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THE PICTURE TUBE - PART I
(TELEVISION PRINCIPLES - CHAPTER 9)

C. E. Dean
Editor

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SPECIFICATIONS SELECTED FROM THIS CHAPTER

Limiting Factor in Brightness of a Given Tube	Spot Size
Light Distribution Across Line	Approximately Cosine-Squared
Type of Decay of Spot Brightness After Each Excitation	Exponential
Efficiency of P_1 Phosphor (Green)	1 to 3 Candles per Watt
Efficiency of P_3 Phosphor (Yellow)	0.5 to 3 Candles per Watt
Efficiency of P_4 Phosphor (White)	1 to 2 Candles per Watt
Maximum Contrast Normally Obtainable in Picture Tubes	20
Gamma of Picture Tube	Approximately 3/2
Electrical Analog to Refractive Index	$\sqrt{\text{Voltage}}$
Most Probable Velocity in Volts of Electron Leaving Oxide-Coated Cathode	0.47 Volt

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THE PICTURE TUBE - PART I
(TELEVISION PRINCIPLES - CHAPTER 9)

INTRODUCTION

The final link in the television chain must convert the electrical video and scanning signals into a visible optical image. In this and the following chapter we discuss electronic methods of producing this transformation; we limit the discussion to means whereby the image is perceived on the fluorescent screen where it is formed, either directly or by a mirror.

The cathode-ray tube used for this purpose is known by various terms including "picture tube", "Kinescope", and "television cathode-ray tube". The last is often abbreviated "TCR tube".

The picture tube is very similar to the cathode-ray oscilloscope tube, which is familiar to electrical laboratory workers, and differs only in that: (1) means are provided for modulating the beam current, and (2) the size of the fluorescent spot must remain below a certain limit during the modulation.

The picture tube in the television receiver can be regarded as an inversion of the camera tube in the transmitter. The cathode-ray beams in the camera tube and picture tube scan their respective areas in synchronism, and in the same phase, thru the action of the synchronizing signals on the receiver scanning oscillators. The brightness of the fluorescent spot on the tube screen in the receiver varies point-for-point with the brightness of the optical image in the camera tube being explored by its cathode-ray beam, thru the action of the video signal on the picture-tube beam current.

An electron ray can be deflected by either an electric field or a magnetic field, or by a combination of these. As a consequence of this fact, both the function of focusing the electron beam to a small spot on the fluorescent screen, and the function of deflecting the electron beam to produce a displacement of the spot for scanning, may be accomplished by either an electric or a magnetic field. This leads to the result that the tube may be designed in any one of four ways: (1) Electric Focus and Electric Deflection; (2) Magnetic Focus and Magnetic Deflection; (3) Magnetic Focus and Electric Deflection; and (4) Electric Focus and Magnetic Deflection. Each of these combinations has been used successfully in design. The choice of any particular combination is influenced largely by the requirement which it places on the associated electrical circuits for anode voltage supply and scanning, and on the desired geometry of the tube. For tubes having fluorescent screens of 5 inches diameter or smaller, the economics of scanning-circuit design direct the choice to electrostatic scanning; for larger tubes the choice is magnetic scanning. The choice of electric or magnetic focus is more evenly balanced, leaning toward magnetic focus for tubes having a high power density at the fluorescent screen, such as projection tubes.

The discussion of picture tubes divides naturally into two parts, namely the electrical characteristics and the optical characteristics. The discussion of the electrical characteristics in this chapter is limited to electrically focused and magnetically scanned tubes. The discussion of the optical characteristics, on the other hand, is valid for any combination of focus and scanning.

GENERAL DESCRIPTION OF THE ELECTROSTATICALLY FOCUSED TUBE

Figure 1 shows a cross-section of a particular design of an electrostatically focused, magnetically scanned tube. The electrodes which are collectively called the electron gun are constructed in such a way that the electrostatic fields which exist within the tube, when the rated potentials are applied,

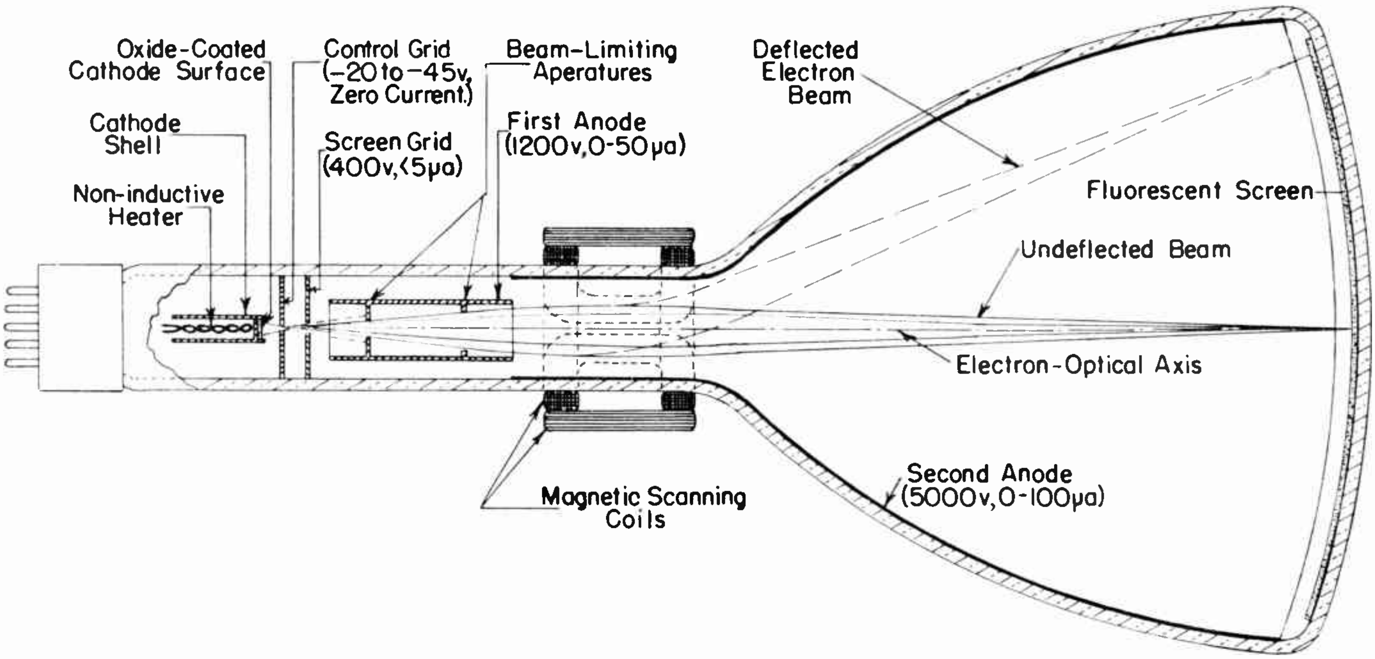


Fig. 1. Cross-Section of Picture Tube with Electric Focusing and Magnetic Scanning, Showing Parts of Electron Gun.

cause the electrons leaving the cathode emitter to form a beam which converges to a small cross-section or focus at the fluorescent screen. All of the electrodes have rotational symmetry and are accurately positioned, so that their axes lie along a common line called the electron-optical axis of the electron gun.

The magnetic scanning fields are produced by electric currents flowing thru two pairs of coils whose axes are at right angles to the electron-optical axis and to each other. These coils are usually curved to fit the cylindrical glass wall of the tube, as shown in Figure 2.

In Figure 1 the electron beam is shown in a solid line under the condition when no scanning field is present. When a magnetic field is produced in the scanning zone at right angles to the plane of the paper, the electron beam undergoes a deflection such as shown by the dotted lines. The amount of deflection on the screen is practically proportional to the current flowing thru the scanning coils. The direction of deflection, that is up

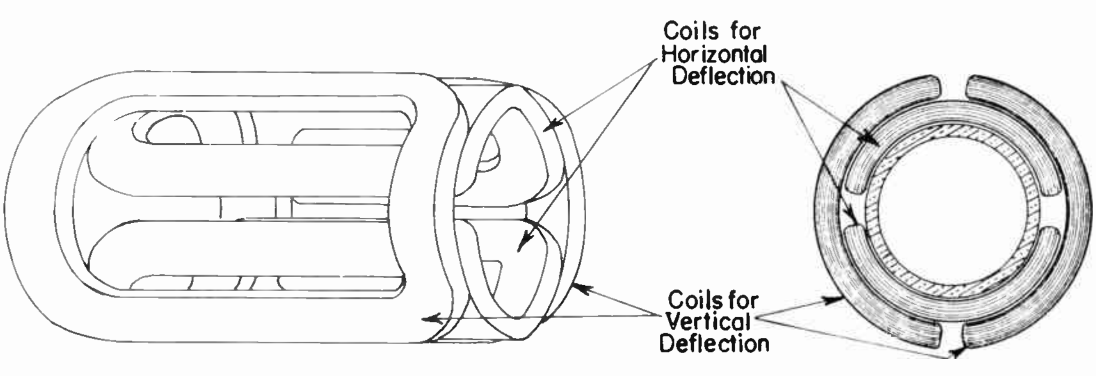


Fig. 2. Arrangement of Scanning Coils Around Neck of Tube.

or down in Figure 1, depends on the sense of the magnetic field or scanning current.

The heater is a non-inductive insulated double spiral, enclosed by a hollow nickel cathode cylinder. One end of the cathode cylinder is covered with a nickel cap which carries the electron-emissive coating of barium and strontium oxides.

The next electrode, called the grid, is a disk which has a small hole or aperture. The potential of this grid determines the amount of current leaving the electron-emissive coating and entering the cathode-ray beam, whence it performs the function of a control grid.

The screen grid is another apertured disk, and the first anode is a hollow cylinder which contains two apertures whose function is to limit the diameter of the electron beam. All parts of the tube are made of non-magnetic metals or alloys with the exception of the nickel cathode which is also non-magnetic at its operating temperature. The second anode is also a cylinder, consisting of a conducting coating of carbon (aquadag) formed on the inside of the glass wall of the tube. This conducting coating extends in a conical shape nearly to the face of the tube which carries a coating of fluorescent material called the fluorescent screen.

