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Report No. 1789

TITLE **THE MOSAIC CAMERA TUBE**
(TELEVISION PRINCIPLES — CHAPTER 2)

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STROMBERG-CARLSON TEL. MFG. CO.

Approved W. A. MacDonald

THE MOSAIC CAMERA TUBE

(TELEVISION PRINCIPLES - CHAPTER 2)

By C. E. Dean

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TELEVISION SPECIFICATIONS SELECTED

FROM THIS CHAPTER

Type of Scanning for Camera Tube	Magnetic
Illumination for Transmission of Studio Scene	1500 Foot-Candles
Representative Output of Camera Tube (Peak-to-Peak)	1 Millivolt
Camera Beam Current	0.1-0.3 Microampere
Camera Beam Voltage	500-1500 Volts
Cross-Sectional Diameter of Electron Beam at Mosaic	7 Mils
Ampere-Turns for 500 Volts and 4 Inches Deflection (Current in Peak-to-Peak Value)	90
Average Diameter of Mosaic Particles	1/5 Mil
Area of Mica Covered with Particles	40%
Total Number of Mosaic Particles	200 Million
Number of Particles under Scanning Spot	500
Photoelectric Sensitivity of Cesiated Silver in Vacuum	20-40 Microamperes per Lumen
Secondary-Emission Ratio for Cesiated Silver at 500 volts	10
Representative Value of Coupling Resistor	6000 Ohms
Thermal Noise in Coupling Resistor for 3-Megacycle Band	17 Microvolts
Minimum Signal-to-Noise Ratio	20 Approx.

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THE MOSAIC CAMERA TUBE

(TELEVISION PRINCIPLES - CHAPTER 2)

INTRODUCTION

Scope of This Chapter

In the preceding chapter of this series, Report 1776, we gave a general description of a modern television system, together with a discussion of scanning, persistence of vision and flicker. The reader is now prepared to go into various aspects of television more fully, and accordingly the present report takes up particularly the parts and operation of the mosaic type of camera tube. At the present time this kind of camera tube is the most widely used means of converting scenes into electrical signals for transmission.

Parts of the Camera Tube

In Figure 1 we show a typical modern camera tube of the mosaic type, such as used in the Hazeltine Laboratories. The design here includes a cylindrical envelope for the main part, which is a recent change from the spherical shape. The general size of the tube may be seen by noting the tube base at the lower left, which is of normal receiving-tube size, and from the fact that the main cylindrical portion of the tube has a diameter of about 7 inches. The cylindrical shape permits a better arrangement of the electron gun and the mosaic; this shape can be used with either a flat window, as shown in Figure 1, or a spherical window, thru which the image passes optically to the mosaic.

The chief parts of the camera tube are indicated in Figure 1. The electron gun consists of the cathode, grid, screen, and first anode. The second anode will be seen to consist of a conducting lining inside the portion of the tube where the deflecting coils are placed, and extending along the underside to contact with a collecting ring which goes around the tube; electrically the collecting ring is therefore part of the second anode. It will be seen that the maximum potential difference for the tube is 500 volts. Usage in this regard varies somewhat, some laboratories employing potentials as high as 1500 volts. In any case, these values are small in comparison with the corresponding figures for the picture tubes used in receivers. The deflection of the electron path, by virtue of which it sweeps over the mosaic plate, is produced by the deflecting coils which fit closely around the neck of the tube as shown.

The usual camera tube differs from all other types of vacuum tubes in having a mosaic plate, which consists of a very large number of silver particles deposited on a sheet of mica and electrically insulated from each other. On the back of the sheet of mica a conducting metallic film is deposited, and this is called the signal plate.

GENERAL OPERATION AND CHARACTERISTICS

Production of Signal by Camera Tube

The individual particles of the mosaic, that is the particles on the front side of the mica, have both photoelectric and secondary-emission sensitivity. Photoelectric sensitivity means that when light shines on a particle, electrons are given off; since electrons are negative charges, this leaves the particle positively charged. Secondary-emission sensitivity means that when electrons strike the particle with a fair speed, additional electrons are "splashed" out of the particle; if the speed of the incident electrons is sufficient, the number of electrons leaving in this way will greatly exceed the number of incident ones. In this way the secondary-emission sensitivity of the particles of a camera mosaic causes them to experience a net loss of electrons when bombarded by the scanning beam. This secondary emission thus operates to make the particles assume a more positive potential. We see therefore that both incident light and the incident fast electrons of the scanning beam cause the mosaic particles to assume positive charges.

The scene to be transmitted is focussed on the mosaic by means of the lens. Each particle of the mosaic then gives off

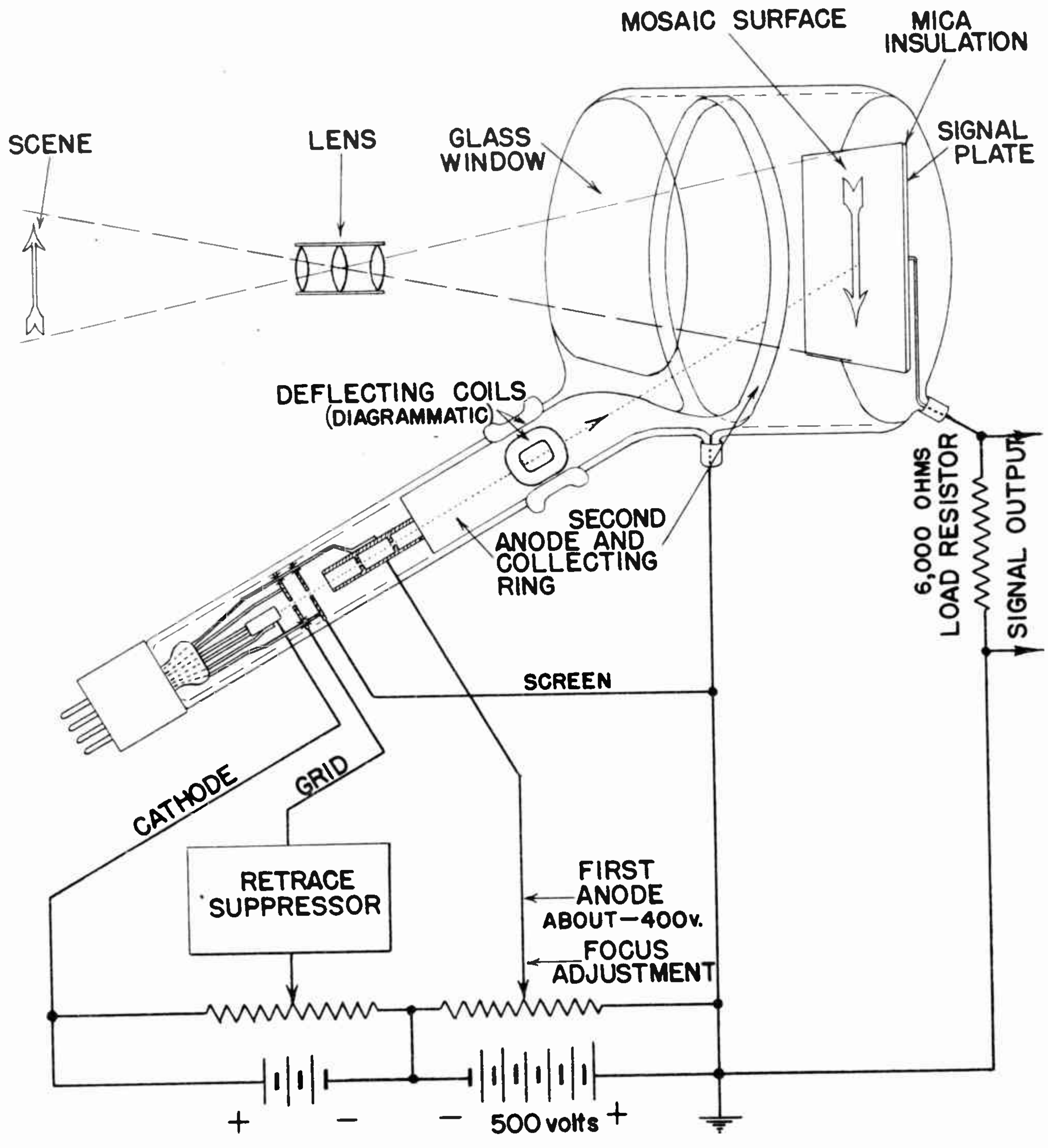


Fig. 1. Mosaic Camera Tube and Connections.
(Tube Connections thru Base Shown
Direct for Clarity)

electrons as a result of the photoelectric character of the surface, and the extent to which this occurs depends on the illumination at the particular point. The brighter portions of the mosaic assume in this way more positive potentials than the darker portions.

