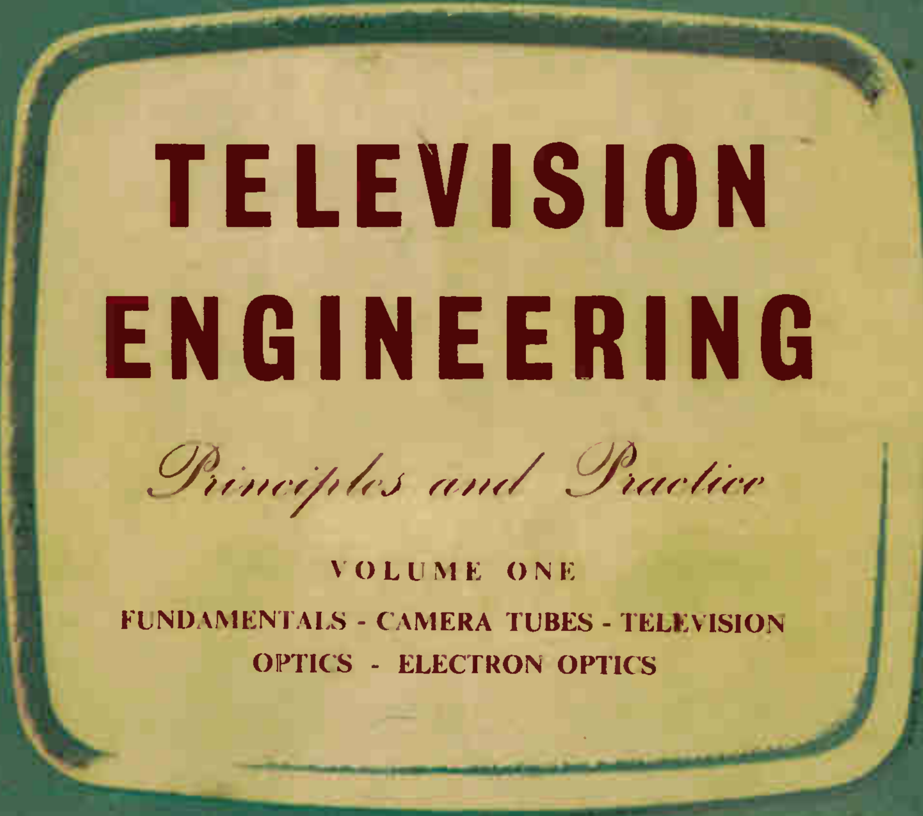
BBC ENGINEERING TRAINING MANUAL



TELEVISION ENGINEERING

Principles and Practice

VOLUME ONE

FUNDAMENTALS - CAMERA TUBES - TELEVISION OPTICS - ELECTRON OPTICS

S. W. AMOS, B.Sc.(Hons.), A.M.I.E.E. and D. C. BIRKINSHAW, M.B.E., M.A., M.I.E.E.
in collaboration with J. L. BLISS, A.M.I.E.E.

A 'WIRELESS WORLD' PUBLICATION

About This Book

This is the first volume of a textbook on television engineering written by members of the BBC Engineering Training Department, primarily for the instruction of the Corporation's own operating and maintenance staff. The work is intended to provide a comprehensive survey of modern television principles and practice, on both the transmitting and receiving sides.

This first volume discusses in detail the vision waveform derived from synchronizing and picture signals. Types of camera tubes in use by the BBC and lenses are then described, and the final chapters are devoted to electron optics, involving a study of electric and magnetic lenses. The second volume, now in course of preparation, will cover vision-frequency amplifiers and waveform generation, and later volumes will deal with the remaining aspects of the subject.

The technical level of the work has been devised to satisfy the student grade; mathematical argument has been excluded from the text, but appendices are included where special treatment of particular subjects has seemed desirable.

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TELEVISION ENGINEERING
Principles and Practice

VOLUME ONE

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BBC ENGINEERING TRAINING MANUALS

TELEVISION ENGINEERING
Principles and Practice

VOLUME ONE:
FUNDAMENTALS, CAMERA TUBES,
TELEVISION OPTICS, ELECTRON OPTICS

By
S. W. AMOS, B.SC.(Hons.), A.M.I.E.E.
and
D. C. BIRKINSHAW, M.B.E., M.A., M.I.E.E.
in collaboration with
J. L. BLISS, A.M.I.E.E.

With 188 illustrations

Published for
Wireless World

LONDON · ILIFFE & SONS, LTD.

First published 1953

Published, by arrangement with the BBC, for "Wireless World" by
*Iliffe & Sons, Ltd., Dorset House, Stamford Street, London, S.E.*1

Made and printed in England at The Chapel River Press, Andover, Hants
BKS 1626 1953

ACKNOWLEDGMENTS

THE BBC acknowledges with thanks the detailed criticisms and suggestions for enlargement of this book made by the following organizations: Messrs. Electric and Musical Industries, Ltd., Messrs. The English Electric Co., Ltd., Messrs. Mullard, Ltd., and Messrs. Pye, Ltd.

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CONTENTS

PREFACE

THIS is the first volume of a BBC textbook on television engineering written primarily for the Corporation's own operation and maintenance staff, and intended to provide a comprehensive survey of modern television principles.

This venture of the BBC Engineering Division was originally inspired by D. C. Birkinshaw, M.B.E., M.A., M.I.E.E., Superintendent Engineer Television, who wrote in 1937 the first BBC television manual on the London Television Station. The text of the present volume has been written by S. W. Amos, B.Sc., A.M.I.E.E., of the Engineering Training Department, working in collaboration with D. C. Birkinshaw and with J. L. Bliss, A.M.I.E.E., of the Designs Department. The Technical Instructions Section of the Engineering Training Department has been responsible for final editing.

In this volume, the vision waveform derived from synchronizing and picture signals is discussed in detail; various camera tubes and lenses are described; in the final chapters attention is given to electron optics, involving a study of electric and magnetic lenses. Volume Two, in preparation at the time of writing, will cover vision-frequency amplifiers and waveform generation.

The technical level of this volume has been devised to satisfy the student grade; mathematical argument has been excluded from the text, but appendices are included where special treatment of particular subjects has seemed desirable.

In permitting publication of this book, the BBC is continuing its policy of placing the specialized knowledge gained by its engineers in building up and operating a national service at the disposal of all those interested in the development of broadcasting and television engineering.

PRINCIPAL SYMBOLS USED

A	Area
B	Brightness
C	Capacitance
D	Displacement of electron beam on target
E	Illumination
E_n	Normal illumination
F	(i) Mechanical force
	(ii) Luminous flux
I	(i) Electric current
	(ii) Luminous intensity
L	Number of lines in television system
M	Magnification of an optical system
N	Number of turns on a coil
P	Picture frequency
Q	Quantity of electricity
R	Radius of curvature of a mirror or lens surface
S_l	Duration of line-suppression signal
S_p	Number of lines suppressed by picture-suppression signal
T	Periodic time of an oscillation
T_l	Time of one line (= 1/line frequency)
V	Electric potential

a	(i) Acceleration
	(ii) Observed aspect ratio
	(iii) Spacing between electrostatic deflecting plates
a'	Electrical aspect ratio
b	Length of electric or magnetic deflecting field
c	(i) Velocity of light
	(ii) Diameter of circle of confusion
d	(i) Distance
	(ii) Diameter of entrance pupil of a lens system
e	Charge on an electron
f	(i) Frequency
	(ii) Focal length of a spherical mirror or lens
h	Height
i	(i) Electric current
	(ii) Angle of incidence of light ray
k	Secondary-emission ratio
m	Mass (in particular of an electron)
n	Refractive index

r	(i) Angle of reflection or refraction (ii) Radius of a circle
t	(i) Time (ii) Thickness of a dielectric
v	Velocity (in particular of an electron)
w	Width
x	Distance (in particular of an object from the pole of an optical system)
x'	Distance of an image from the pole of an optical system
x_h	Hyperfocal distance

ϵ	Electric intensity
α	Angular field of a lens system
γ	Gamma value of a television system
ρ	Reflection coefficient
τ	Transmission coefficient
θ	(i) Angle of incidence of a light beam (ii) Angle subtended by entrance pupil at object point
θ'	Angle subtended by exit pupil at image point
ϕ	Angle subtended by an object at principal point of an optical system
ϕ'	Angle subtended by an image at the principal point of an optical system
ω	(i) Angular frequency ($= 2\pi \times$ frequency) (ii) Solid angle

PART I: FUNDAMENTALS

CHAPTER 1

FUNDAMENTAL PRINCIPLES

1.1 INTRODUCTION

TELEVISION is the art of instantaneously producing at a distance a transient visible image of an actual or recorded scene by means of an electrical system of telecommunication.*

The term " scene " as used in this definition has a wide technical meaning; fundamentally, any area capable of sending out light (usually by reflection) constitutes a scene. Examples of scenes are a cricket pitch, a drawing room, the field of view of a microscope and one picture (i.e., one frame) of a cinema film: the last-mentioned is an example of a recorded scene.

The first process in a television system is the production of an optical image of the scene. This image is regarded as composed of a large number of small sub-areas known as *elements*. If all the elements reflect the same amount of light, they have the same brightness or tonal value and the scene has no detail. Such a scene is blank and conveys no intelligence to the observer. If, however, some elements reflect more or less light than others, the scene possesses detail and can convey intelligence to the observer. It is the function of a television system to transmit this intelligence to a distant point, and to reconstitute at that point an image or picture which sends to the eye of an observer substantially the same intelligence as he would receive by standing before the original scene.

To televise a scene, information about the tonal values of the elements is collected and sent over a transmission line or a radio link to the receiving point. The intelligence received from the scene in the form of light must be converted into electrical intelligence which can be transmitted over the link and, for this purpose, a television camera tube based on photo-electric principles is used.

If such a tube collects the light from one particular element of the optical image, the tube output will vary with time in a manner dependent on the variation with time of the tonal value of the

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* Definition 5101, B.S.204 : 1943, British Standards Institution.

element. The tube output can be transmitted, after amplification if necessary, over a link to the receiving end where the electrical intelligence is converted into visible intelligence, usually by means of a cathode-ray tube.

The camera-tube output gives information at any instant about the tonal value, at that instant, of one element only and it is impossible, using only a single varying quantity such as the camera output, to create instantaneously a complete image of the scene at the receiving point. This difficulty could be overcome by using a large number of varying currents to represent the electrical intelligence from an equal number of elements, the currents being transmitted simultaneously over a number of links, as suggested in Fig. 1. It is more convenient and more economical, however, to use a single current and to adopt some system by which the intelligence from the elements constituting the image is transmitted successively. This process is termed *scanning*.

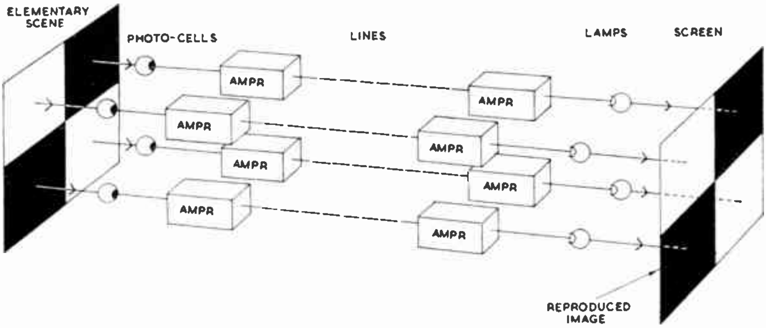

Fig. 1—Use of four varying currents to transmit intelligence concerning a four-element picture

1.2 SCANNING

In sequential scanning, the television camera examines each element of the scene in turn and gives an electrical output determined by the tonal value of each. When the last element has been examined, the scanning agent returns to the first element and the cycle is repeated indefinitely. At the receiving end of the link, there is another scanning agent which follows the movements of that at the transmitting end. A finite time is taken in examining all the elements of a scene and in building up a complete image at the receiver. This time must be short to enable pictures to be transmitted in quick succession, as in cinema film projection, persistence of vision ensuring that transmission appears continuous and that the reproduction of action and movement in the image appears natural.

The number of complete pictures transmitted per second is known as the *picture frequency* and must be high enough to give the impression of natural movement and to minimize flicker. It is difficult to give a precise minimum value for the picture frequency because the flicker depends on the brightness of the image and on the decay time of the receiving screen material, but with sequential scanning results are reasonably satisfactory with a picture frequency of 50 per second.

The scanning agent at the transmitter is usually an electron beam and may move over the image in a number of different ways; for example, it may cover the image in a series of horizontal, vertical or spiral lines. Whatever pattern is adopted the scanning beam at the receiver must faithfully follow the movements of the beam at the transmitter. It might appear that the form of the scanning pattern does not greatly matter but in practice best results are obtained when the elements constituting the image are arranged in horizontal rows or lines and most television services use a pattern of this type. During transmission, the scanning beam moves along the rows of elements from left to right, passing over each of the elements in turn and returning rapidly at the end of each line to the left-hand side of the image. The movement of the beam along the lines and the rapid flyback may be compared with that of the eye in reading a printed page.

The scanning beam also has a vertical component of motion which is slow compared with the horizontal movement and during the time occupied by each horizontal traverse and flyback the beam moves downwards through a distance equal to the vertical dimension of an element. The effect of these two motions at right angles is that the whole image is traversed in a number of approximately horizontal lines. When the scanning beam reaches the bottom right-hand corner of the scene there is a flyback which returns the beam to the top left-hand corner to repeat the scanning cycle.

The scanning system just described is termed *sequential* and in a television system using sequential scanning there is one vertical sweep of the scanning beam for each transmitted picture. But, provided the scanning beams at receiver and transmitter keep in step, there is no need for the lines to be traversed in this order and in *twin-interlaced* scanning the odd-numbered lines are first scanned, the even-numbered ones being missed, after which the even-numbered lines are scanned and the odd-numbered ones missed. In such a system there are two vertical sweeps of the scanning beam for each complete picture. Interlaced scanning has certain advantages over sequential scanning and these will be described later.

The half-pictures composed entirely of odd-numbered, or entirely of even-numbered, lines are termed *frames* and the number of frames transmitted per second is known as the *frame frequency*. In a twin-interlaced system the frame frequency is twice the picture frequency.

1.3 Synchronizing Signals

To obtain a picture at the receiving end of the link, the scanning beam at the receiver must keep accurately in step with that at the transmitter; in other words, at any instant, both scanning beams must be moving over the same line of the image and must be at the same point in that line. This is achieved by means of synchronizing signals which are sent from the transmitter to the receiver for this purpose. These signals are additional to and separate from the picture signals which represent the light and shade of the elements composing the scene.

A synchronizing signal is sent out every time the scanning beam at the transmitter reaches the end of a line; this signal is termed the line-synchronizing signal (abbreviated to *line-sync* signal) and has the function of initiating line flyback at the receiver. Another synchronizing signal is sent out every time the scanning beam at the transmitter reaches the bottom of the image; this signal is termed the frame-synchronizing signal (abbreviated to *frame-sync* signal) and has the function of initiating frame flyback at the receiver. It must be possible at the receiver to separate the line- from the frame-sync signal by relatively simple means and the frame-sync signal is, therefore, different in form from the line-sync signal.

Thus in a television system two sets of signals must be transmitted to the receiver:

(1) the picture signal carrying the intelligence corresponding to the brightness and detail of the picture,
(2) the synchronizing signals enabling the receiver to reconstitute the picture so that all details take up their correct relative positions.

These two sets of signals have separate functions to perform at the receiver and must be effectively transmitted as separate entities, each signal retaining its particular shape. Fundamentally two separate currents must be sent to the receiver, one to represent the picture signals and the other the synchronizing signals, but it is possible and more economical to transmit both signals by use of one varying current. This method gives satisfactory results provided that the picture and synchronizing signals are combined in such a way that they can be easily separated at the receiver. The composite signal obtained by combining a picture with a synchronizing signal is known as a *vision signal.*

The sound accompaniment for the picture is usually transmitted by a separate current over a separate link to the receiver although television systems have been developed in which the sound is combined with the sync signals and can be transmitted over the same link as the picture and sync signals. In the present BBC television system vision and sound signals are transmitted over separate links but it is common practice for the aerial and early stages of receivers to accept and amplify vision and sound transmissions together.

1.4 PICTURE SIGNAL

White and Black Levels

The picture signal voltage at any point in a television system varies between two limits, one representing the maximum brightness it is intended to transmit and known as *white level* and the other representing zero tonal value or black and known as *black level.* White level may be positive or negative with respect to black level but for the sake of consistency is shown as positive in Figs. 2 to 6. The magnitude of picture signals is usually expressed as a potential difference with respect to black level.

The voltage representing black level has different values at different points in the chain of equipment between camera and receiving cathode-ray tube, and may be positive, negative or zero. At certain points in the chain, for example at a picture-tube input, black level must be a fixed voltage but at other points in the chain, for a reason given later, black level may vary with the picture brightness. At any given point in the chain there is a fixed potential difference between white level and black level; thus white level is also fixed at those points in the chain where black level is fixed but varies with picture brightness at others.

Typical picture waveforms are shown in Figs. 2, 3 and 4; in Fig. 2 black level is zero voltage, in Fig. 3 it is a positive voltage and in Fig. 4 a negative voltage. In all diagrams white level is shown as positive with respect to a black level but in practice, of course, it may be negative. It is possible to " lift " a picture signal of the form shown in Fig. 2 to that shown in Fig. 3, by superimposing on it a steady positive voltage; alternatively this same signal may be converted to the form of Fig. 4 by combining with it a steady negative voltage.

The output of a television camera depends on the amount of light associated with the elements comprising the image; this light can vary between zero for elements in black areas of the image and a maximum for elements in the brightest parts of the image.

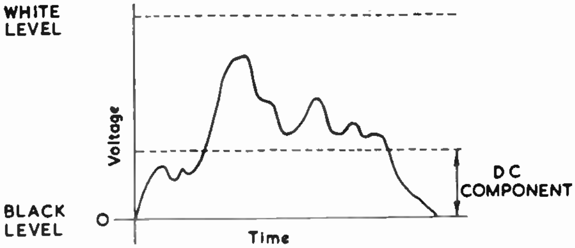

Fig. 2—Waveform of picture signal when black level is zero voltage

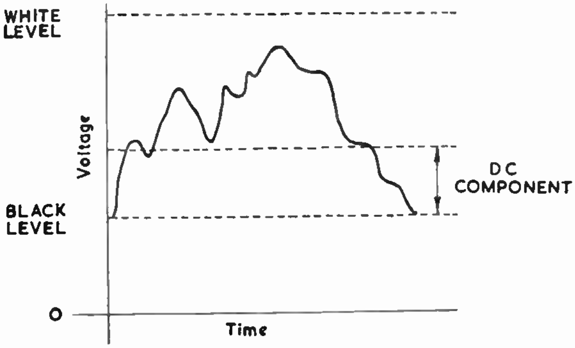

Fig. 3—Waveform of picture signal when black level is a positive voltage

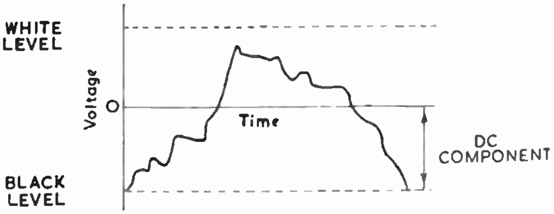

Fig. 4—Waveform of picture signal when black level is a negative voltage

Clearly no element can have less than zero light and the camera output signal is always positive or always negative with respect to black level; in other words the picture waveform lies wholly to one side of the black level datum line as shown in Figs. 2 and 4.

The picture signal, measured with respect to black level, is unidirectional and can be regarded as a mixture of a direct or d.c. component and an alternating or a.c. component. For example, the picture signal illustrated in Fig. 5 (a) can be resolved into the d.c. component of Fig. 5 (b) and the a.c. component of Fig. 5 (c). The magnitude of the d.c. component is indicated in Figs. 2 to 4. The d.c. component is equal to the mean value of the picture signal and represents the mean brightness of the elements scanned whereas the a.c. components represent the detail in the picture.

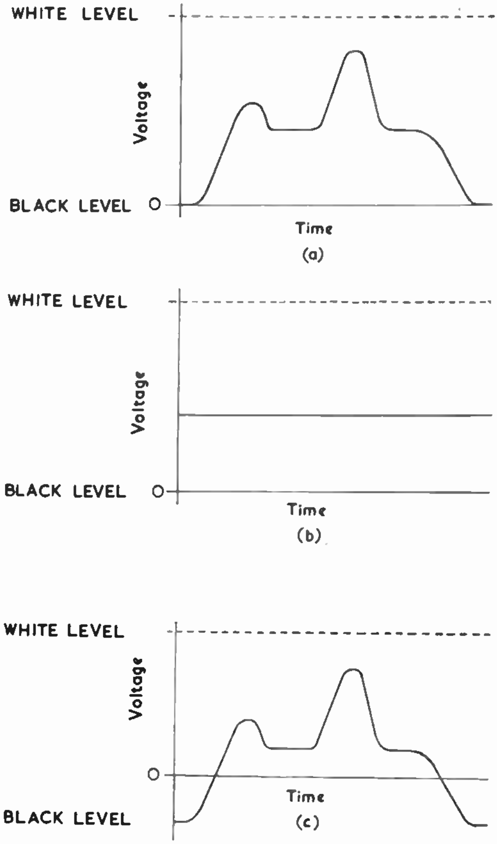

Fig. 5—Typical picture waveform (a) with the d.c. component shown at (b) and the a.c. component at (c)

D.C. Component

The d.c. component represents the mean brightness of the image and varies with time in a manner dependent on the distribution and variation of light and shade in the picture. The magnitude of the d.c. component can be envisaged by considering the extreme cases of images which are completely white or completely black. If the image is completely black the picture signal is steady and equal to zero (with respect to black level); the d.c. component is also zero. On the other hand if the image is completely white the picture signal is constant and equal to white level; the d.c. component is now a maximum and is equal to the difference between white and black levels. For a picture in which the upper half is black and the lower half white, the picture signal will be zero for the first half of the picture period and a maximum for the remaining half, the d.c. component being equal to half the difference between white and black levels.

To consider more practical types of image: for an image of a darkened room the picture signal has a very small d.c. component; when the room lights are switched on to brighten the scene the d.c. component increases. It is thus possible to have two picture signals of similar waveform, one situated near black level and the other near white level; these signals represent the same picture detail, but the first represents a darkened scene and the second a brighter scene. Thus the d.c. component is an essential part of the picture signal and must be present when the signal is finally applied to the reproducing cathode-ray tube.

Provided the d.c. component is present, the voltage representing black level at any point in the television chain is a fixed voltage which does not vary with the picture signal. White level, too, is a fixed voltage at any point where the d.c. component is present.

If the d.c. component in the picture signal is to be retained throughout the television chain, each link must be made capable of carrying d.c. and each amplifier must be direct-coupled, containing no transformers and no coupling capacitors. This is impractical because multi-stage d.c. amplifiers are complex in design and tend to be unstable in use.

Use of A.C.-coupled Picture-signal Amplifiers

If the d.c. component of a signal such as that illustrated in Fig. 2 is lost (by passing it through a capacitor or a transformer) it is possible, under certain circumstances, to recreate the missing component by a method known as *d.c. restoration* which is described in another volume in this series. D.c. restoration is only possible provided the picture signal contains a reference signal related to black level and the television waveform therefore includes such a signal. Thus the picture signal may be amplified by conventional a.c.-coupled amplifiers, the d.c. component being reintroduced by d.c. restoration whenever it is required.

When the d.c. component is rejected, the picture signal becomes alternating with equal areas above and below zero voltage as shown in Fig. 5 (c). In effect the signal has been bodily " lowered " until the line indicating the mean value of the waveform coincides with zero volts. Black level is now a negative voltage numerically equal to the d.c. component of the signal and varies with the d.c. component of the signal. As shown in Fig. 6, black level is more negative when the image is bright than when it is dark. Thus at points in the television chain where the d.c. component is absent, black level varies with the mean picture brightness. White level, which at any given point in the chain is always a fixed p.d. above or below black level, must also vary when the d.c. component is missing.

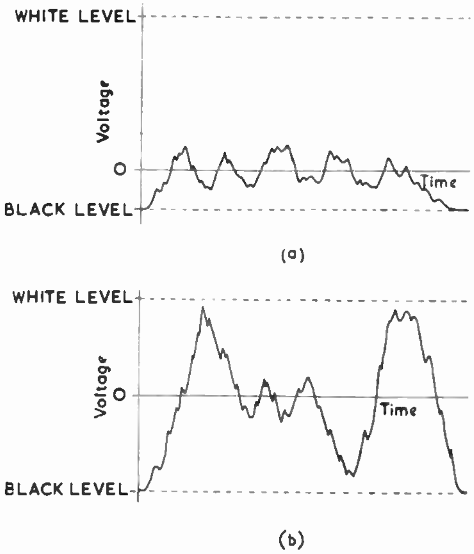

Fig. 6—When the d.c. component is missing black level is more negative when the mean brightness is high (b) than when it is low (a)

The conclusions of the previous paragraphs can be briefly summarized as follows: at points in the chain where the d.c. component is present, white and black levels are fixed but the d.c. component of the picture signal varies with the mean brightness of the image; at points where the d.c. component is absent, the average value of the picture signal is fixed but white and black levels vary with the image brightness.

1.5 VISION SIGNAL

The synchronizing signals occur at regular intervals and have the form of rectangular pulses as shown in Fig. 7; the signals here are illustrated as a series of negative-going pulses.

The picture and sync signals are combined to produce a single composite signal in which the individuality of both components is preserved and which can be represented by one varying voltage.

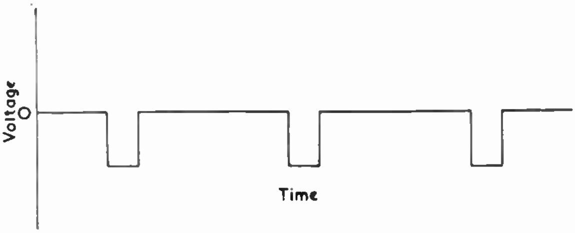

Fig. 7—Train of rectangular sync pulses

This is achieved by arranging for the datum line of a positive-going picture signal such as that in Fig. 2 to coincide with that of a negative-going sync signal such as that in Fig. 7. The composite signal so obtained has a waveform similar to that shown in Fig. 8; this signal is shown with a black level of zero volts, but the black level voltage may have a positive, negative or zero value, depending

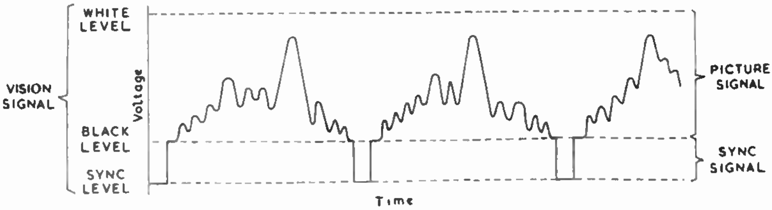

Fig. 8—Vision signal obtained by combining a picture signal with a sync signal

on the point in the chain at which it is measured. Provided the d.c. component is retained, black level can always be made to coincide with zero volts by superimposing the vision signal on a steady voltage of correct sign and amplitude.

The essential feature of this composite signal is that the shape of picture and sync signals is preserved, the positive part of the composite signal representing the detail in the picture whilst the negative part maintains synchronism. The two components of the composite signal can be separated easily by methods based on sense or polarity.

The sync pulses are produced by reducing the voltage to a value below black level; the reduced level corresponds to " blacker than black " and the sync pulses make no visible effect on the receiver screen. The voltage value during the transmission of the sync pulses is known as sync level; this voltage value together with that corresponding to white and black levels are three important voltage characteristics of a television system. The dividing line between picture and sync signals corresponds, of course, to black level and the transmission of a steady voltage equivalent to black level represents periods when neither picture nor sync signals are being transmitted.

Picture-sync Ratio

In Fig. 8 the picture signal occupies the signal range WB and the sync signals occupy range BS. The ratio of picture-signal range to sync-signal range is termed the *picture-sync ratio* and is a further important characteristic of a television system.

$$\text{Picture-sync ratio} = \frac{WB}{BS}$$

This ratio has different values at different points in the television chain. In the modulated carrier radiated from the transmitter the picture-sync ratio is 7 : 3 both in the BBC and other television systems, but in some of the early links in the chain the ratio is made 1 : 1, i.e., the sync-signal amplitude is equal to the peak white-signal amplitude.

If the picture-sync ratio is high, say 3 : 1, and the signal-noise ratio low, the sync signal may not be adequate to give reliable synchronism, although the picture signal may be capable of providing an acceptable picture. On the other hand if the picture-sync ratio is low, say 1 : 1, synchronism may be still good when the signal-noise ratio is too low to give a picture of reasonable entertainment value. In either case the power of the vision-frequency amplifiers is not used very efficiently.

The power of the vision-frequency amplifiers is used to best advantage when the picture-sync ratio is approximately 7 : 3 and this is the value used in most television systems. With this particular value of picture-sync ratio, when the signal-noise ratio is low and the picture signal is just acceptable, the sync signal is also just acceptable and any deterioration in signal-noise ratio causes the picture to become unsatisfactory and the sync signal incapable of holding it steady.

Vision-frequency Range

The vision signal is generated by repeatedly scanning the elements composing an image of the scene; the beam moves over them in a series of lines and the output at any element represents the tonal value of that element. The vision signal contains two strongly marked frequencies, the first equal to the number of frames transmitted per second, and the second equal to the number of lines scanned per second. The second component is known as the *line frequency* and is equal to LP where L is the number of lines composing the picture and P is the number of pictures transmitted per second. If $L = 405$ and $P = 25$, the line frequency is $25 \times 405 = 10{,}125$ per second.

In addition to these two alternating components, the vision signal has a d.c. component and high-frequency components (harmonics of the frame and line frequencies) corresponding to detail in the picture. The upper frequency limit depends on the picture frequency, the number of lines composing the picture and the shape of the picture, and can be assessed in the following way:

An element of a television picture may be defined as an area, generally assumed to be square, with a maximum dimension equal to h/L where h is the height of the picture and L is the number of lines composing it. Fig. 9 illustrates a picture which is composed of alternate black and white square elements. The scanning beam at the transmitter usually has dimensions approximately equal to those of an element and the finest detail which can then be transmitted has the size of an element; this is the detail which exists when a white element is next to a black one. Thus if Fig. 9 has L horizontal rows of elements, this diagram represents the finest detail which can be transmitted when the scanning beam has dimensions approximating to those of an element.

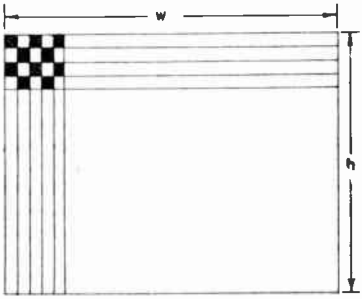

Fig. 9—A picture divided into alternate black and white elements

The vision signal does not consist of an uninterrupted succession of picture signals generated by scanning rows of elements. At the end of each line, a line-sync signal is introduced and this signal is contained within the period of black level known as the *line-suppression period.* This period has a duration S_l appreciable compared with the period T_l of one line ($T_l = 1/\text{line frequency}$). Moreover at the end of each frame, a frame-sync signal is introduced and this signal is similarly contained within a period of black level known as the *frame-suppression period.* This period has a duration which is an appreciable fraction of the frame period (1/frame frequency) and has the effect of suppressing a number of lines S_p. The number of lines seen in the reproduced picture (known as *active* lines) is thus $(L - S_p)$.

If Fig. 9 represents the reproduced picture, there are $(L - S_p)$ horizontal rows of elements and the vertical dimension of each element is $h/(L - S_p)$. The ratio of width to height of the received picture is known as the *aspect ratio a*, and if we assume the elements to be square, there are $a\,(L - S_p)$ elements in each row.* During scanning of each line, the vision signal rises when the scanning beam traverses a white element and falls when it traverses a black element. One rise followed by a fall constitutes one cycle of alternation in the vision signal since the positive half of one cycle corresponds to a white element and the negative half to a black element. The number of cycles corresponding to one line is thus $a(L - S_p)/2$ and these are generated in the camera in a period $T_l - S_l$. Thus the frequency corresponding to detail of the size of an element is given by

$$f = \frac{a(L - S_p)}{2(T_l - S_l)} \quad \cdot\cdot \quad \cdot\cdot \quad (1)$$

In the British television system $a = 4/3$, $L = 405$, $S_p = 28$, $T_l = 98{\cdot}7$ μsecs and $S_l = 18$ μsecs. Substituting these values in expression (1) gives

$$f = \frac{1{\cdot}333 \times 377}{2(98{\cdot}7 - 18)}$$
$$= 3{\cdot}11 \text{ Mc/s.}$$

The vision signal corresponding to a picture composed of alternate black and white elements is, of course, a square wave with a frequency given by expression (1) and if such a picture were scanned in a camera with an electron beam of negligibly small dimensions, the camera output would have a square waveform. Such a signal

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* The assumption that the elements are square is equivalent to assuming that the horizontal definition of the television system is equal to the vertical definition: but the reproduced picture is made up of horizontal lines and the vertical definition (or resolution) differs in nature from the horizontal definition as explained on page 27.

has components at frequencies f, $2f$, $3f$, etc., up to an infinite frequency. If, as in practice, the scanning beam has dimensions comparable with those of an element, as assumed above, the upper frequency components are greatly attenuated and the camera output tends to be sinusoidal in form and with a frequency given by (1). This frequency, the fundamental component of the square wave corresponding to a picture of alternate black and white elements, is generally regarded as the upper frequency limit in vision-frequency amplifiers.

