared with the difference between V_0'' and V_0' .)

The most important features of the iconoscope will now be briefly discussed.

Sensitivity

As already explained, it is due to the redistribution effect that photo-emission can take place, but this is only possible during a fraction of a scanning period. Thus we are still far removed from a continuous photo-emission such as was imagined in the case of an ideal storage tube! This is one of the reasons for the rather low sensitivity of the iconoscope.

A second cause of the lack of sensitivity lies in the mosaic form of the light-sensitive layer. The insulation between the elements does not contribute towards photo-emission, so that a considerable part of the surface of the target is photo-electrically inactive.

Spurious signals

Another drawback attaching to the iconoscope is the fact that, in the case of the non-illuminated tube, the potential surge from V_0' to V_{\max} when the element is scanned (fig. 6) varies with the position on the mosaic. Thus a certain signal, a "spurious" signal, is given also when the iconoscope is not illuminated.

The main cause of spurious signals (see the literature quoted in footnote ³) is that the redistribution does not take place in the same way all over the mosaic, owing to the surroundings of the elements not being the same everywhere. When a certain line is being scanned the part of the mosaic above that line was more recently scanned than the part below it and thus has higher potentials. This is manifested in the picture at the receiving end showing a luminance increasing from top to bottom.

There are similar differences between the left and right sides and between the edge and the middle: the side of the picture where the lines end is reproduced with a higher luminance than the side where they begin, and the edge is lighter than the middle of the picture.

An additional effect is the variation, taking place during the scanning, in the angle at which the beam strikes the mosaic. This angular variation is accompanied by a variation both in the size of the area of the picture element and in the secondary emission coefficient.

When the iconoscope is illuminated the spurious signal is superposed on the picture signal and only if the latter is of a reasonable strength is the spurious signal not very disturbing. It is for this reason that with the iconoscope very high intensities of illumination are needed.

Linearity

The stronger the illumination on a certain part of the mosaic, the higher is the potential V_0'' at that spot just before it is scanned by the beam. This has two consequences: there is slightly less chance of further photo-electrons escaping, and there is a somewhat greater attraction of redistributed secondary electrons. Both these effects result in the amplitude of the signal increasing less than proportionately with the illumination. This non-linearity is rather an advantage than a disadvantage in that it compensates fairly well an inverse non-linearity between the beam current and the control voltage in the picture tube of the receiver. Thus

there is no need to take steps to compensate the latter non-linear effect.

Other features

Apart from the non-linearity there are some other favourable features of the iconoscope, namely that the pictures obtained with it are good both in geometrical configuration and in gradation, and that its installation and operation do not involve any particular technical difficulties.

The image iconoscope

The greatest disadvantage of the iconoscope is its lack of sensitivity, and it is for that reason that attempts have been made to develop camera tubes with greater sensitivity, while still retaining the good picture quality obtained with the iconoscope when the scene is sufficiently illuminated.

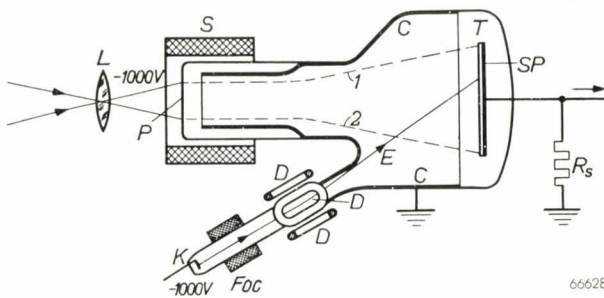


Fig. 7. Image iconoscope. *P* photocathode, *S* coil of the magnetic electron lens, *1* and *2* paths of photo-electrons, *Foc* focusing coil. Other letters have the same meaning as in fig. 4.

A year or two prior to 1940 a more sensitive version of the iconoscope, called the image iconoscope, was developed in the U.K. and in the U.S.A.⁴⁾ Some improvements on this have since been made in the Philips Laboratory at Eindhoven, as will appear in the course of this article.

In the case of the image iconoscope (fig. 7) a lens (objective) projects an optical image of the scene to be televised onto a continuous, transparent photocathode. The local density of emission of the photo-electrons corresponds to the local luminance of the optical image. This photo-emission image is focused by an electron lens onto a target consisting in this case of a thin layer of insulating material applied to the signal plate. The metallized inner wall of the envelope serves as collector. An electron gun mounted in an arm of the envelope supplies the beam of electrons scanning the target.

The differences, compared with the conventional iconoscope, which are mainly responsible for the gain in sensitivity, are the following:

- 1) The surface of the photocathode is continuous, so that none of its effective area is lost in insulation between the separate photo-electric elements.
- 2) The stream of photo-electrons reaching the target is reinforced by secondary emission, each photo-electron releasing on an average more than two secondary electrons.
- 3) The secondary electrons released from the target by the photo-electrons have a much greater energy than the photo-electrons in the ordinary iconoscope, so that secondary emission from a surface element begins immediately after that element has been stabilized by the scanning beam. This means a considerable gain in storage action. The curve for the potential V of a surface element is therefore similar to that in fig. 6, except that in the case where the cathode is illuminated the curve begins to diverge earlier from the curve applying for a non-illuminated cathode, the difference between V_0'' and V_0' thus being greater.

Let us now consider more closely the principal parts of the image iconoscope and also the important question of electron-optical projection. The Philips type of image iconoscope is illustrated in fig. 8.



Fig. 8. The Philips image iconoscope, type 5854.

⁴⁾ See, e.g., H. Iams, G. A. Morton and V. K. Zworykin, The image iconoscope, Proc. Inst. Rad. Engrs. 27, 541-547, 1939.

The photocathode

Contrary to ordinary photo-electric cells, an image iconoscope must have a photocathode which is semi-transparent, because the light enters from the outside while the photo-electrons have to emerge on the inside.

In addition to this transparency great sensitivity is needed (at least some tens of μA photo-current per lumen incident light) and moreover the spectral sensitivity must not deviate too much from the relative luminosity curve of the average human eye.