The diameter of the fluorescent screen is an important quantity because it determines the maximum size of the picture which the tube will produce. Tubes for television use have been made with diameters as small as 3 inches and as large as 20 inches. These values may be regarded as extremes, limited on one hand by the necessity of viewing the picture quite near the tube for a 3-inch screen, and on the other hand by the unwieldy size of a tube having a 20-inch screen. To maintain the brightness of the larger pictures, the cathode-ray beam should increase in power in proportion to the picture area, since the brightness should be independent of the size. This increase in power is accomplished by an increase in the beam voltage which in turn calls for an increase in the power applied to the scanning fields, whether these be electric or magnetic. Thus the cost of not only the tube itself but also that of all associated electrical equipment increases very rapidly with the diameter of the screen.

ELECTRICAL CHARACTERISTICS

If, for the moment, we ignore the scanning circuits associated with the picture tube and consider only the circuits associated with the electron gun for forming and modulating the electron beam, we can regard the tube as a specialized thermionic amplifying tube. The names of the electron gun parts have been chosen because their electrical behaviors are analogous to those of the corresponding parts in an ordinary amplifying tube.

The electrical features of the picture tube and the thermionic amplifying tube differ in the following aspects:

(1) In the picture tube, all the useful work is done within the tube (electrons striking the fluorescent screen and producing visible light), and any work done external to the tube or on electrodes other than the screen is wasted -- in a thermionic amplifier tube just the reverse is true, all work done by the electrons within the tube being wasted, and only work done in an external impedance being useful; and

(2) In a thermionic tube, the electrons strike an electrical conducting surface (the plate) and flow thru this to the external electrical circuit, while in the picture tube the electrons strike the fluorescent screen, which is a fairly good insulator. It is, of course, necessary for the electron current to leave the screen and complete its path thru the external circuit, and this is effected by secondary emission from the fluorescent spot under electron bombardment. The number of secondary electrons released by the cathode-ray beam must equal or exceed the number of primary electrons in the beam. The fluorescent spot charges to a positive voltage relative to the second anode, of such a value that the resultant electric field

allows only one secondary electron to escape to the second anode for each electron in the beam, thus maintaining the necessary balance of current. The electric field causes the excess secondaries to return to the screen.

An important electrical characteristic of the tube is the relation between the grid voltage and the second-anode current (which, as we have just seen, equals the beam current).

Figure 3 shows this relation plotted for a typical picture tube. The heaviest curve is for the normal screen-grid voltage, the solid portion being the normal operating range. The operating range is restricted to negative grid voltages not only to prevent grid current, but also, as we shall discuss later, to avoid loss of detail due to excessive spot size. The other curves show how the characteristic changes for different screen-grid voltages, this change amounting to a horizontal shift of the curve along the axis of grid voltage. Only a relatively small change is produced in these characteristic curves if the first and second anode voltages are changed over a wide range (say 4000 volts to 6000 volts for E_{p2}, and 960 volts to 1440 volts for E_{p1}).

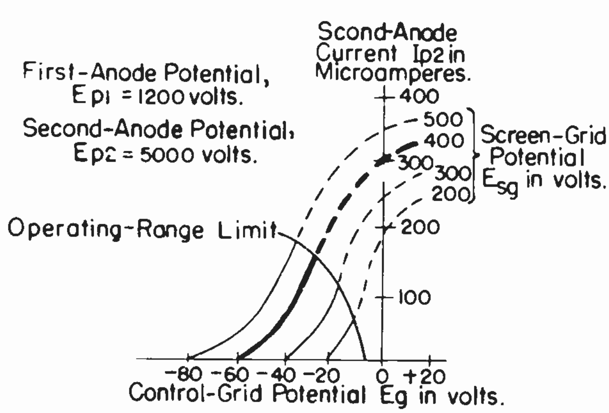


Fig. 3. Second-Anode Current of Picture Tube as Function of Potentials of Control Grid and Screen Grid.

In the operating range, these characteristic curves follow approximately the 3/2-power law of space-charge-limited electron emission. This characteristic curve, once its operating portion has been determined on the basis of spot size, contains the following vital information regarding the tube characteristics:

(1) Grid-bias voltage for beam cutoff;

(2) Maximum allowable grid swing; and

(3) Maximum available beam current (which, when multiplied by the second-anode voltage, gives the maximum available beam power).

The current to the first anode is wasted as far as fluorescent-light output of the tube is concerned, but it is important to know the first-anode current as a function of grid voltage, so that this factor may be taken into account in the design of the voltage-supply circuit.

DETAIL

The function of the tube is of course to produce a visible optical image. The essential qualities of an optical image are detail, brightness, contrast, gamma and color, and we now discuss these, beginning with the subject of detail. Starting with a discussion of detail along the lines of Chapter 5 (Report 1853), we proceed with a consideration of the limiting effective line width and methods of measuring the effective line width.

The image on the fluorescent screen is of course produced by the movement of the cathode-ray beam in parallel consecutive lines to produce a picture field or raster. It is immaterial for this discussion whether or not, or in what manner, the picture is interlaced.

Effective Line Width

If we examine the fluorescent spot produced by a stationary electron beam from a well designed and accurately constructed electron gun it will be found to have a circular luminous brightness distribution of the type shown in Figure 4A.

Let us suppose that the spot is scanned to form successive lines of a television raster and that the lines are well separated so that there is no overlapping. The brightness distribution measured across a single line, as far as the eye is concerned, would have a form such as is shown in Figure 4B. This distribution is found to be approximately represented by a cosine-squared relation between the brightness and the position across the line measured at right angles to the direction of the line scanning.

In this discussion we shall assume that this light intensity distribution is given by the relation $B = K \cos^2 \frac{\pi y}{2D}$ between the values $y = +D$ and $y = -D$. This is illustrated in Figure 5A. The total width of the scanning line is seen to be equal to 2D. In Figure 5B four successive scanning lines are shown with a center-to-center separation of D so that they overlap each other as indicated. The combined intensity of these lines is also shown in this figure as a dotted line, and it may be seen that this has a constant height. This condition obtains only when the separation of the lines is equal to D. Figure 5C shows the appearance of the combined intensity when the separation of the lines is respectively

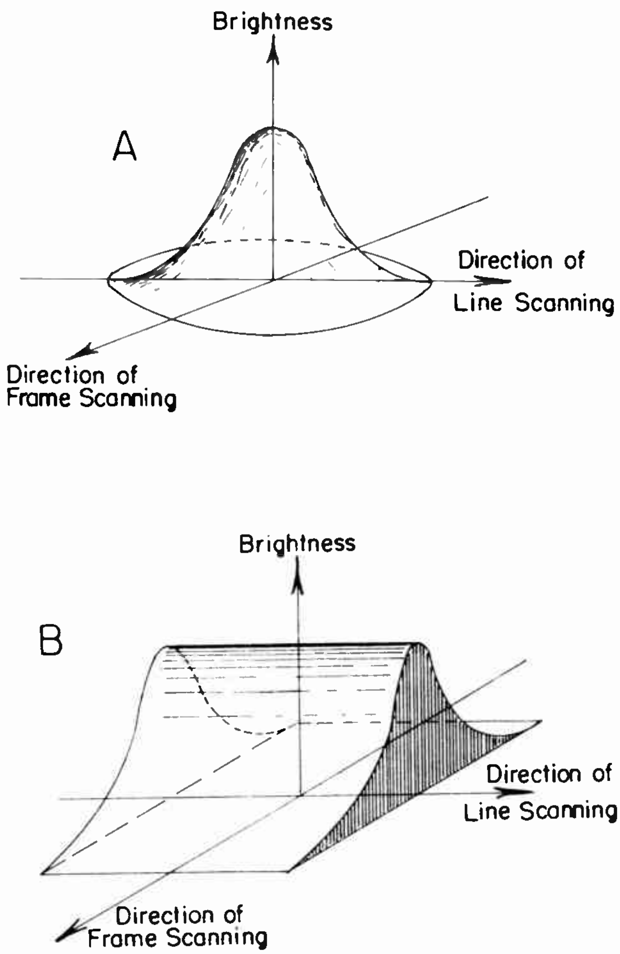


Fig. 4. Brightness Distribution Over Scanning Spot and Line.

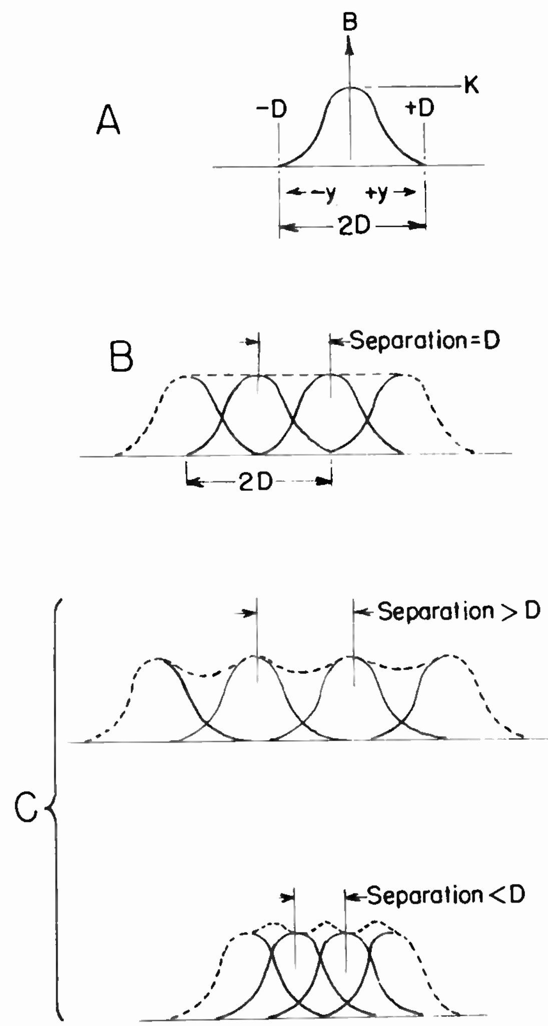


Fig. 5. Uniform or Non-Uniform Brightness Across the Lines According to Spacing in Terms of Effective Line Width.

greater than and less than D. Therefore, when a raster of successive lines is scanned, the screen of the tube will appear to be uniformly illuminated if the intensity distribution across each line follows a cosine-squared relation and the center-to-center separation of the lines is made equal to one-half the total width of an individual line. This half of the total width is called the "effective line width", that is D is the effective line width.