1.6 ELECTRICAL AND OBSERVED ASPECT RATIO

If the line-suppression period did not exist, the length of each line on a receiving screen would be longer in the ratio $T_l/(T_l - S_l)$. Similarly, if the frame-suppression period did not exist, the vertical height of the reproduced picture would be greater in the ratio $L/(L - S_p)$. These increases are illustrated in Fig. 10, in which the inner rectangle $CHFJ$ represents the observed picture with an aspect ratio of a. Rectangle $ABCD$ contains that part of the line length which is not seen because of the line-suppression period, and rectangle $AEFG$ contains those lines which are not seen because of the frame-suppression period. The aspect ratio of the outer rectangle $ABJE$ is known as the electrical aspect ratio a' and is related to the observed aspect ratio a by the expression

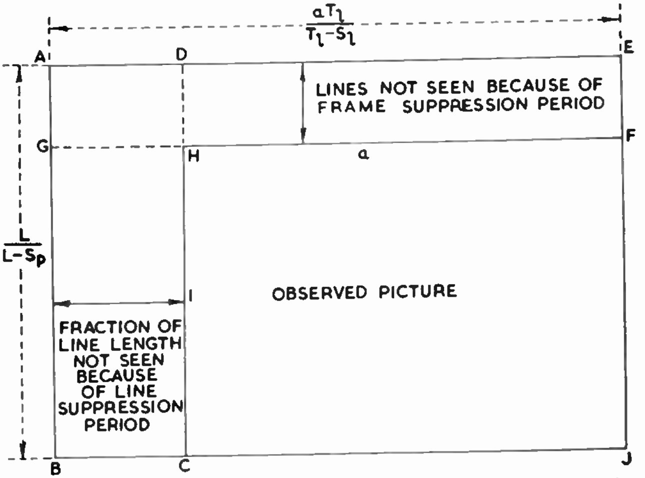


Fig. 10—Relationship between electrical and observed aspect ratios

$$a' = a \cdot \frac{T_l}{T_l - S_l} \cdot \frac{L - S_p}{L} \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

Substituting the British standards

$$\begin{aligned} a' &= 1{\cdot}333 \times \frac{98{\cdot}7}{80{\cdot}8} \times \frac{377}{405} \\ &= 1{\cdot}516 \end{aligned}$$

A useful feature of the electrical aspect ratio is that the frequency limit for vision-frequency amplifiers can be calculated from it using the relationship

$$f = \frac{Pa'L^2}{2} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (3)$$

For the British standards $P = 25$, $a' = 1{\cdot}516$, and $L = 405$. From expression (3) f is thus given by

$$\begin{aligned} f &= \frac{25 \times 1{\cdot}516 \times 405^2}{2} \\ &= 3{\cdot}11 \text{ Mc/s as before.} \end{aligned}$$

Expression (3) can be deduced from Fig. 9 if this is regarded as divided into L horizontal rows of alternate black and white elements. If the elements are assumed square, there are $a'L$ in each line and $a'L^2$ in the complete picture. This number of elements corresponds to $a'L^2/2$ cycles which are generated in the camera in one picture period. The number of cycles generated per second is thus $Pa'L^2/2$.

1.7 HORIZONTAL AND VERTICAL RESOLUTION

The horizontal definition or resolution of a television system is its ability to reproduce abrupt changes in tonal value occurring along the scanning lines; in other words the horizontal definition measures the sharpness of reproduction of vertical edges or lines. Similarly the vertical definition or resolution is the ability of the system to reproduce abrupt changes in tonal value occurring along a line at right angles to the scanning lines. The vertical resolution measures the sharpness of reproduction of horizontal lines in the image.

The reproduced image is built up of a number of horizontal lines and the vertical resolution is different in nature from the horizontal resolution; this difference will be illustrated by two features of the image:

(i) The greatest vertical resolution occurs when a point in a particular line is black and the corresponding point in the line immediately above or below is white. This maximum resolution can be obtained with a vision frequency no greater than half the line frequency and cannot be improved by increasing the vision frequency above this value. Vertical resolution can only be increased by using more lines. Horizontal definition, on the other hand, increases as the vision frequency is raised.

(ii) There are certain types of image, notably those containing horizontal lines, for which the vertical resolution depends on the position of the detail relative to the scanning lines at the transmitter. An example of such an image is Fig. 9 which has a number of horizontal lines of alternate black and white elements. If the relative position of image and scanning lines is such that the centre of the transmitting scanning beam travels along the centres of a row of black and white elements, the vertical resolution is perfect; if the scanning beam falls half on one horizontal row and half on the row above or below, the pattern is reproduced as uniform grey and resolution is zero. The horizontal resolution of Fig. 9 is independent of the position of the pattern relative to the scanning lines.

If the vision-frequency range up to $Pa'L^2/2$ is reproduced, the horizontal and vertical resolutions would be equal if the lines of detail always coincided with the transmitting scanning lines. Clearly this condition cannot always be satisfied and, on a statistical basis, the horizontal resolution will be better than the vertical resolution if frequencies up to $Pa'L^2/2$ are reproduced. On this basis it has been estimated that the frequency range could be reduced in the ratio $1/\sqrt{2}$ to give approximate equality in horizontal and vertical resolution which is sometimes advocated as an ideal. Nevertheless, if this economy is practised the definition as a whole must inevitably suffer.

All the components of the vision signal must be reproduced at the correct amplitude to avoid distortion in the reproduced image; moreover, they must all take the same time to reach the receiver screen. To achieve this there must be no phase distortion within the system and this usually means that the bandwidth of all circuits must be greater than the value of highest frequency calculated above. This point will be elaborated further in the chapters on vision-frequency amplification in volume 2 of this work.

A wide bandwidth in all circuits is also necessary to transmit the sync pulses without distortion. If the sides of these pulses are to be kept steep, a large number of harmonics of the fundamental pulse frequency must be transmitted without serious attenuation or phase shift. This can be shown from the relationship

$$f = \frac{1}{2t}$$

which relates the time t taken for a pulse to reach its maximum amplitude to the frequency range f which must be transmitted. For successful operation of a receiver line time base it may be desirable to make the rise time of the line-sync pulses 0·2 μsec. From the above relationship it is clear that the frequency range necessary to transmit a pulse as steep as this extends to 2·5 Mc/s.

1.8 INTERLACING

For a given number of lines and aspect ratio the bandwidth occupied by the components of the vision signal is directly proportional to the picture frequency; this is shown in expression (3). Moreover, in a television system employing sequential scanning, the amount of flicker observed in the reproduced image also depends on the picture frequency, decreasing as the picture frequency is increased, although other factors such as image brightness and the decay time of the reproducing-screen material also affect the amount of flicker. To minimize flicker in such a system a high picture frequency is necessary, but this necessitates a wide bandwidth for distortionless transmission. Wide bandwidths are difficult to achieve technically and make television equipment expensive. For a given definition and flicker an economy in bandwidth can be obtained by use of interlaced scanning.

In a television system using interlaced scanning the amount of flicker depends on the frame frequency whereas the bandwidth occupied by the components of the vision signal is still proportional to the picture frequency. Thus for a given definition and flicker, a system using interlaced scanning occupies a smaller bandwidth than one using sequential scanning. The use of interlaced scanning affects the shape of the vision waveform in a manner explained in chapter 2.

Other methods of interlacing are possible: for example, in triple-interlaced scanning, lines numbers 1, 4, 7, etc., are scanned in frame 1, lines 2, 5, 8 in frame 2 and lines 3, 6, 9 in frame 3. In such a system the scanning spot makes three vertical sweeps of the image to complete each picture, i.e., the frame frequency is three times the picture frequency.

Twin and triple interlacing are both examples of line interlacing and in both, as in sequential scanning, the elements in each line are scanned sequentially.

An alternative method of achieving interlacing is by element- or dot-interlacing in which, to quote an example, elements number 1, 4, 7 in a particular line may be scanned in frame 1, elements 2, 5, 8 in frame 2 and elements 3, 6, 9 in frame 3.

CHAPTER 2

SIGNAL WAVEFORM

THIS chapter deals in greater detail with the shape of the signal waveform which was briefly described in the previous chapter. The waveform contains all the information required by a receiver to produce a picture and, in practice, is more elaborate than is required from fundamental considerations only.

2.1 LINE-SYNC SIGNAL

Fig. 11 is a diagram of the synchronizing signals between lines. The number of lines per picture is *L* and the picture frequency is *P* per second; thus there are *LP* lines per second. To keep the receiver line-scan generator in step, a synchronizing signal must be transmitted at the end of each line; hence *LP* line-sync signals must be radiated per second. The line apparatus in the receiver is voltage operated and the synchronizing signal must reach its maximum amplitude in the shortest possible time, otherwise the exact moment at which the line-scan generator is triggered by the synchronizing

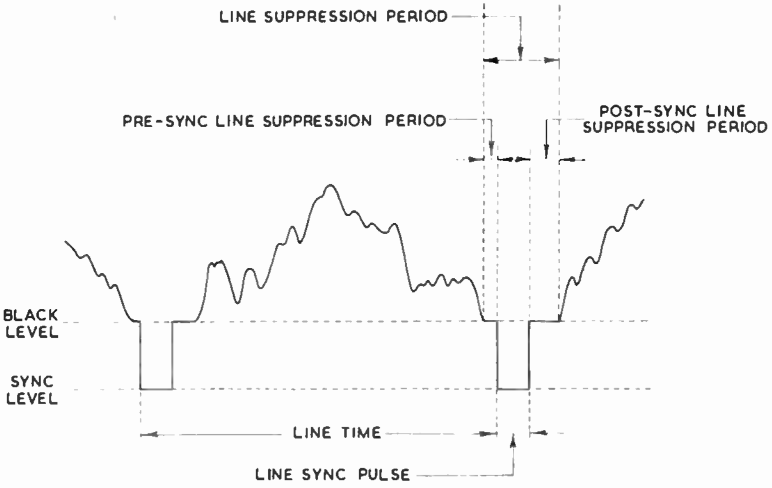


Fig. 11—Details of signals between lines

signal will vary and there will be positional distortion of detail in the picture.

The line-sync signals have the form of square-topped pulses operating downwards from black level as shown in Fig. 11. The duration of the line-sync signals is important; it must not be too long or it takes up time which might be better employed in transmitting pictures; on the other hand the pulse must last long enough to reach an amplitude capable of triggering the line-scan generator with precision. The line-scan generator at the receiver is triggered by the leading edge of the sync pulse which must therefore be as steep as possible.

In most television systems the duration of the line-sync pulse is of the order of 10 per cent of the time for one line, which here implies the time occupied by picture and synchronizing signals. The time for one line is given by $1/LP$ secs and if $L = 405$ and $P = 25$ is approximately 100 μsecs. This is the line time for the British television system and the duration of the line-sync pulse is approximately 10 μsecs.

2.2 LINE-SUPPRESSION SIGNAL

The synchronizing signals are not the only form of intelligence which must be transmitted between lines: an additional signal, known as the *line-suppression signal*, must also be inserted. This signal is a period of black level lasting from just before the line-sync signal until just after it; the suppression signal may be regarded as forming a level top from which the synchronizing signal hangs.

The term suppression arose in the following way:—The period between the end of one line and the beginning of the next should be devoid of any picture signals, since no parts of the scene are scanned during this period. In this interval there may be, however, spurious signals generated by the television camera tubes and it is essential to suppress these unwanted voltages. This is done by adding a rectangular pulse of the correct duration and timing (the *line-suppression pulse*), and then limiting the pulse at black level, the spurious signals being lost in the limiter. Although this pulse does not appear as such in the ultimate standard waveform, the interval of black level which its introduction has created is there (interrupted by the sync signal) and for convenience it is customary to show this interval under the title of the pulse which causes it.

The suppression signal serves two other useful purposes: when a line-sync pulse arrives at a receiver it starts the spot flying back to the left-hand side of the picture, and the flyback takes a certain finite time, which because of the limitations of practical apparatus is longer than the duration of the line-sync signal. No picture signals must be transmitted before the spot has reached its starting point or the spot will be modulated whilst it is moving at high velocity to the left; as a result of this, there will be an area of the screen where two images are superimposed. This possibility is eliminated by maintaining the modulation of the spot at black level until it is ready to begin a new line.

In general, receivers of commercial design require a line-suppression period of not less than 15 per cent of the time of a line and the practical values listed at the end of this chapter comfortably cover this minimum value.

2.3 Post-sync Line-suppression Period

The second reason for the provision of line-suppression pulses is concerned with the restoration of d.c. This subject was mentioned on page 20 and is described more fully in a later volume; it is sufficient at this point to state that at various places in the vision-frequency chain it is necessary to carry out d.c. restoration and this process necessitates a period of black regularly occurring at a fixed position during the intervals between the lines. For this purpose the period of black immediately following the line-sync signal is quite convenient; this period is termed the *post-sync line-suppression period* and is shown in Fig. 11.

2.4 Pre-sync Line-suppression Period

From Fig. 11 it can also be seen that there is a brief period of black level occurring immediately before each line-sync signal. This is known as the *pre-sync line-suppression period* and is necessary for the following reason:—The voltage at any time during the scanning of a line is, of course, quite arbitrary and at the end of the line it may be either high, corresponding to white, or low, corresponding to black, or at an intermediate value corresponding to a tonal value between white and black. To execute the line-sync pulse the voltage must return to black level and if the picture voltage is high, it takes a finite time for the voltage to fall to black level in order to begin the line-sync signal. On the other hand if the picture voltage is low at the end of a line, the line-sync signal can begin immediately. The practical effect of this, for left-to-right scanning, is that if the right-hand edge of the picture is white, the synchronizing signals immediately following are late in comparison with those following lines with black right-hand edges. This results in positional distortion in the reproduced image, the effect being that vertical lines in the image are reproduced with ragged edges; this is obviated by the pre-sync line-suppression period.

2.5 Line Numbering

Before the waveform of the frame-sync signals is considered, the system of line numbering must be explained. In twin-interlaced scanning, each complete picture is composed of an odd and an even frame. An even frame is one containing the even-numbered lines whereas an odd frame is one containing odd-numbered lines; and the lines are numbered according to the positions they occupy in the raster, number 1 being the top line and, in the British system, 405 the bottom line.

In accounts of sync signals, however, it is more convenient to number the lines in the order in which they occur in time and line 1 is assumed to be the top line of the picture and the first line of the odd frame. The odd frame thus contains lines numbered 1, 2, 3, etc., up to line 203 (which is uncompleted at the bottom). The even frame contains lines numbered 204 (at the top of the picture), 205, 206, etc., to 405 (at the bottom of the picture). This is made clear in Fig. 12 where the lines in a picture are numbered in time sequence.

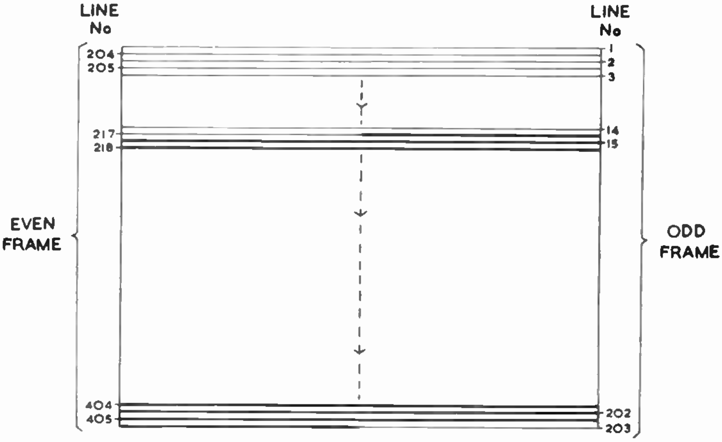


Fig. 12—Line numbering of television picture

2.6 Frame-sync Signal

Fundamentally the frame-sync signal may have the same form as the line-sync signal and consist of a period of sync level at the end of each frame. To facilitate separation of the two types of sync signal at the receiver, the frame signal must differ in some way from the line-sync signal. A rectangular pulse has only two properties, namely amplitude and duration; the amplitude is the difference between black level and sync level and is fixed. Thus the frame-sync signal must have a different duration and in practice is made equal to that of several lines. Such a signal has the required effect of triggering the receiver frame-scan generator but is unsatisfactory because it interrupts the continuity of the line-sync signals, which cease for the duration of the frame-sync signal. During this period the receiver line-scan generator deviates from its proper frequency and some time is required at the beginning of each frame for the generator to be pulled into synchronism; as a result there may be positional distortion of detail in the first few lines of every frame. To avoid this, the frame-sync signals must be so constituted that they do not interrupt the continuity of the line-sync signals. This is possible if the frame-sync signal is arranged to contain a component at line frequency, i.e., PL c/s.

There is, however, a further requirement which the frame-sync signal must satisfy. In interlaced scanning each picture contains an odd number of lines and each frame must therefore contain an integral number plus half a line. Thus if the odd frame begins at the start of a line it must end $1/2P$ seconds later at the middle of a line. The frame-sync signal must therefore start precisely at the mid-point of a particular line or at the end of another particular line.

This requirement may be satisfied by generating continuously a series of pulses at twice line frequency, i.e., $2PL$ c/s, and synchronized with the line-sync pulses. These new pulses are inserted in the vision signal at intervals of precisely $1/2P$ seconds, whenever in fact the frame-sync signal is due. This ensures that the frame-sync signal starts at exactly the mid-point or the end of a line.

Waveform of Frame-sync Signal

The frame-sync signal is transmitted at intervals of precisely $1/2P$ seconds and has the form of a sequence of pulses (Fig. 13) which, as for the line-sync signal, cut the vision signal from black level to sync level. The sequence consists of a number of pulses, each with a duration approximately 40 per cent of that of a line; the intervals between these pulses are approximately 10 per cent of the line time. The intervals between the pulses are of smaller duration than the pulses themselves and for this reason the pulses are described as *broad*. The sequence of pulses occupies a total period of several lines and for most of this time the vision signal is at sync level; this group of pulses thus has very much greater duration than the line-sync pulses, a feature which is utilized in receiver design as a means of distinguishing the frame-sync signal from the line-sync signal. During the intervals between the broad pulses the vision signal is restored to black level; the leading edges of the broad pulses thus occur at $1/2PL$ second intervals and when applied to the line-scan generator in a receiver have the same effect as the leading edges of the line-sync signals (which normally occur at $1/PL$ second intervals) thus maintaining line synchronism at the receiver during the frame-sync signal. The receiver line-scan generator is designed to be insensitive to the leading edges of every alternate broad pulse in the frame-sync signal.

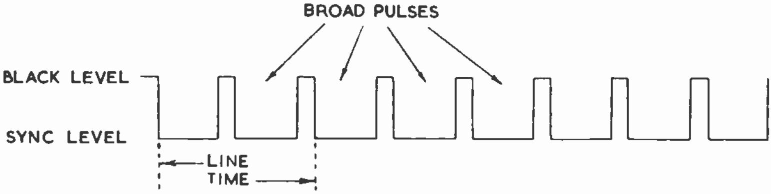


Fig. 13—Waveform of frame-sync signal

2.7 Frame-suppression Signal

Associated with the frame-sync signal there is a frame-suppression signal corresponding in function with the line-suppression signal but having an appropriately longer duration. The frame-suppression signal occupies the interval between the end of one frame and the beginning of the next and may be described as a period of black level intended to black out the electron beam in receivers whilst frame flyback occurs. The period allowed is of the order of 1,000 μsecs and is adequate for flyback in receivers of average specification. The first part of this period is occupied by the frame-sync signal, i.e., the broad pulses which cut the vision signal from black level to sync level. The remainder of the suppression period, known as the *post-sync frame-suppression period*, consists of a period of black level approximately twice the duration of the frame-sync pulse and interrupted at $1/PL$ sec intervals by the line-sync pulses. Thus receiver line scanning is not interrupted at any time during the frame-suppression period.

2.8 Signals Between Frames

The signals at the end of all frames have the same form and consist of a frame-sync signal followed by a post-sync frame-suppression period. Each frame, however, contains an integral number of lines together with half a line and if the signals at the

Fig. 14
(Left)

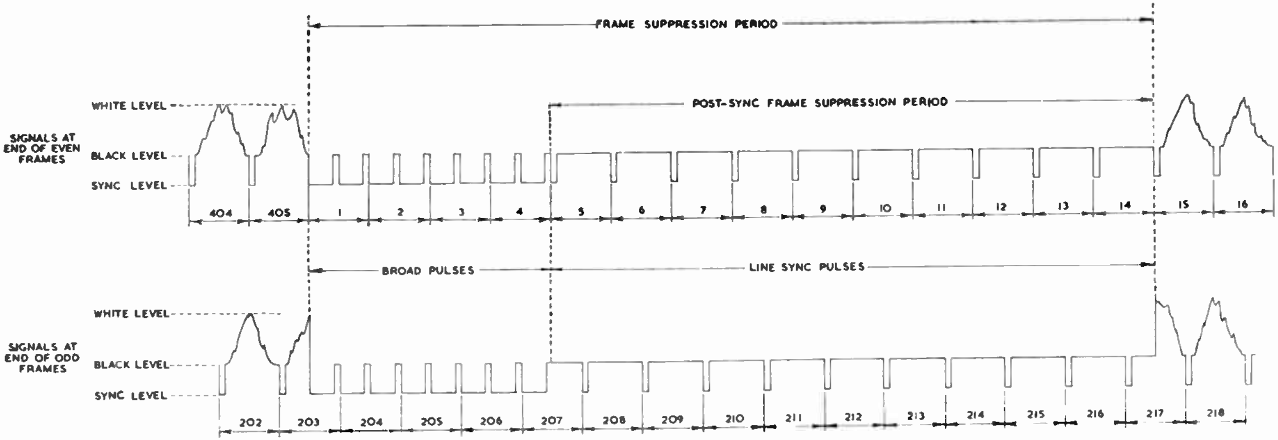
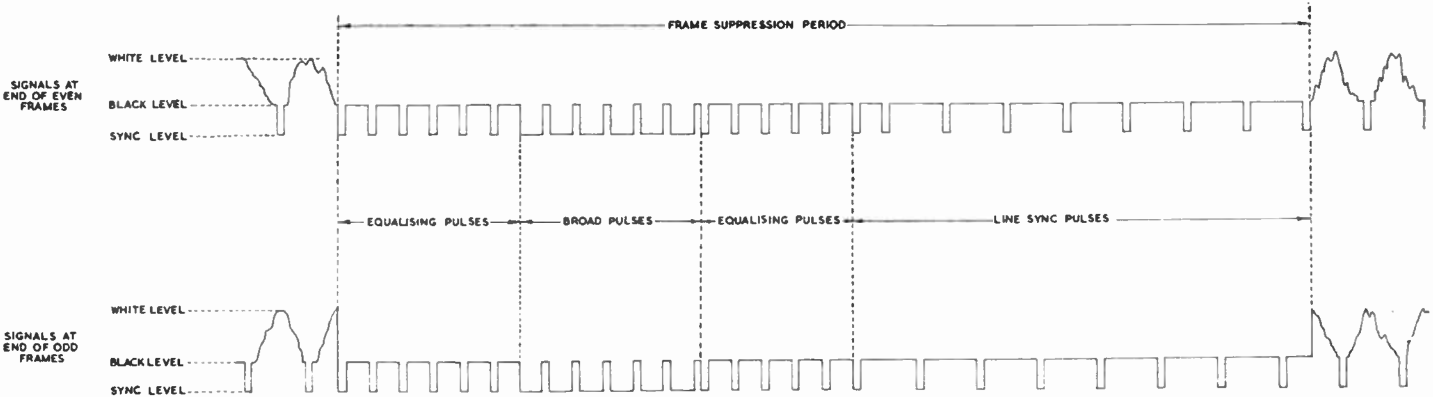


Fig. 15
(Below)



end of even frames start at the end of a line those at the end of an odd frame must start half-way along a line. This is illustrated by Fig. 14 which shows the sync signals at the end of the even and odd frames respectively in the British television system.

Examination of Fig. 14 shows that after even frames the broad pulses begin one line after the previous line-sync pulse but after odd frames the broad pulses begin half a line after the previous line-sync pulse. Similarly after even frames the line-sync pulses begin one line after the broad pulses but after odd frames the line-sync pulses begin half a line after the broad pulses. These differences follow from the fact that each frame contains an integral number of lines together with half a line.

In American television practice precautions are taken to ensure precise similarity in the sync pulses after odd and even frames. To this end a series of pulses known as *equalizing pulses* (additional to the frame- and line-sync signals) is inserted in the intervals between frames. These pulses are at twice line frequency and are inserted for a period of three lines before and after the frame-sync signal as shown in Fig. 15.

2.9 INTERLACING

Each frame occupies exactly one half of the total time of one picture and interlacing is automatic if an odd number of lines is used. The forward trace of the line scanning is not horizontal but sloping slightly downwards, because the spot is deflected by the line- and frame-scanning systems simultaneously. In the time taken by the spot to move fully across the screen from left to right, it moves downwards the space of two lines; in moving half-way across the screen, it moves downwards a space equal to the width of one line. Consider the scanning of line 203 (lower half of Fig. 14). At the middle of this line, the frame flyback begins and returns the spot to the top of the screen to a point one line width above the first line of the previous frame and the following lines will, if the interlacing is perfect, place themselves symmetrically between the lines already scanned (i.e. the lines of the odd frame). To obtain perfection of interlacing it is essential that the frame flyback should occupy the same period after odd and even frames, but perfect interlacing requires careful design of the synchronizing circuits in the receiver.

OPPOSITE PAGE

Fig. 14—Signals at the end of even and odd frames in the British television system

Fig. 15—Signals at the end of even and odd frames in the American television system

2.10 BBC Television Standards

Number of lines per picture	405
Picture frequency (per second)	25
Twin interlacing giving a frame frequency (per second)	50
Aspect ratio	4 : 3
Line period	98·7 μsec
Line-suppression period	18·0 μsec
Duration of line-sync pulse	10·0 μsec
Rise time of line-sync pulse	0·2 μsec max.
Pre-sync line-suppression period	1·5 μsec
Post-sync line-suppression period	6·5 μsec
Number of broad pulses per frame-sync signal	8
Duration of frame-sync signal	394·8 μsec
Duration of each broad pulse	39·35 μsec
Frequency of broad pulses	20,250 per sec
Post-sync frame-suppression period	987 μsec

PART II: TELEVISION CAMERA TUBES

CHAPTER 3

GENERAL CONSIDERATIONS

3.1 INTRODUCTION

A TELEVISION camera tube is an electronic vacuum tube used in a television system to produce picture signals by scanning an electric charge image derived from an optical image. The tube with its associated optical system and viewfinder are the principal components in a television camera; the camera may, however, contain additional apparatus such as scanning generators and vision-frequency amplifiers.

The camera tube has two essential functions: first it must, in effect, subdivide the optical image into elements; secondly, it must scan these elements in a certain order and at each one produce an electrical output with an amplitude corresponding to the tonal value of that element.

There are various ways in which these two processes can be carried out and a number of different types of camera tube have been produced, each with its particular advantages and disadvantages. A description of the various types of tube in common use, together with their characteristics, is given later in this book. There is one feature, however, which all types have in common and, because of its fundamental importance, this will be described first. This feature—it could almost be called a principle—is that of scanning a target electrode by an electron beam.

3.2 PRINCIPLES OF OPERATION OF CAMERA TUBES

Fig. 16 represents an evacuated glass tube of cylindrical form containing a light-sensitive electrode at one end and an electron gun at the other. This diagram is not intended to illustrate any particular type of camera tube although the electrodes are in the same relative positions in the envelope as in the orthicon tube. An optical image of the scene to be transmitted is focused on one side of the target by an optical system and the electron beam from the gun is focused on the other side. The electron beam can be deflected horizontally and vertically (by means not shown in the diagram) so as to scan the target. The vision-frequency output of the tube is taken from the target and may be developed in any of the following three ways:

(1) Potentials produced on the target by light may control the number of scanning-beam electrons reaching the target, i.e., electrons may land on each element of the target in direct proportion to the amount of light falling on that element.

(2) Target potentials due to light may vary the *secondary-emission ratio** of the target, i.e., the number of secondary electrons liberated from each element of the target may be directly proportional to the amount of light falling on that element.

(3) Target potentials due to light may regulate the escape of secondary electrons, i.e., though the same number of secondary electrons may be liberated from each element of the target under bombardment by the scanning beam, the light on a particular element may control the number of secondary electrons which are collected from that element by a nearby electrode.

Of these three ways in which signals may be produced, (3) is used in a number of types of camera tube, notably the iconoscope (standard Emitron), which have been in regular use since the inception of high-definition television and (1) is utilized in a number of the more modern tubes such as the image orthicon and C.P.S. Emitron. Although a tube using (2) has been demonstrated in the laboratory, no tubes of this type have been in regular use in television services.

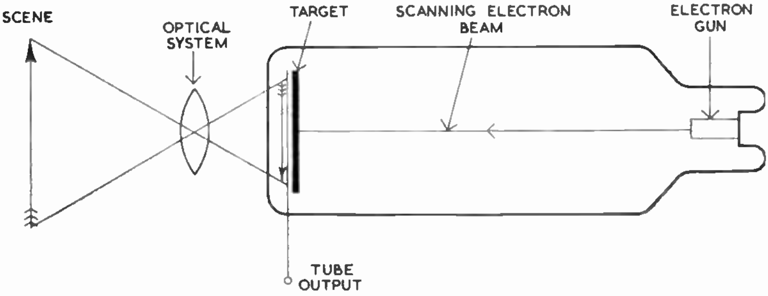


Fig. 16—Target scanning by an electron beam

In the camera tubes now used in television services and in those which have been used in the past, the light-sensitive electrodes are *photo-emissive*, i.e., they release electrons on exposure to light;

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* The secondary-emission ratio of a material is the number of secondary electrons released from it for each primary electron striking it. The subject of secondary emission is discussed more fully in Section 3.3 of this chapter.

this section is devoted almost entirely to tubes using this type of photo-sensitive surface. An electrode may, however, be sensitive to light in other ways; for example, it may be *photo-voltaic*, i.e., develop e.m.f.s when illuminated, or it may be *photo-conductive*, i.e., change its electrical resistance on exposure to light. The photo-voltaic surfaces so far constructed have tended to suffer from serious time lag and more interest has been taken in the photo-conductive type, which appears to be better suited for use in camera tubes. Experimental photo-conductive tubes have shown a number of advantages over other types, notably in light-sensitivity and simplicity of construction and it is possible that there may be extensive development of these tubes in the future. Some information on photo-conductive tubes is given in chapter 6.

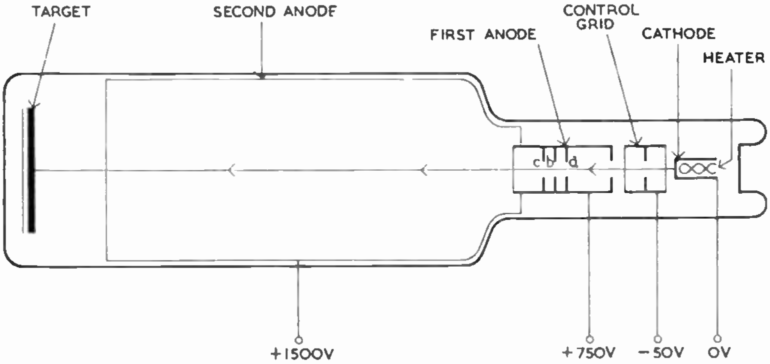


Fig. 17—Typical electron gun and target

Methods of signal production (2) and (3) both depend on secondary emission from the target, and, to obtain appreciable secondary emission, the scanning beam must be of high velocity. On the other hand, no secondary emission is utilized or desirable in mode (1) and the scanning beam must be of low velocity to minimize it. Thus camera tubes can be broadly classified under two headings: those, such as the iconoscope, which employ a high-velocity scanning beam and those, such as the orthicon, which use a low-velocity beam.

The initial beam velocity depends on the magnitude of the accelerating potentials applied to the electrodes of the gun but the final beam velocity depends on the target potential. The construction of a typical gun is shown in Fig. 17; it consists of a heater, an indirectly-heated cathode, a control grid (sometimes termed a *modulator*) and two anodes. The control grid has the form of a short metal cylinder containing an aperture plate and its potential relative to the cathode controls the density of the electron beam. The first anode, i.e., that nearest the cathode, is a longer metal tube containing a number of aperture plates whilst the second anode is in the form of a conductive coating deposited on the inside walls of the glass envelope. Electrodes prepared in the manner of this second anode are often referred to as *wall anodes*.

The two anodes constitute an electrostatic lens system which can be used to focus the electron beam on the target. Electron beams can be focused by electrostatic or magnetic fields but the mechanism of the process is too large a subject to be described in this section; more information can be obtained from chapter 10 on Electron Optics. At this stage it is assumed that the electron beam can be brought to a focus at the target by applying potentials to the various electrodes with values such as those shown in Fig. 17.

The velocity of the scanning beam is one of a number of factors which determine the potential acquired by an insulated target scanned by an electron beam and the target potential has a great bearing on the performance of a camera tube. In general if the scanning beam is of low velocity the target stabilizes at approximately the potential of the electron-gun cathode, and if the scanning beam is of high velocity it stabilizes at the potential of the final anode of the gun or at a potential characteristic of the target material and known as the *second cross-over potential*. This subject is, however, of such fundamental importance in a study of camera tubes that it is dealt with separately in the following section.

3.3 TARGET STABILIZATION

Consider an evacuated tube containing an electron gun and a target, such as that shown in Fig. 17 (page 41). When the potentials are applied to the gun electrodes, the electron beam strikes the target and under certain conditions releases secondary electrons from it. The number of secondary electrons emitted for each primary electron striking the target is, of course, the *secondary-emission ratio*, *k*, and has a value depending on the velocity of the primary electrons, their angle of incidence and the nature of the target material. The coefficient has a maximum value at a certain primary electron velocity but increases with increase in the angle of incidence, and may have a value approaching 10 for a material of low work function such as a photo-electric surface. On the other hand the secondary-emission ratio may have a maximum value of less than unity for certain materials and the maximum is approximately two for a target consisting of a clean metal plate.

The way in which the secondary-emission ratio varies with the velocity of the primary electrons is illustrated in Fig. 18, which applies to a clean metal target. The primary electron velocity is expressed in *electron-volts*, an electron-volt being the energy acquired by an electron in moving from one point in an electric field to another point where the potential is 1 volt greater. If the potential difference through which the electron moves is V volts, the energy gained is eV electron-volts where e is the charge on the electron. If the electron starts from rest, its kinetic energy at the point of higher potential equals the energy received, i.e., $\frac{1}{2}mv^2 = eV$ where m is the mass of the electron. The electron-volt may also be defined as the energy lost by an electron which has moved from one point to another where the potential is 1 volt lower. Electron velocities may be expressed in electron-volts though strictly kinetic energy is meant. (See page 222.)