Some of the electrons produced by the photoelectric action and by secondary emission go to the collecting ring and thus complete the circuit which includes the high-voltage battery and the scanning beam of electrons. However, most of the electrons which leave the mosaic due to the photoelectric and secondary-emission actions return to the mosaic as a "gentle rain" of low-velocity electrons. The velocity of these electrons is too low for them to produce secondaries, so they add negative charge to the portions of the mosaic where they strike. This rain of electrons on the various particles therefore opposes the positive-charge effects of photoelectric and secondary-emission activity. The overall result is that just before being scanned the most intensely illuminated portions of the mosaic have a potential about equal that of the signal plate and collecting ring, while dark portions of the mosaic have a potential of about 1.5 volts negative. Portions of the mosaic where the shade of the scene is intermediate have, of course, potentials between zero and -1.5 volts.

Let us now consider the action of the scanning beam. The effect of this is to establish a definite potential for the successive regions which it strikes; this potential has a value of about 3 volts positive. This one value of potential is obtained regardless of the light or dark condition of the particular part of the mosaic, that is, regardless of the original potential of this part of the mosaic. This action is shown in Figures 2(A) and 2(B) for a case where the left half of the mosaic is illuminated and the right half is dark. It will be seen therefore that the amount of change of potential of each portion of the mosaic is dependent on the light on this part; this is shown in Figure 2(C).

Each portion of the mosaic is capacitively coupled to the signal plate thru the mica. Therefore the change of potential of each portion of the mosaic, as it is scanned, induces electrostatically a corresponding change of potential on the signal plate. In this way the desired video signal voltages are obtained across the 6,000-ohm load resistor of the camera tube. This is an alternating-current wave, that is there is no direct-current component, and it is shown in Figure 2(D) for the simple image we have been considering.

This explanation accounts for the main action of the camera tube. However, it is well to realize that the discussion is simplified by the omission of various topics; in particular, the subjects of keystone correction, shading effect, and surge are deferred to appropriate positions in later sections.

Characteristics of Camera Tube

Three characteristics of the mosaic camera tube are evident from the description in the foregoing paragraphs. First, there is a cumulative or storage action in that light falling on any portion of the mosaic has a relatively long time for the ejection of photoelectrons and the establishment of the potential of this portion of the mosaic while the scanning spot is passing over other portions. In particular, the relatively long time of almost 1/30 second, the frame period, is employed in this way. This storage feature accounts for the improved sensitivity of the device in comparison with mechanical scanners where very much shorter lengths of time are available, in particular only the time required to scan one picture element.

An interesting result of the storage feature is that the mosaic has a "memory". It may be illuminated momentarily and then be scanned in darkness; in this case a satisfactory picture is obtained, and in fact this method is used for transmitting motion-picture film by television. The necessity for this type of operation in transmitting film with the mosaic tube arises from the fact that the intermittent mechanism in motion-picture projectors cannot operate fast enough to change frames during the field retrace; the normal intermittent mechanism for 35-millimeter film requires about 1/4 x 1/24 second, or 1/96 second for its action,

FIG. 2 (A)
APPEARANCE
OF
MOSAIC

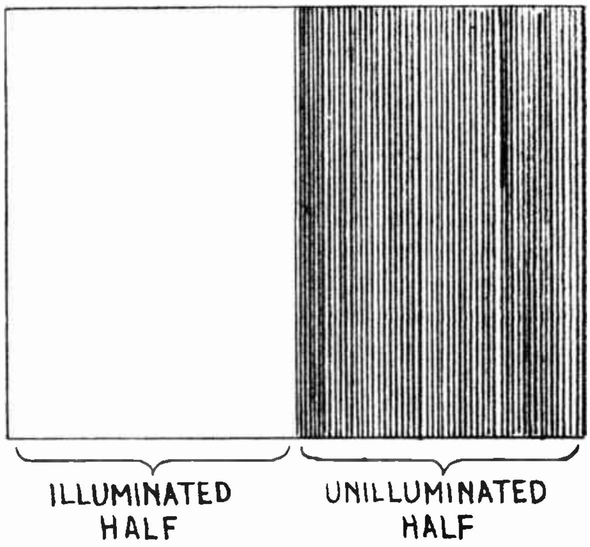


FIG. 2 (B)
POTENTIAL
OF MOSAIC
PARTICLES.

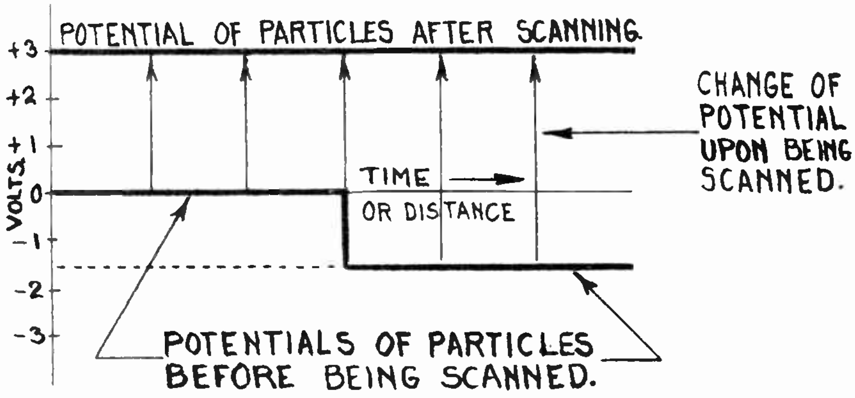


FIG. 2 (C)
CHANGE OF
POTENTIAL
OF PARTICLES
WHEN SCANNED.

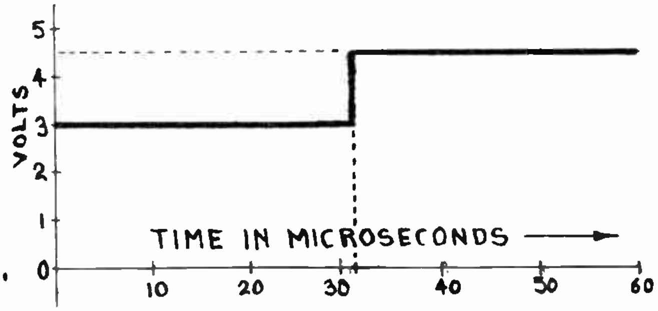


FIG. 2 (D)
POTENTIAL
OF SIGNAL
PLATE.

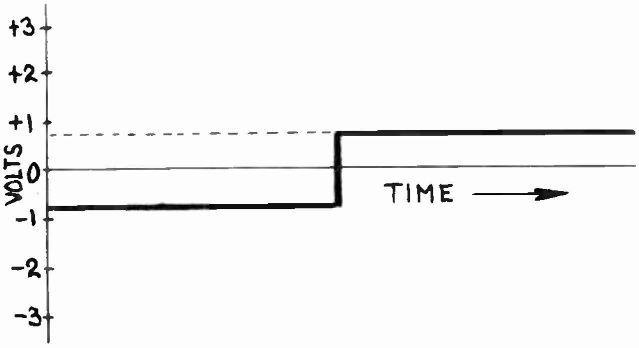


Fig. 2. Production of Signal by Mosaic Camera Tube.

whereas the field retrace lasts only 1/10 x 1/60 second, or 1/600 second.

A second characteristic of the camera tube which may be seen from the description which is given above, is that the output signals contain no direct-current component. This is evident from the fact that the output terminal connects internally only to the signal plate which is insulated by the mica and by air from all other parts. This capacitive coupling naturally prevents any flow of direct current such as would be necessary to maintain a direct-current voltage across the 6,000-ohm load resistor. For this reason the camera tube itself gives only an indication of change in brightness between parts of the scene; there is no indication of the reference level. The camera tube therefore does not give an indication of the average scene brightness, and other apparatus is required for this purpose.

The third characteristic of the camera tube which may be seen from the description of its action is that the output signal has a negative polarity. We have seen in Figure 2(D) that for illuminated points the camera tube produces a negative output voltage on the signal plate, and that for dark points it produces a positive output voltage. This polarity of a video signal is called negative, whence the statement that the mosaic camera tube produces a signal of negative polarity.