These three requirements greatly restrict the choice of photo-electric material to be used. The photocathode in the Philips image iconoscope consists of a very thin coating of cesium, antimony and oxygen applied to a flat part of the glass envelope. The sensitivity for the light from an incandescent lamp with colour temperature 2600 °K is about 45 μA per lumen. The spectral sensitivity curve, compared with the relative luminosity curve for the normal eye, is slightly displaced towards the blue (fig. 9).

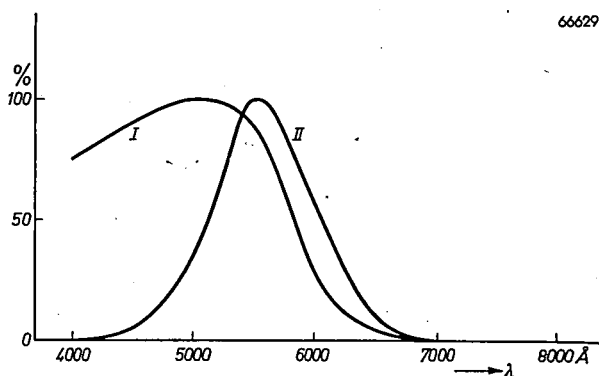


Fig. 9. Relative spectral sensitivity of the type 5854 image iconoscope, (curve I), compared with the relative luminosity curve (II), as functions of the wavelength λ of the light.

Electron-optical image formation

The optical image of the scene is converted into a corresponding photo-emission image on the photocathode. The next step is to produce on the target an electrical image which is a faithful replica of the photo-emission image. This requires that the small beams of photo-electrons emitted from points of the photocathode are focused on corresponding points on the target. For this electron-optical image formation an electron lens is needed. As such use can be made of electric and/or magnetic fields.

For the image iconoscope the choice of the nature of the electron lens is determined mainly by the following considerations:

- 1) For the emission of photo-electrons to reach the saturation point an accelerating electric field is needed at the photocathode.

- 2) For a faithful image of a large part of the cathode surface to be produced in a not too long tube, the useful visual field angle of the electron lens — i.e. the angle from which the edges of the image are seen from the centre of the electron lens — must be large.

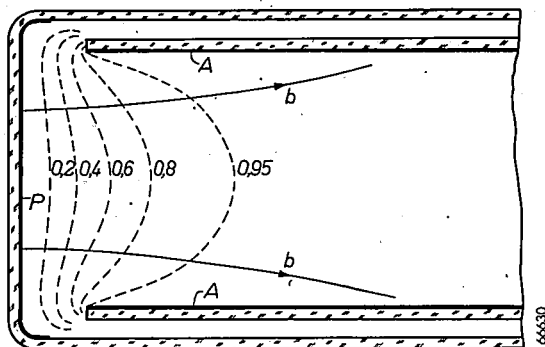


Fig. 10. Between the photocathode P and the metal coating A (on the inner wall of a glass cylinder) is an accelerating electric field. Broken lines: equipotential planes (the potential of P is zero, and that of A is taken as 1). b are electron paths, in the absence of other fields.

- 3) The image formed must be sufficiently sharp at all points. A prerequisite is that both the cathode and the target are flat (if the photocathode were curved it would be necessary to employ means of optical correction for the proper projection of a scene upon it; a curved target is very difficult to make and when scanned would cause barrel distortion).

Condition (1) implies that an electric field has to be employed. This is obtained by means of a metal cylinder (e.g. the metal coating on the inner wall of a glass tube, fig. 10) facing the photocathode and applying a potential difference of, say, 1000 V between these electrodes. Since the cylinder forms, electrically, one whole with the earthed collector, the photocathode is given a potential of -1000 V with respect to earth.

This electric field alone, however, does not suffice. Fig. 10 shows some equipotential planes and some electron paths, from which it is seen that the latter diverge, so that we have here a negative electron lens. Now a negative lens cannot produce a real image from a real object. Therefore, in order to obtain a positive lens, either the shape of the electric field has to be changed in some particular way or a magnetic field has to be added which focuses each electron pencil.

The first alternative comes into conflict with the requirements (2) and (3), for it has not yet been found possible to design an electrostatic lens system which is capable of forming a faithful image of a

sufficiently large part of a flat photocathode on a flat target.

The addition of a magnetic field is therefore indicated. Such a field can be produced by means of a coil placed concentrically around the tube. The coil has to be of such dimensions and in such a position as to minimize aberrations, whilst the

we have to consider what electrostatic and magnetic forces act upon an electron leaving the cathode with zero velocity (e.g. at the point *M* in *fig. 12*.)

The cathode being an equipotential plane, the electric lines of force (field strength *F*) are perpendicular to it. Provided the cathode is at a sufficient depth inside the coil, the same may be said to be

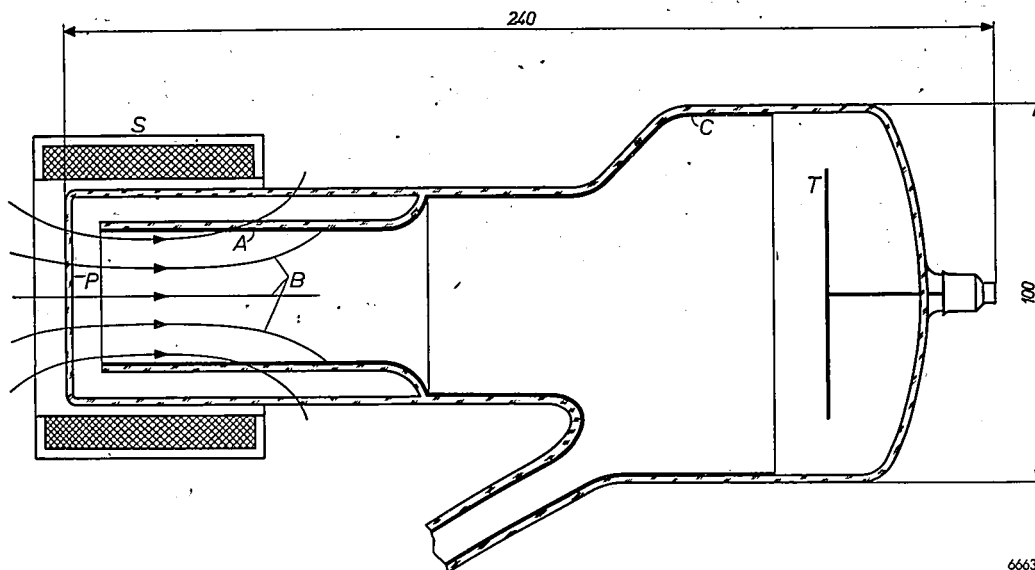


Fig. 11. Formation of the electron-optical image of the photocathode *P* on the target *T* with the aid of an electric field (between *P* and the cylinder *A*, cf. *fig. 10*) and a magnetic field. The latter (lines of flux density *B*) is produced by a focusing coil *S*.