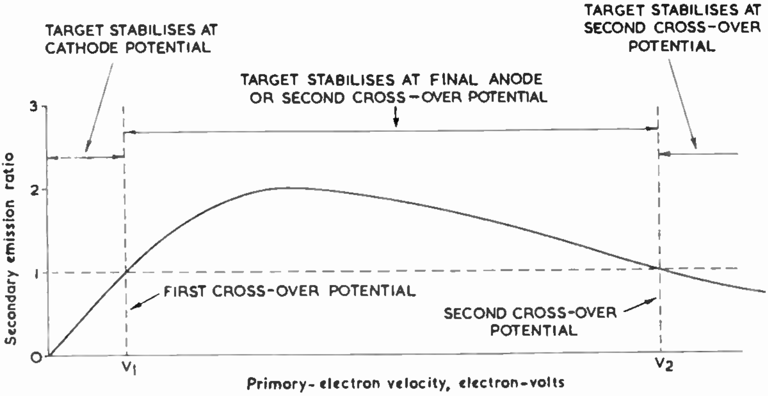


Fig. 18—Variation of secondary-emission ratio with primary beam velocity

The primary electron velocity depends on the target potential; thus the abscissae in Fig. 18 may be taken as representing the primary electron velocity or the target potential. For a primary electron velocity less than a value V_1, known as the first cross-over potential, the ratio is less than unity; for potentials greater than V_1 but less than V_2 (known as the second cross-over potential) the ratio exceeds unity and has a maximum value of approximately 2; for a potential exceeding V_2 the ratio is again less than unity.

If the target is not connected to any point of fixed potential, it will acquire a certain potential as a result of bombardment by the primary beam and its final equilibrium potential depends on its initial potential and the net loss or gain of primary or secondary electrons.

If the target potential is initially below V_1, the primary beam velocity is low and k is less than unity. The number of primary electrons striking the target exceeds the number of secondary electrons released from it and the target potential falls. As the potential falls the primary electron velocity falls and finally a state of equilibrium is reached in which the target is sufficiently negative to reduce the velocity of the electrons immediately in front of it to zero. The target potential is now slightly less than that of the electron-gun cathode; this process is known as *cathode-potential stabilization* and is used in all low-velocity television camera tubes.

The secondary electrons liberated from the target during the initial period of bombardment by the primary beam may return to the target or may be collected by a nearby electrode such as the final anode of the electron gun. Provided the initial target potential is less than V_1, what happens to the secondary electrons has no influence on the final potential acquired by the target; cathode-potential stabilization occurs no matter what the final anode potential. If, however, the initial target potential exceeds V_1, the value of the final anode potential has a great bearing on the equilibrium target potential.

If the initial target potential is between V_1 and V_2, k exceeds unity and the number of secondary electrons released from the target exceeds the number of primary electrons striking it. The equilibrium value of the target potential now depends on whether the secondary electrons are removed from the target or not; if the field between the target and the final anode is accelerating, the target will lose more electrons than it gains and its potential will rise: if the field is retarding, secondary electrons will be returned to the target and its potential will fall. Thus the relative values of the initial target potential and final anode potential decide the final equilibrium potential of the target. For an initial target potential between V_1 and V_2, there are three possible states of stabilization which occur when the final anode potential is:

(a) less than V_1,
(b) between V_1 and V_2,
(c) at or above V_2.

These three states also apply when the initial target potential is greater than V_2, for at such potentials k is less than unity and the target gains more primary electrons than it loses secondary electrons; thus, its potential falls to V_2 and its final stabilization potential depends on the final anode potential as set out below.

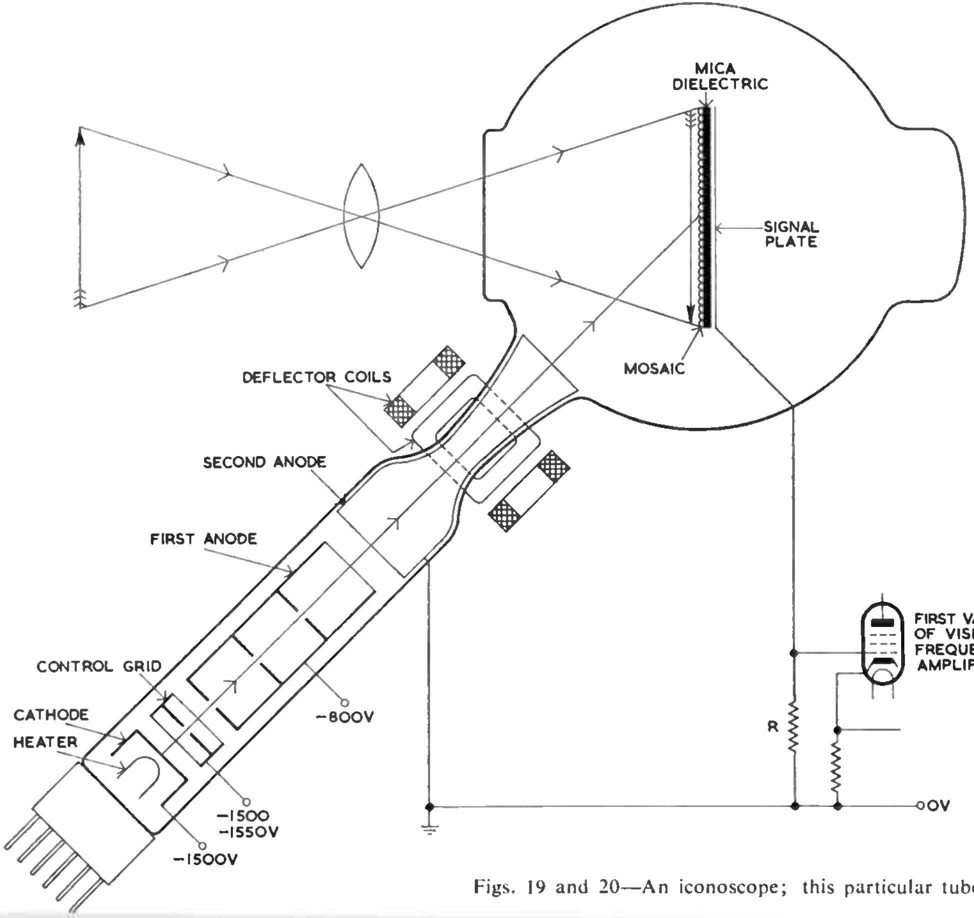
(a) If the final anode potential is less than V_1 there is a retarding field between target and final anode and all the secondary electrons released from the target are returned to it, with the result that its potential falls. When the potential falls below V_1, the secondary-emission coefficient is less than unity and the potential continues to fall to the cathode value as explained above.

(b) If the final anode potential is between V_1 and V_2, the target potential being initially below that of the final anode, all the secondary electrons released from the target are collected by the final anode and the target potential rises. If the initial target potential is above that of the final anode, there is a retarding field between target and anode which repels secondary electrons to the target. This, in effect, reduces the secondary-emission ratio and the target potential falls. Thus, no matter what the initial target potential (provided it is above V_1), the target ultimately stabilizes at a potential such that the number of secondary electrons reaching the final anode equals the number of primary electrons received from the beam. In this final state of equilibrium, the target potential is slightly positive with respect to the final anode potential and the target is said to be *final anode-stabilized* (usually *second anode-stabilized* because most guns contain two anodes). This type of stabilization occurs in all high-velocity camera tubes and in cathode-ray tubes used in oscilloscopes and television receivers.

(c) If the initial target potential is between V_1 and V_2 and the final anode has a potential at or above V_2, all the secondary electrons released from the target are collected by the final anode and the target potential rises to a potential near V_2. If the target potential tends to rise above V_2 the secondary-emission ratio falls below unity with the result that the target potential falls to near V_2 again. Thus, provided the final anode potential exceeds V_2, the target will stabilize at the cross-over potential. This form of stabilization is not used in any form of camera tube in common use.

The conclusions reached in this section may be summarized thus:

Initial Target Potential	*Final Anode Potential*	*Target Stabilization Potential*
below V_1	any	cathode
above V_1	below V_1	cathode
above V_1	between V_1 and V_2	final anode
above V_1	at or above V_2	V_2



Figs. 19 and 20—An iconoscope; this particular tube is a standard Emitron

CHAPTER 4

PHOTO-EMISSIVE HIGH-VELOCITY CAMERA TUBES

THE first camera tubes to be used in high-definition television services used high-velocity scanning beams, and in the following descriptions of the various commonly used tubes the high-velocity types will be described before those employing low-velocity scanning beams. Thus the descriptions are arranged in approximately correct chronological order.

4.1 ICONOSCOPE (STANDARD EMITRON)

Introduction

The standard Emitron camera tube was developed in this country during the early 1930's and, except for the period of the Second World War, has been in regular use in the BBC Television Service since it began in 1936. The tube is very similar to the iconoscope* which was developed in America about the same time and has been extensively used in television services in the U.S.A. The following account applies equally to both tube types.

The tube contains a light-sensitive target on which the optical image is focused and which is scanned by a high-velocity electron beam. The target is, however, not transparent to light and the tube cannot have the simple shape of Fig. 17. The scanning beam and the incident light are projected on the same side of the target and hence either the light or the electrons must strike the target at an oblique angle. As it is easier to correct for oblique scanning than for oblique projection of the light image, the target is mounted perpendicular to the optic axis and the tube has the shape shown in Fig. 19. A photograph of an iconoscope is given in Fig. 20.

Construction

The tube consists of a spherical glass bulb approximately 7½ inches in diameter, near the centre of which the target is mounted (Fig. 19). The optical image is focused on the target by an external lens system, the light passing through a flat window in the bulb. A side tube, 1½ inches in diameter and attached to the bulb, contains an electron gun similar to that illustrated in Fig. 17. The axis of the gun passes through the centre of the target and makes an angle

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* Derived from the Greek *Ikon* (image) and *Skopein* (to see).

of about 35 deg with the normal. The second anode of the gun is in the form of a conductive coating deposited on the inside wall of the side tube and extending well into the bulb. Near the second anode there is a conical constriction of the side tube around which two pairs of deflector coils are clamped. These are fed with currents which deflect the beam both horizontally and vertically so that the target is scanned in the desired manner. More details about the beam deflection are given later.

The earliest iconoscopes also had spherical bulbs but later types had an improved bulb consisting of a cylindrical centre section closed at each end by glass plates cut from a large sphere (see Fig. 21). These ends are sufficiently rounded to give the necessary mechanical strength and are polished to avoid geometrical distortion of the light image on the mosaic. In this type of tube the second anode is extended in the form of a narrow conducting band deposited on the inside of the cylindrical surface.

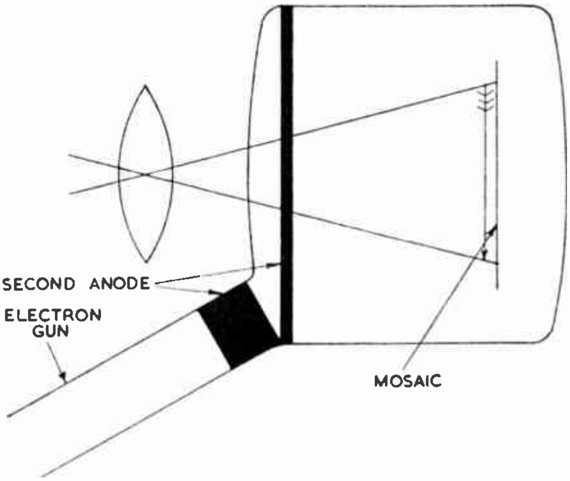

Fig. 21—Shape of iconoscope with cylindrical bulb

The necessity for scanning the illuminated side of the target results in an awkward tube shape which is not well suited for mounting in a camera. Moreover, the inherent insensitivity of the tube together with the size of the target (approximately 5 inches by 4 inches) and its distance behind the glass window impose limitations in the design of the external optical system and in practice result in a restricted depth of field.

The light-sensitive target consists of a sheet of insulating material, such as mica, covered on one side by a mosaic consisting of a very large number of minute islands of photo-electric material such as caesiated silver* or antimony, each island being electrically insulated from its neighbours. The other side of the mica has a conductive metallic coating known as the *signal plate* and from which the output of the tube is taken.

Mechanism of Signal Production—Simplified Account

A simplified account of signal production in the iconoscope tube will first be given. A more detailed and accurate explanation, taking into account the important part played by secondary emission, is given on page 56.

The mosaic surface is composed of a very large number of photo-electric cells each of which has a small capacitance to the signal plate. When a light image falls on the mosaic each of these cells liberates photo-electrons in direct proportion to the amount of light falling on the cell. By loss of these electrons each cell becomes positively charged and the capacitance associated with it develops a potential representing the tonal value of that part of the light image which coincides with the cell. This potential grows with time as more photo-electrons are emitted, the charge being stored in the capacitance. Thus a charge image is built up on the mosaic, areas of positive potential corresponding to highlights in the optical image.

During scanning, the electron beam passes over the surface of the mosaic in a series of straight lines, touching each cell in turn. In touching each cell it discharges the capacitance associated with it and the resulting sequence of discharge currents passes through a resistor connected between the signal plate and the second anode, developing a potential difference constituting the tube output.

During discharge of the mosaic the electron flow in the external circuit between signal plate and second anode is from the signal plate towards earth. Thus the polarity of the output at the signal plate is negative, i.e., negative pulses correspond to highlights in the image.

The beam is sometimes described as a contactor which touches each cell in turn but this concept is found to be unsatisfactory when attempts are made to calculate the resistance of the contactor. This resistance, given by $\Delta E/\Delta I$ where ΔE is a small change in element potential and ΔI is the corresponding change in beam current, is found to be practically infinite, the beam current being independent of the element potential. A better method of explaining the discharging process is to say that the beam returns to each cell the number of electrons necessary to make up its normal neutral complement.

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* Silver treated with a small amount of caesium.

The mechanism of signal production in an iconoscope tube can be explained in terms of two currents i_p and i_s flowing in the directions drawn in Fig. 22. The arrows in the diagram indicate directions of electron flow. These currents flow in opposite directions in the signal resistor *R* and the output voltage is directly proportional to the difference between them. The current i_p is caused by photo-electric emission from the mosaic as a whole and is proportional to the mean brightness of the image. This current flows between mosaic and second anode and its rate of change is very slow compared with that of the other component.

The second current i_s is due to the successive discharge of the elements in the mosaic during the scanning process and flows in the external circuit connecting signal plate and gun cathode. This current contains components of very high frequency and, in the signal resistor, " rides " on the current i_p, which, because of its slow rate of change, may be regarded as a bias component. The number of electrons lost by the target in the form of photo-electric emission is equal to the number collected from the primary beam during scanning. Thus over a long period i_p equals i_s and the average target potential does not alter. The output waveform has, therefore, an average potential of zero as illustrated in Fig. 23, which, for simplicity, illustrates the discharge of a single element.

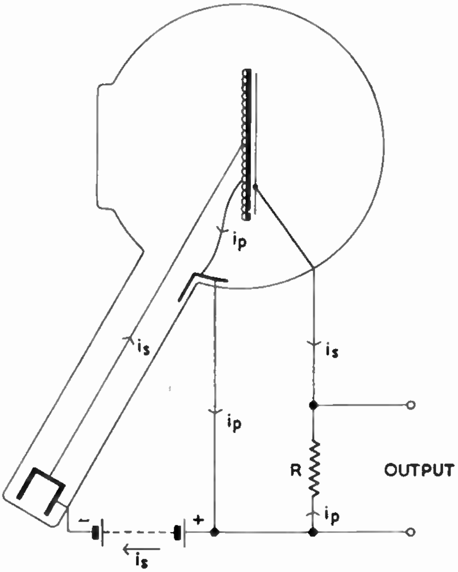

Fig. 22—Currents in iconoscope

This explanation of signal production is useful in accounting for the polarity of the output signal and its average value of zero, but it fails to show that tube output could also be taken from the second anode, as explained on page 58.

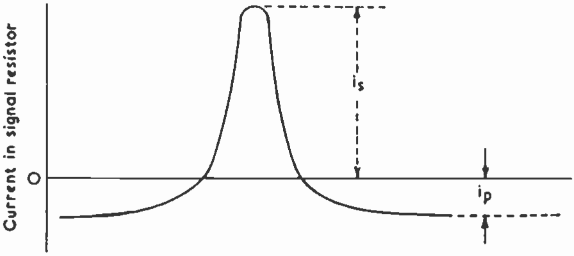

Fig. 23—Currents in signal resistor

Storage Principle

Each cell in the mosaic is discharged once during each alternate vertical sweep of the scanning beam. Between two successive discharges there is thus an interval equal to the picture period, during which a charge accumulates on each cell due to photo-emission. This is a very long period of charge storage compared with the value obtained in earlier television equipment such as mechanical scanners in which the storage period—if such it can be called—is equal to the time taken to scan one element. If full advantage is taken of charge storage, the iconoscope is more sensitive than a mechanical scanner by a factor equal to the number of picture elements scanned during the picture period. This factor is equal to the total number of elements composing the picture and is given by L^2a where L is the number of lines in the system and a is the aspect ratio. If L is 405 and a is 4/3, the factor is approximately 2×10^5. This represents an enormous gain in sensitivity and although only a small percentage of it is realized in the iconoscope, a very great advantage is obtained by using the storage principle. In fact, it was not until the principle of charge storage was applied to camera tube design that a camera sensitive enough for a regular television service could be produced. All the camera tubes described in this section make use of charge storage and can therefore be termed *storage tubes*.

Oblique Scanning

A total of four coils is used to deflect the scanning beam; one pair of opposite coils is arranged to deflect the beam horizontally and is fed with current of saw-tooth waveform and line frequency. By this means the scanning spot is caused to move across the target at a constant velocity and, at the end of each line, to return very quickly to the beginning of the next line. The other pair of coils gives vertical deflection and is fed with current of saw-tooth waveform and frame frequency. Under the action of these two magnetic fields, the electron beam is made to scan the target in a series of nearly horizontal lines.

If the scanning beam sweeps through a constant angle in the horizontal plane at all positions in the vertical plane, the scanned area has a trapezoidal shape similar to that of a keystone. To avoid keystone effect and obtain a true rectangular scanned area, the line saw-tooth current is modulated by the frame saw-tooth current so that the angular sweep in the horizontal plane is decreased as the beam moves up the mosaic.

If the frame saw-tooth current rises linearly with time, the vertical sweep of the scanning beam is at constant angular velocity and the line spacing is not uniform, increasing as the beam moves up the mosaic. This is corrected by distorting the saw-tooth so as to give uniform line spacing.

Electron Gun

The electron gun is an electrode assembly designed to produce a narrow beam of electrons. All types of cathode-ray tubes contain a gun but the beam-forming electrodes of a camera tube, such as an iconoscope, differ from those used, for example, in cathode-ray tubes for television reception. The difference in construction is necessary because the gun of a camera tube is required to produce a very small beam current, often less than 1μA, but in most cathode-ray tubes the beam current is an appreciable fraction of a milliamp.

In cathode-ray tube guns the beam strikes the gun electrodes and releases secondary electrons from them. The secondary current is, however, small compared with the primary beam and because of their small initial velocities the secondary electrons are widely scattered by the fields of the deflecting system. The few secondary electrons which reach the screen are so widely scattered as to be of no consequence.

If, however, there is appreciable secondary emission from a camera-tube gun, then any secondary electrons which reach the target will give rise to a very diffuse secondary image superimposed on the normal image; the electron gun must thus be designed to eliminate secondary emission as completely as possible.

One form of camera-tube gun is illustrated in Fig. 24. The beam cross-section is restricted and secondary content minimized by use of a first anode containing a number of apertured electrodes. The first two apertures (labelled *a* and *b*) prevent secondary electrons released from the curved walls of the anode being emitted through aperture *b* whilst aperture *c* prevents the field due to the second anode dragging secondary electrons into the beam. This form of gun is reasonably successful but suffers from the disadvantage that the potential of the first anode, which is adjusted to focus the beam, also affects the beam current; moreover, there is a small secondary content in the beam.

Fig. 25 shows a modified form of gun which overcomes both disadvantages. In effect, the second anode is split into two separate structures, one of which is placed between the first anode and the control grid to act as a screen. The beam current is now determined by the control grid and second anode potentials and is independent of the first anode potential, which is varied to focus the beam as before. Secondary electrons liberated from the second anode, next to the control grid, are returned to their source by the retarding field existing between second anode and first anode. This field is, however, insufficient to stop the main beam.

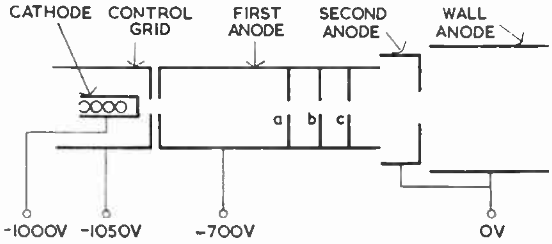

Fig. 24—Early form of camera-tube electron gun

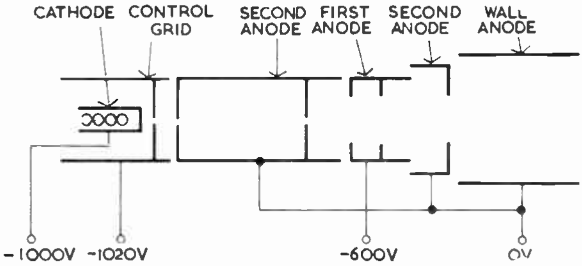

Fig. 25—Camera-tube electron gun designed to minimize secondary emission

Mosaic

For satisfactory performance the capacitance of an element of the mosaic to the signal plate must be large compared with its capacitance to neighbouring elements. If this is not so an appreciable fraction of a charge on one element will be transferred to neighbouring elements through mutual capacitance. This causes blurring of the reproduced image, particularly when the scene contains movement.

Thus the thickness of the mica sheet, which determines the capacitance of an element, is an important dimension. This cannot be made thinner than about 0·002 inch, otherwise the mica becomes difficult to handle, and a value of 0·003 inch is used in practice. The dimensions of an element must be at least several times this thickness to minimize distortion, and a value of 0·01 inch was chosen. Thus the dimensions of the scanning agent, i.e., the cross-section of the electron beam at the target, must not exceed 0·01 inch in diameter and, for a 405-line system with an aspect ratio of 4 : 3 the overall dimensions of the mosaic are approximately 5¼ inches by 4 inches.

The mosaic must be of very fine construction with a number of individual cells to each element otherwise the cells show up in the reproduced image as a grain. Performance is satisfactory if there are at least 10 cells per element; the resolution of the camera tube is then limited by the cross-sectional area of the scanning beam at the target and not by the properties of the mosaic. The total number of cells per mosaic may be as great as 1,000 million and the mosaic may be regarded as approximating to a continuous surface with infinite transverse resistance.

The insulating base on which the mosaic is deposited is usually high-quality mica, but a film of aluminium oxide formed on an aluminium sheet can also be used, the sheet itself acting as the signal plate. The photo-electric material used is mainly silver; a number of methods are available for depositing it on the insulating base and aggregating it into the required state of subdivision. Most methods involve the evaporation of silver *in vacuo* on to the surface which is afterwards heated to several hundred degrees Centigrade, causing aggregation of the silver into small globules. In one method oxygen is then admitted under low pressure and a glow discharge is produced to oxidize some of the silver to silver oxide, Ag_2O. The sensitivity of the mosaic so obtained is produced by treating the surface with a little caesium. The amount of caesium which can be used is very critical; if too much is added the mosaic has poor insulation and the electrostatic charges spread, resulting in blurred images; if too little caesium is used, the insulation is good, but the photo-electric sensitivity is poor. If the mosaic insulation were of no importance, photo-sensitivity could be improved and advantage of this has been taken in the design of other camera tubes such as the image iconoscope. Under favourable conditions the insulation of the mosaic may be so good that a charge-image can be preserved for several hours—or even days—without appreciable spreading.

One difficulty experienced with early mosaics was due to reflection of the optical image from uncoated parts of the mica sheet. The light so reflected was returned to the mosaic again after a second reflection at the inner surface of the glass bulb and gave rise to a second reproduced image displaced from the first image and of different size. This can be overcome by sandblasting the mica sheet before the mosaic is prepared; this gives a dull surface to the mica so that incident light is scattered on reflection and does not form a second image.

Distribution of Potential Across Surface of Scanned Mosaic

The mosaic is a very efficient secondary emitter, the secondary-emission ratio for a caesiated silver surface being as high as 7. When such a surface is scanned by a high-velocity electron beam, as in the iconoscope, there is copious secondary emission and the mosaic takes up a potential, averaged over the surface, such that the total number of secondary electrons collected by the second anode is equal to the number of primary electrons received from the scanning beam. For an unilluminated mosaic this equilibrium

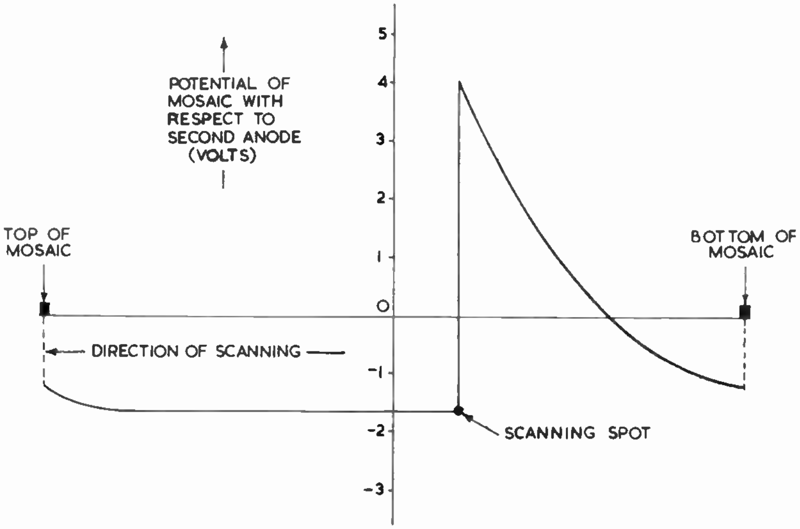

Fig. 26—Distribution of potential over mosaic surface

potential is between 0 and —1 volt with respect to the second anode potential, but there are potential variations of several volts between one point and another on the mosaic surface, depending on the position of the scanning beam.

Fig. 26 illustrates the distribution of potential in the vertical plane over a scanned mosaic surface assumed to be in darkness. When the scanning beam strikes an element initially at the minimum potential of say —1·5 volts, with respect to the second anode, there is a burst of secondary emission. Some of the liberated electrons are collected by the second anode, others are distributed as a more or less uniform rain over the surrounding area of the mosaic and a number return to the element itself. By loss of these electrons the element becomes positively charged and its potential rises to a value of about +4 volts with respect to the second anode, this being the potential at which one secondary electron escapes from the element under the scanning beam for each primary electron arriving, the rest of the secondary electrons returning to the element. When the scanning beam moves on to the next element it again releases a number of secondary electrons with the result that this element is also charged to +4 volts. Many of the electrons released from the second element are attracted towards the positively charged first element and cause its potential to fall. As the scanning beam moves to other elements, the potential of those just scanned falls to the minimum value of about —1·5 volts as they receive the rain of secondary electrons liberated from the elements being scanned. The rate of fall of potential of the scanned elements becomes less as the scanning beam recedes from them and the chances of receiving secondary electrons become less. Thus areas of the mosaic which are about to be scanned have a potential of —1·5 volts; areas being scanned are at +4 volts and areas which have been scanned have a potential which falls to —1·5 volts with increase in distance from the beam.

Mechanism of Signal Production—Detailed Account

The performance of a camera tube with a high-velocity scanning beam is determined to a very large extent by the weak electron-collecting field existing between second anode and target. The field is weak because the target potential is nearly equal to that of the second anode. Only a small fraction of the total number of secondary electrons liberated from the mosaic during scanning is collected by the second anode; the majority return to the target under the action of the electric field generated at the mosaic surface during scanning. This field, termed the *surface field* in subsequent text, is much stronger than the collecting field between mosaic and second anode and its direction is from the area about to be scanned towards that which has just been scanned.

When an optical image falls on the mosaic, photo-electrons are emitted from each element in proportion to the amount of light falling on it. Because of the weak collecting field very few of these reach the second anode and the majority are urged by the surface field towards the target area just scanned. The surface field is particularly strong in the area occupied by, say, twenty scanning lines ahead of the primary electron beam and practically every photo-electron liberated in this area is removed, i.e., in this area photo-emission is saturated.

By loss of photo-electrons the area ahead of the beam carries a charge image, each element having a potential corresponding to the tonal value of the picture element with which it coincides. Elements in dark areas of the optical image have a low potential because they have lost few if any photo-electrons whereas those coinciding with highlights have a high positive potential due to larger photo-emission. When these elements are scanned, the electron beam liberates approximately the same number of secondary electrons from each, i.e., the secondary-emission ratio does not vary with the potential of the elements. But the fraction of the secondary emission from a particular element collected by the second anode depends on the strength of the collecting field surrounding this element and this does depend on the potential of the element. An element in a high-light area of the optical image may well be slightly positive with respect to the second anode; the collecting field is then retarding and only the fastest-moving secondary electrons are able to reach the second anode. On the other hand an unilluminated element is appreciably negative with respect to the second anode and the collecting field is accelerating with the result that electrons with lower velocities arrive at the second anode. Although the secondary emission from each element is constant, the second anode collects more secondaries from elements in darkness than from those which are illuminated. During scanning, therefore, the number of secondary electrons arriving at the second anode varies depending on the potentials of the elements, i.e., the secondary-electron stream is amplitude modulated, maximum density corresponding to black areas in the optical image.

As the scanning beam touches each element of the mosaic in turn, a number of secondary electrons escape to the second anode, the number depending on the amount of light each element has received since the previous scan. The loss of these secondaries on scanning causes the potential of the element to change suddenly and a corresponding potential pulse is induced in the signal plate which is capacitively coupled to all the elements in the mosaic. An element which has been in darkness has a low potential before scanning and on being scanned loses a large number of secondaries to the second anode; its potential jumps positively when scanned and causes a positive potential to appear at the signal plate. Thus the vision-frequency signal at the second anode is in anti-phase to that generated at the signal plate but, to avoid interference from the scanning fields experienced at the second anode, the tube output is usually taken from the signal plate.

It has been pointed out that the scanning beam cannot be regarded as a mechanical contactor because the differential beam resistance is practically infinite. The concept of a contactor can, however, be retained provided that it is regarded as bridging second anode and mosaic. The resistance of the contactor, given by $\Delta E/\Delta I$ where ΔE is a small change in element potential and ΔI is the corresponding change in secondary current arriving at the second anode, is now more reasonable and is of the order of a megohm. The concept still has limitations, however; for example, it does not account for the redistributed secondary and photo-electrons.

It is estimated that approximately one-quarter of the photo-emission is effective in building up the charge image and that approximately the same fraction of the secondary emission contributes to the signal output. The overall efficiency is thus as low as 6 per cent; but the gain in sensitivity due to charge storage is so enormous that it more than makes up for the inefficiency of the tube.

Line Sensitivity

To obtain maximum benefit from the storage principle, photo-emission should be saturated for the whole of the picture period. This does not occur in the iconoscope and is one of the reasons for its low efficiency. But the fact that photo-emission is completely saturated for a fraction of the picture period accounts for the very sharp images of rapidly moving objects obtained from this type of camera tube.

Consider a particular element of a mosaic which is exposed to an optical image and is being scanned. When the scanning beam is some distance from the element, photo-emission is very inefficient because the collecting and surface fields are weak. Any photo-electrons which do escape from the element either return to it or to neighbouring elements with a more positive charge. As the scanning beam approaches the element, the surface field increases and photo-emission becomes more efficient but photo-emission is saturated only during the interval in which the beam scans the few lines before the element.

Thus the potential developed on any part of the mosaic by photo-emission is accumulated, for the greater part, in a very short period estimated at 1/250th second immediately before that part is scanned. In a tube in which full advantage is taken of charge storage, photo-emission is saturated for the whole of the picture period and images of moving objects are blurred to approximately the same extent as in a photographic camera having 1/25th of a second exposure. The iconoscope has, in effect, an exposure time of only 1/250th of a second and for this reason is said to have great *line sensitivity*.

Signal-light Characteristic

During operation of the tube a large percentage of the secondary electrons released by the scanning beam and of the photo-electrons released by the incident light falls back to the mosaic again. These reduce the sensitivity of the tube since they reduce the positive potential of the elements of the mosaic; in an ideal tube all electrons released from the mosaic would be collected by the second anode and would contribute to the tube output. This loss in sensitivity can also be explained by regarding the returning electrons as a high-resistance shunt across the mosaic surface. The redistributed electrons do not reduce the potential of all elements to the same extent; they tend to fall on those parts of the mosaic which have the highest positive charge. Thus the output of the tube corresponding to highlights in the optical image is reduced more than that corresponding to darker tones. For this reason the tube output is not directly proportional to the light input and the signal-light characteristic is curved as shown in Fig. 27.

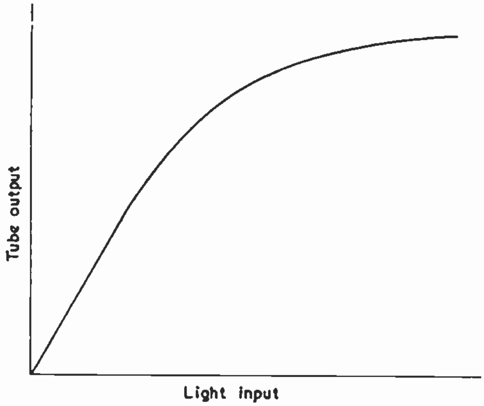

Fig. 27—Signal-light characteristic of iconoscope

The relationship between the signal output and light input of a vision camera tube is usually expressed in terms of *gamma*, γ, the slope of the curve obtained by plotting the logarithm of the output against the logarithm of the light input. A gamma of unity signifies that the signal output is directly proportional to the light input; the gamma of the iconoscope is about 0·5. The cathode-ray tubes used in television receivers have a gamma of about 2·2 and the overall gamma of the television system is thus about 1·1 when an iconoscope is in use. What value of overall gamma is desirable in a television system is influenced to some extent by the viewer's preferences and it seems generally agreed that the pictures obtained from the iconoscope tube have an acceptable gamma. This agrees with standard photographic practice in which an overall gamma of greater than unity is advocated in monochromatic reproduction where the contrast due to colours is missing. Thus one advantage of the iconoscope is that normally no gamma correction is required.

A gamma value of less than unity can be regarded as indicating compression since a given contrast ratio in the optical image is reduced to a smaller ratio at the camera-tube output whilst the receiving cathode-ray tube acts as an expander and restores the original, or gives slightly greater, contrast. For a given ratio of maximum to minimum value of vision-frequency signal, the lower the gamma of the camera tube the wider the range of tonal values which can be transmitted.

Spurious Signals

The iconoscope develops a number of unwanted signals in addition to the picture signal. These are present whether the mosaic is illuminated or not and if not removed give rise to undesirable patches of white and dark on the reproducing screen. These *shading* signals are caused by the redistribution of the secondary electrons released on scanning.