The general sensitivity of the mosaic tube is comparable to that of motion-picture cameras. For indoor scenes fairly intensive light is required for satisfactory operation in either case. With the usual studio scene, an illumination of 1500 foot-candles is representative; this gives the scene a brightness of about 40 candles per square foot. Light from the scene passes thru the lens and produces an illumination on the mosaic itself of about 5 foot-candles. Under these conditions a signal output of about 1 millivolt is obtained from the camera tube, and a good picture is seen on the receiver. For satisfactory reproduction the minimum signal from the camera tube which can be used is about 1/3 of a millivolt.

DESCRIPTION OF PARTS

Electron Gun of Camera Tube

An electron gun is provided in the usual camera tube, such as shown in Figure 1, and also in the cathode-ray picture tube employed at the receiver. The function of the gun is to shoot out a beam of electrons for scanning the mosaic or the fluorescent screen. The beam, however, must converge to a very small point where it strikes, since otherwise the sharpness of definition will be impaired. The gun must have a suitable design to produce the electrons and also to control the number of them. In particular the electron gun of a camera tube must cut off the electron beam entirely during the field retrace interval, and in a picture tube it must cut off the beam during both field and line retraces and also control the number of electrons in accordance with the video signal while the reproduction of each line is taking place. The scanning of the electron beam from the gun is accomplished by electrostatic plates or magnetic deflecting coils. In the case of electrostatic scanning, the plates may be mounted on the gun and can then be considered to be part of the gun. For magnetic scanning the coils are outside the tube and therefore considered to be separate from the gun.

In a camera tube the electron gun is located in an auxiliary neck as shown in Figure 1. The angle between the neck and the optical axis, which is perpendicular to the mosaic plate, is 30 degrees. A gun for camera use must have a "depth of focus" of about 2 inches, since the distance from the gun to the center of the lower edge of the mosaic plate is shorter by about this amount than the distance from the gun to an upper corner of the mosaic plate. This depth of focus is obtained by making the various electrons in the beam have paths which intersect at about the average distance to the mosaic, and which differ in direction by only a very small angle. The amount of current required in the electron beam of a camera tube is small, usually 0.1 to 0.3 microampere. The focusing, that is the electrical operating adjustment to obtain the necessary small size of spot, is made by variation of a direct-current potential, and in Figure 1 it may be seen that the potential of the first anode is adjustable for this purpose. The parts of electron guns may be advantageously made of non-magnetic metal in order to prevent erratic effects from magnetization.

The electron guns of picture tubes differ from those in camera tubes because of the marked difference in operating requirements. In the picture tube a high degree of spot brightness is desired, whence much higher current and voltages are used; also there is no depth-of-focus requirement since all parts of the fluorescent screen are equally distant from the gun. The result of these different conditions is that guns for picture tubes have larger apertures and different spacings of the electrodes from camera guns.

Electron guns may be made with various numbers of electrodes, the different types being somewhat comparable to triodes, tetrodes, pentodes, etc., in the family of ordinary vacuum tubes. The design in Figure 1 has given successful performance in the Hazeltine Laboratories, and includes a grounded electrode with an aperture located between the control-grid aperture and the first anode. This electrode has a position corresponding to the screen of a tetrode, and for this reason is also called a screen. The control grid will be seen to consist merely of a plate with a central aperture. During the field retrace interval a negative potential of about 8 volts with respect to the cathode is applied to this grid by the retrace-suppressor circuit, and cuts off the electron beam. It has not been found necessary to suppress the beam during the line retrace interval.

The necessary sharpness of focus of the beam of a camera gun can easily be computed. If the height of the used portion of the mosaic is taken as 3 inches, and this is divided into 400 horizontal lines, the width of each line will be found to be 7.5 mils. However, the diameter of the electron beam must be smaller than this on account of the angle at which the beam strikes the mosaic plate. Upon multiplying 7.5 mils by the cosine of 30 degrees, to take this effect into account, we obtain a figure of 6.5 mils, which in round numbers we will call 7 mils. We use the figure of 400 lines in this computation instead of 441 in order to allow a loss of 10 per cent of the lines during the vertical retraces.

The study of electron guns, by which electrons proceeding from a cathode in various directions may be brought to a final sharp focus, has brought out a close resemblance to the focusing of rays of light from a source; from this analogy, the term "electron optics" has been introduced as a name for this branch of applied physics. By suitable arrangement of concentric cylinders, having different sizes and operated at different potentials, it is possible to make electron paths converge or diverge in the same way that rays of light are made to converge or diverge by suitable lenses. Focal lengths can be derived in electron optics having similar significance to the focal lengths of glass lenses in ordinary optics. One point of interest in electron optics is that the focal lengths of a system of two cylinders, when expressed in terms of the gun diameter as a unit of length, depend only on the ratio of the two voltages and on the ratio of the diameters of the two cylinders. The gun diameter here is the diameter of the first cylinder, which is always smaller than the second. Such an electron lens is included in the tube of Figure 1 at the point where the first anode stops and the second anode begins.

Deflecting Coils for Camera Tube and Keystone Correction

The beam of electrons produced by the electron gun in the camera tube is deflected horizontally and vertically for scanning by means of suitable magnetic fields. These are produced by coils placed around the neck of the tube near the point of attachment. The electron beam must be deflected vertically 60 times per second, or once for each field of interlaced scanning. The horizontal deflection of the beam must take place at a rate of 441 lines for each of the 30 frames or 441 x 30 = 13,230 lines per second. This is, of course, equivalent to 220-1/2 lines per field.

The number of ampere-turns (where the amperes are peak-to-peak of the sawtooth wave), with an air-core design, to scan a camera or picture tube having a neck of 1.5 inches diameter is given approximately by the following formula:

$$F = 8W\sqrt{V}/D\ d,$$

where F is the desired magnetomotive force in peak-to-peak ampere-turns, W is the total width of the desired deflection in inches on the mosaic or screen, V is the beam drop in volts, D is the distance in inches along the beam from where it enters the magnetic field to where it strikes the mosaic or screen, and d is the length in inches of the coil window along the neck of the tube. As an example of the use of this formula, we find that a four-inch deflection of a camera tube, with 500 volts and distances D and d of 8 inches and 1 inch respectively, requires about 90 ampere-turns. In case a camera tube rated at 1000 volts is to be scanned, other quantities being the same, the number of ampere-turns will be 40 per cent greater, or about 130 ampere-turns.

As a representative design for a 500-volt camera tube, the two coils for the horizontal deflection may each consist of 350 turns of #36 double-silk-covered wire having a series-aiding inductance, measured as in use, of 20 millihenries. The windows measure 1 inch along the neck of the camera tube and 1-3/4 inches around the neck of the tube. The depth of winding is 1/16 inch. The current thru these coils, stated as peak-to-peak, may be 120 milliamperes, corresponding to 84 ampere-turns.

It is necessary to arrange the deflecting coils so as to avoid magnetic coupling between them, and in addition it is necessary to provide an electrostatic shield between them. These results are accomplished in practice by assembling all the coils into a scanning yoke thru which the neck of the tube is passed. In such a yoke the electrostatic shielding may be obtained by having the line deflecting coils next to the neck of the camera tube, then an electrostatic screen outside these coils, then the field deflecting coils outside this shield, and then a final electrostatic shield outside of the field deflecting coils. The shields are of course grounded.

The two coils for the vertical deflection may each have 2000 turns of #38 double-silk-covered wire. These are connected series-aiding and have a total inductance of the order of one henry. The windows of these coils measure 3/4 inch along the neck of the camera tube and 2-1/4 inches circumferentially. The saw-tooth wave of field scanning current may have a peak-to-peak value of 15 milliamperes. The peak current, measured from the alternating-current axis thru the center of the saw-tooth wave has of course a value of half this amount.

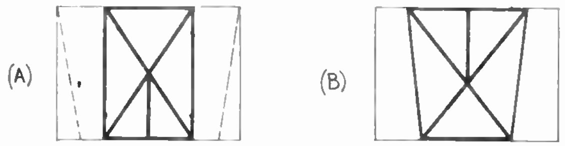
The use of laminated iron in scanning yokes has been found to give little improvement in performance and to make the design and construction considerably more critical. Powdered-iron cores, however, are not open to these objections, and are a means of lowering the reluctance of the magnetic circuit. These points are of chief interest in the scanning of picture tubes in television receivers and will be considered further in the appropriate later chapter of this series. At the present time it is sufficient to note that deflecting yokes for picture tubes are considerably different from those for camera tubes. One point of difference is that more ampere-turns are required for picture tubes; another point is that a transformer is sometimes used in receivers so as to operate with fewer turns and larger scanning current.