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magnetic field must not disturb the movement of the scanning beam. As the best solution a fairly long coil was used (see the article quoted in footnote ⁴), protruding beyond the end of the tube (see *fig. 11*) far enough for the plane of the photocathode to be intersected practically at right angles by a uniform magnetic flux.

For a theoretical treatment of the mechanism reference may be made to a publication elsewhere ⁵, but the results of this study may be summarized and qualitatively commented upon here.

The movement of the electrons depends not only upon the two fields mentioned but also upon the velocities of the electrons leaving the photocathode. Some of them have zero initial velocity, and the paths they follow are called the principal rays. Generally, however, the electrons leave the cathode with a certain velocity, with the result that they follow a more complex path.

In order to get some idea of the principal rays

approximately the case with the lines of magnetic flux density *B*. Thus, under the influence of the electric field the electrons following a principal path emerge from the cathode at right angles to its plane; at first they are not subject to any force from the magnetic field.

Very soon, however, there will be a noticeable divergence of the *F* lines, and a force directed radially outward deflects the path of the electrons outward (*fig. 10*), thereby causing it to intersect *B* lines before these diverge. The electron is then subjected to a tangential Lorentzian force, which, with the direction of the *B* lines as drawn in *fig. 11* and for an electron travelling above the centre line, is directed forward. Thus a rotation about the axis of the tube (the *z* axis) is superposed on the movement of the electron along the lines denoted by *b* in *fig. 10*; viewed in the direction of the positive *z* axis (*fig. 12*), the electron therefore rotates clockwise. Consequently the principal ray is no longer a planar curve but describes a sort of helix about the *z* axis. Owing to its having acquired tangential velocity the electron becomes subject to a secondary Lorentzian force directed radially towards

⁵) J. C. Francken and R. Dorrestein, Paraxial image formation in the "magnetic" image iconoscope, Philips Res. Rep. 6, 323-346, 1951 (No. 5).

the z axis and thus counteracting the divergence of the path.

Towards the end of the coil the B lines diverge more with respect to the z axis than does the principal path of the electrons, so that there the electron becomes subject to a Lorentzian force which is tangential, like the first one, but directed backward instead of forward (for an electron above the z axis), because the angle between the B lines and the direction of motion is of opposite sign. Thus the clockwise rotation about the z axis is retarded and even reversed. Then a force comes into action which is directed radially away from the z axis.

Briefly, therefore, the course of a principal ray is as follows: at first the path is approximately parallel to the z axis, then it diverges farther and farther from that axis, thereby turning about the z axis first clockwise and later anti-clockwise in the form of a widening helix.

Although most of the electrons which leave the photocathode have velocities greater than zero and thus do not follow any principal paths, still it is the principal rays which determine the geometry of the electron-optical image. Each forms the axis of a small electron pencil.

This may be explained as follows. Let us resolve the initial velocity into three components: a radial one (v_r) and a tangential one (v_ϕ) in the plane of the cathode, and an axial one (v_z) parallel to the z axis (see point N in fig. 12).

Electrons with initial velocity components $v_z = 0$ but v_r and $v_\phi \neq 0$ follow a path more or less helical about the principal ray but ending, owing to the secondary Lorentzian forces, in the same point on the target as the principal ray. Thus the components v_r and v_ϕ do not cause any aberrations.

Such is not the case, however, with v_z . This component gives rise to a certain "chromatic" aberration: a point of the photocathode from which electrons emerge with axial velocity does not result in a point being formed on the target but a small circle (scattering circle), the diameter of which is:

$$d = \text{const.} \frac{\epsilon}{F}$$

where ϵ is defined by $e\epsilon = \frac{1}{2}m v_0^2$ (e = charge, m = mass and v_0 = initial velocity of the electron), and F = electric field strength at the cathode. In the image iconoscope ϵ is in the order of 1 volt, F about $6 \cdot 10^4$ V/m. Owing to this high value of F the diameter d is so small — thus the image so sharp — that the image iconoscope can quite well be worked with more than 600 scanning lines. In the image orthicon, on the other hand, F is ten times smaller⁶⁾, so that with this type of tube the formation of the electron-optical image is a limiting factor for the number of lines.

⁶⁾ H. B. De Vore, Proc. Inst. Rad. Engrs 36, 335-345, 1948.