For satisfactory operation of the tube, each element of the mosaic must be scanned only once per picture period, and, to prevent the elements being discharged during line and frame flyback periods, the scanning beam is suppressed between the end of each line and the beginning of the next and also between the end of each frame and the beginning of the next.

When the beam is restored at the start of each line there is a burst of secondary emission as the beam strikes the first element. Under normal conditions most of these secondary electrons would be captured by nearby elements previously scanned and having an appreciable positive charge. At the beginning of a line, however, such conditions do not exist because the last elements to be scanned are at the other side of the mosaic. Thus an abnormally large percentage of secondary emission is collected by the second anode at the start of each line; this represents a potential pulse in the tube output in the black direction. As the beam moves along each line, normal conditions are established and the beam leaves behind an increasing number of positively charged elements. These capture more and more of the redistributed secondary electrons as scanning proceeds and the number of secondary electrons arriving at the second anode gradually falls to a minimum value as the beam approaches the end of each line. Thus the vision signal at the second anode gradually drifts in a positive direction, i.e., towards white as the line is scanned. When the beam is suppressed at the end of the line, secondary emission from the mosaic abruptly ceases; this is equivalent to a sudden pulse in the white direction. These three forms of spurious signal, the pulses at the start and finish of each line and the gradual drift towards white, are illustrated in Fig. 28.

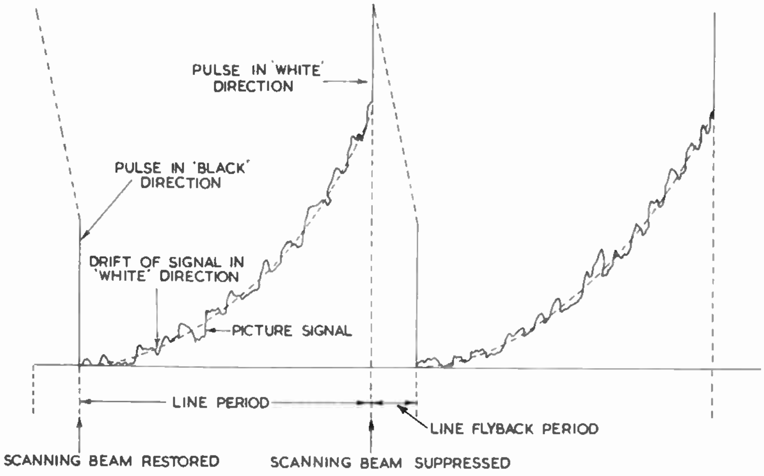

Fig. 28—Waveform of spurious signals

Unwanted signals of similar waveform but at frame frequency also occur; these are associated with the vertical movement of the scanning beam.

The effect of the spurious signals at line and frame frequencies is shown in Fig. 29, which is a photograph of an image from an iconoscope with no light on the target. The shading signals cause a white flare at the right-hand and bottom edges of the picture which should, of course, be a uniform black. The spurious signal at frame frequency is of greater amplitude than that at line frequency because the deficiency in electrons which occurs towards the ends of most line scans is partially made good by electrons liberated from lines

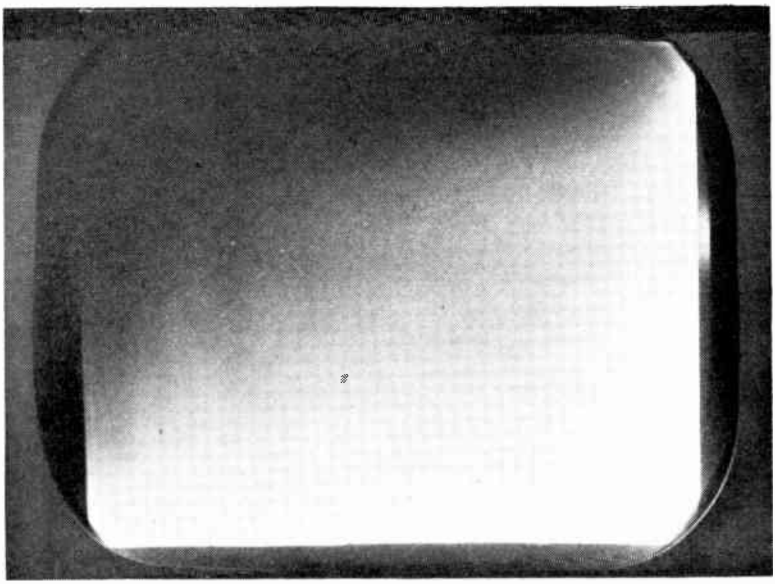

Fig. 29—Background shading due to spurious signals in iconoscope

Fig. 30—Effect of shading signals on image reproduced from an iconoscope

scanned immediately afterwards. This cannot occur, however, for lines near the top of the mosaic (bottom of picture) because the beam abruptly returns to the bottom of the mosaic. The electron deficiency for the few lines near the top of the mosaic is thus most marked, resulting in a strong shading signal at frame frequency.

Other spurious signals are caused by the variation in angle of incidence of the electron beam during scanning; this tends to give greater secondary emission as the angle of incidence increases. Moreover, if the mosaic is not symmetrically positioned with respect to the second anode, the collecting field is stronger at the bottom of the mosaic than at the top; this also tends to produce a shading signal.

Unwanted signals due to this cause can be eliminated as shown in Fig. 21 by extending the second-anode coating in the form of a narrow metal band which encircles the bulb and is symmetrically placed with respect to the mosaic. This form of construction also has the advantage of reducing the capacitance between signal plate and second anode and hence the output capacitance of the tube.

Spurious signals of the type illustrated in Fig. 29 are also obtained when a metal sheet is substituted for the mosaic but they disappear if the sheet is biased negatively with respect to the second anode (so as to saturate secondary emission) and if the sheet is biased positively (so as to suppress secondary emission).

When the mosaic is illuminated, the vision signal is modulated by the shading signal as shown in Fig. 28. The effect of the spurious signals on a reproduced picture is shown in Fig. 30. If the beam current is large the magnitude of the shading signal may exceed that of the wanted signal; on the other hand the beam current cannot be reduced below a certain value otherwise the elements are not fully discharged in the frame period. If several scans are required to discharge the mosaic, reproduced images of moving objects tend to be blurred.

The spurious signals are removed at a very early stage in the vision-frequency amplifying chain; the drift of the signal in the white direction is counteracted by mixing with the picture signal correcting signals of suitable waveform and amplitude. Satisfactory images can be obtained by use of a combination of a saw-tooth (known as *tilt*) and a parabolic (known as *bend*) waveform for correcting the spurious signals at line frequency with a similar tilt and bend combination used at frame frequency.

The pulses produced in the camera-tube output at the start and finish of each line (and frame) flyback period are eliminated by suppressing one of the amplifiers in the vision chain for a period beginning just before the flyback period and ending just after it.

An unfortunate feature of the shading signals is that they are not constant for a given tube but vary with the distribution of light and shade in the optical image. In other words a redistribution of light in one part of the image affects the background tone in another part of the image. For this reason images must be continuously monitored during transmission and the tilt and bend controls adjusted to balance out the changing amplitudes of the spurious signals. These amplitude changes can be minimized by choosing images, wherever possible, which do not contain large areas of uniform tone; images with a wealth of detail are much to be preferred.

Black Level

One of the most important features of a camera tube is the output which corresponds to black in the optical image. In certain types of tube, for example the orthicon, the output signal during line or frame flyback periods always corresponds accurately to black; such tubes are said to have a definite black-level output. There is, however, no definite output corresponding to black for the iconoscope.

When an unilluminated picture element is scanned the output voltage from an iconoscope depends on the magnitude of the shading signal at that instant and this in turn depends on the position of the element in the mosaic and the distribution of light and shade in the optical image. A black-level reference voltage is, therefore, determined arbitrarily and, for each frame, is taken as the voltage corresponding to the lowest tone in the frame. This gives satisfactory results provided that there is always some true black in the field of view of the tube; if no black is present the reproduced images will have unnatural contrast. When an iconoscope is used, therefore, the scenes must be so arranged that there is always some true black present.

PERFORMANCE OF THE ICONOSCOPE

Sensitivity

The sensitivity of the iconoscope is limited by two factors:

(1) The noise generated in the coupling resistor to the following amplifier and in the first stage of the amplifier. The output from the tube must be large compared with the noise, for if the signal-noise ratio is poor the noise becomes visible as a grain in the reproduced image.

(2) The shading signals. If attempts are made to increase the tube output (by increasing beam current, for example) the shading

signals increase to a value at which it becomes impossible to correct them by the tilt and bend controls.

For an excellent reproduced picture (in which the signal-noise ratio is better than 30 : 1) the incident scene illumination necessary is approximately 200 foot-candles for a camera equipped with a lens of *f*/3 aperture. This is a strong but not unduly uncomfortable illumination for studio work; it should be compared with the value of 5,000 foot-candles obtained from the sun on a clear summer day.

The sensitivity of the tube decreases as the amount of light incident on the mosaic increases. This is illustrated by Fig. 31, which shows that the curve relating light input and voltage output has a high slope indicating high sensitivity at low values of illumination of the mosaic. The slope becomes lower as the illumination is increased; this, of course, indicates that the gamma is less than unity.

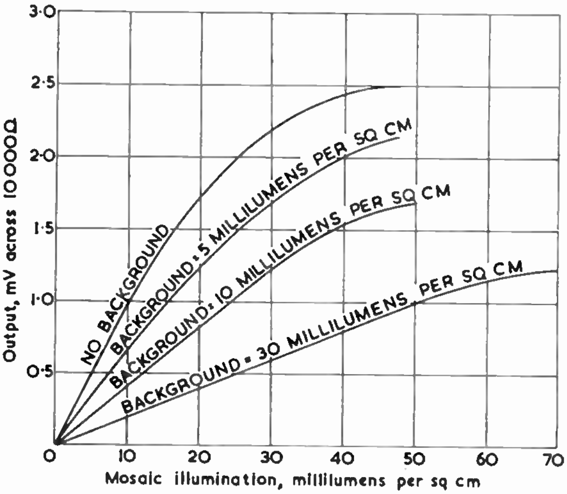

Fig. 31—Signal-light characteristics for iconoscope showing variations of sensitivity with illumination

The sensitivity of the tube and the depth of field are interdependent; the distance an object may move towards or away from the lens for a given amount of blurring of the image is inversely proportional to the diameter of the lens (see Chapter 9). If the full aperture of the lens must be used to obtain adequate illumination of the mosaic, the depth of field is a minimum but if abundant light is available, the lens may be stopped down and increased depth of field obtained.

The sensitivity of the iconoscope can be improved as much as three times by use of a *bias light*, a small bulb of about 1-watt rating situated within the camera housing and positioned behind the mosaic so that weak illumination falls on the tube walls but no light falls directly on the mosaic. For a given tube output, use of this light enables the beam current to be reduced, giving a welcome reduction in the amplitude of the shading signals. The mechanism of this effect is not completely understood, but one possible explanation is that the illumination from the lamp liberates photo-electrons from the tube walls which are coated with a thin layer of photo-electric material during the sensitizing of the mosaic. Some of the liberated electrons are attracted towards positively charged areas of the mosaic and greater secondary emission flows from mosaic to second anode to keep the average mosaic potential constant.

Resolution

The ability of the iconoscope to portray image detail in the output is not limited by the structure of the mosaic provided there are at least 10 cells per element. If the vision-frequency amplifiers have adequate high-frequency response, the chief factor limiting the resolution is the size of the scanning spot, i.e., the cross-sectional area of the electron beam where it meets the mosaic. If the beam is focused at a point on the mosaic, the area covered can be reduced to satisfactory proportions by adjustment of the electron-gun potentials. When the beam is deflected, however, the point of accurate focus traces out part of the surface of a sphere and the only points on the mosaic where the beam is accurately in focus are where the imaginary sphere cuts the surface; at all other points it is out of focus. Fortunately, the required beam current is very small —less than 1 μA—and the cross-section can be restricted in the gun by a series of small apertures. By focusing the beam accurately at the centre of the mosaic it is possible to keep the spread within satisfactory limits even at the corners. This point is discussed fully in Appendix A.

There is, however, some loss of resolution at the corners, not all of which is due to insufficient depth of beam focus; contributory causes are the scanning fields which tend to destroy the beam focus at maximum deflection, and loss of optical focus.

Colour Response

The colour response of the iconoscope camera tube is largely determined by the materials used in the mosaic and the method of sensitization, but the glass window also causes absorption effects.

The mosaics of early standard Emitron tubes consisting of silver treated with caesium were prepared before being mounted in the camera tube and an unfortunate feature was a peak in the photoelectric response between 7,000 and 8,000 Å.* Maximum response of the human eye occurs between 5,000 and 6,000 Å. Thus the mosaic was most sensitive to red or infra-red light and the tube gave images of unnatural contrast. These mosaics were the only types available in the early days of television and it was customary for the artists to use heavy make-up to give more natural contrast in reproduced images.

Better results were obtained from later tubes by preparing the mosaic *in situ*, that is by depositing the photo-electric material on the mica sheet in the camera tube. By admitting silver and caesium in regulated doses, it is possible to reduce the wavelength of maximum photo-electric response to obtain a much better approximation to the response of the eye. The need for special make-up thus disappears, and provided adequate light is available the tube can be used to transmit satisfactory images of outdoor scenes.

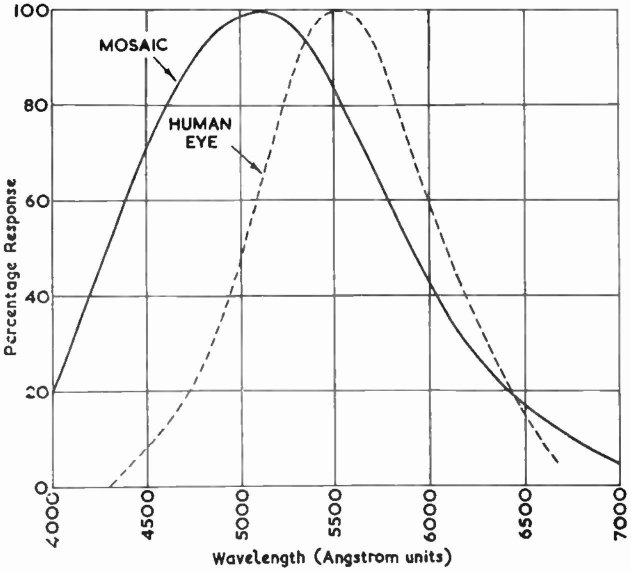

Fig. 32—Colour response of a standard Emitron

A typical colour response curve for a standard Emitron is illustrated in Fig. 32. There is inevitably some variation in the colour response of mosaics prepared *in situ* and some difficulty may be experienced in selecting two or more matched tubes for use in a vision channel.

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* Å is the abbreviation for Ångstrom unit. 1 Ångstrom unit = 10^{-8} centimetre.

ADVANTAGES AND DISADVANTAGES OF ICONOSCOPES

Iconoscope camera tubes have given satisfactory results in television services over a number of years. Their advantages over other types are as follows:

(1) They are completely stable. Certain types of low-velocity camera tubes can become unstable when exposed to too much light or if the operating potentials are incorrectly adjusted. As a result of this instability, the tube is rendered useless for a brief period. This does not occur with the iconoscope.
(2) Iconoscopes have a very low effective exposure time and give very sharp images of rapidly moving objects.
(3) The colour response approximates to that of the human eye and the contrast in reproduced images is natural.
(4) The gamma value of the iconoscope is less than unity and is well matched to the gamma of receiving cathode-ray tubes. No gamma correction is normally necessary.
(5) There is very little geometric distortion in the images from an iconoscope in spite of oblique scanning.

The chief disadvantages of the iconoscope are as follows:

(1) The presence of strong shading signals. These require artificial correction and expert operators are necessary to adjust the tilt and bend controls.
(2) Absence of a definite black-level output signal.
(3) Limited sensitivity. The sensitivity is adequate for studio productions and for outdoor transmissions when plenty of light is available, but reproduced images are likely to be disappointing if the tube is used out of doors on a dull day.
(4) Necessity for keystone modulation of the scanning waveforms. The correction for oblique scanning of the target can be so accurately carried out that there is virtually no geometric distortion in the reproduced image. Nevertheless the fact that correction is necessary constitutes a disadvantage.
(5) The tube is an awkward shape for mounting in a camera; moreover, the size of the mosaic and its distance from the window impose limitations on the design of the external optical system and, unless very great illumination is available, result in a limited depth of field.

4.2 IMAGE ICONOSCOPE (SUPER-EMITRON, PHOTICON)

Introduction

The image iconoscope camera tube was developed as a result of experiments to improve the sensitivity of the iconoscope.

In Great Britain the earliest image iconoscopes were termed Super-Emitrons and more recent tubes of smaller size are the midget Super-Emitron and the Photicon. The following description applies equally to all these tubes.

One of the factors limiting the sensitivity of the iconoscope is the need for adequate mosaic insulation; if sufficient caesium is added to the silver coating to give maximum photo-sensitivity, the insulation is poor and reproduced images are blurred. The amount of caesium is, therefore, limited to give adequate insulation but the photo-sensitivity is then not a maximum. The improved sensitivity of the image iconoscope is obtained by separating the functions of photo-emission and secondary emission and using separate electrodes for the two purposes. The light image is projected on a photo-sensitive electrode, which is treated to give maximum photo-emission but need not be constructed in the form of a mosaic, and the photo-electrons released are focused by a magnetic or electric lens system on the target which is designed for maximum secondary emission. The insulation of the photo-electric surface and the photo-sensitivity of the target are now of secondary importance. A further advantage of this form of construction over that of the

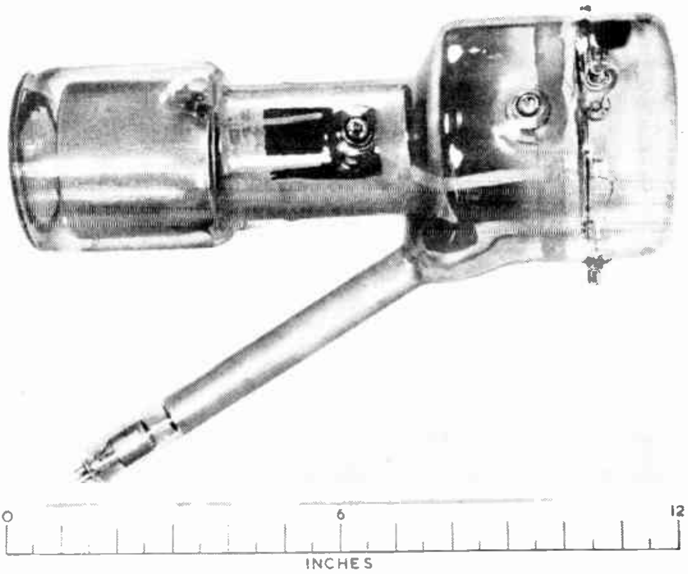

Fig. 33—An image iconoscope. The particular tube illustrated is a Photicon

iconoscope is that photo-emission can be saturated from the light-sensitive electrode. These advantages result in an improvement in overall sensitivity of about 5–10 times that of an iconoscope. The image iconoscope may be regarded as an iconoscope (with a modified target) to which has been added a photo-electric electrode and means for directing and focusing photo-electrons on the target. These additional parts are sometimes described as forming an *image section*. As a result of the improved sensitivity, the addition of the image section enables improved depth of field to be obtained. A photograph of an image iconoscope is shown in Fig. 33.

Construction

The image iconoscope tube has a bulb and side tube similar to those of the iconoscope but in place of the window of the iconoscope there is an extension tube which contains the image section. The extension tube has a flat window at its far end and the photo-sensitive electrode is mounted parallel with this or is formed on the surface of it. This electrode is smaller than the iconoscope target and the external optical system can be placed very near to it; thus the shape of the image iconoscope does not impose limitations on the design of the external optical system as occurs in the iconoscope.

Photo-cathode

This electrode must be reasonably transparent because the optical image focused on one side of it must release photo-electrons from the other; it must also be conductive because the whole surface must be maintained at a negative potential with respect to the second anode of the electron gun to saturate all photo-emission to the target. Because it is photo-sensitive and is maintained at a negative potential, the light-sensitive electrode is known as a *photo-cathode* and it usually has the form of a glass disk—or the tube end—on which a very fine layer of photo-emissive material is evaporated. Early Super-Emitron tubes had a photo-cathode mainly composed of antimony and caesium but the more modern midget Super-Emitron uses bismuth, silver and caesium. The coating is in contact with a narrow metal border surrounding the photo-cathode and to which the negative potential is applied.

Image Sections with Electrostatic Focusing

Some image iconoscopes have electrostatic focusing in the image section; the extension tube contains a number of conducting rings which are situated between the photo-cathode and the target and connected to tappings on a potential divider. The photo-electrons are thus focused on the target by a method similar to that used in electron guns. The photo-electrons liberated from the photo-cathode leave it with a certain velocity even when there is no electric field to draw them away; this velocity is known as the *initial velocity*. This effect is similar to that which occurs in a thermionic valve and which causes a diode valve to take a small anode current even when the anode is slightly negative with respect to the cathode. The initial velocities of the electrons liberated by light from a photo-cathode are small, only a few electron-volts, but the magnitude and direction of the velocity vary from electron to electron. Thus the photo-electrons have appreciable lateral components of initial velocity and these cause distortion of the charge image on the target. To minimize this distortion, the photo-electrons must be attracted to the target by potentials which are great compared with the initial velocities.

Thus potentials as high as 3,000 volts are used to saturate photo-emission to the target, the potential depending on the degree of resolution required. Distortion can also be minimized by curving the photo-cathode so that it presents a concave surface to the target; some correction is then necessary in the external optical system to compensate for the photo-cathode curvature. Most image iconoscopes used in television services have magnetically focused image sections.

Image Sections with Magnetic Focusing

In tubes with magnetically focused image sections, a steady potential of several hundred volts is maintained between the photo-cathode and the target, and a coil carrying a direct current surrounds the extension tube. In the tube illustrated in Fig. 34 a short coil is situated between the photo-cathode and the target. This produces a charge image, the size of which depends on the distance between the photo-cathode and the coil and between the coil and the target. One effect of this magnetic lens is to rotate the charge image through an angle of approximately 30 deg about the axis of the extension tube. This is compensated by mounting the camera tube in the camera housing at the correct angle with respect to the extension-tube axis. There is some geometric distortion of the charge image, points at the edge of the image suffering more rotation than points near the centre, but this can be minimized by careful design of the focusing coil.

If the magnetic field of the scanning coils interacts with that of the focusing coil, the photo-electrons oscillate across the surface of the target and serious loss of definition results. Moreover, if the field of the focusing coil affects the electron beam, it distorts the raster and causes geometric distortion of the image. To prevent

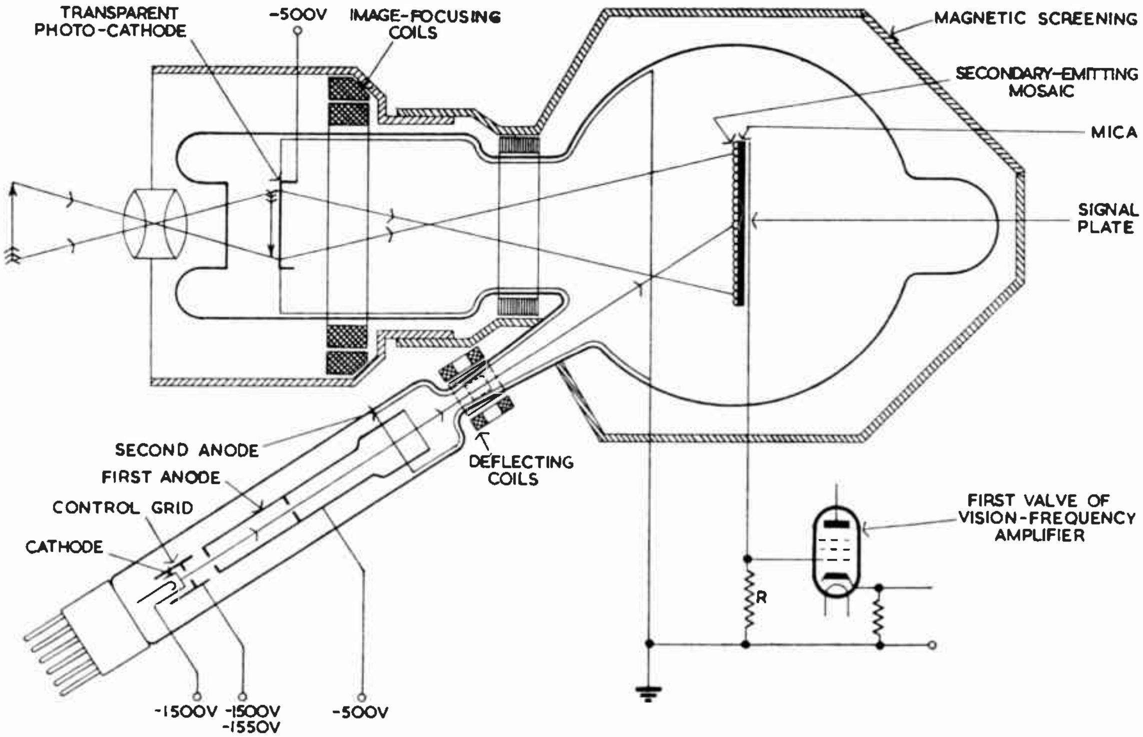

Fig. 34—One type of image iconoscope: a Super-Emitron tube

the magnetic fields interacting, the focusing coil is screened from the deflecting coils by mumetal partitions as shown in Fig. 34.

Target

The target may be similar to that of an iconoscope and have the form of a mosaic made up of a very large number of individually insulated cells on a sheet of mica backed by a signal plate but in the image iconoscope the mosaic is treated to give good secondary emission and have high transverse resistance. Very good results can, however, be obtained with a target not in the form of a mosaic but consisting simply of a thin sheet of mica, one side of which has a thin conductive coating to act as signal plate, the other side being treated with a small amount of caesium to give the require secondary emission and transverse resistance. Alternatively, the target may consist of a signal plate coated on the scanned side with an insulator such as china-clay in the form of a very finely divided powder.

Mechanism of Signal Production

Photo-electrons are liberated from various elements of the photo-cathode in direct proportion to the light incident on the elements. These electrons are attracted towards the target by the electric field between it and the photo-cathode and are focused on the target by an electrostatic or magnetic lens system. On striking the target the photo-electrons liberate secondary electrons (under favourable conditions approximately 5 per photo-electron) to produce a charge pattern in which positive areas correspond with highlights in the image. The target is scanned by the electron beam and the output signal is generated at the signal plate in substantially the same way as in the iconoscope.

The line sensitivity of the image iconoscope is inferior to that of the iconoscope; this can be explained as follows. The secondary electrons released from the image iconoscope target have an average initial velocity approximately 6 times that of the photo-electrons released from the iconoscope mosaic. In an iconoscope tube most of the photo-electrons released from areas of the mosaic remote from the scanning beam fall back on the target and, because of the low velocity of release, very few are captured by the second anode. But nearly all the photo-electrons liberated from areas immediately ahead of the beam are captured by the surface field. Thus the efficiency of removal of photo-electrons varies considerably over the mosaic surface and is a maximum immediately ahead of the beam; this accounts for the great line sensitivity.

In the image iconoscope tube the secondary electrons released from the target have an appreciable initial velocity and a significant fraction of them are captured by the second anode. Thus there is a steady removal of secondary electrons from the whole surface of the target and the effect of the surface field is less pronounced than in the iconoscope. The efficiency of removal of secondary electrons over the target surface does not vary to the same extent as in the iconoscope, i.e., the line sensitivity is inferior. But the build-up of positive charge at areas of the target remote from the scanning beam is more efficient than in the simpler tube; this effect, sometimes described as *frame sensitivity*, offsets the lower line sensitivity.

The image iconoscope tube develops spurious signals in the same way and of similar waveform as the iconoscope but they are of smaller amplitude because of the higher initial velocities of the secondary electrons.

PERFORMANCE OF THE IMAGE ICONOSCOPE

Sensitivity

The photo-electric sensitivity of a photo-cathode can be between 30 and 40 μA per lumen, compared with 10 μA per lumen for the standard Emitron mosaic. The gain due to secondary emission is approximately 5 and thus the overall gain due to the image section is between 15 and 20 times. Of this a factor of about 5 is used in improving the optical system; for example, the area of the photo-cathode of a Super-Emitron is about 1/5th of that of the target and lenses of short focal length (such as 2 inches) and large aperture (such as *f*/2) can be used, giving greater depth of field than is obtainable from the standard Emitron. Such a lens has less than 1/4 the light-gathering capacity of the standard Emitron lens and the overall sensitivity of the Super-Emitron is 4 or 5 times that of the standard Emitron; the Super-Emitron can give satisfactory images with an illumination of 40 or 50 foot-candles using a lens of *f*/2 aperture. For this reason Super-Emitron tubes have been used mainly for outside broadcasts and were first used for this purpose by the BBC when the Armistice Day ceremony was televised on November 11th, 1937.

The useful sensitivity of the image iconoscope tube, like that of the iconoscope, is limited by the noise generated in the coupling resistor to the following amplifier and in the first stage of the amplifier and by the amplitude of the shading signals.

Unlike the iconoscope, the image iconoscope can be over-loaded if too much light is allowed to reach the photo-cathode; excessive light causes defocusing and compression of the tonal values (known as *crushing*) on the white parts of the image; this can be avoided by stopping down the lens so as to reduce the amount of light reaching the photo-cathode.

Resolution

In spite of the addition of the image section, the resolution of the image iconoscope is equal to, if not better than, that of the iconoscope. If required, however, the resolution of both tubes can, in effect, be improved by use in the following amplifier of compensating circuits giving increased gain as frequency rises. Such circuits also cause the amplifier noise—mainly shot noise at the grid of the first valve—to increase with frequency. Thus the noise is concentrated into the upper frequencies and the signal-noise ratio is impaired. The amount of correction which can usefully be employed increases with increase in tube sensitivity. Provided adequate light input is available, more correction can be used with the image iconoscope than with the iconoscope and the resolution is correspondingly better. If, however, the available light input is low, the full sensitivity of the tube is required and little compensation can be used.

Colour Response

The colour sensitivity is determined by the material used in the photo-cathode and the treatment during sensitization and it is now possible with a coating of bismuth, silver and caesium to obtain a response which approximates to that of the human eye together with very good photo-sensitivity.

MINIATURE IMAGE ICONOSCOPES

Since the Second World War improvements in manufacturing technique have enabled much smaller image iconoscopes to be made. Two examples of this small type of tube are the midget Super-Emitron* and the Photicon, the dimensions of both tubes being approximately one-half of the earlier Super-Emitron. The electron gun of the new tubes does not protrude beyond the plane of the photo-cathode; this, combined with the smaller dimensions, makes these tubes quite convenient for mounting in a camera and removes one of the disadvantages of the original Super-Emitron. The midget Super-Emitron is approximately twice as sensitive as the larger tube and gives good images with an illumination of 40 foot-candles.

Photo-electron Stabilization of Image Iconoscope

Two of the main disadvantages of the image iconoscope, namely

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* J. E. I. Cairns, " A Small High-velocity Television Pick-up Tube." *Proceedings of the I.E.E. Television Convention* 1952, Paper No 1311.

the presence of spurious signals and the absence of a signal representing black level, can be overcome by a method known as *photo-electron stabilization.** In this method two additional strip electrodes are mounted inside the bulb near the edges of the target which are responsible for the white flare. The tube has an additional semi-transparent photo-cathode of large area surrounding the storage plate, as shown in Fig. 35. Leads from the strips are brought outside the bulb to permit the strips to be given an adjustable bias of a few volts positive with respect to the nearby photo-cathode.

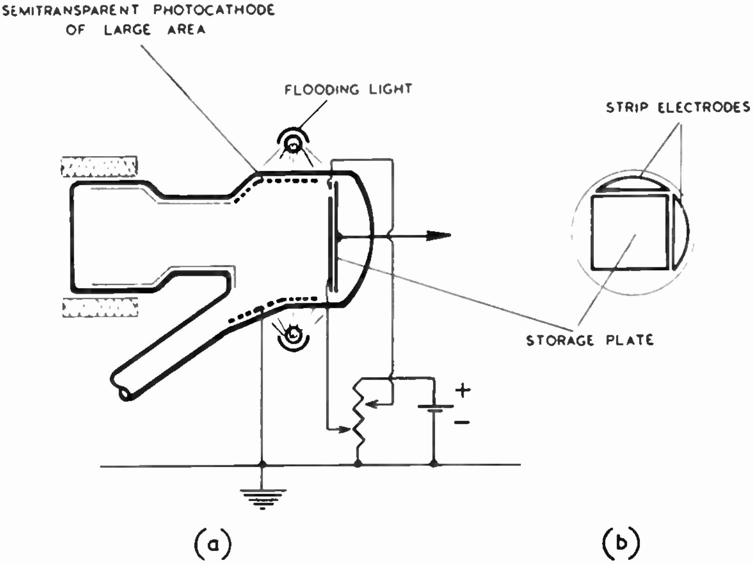

Fig. 35—Photo-electron stabilization of an image iconoscope

The photo-cathode is illuminated by small bulbs situated near the tube and gives rise to a cloud of photo-electrons which are attracted to the strips and flood the adjacent areas of the target. The strips are mounted near the target areas which are deficient in electrons under working conditions and in this way electron equalization of the storage surface can be achieved. The strips have a second-order effect improving tube performance because they act as part of the secondary-electron collector, improving collection to one side and at the bottom of the picture.

Photo-electron stabilization modifies the mechanism of signal generation. In an iconoscope the number of electrons received by

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* J. E. Cope, L. W. Germany and R. Theile, "Improvements in Design and Operation of Image Iconoscope Type Camera Tubes." *Journal of the British Institution of Radio Engineers*, Vol. XII, No. 3, March 1952.

the target from the scanning beam during a picture period is equal to the number lost by photo- and secondary-emission. Thus, over a picture period, the average value of the tube output signal is zero. In a photo-electron stabilized image iconoscope the output, for zero light input, is not zero but has a uniform level which is slightly negative with respect to the second-anode potential; on the average more secondary electrons leave the storage surface than are received from the scanning beam, the difference being due to the flood of photo-electrons received from the nearby photo-cathode.

If the strip bias and photo-cathode illumination are suitably adjusted when a scene is televised the output signal after clamping the inter-line pulses is unidirectional with respect to the clamping level and the signals corresponding to black areas in the image have a constant value with respect to clamping level. Thus the tube has now a definite black-level output signal.