The deflecting coils and their saw-tooth current supply must produce a magnetic field which changes almost exactly linearly with time during the main scanning portion of the cycle. If this requirement of linearity is not met sufficiently closely, the received picture will be impaired. For example, a fault in the line-scanning linearity may make a man walking across the scene change from lean to fat. A fault in the vertical linearity may make a man of normal proportions appear long-faced and pot-bellied.

In the above discussion of magnetic scanning of the camera tube we refer to "saw-tooth" waveforms, but strictly speaking this has to be qualified on account of the fact that the mosaic plate is not perpendicular to the scanning beam. If no preventive measures were taken, the width of the scanned area would be wider at the top of the mosaic than at the bottom, as shown by the dashed lines in

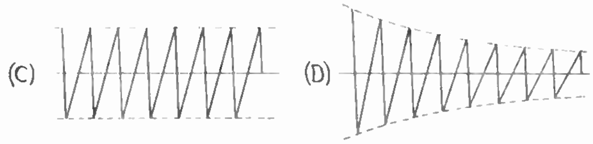
Figure 3(A). A rectangular figure on the mosaic would then be reproduced at the receiver with a prominent keystone appearance, as shown in Figure 3(B). The phenomenom is therefore called "keystone error", and its prevention by suitable means is called "keystone correction".

Some further explanation of Figures 3(A) and 3(B) will be of interest. The original scene is not shown; this consists of a rectangle, taller than it is wide, with diagonals and with a vertical line in the upper portion. The lens of the television camera inverts the picture in projecting it onto the mosaic and also exchanges the left and right sides. This inversion causes the picture on the mosaic to look as in Figure 3(A). Since at the receiver the scanning is to be reproduced from top to bottom and from left to right, as one reads a book, it is necessary in scanning the mosaic that the field scanning should proceed gradually up the mosaic from the bottom and that the line scanning should proceed across each line from right to left. In this way a second inversion takes place between the camera and the receiver, and the picture is finally seen right side up. The side of the rectangle along the top of the mosaic in Figure 3(A) has a length equal to half of the scanning line, but the side of the rectangle along the bottom of the mosaic is more than half a scanning line in length because here the scanning line is shorter. This latter is the side having the perpendicular to the center of the rectangle, and it is seen to be reproduced as a longer line in Figure 3(B).



ILLUMINATED MOSAIC (AREA OUTSIDE DOTTED LINES NOT SCANNED UNLESS KEYSTONE CORRECTION USED.)

REPRODUCTION WITHOUT KEYSTONE CORRECTION



UNCORRECTED LINE-SCANNING WAVEFORM ENVELOPE.

CORRECTED LINE-SCANNING WAVEFORM ENVELOPE (EXAGGERATED)

UNCORRECTED FIELD SCANNING WAVE FORM.

CORRECTED FIELD SCANNING WAVEFORM. (EXAGGERATED)

Fig. 3. Keystone Correction with Camera Tube.

For keystone correction, the angular sweep of the scanning beam for the successive lines, as the beam proceeds up the mosaic, must decrease in order to scan a rectangular area on the mosaic plate. This result is accomplished in the scanning generator, used to supply the line scanning current for the camera tube, by modulating the line scanning current with the field scanning current; in this way the successive saw-tooth impulses for line scanning are gradually reduced in amplitude as the scanning spot approaches the top of the mosaic, so that the length of the scanning line on the mosaic remains constant as the spot scans successive lines from bottom to top. The diagrams of Figures 3(C) and 3(D) show this correction of the amplitude of the line scanning.

There is another effect associated with keystone correction. This is the unequal spacing of the scanning lines which will occur if the scanning spot moves vertically upward at a uniform angular rate. It will be seen in fact that if the lines are correctly spaced at the center of the mosaic, they will be too close together at the bottom and too far apart at the top. For this reason it is desirable to avoid the use of a wave having a strictly saw-tooth shape for the field scanning. Instead, the field scanning current, as shown in exaggerated form in Figure 3(F), must rise slightly more rapidly at the start than for a saw-tooth waveform, in order to spread out the lines at the bottom of the mosaic which would otherwise be too close together; the upward progress of the scanning spot then continues at a gradually declining rate so as to avoid leaving greater spaces than desired between the scanning lines in the upper part of the mosaic. Theoretical and practical study of the subject has led to the conclusion that the waveform should depart from linearity slightly and have approximately a shape given by $A(1-e^{-Bt})$.

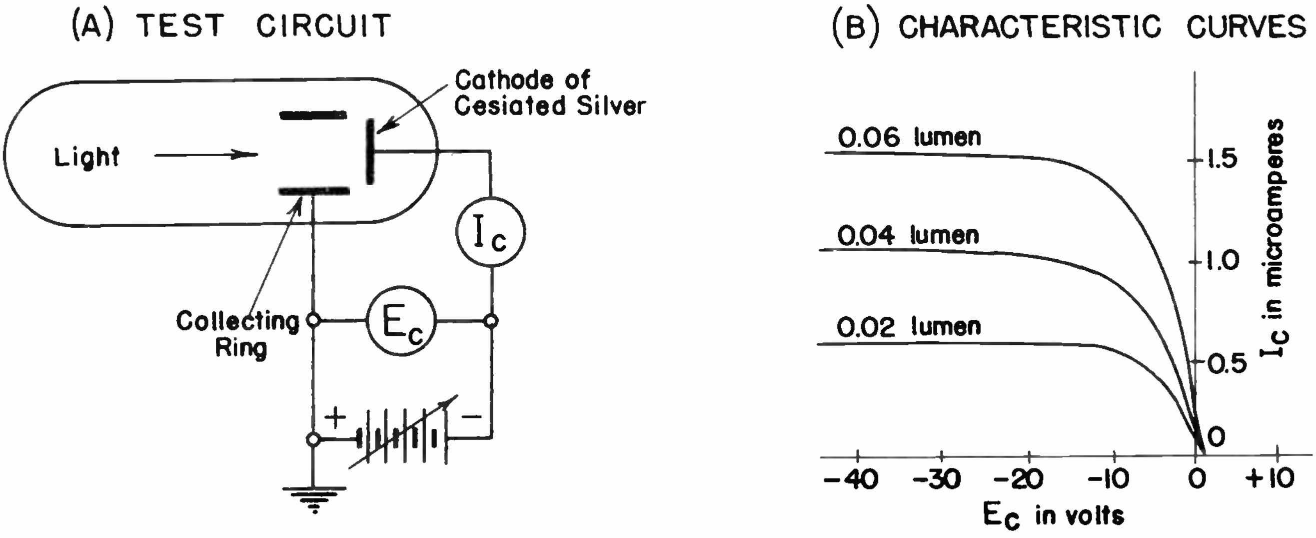
In visualizing this control of the line spacing by the field scanning waveform, it is well to bear in mind that the desired relation between lines is a uniform spacing with just the proper room between the lines to accommodate the lines of the next field; in this way proper interlacing is obtained.

The Mosaic

The mosaic on the front side of the mica insulator consists of a great number of separate silver particles, which may be seen on a mosaic that is not inside a tube by using a microscope giving moderate magnification. The size of the particles varies, but 1/5 of a mil may be taken as a representative value for the diameter of one particle. The number of particles is controlled in making the mosaic so as to cover about 40 per cent of the area of the mica. From these figures we may obtain the result that a mosaic with dimensions of 3.6 inches by 4.8 inches has a total of about 200 million silver particles.

It is of interest to consider the number of particles of the mosaic which are struck by the scanning beam at a given instant, that is the number of mosaic particles which lie within the elliptical area occupied by the scanning beam on the mosaic at a given moment. As mentioned above on page 28, this ellipse has a maximum diameter of 7.5 mils. As a satisfactory approximation we may say that the area of this ellipse is equal the area of a circle with a diameter of 7 mils. The ratio of spot diameter to particle diameter is then 7/0.2, or 35. The square of this ratio is about 1200, so that if the particles covered the entire mosaic there would be 1200 of them under the scanning spot. However only 40 per cent of the area is covered by particles, so we may say that as a representative figure, 500 mosaic particles are struck by the scanning beam at one instant.