In order to reproduce all the detail contained in the television signal, it is necessary to have the effective line width equal to or less than the picture height divided by the number of scanning lines in the picture. If the effective line width exceeds this value, detail is lost due to overlapping of picture elements which should be separate. If the effective line width is less than this value, the detail in the vertical direction, which is limited by the line structure of the image, remains the same. On the other hand, the detail in the horizontal direction will increase as the spot size is diminished until a limit is reached which is imposed by the signal content. Since the filter characteristics of the television system do not cut off sharply at the upper frequency, this limit will not be sharply defined. Thus if the line width were less than the limiting value expressed above, no increase in detail appears in the image in the vertical direction, and a limited increase occurs in the horizontal direction.

For a 441-line television signal, about 10 percent of the picture time is required for frame retracing, so that the picture contains about 400 lines. A formula for the limiting effective line width required for reproducing the entire picture detail can therefore be stated thus:

$$D_o = \frac{h}{400},$$

where D_o = Limiting effective line width in inches, and

h = Height of image in inches.

If the image is reproduced on a tube screen of diameter d and is adjusted to the proper aspect ratio of 4/3 and allowed to fill the screen so that the corners of the image are at the edge of the screen, the relation between h and d will be the following:

$$h = 3/5\ d.$$

This allows us to rewrite the first equation in a convenient form,

$$D_o = \frac{d}{667},$$

where D_o = Limiting effective line width in inches, and

d = diameter of tube screen in inches.

Methods of Measuring Effective Line Width

If the cathode-ray spot is round and if the distribution of light intensity across a scanned line follows a cosine-squared relation, the effective line width can be measured by adjusting the line spacing until the brightness of a scanned raster appears uniform and free from line structure; this may be seen from Figures 5B and 5C.

A second method of measuring the effective line width is by spreading the lines well apart. The width of an individual line is then measured with the calibrated scale in the eyepiece of either a microscope or a telescope. The width measured in this way must be multiplied by an experimentally determined factor k, which is slightly greater than unity, to give the true total width 2D.

If the electron spot does not fulfill the conditions stated above, these methods of measuring the effective line width are no longer valid and might lead to false results. However, the effective line width can be measured by applying to the tube a television signal obtained from a resolving-power chart. A measurement made by this method is independent of the spot shape or distribution. Figure 6 shows one type of resolving-power chart. The scale divisions on this chart represent the total number of lines, counting black and white, required to measure off a distance equal to the picture height. The same scale is used for horizontal and vertical resolution, whence the former is the number of lines in a horizontal distance equal to the picture height.

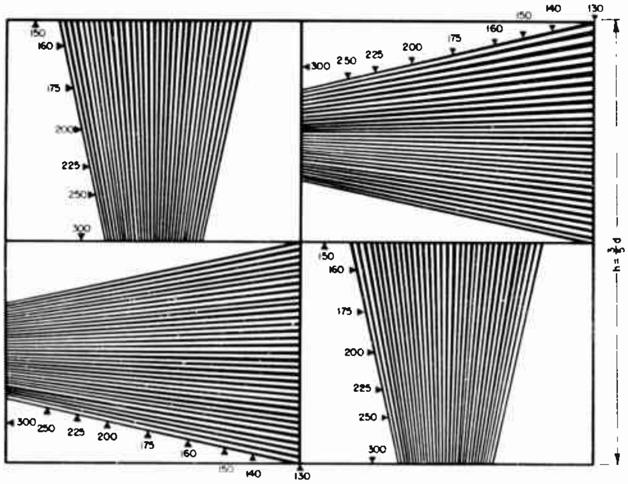


Fig. 6. Simple Resolution Chart.

A chart of the type shown may be placed before the television camera, or a special cathode-ray signal-generating tube (such as a Monoscope) having such a chart on its target may be used, for generating the television signal. The image is observed on the picture tube of a television receiver and the size of the image is adjusted so that the diagonal equals the diameter of the screen. Under this condition, the resolving-power scale divisions will correspond to the numbers indicated on the chart. The reading is taken according to the directions on page 95 of Chapter 5 (Report 1853). Two readings of horizontal and vertical resolving power may be made from this chart. The maximum value of vertical resolving power (measured on lines running horizontally), as limited by the line structure of the image, will be equal to $400/\sqrt{2} = 280$ lines. The maximum value of the horizontal resolving power (measured on lines running vertically) will be limited only by the frequency content of the television signal. This should be equal to or slightly greater than 280 lines in accordance with present-day television practice.

By making measurements on the television image as described, it is possible to determine the resolving power of the tube in both horizontal and vertical directions. If it is desired to make a measurement for a line number in excess of the limit of the chart, the image on the screen may be reduced by a factor k, which is less than unity. The resulting measurement is then divided by k to obtain the desired number of lines. This reduction in the image size makes it possible to determine the resolving power of the tube alone even though the available signal does not contain the necessary high-frequency components.

BRIGHTNESS

The brightness of individual picture elements in the television image appearing on the tube screen may vary from a very small value, when the beam current is zero, to the brightness produced by the maximum beam current. It is important to know the amount of this maximum brightness value. In the present section we discuss the various factors influencing brightness as well as methods of measuring it.

Variation of Brightness of Point During Frame Period

Let us examine an area of the phosphor, which is very much smaller than the scanning spot, and consider how the actual brightness of the light from this small area varies during the scanning cycle. This is illustrated in Figure 7 where the actual brightness of this small area is shown as a function of time.

Let t_1 equal the time required for the scanning spot to traverse the small area. Let $t = 0$ be the time at which the scanning spot just arrives at the area under consideration. As the scanning spot moves over the small area, the excitation of the screen and therefore the fluorescent brightness will increase from the value B_2, left from the preceding scanning, to the value B_1 whereupon the spot leaves the small area and the current to this area drops to zero.

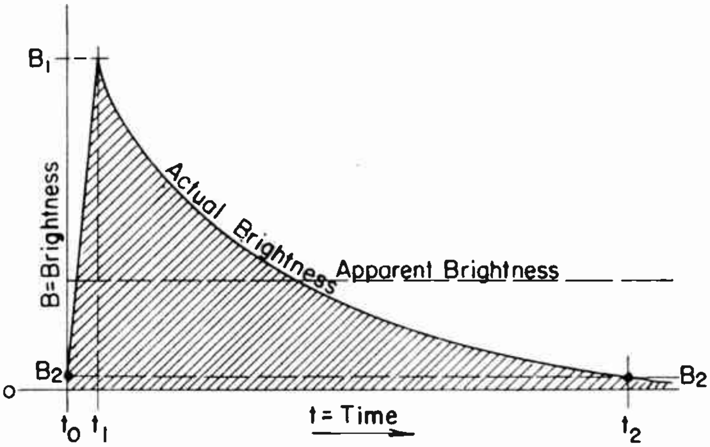


Fig. 7. Instantaneous and Apparent Brightness.

Because of the speed of the scanning spot, the brightness does not reach saturation as it would with a fixed spot. Thus after time t_1 the brightness of the small area has reached a value B_1, and electron excitation has ceased. The brightness, however, does not drop to zero immediately with the excitation but persists for an appreciable time, following an exponential decay curve. After the lapse of a time t_2, equal to the scanning time of a complete picture, the scanning spot has returned to the same position it had at the initial time $t = 0$, and is ready to repeat the same cycle we have discussed above. In the meantime the brightness of the small area has fallen to a value B_2, as shown in Figure 7. (The time t_1 in Figure 7 has been greatly exaggerated compared to t_2 in order to make it visible on the graph.)

The shaded area under the curve of Figure 7 is proportional to the total quantity of light given out by the small fluorescent area during one scanning period. If now we consider an element of area equal to the scanning spot, the brightness as a function of time is a summation of a large number of curves such as in Figure 7, and this overall curve will have the same general shape as the individual curves. Therefore Figure 7 can be considered to give the brightness of an area the size of the scanning spot.

Although the actual brightness of this area goes thru the cycle of rapid increase and exponential decay, the apparent brightness to the eye is that which would be produced by the same quantity of light given out at a constant rate over the same time interval. In other words the eye integrates the actual brightness curve of Figure 7 and responds to the average value of the brightness. This relation between the actual brightness and the apparent brightness of a periodically varying light intensity is known as Talbot's law. This law begins to fail when the length of the period of variation of the light intensity exceeds a certain threshold value which depends upon the color and brightness of the light. If the period is increased beyond this threshold value, flicker becomes apparent. The period used in television pictures is such that, with the light intensities usually encountered, flicker is not observed and Talbot's law applies quite closely. With double-interlaced scanning, the frequency, as far as flicker effect is concerned, is approximately that of the field frequency, or 60 per second.

In Figure 7 the brightness B_2 represents the value reached just before reexcitation. If B_2 is not much smaller than B_1, that is if the decay period of the phosphor is long, the television picture will persist on the screen for an appreciable time. This will not affect a fixed picture but will produce a trail behind a rapidly moving part of the image. For this reason the value of B_2 should not greatly exceed about 5 percent of B_1.