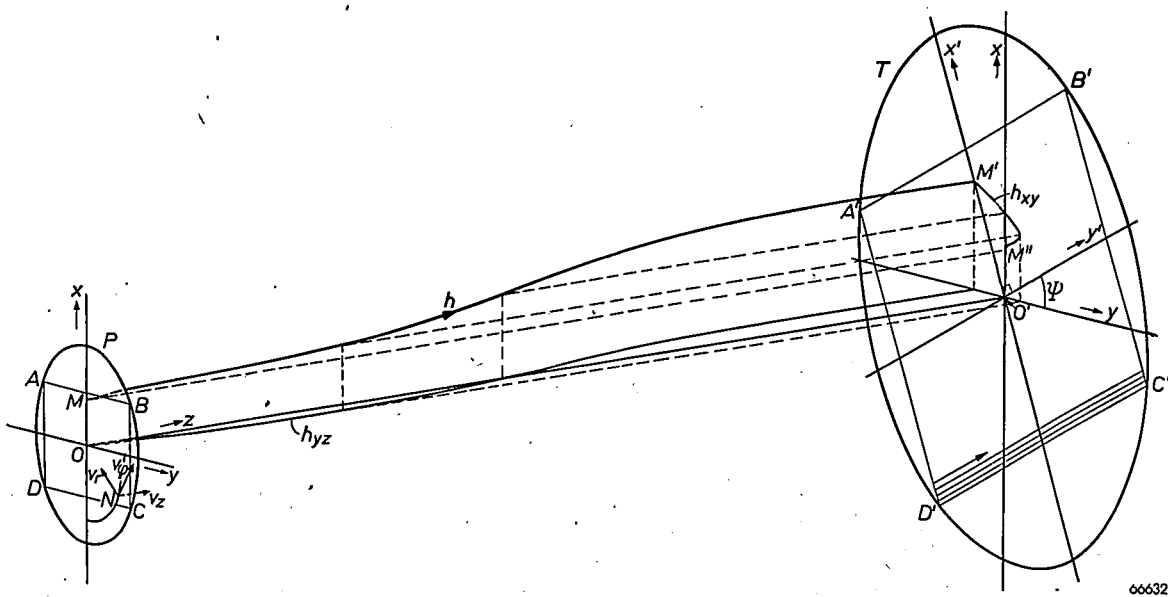


Fig. 12. Formation of the electron-optical image of the photocathode P on the target T : h is a principal path followed by a photo-electron emerging at M with zero initial velocity and reaching the target at M' . M'' is the projection of M on T , h_{xy} the projection of h on T , and h_{yz} the projection of h on the yz plane. At the point N on the photocathode are drawn the three components v_r , v_ϕ and v_z of the velocity of an electron emitted with a certain initial velocity.

The electrical image on the target is turned over an angle Ψ with respect to the image on the photocathode. $A'B'C'D'$ is the part of the target scanned (a few lines are drawn on it), $ABCD$ the corresponding part of the photocathode. The diagonal $A'C'$ is 75 mm long, while the length of the diagonal AC is normally 20 mm; when other coils are used AC is maximum 27 mm and minimum 10 mm.

Owing to the predominance of the diverging forces acting upon the electrons following the principal path the image on the target is magnified, and owing to the tangential forces the electron image is rotated with respect to the optical image on the photocathode, the angle of rotation Ψ (fig. 12) being about 30 to 40 degrees.

The degree of magnification is related to the effective length of the magnetic field: if the field is lengthened (in the direction of the target) it takes longer for a photo-electron to reach the area where the B lines appreciably diverge, and the secondary Lorentzian force radially directed towards the z axis is active longer, so that this converging force then has greater influence and hence the magnification is smaller. Conversely, the shorter the effective magnetic field, the greater is the magnification.

With our image iconoscope the magnification is normally 3.75, which means to say that the scanned part of the target, which always covers an area of 45 mm \times 60 mm, corresponds to an area of 12 mm \times 16 mm on the photocathode (the diameter of the active part of the photocathode is 20 mm). By exchanging the coil for another of different dimensions it is also possible, however, to work with a larger or a smaller magnification, thus projecting a smaller or a larger part of the photocathode on the target. The choice as regards the size of the effective photocathode is governed by requirements of an optical, light-technical and camera-technical nature. The limits for the magnification are 2.75 and 7.5 (diameter of the projected part of the cathode respectively 27 mm and 10 mm).

With a magnification greater than 7 to 8, owing to the "chromatic" aberration of the photo-electrons emerging with axial velocity (see above) there is too great a loss in resolving power.

The lower limit of 2.75 is due to various other aberrations, which with a smaller magnification can no longer be sufficiently compensated. As such may be distinguished: field curvature, pin-cushion distortion and so-called S distortion. The first two are known from light-optics⁷⁾. By S distortion is meant the effect of the image of a straight line being projected as a line curved somewhat in the shape of the letter S (fig. 13). This effect, which always occurs to a certain extent with magnetic lenses, is due to the fact that the principal rays at the edge of the image are rotated over a larger angle than those nearer the middle. As is the case with pin-cushion distortion, S distortion is proportional to the third power of the diameter of the active part of the photocathode, thus in the case where the size of the image on the target is constant this distortion is inversely proportional to the third power

of the magnification. If the magnification is not too small the S distortion can be sufficiently corrected by electrical means (which we cannot enter into here), but if it is less than 2.75 this is no longer possible. In fig. 14a a picture is given showing all three aberrations to a marked extent. The picture in fig. 14b, however, has only a scarcely perceptible S distortion, which is not troublesome.

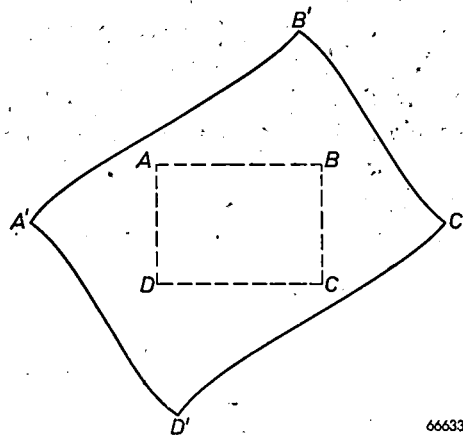


Fig. 13. $ABCD$ is an image on the photocathode, $A'B'C'D'$ the corresponding electrical image on the target. The latter is magnified and turned with respect to $ABCD$ and also shows some S distortion, which always occurs when magnetic lenses are used (straight lines are projected with a slightly S-shaped curve). If the magnification is too small the S distortion becomes so pronounced that it can no longer be sufficiently corrected.