It will be realized that if the discontinuous nature of the mosaic were very prominent, there would be appreciable fluctuations in the output-signal waveform as the scanning spot struck each new particle in its forward motion and as it left each particle; this would result in noise. However, a study of this subject has led to the conclusion that if the scanning spot covers 15 or more particles, noise due to this cause will be inappreciable. The figure of 500 shows therefore that there is no problem of noise due to the discontinuous nature of the mosaic surface. As a theoretical matter, such noise having frequencies far above any of interest must


(A) TEST CIRCUIT

(B) CHARACTERISTIC CURVES

Fig. 4. Photoelectric Characteristics of Cesium-Silver-Oxide Surface.

be produced; the electron beam scans the silver particles at a rate of 35 billion per second.

The preparation of the mosaic in making a camera tube consists of a number of steps, the first group of which produce the silver globules, and the second group of which sensitize the globules to increase their photoelectric and secondary-emission sensitivities. The first step is to dust the mica with very fine silver-oxide powder; this is then heated in a furnace, whereupon the silver oxide is chemically reduced to silver; this may be made to form in the desired separate droplets. Repetitions of this process may be made until 40 per cent of the area of the mica is covered by the droplets. The coverage after each treatment is measured by noting the optical transparency; at the end the transparency is 60 per cent of the value for the clear mica at the beginning. All these operations are performed before the mica is placed in the camera tube.

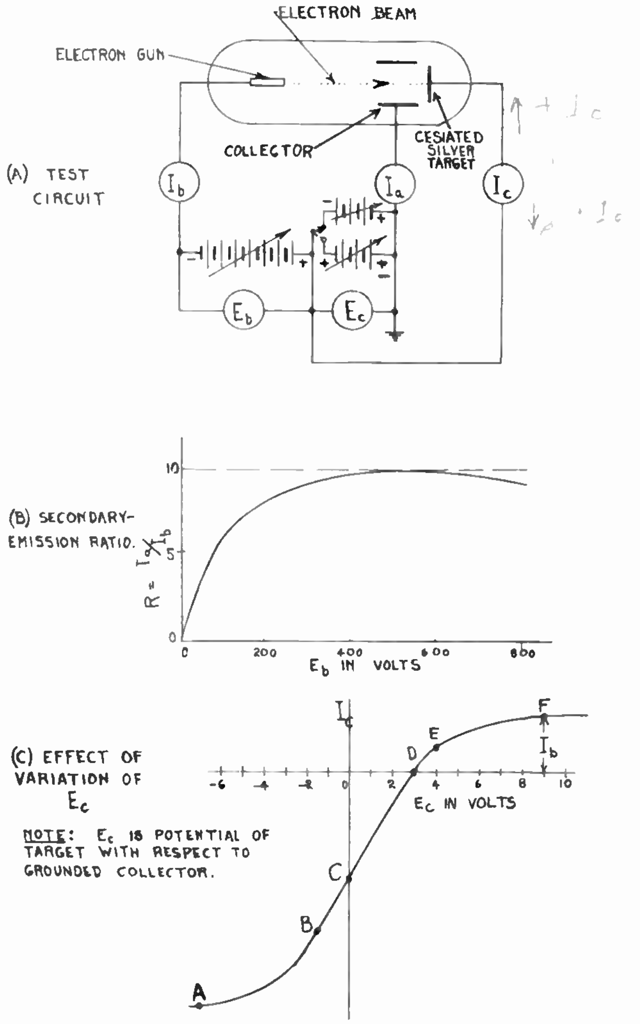


Fig. 5. Secondary-Emission Characteristics of Cesium-Silver-Oxide Surface.

The sensitization procedure is carried out after the tube is assembled, and is a cesium process similar to that generally used with photoelectric cells. After the tube is completed, the scanning beam must not be allowed to remain on one spot, since it would disturb the conditions at this spot in regard to the cesium sensitization. The scanning voltages must therefore always be operating when the beam is turned on.

The capacitance between the mosaic particles and the signal plate can be computed from the dielectric constant of mica, which is 7.3, and the thickness of the mica, which is in the neighborhood of 1 or 2 mils. For dimensions of 3.6 by 4.8 inches and a thickness of about 1.3 mils, the total capacitance is 10,000 micro-microfarads, or about 600 micro-microfarads per square inch. In this computation account is taken of the fact that only 40 per cent of the area of mica is covered with silver particles. Generally it is advantageous for the reduction of shading to avoid using the edge of the mosaic area; for example the used portion may measure 3 x 4 inches. The capacitance for this area is of course less than for the entire mosaic. Taking the scanning spot to be a circle of 7-mil diameter, the capacitance to the mosaic is 0.02 micro-microfarad.

PHOTOELECTRIC EFFECT AND SECONDARY EMISSION

Photoelectric Effect

The phenomenon known as the photoelectric effect consists in the emission of electrons by metals when illuminated. Some metals exhibit the effect only if the light has a wavelength in the ultra-violet region. Other metals will respond to either visible or ultra-violet light. In a high vacuum the number of photo-electrons given off in unit time is always accurately proportional to the intensity of the light.

We are particularly concerned with the photoelectric characteristics of the cesiated silver surface used in camera tubes. In Figure 4(A) there is shown a circuit for measuring photoelectric characteristics, and in Figure 4(B) a family of curves giving typical results for the conditions of surface and electrode arrangement as found in camera tubes. The collecting ring is grounded in accordance with the grounding of the collecting ring of a camera tube. It will be seen that the larger the battery in Figure 4(A), the more negative will be the cathode of the tube, and the more vigorously it will repel the photoelectrons which are emitted.

In Figure 4(B) it will be seen that with a given illumination, more negative potentials on the cathode cause increasing values of current until a limiting value is reached. This limiting value is encountered because all the electrons emitted by the light are then drawn to the collecting ring. This phenomenon is called "saturation", and under these conditions the cell can be said to be operating at photoelectric saturation. The intensity of the light for each curve is stated in lumens on the basis of a standardized source of light consisting of a tungsten filament operating at 2870 degrees Kelvin. It may be seen that an illumination of 0.04 lumen gives a saturated current very close to 1 microampere, from which a sensitivity value of 25 microamperes per lumen is obtained. Values from 20 to 40 microamperes per lumen are representative of cesiated silver cathodes.

We have seen above on page 25 that the various portions of the mosaic of the camera tube assume potentials from 0 to -1.5 volts with respect to the collecting ring, the value at each point depending on the illumination. These values of potential are small in comparison with what would be required to produce photoelectric saturation. From Figure 4(B) it may be seen that potentials of 7 to 15 volts are required to approximate the saturated condition, the particular value depending on the illumination. In the mosaic camera tube this absence of photoelectric saturation causes a reduction of sensitivity to about 1/5 of what would otherwise be obtained. There is also a similar loss of sensitivity due to the absence of secondary-emission saturation, which is discussed in the following section. These two effects combine to give the tube an overall sensitivity of only 5 or 10 per cent of what it would otherwise have. These losses are serious, but the storage feature of the mosaic tube is such a substantial advantage that at the present time this type of tube is the most widely used pick-up device.

Secondary Emission

When electrons strike a metal surface with sufficient velocity they "splash out" other electrons. The ejection of electrons by metal under such bombardment is called secondary emission. We give in this section a discussion of secondary emission on account of its importance in the operation of the camera tube. In Figure 5(A) we show schematically a tube like that of Figure 4(A) except that an electron gun has been added. The conditions are the same as in Figure 4(A) except that the illumination of the cathode has been removed and instead the cathode or target is bombarded with a beam of electrons from the electron gun. Again we ground the collector to simulate camera-tube practice, and adjustable batteries are provided to give various values of E_c, the potential of the target with respect to the grounded collector. The voltage E_c, which we will now vary in polarity as well as amount, obviously determines what proportion of electrons leaving the target go to the collector and what proportion return to the target.

The battery supplying voltage E_b in Figure 5(A) is connected between the electron gun and the target, and therefore determines the voltage drop thru which the electrons of the beam fall. Since the velocity with which any electron strikes a target is dependent only on the difference of potential thru which it has fallen, the value of E_b determines the velocity of the electrons striking the target; these electrons are the "primaries", that is they are the ones which, upon impact, produce the "secondaries" by secondary emission. The number of secondaries produced by one primary electron depends on the velocity of the primary electron and also on the character of the surface. This number is obviously equal to the ratio of the secondary-emission current to the primary current; we call this secondary-emission ratio $\underline{R}$, and in Figure 5(B) it is plotted as a function of E_b, the voltage drop between the electron gun and the target. In taking this curve the value of E_c was negative (switch up) and large enough so that all the secondaries produced at the target were repelled and proceeded to the collector. It will be seen that numerical scales are given in Figure 5(B) for both the abscissas and ordinates; the curve gives representative values of the secondary-emission ratio for a cesium-silver-oxide surface.