The improvement in the reproduced images brought about by photo-electron stabilization is illustrated in Figs. 36 and 37.

Image Iconoscope using Electron Multiplier

The limiting factor in low-light operation of an image iconoscope is the threshold set by pre-amplifier noise. This limit can be avoided by amplifying the secondary-electron current from the target in an electron multiplier but it is difficult to arrange for the very diffuse spray of secondary electrons from the target to enter the input of a conventional electron multiplier. It is possible,* using an electron-transmissive screen in front of the first multiplier dynode, to obtain complete collection and sufficient acceleration of the secondary electrons leaving the target. If the geometry of the multiplier and target assembly is suitably chosen a plane field can be presented to the target surface, achieving uniform picture generation over the target area. The multiplier assembly could have the form of closely spaced annular disks enclosed by a circular screening box. Moreover, by photo-electron stabilization, the shading signals can be eliminated and a definite black-level output obtained.

ADVANTAGES AND DISADVANTAGES OF IMAGE ICONOSCOPES

Image iconoscopes have been extensively used in the BBC Television Service since 1937, for studio and outside broadcasts. Image iconoscopes have all the advantages of the iconoscope (see page 68) but their disadvantages are fewer; for example, the sensitivity

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* R. Theile and H. McGhee, "An Investigation into the Use of Secondary-electron Signal Multipliers in Image Iconoscopes." *Journal of the Institution of Electrical Engineers.* Convention on British Contribution to Television, May 1952.

Fig. 36—Reproduced image from an image iconoscope with photo-electron stabilization

Fig. 37—Reproduced image from an image iconoscope without photo-electron stabilization

is good and the miniature tubes are quite convenient for mounting in a camera and impose no serious limitations on the design of the external optical system.

4.3 MONOSCOPE

A monoscope is a camera tube containing a target on which a pattern or photograph is printed and which, by scanning the target, generates a picture signal corresponding to the printed image.* The tube output can be used for test purposes or, in television services, to provide station identification or interval signals. Monoscopes may thus take the place of a complete camera channel when a stationary pattern or picture is to be transmitted. A photograph of a monoscope is given in Fig. 38.

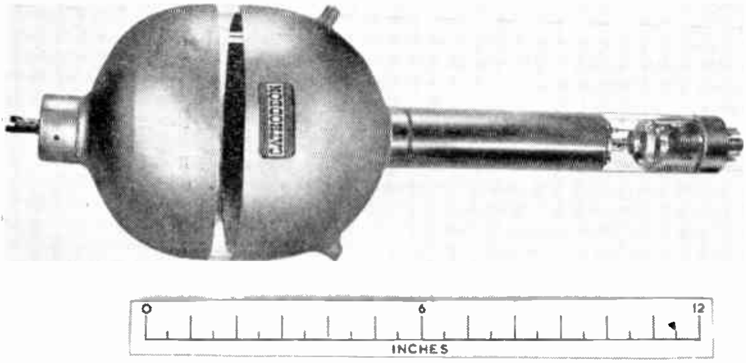

Fig. 38—A monoscope

It was pointed out on page 40 that picture signals can be obtained from a camera tube if the secondary-emission ratio of the target can be varied locally in accordance with the scene to be transmitted. In monoscopes the pattern or photograph is printed on the target in a pigment which modifies the secondary-emission ratio in this way. The tubes are usually high-velocity types, with electromagnetic scanning coils of the types used for receiving cathode-ray tubes and focusing may be electromagnetic or electrostatic. The target is biased approximately 30 volts negative with respect to the final gun anode to enable all the secondary electrons liberated from the target to be collected by the anode. This saturation of the secondary emission leads to efficient picture signal generation and also eliminates shading signals.

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* R. D. Nixon, "The Monoscope." *Proceedings of the I.E.E. Television Convention* 1952, Paper No. 1293.

CHAPTER 5

PHOTO-EMISSIVE LOW-VELOCITY CAMERA TUBES

5.1 INTRODUCTION

CAMERA tubes with high-velocity scanning beams can give images of good quality and have been used successfully in high-definition television services for a number of years. Nevertheless, they have certain disadvantages which have proved inconvenient; all of these result from the use of a high-velocity scanning beam and the consequent stabilization of the target at or near second-anode potential. These disadvantages are as follows:

(1) Sensitivity is limited. In the iconoscope it is limited by the weak collecting field between target and second anode which attracts only a small fraction of the photo and secondary electrons liberated from the target to the anode. The image iconoscope is more sensitive because all the photo-emission from the photo-cathode is collected by the taaget, but the field between target and second anode is again weak and only a small fraction of the secondary electrons released from the target are collected by the anode. In both tubes the failure to collect all the secondary electrons implies that full advantage is not taken of the storage principle and that the tubes give a small percentage of the efficiency theoretically possible.*

(2) The presence of shading signals caused by secondary emission from the target.

(3) The absence of a definite output signal corresponding to black in the image.

Although the two last-mentioned disadvantages can be eliminated by photo-electron stabilization, a camera tube with a low-velocity scanning beam and with a target stabilized at cathode potential offers an opportunity of eliminating all these disadvantages. A strong collecting field can be provided to collect all the photo-emission and full advantage can be taken of the storage principle to obtain high sensitivity; there is no secondary emission from the target and no shading signals similar to those of the iconoscope; a definite black-level signal can be obtained.

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* But the weak collecting field responsible for the limited sensitivity also gives high-velocity tubes their low gamma and good reproduction of moving objects.

Research on low-velocity camera tubes started before the Second World War and the main difficulties experienced were in maintaining the target at cathode potential and in controlling, i.e., focusing and deflecting, the low-velocity scanning beam. The first low-velocity tube to be used in a television service was the orthicon* in 1939 and post-war tubes embodying the same basic principles have included the C.P.S. Emitron and the image-orthicon. The following sections are devoted to these tubes which are described in the order given above.

5.2 ORTHICON

Introduction

The orthicon (orthiconoscope in full) was developed by Rose and Iams in America and used in that country immediately before the Second World War for outside broadcasts.

In essentials the tube consists of an evacuated glass cylinder containing a mosaic which is scanned by an electron beam; in layout the tube resembles that shown in Fig. 17. The orthicon differs from the two types of tube already described in having a low-velocity beam and also because the optical image is projected on one side of the target and the electron beam scans the other side. This technique was made possible by the development of a target similar to that of the iconoscope but with a transparent signal plate, dielectric and mosaic; such a target avoids the necessity for keystone modulation of the scanning fields and results in a camera tube conveniently shaped for mounting in a camera.

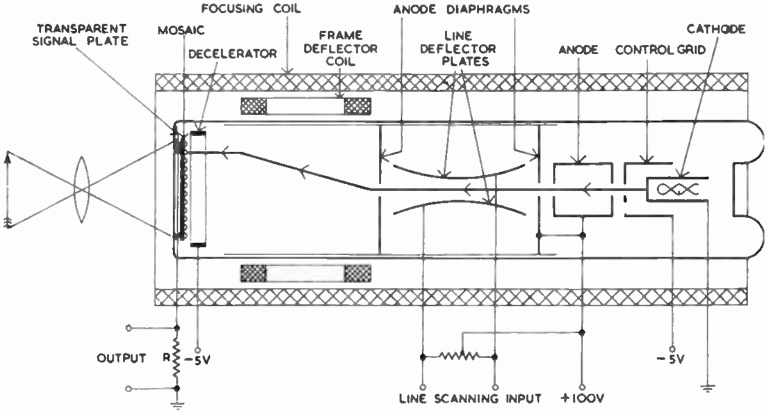

Fig. 39—Orthicon camera tube

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* A. Rose and H. Iams, "The Orthicon, A Television Pick-up Tube." *RCA Review*, Vol. IV, No. 2, pp. 186–199, October 1939.

Construction

The orthicon (Fig. 39) consists of an evacuated cylindrical glass tube with an electron gun at one end and the target at the other. By means of a lens system an image of the scene to be televised is focused on the target through the end wall of the tube. The electron gun is simple, having an indirectly-heated cathode, a control grid and anode. To the anode are connected two apertured electrodes or diaphragms and a metallic coating deposited on the walls of the tube and extending for most of the length of the tube. The first diaphragm (nearest the gun) has a circular hole larger than the required beam cross-section and the second diaphragm has a slot parallel with the deflector plates (i.e., at right angles to the plane of the paper). In the space between the two diaphragms is a pair of deflector plates between which the electron beam passes; between the second diaphragm and the target the beam passes through the magnetic field of two saddle coils clamped to the outside of the tube. A short cylinder immediately in front of the mosaic is held at a small negative potential. A large solenoid carrying direct current surrounds the entire tube and produces an axial magnetic field.

Mechanism of Signal Production

The process of target stabilization occurs in the following manner:—Initially, scanning-beam electrons strike the target and give it a negative potential which increases with time. This potential sets up between the target and the gun anode an electric field, also increasing with time, which slows down approaching beam electrons and decreases the rate of increase of target potential. Eventually a state of equilibrium is reached in which the retarding field before the target is strong enough to prevent any scanning-beam electrons from reaching the target; the target potential is now approximately equal to that of the electron-gun cathode.

When the target has been thus stabilized, the behaviour of the electrons in the tube is as follows:—If the initial emission velocity is neglected, electrons leave the gun cathode at zero velocity, and are accelerated by the electric field between cathode and anode to a certain velocity in the direction of the target. As the electrons enter the field between anode and target, their velocity falls and reaches zero immediately before the mosaic. The electrons are now accelerated back along their initial path by the field between target and anode and are finally captured by the anode.

Because the electron velocity is zero near the target only a very small positive potential applied to the target is sufficient to cause scanning electrons to land on it. Provided the applied potential is small enough, the velocity with which they land is so small that little or no secondary emission occurs.

When the mosaic is in darkness there is no photo-electric emission and the target takes up a minimum potential low enough to repel all the primary electrons and prevent them striking the target. When an optical image is focused on the mosaic, photo-electrons are released from the various elements of the mosaic in direct proportion to the light on those elements; these electrons are accelerated to the anode by the electric field between target and anode. All the photo-electrons released from the mosaic are removed immediately and very few, if any, return to the mosaic to reduce the tube efficiency as in the iconoscope. The charge image so established on the mosaic grows during the interval between successive scans and full advantage of the storage principle is obtained. During scanning of the illuminated mosaic, primary electrons land on the mosaic in sufficient numbers to neutralize the charge and restore the mosaic to its minimum potential. This induces e.m.f.s in the signal plate which is capacitively coupled to the mosaic elements as in the iconoscope and the output of the tube is developed across the signal resistor connected between signal plate and electron-gun cathode.

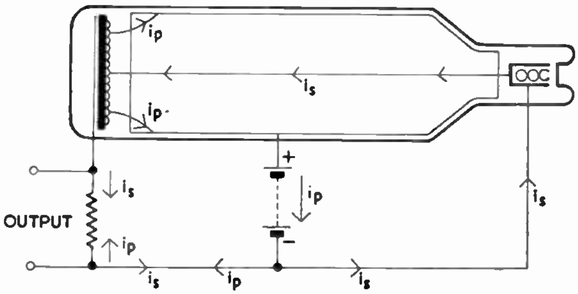

Fig. 40—Signal currents in the orthicon

The method of signal production in the orthicon can be explained in terms of two signal currents i_p and i_s flowing in opposite directions through the signal resistor as shown in Fig. 40. The current i_p is due to photo-electric emission from mosaic to anode and changes comparatively slowly; this current flows independently of the scanning process. The current i_s is caused by sequential discharge of the mosaic elements by the scanning beam and contains very high-frequency components; this current is interrupted during line and frame flyback periods when the scanning beam is suppressed.

This explanation is very similar to that given for signal production in the iconoscope, with the exception that the signal resistor is returned to electron-gun cathode in the orthicon and to second anode in the iconoscope. The mechanism of signal generation in the iconoscope is complicated by secondary emission from the target and the explanation in terms of i_p and i_s is suitable only for inclusion in simplified accounts. There is, however, no secondary emission from the orthicon target and the explanation of signal production given here is in full agreement with the behaviour of the tube.

Definite Output Signal Corresponding to Black Level

The component i_s of the output current depends on the number of scanning electrons which land on the target; at points on the target corresponding to highlights a comparatively large number of electrons reach the target; at points which are unilluminated and correspond to black areas in the image, no electrons land and i_s is zero. Thus the output signal which corresponds to black in the image is that developed by i_p only in the signal resistor. The current i_s is zero during line and frame flyback periods when the scanning beam is cut off and the output signal during these periods can be taken as representing black level.

The signal during frame flyback periods is a true indication of black level only if the mean illumination over the mosaic does not appreciably change during the frame period. This occurs when the scene is lit by lamps on a d.c. source or by natural light. If, however, the scene is illuminated by lamps on an a.c. source, the frequency of which is synchronized with the frame frequency, objectionable *hum-bars* may appear across the reproduced image as a consequence of the illumination varying during the frame period. This interference is particularly bad if the lamps are of the discharge type; images are tolerable if filament lamps are used.

These difficulties disappear if the signal during line flyback periods is taken as black level but careful screening may be necessary to avoid induction in the signal plate of a strong signal radiated from the line-scanning system.

Modulation of Return Scanning Beam

When the mosaic is in darkness none of the primary electrons lands and all are reflected back along their incident path. When the mosaic is illuminated, some of the primary electrons succeed in reaching the mosaic and there is a corresponding drop in the number of primary electrons returned along the original path. Thus the return electron beam contains a component at signal frequency but in opposite phase to i_s. In some types of low-velocity tube, notably the multiplier orthicon and image multiplier orthicon, the return electron beam is collected in an electron multiplier, the output of which constitutes the tube output.

Target

The target is similar in construction to that of an iconoscope but the mosaic, dielectric and signal plate must all be reasonably transparent. Such targets are difficult to manufacture and the photo-efficiency obtained in early tubes was only approximately 2 μA/lumen, i.e., about 1/5th that of a standard Emitron target. This and other losses associated with the smaller area of the orthicon target are offset by the more efficient use of the storage principle but the overall sensitivity of the orthicon was not very much greater than that of the iconoscope and is certainly less than that of the image iconoscope.

Difficulties of Low-velocity Beam Scanning

The use of a low-velocity scanning beam introduces a number of difficulties; one is that of keeping the beam accurately in focus as it is deflected over the target surface. The same difficulty is experienced with high-velocity beams (see page 66) but is aggravated here because the beam is very unstable when slowed down to zero velocity. Not only does the beam tend to spread due to the natural repulsion of its constituent electrons but it is also greatly affected by small nearby potentials on the walls and the target—and the target can acquire potentials even when unilluminated. Thus the beam tends to spread, i.e., to become defocused as it approaches the target.

To minimize this effect, the wall anode is extended for a considerable proportion of the length of the tube to maintain the beam at a comparatively high velocity to within a very small distance of the target.

A second difficulty is associated with oblique incidence of the electron beam on the target. If the beam is deflected by methods similar to those used in cathode-ray tubes, it falls perpendicularly on the target only when travelling along the axis of the tube in its undeflected position and it then strikes the target at its centre. To strike other points of the target, the beam must be deflected and it then strikes the target at an oblique angle. Let us assume that the target is initially at a uniform potential. To land on it, scanning-beam electrons must have a certain minimum velocity (dependent on the target potential) *perpendicular to the target.* It is possible, therefore, for electrons approaching the target at normal incidence to have sufficient velocity to land at the centre, whereas electrons travelling obliquely towards the target edges are repulsed and never reach the target. This can occur even though all electrons have the same velocity along their line of travel because the component of electron velocity perpendicular to the target is smaller for electrons travelling towards the target obliquely than for those travelling normally towards it. Under these conditions more electrons land at the centre of the target than at the edges and the centre is driven to a more negative potential than the remainder of the surface.

This occurs during each scanning cycle and the edges of the mosaic soon attain such a positive potential relative to the centre that the scanning beam is attracted with sufficient velocity to cause secondary emission. This accelerates the growth of the positive charge with the result that the edges of the mosaic soon rise to anode potential. Once this has happened the whole of the target rapidly assumes anode potential, and normal operation of the tube cannot be resumed until the wall-anode potential is reduced to a few volts positive with respect to gun cathode. The secondary electrons liberated from the target cannot then escape and are redistributed on the target, thus re-establishing its potential near cathode value.

This breakdown of cathode-potential stabilization can be prevented if the scanning beam can be constrained so as to fall on all points of the target at the same angle of incidence. It is usual to arrange for the beam to strike the target at normal incidence; this is known as *orthogonal scanning*.

Beam Focusing

The beam is focused and orthogonal scanning secured by use of the axial magnetic field of a focusing coil surrounding the tube and carrying direct current. Electrons emitted from the gun parallel with the magnetic field are not deflected by it and travel in a straight line to the target. Electrons emitted at an angle to the magnetic field experience a deflecting force which causes them to move in a helical path on their way to the target; the magnitude of the helical motion increases with increase in the angle between the initial electron velocity and the magnetic field. As a result of this motion the beam is focused and refocused a number of times between the gun and the target, the foci being spaced at equal intervals along the tube axis as shown in Fig. 41. By varying the final anode potential (which controls the electron velocity) one of the focal points can be made to coincide with the target; to a first approximation the cross-sectional area of the beam at the target is then equal to that of the final aperture in the gun. This neglects aberrations in the image due to variation in electron velocities and repulsion between electrons.

Although the axial magnetic field greatly reduces deflection of the beam by the target potentials, these potentials and the tendency of the beam to spread as a result of the mutual repulsion of its constituent electrons modify the shape of the final focusing lobe with the result that if the beam is accurately focused on highlights in the image, it is out of focus on black parts. Moreover, the potential of an illuminated element changes whilst it is being scanned. Thus if the beam is in focus at the beginning of the scanning time of a white element it is defocused by the time the element has been restored to cathode potential. Increase in magnetic field strength reduces this change in focus but requires greater scanning power.

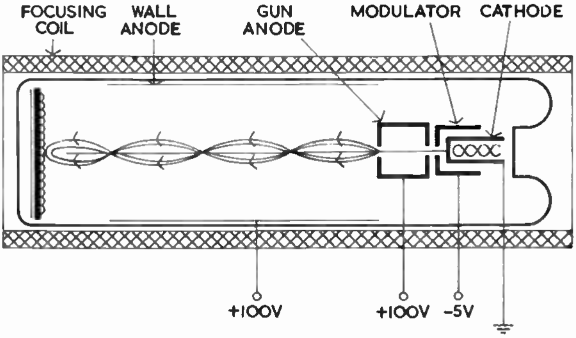

Fig. 41—Focusing of orthicon scanning beam

The electric field between the target and the final anode should be perpendicular to the target at all points on the target but in practice this ideal is difficult to obtain. At the centre of the target the field is very nearly perpendicular but at the edges of the target is inclined at a small angle to the normal. Where the field is inclined, it can be resolved into two components, one perpendicular to the target (axial component) and the other parallel to the target surface (lateral component). The lateral components radiate from the centre of the target like the spokes of a wheel; their amplitude is negligible at the centre of the target but appreciable at other points, being a maximum at the corners.

The lateral component deflects the scanning beam away from the centre of the target and causes it to cut the axial magnetic field. The beam thus experiences a further deflection in a direction at right angles to the lateral electric component and to the axial magnetic field, i.e., the deflection is parallel to the target surface and at right angles to the spokes of the wheel. As a result of this, the raster on the target is bodily rotated through an angle of about 5 deg; this is of little consequence because the scanning system can be rotated through a corresponding angle to correct for it. Unfortunately the angular rotation is not constant for all points on the target; because of the larger lateral component of electric field at the edges of the target, the angular rotation for points at the edges is greater than for points near the centre. Thus the reproduced images suffer from geometric distortion, straight lines across the image passing through the centre being bent into the shape of an elongated letter S.

This effect can be reduced by the decelerating ring, a circular electrode surrounding the target and held at an adjustable negative potential. The electric field of this electrode is greater at the edges than at the centre of the target and by suitable adjustment of its potential the geometric distortion of the reproduced image can be reduced.

Orthogonal Scanning

The electron beam is restricted by small holes in the control grid, the anode itself and the first anode diaphragm to the cross-sectional area required in the final scanning spot. The electrical axis of the electron gun must be parallel to the axial magnetic field otherwise electrons moving in directions not parallel to the magnetic field describe spirals of large diameter and are collected by the anode diaphragm as shown in Fig. 42.

After passing through the first anode diaphragm the electron beam enters the electric field between the line deflector plates which deflect the beam in a direction at right angles to the plane of the paper. Between these plates the beam is subjected to the vertical electric field and the axial magnetic field and is deflected in a direction parallel to the plates. On emerging from the plates the beam comes under the influence of the magnetic field only and is deflected so that it is parallel to its initial path, but is displaced laterally from it.

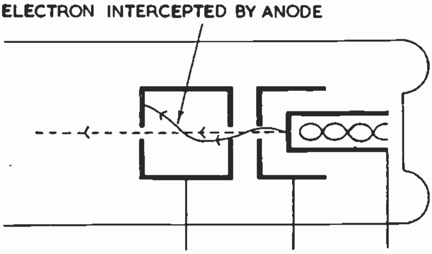

Fig. 42—Method of producing parallel electron beam

The lateral displacement so obtained is directly proportional to the electric field and is inversely proportional to the electron velocity and the magnetic field strength. Thus by varying the electric field the lateral displacement can be varied, and if the field is reversed the displacement is in the opposite direction. This gives a method of scanning the target in which the beam always approaches the mosaic at normal incidence.

The mechanism of line deflection is different from that encountered in normal cathode-ray tube technique in which electrons move towards or away from the plates, i.e., are deflected in a direction at right angles to the plane of the plates. Moreover, in a cathode-ray tube the beam, after deflection between the plates, continues to travel in a straight line along its new path. The presence of the axial magnetic field in the orthicon brings about an entirely different action and the beam emerges parallel with its original path but displaced laterally from it.

Electrostatic Line Deflection

The mechanism of electrostatic line deflection in the presence of an axial magnetic field is described in Chapter 10; very briefly the process may be described as follows. The beam describes a cycloidal path between the plates and emerges parallel to its initial path but displaced laterally from it as shown in Fig. 43, the extent and direction of the displacement depending on the magnitude and polarity respectively of the electric field. If electrons leave the plates with appreciable lateral velocities, it may prove impossible to focus the beam accurately on the target; to minimize the lateral velocities the plates may be curved as shown in Fig. 39. The theory underlying this is given in Chapter 10.

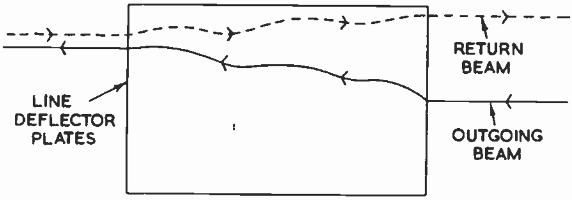

Fig. 43—Separation of forward and return beams by electric field

For a given axial magnetic field, the direction of lateral displacement of the electron beam between the line deflector plates can be reversed by reversing the direction of the electric field (as here in orthicon line scanning) or by reversing the electron-beam velocity. Thus the return electron beam, in passing between the deflector plates, is displaced laterally in the opposite direction to the forward beam as shown in Fig. 43. This forms the basis of a method for separating the return from the outgoing beams and is used in some types of low-velocity tube to guide the return beam into an electron multiplier.

Magnetic Frame Deflection

The beam now enters the vertical magnetic field of the saddle coils; between these the beam electrons are subjected to the transverse (vertical) and axial magnetic fields as well as the axial electric field and are deflected so as to describe helical paths around the resultant line of action of the combined magnetic fields. On leaving the region of the combined magnetic fields, the beam cuts across the axial magnetic field and, as a result of this and the axial electric field, is deflected so as to move parallel to its initial direction, i.e., parallel to the tube axis. Thus the transverse magnetic field has the effect of displacing the beam laterally in the vertical direction; the extent and direction of the displacement depend on the magnitude and direction of the transverse field and frame scanning can be obtained by feeding currents of saw-tooth waveform into the saddle coils.

If the direction of the electron velocity is reversed there is no corresponding change in the direction of displacement in the combined magnetic field; thus return electrons retrace the outgoing path.

The lateral displacement of the scanning beam by the transverse magnetic field of the saddle coils is in a direction of 90 deg to that obtained by magnetic deflection in cathode-ray tubes where there is no axial magnetic field.

Spurious Signals

The orthicon is entirely free from the type of shading signal obtained from the iconoscope but it does, however, suffer from other types of spurious signal; the reproduced images often have a vertical black bar on white parts of the pictures and a white *ion spot* in the centre which gets more intense as the tube ages. The mechanism by which the vertical bar is generated has not been investigated but it is clearly associated with electrostatic line scanning because it is not present when electromagnetic line scanning is employed. The ion spot is caused by positive charges impressed on the mosaic by ions of residual gas which are attracted to the target. It is not possible to obtain a very good vacuum in an orthicon because the heat treatment necessary during degassing is liable to distort the line-scanning plates.

The earliest orthicon tubes used electrostatic line scanning because it was difficult at that time to generate conveniently the rather large power required for electromagnetic line scanning at frequencies of the order of 10 kc/s. This can now be done and modern orthicon tubes and their derivatives such as the image orthicon and multiplier orthicon are free from the two types of spurious signal mentioned above.

Operation

A number of precautions must be taken in setting up an orthicon tube ready for use; for example, before the operating potentials are applied to the various electrodes and coils, a hood must be placed over the optical system so that the mosaic is in darkness. After a while, the mosaic assumes target, i.e., cathode potential, by slow electrical leakage. Scanning can now begin; initially primary electrons land on the mosaic and drive it negative but after an interval the target is sufficiently negative to repel the beam and prevent any electrons landing. The mosaic is now at its operating potential and the optical image can be projected on to it. If the optical image is allowed to fall on the mosaic before scanning begins, the mosaic may reach a high positive potential by photo-emission; when scanning begins, the primary beam then lands with a velocity high enough to cause secondary emission with the result that the target potential rises to that of the anode, and normal operation is impossible. Similarly, any area of the mosaic which is not scanned by the primary beam can acquire a positive charge capable of causing the same effect; thus the beam must scan all the mosaic.

This instability may occur if, for any reason, the scanning beam is interrupted for any length of time whilst light is falling on the target; it can also occur during normal operation if the target is directed at a very bright highlight such as the image of a lamp at a reflecting surface. When the target potential rises to anode potential the anode potential is lowered temporarily and the light cut off from the target until the mosaic has reached cathode potential. Loss of cathode-potential stabilization is one of the major disadvantages of this type of camera tube.

PERFORMANCE OF ORTHICON TUBE

Sensitivity

The photo-efficiency obtained from early transparent targets was approximately 2 μA/lumen, 1/5th of that obtained from a standard Emitron target, but this is more than compensated by the greater efficiency of charge and discharge of the orthicon target. This efficiency has been estimated at 71 per cent by Rose and Iams*

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* A. Rose and H. Iams, " Television Pick-up Tubes using Low-velocity Electron-beam Scanning." *Proc. I.R.E.*, September 1939.

and is hence approximately 15 times that of an iconoscope. The sensitivity of the orthicon tube is thus between that of an iconoscope and image iconoscope.

Distortion

The images obtained from an orthicon tube tend to suffer from considerable geometric distortion; there is a wave-like distortion of the scanning lines which is very disturbing. Very critical adjustments of the magnetic field, electron-gun anode potential and decelerating ring potentials are necessary to obtain acceptable results.

Resolution

If the beam focus is very carefully adjusted, a limiting resolution of about 1,000 lines can be obtained at the centre of the image but this falls off markedly towards the edges of the image. Moreover, if the beam is critically focused for white areas of the image, it is slightly out of focus for black areas.

Signal-light Characteristic

Full advantage of charge storage is taken in the orthicon and the output voltage is directly proportional to the light input; in other words the tube has a gamma value of unity. This means that the images have a greater contrast than those from the iconoscope. It is possible to reduce the contrast range in the amplifier following the tube but this implies some sacrifice in sensitivity and signal-noise ratio.

ADVANTAGES AND DISADVANTAGES OF THE ORTHICON

The main advantages of the orthicon are as follows:

(1) A definite output signal corresponding to black in the image.
(2) No shading signals such as those obtained from the iconoscope.
(3) The sensitivity is slightly greater than that of the iconoscope.
(4) No necessity for keystone modulation of the scanning waveforms.

The disadvantages are as follows:

(1) Liability to instability if the scanning beam is interrupted or if too much light falls on the target.
(2) Geometric distortion of images.
(3) Gamma value is slightly higher than is desirable for most reproducing picture tubes.
(4) An effective exposure time of 1/25th second, which gives blurring in images of fast-moving objects.

5.3 C.P.S. EMITRON

Introduction

The C.P.S. (cathode-potential stabilized) Emitron camera tube is an orthicon and operates on the principles given above. There are, however, several differences between the C.P.S. Emitron and the early orthicon:—The C.P.S. Emitron tube has electromagnetic line scanning, the axis of the scanning coils being at right angles to that of the frame scanning coils; this results in a tube shorter than the orthicon. Short subsidiary deflecting coils are used in the C.P.S. Emitron tube to align the scanning beam with the axial magnetic field. These behave as alignment coils, i.e., they cause a permanent change in the direction of electron velocity, because they are short compared with the length of a loop of beam electrons. These alignment coils, together with magnetic line scanning, considerably reduce geometric distortion of the images. Spurious signals in the form of a white ion spot are eliminated by use of an ion-trap mesh situated close to the target.

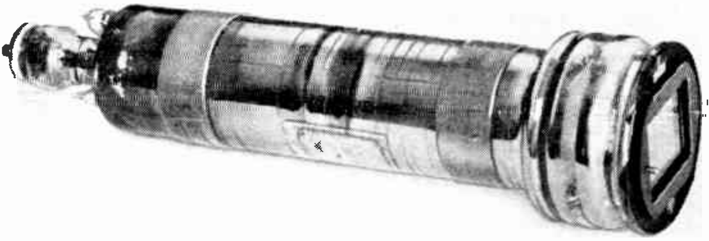

Fig. 44—C.P.S. Emitron camera tube

The target of the C.P.S. Emitron tube has greater photo-sensitivity than that of the early orthicon tube (it is better even than that of the standard Emitron tube) and the overall tube sensitivity is higher than for any of the tubes already described. The C.P.S. Emitron tube is liable to instability if exposed to too much light but, by careful design, this possibility can be made comparatively rare; moreover, the period during which the tube is unusable as a result of target instability can be minimized by automatic circuits designed to reduce the anode potential temporarily to zero. A photograph of a C.P.S. Emitron tube is given in Fig. 44.

Construction

The essential features of the tube are illustrated in Fig. 45. It consists of an evacuated cylindrical tube, about 2½ inches in diameter, having a narrow neck at one end and a section 3½ inches in diameter at the other. The narrow neck contains a simple electron gun and the large diameter section the target and ion-trap mesh. The centre section has an internal wall anode and is surrounded by four saddle coils clamped to the outside of the tube, two opposite coils for line deflection and the other pair for frame deflection. Smaller alignment coils surround the opening of the electron gun. The whole of the tube is surrounded by a focusing coil, the axis of which coincides with that of the tube.

Target

The target is similar in construction to that of an iconoscope in that it consists of a sheet of mica or glass, having a mosaic on one face and a signal plate on the other. Signal plate, dielectric and mosaic must be transparent to light, however, because light must travel through all three layers to liberate photo-electrons from the mosaic; the signal plate used is a very thin conductive coating which absorbs only between 10 per cent and 20 per cent of light incident on it. For a mosaic of antimony treated with caesium the photo-sensitivity is 25–30 μA/lumen compared with 10 μA/lumen for the standard Emitron target and 2 μA/lumen for the early orthicon target; it is prepared by evaporating the photo-electric material on to the glass surface through a stencil mesh having 1,000 meshes per linear inch and a shadow ratio of about 30 per cent.

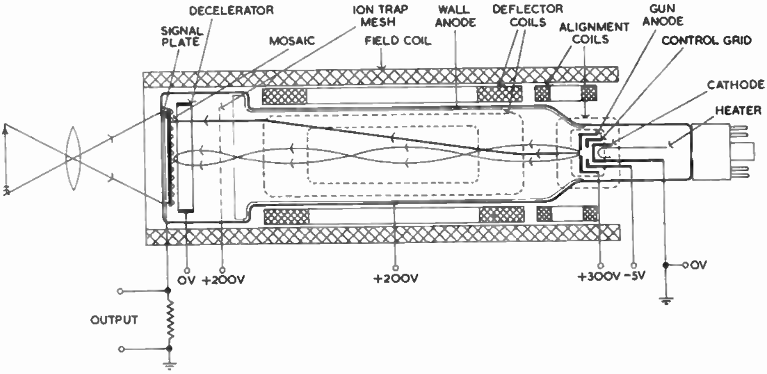

Fig. 45—C.P.S. Emitron camera tube

Scanning

Line scanning and frame scanning are carried out in the same section and electromagnetic deflection is used for both. About 17 volt-amps is required for line scanning; this can be obtained quite easily from modern valves.

Beam Alignment

One of the sources of geometric distortion in the early orthicon tube was lack of alignment between the axes of the electron gun and the magnetic field. This source of distortion is eliminated in the C.P.S. Emitron tube by the use of four short deflecting coils grouped around the exit of the gun. By passing direct current of correct amplitude and direction through these the electron beam can be accurately aligned with the magnetic axis.

Ion-trap Mesh

In spite of the most careful exhaustion and degassing of the tube there generally remain sufficient gas molecules to cause an ion spot on the reproduced image. The gas molecules are ionized by collision with the scanning beam and the positive ions released are urged towards the mosaic by the electric field between anode and target which is convergent on the centre of the mosaic. These ions have relatively great mass and are only slightly deflected by the magnetic deflecting fields; unless precautions are taken, these ions land near the centre of the mosaic and raise its potential, causing a white circular patch at the centre of the reproduced image. This effect has been eliminated in the C.P.S. Emitron tube by means of a mesh placed between the target and the gun and connected to the wall anode. The mesh is of fine structure, having about 200 meshes per linear inch, and is situated where the beam is of maximum cross-section, i.e., where the beam is out of focus. The mesh has the effect of producing a field-free space over most of the length of the tube. Thus the ions are not accelerated towards the target and most land on the tube walls. Only the few ions generated between the mesh and the target are accelerated towards the latter. These are spread uniformly over the target area and do not form an obvious spot because the field between ion-trap mesh and target is substantially uniform and parallel to the tube axis.