Efficiency of Phosphors

Suppose that the tube screen is being scanned with a raster by a constant-intensity cathode-ray beam. The fluorescent light from the screen will have a certain brightness which could be measured by means of a suitable photometer; for example one could use a Lummer-Brodhun photometer, or a photoelectric cell with a visual-correction filter such as the Weston Photronic Cell with Viscor Filter. Let us call this measurement of brightness $\underline{B}$, which may be expressed in candles per square foot. Let the area of the raster be represented by the value $\underline{A}$ expressed in square feet. The cathode-ray beam will have a certain power $\underline{P}$, which equals the product of the beam voltage E_{p2} and the beam current I_{p2}. Thus,

$$P = E_{p2} \times I_{p2}.$$

This power is distributed over the area of the screen by the scanning so the average power density will be given by

$$D = \frac{P}{A} = \frac{E_{p2} \times I_{p2}}{A}.$$

(Watts per square foot)

The quotient of the brightness of the screen divided by the power density of the cathode-ray beam gives a measure of the luminous efficiency of the screen material; this we represent by $\underline{L}$. It may be written as follows:

$$L = \frac{B}{D} = \frac{B \times A}{E_{p2} \times I_{p2}}.$$

(Candles per watt)

The luminous efficiency is a property of the phosphor. In Table I this and other characteristics are given for a number of phosphors used for picture-tube screens. The designation of silver or manganese following the hyphen in the first column indicates that this material is the activator in the preparation of the phosphor. (The information in Table I is largely from data published by Dr. L. B. Headrick of the RCA Radiotron Division in ELECTRONICS, December 1938, page 31.)

The luminous efficiency of a given phosphor depends to a small extent on the beam current as is shown in Figure 8A. For the range of currents used in the usual picture tube we can assume that the efficiency is independent of the beam current. The effect of change of beam voltage is entirely different, and is illustrated in Figure 8B. At high beam voltages, the efficiency approaches a limiting value, but as the beam voltage is decreased the efficiency drops more and more rapidly until a critical value E_o is reached where the beam no longer produces fluorescence. When the voltage of the beam is lower than this critical voltage (or "dead voltage"), the electrons never reach the screen but are repelled by a charge on the screen whose voltage equals the cathode potential. The value of E_o varies widely for different phosphors and may be as low as 100 volts or as high as 1000 volts. The relation shown in Figure 8B is expressed by Lenard's Equation,

$$L = K\left(1 - \frac{E_o}{E_{p2}}\right),$$

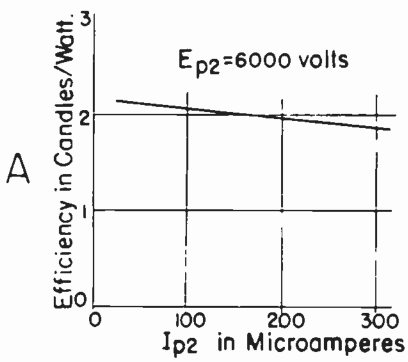
where K = a constant, and

E_o = the dead voltage.

TABLE I. CHARACTERISTICS OF PICTURE-TUBE PHOSPHORS

Phosphor	Formula	Color	Spectral Maximum in Angstroms	Efficiency in Candles/Watt at 1 to 6 Kv and 1 $\mu a/cm^2$
Zinc Sulphide	ZnS	Light Blue	4700	1 to 3
Zinc Sulphide-Silver	ZnS-Ag	Blue-Violet	4500 to 4700	1 to 3
Zinc Cadmium Sulphide-Silver	ZnS+CdS-Ag	Blue to Red	4600 to 7500	1 to 5
Zinc Silicate-Manganese (P_1)	$ZnO+SiO_2$-Mn	Green	5230	1 to 3
Zinc Beryllium Silicate-Manganese (P_3)	ZnO+BeO+SiO_2-Mn	Yellow	5350 to 5400	0.5 to 3
Zinc Sulphide-Silver Plus Zinc Beryllium Silicate-Manganese (P_4)	ZnS-Ag Plus ZnO+BeO +SiO_2-Mn	White	4500-4600 and 5600-5800	1 to 2
Cadmium Tungstate	$CdWO_4$	Blue-White	4900	Less than 1

Note. The phosphor designations P_1, P_3, etc., are in accordance with usage by manufacturers of cathode-ray tubes.



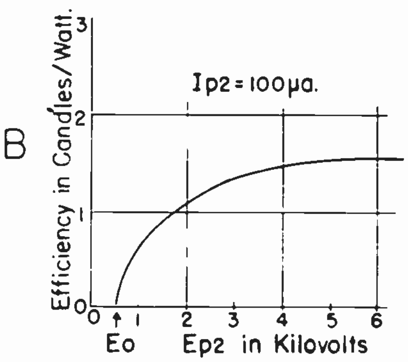


Fig. 8. Efficiency of Screen at Various Beam Currents and Voltages.

CONTRAST

If two areas on the tube screen have different brightnesses, the eye perceives this difference as contrast. The eye can perceive such a difference if it amounts to about 2 percent or more in the case of adjacent areas, and the minimum figure, expressed in percent, is largely independent of the actual brightness of the areas; this is known as Fechner's Law. It breaks down in the case of extremely dim light, for which the percentage difference of brightness required for perception is greater.

The contrast between two areas may be represented numerically by dividing the brightness of the brighter area by the brightness of the darker area. The fraction in Fechner's Law therefore corresponds to a contrast of 1.02.

In the case of directly viewed tubes, the upper operating limit of screen brightness is a definite value imposed by the spot-size requirement. The lower limit of brightness is obtained when the beam current is zero. If this lower limit of brightness were zero, the maximum contrast available would be infinite. The lower limit of brightness is not zero however, since it is possible for a small amount of the light leaving a bright portion of the screen to fall upon a part of the screen where the beam current is zero. This leakage of light is effected in the following ways:

(1) If the fluorescent screen is deposited on a concave surface, light leaving the fluorescent spot at a sufficiently large angle from the normal will fall on surrounding parts of the screen;

(2) Light leaving the fluorescent spot in a direction toward the interior of the tube will be reflected and diffused by the interior walls and electrodes, and some of this light will return to the screen; and

(3) Light leaving the fluorescent screen and entering the glass on which the screen is deposited will suffer total internal reflection and not pass thru the outer surface of the glass if it strikes this outer surface at an angle from the normal which is greater than the critical angle.

The critical angle i is such that $\sin i = \mu_2/\mu_1$, where μ_2 is the refractive index of the second medium and μ_1 is the index for the first medium. Light reflected in this way at the outer glass-air boundary of the tube wall is returned to the surrounding fluorescent screen. The part of this light which is diffused by the fluorescent material of the screen will appear as a halo surrounding the fluorescent spot. This halo of course accompanies the spot in its scanning and modulation so that it cannot be observed in a raster except at the edges or at isolated bright points in the image. This effect is called "halation".

The combination of these effects reduces the maximum contrast in conventional tubes to 20 or less. Of course any additional light falling on the screen, such as sunlight or other illumination in the room, will decrease the maximum contrast of the optical image still further. The maximum contrast obtainable from a given tube may be measured by scanning a raster of reduced size (say half normal area), using the maximum beam current, and then measuring the brightness of the screen at each side of a boundary between bright and dark portions of the screen. Measurements may be taken close enough to the boundary to include the halation effect, or further away so as not to include this.

GAMMA

The image appearing on the tube screen is a more or less faithful reproduction of the variations of light and shade in the original scene.

The reproduction of values of light and shade is subject to distortion, and it is convenient and useful to have an index for this distortion. For this purpose we have borrowed the concept of gamma from the photographic art. If the logarithms of the brightnesses of various areas in the original scene are plotted on a graph as abscissas and the logarithms of the brightnesses of the corresponding areas of the reproduced image are plotted as ordinates, a curve will be obtained as shown, for example, in Figure 9A. The slope of this curve is defined as the value of gamma for the reproduction.

If the relation between the brightness of the original and the brightness of the reproduction is as follows:

$$B_r = k\,(B_o)^N,$$

where B_r = brightness of reproduction;

k = a constant;

B_o = brightness of original; and

N = a constant,

then we have upon taking logarithms

$$\log B_r = N \log B_o + \log k.$$

Therefore if we plot $\log B_r$ against $\log B_o$ we will get a straight line whose slope will be N. The relation $B_r = k\,(B_o)^N$ therefore represents a type of distortion characterized by a constant gamma equal to N. The actual distortion of reproduction of intensity values in the image does not necessarily correspond to a constant gamma. As suggested in Figure 9A, where the line is not straight, there may be a variation of gamma as a function of B_o. Nevertheless it is found in photography and television that the useful part of the curve is sufficiently straight to warrant the approximation of constant gamma. Figure 9B illustrates plots of $\log B_r$ versus $\log B_o$ representing various values of gamma. The curve having unit slope, or gamma equal to unity, represents faithful reproduction if it extends indefinitely toward lower values of B_o and extends to sufficiently high values of B_o to include the brightest part of the original.

A type of transformation which must be included in this discussion is the inversion of the light and dark values of a picture. For example, the electrical output of the camera tube would show a negative image if it could be viewed

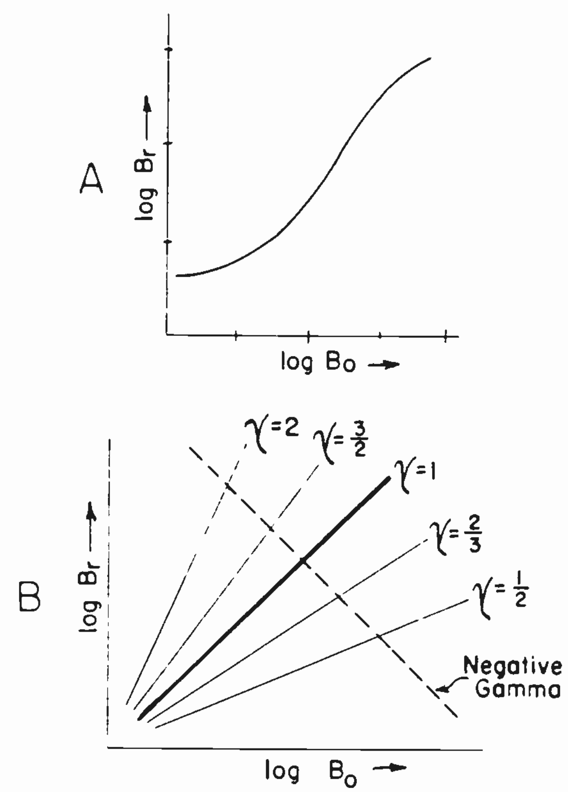


Fig. 9. Curves Relating to the Gamma of a Television System.

directly with a picture tube, but each plate-loaded stage of the amplifier causes an inversion, so that if the output of the first plate-loaded amplifier tube following the camera could be viewed with a picture tube, a positive image would be observed. Successive stages would yield alternate positive and negative images. Such an inversion of the light and dark values of the picture is represented by a negative gamma.