The decline in the value of the secondary-emission ratio shown in Figure 5(B) for voltages above about 500 volts is considered to be due to the primary electrons penetrating so deeply into the target that some of the secondaries cannot escape. This downward trend of the curve continues until at a very high voltage in the neighborhood of 10,000 volts the secondary-emission ratio falls to unity. A point of interest is that at about 500 volts the secondary-emission ratio has a maximum value in the neighborhood of 10 which is effective in the operation of the usual camera tube.

The scales in Figure 5(B) do not permit accurate reading at very small voltages, so we will state that the secondary-emission ratio is unity at about 10 volts. This has the important significance that electrons striking this surface with velocities greater than 10 volts produce more secondaries than the number of primaries, giving the surface a positive charge; vice versa, electrons with velocities of less than 10 volts striking this surface produce fewer secondaries than the number of primaries, and give the surface a negative charge.

Another point of special interest is that the secondaries produced by secondary emission have mostly very low velocities in the neighborhood of a value corresponding to a fall thru 3 volts of potential difference. A few of the primary electrons are reflected and retain their original velocity. Since the great majority of the electrons coming off have very low velocities, when they fall upon adjacent regions of the mosaic of the camera tube they give these regions negative charges. This is important because it accounts for the loss of sensitivity described above on page 33.

In Figure 5(C) we show the effect of varying the collecting voltage while keeping the gun voltage constant. The velocity of the primary electrons and the secondary-emission ratio are constant since these are independent of the collector voltage. All the values of the collector voltage are small in comparison with the gun voltage, and for this reason the beam current may also be considered constant. In Figure 5(C) values of the target current I_c are plotted for various collecting voltages E_c. At point A at the lower left of this curve, the voltage E_c is sufficiently negative so that the target repels all secondary electrons, and they all proceed to the collector; this was the condition in Figure 5(B) for observation of the secondary-emission ratio. The only electrons striking the target under these conditions are those in the primary beam which arrive at high velocities. The condition here is described as saturated secondary emission, meaning that all the secondary electrons are collected. The electrons striking the target constitute a current I_b, and those leaving it amount to RI_b, where $\underline{R}$ is the secondary-emission ratio; the net current in the target connection is therefore the difference between these two quantities, namely

$$I_c = RI_b - I_b = (R - 1)\, I_b.$$

Physically it may be noted that the flow of electrons thru the microammeter where I_c is measured, is upward in the drawing, these electrons proceeding to the target in order to replace those lost thru the secondary-emission effect.

At point B in Figure 5(C) the negative voltage on the target with respect to the collector has been considerably reduced although it is still negative in sign. Under these conditions a space charge comes into existence and some of the secondaries produced at the target return to the target instead of going to the collecting ring. These electrons are therefore not lost by the target, and do not have to be supplied by the battery E_c, whence the current I_c is less than at point A. Point B is of interest because in the camera tube a potential of about this value is assumed by dark portions of the mosaic before being scanned.

At point C the potential E_c is zero; the collector and the target are at the same potential, namely ground, and about half of the secondaries return to the target. This point is of interest in connection with normal camera-tube operation because intensely illuminated portions of the mosaic in the camera tube assume a potential of about zero before being scanned.

We now reverse the polarity of the battery supplying the E_c voltage by moving the switch from its upper to its lower position, so that for points D, E, and F, the target is positive with respect to the collecting ring. This of course increases its tendency to recapture electrons which have escaped from the surface. Point D in Figure 5(C) is where I_c is zero, that is there is no current in the external target lead. This condition will be seen to occur at a point where the target is about 3 volts positive with respect to the collector, or in other words the collector is 3 volts negative with respect to the target. This retarding potential of 3 volts, which equals the value we have already noted as the predominant velocity of emitted secondary electrons, prevents the great majority of them from reaching the collector. Those which do reach the collector are just equal in number to the electrons constituting the primary beam, so that the collector current I_a is equal to the beam current I_b. This point D is of special interest because it represents the condition which mosaic particles reach while the scanning beam is upon them. These particles assume the equilibrium potential of +3 volts because at this potential the number of electrons escaping just equals those arriving in the beam. In this way the current I_c is zero, corresponding to the insulated mosaic particles.

At point E the positive voltage on the cathode is so high that most of the secondary electrons return to the target.

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TABLE I. ELECTRICAL CONDITIONS AT VARIOUS POINTS ON CURVE OF FIGURE 5(C)

Point	Approx. Potential E_c	Target Current I_c	Collector Current I_a	Remarks
A	-6 Volts	$(R-1)\ I_b$	RI_b	Saturated secondary emission; all secondaries collected.
B	-1.5	I_c and I_a less than for Point A.		Collection limited by space charge; this is potential corresponding to dark mosaic points before scanning.
C	0	I_c and I_a less than for Point B.		Potential corresponding to bright mosaic points before scanning.
D	+3.0	0	I_b	Potential corresponding to all mosaic particles at end of scanning.
E	+4	Opposite direction and slightly less than I_b.	Small	Positive potential on target causes recovery of most of secondaries. Only fast secondaries go to collector; since these are less than I_b, sign of I_c is reversed.
F	+9	Still opposite direction; magnitude equal I_b.	0	All secondaries return to target. No secondaries collected.

Those collected by the collecting ring are fewer in number than those in the electron beam. There is therefore a net gain of electrons by the target, and there is a downward flow of these electrons thru the microammeter which reads the I_c current. The direction of I_c is therefore opposite to that at points A, B, and C.

At point F the positive voltage on the target is sufficiently large to recover all of the electrons which are given off by secondary emission; no electrons reach the collector, so that I_a is zero. It is obvious that I_c equals I_b and point F is indicated in Figure 5(C) as having an ordinate of I_b. This point F is the extreme opposite of saturated secondary emission; this is where no secondaries whatever are collected by the collecting ring. The conditions at the various points in Figure 5(C) are listed in Table I.

Characteristic Curve of Camera Tube

We have dealt particularly with the secondary-emission characteristic in Figure 5(C) because a curve of this kind can be taken as the characteristic curve of a camera tube. Let us suppose that a condenser is connected in circuit in the target lead in Figure 5(A); this makes the target an insulated conductor like a particle of the mosaic. The current I_c can now only be a charging current, whose duration is, of course, short. Under these conditions a curve such as Figure 5(C) can represent the potentials and charging currents of the mosaic particles. In Figure 6 we show several such curves for various beam voltages and currents.

At this point it is well to emphasize one matter which we have already suggested, namely the acquirement of equilibrium potentials by the mosaic particles under various conditions. As a general statement, any insulated conductor subjected to the acquirement and loss of electrons must assume an equilibrium potential such that the number of electrons lost in a given time equals the number acquired. For example, if the acquisition initially exceeds the loss, the potential will change in the negative direction, thus discouraging further acquisition and encouraging the loss of electrons, until such a potential is reached that the gain and loss are equal, or in other words the net gain is zero. We see therefore that any inequality between electrons gained and lost is self-correcting by virtue of a change of potential until equilibrium is reached. This rule is immediately applicable to the mosaic particles of the camera tube which are insulated conductors. While not being scanned, these particles lose photoelectrons and gain electrons from the general rain; while being scanned they also gain primary electrons and lose secondary electrons. The result is that while not being scanned, the particles assume equilibrium potentials between zero and -1.5 volts depending on the illumination; and while being scanned, the particles assume a potential of +3 volts. At the moment of scanning the particles change quickly from the zero or negative equilibrium value to the +3 volts equilibrium value.

It is seen therefore that the mosaic particles before being scanned are at equilibrium potentials and the charging current is zero; their condition is represented in Figure 6 by points P_1, P_2, P_3, O, and the intermediate points, the particular point depending in each case on the illumination.

During the scanning operation, the mosaic plays the part of the target in the analysis of secondary emission, and there is an attraction or repulsion of the secondaries according to the potential of the point. The result of this process is that the point quickly arrives at the equilibrium value of +3 volts. To follow the action more closely, let us consider a dark point of the mosaic. Just before being scanned this has a potential of -1.5 volts as shown at P_1. At the moment that the scanning beam reaches it, it gives off secondary electrons constituting such a current that we move on the chart of Figure 6 from point P_1 to point B_1. Further loss of secondaries makes the potential more positive and the current less in magnitude, so that we progress rapidly thru points B_2, B_3, and C until the equilibrium value at point D is reached.