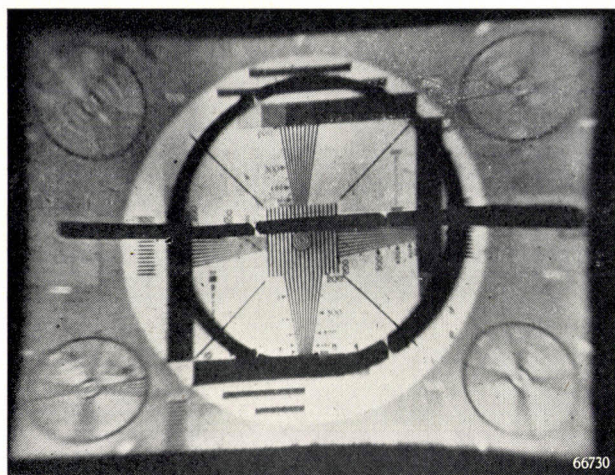
The effective length of the magnetic field can, in principle, be varied in a simpler way than by exchanging the coil, namely by shifting the coil along the tube. In practice, however, the magnification can be only slightly varied in this way: as the coil is shifted farther towards the target a strong field curvature very soon arises (the B lines are then no longer at right angles to the photocathode), whilst if it is slightly shifted in the other direction it touches the objective (to give the camera a large visual field an objective with a short focal length is used, and it is therefore close to the photocathode).

The electron gun

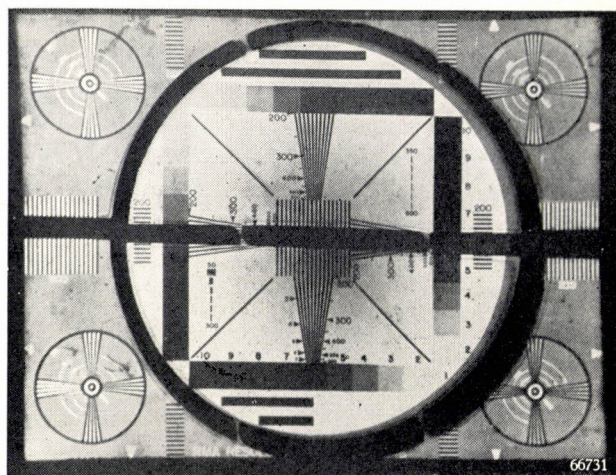
The electron gun supplies the scanning beam. Just as is the case with most picture tubes, in the image iconoscope the beam is focused and deflected with the aid of magnetic fields.

In regard to the sharpness of the scanning, there are two things to be considered. First let us deal with the non-deflected beam. This is focused on the centre of the target, where its diameter must be so small that the lines do not overlap when being scanned. If it is desired to work for instance with 1000 lines then, if the height of the scanned part of the target is 45 mm, the effective diameter of the focus must not be more than 45 μ . This requirement is all the better fulfilled the higher the acceleration voltage is chosen, but, as will be shown in the next section, this voltage should preferably not exceed 1000 V.

⁷⁾ A review of various optical aberrations is to be found, for instance, in: W. de Groot, Philips techn. Rev. 9, 301-308, 1947, in particular pages 304 and 306.



a



b

Fig. 14. a) Picture showing a marked field curvature, pin-cushion distortion and S distortion. b) Here there is only a slight S distortion, which can easily be corrected electrically. These photographs have been taken with the aid of an experimental tube in which a fluorescent screen was used instead of a target. On the photocathode a test pattern was projected as used in television for detecting aberrations and checking the definition and gradation. The heavy black circle and the thick horizontal line in the middle correspond to markings on the photocathode for determining the magnification.

Further, account has to be taken of the fact that in the image iconoscope the electron gun has to be mounted with its axis at an angle to the target. Consequently when the beam is deflected upward or downward the focus is no longer situated on the target. Therefore, to obtain sufficiently sharp scanning also away from the centre, the beam must have a good depth of focus, which means that it has to be extremely narrow. Hence the angle of divergence $2\alpha_f$ (see fig. 15) has to be kept very small.

It is, in general, difficult to obtain a fine focus with a very narrow beam on account of the mutual repulsion of the electrons, but fortunately the intensity of the beam current required is very low, in the order of $0.1 \mu A$.

In addition to this space-charge repulsion there is another factor limiting the spot size obtained with a very narrow beam: there is a very fundamental relationship between the angle of divergence $2\alpha_f$ and the current density in the beam. In the case where the space charge is negligible this relationship is:

$$\sin^2 \alpha_f = \frac{V_0}{V} \cdot \frac{j_f}{j_0}, \dots \dots \dots (1)$$

where $V_0 = 1/2 mv_0^2/e$ (with m = mass, v_0 = initial velocity and e = charge of an electron), V = the potential difference traversed by the electrons, j_f = density of the beam current in the focus, and j_0 that at the cathode of the gun.

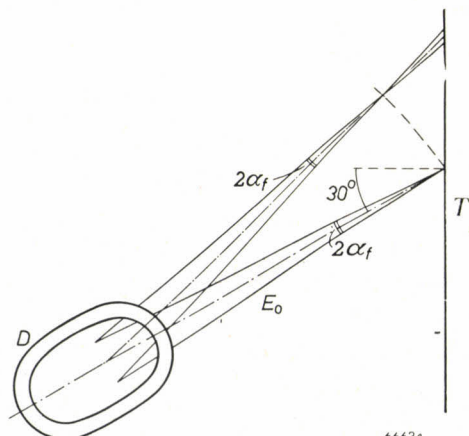
Equation (1) is derived as follows. In optics there is a law (ascribed to Abbe as well as to Helmholtz or to Lagrange) which says that the brightness of a picture

divided by the square of the index of refraction of the space in which the picture is formed is constant (as long as losses through absorption and reflection are negligible). In electron-optics the analogue of this law is expressed in the following formula:

$$\frac{j}{V \sin^2 \alpha} = \text{const.}, \dots \dots \dots (2)$$

where j is the current density and α half the angle of divergence of the electron beam, while V is the potential difference between the point in question and the (imaginary) point where the electron velocity is zero.

The values of these quantities at the cathode are denoted by j_0 , α_0 and V_0 . The value of α_0 is 90° , because the electrons emerge from the cathode in all directions. (The same holds if there is a limiting diaphragm in the beam, as is the case in the gun of our image iconoscope, since the electron spot is formed by small beams of electrons originating from different



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Fig. 15. Assuming that the non-deflected beam E_0 has been focused onto the centre of the target T , when the beam is deflected the focus will no longer be in the plane of T . This gives rise to blurring, the extent of which increases with the angle of divergence $2\alpha_f$.

points of the cathode and each having a half-angle of divergence of 90° at the cathode⁸⁾). Thus the value of the constant in (2) is j_0/V_0 .