Let us assume that a reproduced image has passed thru a number of transformations or reproductions, each stage having a different gamma. We have then

$$B_r = k_1 B_1^{N_1},$$

$$B_1 = k_2 B_2^{N_2},$$

$$\text{and } B_2 = k_3 B_o^{N_3}.$$

From this

$$B_r = k_1 (k_2 B_2^{N_2})^{N_1},$$

and

$$B_r = k_1 k_2 k_3 B_o^{N_1 N_2 N_3}.$$

The gamma for the complete process may thus be seen to be $N_1 N_2 N_3$, or the product of the individual gamma values. The coefficients k_1, k_2, etc. can be regarded as the associated amplification, or gain. The sign of gamma is negative for the usual camera tubes and for plate-loaded video amplifiers; it is positive for cathode-loaded video amplifiers, picture tubes, and all carrier-frequency amplifiers. The gamma of the entire system must be positive to give a positive image, rather than a negative one, of the transmitted scene.

In connection with the gamma of the picture tube itself, let us assume that the spot brightness is proportional to the current in the cathode-ray beam. This current in the useful range is space-charge-limited, and therefore follows the 3/2-power law as a function of the grid voltage. We have therefore

$$I_{p2} = K_1 (E_g)^{\frac{3}{2}},$$

where I_{p2} = Beam current,

K_1 = A constant,

and E_g = Grid voltage with respect to the cutoff voltage.

We have also

$$B_r = K_2 (I_{p2})$$

where B_r = Brightness of reproduction,

and K_2 = A constant.

As a matter of definition,

$$B_o = K_3 E_g$$

where B_o = "Brightness" of original (that is, of the input),

and K_3 = A constant.

From these three relations it is found that

$$\frac{B_r}{K_2} = K_1 \left(\frac{B_o}{K_3}\right)^{3/2}.$$

The picture tube thus has a gamma value of 3/2 on the assumption of a linear relation between beam current and spot brightness. Actually the luminous efficiency decreases somewhat as the beam current increases, as shown in Figure 8A, so that the gamma of the tube is somewhat less than 3/2.

Figure 10A, which is plotted with logarithmic scales, shows the relation between the spot brightness of the screen and the applied video voltage. Curve #1 represents an ideal tube which has no halation or internally reflected light and is operating with no external light falling on the screen. This curve starts from B_{max} as limited by the spot-size characteristic. Since there is assumed to be no illumination of the "black" parts of the picture on the screen from surrounding luminous areas, the curve continues indefinitely along a straight line as shown. If there is a background illumination equal to B_2, the curve becomes asymptotic to the line $B_r = B_2$ as shown by curve #2. The maximum contrast therefore becomes equal to $(B_{max} + B_2)/B_2$. The value of B_2 in the figure, where it is shown as $(1/20)B_{max}$, is representative of practical tubes in the absence of room illumination. Suppose that additional light is now allowed to fall on the screen from the room illumination so that the total background brightness is B_3, taken as four times B_2. This background brightness will result in the condition shown by curve 3, the characteristic being badly distorted and the maximum contrast being seriously limited.

A brightness adjustment on the receiver permits alteration of the bias of the picture tube. This adjustment should be made to approximately the point where the bias, acting with the direct-current component of the video voltage wave, causes the black level in the wave to fall at the cutoff bias of the tube. Figure 10B, which is also plotted with logarithmic scales, shows the effect of incorrect grid bias on the reproduction characteristics. First let us notice Figure 10C which shows the beam current for various grid potentials. It is evident that at the potential C the beam current is reduced to zero. Should the black level of the wave lie at this value, the spot brightness for various signal voltages will be as given in curve C of Figure 10B, which flattens off at the background brightness due to halation and internal reflection.

If however, the bias is reduced so that the black level falls at A, the brightness is increased throughout the range of shades, but parts of the picture which should be dark have a high background illumination; the contrast, or range of brightness, is materially reduced. Curve B shows a less severe condition of the same type. Erroneous adjustments of this kind may also cause the lines occurring during the field retraces to appear in the picture as shown in Figure 22 of Chapter 3, (page 60 of Report 1822).

With adjustments in the other direction, designated D and E, the bias is too negative, and the curve falls off more rapidly than it otherwise would.

The wide divergence of the curves in Figure 10B over their middle and lower portions shows the sensitive character of the bias adjustment. Too small a negative bias is more objectionable than too large, that is, curve A is worse than curve E. A slightly negative position, between C and D, may be found preferable because it gives a more constant gamma over the medium and upper ranges, although at the expense of clipping the lowest range. The dashed straight line represents a constant gamma of 3/2.

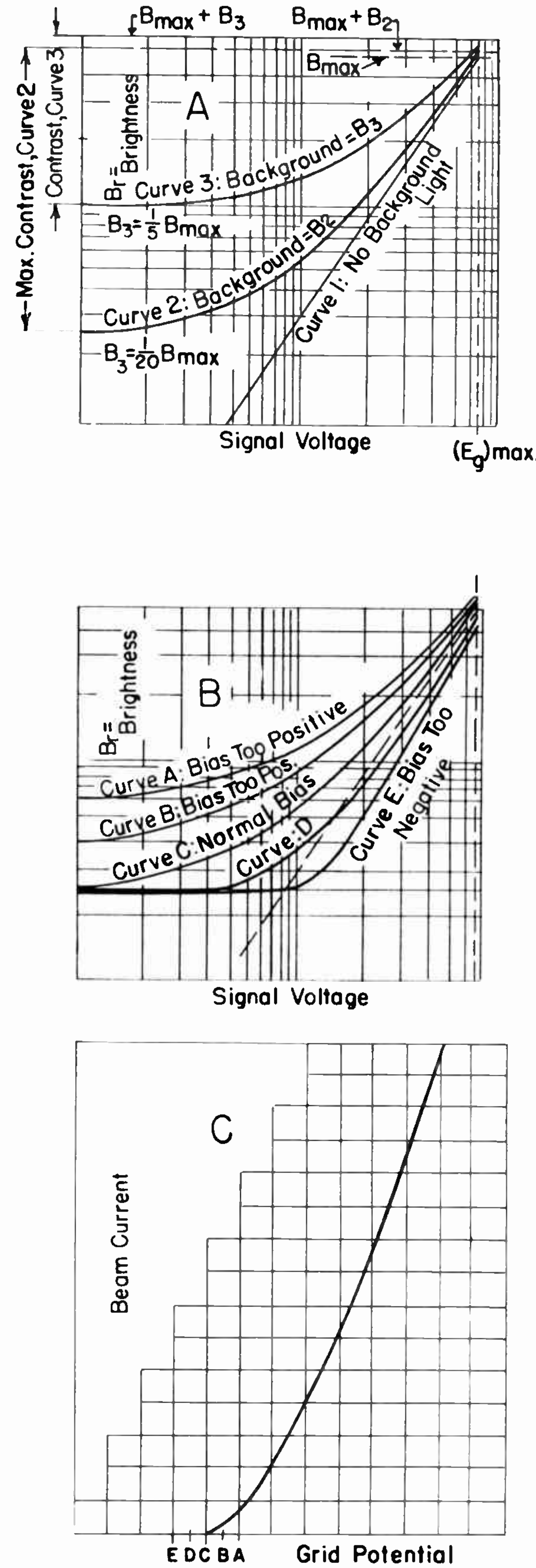


Fig. 10. Effects of Background Light and Improper Bias on Reproduction.

COLOR

The phosphor of the tube screen can be chosen to give almost any color, as is indicated in Table I, on page 199. The majority of observers seem to favor as close an approach to white as is possible. Probably the most common phosphor used at the present time to produce a white color is the P_4, consisting of zinc sulphide-silver plus zinc beryllium silicate-manganese; the latter component is similar to P_3, but not exactly the same.

DISTORTIONS

We have already discussed one type of distortion, namely that having to do with the faithfulness of reproduction of light and shade. There are five additional types of distortion in the picture tube which affect the received image. The first of these is caused by any departure from uniform scanning rates of either frame or line scanning at either transmitter or receiver, since this will lead to a geometrical distortion of the received image. We do not consider this type of distortion in the present discussion. The other four types of distortion are: (1) distortion due to improper spot shape; (2) distortion due to hum voltages; (3) distortion due to lack of perfect regulation of the voltage supply; and (4) distortion due to fringing of the magnetic deflecting field.

Spot-Shape Distortion

The fluorescent spot of the picture tube screen may be observed on the screen without scanning if the beam current is reduced to a fraction of a microampere so that the screen is not overloaded. The spot can then be observed with a low-power microscope.

Figure 11 shows how the spot shape is affected by various defects in the electron-optical lenses of the tube. Any of these distortions result in a loss of detail in the image. Astigmatism is due to a lack of perfect axial symmetry in the second lens of the tube. Coma is due to a lack of perfect coincidence of the axes of the first and second lenses. If the spreading out of the spot due to spherical aberration is excessive, the second lens of the tube has too large an aperture. If the halos due to secondary electrons are present (not to be confused with the halo produced by internal optical reflection), the aperture baffles are incorrectly placed or proportioned.

The tolerance allowable for these types of distortion may best be defined in terms of the amount by which the distortion limits the reproduction of picture detail.

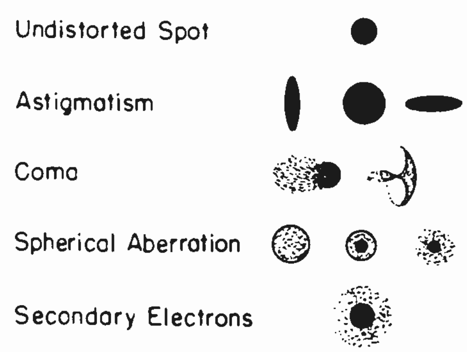


Fig. 11. Distortion of Spot by Faults in Electron Lenses.