As soon as the scanning beam has passed on, the positive charge at the point attracts stray electrons, assumes their negative charge, and returns to its unscanned value between O and P_1, the particular point depending on the illumination. The succession of potentials and charging currents during this storage portion of the cycle is shown diagrammatically in Figure 6 for the four values of illumination which we have been considering. For the brightest points of the mosaic the complete cycle is thru points O, C, D, and back to O. For mosaic points of intermediate brightness, the intermediate cycles starting at P_2 and P_3 are, of course, representative.

From this analysis it may be seen that the charging current accompanying the scanning of a mosaic spot is represented by the ordinates P_1B_1, P_2B_2, etc., so that the amount of charging current is a function of the brightness of the mosaic spot. This is another aspect of the operation of the camera tube, and of course applies just as well as the aspects considered earlier, where we limited ourselves to the potential of the mosaic elements.

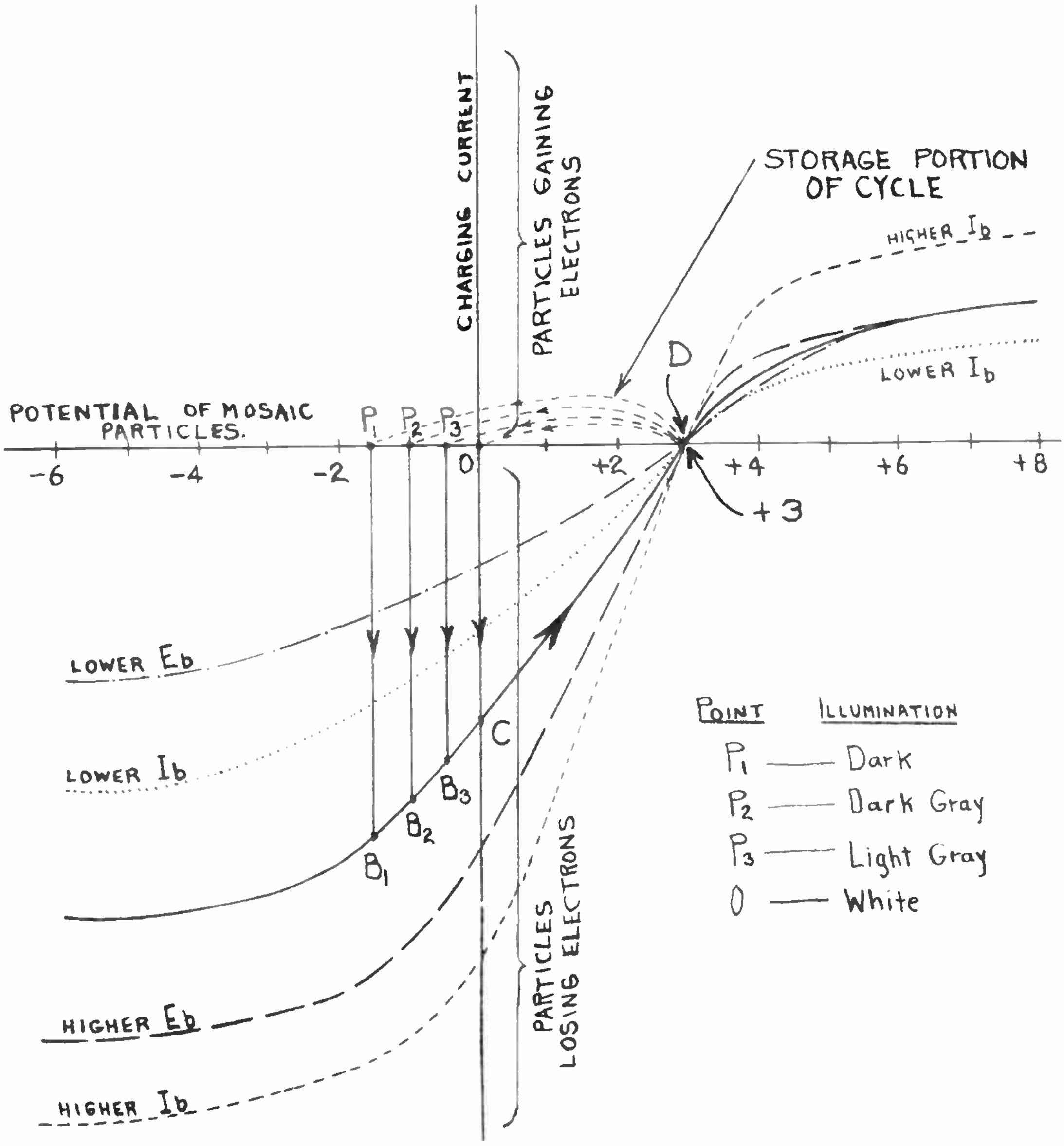

Fig. 6. Characteristic Curves of Camera Tube.

It is of interest to consider the effect of change of beam voltage and of beam current, and in Figure 6 four additional curves are plotted to show these effects. It will be realized that change of beam voltage affects the secondary-emission ratio, and therefore affects the saturated secondary emission which is given by the lower left-hand end of the curve; change of this voltage does not affect the right-hand end of the curve. Alteration of the beam current affects both ends of the curve. The internal impedance of the tube, which is about 1.5 megohms for typical conditions, is the reciprocal of the slope of the curves in Figure 6 over their middle portions, and may be seen to decrease upon increase of either E_b or I_b. Such a decrease of the internal impedance is desirable from the standpoint of increasing the output signal, but it has been found in practice that the best conditions are a voltage to give a good value of the secondary-emission ratio, and a current not large enough to aggravate the production of the spurious shading output. The values of 500 volts and 0.3 microampere are representative of good practice.

OPERATING POINTS

Shading Effect

The camera tube, operated in either darkness or light, produces a large spurious signal commonly known as shading, which is caused by irregularities in the rain of the slow-velocity electrons returning to the mosaic. As mentioned above on page 33, this rain of electrons is associated with the lack of photoelectric and secondary-emission saturation, which greatly reduces the sensitivity of the camera tube. The shading which we consider here is an additional fault associated with this rain of electrons, and is due to variations of the intensity of this rain over the area of the mosaic. A further complication is that the shading is dependent on the character of the picture.

The provision of the collecting ring, shown in Figure 1, which has a circular shape symmetrical with respect to the mosaic, has been found to reduce the magnitude of the shading. Also the use of the smaller values of beam current gives lower shading. Another means of reducing shading is to avoid scanning the edges of mosaic, where the variations in the rain of electrons are greatest; if the scanning beam does not come within 1/4 inch of the edge of the mosaic, some severe shading is obviated. However, after these possibilities are utilized, substantial shading remains, and it is usually larger than the desired signal. Suitable artificial signals must be inserted in the video amplifier to oppose the shading potentials.

The shading has components at both field and line frequencies, so that the voltages used in shading correction are of two frequencies, namely 60 cycles and 13,230 cycles. Waveforms such as sawtooths, exponentials, and parabolic shapes, must be provided with choice of polarity and adjustment of amplitude to be made by the studio personnel. In practice the shading is adjusted during a rehearsal and the necessary settings of the various controls recorded, or left in place on equipment which will not be disturbed. As representative figures, a certain shading panel for two cameras includes a total of 24 control knobs and 16 reversing switches, and utilizes 30 vacuum tubes. Such a number of tubes is of course important; however it is only a fraction of the total required in the complete equipment of a television studio.

In Figure 7 is shown one of the many types of shading; in this figure it will be seen that the output of the tube during the normal scanning of one line may be divided into signal and shading components. Figure 7, however, is a simplified drawing in that it does not show shading which would be associated with the sharp contrast from black to white in the scene. Such shading is observed in television titles, etc., giving a bas-relief effect, similar to the effect of phase distortion in the circuits. Another spurious signal, called surge, occurs during the retrace period. We describe this in the following section.

Surge

Immediately after the completion of each line, and also after the completion of each field, the camera tube produces a large spurious signal called surge. This may take any one of many forms; however its highest amplitude is generally in the positive direction, corresponding to black.