For the electrons which in the gun of the image iconoscope have traversed a potential difference V the relationship between the half-angle of divergence, α_f and the current density j_f in the focus is given by (2) as:

$$\sin^2 \alpha_f = \frac{V_0}{V} \cdot \frac{j_f}{j_0},$$

which is the same as equation (1).

From eq. (1) it is seen that, with given values of V_0 , V and j_0 , a reduction of α_f leads to a reduction of j_f and thus, for a given value of the beam current intensity, to a larger cross section of the focus. Further it appears that the greater the value of j_0 (thus the heavier the cathode may be loaded) and the higher the value of V , the less is the danger of the focus becoming too large.

What has to be found, therefore, is an optimum value for α_f at which, on the one hand, the focus is not too large and, on the other hand, the sharpness at the edges of the image does not differ too much from that in the middle. With our image iconoscope the position is such that this optimum value of α_f lies at about 3×10^{-3} radians.

This small angle of divergence, combined with a low beam current intensity (about $0.2 \mu\text{A}$), has been obtained by placing two diaphragms in the beam. The first, with a narrow aperture, confines the beam within the desired small angle. The second one, with a wider aperture, allows the beam to pass through without hindrance but intercepts the low-velocity secondary electrons formed round the edge of the first diaphragm.

With the focus of 45μ already mentioned (1000 lines at 45 mm) and a beam current of $0.2 \mu\text{A}$, the average current density in the focus is $j_f = 12 \text{ mA/cm}^2$. Substituting this in eq. (1), and for V the value at which the secondary emission coefficient of the target is greatest, viz. 1000 V , and for V_0 the value corresponding to the average initial velocity ($\approx 0.1 \text{ V}$), we find for the average current density at the cathode of the gun $j_0 \approx 120 \text{ mA/cm}^2$. The peak value of the current density is in fact several times greater. Although an ordinary oxide-coated cathode may indeed be continuously loaded with such a current density, it is better to use what is known as an L cathode⁹⁾, since this has a much longer life. It would be quite undesirable if the useful life

of a costly tube such as the image iconoscope were to be dependant upon the life of a component like the cathode of the gun.

From the manufacturing point of view the L cathode also has the advantage that it lends itself well for mounting with very close tolerances of the distance between cathode and grid. Thanks to this property there are fewer rejects, and thus less wastage, in manufacture through errors of mounting in the gun.

The glass arm of the envelope containing the electron gun has been kept as narrow as possible (internal diameter 11 mm , external 14 mm), so that also the focusing coil and the deflection coils may be small. The advantages of this are: (1) that the field of the deflection coils in the space facing the target is so weak as not to have any perceptible influence upon the paths followed by the photoelectrons, and (2) little power is needed for excitation of the coils, so that the generators of the deflection currents, mounted together with the tube in the camera, can also be small. This makes the handling of the camera all the easier. A camera with an image iconoscope is shown in *fig. 16*.

In practical use the resolving power of the Philips image iconoscope is found to be 900 to 1000 lines in the middle of the image and about 700 lines at the edges. (These limits are set by the electron gun; the resolving power of the electron-optical projection is very much greater.)

The target

As in the conventional iconoscope, also in the first of our image iconoscopes the target was of mica (of course without mosaic). In the preparation of the photocathode cesium vapour is driven into the tube. This vapour tends to affect the surface of the mica, thereby causing the secondary emission coefficient, δ , as a function of the energy V_{pr} of the primary electrons impinging on it, to follow a curve as represented by *I* in *fig. 17*. It is true that the peak of this curve lies higher than in the case where the mica has not been in contact with cesium, but then this peak is situated at a point corresponding to a fairly small energy of the impinging electrons. For the electron-optical projection the electric field at the photocathode should be strong, and this, as already stated, is reached with a potential difference of 1000 V . In the electron gun, as we have seen, a high accelerating voltage is necessary in order to obtain a fine focus; for the sake of simplicity a potential difference of 1000 V is likewise chosen here. With an energy of 1000 eV , however, δ remains considerably below the maximum value.

⁸⁾ D. B. Langmuir, Proc. Inst. Rad. Engrs 25, 982, 1937.

⁹⁾ H. J. Lemmens, M. J. Jansen and R. Loosjes, A new thermionic cathode for heavy loads, Philips techn. Rev. 11, 341-350, 1950.