Distortion Due to Fringing of Scanning Field

The spot distortions discussed so far are independent of the position of the spot on the fluorescent screen, that is, they are independent of the scanning. Another type of spot distortion is caused by the fringing field of the magnetic scanning coils. This distortion manifests itself in an increase in effective spot size which occurs to a pronounced degree at the edges of the raster; in fact this distortion increases approximately as the square of the angle of deflection of the beam from the tube axis. The amount of this distortion depends upon the design of the scanning coils which we shall not discuss further here. It follows, as a practical point, that a tube having a large maximum angle of scanning must have more carefully designed scanning coils than a tube in which the maximum scanning angle is smaller.

If the radius of curvature of the fluorescent screen is greater than the distance from the screen to the center of the scanning coils, the position of focus, after adjustment for the center of the screen, will fall short of the screen as the deflection angle is increased, thus causing the outer edges of the raster to be out of focus. The magnitude of this effect depends on the angle of convergence of the electron beam. As this angle is made less, the "depth of focus" increases, and distortion of this kind decreases.

Distortions Due to Interference from Scanning and 60-Cycle Circuits

If voltage components from the scanning circuits or the 60-cycle supply find their way into the video-frequency circuits of the picture channel by capacitive or inductive coupling or by coupling thru the power supply, they will produce a spurious background signal. Figure 12A shows the appearance of the raster when there is a saw-tooth interfering voltage from the frame scanning circuit. (The term "raster" means the appearance of the screen when operating with normal scanning and with a constant video signal corresponding to a uniform light gray or white throughout the field of view.) Figure 12B shows the appearance of the raster if there is an interfering saw-tooth voltage from the line scanning circuit. Figure 12C shows the appearance of the raster if the interference consists of a 60-cycle sinusoidal "hum" or ripple. There is a sinusoidal variation which goes thru a complete cycle in a vertical direction across the raster.

The eye will tolerate a small amount of hum distortion if the pattern remains at rest on the field of the raster. If the pattern shifts on the field, a very small amount of hum pattern is at once evident. The cases represented by Figures 12A and 12B are, from their very nature, at rest in the field. The pattern represented by Figure 12C is at rest when the mains voltage of the receiver has exactly the same frequency as that of the transmitter, since the frequency of the 60-cycle supply at the transmitter determines the field frequency of the transmitted television image. Usually the receiver mains frequency is so nearly equal to that of the transmitter that the frequency difference results in a sufficiently slow rate of drift of the 60-cycle hum pattern.

The hum pattern will stand out more clearly as the beam current is decreased. If the hum pattern is sufficiently small so that it is not evident when the raster is scanned without a video signal at 1/10 the maximum beam current, it will cause a negligible distortion in the received image.

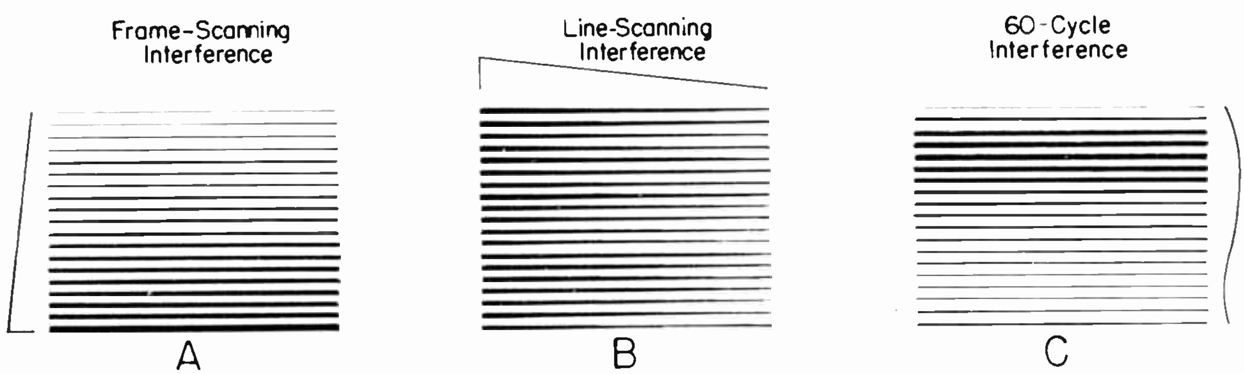


Fig. 12. Effect on Raster of Interference in the Video Channel from Scanning and Power-Supply Circuits.

Distortion Due to 60-Cycle Voltage in the Tube High-Potential Supply

The tube voltage supply is derived from a mains-operated step-up transformer by rectification and filtering. The design of the filter hinges on the question of the percentage of alternating voltage which is acceptable in the output. In order to answer this question we shall examine the effect which alternating voltage in the tube supply has on the scanned raster. For this purpose let $\underline{W}$ be the average length of a scanned line on the tube screen, that is, the picture width, and $\underline{E}$ be the average second-anode voltage. Then for a magnetically scanned tube

$$W = \sqrt{K/E} \; ,$$

where $\underline{K}$ is a constant.

Let the second-anode voltage contain an alternating component whose maximum voltage is ΔE, this component being small in comparison with $\underline{E}$. This will produce a variation in line length of ΔW, which can be shown to be

$$\Delta W = -1/2 \sqrt{\frac{K}{E^3}} \; \Delta E.$$

Dividing this equation by the one for $\underline{W}$, we obtain the formula,

$$\frac{\Delta W}{W} = -1/2\left(\frac{\Delta E}{E}\right).$$

The appearance of the resulting raster is shown in Figure 13. The 60-cycle voltage component in the direct-current voltage supply is saw-tooth as represented because the filter condenser charges thru only a small portion of the cycle and discharges approximately linearly during the remainder of the cycle. The variation of deflection sensitivity acts on the frame scanning as well as the line scanning and causes the lines to crowd together as they get shorter. This pattern is practically stationary on the field for the same reason as with the grid hum pattern. The accompanying variations in beam current and spot brightness are negligibly small. For an electrostatically focused tube, the variations in spot size are also negligible. If the relative variation of $\underline{W}$ is kept below 1/2 percent the geometrical distortion is found to be negligible. Thus from the formula we see that the peak-to-peak value of the ripple voltage should be kept below 1 percent of the second-anode voltage.

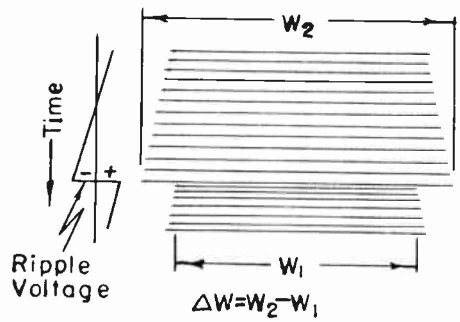


Fig. 13. Effect on Raster of Insufficient Filtering in High-Voltage Supply to Tube.

GENERAL CHARACTERISTICS OF ELECTRON-OPTICAL LENSES

The shape of the path which an electron or other charged particle will take in an electric field depends on the electric-field configuration. The electric field in the space between electrodes can be represented by equipotential surfaces. The electrode surfaces, being conductors, are equipotential surfaces whose shape is fixed but whose potential can be controlled.

It is possible to produce electric fields of such a nature that electrons (or other charged particles) having equal initial velocities and starting from a common point but leaving in various directions, will converge at some other point in the electric field. It is thus possible to produce an "electron image" of a more or less extended "electron object" in a way analogous to that by which a glass lens produces a luminous image of a luminous object. The electrodes and the associated electric field produced when potentials are applied to the electrodes are spoken of as an "electric electron lens". An analogous condition obtains when a moving electron is subjected to a magnetic field and it is possible to produce an electron image of an electron object by means of a magnetic field. The magnetic field producing such an effect is spoken of as a "magnetic electron lens". We restrict the discussion in the present chapter to the electric type of electron lens, leaving the magnetic type for the following chapter.

The analogy which exists between electric and magnetic electron lenses and optical lenses is not essential to the development of electron-optical theory. However, it is convenient and useful to pursue this analogy, since we can carry over into electron optics well-known optical concepts, such as focal length and image defects.

Figure 14A shows an electric double layer which can be visualized as two plane parallel conductors which are permeable to electrons. (This would be approximated by two sheets of very fine-mesh metallic screen). Let the potential of the conductor at the left be E_1 and the region to the left of this be field-free. Similarly let the conductor to the right have a potential E_2 and let the space to the right be field-free. If an electron passes thru this electrical double layer, entering with a velocity v_1 it will leave with a different velocity v_2, which will be greater than v_1 if E_2 is more positive than E_1. The increase in velocity of the electron will be due to the electric field between 1 and 2, this field being normal to these two surfaces. Therefore v_2 will have a greater component normal to the surfaces than v_1, whereas v_2 will have a component v tangential to the surface which is the same as the tangential component of v_1. If the angles which v_1 and v_2 make with the surface normal are respectively θ and ϕ, it is clear from the vector diagrams shown in Figure 14A that

$$\sin\theta = \frac{v}{v_1},$$

and $$\sin\phi = \frac{v}{v_2},$$

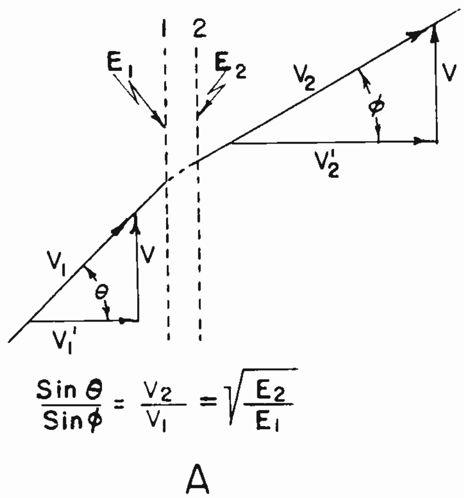
from which it follows that

$$\frac{\sin\theta}{\sin\phi} = \frac{v_2}{v_1}.$$

If the electron has started from rest at a point whose potential is zero, the velocity v_1 at a point whose potential is E_1 is given by

$$\frac{1}{2}\, m\, v_1^2 = E_1 e$$

where m = mass of electron,
v_1 = velocity of electron at point under consideration,
E_1 = potential of point under consideration,
and e = charge of electron.