The surge occuring after the scanning of each line is called line surge, and is experienced with about equal severity when the electron beam is cut off for the retrace as when the electron beam continues during this time. In case the electron beam is cut off, it will be readily understood that the stopping of the beam constitutes in itself a considerable disturbance in conditions, and would account for a surge. For this reason there is little or no benefit in cutting off the beam during the line retrace, and it is simpler to let it continue during this period. With the beam on, the disturbance seems to be dependent on the velocity of the scanning spot during the retrace, so that the largest amplitude occurs about the center of the retrace where the velocity is greatest. In the ideal sawtooth wave, the retrace velocity is constant, but in actual practice this condition cannot be obtained and there is a maximum about the center of the retrace. A typical line surge is shown in Figure 7.

During the field retrace it is very desirable that the line scanning currents continue undisturbed. Under these conditions if the beam is not cut off, it will follow a zigzag course, and will affect the mosaic along this path. The points in this path will be given more positive charges, due to secondary emission under the influence of the beam, than they would otherwise have, and the memory feature of the tube will cause the zigzag path of the field retrace to appear in the subsequent normal scanning of the scene. This effect is prevented by driving the grid of the camera tube to cutoff, so that the beam is suppressed, during the field-retrace period.

The fault of surge is a less serious defect in the camera tube than shading. Surge occurs only during retrace periods, so that its effect is to complicate slightly the provision of blanking and synchronizing signals which are transmitted during these intervals.

Thermal Noise

The lowest usable signal from the mosaic camera tube is determined by the thermal noise originating in the load resistor which couples the output to the first amplifying stage. The reader is probably already acquainted with this type of noise, since it determines the limit of useful amplification in various branches of the communication art.

For resistances having a temperature about equal the usual room value, the noise may be expressed in microvolts as $4\sqrt{R \cdot \Delta f}$, where R is the value of the resistance in megohms and Δf is the band width in kilocycles transmitted by the associated apparatus. This formula, or the equivalent expression in other units, will be recognized by receiver engineers who have been interested in the design of

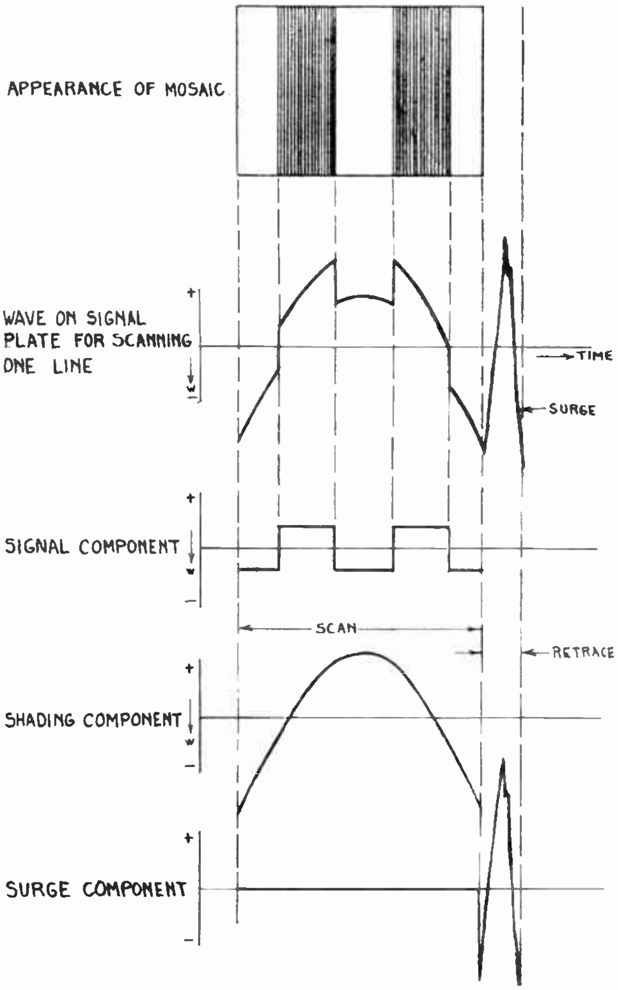

Fig. 7. Output of Camera Tube Showing Signal, Shading, and Surge Components.

sensitive broadcast receivers having low noise. In terms of ohms and megacycles this formula is $0.126\sqrt{R \cdot \Delta f}$. The following gives some values of thermal noise:

Thermal Noise in Microvolts (R.M.S.)

Δf	R = 5000 Ohms	6000	7000	10,000
1 Mc	9	10	11	13
2	13	14	15	18
3	15	17	18	22
4	18	20	21	25
5	20	22	24	28
6	22	24	26	31
7	24	26	28	33
8	25	28	30	35

The figures as given in this table are applicable directly in the consideration of video amplifiers, where the frequency band extends from zero to a particular value. With carrier amplifiers modulated with video signals, the band width will generally be greater than the highest video frequency, and in case all components of both sidebands are transmitted, the band width in which noise components will exist is twice the value of the highest video-frequency component. The band-width figure is, of course a characteristic of the apparatus, not of the signal; if the signal is replaced with one of a narrower frequency spread, or if the signal is removed, the noise from the particular apparatus remains the same.

As an illustration of the importance of thermal noise, we may take the case where a 6000-ohm load resistor is used and video frequencies up to 3 megacycles are accepted by the video amplifier. For these conditions the thermal noise will be seen to be 17 microvolts. If the signal is about the minimum value of 1/3 millivolt, or 330 microvolts, the signal-to-noise ratio is about 20 to 1. Since 1/3 of a millivolt is about the lowest useful signal, we may say that the lowest usable signal-to-noise ratio is about 20 to 1. However, this value depends, as we have just seen, on the band width.

Values of load resistor in use generally lie between 5000 and 10,000 ohms. Higher values would give somewhat more noise but considerably greater signal, so that the signal-to-noise ratio would be desirably increased; the difficulty is that such an increase of the load resistance gives more output for the low video frequencies, where the gain is not needed, but gives little improvement for the higher video frequencies where more output would be very welcome. These remarks apply to the simple circuit where the signal across the load resistor is applied directly to the first tube of the pre-amplifier. Coupling networks of several elements are sometimes used and offer some advantages.

REFERENCES

The mosaic camera tube is discussed in the paper, "Theory and Performance of the Iconoscope", by V. K. Zworykin, G. A. Morton, and L. E. Flory of the RCA Manufacturing Company, in the PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS for August 1937, pages 1071-1092, which is reprinted in the second volume of "TELEVISION", the book of RCA reprints, pages 374-395.

Electron optics and the electron gun are dealt with at length in the recent book, "Electron Optics in Television", by I. G. Maloff and D. W. Epstein of the RCA Manufacturing Company, published in 1938 by the McGraw-Hill Book Company, Inc., and sold at $3.50. This is a book of 299 pages, and is based on extensive experience of the authors in the field.

Many physicists, including Einstein, have investigated the photoelectric effect and there is a large amount of literature on the subject. We may mention two books as follows: (1) "Photoelectric Phenomena", by A. L. Hughes, Washington University, and L. A. DuBridge, now of the University of Rochester, a volume of 531 pages, published by the McGraw-Hill Book Company, Inc., in 1932, and sold at a price of five dollars; and (2) "Photocells and Their Application", second edition, by V. K. Zworykin of the RCA Manufacturing Company, and E. D. Wilson of the Westinghouse Research Laboratories, published by John Wiley and Sons, Inc., a volume of 348 pages, selling at three dollars.

Considerable experimental data on secondary emission are given in the paper, "The Secondary Emission of Electrons from Caesium Cathodes", by Paul Shmakov in the JOURNAL OF THE TELEVISION SOCIETY for

December 1935, pages 68-74. The office of the Society is at 25, Lisburne Road, Hampstead, London, N.W. 3, England.

The development and significance of the expression for thermal noise have been covered in numerous papers, of which it is sufficient to mention one entitled "Limits to Amplification", by J. B. Johnson and F. B. Llewellyn of the Bell Telephone Laboratories, published in ELECTRICAL ENGINEERING for November 1934, pages 1449-1453, and in the January 1935 issue of the BELL SYSTEM TECHNICAL JOURNAL, pages 85-96. This paper concludes with a bibliography of forty-two references on related topics.

The following portions of the text, "Television Engineering", by J. C. Wilson, which was listed on page 19 (Report 1776), pertain to the subject matter of the present chapter: general description of mosaic tube, pages 376-378 and 380-381; photoelectric emission, pages 117-120, 126-145, and 147-153; secondary emission, pages 145-147; electron speed for various voltages, pages 259-260; magnetic deflection, pages 262-263 and 296-297; points related to gun design, pages 266-286; and thermal noise, pages 174-175.

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