Mechanism of Signal Production

The mechanism of signal production in the C.P.S. Emitron tube is similar to that of the orthicon tube. (See page 82 for details.)

PERFORMANCE OF C.P.S. EMITRON TUBE

Sensitivity

To minimize capacitance to earth in the coupling between signal plate and the grid of the first valve in the vision-frequency amplifier, the valve is mounted as close to the signal plate as possible. Even so, the total capacitance shunting the signal resistor cannot be reduced below approximately 20 pF and the resistor value cannot exceed approximately 2,000 ohms* if frequencies up to 3 Mc/s are to be transmitted without appreciable attenuation. The noise voltage due to the first valve, for a 2,000-ohm grid resistance, is approximately 2·5 μV and to give a signal-noise ratio of 32 db a p.d. of 100 μV must be developed across the signal resistor for a peak white signal; this corresponds to a signal current of 0·05 μA.

A signal-noise ratio of 32 db gives an acceptable picture provided the valve noise is confined to the upper end of the vision-frequency band. Low-frequency noise causes streaks in the reproduced image and these are very objectionable, whereas high-frequency noise causes a snow-storm effect which is more tolerable.

About 1/10th of the scanning beam is absorbed in the mosaic in areas of peak white illumination. Thus a beam current of 0·5 μA is required; a greater current can be used with advantage since a high current will prevent the target potential rising to that of the gun anode when the tube is exposed to too great an illumination. The only factors limiting the density of beam current that can be used are the ability to focus it adequately and ionization of the residual gas.

A good tube will deliver 200 μV from a white surface illuminated by 2 foot-candles and focused by a lens of aperture *f*/2. The noise of the amplifier limits the useful sensitivity of the tube but a fair picture can be obtained with illumination of only 1 foot-candle. This represents sensitivity far greater than that of the other camera tubes described previously.

Stability

If the beam current is 0·1 μA, the target potential must rise to a theoretical value of approximately 6 volts or first cross-over potential, depending partly on target capacitance, before instability occurs, but in actual fact the target will usually stand a much larger voltage without instability. McGee† gives the following possible explanation of this effect: The insulating strips of mica or glass separating the individual cells do not lose electrons when the target is illuminated but remain at or near zero potential. These insulating strips may be an appreciable fraction of a volt negative with respect to the photo-electric surface and tend to prevent emission in the same way as the grid of the valve reduces anode current when made

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* For further information see section on vision-frequency amplification.

† J. D. McGee, "A Review of Some Television Pick-up Tubes." *J.I.E.E.*, Vol. 97, No. 50, November 1950.

negative. Because of the very small distance between these strips and the cells the potential gradient is greater than that between the wall anode and cells. This grid action becomes more effective as the illumination is increased; thus the signal-light characteristic tends to curve over as shown in Fig. 46. This is a useful feature since it tends to make the tube more stable than predicted from theory.

Signal-light Characteristic

Up to a certain value of incident light, the signal-light characteristic is linear, the output being directly proportional to the light input. Above this particular input the curve bends over as shown in Fig. 46. The light input at which this bend occurs depends on the ratio of conducting to insulating area on the target and is chosen to occur above the maximum light input likely to be encountered in normal use. Thus although the curve of Fig. 46 is similar in shape to that for the iconoscope (Fig. 27) the C.P.S. Emitron is normally operated below the knee of the curve and the signal-light characteristic is linear.

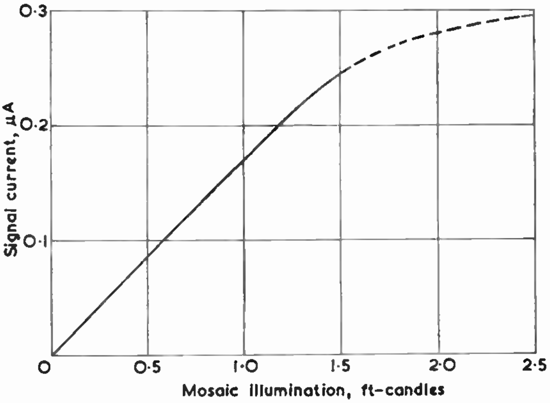

Fig. 46—Signal-light characteristic of C.P.S. Emitron tube

Normally the tube has a gamma value of unity, and the contrast in reproduced images is greater than from an iconoscope. Unless the scene is deficient in contrast, some gamma correction is necessary and is carried out in the following amplifier.

The design of gamma-correction circuits for vision-frequency amplifiers is difficult unless the camera tube has a definite output signal corresponding to black level; moreover such circuits inevitably impair the signal-noise ratio. It is more convenient, therefore, to employ gamma correction with the C.P.S. Emitron tube than with the other types already described, because it has high sensitivity and a definite black-level output.

Image Movement

The C.P.S. Emitron has an effective storage time of approximately 1/25th second which is considerably greater than that of the iconoscope. Images of moving objects thus tend to be blurred to the same extent approximately as in 16-mm motion film, and viewers who are accustomed to the sharp images of moving objects given by the iconoscope may find that the images from the C.P.S. tube are somewhat unfamiliar at first.

Sharper images can, however, be obtained from the C.P.S. Emitron by use of a shutter operated at frame frequency but this necessarily entails some sacrifice in output signal. The shutter is designed to cut the light from the target for a fraction of each frame period, allowing the light to fall on the mosaic for a fraction of a second before it is scanned. For this to be successful, the black-level signal must be obtained at the end of each line during the fly-back period. It was pointed out on page 84 that the value of i_p during frame flyback periods can be taken as representing black level provided that the illumination of the mosaic does not greatly change during the frame period. When such changes do occur, as, for example, when a shutter is used to cut the light from the mosaic, it is essential to take the value of i_p during *line* flyback periods as representing black level.

Blurring can also occur due to other causes; for example, when very weak illumination falls on the target, the corresponding positive charges developed on the mosaic are very small and consequently inefficiently neutralized by the scanning beam. This is because only those electrons in the beam which have maximum axial velocity succeed in reaching the target. Several scans may be necessary to discharge the target fully and blurring occurs.

As illumination is increased, the positive charges become greater and the discharging action of the beam becomes more efficient until a point is reached at which the scanning beam lands with sufficient velocity to cause secondary emission; if illumination is appreciably increased beyond this point, the target potential ultimately rises to that of the electron-gun anode. If secondary emission does occur, the discharging action is again inefficient and several scans may be necessary to discharge the target completely. Thus, there is a tendency for a very bright moving object to develop a *comet tail*. This effect can be reduced by increasing beam current, but if beam current is increased beyond a certain value it becomes difficult to maintain good focus.

Blurring can thus occur at low and high mosaic potentials, that is for high and low illumination levels of the target; between these extremes there is a range of light input for which blurring is a minimum.

If the beam current is already at a maximum, blurring at high illumination levels can be minimized by correct choice of dielectric thickness in the target. The illumination on the target determines the quantity of electricity (Q) lost from the mosaic by photo-emission; the potential (V) developed at the mosaic surface is given by Q/C and is thus inversely proportional to C, the capacitance of the mosaic, which, in turn, depends on the dielectric thickness. Thus, for a given illumination on the target, the mosaic potential depends on the dielectric thickness; the thickness is, therefore, chosen to give a mosaic potential within the range for which blurring is a minimum. In practice, the thickness used is such that discharging is efficient when the image on the target has a good signal-noise ratio in the highlight areas. With this thickness some blurring may occur at low illumination levels but this is not serious because, for such low light inputs, the tube output is comparable with the noise generated in the following vision-frequency amplifier.

Resolution

From the mosaic dimensions given below it is clear that for a 405-line system each element contains 12 cells and the mosaic structure imposes no serious limitations on the resolution obtainable. The optical system and scanning-beam focus are chiefly responsible for resolution limitations but the tube will resolve 750 lines easily.

Colour Response

The mosaics for C.P.S. Emitron tubes are prepared by use of a stencil mesh and the colour response depends on the materials used for the mosaic. A substantially panchromatic response is obtained with a mosaic of bismuth, silver and caesium. C.P.S. Emitron mosaics are very constant in their colour response and images from two tubes focused on the same scene have the same tonal values.

SMALL-TARGET C.P.S. EMITRON

A second type of C.P.S. Emitron tube has been introduced to give a narrow field of view in the horizontal plane. It has a small target measuring 25 mm by 20 mm but is otherwise identical to the standard C.P.S. Emitron tube.

The standard tube has a target measuring 35 mm by 44 mm which does not impose serious limitations on the design of the external optical system unless a very narrow field of view is required. For example, an angular field of between 5 deg and 40 deg can readily be obtained, the minimum value requiring a lens of 17 inches focal length. To obtain a more restricted field with these mosaic dimensions a lens of very long focal length is necessary and to keep the lens diameter reasonably small a small *f*-number is inevitable; this results in a serious loss in sensitivity.

The difficulty has been solved by the introduction of the second type of tube in which the target has 1/3rd the area of the standard target. The new tube has a field of view of 3 deg in the horizontal plane using a lens of 17 inches focal length.

The new mosaic is prepared with a stencil having 1,500 meshes per linear inch, but the tube is operated with a higher anode voltage than the standard model and by this means it has proved possible to maintain the resolution of the small-target tube at the same value for the standard tube.

ADVANTAGES AND DISADVANTAGES OF THE C.P.S. EMITRON TUBE

C.P.S. Emitron tubes are in regular use in the BBC television service. Their chief advantages are as follows:

(1) Definite black-level output signal.
(2) No shading signals.
(3) The tube is a convenient shape for mounting in a camera and imposes no serious limitations on the design of the associated optical system.
(4) Sensitivity and resolution are much better than in the iconoscope and image iconoscope tubes.
(5) Keystone modulation of the scanning waveforms is unnecessary.
(6) Geometric distortion in reproduced images is as low as for the iconoscope and is lower than for the image iconoscope or early orthicon tubes.

In the absence of correction circuits the gamma value for the C.P.S. Emitron tube is unity, but the tube is sensitive and gamma-correction circuits can be used in following amplifiers whilst still maintaining an adequate signal-noise ratio. Thus one of the advantages of the tube is that the gamma value can be varied to suit the contrast range in the scene being televised.

The disadvantages are:

(1) Liability to instability if too much light falls on the target. This is by no means such a likely occurrence as in early orthicon tubes and in practice has caused very little trouble.
(2) Exposure time is 1/25th of a second and blurring occurs on moving images. The blurring can, however, be reduced by a

shutter operating at frame frequency provided adequate light is available.

It will be clear that the C.P.S. Emitron is a better approximation to the ideal tube than any of the types previously described.

5.4 Image Orthicon

Introduction

The image orthicon tube may be regarded as a combination of an orthicon tube with an image stage similar to that used in the image iconoscope. The image stage gives a gain in sensitivity and a further increase in sensitivity is obtained by use of an electron multiplier into which the return scanning beam is directed. The overall improvement in sensitivity is of the order of 100–1,000 times, resulting in a highly sensitive tube very suitable for use in outside broadcasts.

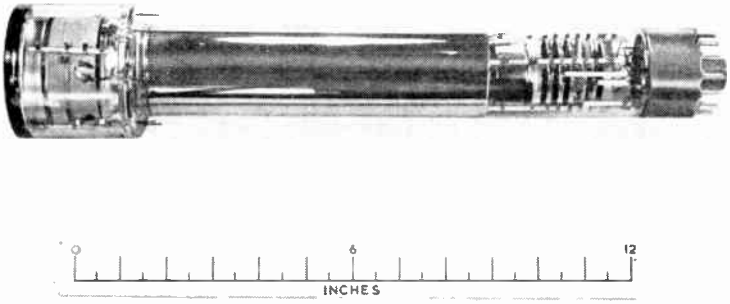

Fig. 47—Image orthicon camera tube

Electromagnetic deflection is used for line and frame scanning and the beam from the electron gun is aligned with the axial magnetic field by a single coil which carries d.c. and can be rotated around the tube.

Instability of the type encountered in the orthicon and C.P.S. Emitron tubes is prevented in the image orthicon by a fine mesh situated very close to the target. As explained later, this prevents the whole target surface from rising to anode potential.

The orthicon target is double-sided in the sense that a charge pattern develops on one side when an optical image is projected on the other; the image orthicon target is also double-sided but is designed to develop a charge pattern on one side when the other side is bombarded by photo-electrons released from the photo-cathode. A photograph of an image orthicon tube is given in Fig. 47.

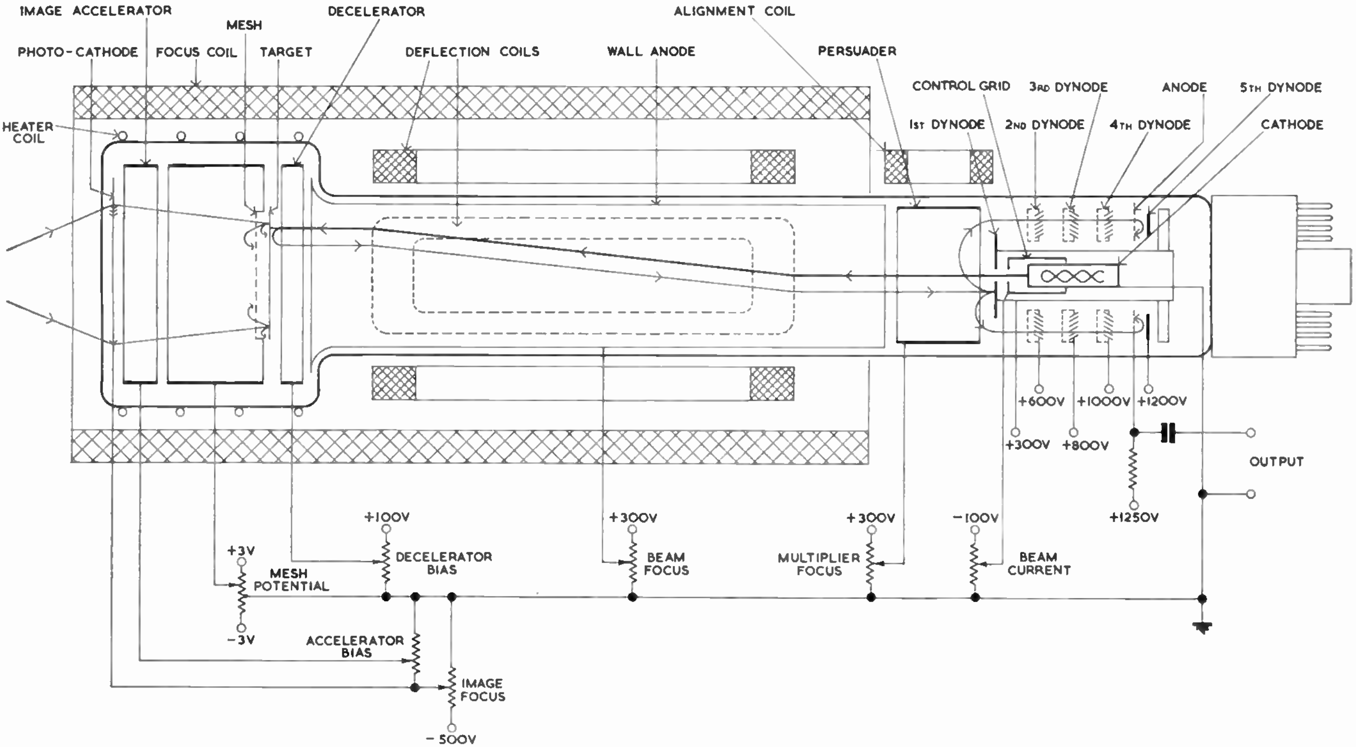

Fig. 48—Image orthicon camera tube

Construction

The image orthicon consists of an evacuated cylindrical glass tube, at one end of which is an extension of larger diameter containing the image section. At the end of this section is a transparent photo-cathode upon which an image of the scene is focused and a few inches behind this is the target in front of which is a fine mesh. At the smaller end of the tube is a simple electron gun consisting of an indirectly-heated cathode, control grid and anode which is surrounded by an electron multiplier. Clamped to the outside of the small diameter section are two saddle coils for line deflection and a similar pair for frame deflection, with their common axis at right angles to that of the line deflector coils. Opposite the exit of the electron gun is a small alignment coil which carries d.c. and is positioned so as to bring the scanning beam into alignment with an axial magnetic field. The inside walls of the tube are lined with a metallic coating occupying approximately the same length as the deflector coils.

The tube is surrounded for most of its length by a focusing coil which carries d.c. and produces the axial magnetic field.

Mechanism of Signal Production

The transparent conducting photo-cathode releases photo-electrons in direct proportion to the light falling on it. These electrons move towards the target electrode under the action of the electrostatic field between the mesh and photo-cathode (and that due to the accelerator electrode situated near the photo-cathode) and are focused on the target by the axial magnetic field of the focusing coil. The velocity of the photo-electrons is sufficient to cause secondary emission from the target and the secondary electrons liberated are collected by the mesh close to the target, leaving the target deficient of electrons, i.e., positively charged. Thus a positive charge image is built up on the image-section side of the target. The other side of the target is stabilized at gun-cathode potential by the low-velocity scanning beam. Thus a potential gradient is established between opposite faces of the target and as a result current flows through the thickness of the target, i.e., parallel to the tube axis. At any particular point on the target the magnitude of this current is proportional to the brightness of the corresponding point of the optical image. The current flowing through the target thickness should neutralize the charge image in a picture period; if neutralization is not complete in this period, reproduction of moving objects tends to be blurred, an effect known as *smearing*. To maintain the current in the target, scanning electrons land on it;

ideally sufficient electrons should land to maintain the scanned face at its minimum potential. Thus, as in the orthicon, the number of scanning electrons which land at any particular point on the target is proportional to the brightness at the corresponding point in the optical image. Few electrons, if any, land in areas corresponding to black parts of the image whereas considerable numbers land in areas corresponding to highlights. Those electrons which do not land are repelled back along their original path and ultimately arrive at the electron-gun anode. The return beam is amplitude modulated by the target charge pattern and constitutes the vision signal; on striking the anode the return beam releases secondary electrons which are guided into the electron multiplier by the combined electric field of the gun anode and an electrode aptly termed the *persuader*. The electron multiplier gives very considerable voltage gain without introducing appreciable additional noise and the tube output is taken from the final multiplier anode.

Target

The advantage of separating the functions of photo-emission and secondary emission has already been made clear (page 69); briefly, it makes possible a gain in sensitivity.

The target in a tube such as the image orthicon is bombarded by photo-electrons on one face and is scanned on the other. The properties desired in such an electrode are as follows:

(a) It should readily conduct charges from one face to the other, i.e., in a direction parallel with the tube axis.

(b) There should be no appreciable lateral spreading of charge over either face, i.e., in a direction at right angles to the tube axis.

(c) It should have the form of a capacitance to enable charges to be stored during the picture period.

Requirement (b) is usually satisfied by a mosaic form of construction, but in the image orthicon a satisfactory performance is obtained by use of a plain sheet of glass as target.

Requirements (a) and (c) can be met provided that the thickness of the glass is very small compared with the distance between neighbouring elements; by this means it is possible, provided that a suitable value of resistivity can be obtained, to arrange that charges are conducted from one face to the other within a picture period and that there is inappreciable spreading of charge over each face during the same period; these are the criteria for successful performance.

It follows that if the target is reasonably small (say 2 inches by

1½ inches) then the thickness must be very small indeed. The distance between neighbouring elements for a 400-line system is 1·5/400in, i.e., approximately 4 mils. For successful results the thickness of the glass should not exceed 1/10th of this and should preferably be 1/100th. The latter value corresponds to a thickness of approximately 0·04 mil, twice the wavelength of visible light and an impossible thickness to work with. In practice a thickness of about 0·20 mil is used and the glass must have a rather low value of specific resistivity.

The resistivity of the glass used for the target is very critical; if it is too low, appreciable lateral spreading of charges can occur in a picture period and the resolution of the tube is impaired; if resistivity is too high, the positive charge image is not neutralized in a picture period and smearing of the reproduced image occurs. The resistivity of the target varies with temperature and to ensure consistent results the temperature of the image section of the tube must be maintained within fairly close limits. The image section can be warmed when necessary by passing current through a heater coil surrounding it and can also be cooled by a current of cold air provided by a blower included within the camera.

When the target is cold as, for example, in the period immediately after switching on the tube, the resistance is too high; this results in smearing of dynamic images and " sticking " of stationary ones. This effect disappears with time as the target gradually acquires its normal working temperature (35–60 deg C). Sticking of images also tends to occur as the target ages; this is due to exhaustion of the target ion supply, an effect which limits the effective life of the tube. Sticking sometimes occurs through neither of these causes and it is found, after the tube has been exposed to a stationary image such as a test card for some time, that a negative image of the card is superimposed on images when the tube is used subsequently. This is thought to be due to coating of the target by caesium which is directly transferred from the photo-cathode and in direct proportion to the light falling on it. This causes local variations in the secondary-emission ratio of the target, thus causing the negative image. This sticking may persist for several days but can usually be eliminated by directing the tube at a uniformly bright object for a long period.

Stabilizing Mesh

The target is capacitively coupled to a copper mesh placed close to it on the photo-cathode side. The photo-electrons pass through the mesh on their way to the target and to avoid collecting an appreciable fraction of them the ratio of open space to conductor in the mesh must be high; the number of meshes must also be very high otherwise a charge image of the mesh forms on the target and is visible in the reproduced image. By special manufacturing techniques it is now possible to produce highly uniform meshes of about 500 meshes per linear inch with about 50–70 per cent open space; these have proved extremely successful.

This mesh must be mounted parallel with the target and between 0·0005 and 0·02 inch from it. Both target and mesh must be flat and able to resist temperatures of the order of 350 deg C without appreciable warping (such temperatures occur during evacuation and degassing of the tube). This has been found possible by mounting both electrodes under slight tension.

The potential of the mesh is adjustable over a small range and is normally maintained at approximately 1 volt positive with respect to the electron-gun cathode. It is thus positive with respect to the average target potential and the electric field between mesh and target accelerates secondary electrons emitted by the target to the mesh. If, however, an excessive number of secondary electrons are emitted as a result, for example, of pointing the tube at a very bright light, the target potential tends to rise above that of the mesh. The electric field between mesh and target is now retarding and large numbers of secondary electrons are returned to the target and lower its potential. Provided the scanning beam current is adequate to discharge the target fully in each picture period, the target potential is stabilized by the return of secondary electrons and cannot appreciably exceed +1 volt no matter what the value of incident light. The return of secondary electrons to the target has two other important consequences; it causes black *halos* around highlights in reproduced images and, provided the incident illumination is greater than a certain value, it tends to make the tube output independent of the light input.

A definite black-level output signal can be obtained from the image orthicon by giving the target mesh a rectangular negative pulse during the line flyback period. This pulse repels the scanning beam and prevents it landing on the target; thus all the scanning beam returns to the multiplier during line flyback periods. During normal scanning the beam also returns to the multiplier at full amplitude when it scans target areas with no charge, i.e., target areas corresponding to black areas in the optical image. Thus the multiplier output, during flyback periods, corresponds to black level. The multiplier is normally RC-coupled to the succeeding vision-frequency amplifier and the d.c. content of the multiplier output is lost; this d.c. is, in any case, dependent on the setting of the beam current. At a suitable point in the vision-frequency chain the inter-line pulses are clamped at a fixed potential and a signal with a definite black level is obtained.

Orthogonal Scanning

During normal operation of the image orthicon, the target potential fluctuates between approximately zero (to which it is driven by the scanning beam) and +1 volt (to which it is driven by loss of secondary electrons released by the photo-electrons). The output signal of the tube is directly proportional to this potential swing of the target. If the scanning beam approaches the target at other than normal incidence, or if the electrons have appreciable helical motion when they reach the target, the target potential is not reduced to zero but is left appreciably positive. The potential swing is thus reduced and the output of the tube correspondingly limited. It is important, therefore, that the scanning beam should approach the target strictly at right angles at all points; in other words orthogonal scanning is necessary. It is obtained by methods similar to those employed in the orthicon and described on page 88.

Electron Multiplier

The scanning beam is of constant density but some of the electrons land on the target to neutralize the positive charges caused by secondary emission and the return beam is of less density. Thus, during scanning, the return beam is amplitude modulated by the vision signal and under favourable conditions a modulation depth of 50 per cent can be obtained. If the return beam is directed into an electron multiplier the tube output can be increased until it is well above the noise level of conventional vision-frequency amplifiers. A multiplier gain of 1,000 times can readily be obtained and a most useful feature of this amplification is that it is almost noiseless; the multiplier introduces very little noise and the signal-noise ratio at the multiplier output is only slightly greater than that of the return beam itself. The signal-noise ratio of the succeeding amplifier is of no consequence in image orthicon design whereas it is of fundamental importance in the design of iconoscopes.

A conventional electron multiplier is not well suited for use with the image orthicon tube because of the difficulty of ensuring that the diffuse spray of return electrons enters its mouth. A new multiplier design was therefore prepared which is suitable for surrounding the electron-gun structure; it consists of a number of electrodes known as *dynodes* which are coated with material having a high secondary-emission ratio and are grouped around the electron gun behind the gun anode. The gun anode is treated with material to act as first dynode and the final dynode is an annulus surrounding the gun;

intermediate dynodes are of venetian-blind structure, consisting of a number of fins arranged in radial formation about the gun and each dynode is connected to a wide-mesh grid as shown in Fig. 48. The output electrode is of grid formation and is situated between the final and penultimate dynodes.

Operation of Electron Multiplier

Very briefly electron multipliers operate in the following manner:—The incident electron beam strikes the first dynode and liberates secondary electrons from it; under favourable conditions approximately four secondary electrons are liberated for each incident primary electron. These secondary electrons are guided to the second dynode where they release more secondary electrons and a further gain of approximately four times is obtained. This multiplying process continues over the total number of stages, the secondary electrons liberated from the final dynode being collected by a conventional anode. The overall gain is approximately 4^n where n is the number of dynodes. The process of electron multiplication in the image orthicon will now be considered in greater detail.

The electron-gun anode (first dynode) is held at +300 volts with respect to the gun cathode and the return scanning beam strikes it with considerable velocity, releasing a large number of secondary electrons. These electrons are guided to the second dynode by the resultant electric field of this dynode and the persuader. The second dynode is held at a fixed potential of +600 volts, i.e., 300 volts more positive than the first dynode, and the persuader potential can be set to any value up to +300 volts. The persuader bias is adjusted to direct as much as possible of the secondary stream liberated from the first dynode into the second dynode; the persuader bias control therefore behaves as a multiplier focus control.

The grid situated before the second dynode is of wide mesh and intercepts few of the secondary electrons directed towards the dynode. The dynode itself is designed to be fairly opaque to the incident beam and intercepts most of it but allows secondary electrons liberated from it to be readily released to the next stage.

Some of the secondary electrons are released from the second dynode with appreciable initial velocities in the direction of the first dynode and if the wide-mesh grid is not present these electrons are returned to the second dynode by the electric field between it and the first dynode. These electrons do not reach the third dynode and do not contribute towards the amplification of the multiplier. The number of electrons which are lost in this manner is reduced by the grid; the electric field between the first and second dynodes terminates on this grid, leaving the space between the grid and second dynode free of any field tending to return secondary electrons to their point of emission. The field between second and third dynodes originates on the second dynode vanes and guides a considerable fraction of the secondary emission away from the second and towards the third dynode. The grids connected to the other dynodes function in the same manner and are partly responsible for the high efficiency of this type of multiplier.

The third dynode is similar in construction to the second but the fins are arranged in opposition to improve interception of electrons released from the second dynode. The potential of the third dynode is +800 volts, 200 volts more positive than that of the second dynode, and the field between these electrodes accelerates secondary electrons released from the second dynode to the third where further secondary emission occurs. The secondary emission from the third dynode is attracted to the fourth which is held at a fixed potential of +1,000 volts; this dynode is also a venetian-blind structure and its vanes are opposed to those of the third.

Secondary emission from the fourth dynode is directed to the fifth (final) dynode by the electric field of the final dynode and of the anode which are held at fixed potentials of +1,200 volts and +1,250 volts respectively. The anode has the form of a wide-mesh grid and most of the electron stream passes through it to strike the final dynode which has the form of an annulus surrounding the electron gun. The electron field between fourth dynode and anode gives the electrons released from the fourth dynode sufficient acceleration to penetrate the retarding field between anode and final dynode and to strike the final dynode with sufficient velocity to cause secondary emission. The electrons released from the final dynode are urged to the anode by the field between dynode and anode and are collected by the anode.

The multiplied and modulated electron stream flowing into the anode passes through a load resistor to develop a p.d. which is transferred to the next link in the vision-frequency chain by conventional RC coupling. A stage gain of 500–1,000 times is obtained from an electron multiplier of this type corresponding to a gain per dynode of approximately four.

PERFORMANCE OF THE IMAGE ORTHICON

Sensitivity

The most sensitive types of image orthicon tubes can give recognizable though noisy images of objects with a surface brightness as low as 0·02 foot-lambert, approximately that of a white object illuminated by bright moonlight. This sensitivity is greater than that of the

C.P.S. Emitron and, in fact, is comparable with that of the human eye. For good results in the studio, however, an illumination of the order of 20–30 foot-candles is necessary to give reasonable depth of focus.

Signal-noise Ratio

One of the limiting factors in iconoscope design is the noise in the following amplifier: the output signal from the tube must exceed the noise generated in early stages of the amplifier to give an acceptable signal-noise ratio. This consideration has confined use of these tubes to the studio where high illumination (and hence high output) can readily be obtained.

The performance of the image orthicon is dictated by the random noise in the return scanning beam and this is much greater than the noise generated in, say, an orthicon tube because of the smaller target capacitance of the image orthicon. The multiplier does not itself produce appreciable noise and the useful gain that can be obtained from it is that value which gives a noise at the multiplier output large compared with the noise generated in a valve amplifier.

For the best results the beam current must be adjusted to a density just sufficient to discharge the target completely in a picture period. If a smaller beam current is used the target is not fully discharged in this period and a negative image is produced, this effect being associated with the landing characteristics of low-velocity electrons. If the beam current is too great, a badly shaded picture is obtained. Thus there is an optimum value of beam current and provided that the beam current is always adjusted to the optimum, the modulation depth of the return scanning beam is reasonably constant, usually between 25 and 50 per cent. Thus the signal output from the tube is very nearly directly proportional to the beam current.

The noise in the scanning beam is directly proportional to the square root of the beam current; thus the signal-noise ratio is also directly proportional to the square root of the beam current and, to obtain a good signal-noise ratio, the beam current must be kept high.

The only way of increasing beam current without sacrificing picture quality is by developing a greater charge image on the target. The charge (Q) on the target is given by the product of the target potential (V) and target capacitance (C); Q may thus be increased by increasing V or C. The target potential (V) cannot be increased because it must not exceed the mesh potential and the mesh potential cannot be made more than approximately 2 volts positive with respect to the gun cathode, otherwise there is a tendency for positive areas of the target to deflect the scanning beam, resulting in distortion of the reproduced image. Thus the only way in which a greater charge (and improved signal-noise ratio) can be obtained is by increasing the target capacitance, c; i.e., by decreasing the spacing between target and mesh. The resulting increase in q can only be obtained by increased photo-emission which in turn implies greater light input. Thus the improvement in signal-noise ratio is accompanied by a decrease in tube sensitivity. This decrease is comparatively unimportant in image orthicon tubes intended for use in studios where good illumination can readily be obtained and closer target-mesh separation (about 0·0005 inch) is used in studio type tubes than in types used in outside broadcasts (0·002 inch). The improvement in signal-noise ratio is approximately proportional to the square root of the increase in capacitance.

Signal-light Characteristic

There are two principal modes of operation of the image orthicon tube known as the high-light and low-light regions. In the low-light region the tube operates at maximum gain and is extremely sensitive, being capable of giving recognizable pictures with an illumination of only 0·02 foot-candle. With such a small amount of incident light, the target potential excursion is very small compared with 1 volt and all the secondary emission of the target is collected by the mesh. The output of the tube is directly proportional to the incident light as in the orthicon and the tube has a gamma value of unity. Used under these conditions of low lighting, a very small beam current must be used and the signal-noise ratio is poor.

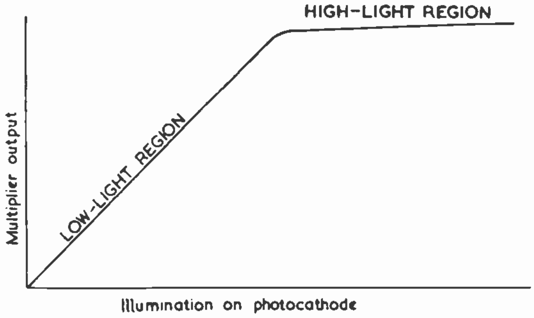

Fig. 49—Signal-light characteristic of image orthicon tube

If the light input is increased until the target potential excursion approaches 1 volt, the second mode of operation occurs and the output of the tube tends to be independent of the light input. The signal-noise ratio is now very much higher but halos are now present in the reproduced images.

The mechanism of the compression effect which keeps the output constant may be explained as follows. For target excursions up to approximately 1 volt, the mesh collects all secondary electrons emitted by the target but if the light input is increased to such an extent that the target potential tends to rise above 1 volt the mesh does not collect all secondaries but returns the low-velocity ones to the target, thus reducing target potential and tube output. The greater the incident light the greater is the ratio of secondary electrons returned to the target. Thus the tube output does not increase linearly with increase in incident light but tends to remain constant and the signal-light characteristic has the shape illustrated in Fig. 49.

Picture Quality

The return of secondary electrons to the target prevents the target potential from appreciably exceeding 1 volt and avoids instability of the type experienced with the orthicon.