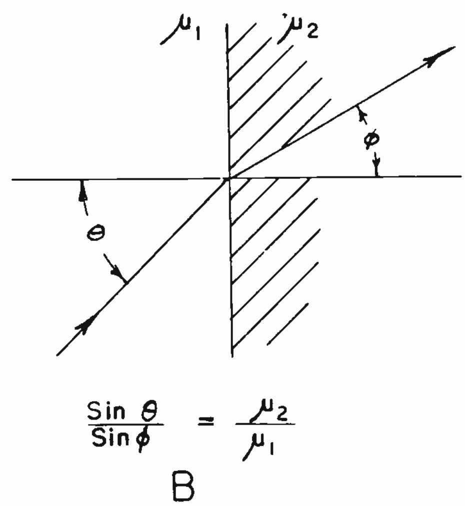


Fig. 14. Analogy Between Electric Double Layer and Passage of Light Ray Thru Interface of Two Media.

Likewise $\frac{1}{2} m v_2^2 = E_2 e.$

It follows that

$$\frac{v_1^2}{v_2^2} = \frac{E_1}{E_2},$$

so that we can write

$$\frac{\sin \theta}{\sin \emptyset} = \sqrt{E_2/E_1}.$$

The light-optical analogy of the electron-optical example of Figure 14A is illustrated in Figure 14B. A ray of light passing from the optical medium of refractive index μ_1 into an optical medium of refractive index μ_2 thru a flat interface at an angle of incidence θ is refracted and leaves the interface at an angle $\emptyset$. The well-known optical law of Snell describing these relations is

$$\frac{\sin \theta}{\sin \emptyset} = \frac{\mu_2}{\mu_1}.$$

From the discussion of Figures 14A and 14B there may be gathered the following electron-optical principles (which can be theoretically deduced with complete rigor and generality):

(1) The geometrical path of an electrically charged particle starting from rest in an electric field, is independent of the magnitude of its charge or its mass. (Of course the sign of the charge on the particle determines in which of two directions it is urged by the electric field.)

(2) The geometrical path of an electrically charged particle in an electric field is independent of the magnitude of the electrode potentials (of which there may be two or more), but depends only on the ratios of these potentials.

(3) The square root of the potential plays the same role in electron optics which the refractive index does in light optics.

Let us now consider two electric double layers of the type described above, which are not plane-parallel, each layer being curved into a spherical shell so that the space between the two layers has a lens shape. This is illustrated in cross-section by Figure 15A, and the light-optics analogy, which is a double convex lens, is shown in Figure 15B. The lens-shaped electric double layer will have the property of being able to focus electrons proceeding from an electron object into an electron image in the same way that the light-optical lens has the property of focusing the rays proceeding from a light object into a light image. In fact, the formula which states the focal length of the light-optical lens in terms of the radii of curvature of the surfaces and the refractive indices of the lens and the surrounding medium can be converted to the corresponding formula for the electron-optical lens by substituting $\sqrt{E_1}$ for μ_1 and $\sqrt{E_2}$ for μ_2.

The light-optical lens is subject to two limitations, namely (1) the refractive indices available for the material (glass) of the lens are limited to about 1.6 times that of the surrounding medium; and (2) the refractive indices are constant and therefore the focal length of a given lens is constant. The electron lens, on the other hand, may have any desired ratio of the voltages E_1 and E_2, and this ratio may be changed at will, thus changing the focal length. The electron lens shown in Figure 15A may be made converging or diverging, or it may even act as an electron mirror, according to the ratio and sign of E_1 and E_2.

However, electron lenses of the type described have no practical utility because no conductors which are freely permeable to electrons are known. If a metallic mesh is used, then no matter how fine the metallic mesh is made, those electrons passing very close to the mesh would be deviated more than those passing thru the aperture centers, thus producing a sort of diffraction effect which would blur the image.

To construct a useful electric electron lens, it is necessary to produce suitably curved equipotential surfaces in free space. This can be done in a large variety of ways. In fact, if any system of arbitrarily shaped apertured conductors,

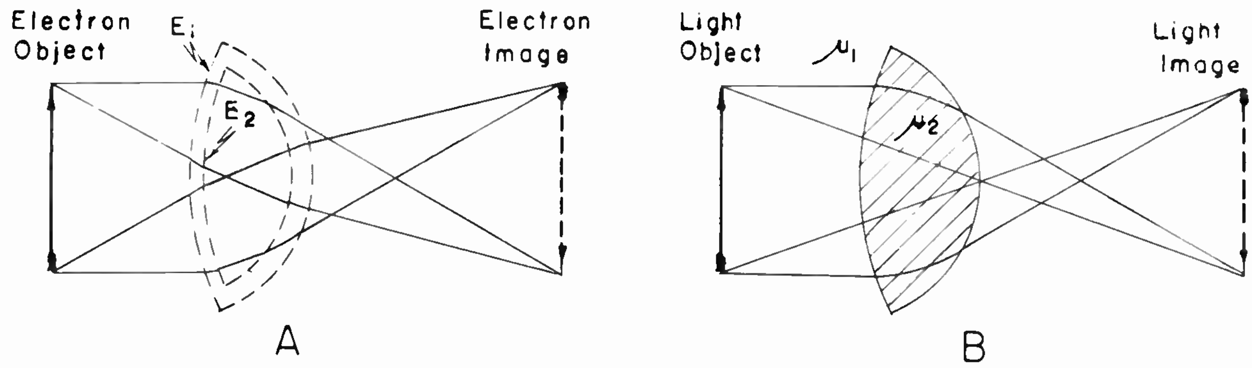


Fig. 15. Hypothetical Electron Lens Made of Double Layers, and the Corresponding Light Analog.

which are surfaces of revolution about a common axis, is connected to an arbitrary set of potentials, an electric electron lens will be produced. The equipotential surfaces of the resultant electric field will in general be curved and they will be surfaces of revolution about the common axis, which is called the electron-optical axis of the system. Of course the usefulness and efficiency of the resultant electric field as a lens will depend on the specific shape and potentials of the conductors. We shall now examine a few of the useful and efficient structures which are used for electric electron lenses in picture tubes.

THE FIRST LENS OF THE ELECTRON GUN

Figure 16 shows a cross-section of the electric equipotential surfaces representing the field produced by a particular electron gun. The grid and the screen grid are metal disks having circular apertures which are accurately aligned on the electron-optical axis. These electrodes constitute the "first lens" of the electron gun.

Phenomena at Cathode

On the cathode surface there is a circular disk (whose diameter is indicated by the line A-B in Figure 16); in front of this disk the potential is positive because the effect of the positive screen grid exceeds that of the negative control grid. Thermionic emission can therefore take place over this disk. Outside of the region of this disk, that is beyond the ends of diameters such as AB, the potential is negative so that thermionic emission is prevented. The boundary of this disk is not sharply defined since the thermionic electrons have some initial velocity with which to overcome a slight retarding field. This velocity distribution is Maxwellian with a most probable velocity of 0.47 equivalent volt for an oxide-coated cathode. As the

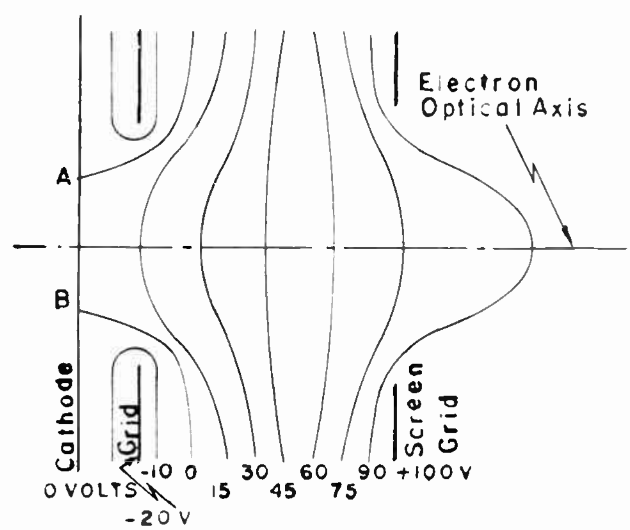


Fig. 16. Equipotential Surfaces at First Lens of Electron Gun.

potential of the grid electrode in Figure 16 is made more negative, keeping the screen-grid voltage constant, the diameter A B of the emitting disk decreases until a value of grid voltage is reached when A B becomes zero and all thermionic emission from the cathode is prevented. This voltage is the grid-cutoff voltage.

Paths of Electrons

The curved equipotential surfaces produce an electron-optical lens effect, but the computation of this effect is no longer as simple as in Figure 15A. Indeed, the light-optical lens which would be the analog of the electron-optical lens of Figure 16 would consist of a nest of infinitely thin lenses having the shapes of the equipotentials, with each successive lens having an infinitesimally different refractive index from the preceding one.

It is possible to determine by both theoretical and experimental means the paths which electrons will take in going thru an electrostatic electron lens. Figure 17 shows the paths of electrons thru a lens of the type of Figure 16.