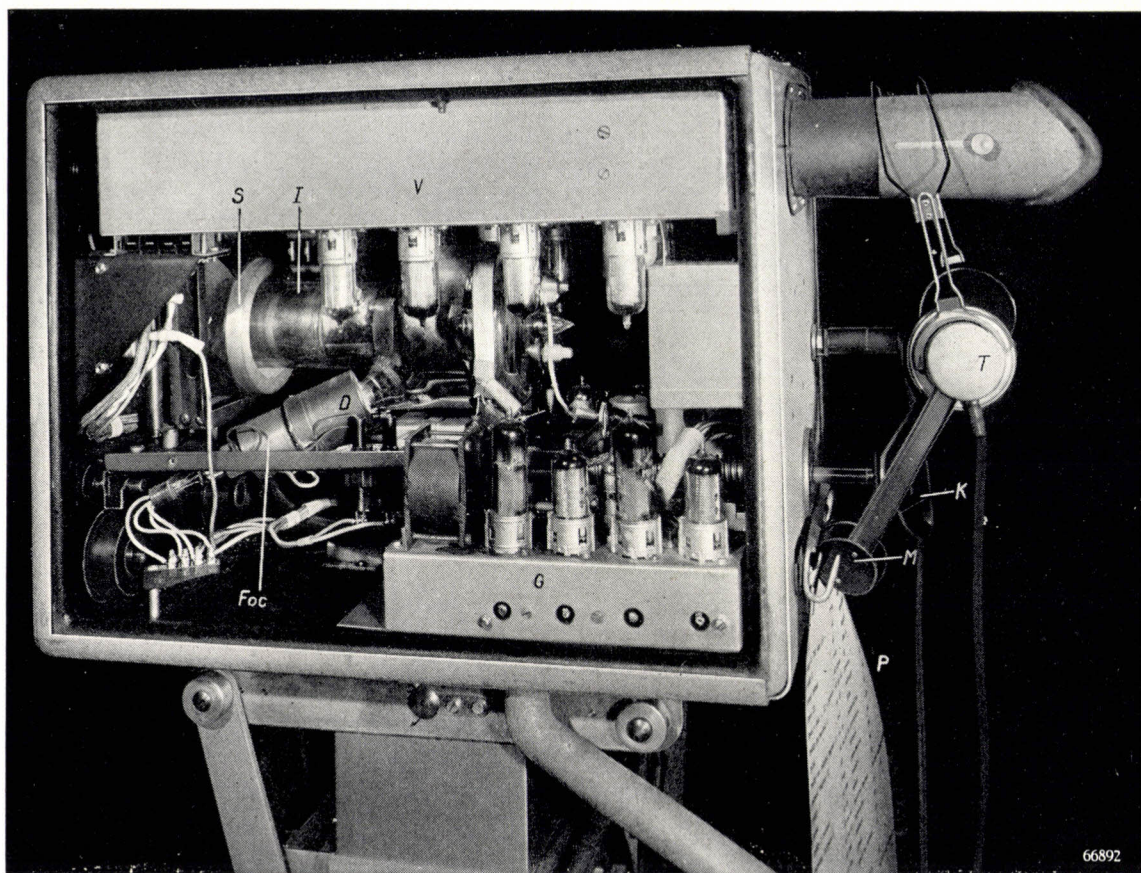


Fig. 16. One of the cameras used for the experimental television broadcasts at Eindhoven. One side panel and a screen have been removed. *I* image iconoscope, type 5854. *S* image coil, *Foc* focusing coil. *D* deflection coils. *G* time-base generator. *V* chassis with monitor picture tube and accessories. *M* microphone and *T* telephone for communication between the operator and the control room. *K* knob for exchanging the objective. *P* playbook.

An improvement has been reached by coating the mica with a thin layer of MgO. The curve $\delta = f(V_{pr})$ now has the shape of curve *II* in fig. 17: at $V_{pr} \approx 1000$ V the coefficient δ is about 4,

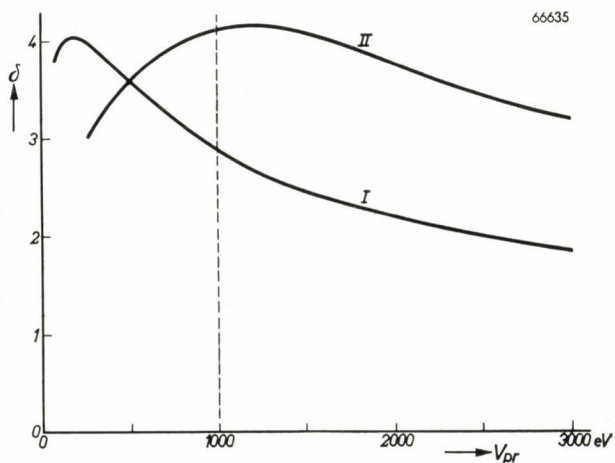


Fig. 17. Secondary-emission coefficient, δ , as a function of the energy V_{pr} of the primary electrons, *I* for mica affected by Cs, *II* for mica coated with MgO. At $V_{pr} \approx 1000$ V *II* is much more favourable than *I*.

which means a considerable gain in sensitivity. Furthermore, owing to the coating of MgO, stains on the mica which cannot be removed and otherwise show up clearly in the picture are thereby made invisible.

Notwithstanding this gain, the sensitivity of the first tubes made was still unsatisfactory. A suitable method of measuring the sensitivity of the target — i.e. the ratio of the signal current to the electron current striking the target — is the following. Except for a narrow vertical strip in the middle, which is kept dark, the photocathode is uniformly illuminated with a variable intensity of light. Each time the scanning beam passes one of the edges of the “black” strip on the target the signal current suddenly changes. The magnitude of this current surge I_s at the transition from “black” to “illuminated” is measured as a function of the photocurrent I_{ph} , which is varied with the strength of illumination.

The result, at first, was that the signal did not rise sufficiently above the noise level of the first

amplifying valve. In order to gain an insight into the factors determining the shape of the signal curve an attempt was made to approach theoretically the problem of the stabilization of the potentials on the target and the production of the signal. Suffice it to say here that these investigations¹⁰⁾ led to the conclusion that the capacitance of a surface element of the target with respect to the signal plate is an important factor, and that an increase of this capacitance must lead to greater sensitivity.

New tubes were therefore made with a mica sheet of only about 25 μ thickness (also with a layer of MgO, thin compared with the mica) instead of the original sheet thickness of 50 μ .

The success attained from these two measures — applying a layer of MgO and halving the thickness of the mica — is evident when comparing curve II in fig. 18 with curve I.

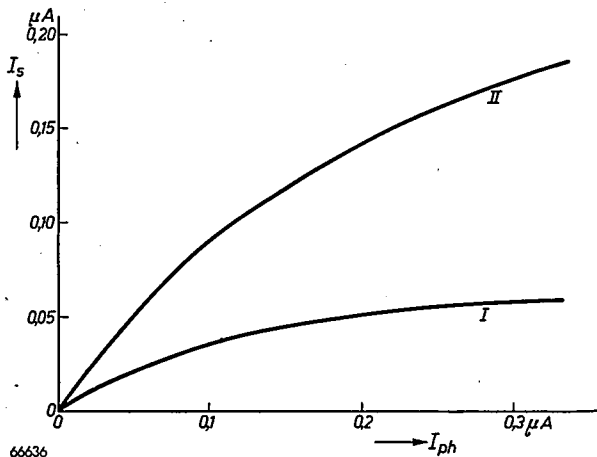


Fig. 18. The current surge I_s in the signal current each time the scanning beam passes from a "black" strip on the target to an "illuminated" part, plotted as a function of the photo-current I_{ph} . Curve I applies for a mica sheet 50 μ thick without MgO, curve II for a sheet 25 μ thick coated with MgO.