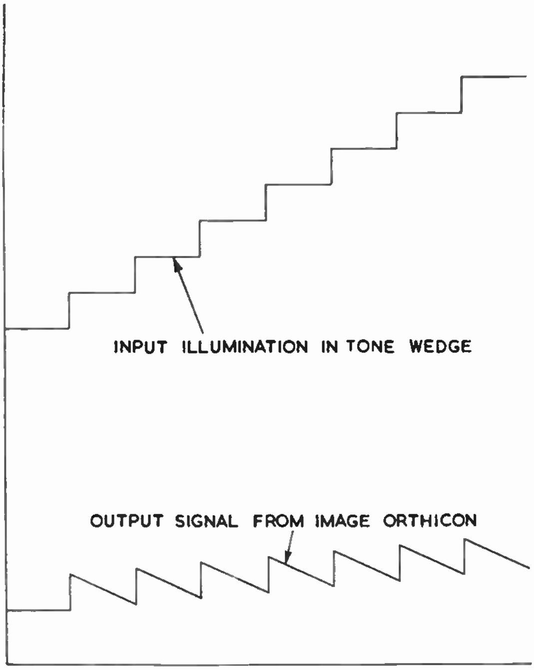

Fig. 50—Response of image orthicon to tone wedge

The return of secondary electrons to the target also causes halos in the following way: The secondary electrons emitted from an area of the target corresponding to an image highlight are returned to the target over an area exceeding that from which they were released, thus lowering the potential of a border surrounding the highlight. The reproduced image thus has a dark halo surrounding the highlight region which tends to make the highlight more obvious than it would be otherwise. If the image has much fine detail the halos are small and may be almost imperceptible but the " plastic effect " makes the image extremely clear. This effect is sometimes useful; for example, it enables the tube to give good reproduction of detail in, say, dark parts of a bright picture. It makes measurements of contrast law very difficult, however, for the reproduction of a step tone wedge appears somewhat as shown in Fig. 50; although each step is quite clear, the tonal value changes along each step.

The plastic effect improves the reproduction of moving images; for if the charge image of a highlight moves across the target, the secondary electrons sprayed into the area into which the highlight is moving erase the previous image by discharging it. Thus reproduction of moving objects is sharp and distinct, not blurred to the extent expected from 1/25th second exposure.

Colour Response

The colour response of early image orthicons was not good because of an excessive output at the red and infra-red end of the spectrum. Moreover, there were considerable variations in response between two tubes of the same type and it was difficult to obtain two matched tubes. The photo-cathodes now used have very much better colour response which does not greatly differ from that of the human eye and the differences in response of tubes of the same types are now very much less.

Resolution

The picture obtained from an image orthicon tube undergoes three transformations:

(1) Optical image to electron image liberated from the photo-cathode.
(2) Electron image to charge pattern on the target.
(3) Charge pattern to modulated electron beam.

At each step resolution can be lost; for example, the resolution obtainable at transformation (1) is limited by the initial velocities of the photo-electrons; at (2) resolution depends in part on the mesh of the screen and by leakage across the target; the ability of the scanning beam to resolve the charge pattern depends amongst other factors on the defining-aperture diameter, the angle of approach to the target and the magnitude of the potential differences in the charge pattern. Under favourable conditions, however, the resolution obtainable is of the same order as in an iconoscope.

ADVANTAGES AND DISADVANTAGES OF THE IMAGE ORTHICON TUBE

Image orthicon camera tubes have been used extensively for studio and outside broadcasts in America and to a smaller extent for both types of broadcasts in this country. Their chief advantages are:

1. Very high sensitivity. They can give satisfactory though noisy images with a very small amount of illumination and when other types of tube would be useless.
2. Properly operated they are completely stable.
3. They have a definite black-level output signal.
4. Good reproduction of moving images; the effective exposure time is less than the picture period.
5. Keystone modulation of the scanning waveforms is unnecessary.

The disadvantages are as follows:

1. The signal-noise ratio is directly proportional to the square root of the light input and is poor for low-light inputs. Moreover, the noise in the return scanning beam is uniformly distributed over the vision-frequency spectrum and is appreciable at low frequencies, giving rise to undesirable streaking in reproduced images.
2. If the light input is increased to obtain a good signal-noise ratio, the reproduced images develop halos around highlights.
3. The temperature of the target must be kept within certain limits otherwise loss of resolution or smearing may result.
4. Because of the complexity of the tube there are a large number of controls to adjust; for example, to obtain satisfactory images requires critical adjustment to optical focus, image focus, scanning beam focus, multiplier focus,* target potential and scanning beam current. The beam alignment control must also be adjusted, but once set should not require further attention.

*If the surface of the first dynode has any blemishes or spots where the secondary-emission ratio differs from that of the rest of the surface, best results are obtained when the return beam is not quite in focus on this dynode. The return beam performs a small raster on the dynode and, if it is sharply focused, the reproduced picture has spots corresponding in position to the blemishes on the dynode.

CHAPTER 6

PHOTO-CONDUCTIVE CAMERA TUBES

6.1 INTRODUCTION

A PHOTO-CONDUCTIVE material is one in which the electrical resistance changes when the material is exposed to light. The existence of photo-conductive materials has been known for some time but they have not been used in camera-tube targets because the change of conductivity is normally comparatively slow. For this reason camera tubes with such targets are more suitable for industrial applications than for use in television services. In America photo-conductive tubes have been given the name *Vidicon*: a British tube using the same principles is the *Staticon*.

The sensitivity of a photo-emissive target is limited because the energy necessary to emit photo-electrons must be supplied by the

Fig. 51—A camera intended for industrial use and using a photo-conductive tube (Staticon)

incident light; the theoretical maximum photo-efficiency is approximately 500 μA/lumen and values approaching 1/10th of this value have been obtained in practice but one of the main difficulties in the design of photo-emissive targets is to combine high efficiency with a good colour response.

The efficiency of a photo-conductive target can be very high; the current flowing through the target is supplied from an external source and the light acts as a relay which controls the current by varying the target resistance. The operation of a photo-conductive tube can be compared with that of a valve in which the power dissipated in the anode circuit is controlled by the grid potential, the power absorbed in the grid circuit being almost zero. In practice, photo-efficiencies as high as 10,000 μA/lumen can be obtained from a photo-conductive target and Vidicon camera tubes are thus highly sensitive. The time lag is, however, considerable for low-light inputs and to give satisfactory reproduction of dynamic scenes the Vidicon requires a large light input; thus its full sensitivity is not realized in television applications. The properties of the Vidicon together with its small size make it particularly suitable for industrial use. A photograph of a camera tube intended for use in industry and containing a Staticon tube is given in Fig. 51. Fig. 52 is a photograph of the Staticon tube itself; the ruler alongside it gives some indication of its small size.

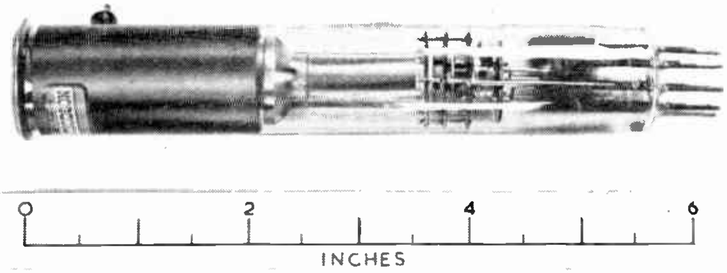

Fig. 52—Photo-conductive camera tube (Staticon)

6.2 VIDICON

Construction

The Vidicon camera tube consists of an evacuated glass cylinder, which may be as small as 1 inch in diameter, containing an electron gun at one end and a photo-conductive target at the other. The gun consists of an indirectly-heated cathode, a control grid and an anode; the target is a transparent signal plate coated on one side with photo-conductive material. A wall anode extends for most of the length of the tube and is connected to a screen situated near the target. Line and frame deflector coils are grouped around the tube and are surrounded by a focusing coil which produces an axial magnetic field. A small alignment coil is situated opposite the exit of the electron gun.

Signal Production

The electrical connections for a Vidicon tube are illustrated in Figs. 53 and 54. The target may be stabilized at anode potential or at cathode potential but to avoid shading signals a low-velocity scanning beam is preferable. The signal plate is biased approximately 20 volts positive with respect to the cathode and the scanned side of the target is stabilized near cathode potential by the electron beam; thus a considerable electric field is established between opposite faces of the target. As a result of this field, current flows between the opposite faces of the target, i.e., parallel to the tube axis at the point where the scanning beam strikes the target.

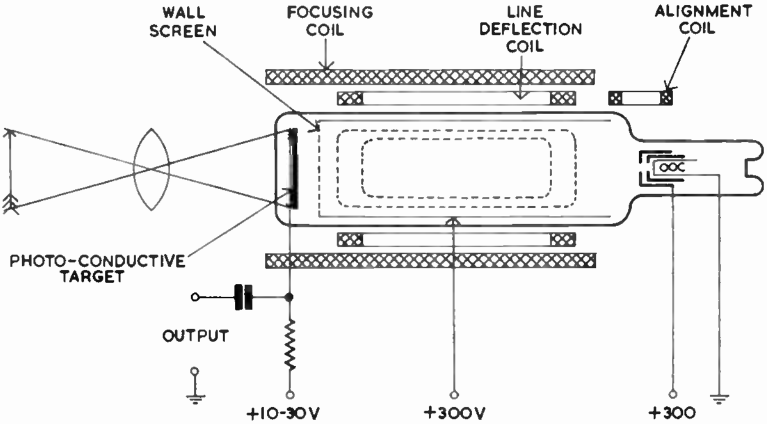

Fig. 53—Vidicon camera tube

The magnitude of the current depends on the signal-plate bias and the conductivity of the target, the latter depending, in turn, on the light incident on the target. Provided the target thickness and conductivity are suitable, charge storage occurs in the Vidicon by a process similar to that in the image orthicon; the chief difference is that the positive charge occurs through target conduction in the Vidicon and by secondary emission in the image orthicon. To obtain efficient storage in the Vidicon the time constant of the target, i.e., the product of the capacitance and the resistance between the opposite faces, must be long compared with the picture period.

For successful performance of this tube the target current must be strictly parallel to the tube axis; loss of resolution occurs if the current can flow at appreciable angles to the tube axis. In other words the lateral resistance of the target must be large compared with the axial resistance. This condition also applies to the image orthicon target and requires the same solution, namely, a very thin target, in this case a very thin coating of photo-conductive material. A very high value of specific resistivity is required and a value of the order of 10^{12} ohms-centimetre for an unilluminated target is used.

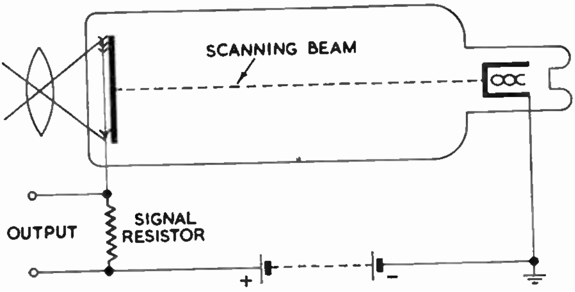

Fig. 54—Elements of Vidicon tube

The target is completely stable and there is no tendency for the target potential to rise to that of the electron-gun anode when the tube is directed at a very bright light.

The method of focusing the scanning beam and the mechanism of electromagnetic line and frame deflection are similar to those of the orthicon and are described on pages 85–90. The alignment coil carries d.c. and is used to deflect the electron beam as it leaves the gun to make it coincide with the axial magnetic field. The wall screen provides a uniformly strong decelerating field at the target to minimize the effects of beam bending; in addition it prevents the formation of an ion spot, as described on page 90.

PERFORMANCE OF VIDICON TUBE

Vidicon tubes are still in the experimental stage and few details of their performance are yet available. Because of their small size, robust and simple construction it is likely that Vidicon tubes will find their main application in industry.

6.3 CONDUCTRON

If the target resistance of a Vidicon is small and the time constant is small compared with the picture period, the tube still functions but there is no charge storage. Tubes with such targets are termed *conductrons.*

Signal Production

The mechanism of signal generation in the conductron is somewhat different from that in the Vidicon. The target bias supply drives a current through the target and the signal resistor, the circuit being completed by the electron beam, as shown in Fig. 55. The magnitude of this current depends on the signal-plate bias and the conductivity of the target, the latter depending in turn on the light falling on the target. The p.d. developed across the signal resistor depends on the current and thus on the light striking the target.

When the target is in darkness the conductivity is low and very little current flows in the signal resistor; when light falls on the target the conductivity and signal current both increase. When an optical image falls on the target the axial current is large at points corresponding to image highlights and low at points where there is little light. Thus the current in the signal resistor varies with time as the target is scanned and the correspondingly varying p.d. across the signal resistor constitutes the required vision signal and tube output.

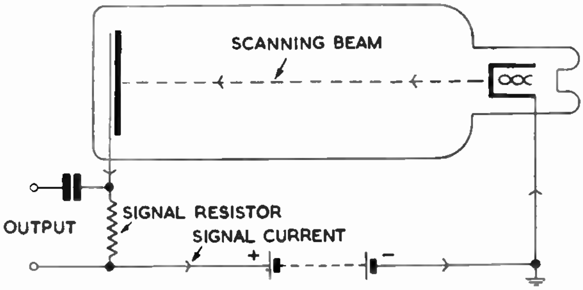

Fig. 55—Signal current in Conductron tube

PART III: TELEVISION AND ELECTRON OPTICS

CHAPTER 7

LIGHT: BASIC CONSIDERATIONS

7.1 INTRODUCTION

A TELEVISION camera usually produces picture signals by scanning a charge image which is derived from an optical image: thus the first process in a television system is the production of an optical image of the scene to be televised. This image is obtained by use of a lens system similar to that employed in photographic camera objectives; a separate lens system may also be required in the camera viewfinder. At the other end of the television chain, optical systems employing spherical mirrors are used in projection-type television receivers.

This chapter gives an account of the fundamental principles underlying the optical systems used in television equipment; it begins with a brief description of the nature of light and gives definitions of the light terms used in this and the previous sections.

7.2 NATURE OF LIGHT

In the study of optical systems light is regarded as an electromagnetic wavemotion of the same nature as radio waves but with a very much shorter wavelength. For visible light in air the wavelength extends from approximately 4,000 Å for violet light to 7,000 Å for red light, and the intermediate colours of the spectrum have wavelengths between these limits. For example, sodium light (an intense yellow) has a wavelength of 5,893 Å. For all colours the velocity of light *in vacuo* is 3×10^{10} cm/s (as for radio waves), and, from the relationship $f = c/\lambda$, the frequency range of visible light can be shown to extend from 4×10 Mc/s to $7 \cdot 5 \times 10^8$ Mc/s, each frequency corresponding to a particular colour. The velocity of light varies for different media, being less in non-gaseous media such as water and glass than in air, but there is no change in frequency when light passes from one medium to another. It follows that the wavelength of the light changes in the same ratio as the velocity.

The human eye does not respond equally to the full range of visible light but has maximum sensitivity at approximately 5,600 Å as shown in Fig. 56. In the design of mosaics and photo-cathodes for camera tubes one of the aims is to obtain a response similar to that of the human eye.

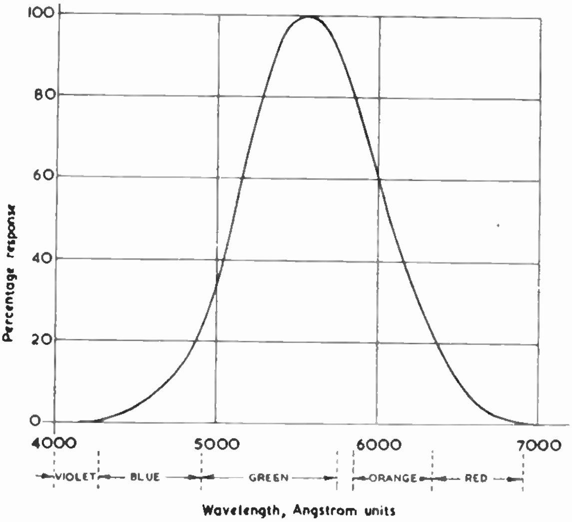

Fig. 56—The photopic curve, i.e., the spectral response of the average human eye

7.3 Reflection, Refraction and Absorption

When a ray of light travelling in a transparent medium 1 (Fig. 57) strikes the boundary of another medium 2, three effects may occur. Firstly, the incident ray AO may be reflected at the surface FG and returned to medium 1; the light may be either scattered on reflection so that it returns along numerous different paths, or it may be reflected so that most of the light is confined to one particular path such as OC. Secondly, if medium 2 is transparent, the light may pass into it, suffering a change of direction as it crosses the boundary; this is termed *refraction*, and one path the refracted light may take is OD in Fig. 57. Thirdly, the light may be absorbed at the boundary.

In general all three effects occur together, but the two media and the nature of the boundary between them can be chosen to favour or to minimize one or more of the effects. For example, if medium 2 is opaque and if its surface is highly polished, practically all the incident light is reflected and there is little or no refraction or absorption. On the other hand, if the surface of medium 2 is rough and black, practically all the incident light is absorbed and very little is reflected or refracted. Finally, if medium 2 is transparent, most of the light is refracted, although a fraction is reflected and a little absorbed.

That fraction of the incident light energy which is reflected is known as the *reflection factor* or *reflection coefficient*, and some typical values for various materials are given later in this section; knowledge of such factors is useful in calculating surface brightnesses. That fraction of the incident light energy which is transmitted is known as the *transmission factor* or *transmission coefficient* τ.

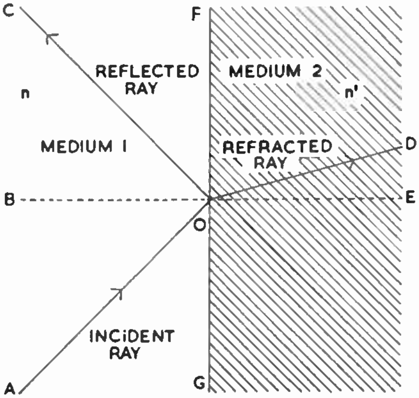

Fig. 57—Reflection and refraction at the boundary of two media

When the boundary between the two media in Fig. 57 is flat and smooth, as in a plane mirror, light is reflected so that the angle of incidence ($\angle$AOB) is equal to the angle of reflection ($\angle$BOC); this is termed *regular* or *specular* reflection. If the dimensions of the surface irregularities are comparable with the wavelength of the light, the light is scattered in all directions on reflection. This is termed *diffuse* reflection: blotting paper is a good example of a diffuse reflector. If the reflecting surface is sufficiently rough, the distribution of the reflected light follows a cosine law, maximum light being reflected at right angles to the surface and no light along the surface. A surface with this property is described as *perfectly diffusing*, and, as will be shown later, appears equally bright no matter from what direction it is viewed.

7.4 FUNDAMENTAL LIGHT DEFINITIONS

The terms luminous intensity, luminous flux, illumination and brightness are used extensively in this book and will now be defined. The terms are interrelated as indicated in the following brief definitions:

Luminous Intensity of a light source in a particular direction is determined by the luminous flux emitted in that direction and is a measure of the illuminating power of the source in the direction considered. This may be compared with electric power.

Luminous Flux is the quantity of light flowing per second across a particular area and may be compared with the electric power transmitted through the cross-section of a conductor.

Illumination is a measure of the luminous flux received by unit area of a surface (i.e., power received per unit area).

Brightness is a measure of the luminous flux emitted or reflected by unit area of a surface (i.e., power transmitted per unit area).

These terms and the units in which they are measured will now be examined in more detail. For some of the terms (for example, luminous flux) only one unit is in common use, but others (for example, illumination) are measured in several different units, depending primarily on whether the British or metric system is employed. For the sake of simplicity only the British units are given in the following text; other units and the interrelationships between the various units are given in Appendix B.

7.4.1 LUMINOUS INTENSITY

The unit of luminous intensity I is that of the new candle or candela, which has a magnitude such that the intensity of a black body at the temperature of solidifying platinum is 60 new candles per sq cm. (The term *black body* implies that the surface completely absorbs all radiation falling on it, irrespective of its nature or direction.) Electric lamps operating under specified conditions are generally used as practical standards of intensity, which is, however, expressed in candelas.

A uniform light source radiates equally in all directions and its intensity is independent of the direction of observation, but most of the light sources commonly used in buildings are designed to radiate best in a particular direction or into a given hemisphere. For such sources the luminous intensity varies with the direction of observation, and a statement of the intensity in a particular direction gives no indication of the total flux radiated or of the illuminating power of the source.

The intensity of non-uniform sources is sometimes expressed in terms of mean spherical or mean hemispherical candle-power. The mean spherical candle-power of a non-uniform source is the average value of the candle-power in all directions and is equal to the candle-power of a uniform source which radiates the same total flux as the source in question but with equal intensity in all directions. The mean upper (or lower) hemispherical candle-power is the mean of the candle-powers in all directions above (or below) the horizontal plane passing through the source.

The luminous intensity (in candles) of a point source in a particular direction is equal to the luminous flux emitted into unit solid angle in the given direction.

The solid angle subtended by an area at a point is obtained by projecting the area on to the surface of a sphere (with its centre at the given point) by straight lines passing through the point: the solid angle is then given by the projected area divided by the square of the radius. If a given area A has spherical curvature and the solid angle required is subtended by this area at the centre of curvature there is no need to project the area, and the solid angle ω is given by A/r^2, where r is the radius of curvature.

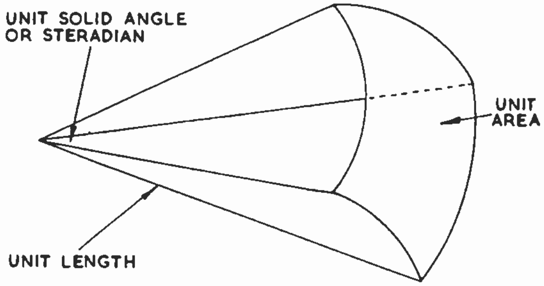

Fig. 58—Illustrating unit solid angle

Unit solid angle is that subtended at a point by unit area which is at unit distance from the point: it is known as the *steradian* (see Fig. 58). The solid angle subtended by the surface of a sphere at its centre is thus $4\pi r^2/r^2$, i.e., 4π steradians, and is independent of the radius.

Luminous intensity may also be defined in terms of the illumination of a nearby surface as follows. The luminous intensity (in candles) of a point source in a particular direction may be defined in terms of the illumination of a nearby surface at right angles to the given direction. It is equal to the product of the normal incident illumination E_n (in foot-candles) and the square of the distance d in feet:

$$I = E_n d^2$$

As an indication of the magnitude of the unit of luminous intensity an average 60 W electric lamp has an efficiency of approximately 1 watt per mean hemispherical candle-power: in other words, the luminous intensity averaged over all directions above (or below) the horizontal plane is 60 candle-power. It is, however, more usual to state the efficiencies of electric lamps in terms of lumens per watt.

If a light source has appreciable area, its luminous intensity in a particular direction may be expressed in candles per unit area of source, but this quantity is more usually termed *brightness* and is discussed under this heading.

7.4.2 LUMINOUS FLUX

The unit of luminous flux is the *lumen*, which is defined as the flux emitted into unit solid angle by a uniform point source having a uniform luminous intensity of 1 candle.

From the definition of solid angle we can say that a lumen is the luminous flux falling on unit area, all points of which are at unit distance from a point source of luminous intensity 1 candle.

The surface of a sphere subtends a solid angle of 4π steradians at its centre; thus a standard candle emits a total of 4π (12·56) lumens, and the total luminous flux F radiated by a source of candle-power I is given by:

$$F = 4\pi I \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (4)$$

The flux emitted into a solid angle ω by the same source is given by:

$$F = I\omega \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (5)$$

A solid angle is a pure number, i.e., it has no dimensions and from expression (4) or (5) it is clear that intensity and flux have the same dimensions, and both therefore compare with electric power. Of these two quantities luminous flux is the more fundamental, but it is more convenient to keep standards of intensity.

The efficiency of electric lamps is usually expressed in lumens per watt, the flux being the total radiated in all directions; thus an efficiency of 12·56 (= 4π) lumens per watt is equivalent to 1 watt per mean spherical candle-power. For gas-filled lamps the efficiency increases steadily with the rating and is approximately 10 lumens per watt for 25 W lamps, 13 lumens per watt for 100 W lamps and 17·5 lumens per watt for 1 kW lamps. Thus a 100 W lamp radiates a total of 1,300 lumens and is equivalent to a source of 1,300/4π, i.e., approximately 100 candle-power.

7.4.3 ILLUMINATION

The unit of illumination or intensity of illumination is the *foot-candle*, which is equivalent to 1 lumen per square foot; it is the illumination on a surface all points of which are at a distance of 1 foot from a uniform point source of 1 candle.

The foot-candle is an unfortunate choice of unit because it suggests, quite wrongly, that illumination is measured by the product of intensity and distance.

The luminous flux emitted from a point source of given luminous intensity I into a given solid angle ω is constant and equal to $I\omega$ as indicated in expression (5). The solid angle is given by:

$$\omega = \frac{A}{d^2}$$

Combining these expressions:

$$F = I\omega = I\frac{A}{d^2}$$

$$\therefore \qquad \text{illumination} = E = \frac{F}{A} = \frac{I}{d^2} \qquad \ldots \qquad \ldots \qquad (6)$$

The illumination is thus directly proportional to the luminous intensity of the source and inversely proportional to the square of the distance. Expression (6) holds for light falling normally on a surface; if the light is incident at an angle θ to the normal, the illumination is given by $I \cos \theta/d^2$.

To show the magnitude of practical values of illumination we will determine the illumination of a surface 4 feet from a lamp which has a luminous intensity of 60 candle-power in the direction of the surface. The illumination is given by $I/d^2 = 60/16 = 3{\cdot}75$ foot-candles or lumens per square foot. An indoor illumination by artificial light of 10 foot-candles is considered good.

For a surface illuminated by parallel light, the flux F falling normally on a surface of area A is given by EA and is independent of the distance from the source. If the light is incident at an angle θ to the normal, the illumination is $E \cos \theta$ and the flux $AE \cos \theta$.

Practical Values of Illumination

The illumination E received from the sun on a clear summer's day may be as high as 10,000 foot-candles on a surface normal to the radiation. On horizontal surfaces the illumination is $E \sin \theta$, where θ is the angle of elevation of the sun, and this illumination increases with increase in θ. In television the illumination of vertical surfaces is possibly more important than that of horizontal surfaces, and this is given by $E \cos \theta$. Over the sun's range of altitude $E \cos \theta$ does not vary so greatly as $E \sin \theta$, and the average value of the illumination on a vertical surface by the sun can be taken as approximately 5,000 foot-candles. This is 500 times as great as the value considered good in a room illuminated by artificial light.

In television studios the illumination used is generally between 30 and 200 foot-candles, the lower value for camera tubes such as the image orthicon and C.P.S. Emitron and the higher value for less sensitive tubes such as the iconoscope.

If the illumination falling on a camera-tube mosaic (or photo-cathode) is known, the photo-electric current can be calculated as follows. Suppose the illumination on the mosaic is 1 foot-candle, the mosaic area 1·4 inches by 1·8 inches and the photo-efficiency 25 μA/lumen: these values are approximately true for a C.P.S. Emitron tube.

The illumination E is 1 lumen per square foot, which is equal to 1/144 lumen per square inch. Thus the flux total F falling on the mosaic is given by:

$$F = EA = \frac{1 \times 1{\cdot}4 \times 1{\cdot}8}{144} \text{ lumens}$$

and the photo-electric current i is thus given by:

$$i = \frac{1 \times 1{\cdot}4 \times 1{\cdot}8 \times 25}{144} \ \mu\text{A}$$

$$= 0{\cdot}44 \ \mu\text{A}$$

7.4.4 BRIGHTNESS

The brightness B in a given direction of a surface emitting light is the quotient of the luminous intensity I measured in that direction and the area of the surface A projected on a plane perpendicular to the given direction. It is expressed in candles per square foot and when applied to an emitting surface is a measure of the luminous intensity of the source per unit area:

$$B = \frac{I}{A} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (7)$$

From (5) $F = I\omega$, and therefore:

$$F = BA\omega \quad \ldots \quad \ldots \quad \ldots \quad (8)$$

which expresses the luminous flux emitted into the solid angle ω by the area A.

Some surfaces are such that the luminous flux radiated or reflected in a direction θ degrees to the normal is directly proportional to $\cos\theta$. The light emitted is thus a maximum normal to the surface and is zero along the surface. Such a surface appears to be equally bright in all directions because both reflected light and the area projected on a plane at right angles to the viewing direction follow the same cosine law. Such a surface is described as uniformly or perfectly diffusing, and most self-luminous smooth surfaces are in practice almost perfectly diffusing. A good example of a perfectly-diffusing surface is freshly fallen snow. Many matt reflecting surfaces such as chalk and blotting paper are also very nearly perfectly diffusing.

A perfectly-diffusing surface is taken as a standard of brightness in the definition of a *foot-lambert*: this is a unit of brightness equal to that of a perfectly-diffusing surface emitting or reflecting a total flux of 1 lumen per square foot.

It is shown in Appendix C that a perfectly-diffusing surface having an intensity of 1 candle normal to the surface radiates a total flux of π lumens. (This should be compared with a point source of 1 candle, which radiates a total of 4π lumens.) If each square foot of this surface has an intensity of 1 candle, each unit area radiates a total of π lumens and, by definition, the surface has a brightness, viewed in any direction, of π foot-lamberts. The brightness may be expressed as 1 candle per square foot or π foot-lamberts, thus:

$$1 \text{ candle per square foot} = \pi \text{ foot-lamberts} \quad .. \quad (9)$$

If a surface is perfectly reflecting in addition to perfectly diffusing, and has an illumination of 1 foot-candle (i.e., 1 lumen per square foot), the light reflected from unit area is 1 lumen and the brightness is 1 foot-lambert, which, from (9), is equivalent to $1/\pi$ candles per square foot. In general, for a perfectly-reflecting and diffusing surface:

$$B = \frac{E}{\pi} \quad .. \quad .. \quad .. \quad .. \quad (10)$$

where B is the brightness in candles per square foot and E is the illumination in foot-candles.

If the surface absorbs some of the incident light, its reflecting power is expressed by the reflection coefficient ρ, defined by:

$$\rho = \frac{\text{total light reflected from surface}}{\text{total light incident on surface}}$$

and the brightness of a perfectly-diffusing surface of reflection coefficient ρ is given by:

$$B = \frac{\rho E}{\pi} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (11)$$

where B is the brightness in candles per square foot and E is the illumination in foot-candles.

Reflection coefficients have been measured for a wide variety of surfaces. Typical values are:

Snow	0·93
Plaster of Paris	0·80
Brown soil	0·32
Grass	0·25
Black velvet	0·01

As a numerical example we will calculate the brightness of a perfectly-diffusing surface of plaster of Paris (reflection coefficient 0·80) which is illuminated by a lamp with an intensity of 150 candles in the direction of the surface. The lamp is 30 feet away and the surface is inclined at 60 deg to the line joining it to the lamp.

The illumination falling normally on a surface at a distance of 30 feet from a lamp of 150 candle-power is given from expression (6) by I/d^2, i.e., $150/30^2$ foot-candles. When allowance is made for the oblique incidence this becomes $(150 \sin 60)/30^2$, i.e., 0·144 foot-candle.

The light incident on each square foot is 0·144 lumen and the light reflected is $0{\cdot}8 \times 0{\cdot}144 = 0{\cdot}115$ lumen.

The brightness is thus 0·115 foot-lambert, or $0{\cdot}115/\pi = 0{\cdot}036$ candle per square foot.

An extended light source appears equally bright at all viewing distances because the light flux entering the eye varies to the same degree as the size of the retinal image when the viewing distance is changed. For example, if the distance of the eye from the source is doubled, the light flux entering the eye falls to one-quarter of its former value; but the area of the image on the retina also falls to one-quarter of its original value. Thus the illumination of the retina remains constant and the brightness of the source is independent of the distance. This is only true if the image on the retina has appreciable area; if the image is so small that the retina is incapable of appreciating changes in image area, as when the eye is looking at a point source, then the brightness is inversely proportional to the square of the distance.

7.5 Summary of Light Terms

The information in the previous paragraphs is summarized in the following table:

Quantity	*Symbol*	*Dimensions*	*Unit*	*Equation*
Luminous intensity	I	Lumens per steradian	Candle or candle-power	$I = \frac{F}{\omega}$
Luminous flux	F	Lumen	Lumen	$F = \omega I$
Illumination	E	Lumens per unit area	Foot-candle (= lumens/sq ft)	$E = \frac{F}{A}$ $= \frac{I}{d^2}$
Brightness ..	B	Candles per unit area or lumens per steradian per unit area	Candles/sq ft or ft-lamberts*	$B = \frac{I}{A}$ $B = \frac{\rho E}{\pi}$
Solid angle ..	ω	Area/(distance)^2	Steradian	$\omega = \frac{A}{d^2}$

* 1 candle per square foot = π foot-lamberts.

CHAPTER 8

MIRRORS

BEFORE discussing the properties of television optical systems in detail we must describe the properties of spherical mirrors and lenses which are used in these systems. Except for concave mirrors, which are used in projection-type receivers, spherical mirrors are not employed to any extent in television equipment. The properties of such mirrors are, however, described here because they form a useful introduction to the more important subject of lenses.

A number of specialized terms are used in describing optical systems, and the fundamental terms will be described first.

8.1 REFLECTION

To illustrate the meaning of the terms, Fig. 59 shows a convex mirror with a very small object, known as a point object, O situated

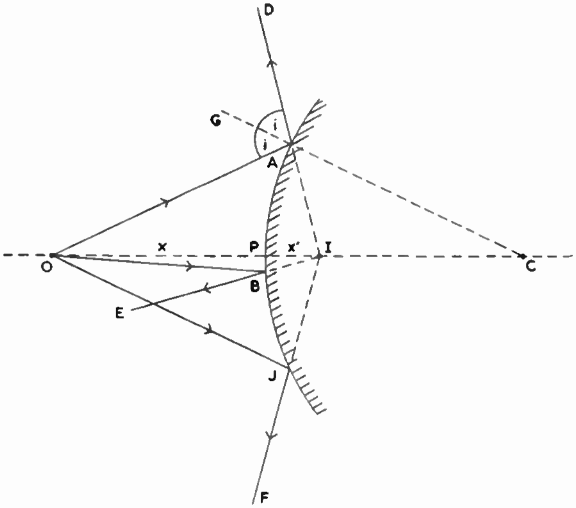

Fig. 59—Formation of a point image in a convex mirror

at a distance x from it. Rays of light radiate from O in all directions, but for the sake of simplicity only three of these rays, OA, OB and OJ, are shown in the diagram. All rays striking the mirror are reflected regularly, i.e., such that the angle of reflection equals the angle of incidence. For ray OA the angle of incidence ($\angle i$) is $\angle$OAG, and this is marked equal to $\angle$GAD, the angle of reflection. AD, BE and JF are the reflected rays corresponding to the chosen incident rays. The directions of the reflected rays, when produced, meet at a single point I, and to an observer it appears that these rays have originated from this point situated behind the mirror. I is termed the *image* of object O and it is situated at a distance x' behind the mirror.

The straight line OC passing through the object, the image and the centre of curvature is known as the *optic axis*; P, where this meets the reflecting surface, is known as the *pole* of the mirror.