Consider a point A on the cathode, which is off the electron-optical axis but within the disk which is producing thermionic emission. From the point A thermionic electrons will be emitted in all directions with velocities

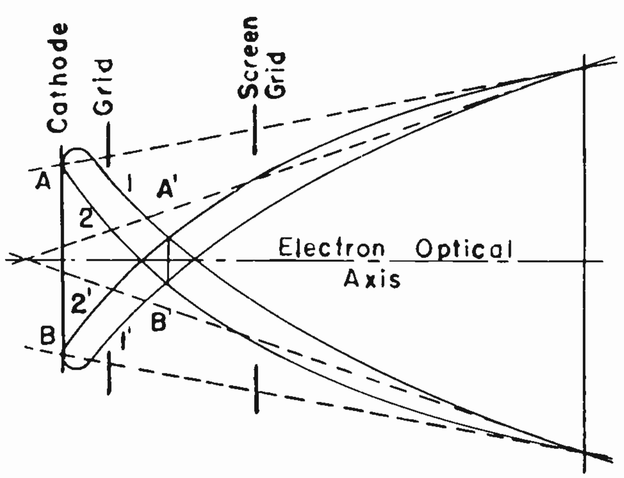


Fig. 17. Electron Paths and Cross-Over in Lens of Figure 16.

having a Maxwellian distribution about a most probable velocity of 0.47 volt. The path of an electron starting from point A in an upward direction tangent to the surface with a velocity of 0.47 volt is shown as curve 1 in Figure 17. An electron starting from point A with the same velocity but going in the opposite direction from the first, that is tangent downward, will travel over the path of curve 2 in Figure 17. If the corresponding paths are determined for similar electrons leaving the point B, diametrically opposite point A with reference to the electron-optical axis, they will of course be found to follow curves 1' and 2' which are geometrically similar to paths 1 and 2.

Electron Cross-Over

Paths 1 and 2' intersect in a point A' whereas paths 2 and 1' intersect in a diametrically opposite point B'. The line A'B' represents the diameter of a disk thru which any electron having a velocity less than 0.47 volt leaving any point on the cathode in any direction must pass. The disk A'B', which is called the "electron cross-over", is not an image of the disk AB but it is the region in which the electron beam has a minimum diameter. For this reason this electron cross-over, which is formed near the cathode by the electric field of the first lens, is used as the electron object which the second lens images on the fluorescent screen. The distribution of electron density over the cross-over varies exponentially along the radius measured from the electron-optical axis. The effect of space charge, which increases with increasing thermionic emission, causes the electron cross-over to spread out laterally as the beam current is increased.

Position of Cross-Over During Modulation

The electron-beam current is controlled by means of the voltage applied to the grid electrode. As the grid potential is varied, the focal length of the first lens is changed and the position of the cross-over changes slightly, moving toward the second lens as the grid is made less negative or the beam current is increased. This effect requires a small adjustment in the focal length of the second lens if the cross-over is to be accurately focused on the fluorescent screen. The relation between focus voltage ratio and grid modulation voltage is shown in Figure 18.

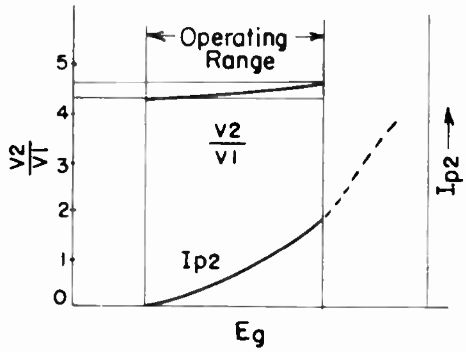


Fig. 18. Second-Lens Voltage Ratio for Perfect Focusing.

THE SECOND LENS OF THE ELECTRON GUN

The function of the electron gun of the tube is to produce a small electron spot at the fluorescent screen. We have seen that the action of the first lens consists of gathering the thermionic electrons from an area of the cathode and converging them thru the much smaller area of the cross-over, as well as directing them along the electron-optical axis. The electron cross-over is used as an electron object by another electric electron lens, referred to as the "second lens", which focuses the cross-over into an electron image thus forming the electron spot on the fluorescent screen.

Two-Cylinder Electron Lens

Figure 19 shows one type of second lens which is commonly used in electrostatically focused tubes. This lens consists of two hollow conducting cylinders whose axes are accurately aligned with the electron-optical axis of the first lens. The equipotential surfaces which represent the electric field produced when potentials are applied to the electrodes, are represented in cross-section in Figure 19. The focal length of the lens can be controlled, as was pointed out above, by controlling the ratio of the electrode voltages. The equipotential surfaces are spherical sections near the electron-optical axis, but are considerably warped from this shape in regions farther from this axis, particularly near the edge of the smaller or first-anode cylinder. This means that the electron beam must be limited to the center portion of the lens so that it does not pass thru the distorted part of the electric field. The distortion which this electron lens produces in the outer zones is analogous to the spherical aberration which an uncorrected glass lens produces in an optical image if too large an aperture is used.

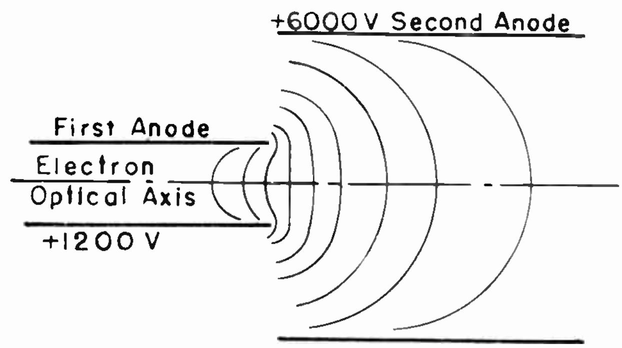


Fig. 19. Arrangement of Second Lens.

Magnification of Lens

The position of this second lens between the electron object and the fluorescent screen determines the magnification which the lens produces. The magnification is given roughly by the following equation:

$$m = \frac{b}{a}\sqrt{\frac{V_1}{V_2}},$$

where m = Magnification = $\frac{\text{Size of image}}{\text{Size of object}}$,

b = Distance of image from lens,

a = Distance of object from lens,

V_2 = Second-anode voltage,

and V_1 = First-anode voltage.

Since we wish to obtain as small an electron spot as possible on the screen, m

should be small. Although it appears from the equation that m can be diminished indefinitely by moving the second lens closer and closer to the screen, thus decreasing b and increasing a, this procedure will have two adverse effects on the tube characteristics, namely: (1) as a is increased, the effective aperture of the second lens is decreased and the beam current is diminished accordingly; and (2) as b is decreased the deflection sensitivity of the tube is decreased. The optimum position of the second lens between electron object and electron image involves a compromise among these and other factors.

Arrangement of One Type of Practical Tube

In Figure 1 on page 192 there has been shown a cross-section of an electrostatically focused type of tube which has been made in our laboratories. The shape of the cathode-ray beam for a particular set of electrode potentials is also shown. The beam-limiting apertures in the first anode allow only a limited central portion of the cone of cathode rays, coming from the first lens, to get into the second lens. The second of these apertures is the larger; it is provided to catch secondary electrons originating at the first aperture, while passing all the normal beam. The portion of the cathode ray which is intercepted by these apertures constitutes the first-anode current. As the grid voltage is made more negative the angle of the cone of electrons from the first lens decreases, approaching zero at the grid-cutoff voltage. When the angle of this cone decreases until the beam no longer strikes the first beam-limiting aperture in the first anode, the first-anode current becomes zero. Figure 20 shows the first-anode current I_{p1} and the beam current I_{p2} plotted on the same ordinate scale against grid voltage E_g.

Focus Voltage Ratio

The focal length of the second lens is determined by the ratio of the first-anode and second-anode voltages. This voltage ratio must be adjusted so that the electron cross-over is accurately focused on the fluorescent screen. The

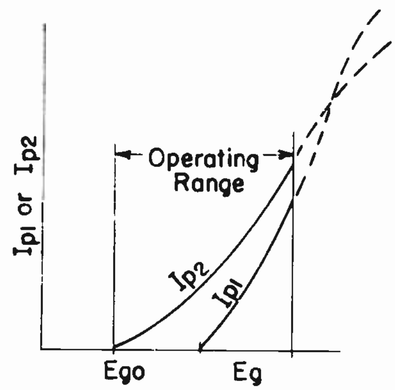


Fig. 20. First-Anode and Second-Anode Currents for Various Grid Potentials.

voltage ratio required for focus is independent of the magnitude of second-anode voltage. If both the first-anode and second-anode voltages are derived from a common potentiometer, this voltage ratio, and therefore the focus, will be independent of variations of voltage across the potentiometer, assuming that the total potentiometer resistance is low in comparison with the tube resistance.

FACTORS DETERMINING MAXIMUM USABLE BEAM CURRENT

If the width of the line in the raster is measured for a number of different values of beam current, it is found that this width increases as the beam current is increased. This effect is produced by the space charge at the cross-over as mentioned above.

Figure 21 shows both the line width D and the beam current I_{p2} plotted as a function of grid voltage for a typical tube. The horizontal line marked D_0 indicates the ordinate for the critical or limiting effective spot size described above. The values of D are measured with a microscope or by means of a resolving-power chart as previously described. The point where the D curve intersects the D_0 limit line determines the upper limit of the operating range. A vertical line dropped from this point to the abscissa axis will intersect the beam-current curve and mark off the upper limit of the beam current I_{p2} as shown.

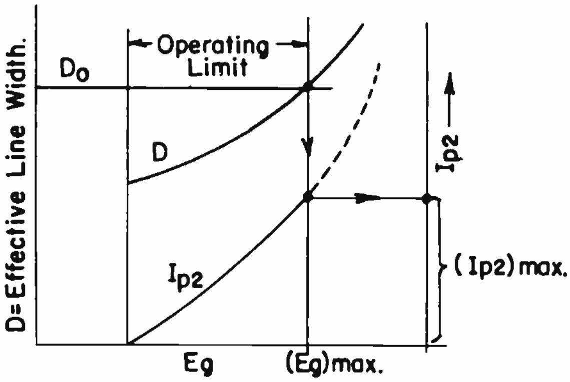


Fig. 21. Determination of Maximum Beam Current According to Spot Size.

If the beam current exceeds this limiting value, the increase of spot size begins to limit the amount of detail. This loss of detail occurs only in the brightest part of the television picture, and it is therefore permissible to exceed this limit slightly. If the slope of the D curve is small compared to the slope of the I_{p2} curve, a large gain in picture brightness can be obtained at the expense of only a small loss of detail which will be confined to the brightest parts of the picture. The amount of excess modulation voltage which can be tolerated depends also on the nature of the image to be reproduced.

FURTHER TREATMENT

The discussion of the picture tube will be concluded in the next chapter.

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