The reproduced picture of a scene televised under the normal studio lighting, or of an outdoor scene in daylight (even in bad weather), with the image iconoscope last described, is almost free of "noise" and shows excellent gradation.

The scanning beam has to erase, as it were, the electric image on the target point by point. For it to be able to do so sufficiently also on a thinner target, the strength of the beam current had to be increased approximately in proportion to the capacitance of the target. The value of 0.2 μA mentioned corresponds to the mica thickness of 25 μ .

In the image iconoscope spurious signals arise from the same cause as in the case of the conventional iconoscope: the various surface elements of the target are not all in the same position with respect to the scanning beam. In the image iconoscope, however, the situation is more favourable: with the tube described (mica 25 μ thick, beam current 0.2 μA) and with an illumination producing a photo-current of more than 0.1 μA , the spurious signals are so weak that there is hardly any need of compensating measures. In practice a photo-current of 0.1 μA can be obtained with an illumination of the scene of about 1000 lux, when using a non-diaphragmed, normal objective with aperture $f:2$.

Comparison of different types of camera tubes

Let us now compare, briefly, the two main types of camera tubes, the high-velocity and the low-velocity types.

In the first place there is the question of sensitivity. This resolves itself into two factors (disregarding the efficiency of the optical system), viz. the sensitivity of the photocathode (photo-current I_{ph} in relation to the light flux falling on the cathode) and the sensitivity of the scanning mechanism (ratio of signal current I_s to photo-current I_{ph}):

As regards the sensitivity of the photocathode it has already been seen that of the two described representatives of high-velocity tubes — the conventional iconoscope and the image iconoscope — the latter has very much the advantage, owing to the continuity of the photocathode. Among the low-velocity tubes there are likewise types with a mosaic cathode and others with a continuous cathode, the latter including the image orthicon, which as regards photocathode sensitivity is equal to the image iconoscope.

The scanning sensitivity of low-velocity tubes (and without an important improvement to be mentioned below) can be directly determined: in these tubes the electrons emitted by the light-sensitive layer are supplemented by electrons from the scanning beam, the scanning sensitivity in this case therefore being exactly 1 μA signal current per μA photo-current. In high-velocity tubes the phenomenon of redistribution complicates matters, but from measurements taken the scanning sensitivity of the ordinary iconoscope can be put at $1/20$ th $\mu\text{A}/\mu\text{A}$ and that of the image iconoscope, with weak to moderate illumination, at about 1 $\mu\text{A}/\mu\text{A}$ (see fig. 18).

Although, therefore, the image iconoscope has about the same scanning sensitivity as the (simple)

¹⁰⁾ P. Schagen, On the mechanism of high-velocity target stabilization and the mode of operation of television-camera tubes of the image-iconoscope type, Philips Res. Rep. 6, 135-152, 1951 (No. 2).

low-velocity tube, there is a difference in the $I_s = f(I_{ph})$ curve in favour of the image iconoscope: in the case of this tube, and also the ordinary iconoscope, the said curve is not linear (see fig. 18), whereas in the case of low-velocity tubes it is linear; the non-linear curve is favourable, as explained when dealing with the iconoscope.

There is a means, however, of appreciably increasing the scanning sensitivity of low-velocity tubes. The electrons from the scanning beam which are not taken up by the target and return to the gun can be collected in a multiplier, placed around the gun, which works with secondary emission and thus multiplies them. This is what takes place in the image orthicon, the camera tube commonly employed in the U.S.A. In this way the scanning sensitivity may be raised to a value of 25 to 100 $\mu A/\mu A$, which is of course a valuable property when, for instance, scenes have to be televised in poor light (e.g. sporting events under artificial light). An inherent drawback is, however, that the current of the returning beam can be modulated only up to about 20% and consequently contains a relatively large amount of noise. More electrons return from dark parts than from light ones, so that the noise from the darker parts is both relatively and absolutely the strongest, and often very troublesome.

It has already been explained that in regard to spurious signals the image iconoscope has a decided advantage over the ordinary iconoscope. The image orthicon is free of spurious signals of this nature, but on the other hand it is subject to another interference connected with the fact that

the secondary-emitting surfaces of the multiplier do not have, exactly the same secondary-emission coefficient over the whole area ("dynode spots").

Electron-optically, high-velocity tubes have undeniably the advantage over those of the other group, in that with electrons of a high velocity it is easier to obtain a scanning beam with a high resolving power, and there is much less trouble from interfering electric and magnetic fields.

Summary. In the introduction television camera tubes are divided into two groups, high-velocity and low-velocity tubes. This article deals only with tubes of the former group, first briefly touching upon the iconoscope and then considering the image iconoscope in more detail.

Discussed in succession are the photocathode, the mechanism for the electron-optical projection, the electron gun and the target as found in the Philips image iconoscope, type 5854. Measured under the illumination from an incandescent lamp with colour temperature 2600 °K, the photocathode (Cs-Sb-O) gives an output of about 45 μA per lumen. For the formation of the electron-optical image an electric and a magnetic field are used, situated in the same space (near the photocathode) and giving a magnified replica of the photocathode image on the target. The electron gun supplies a magnetically focused and magnetically deflected scanning beam (beam-current strength normally 0.2 μA) with such a fine focus and such a focus depth that the resolving power at the middle of the target amounts to 900-1000 lines and at the edges is still 700 lines. The cathode employed in the gun is of the "L" type, which has a long life even under a high specific load. As regards the target it has been found that increasing the capacitance with respect to the signal plate gives greater sensitivity. A very thin mica sheet (25 μ) has therefore been used, coated with a thin layer of MgO in order to increase the number of secondary electrons released by the high-velocity electrons impinging on the target ($\delta > 4$).

The article concludes with a brief comparison between high-velocity tubes and low-velocity tubes, and in particular between the new image iconoscope described and the image orthicon.