In general, images are formed whenever a number of rays originating from a point on an object meet at another point in space or, as in Fig. 59, appear to originate from another point in space. The first type of image is described as *real* and the second *virtual*; the distinction between them is further described on page 144.

8.2 REFRACTION

Light travels more slowly in a material medium than *in vacuo*, and the ratio

$$\frac{\text{velocity of light } in\ vacuo}{\text{velocity of light in medium}}$$

is known as the *refractive index n* of the medium. The velocity of light in air is so nearly equal to that *in vacuo* that the refractive index of air may be taken as unity with very little error. The velocity of light in a much denser medium such as glass is appreciably less than *in vacuo*, and the refractive index of glass is approximately 1·5. In crossing the boundary between two media the light is either accelerated or retarded and, if it is not normally incident on the boundary, suffers a change in direction. This is illustrated in Fig. 60, which shows a parallel beam of light travelling in a medium of refractive index n incident at an oblique angle $\angle i$ on the plane boundary of a second medium with a greater refractive index n'. AB represents the wavefront of the beam at a particular instant of time. Light travels more slowly in the denser medium, and during the time taken for point B on the wavefront to travel to D, point A travels the smaller distance AC in the dense medium. As a result of this relative retardation of part of the wavefront the beam is slewed round, and its direction in the new medium is at an angle $\angle r$ to the normal, where $\angle r$ is less than $\angle i$. This effect may be summarized by saying that the light path is bent towards the normal when light crosses a boundary into a denser medium.

A similar argument may be employed to deduce the change in direction which occurs when the light beam in Fig. 60 leaves the dense medium. EF represents a cross-section of the wavefront, and in the time taken for point F to travel the distance FH, point E travels the greater distance G in the less dense medium. Thus the beam suffers a second change in direction, the light path being bent away from the normal as the light crosses the boundary into a less dense medium. If the two boundaries are parallel as in Fig. 60, and if the final medium is the same as the first, the emergent light is parallel with the incident light. Fig. 60 can be simplified as shown in Fig. 61, in which the beam is represented by a single arrowed line.

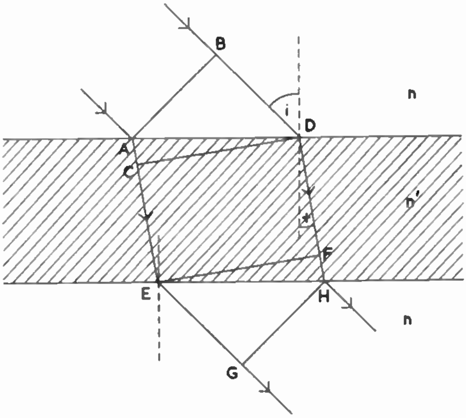

Fig. 60—Change of direction of a light beam during refraction

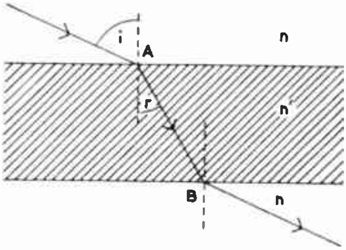

Fig. 61—Refraction of light

For two given media the ratio of the sine of the angle of incidence ($\angle i$ in Fig. 60) to the sine of the angle of refraction ($\angle r$ in Figs. 60 and 61) is constant and equal to n'/n, where n' is the refractive index of the second medium and n is that of the first. This is known as *Snell's law*.

$$\frac{\sin i}{\sin r} = \frac{n'}{n} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (12)$$

If the first medium is air or *vacuo*, $n \simeq 1$ and

$$\frac{\sin i}{\sin r} \simeq n' \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (13)$$

If in equation (12) n' is made equal to $-n$, the equation reduces to

$$\sin i = -\sin r$$

$$\text{i.e.,} \qquad \angle r = -\angle i$$

This is a statement of the law governing specular reflection, namely, that the angle of reflection is equal to the angle of incidence. The negative sign prefacing $\angle i$ indicates that the angle of reflection is measured in an opposite direction to the angle of incidence; in fact the angles of incidence and refraction are both measured in an anticlockwise direction (the conventional positive direction) from the normal, whereas the angle of reflection is measured in a clockwise direction from the normal and must be considered negative.

It is useful to regard reflection as a special case of refraction because it avoids the necessity for developing separate formulae for spherical mirrors and lenses; this concept will therefore be used in this book and a general formula will be developed which applies to all examples of reflection or refraction at a spherical boundary between two media of different refractive index. For the formula to be of universal application a convention of signs for angles and distances must be adopted. Many different conventions are possible, but those adopted in this book are listed below.

8.3 SIGN CONVENTION

1. All measurements of object distances, image distances, radii of curvature and focal lengths are made from the pole of the refracting surface towards the object, image, centre of curvature or focus respectively.
2. Object distances are considered positive when the measurement is made in the opposite direction to the incident ray.

   In most of the diagrams in this book light is incident on the refracting surface from the left, and object distances are positive when the object is to the left of the surface.
3. Image distances are considered positive when the measurement is made in the same direction as the incident light.

   If light is incident on the left of the refracting surface, image distances are positive when the image is situated to the right of the surface.

4. Radii of curvature and focal lengths are considered positive when the measurement is made in the same direction as the incident light.

   If light is incident on the left of the refracting surface, radii of curvature or focal lengths are positive when the centre of curvature or focus is to the right of the surface.

8.4 Refraction at a Single Spherical Surface

Fig. 62 illustrates a spherical boundary separating a medium of refractive index n from another of refractive index n'. A point object O is situated at a distance x from P, the pole of the surface, and gives rise to an image I at a distance x' behind the surface. OA is one of the many rays forming this image. The following general relationship between x and x' is derived in Appendix D.

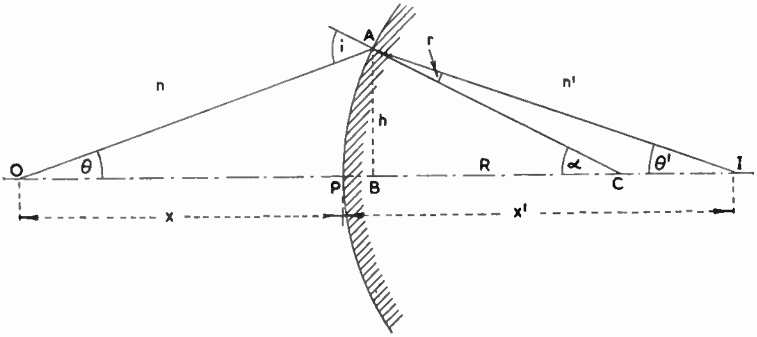

Fig. 62—Refraction at a single spherical surface

$$\frac{n}{x} + \frac{n'}{x'} = \frac{n' - n}{R} \quad \ldots \quad \ldots \quad \ldots \quad (14)$$

where R is the radius of curvature of the spherical surface.

If the image is formed by reflection, n' must be put equal to $-n$, and the general expression for reflection at a spherical surface so obtained is

$$\frac{1}{x'} - \frac{1}{x} = \frac{2}{R} \quad \ldots \quad \ldots \quad \ldots \quad (15)$$

If the reflecting surface is flat, R is infinite, and expression (15) reduces to

$$x' = x$$

i.e., the distance of the image behind a plane mirror is equal to the distance of the object in front of it.

8.5 REFLECTION AT A PLANE MIRROR

This statement can be verified by a geometric construction similar to that of Fig. 59 and is given in Fig. 63. O is a point object before the mirror and OA, OB and OC are three rays of light from it. These rays suffer regular reflection at the mirror surface, and the reflected rays AA′, BB′ and CC′ appear to originate from the virtual image I behind the mirror.

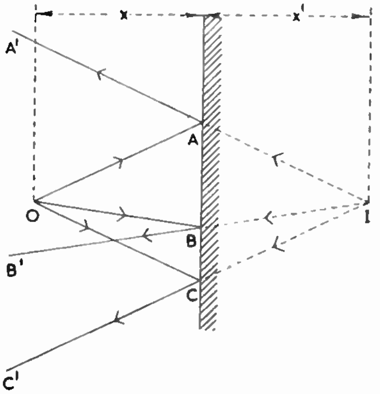

Fig. 63—Formation of a point image in a plane mirror

To determine the position of the image of an extensive object, the object may be regarded as a collection of points each having its own particular image, and the positions of the various point images can be obtained from the construction of Fig. 59. In this way the image of a large object can be shown to be equal to the original object in size, and to be situated at an equal distance from the mirror. The image, however, is laterally inverted; i.e., the left-hand side of the object appears at the right-hand side of the image.

8.6 SURFACE-SILVERED MIRRORS

Most plane mirrors are rear-silvered, i.e., they are silvered on the side remote from the incident light, but for certain applications it is essential to have the silvering on the incident surface: such mirrors are termed *front-* or *surface-silvered.* The necessity for surface-silvering can be appreciated from Fig. 64, which illustrates the formation of an image of an object AB situated near a rear-silvered mirror. Although most of the light is transmitted through the glass and is reflected at the rear surface to form an image, a certain fraction of the incident light is reflected at the front mirror surface (see page 189) and gives rise to a second image. Rays AC and AH are reflected at the front surface and the reflected rays CF and HL appear to originate from A″, which is one image of A; this image is usually faint because only a small fraction of the incident light is reflected at the front surface. Most of the light in ray AC passes into the glass, is reflected at the silvering at D and emerges as ray EG; similarly ray AH emerges as ray KM. The reflected rays EG and KM appear to originate from A′, a second image and usually a much brighter one than A″. By a construction similar to that shown for A the positions of the two images B′ and B″ could be determined, but for the sake of simplicity the construction lines have been omitted from the diagram.

Image A″B″ may be faint and difficult to distinguish, particularly if it is situated very near A′B′; nevertheless if A′B′ represents part of the image on the light-sensitive surface of a television camera tube or on a viewfinder screen, a second image such as A″B″ will degrade the contrast and possibly reduce definition in the image as a whole; such subsidiary images must therefore be avoided. If in Fig. 64 the object distance is increased, the rays AC and AH approach each other and finally coincide when the object is at infinity and rays from it are parallel; if C falls on H, A″ coincides with A′, B″ with B′, and there is only one image. Thus a rear-silvered mirror gives satisfactory images provided the object distance is large and light from it is substantially parallel. Sometimes,

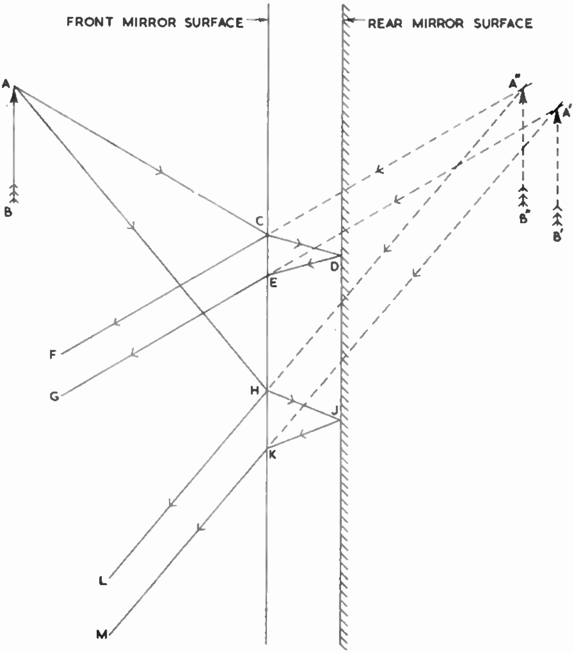

Fig. 64—Formation of twin images in a rear-silvered mirror

however, the light striking the mirror is inevitably convergent or divergent; twin images can then be avoided by arranging for the image to be formed only by light reflected at the front surface of the mirror, in other words by use of a front-silvered mirror.

8.7 CONVEX MIRRORS

Reflection of Light at a Convex Mirror

In general an object is regarded as emitting light in all directions, and a mirror which subtends an appreciable angle at a point object O (Fig. 65) is illuminated by a divergent beam of light from the object. Fig. 65 shows some of the rays from a point object falling on a convex mirror (in practice the mirror would be filled with light from the object, but for simplicity only a few of the rays are drawn). If the distance between the mirror and object is increased, the angle subtended by the mirror at the object decreases and the divergence of the beam illuminating the mirror also decreases. In the limit, when the object is an infinite distance away, the light received by the mirror is parallel as shown in Fig. 66; in practice it is usually justifiable to assume that the light from a small object several feet away is parallel when it reaches the mirror.

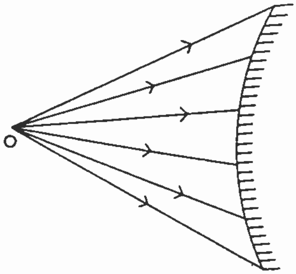

Fig. 65—A convex mirror illuminated by light from a nearby point object

Reflection of Parallel Light at a Convex Mirror

Each of the individual rays constituting the parallel beam suffer regular reflection at the mirror surface; that is to say the angles made by the incident and reflected rays with the radius of the mirror at the point of reflection are equal. The equal angles are shown for one ray in Fig. 66 and are marked $\angle i$. The reflected rays appear to diverge from a point F behind the mirror; this point is known as the *focus* or *focal point* of the mirror, and the distance PF, known as the *focal length f*, is an important characteristic of the mirror. Thus the focal length f is the image distance for an object distance of infinity. Substituting $x = \infty$ and $x' = f$ in (15):

$$\frac{1}{f} = \frac{2}{R}$$

$$\therefore \quad f = \frac{R}{2} \qquad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (16)$$

Thus the focal length is equal to half the radius of curvature. Equation (15) may thus be written

$$\frac{1}{x'} - \frac{1}{x} = \frac{1}{f} \qquad \ldots \qquad \ldots \qquad \ldots \quad (17)$$

The sign of f follows the same convention as that of R and is positive

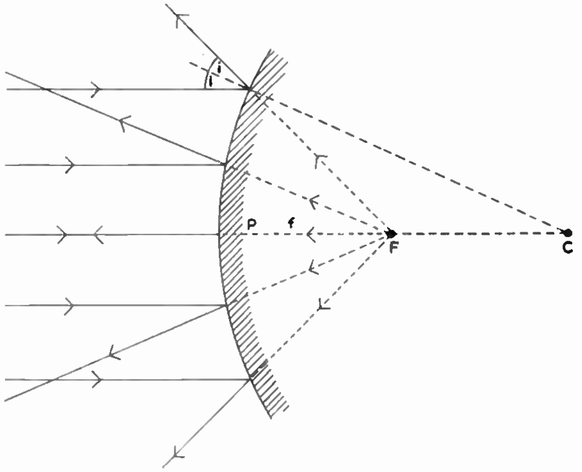

Fig. 66—Reflection of a parallel beam of light at a convex mirror

for a convex mirror because the focus is to the right of the pole. Expression (17) may be written

$$x' = \frac{xf}{x + f} \qquad \ldots \qquad \ldots \qquad \ldots \quad (18)$$

in which x, x' and f are all positive.

Variation of Image Position with Object Position for a Convex Mirror

The relative positions of object and image for various values of object distance x and focal length f can be deduced from expression (18) and are also illustrated in Fig. 67. If x is small compared with f, we have, from (18):

$$x' \simeq x$$

Thus when an object is situated very close to a convex mirror the image is an equal distance behind it. This is illustrated by object O_1 and image I_1 in Fig. 67. For such small object distances the spherical mirror tends to behave as a plane one.

As x increases, x' also increases, and from (18) when $x = f$,

$x' = f/2$. In other words, when the object is situated in front of the mirror, at a distance equal to the focal length, the image is at a distance equal to half the focal length behind it; this is illustrated by object O_2 and image I_2 in Fig. 67.

Further increase in x now causes a comparatively small increase in x'; in fact x must approach infinity before x' approaches f. In Fig. 67 the image of a fairly distant object O_3 is at I_3, and for an object at infinity, O_4, is at I_1 (the focus).

The observations of the last few paragraphs are further illustrated by the curve of Fig. 68, this illustrates the linear relationship between x and x' for small values of x and also shows that x' becomes asymptotic to the line $x' = f$ as x approaches infinity.

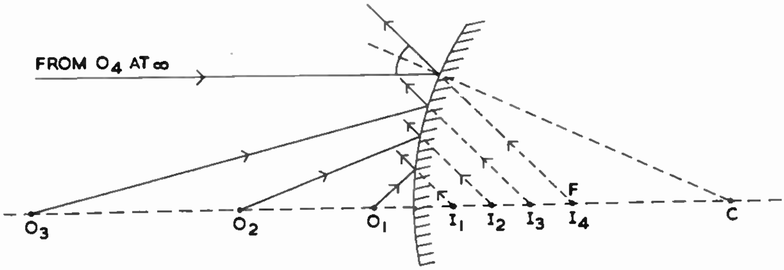

Fig. 67—Variation of image position with object position for a convex mirror

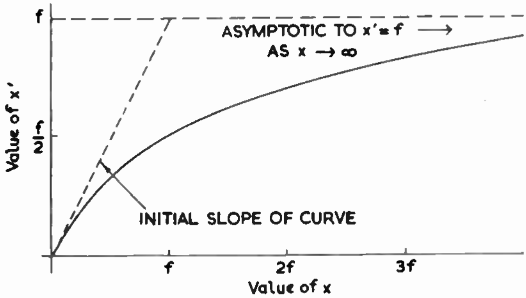

Fig. 68—Curve illustrating the relationship between object and image distance for a convex mirror

Formation of an Image

A large object can be regarded as a collection of point objects, each of which radiates light in all directions. Thus if a mirror is placed near the object, each point of the object gives rise to a divergent beam of light which fills the mirror. Fig. 69 shows a convex mirror receiving light from a point at the top of a large object; for simplicity only a few of the large number of rays from the point object are indicated and no rays from other parts of the object are shown. The diagram shows that the rays, after reflection at the mirror, appear to originate from a virtual image of the point behind the mirror.

It is also true that any point on the mirror receives light from all parts of the object: this is illustrated in Fig. 70, in which five rays only from the object are shown striking the mirror at one point. After reflection these five rays appear to originate from the corresponding five points on the image behind the mirror.

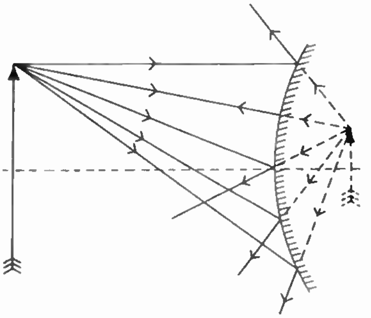

Fig. 69—Rays from one point on a large object reflected at a convex mirror

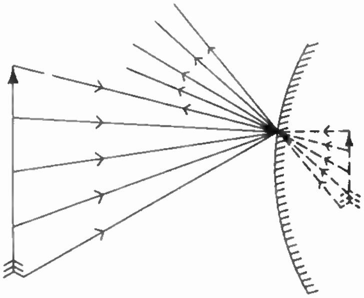

Fig. 70—Rays from five points on an object reflected at one point on a convex mirror

Image of an Object in a Convex Mirror

The position of the image of a large object can be obtained by applying the construction of Fig. 63 to the individual points of the object, but it is generally sufficient to apply the construction only to the extreme points. The image positions for each of these points (and indeed for any object point) can be determined by drawing two rays:

1. The ray parallel to the optic axis. In finding the position of the image of point A in Fig. 71 this ray is AD.
2. The ray (AC in Fig. 71) passing through the centre of curvature of the mirror.

Ray AD is so reflected that it appears to originate from the focus F; ray AC strikes the mirror normally at E and retraces its path, appearing to originate from C. Where AC meets DF gives the position of A′, the image of A. A similar construction is used to determine the position of B′, the image of B. A′B′ shows the position and size of the image; it is closer to the mirror than the object, is upright, and is smaller than the object.

The position of the image can also be determined from equation (17), but this is not very convenient for numerical calculation and a more convenient form is

$$(x + f)(f - x') = f^2 \quad .. \quad .. \quad .. \quad (19)$$

in which x, x' and f are all positive. As a numerical example,

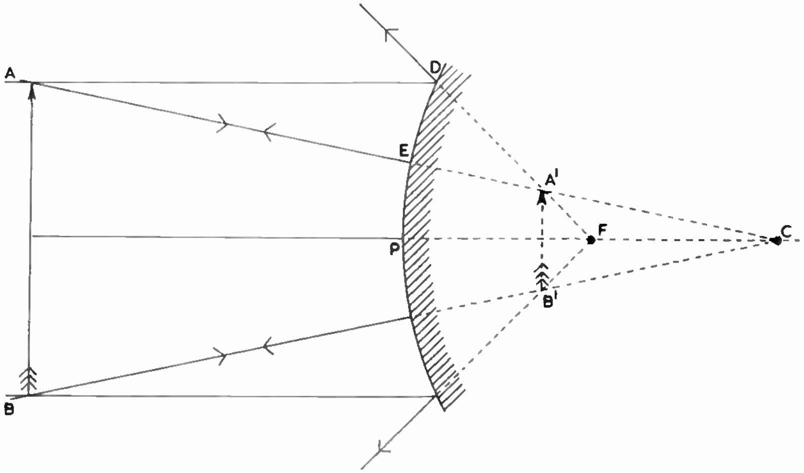

Fig. 71—Geometric construction for the position of an image in a convex mirror

suppose a convex mirror has a focal length of 5 inches and an object is situated 10 inches from the pole. The position of the image is required. Substituting in (19):

$$(10 + 5)(5 - x') = 25$$

$$\therefore \quad (x' - 5) = -1{\cdot}67$$

$$\therefore \quad x' = 3{\cdot}33 \text{ inches}$$

The image is situated 3·33 inches behind the mirror.

The *magnification* M of an optical system is the ratio of the image size to the object size and is given by x'/x; this is proved for a convex mirror in Appendix E, but is universally true. Expression (18) shows that x' must always be less than x, and it follows that the magnification of a convex mirror is always less than unity. Thus the image in a convex mirror is always situated between the pole and the focus, is upright, and is always smaller than the object. Because of the optical reduction, a convex mirror gives a wide field of view; this is perhaps its most useful property.

SUMMARY OF PROPERTIES OF A CONVEX MIRROR

The conclusions reached in the previous paragraphs can be summarized as follows:

Sign of focal length and radius of curvature . .	Both positive
Sign of object distance	Always positive
Sign of image distance	Always positive

The relative positions of object and image can be tabulated thus:

Position of Object	*Position of Image*	*Nature of Image*	*Magnification*
Finite distance in front of mirror	Between pole and focus behind mirror	Virtual, upright	Less than unity
At infinity	At focus behind mirror	—	Zero

8.8 CONCAVE MIRRORS

Reflection of Light at a Concave Mirror

The position of the image formed by a concave mirror depends on the object distance and the focal length of the mirror, and we shall first consider the image position for an object distance of infinity, i.e., when parallel light falls on the mirror as shown in Fig. 72. The reflected rays converge on a point F, known as the focus, which is situated in front of the mirror (cf. convex mirror); the distance PF is the focal length f. The focal length is thus the image distance for an object distance of infinity. Substituting $x = \infty$ and $x' = f$ in (15) we get

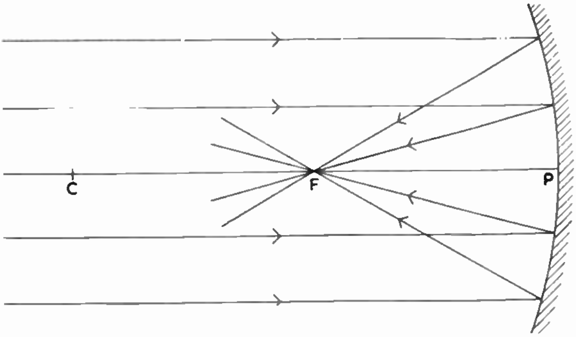

Fig. 72—Reflection of a parallel beam of light at a concave mirror

$$f = \frac{R}{2}$$

as for a convex mirror, but the radius of curvature and thus the focal length of a concave mirror are both negative, since the centre of curvature and the focus are both to the left of the pole. Equations (17) and (18) both hold for a concave mirror, but in (18), repeated here for convenience, x is positive and f negative

$$x' = \frac{xf}{x+f} \qquad \ldots \quad \ldots \quad \ldots \quad (18)$$

Real and Virtual Images

The image in Fig. 72 is different in nature from those formed by plane and convex mirrors. It is formed by a number of rays meeting at a point in space and is known as a *real image*. The images formed behind mirrors (*virtual images*) appear to exist because the directions of the reflected rays are the same as if they had originated from a point behind the mirror, although in fact there are no rays behind the mirror. The difference between the two is best illustrated perhaps by the fact that a real image can be formed on a plane surface for examination, whereas a virtual image cannot.

Variation of Image Position with Object Position for a Concave Mirror

The images given by a concave mirror are not always real; if the object is very close to the mirror a virtual image is obtained.

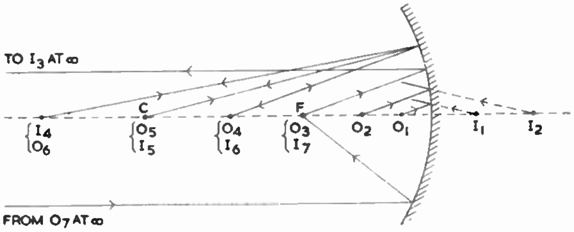

Fig. 73—Variation of image position with object position for a concave mirror

The relative positions of image and object can be deduced from equation (18) and are illustrated in Figs. 73 and 74. When x is small (i.e., when the object is near the mirror), x' is approximately equal to x and is of the same sign (i.e., the image is an equal distance behind the mirror). O_1 represents an object near the mirror in Fig. 73 and the corresponding image I_1 is at an approximately equal distance behind the mirror. As x increases, x' increases more rapidly, and an object at O_2 gives an image at a greater distance I_2 (Fig. 73). As the object approaches the focus, the image distance approaches infinity (O_3 and I_3). This relationship between object and image distance is indicated by curve OA in Fig. 74, which begins with a slope of 45 deg (indicating equality of x and x') but becomes asymptotic to $x = f$ as x' approaches infinity. For objects between the focus and the pole of the mirror (i.e., $x < f$) the image is behind the mirror and is virtual.

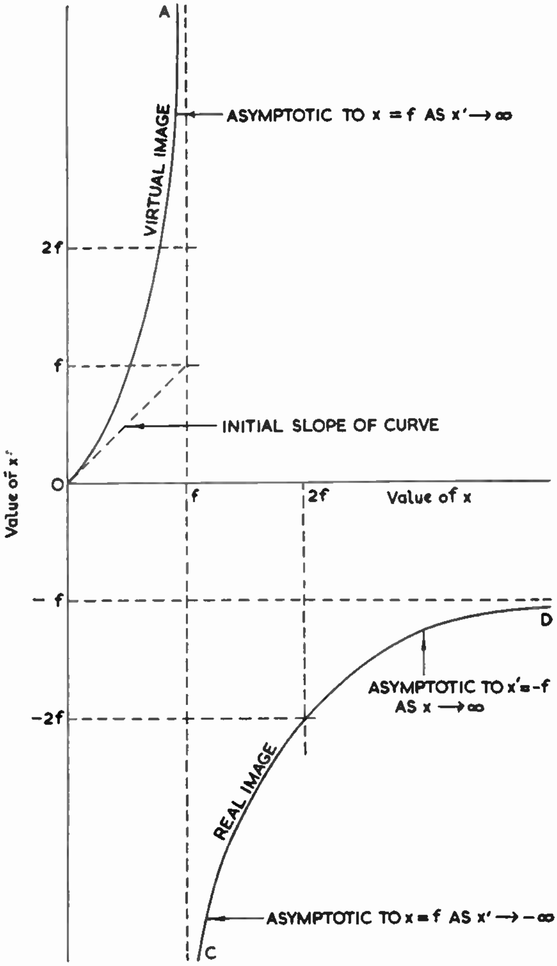

Fig. 74—Curve illustrating the relationship between object and image distance for a concave mirror

When the object is at a distance greater than the focal length ($x > f$), the denominator of expression (18) becomes positive and

x' becomes negative. The image is now in front of the mirror and is real. O_4 in Fig. 73 represents an object between the focus and the centre of curvature, giving an image at I_4. When the object is at C, rays from it strike the mirror normally and retrace their incident path to give an image coincident with the object (O_5 and I_5 in Fig. 73); this may also be confirmed by putting $x = 2f$ in equation (18) to give $x' = 2f$. For object distances exceeding $2f$, the image distance is less than $2f$ and an object at O_6 (Fig. 73) gives an image at I_6. As the object distance approaches infinity (O_7), the image position approaches the focus (I_7).

Provided x exceeds f, the relationship between x and x' is a rectangular hyperbola (Fig. 74) and object and image distances can be interchanged; for example, if an object 5 inches from the mirror gives an image 10 inches from the pole, then an object 10 inches away will give an image at 5 inches distance. This is also illustrated in Fig. 73, where O_4 and I_4 can be interchanged to give O_6 and I_6; similarly O_3 and I_3 can be interchanged to give O_7 and I_7.

Image of an Object in a Concave Mirror

(*i*) *Real Image*

The position of the image of a large object can be obtained by applying the method of Fig. 63 to the individual points of the object; depending on the position of the object relative to the focus, the image may be real and in front of the mirror or virtual and behind the mirror. The geometric construction of Fig. 71 can be used to determine the position of both types of image, and Fig. 75 shows the construction applied to the formation of a real image. The construction can be followed from the description of Fig. 71

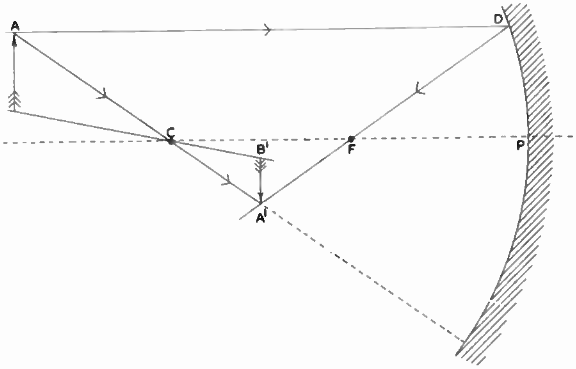

Fig. 75—Geometric construction for the position of a real image in a concave mirror

(Figs. 71, 75 and 76 being lettered similarly), but for simplicity the construction lines for B′ are not included in full in Fig. 75.

A′B′ shows the position of the image of AB; for the particular position chosen for AB the image is smaller than the object and is inverted. When x is greater than f but less than R, the image is larger than the object but is still inverted. The position of the image can be calculated from equation (19):

$$(x+f)\,(f-x') = f^2$$

As a numerical calculation, suppose a concave mirror has a focal

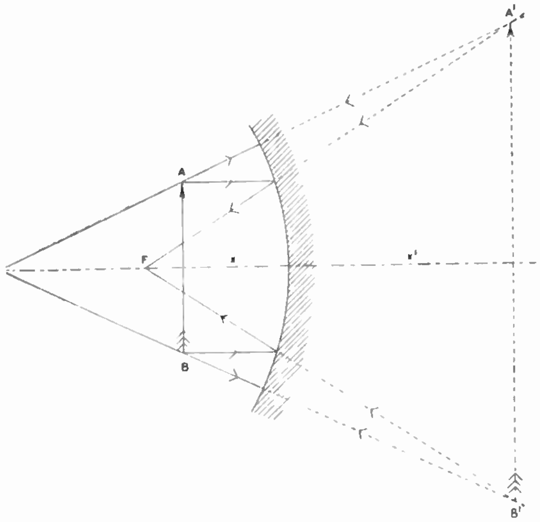

Fig. 76—Geometric construction for the position of a virtual image in a concave mirror

length of 5 inches and that an object is placed 7 inches from the pole. To find the position of the image put $x = 7$ and $f = -5$ in expression (19):

$$\begin{aligned} (7-5)(-5-x') &= 25 \\ (-5-x') &= 12{\cdot}5 \\ \therefore \qquad x' &= -17{\cdot}5 \end{aligned}$$

The image is situated 17·5 inches in front of the pole.

The magnification M of the mirror is given by x'/x as proved for the convex mirror in Appendix E, and in this example is $-17{\cdot}5/7$, or $-2{\cdot}5$ times. The negative sign prefacing M indicates that the image is inverted with respect to the object.

(*ii*) *Virtual Image*

Fig. 76 shows the construction of Fig. 71 used to determine the position of a virtual image in a concave mirror. The object is situated between the focus and the pole, and for each end A and B the usual two construction rays are drawn. The image A′B′ is behind the mirror, is upright and is larger than the object.

As an example of a numerical calculation on a concave mirror when x is less than f, suppose x is 3 inches and f is -10 inches. From (19):

$$(3-10)(-10-x') = 100$$
$$(-10-x') = -14{\cdot}3$$
$$\therefore \qquad x' = 4{\cdot}3$$

The image is hence 4·3 inches behind the mirror and the magnification is given by x'/x, i.e., 1·4 times. The magnification is positive, indicating that the image is upright.

SUMMARY OF PROPERTIES OF CONCAVE MIRROR

The conclusions reached in the previous paragraphs can be summarized as follows:

Sign of focal length and radius of curvature ..	Both negative
Sign of object distance ..	Always positive
Sign of image distance ..	Positive or negative, depending on object distance as set out below

In the following table the focus and centre of curvature are in front of the mirror unless otherwise stated:

Position of Object	*Position of Image*	*Nature of Image*	*Magnification*
Between pole and focus	Behind mirror. Distance less than focal length	Virtual, upright	Greater than unity
At focus	At infinity	—	Infinite
Between centre of curvature and focus	Between infinity and centre of curvature	Real, inverted	Greater than unity
At centre of curvature	At centre of curvature	Real, inverted	Unity
Between infinity and centre of curvature	Between focus and centre of curvature	Real, inverted	Less than unity
At infinity	At focus	—	Zero

APPLICATIONS OF CONCAVE MIRRORS

The use of concave mirrors in projecting television images is described later in this book. Another application of such mirrors is with the lamps used for illuminating television studios. In these a combination of an electric bulb and a concave mirror is used to produce a convergent, divergent or parallel beam of light. As shown above, the lamp must be at the focus of the mirror to give a parallel beam of light and must be between the focus and the pole to give a divergent beam.

If the mirror is so positioned that the lamp is at the centre of curvature, an image of the filament is formed coincident with the object. It is unwise to make this adjustment, because the concentration of heat may be sufficient to damage the filament.

8.9 ABERRATION OF SPHERICAL MIRRORS

It has been assumed that parallel light is brought to a single-point focus by a concave mirror and appears to radiate from a single-point focus when reflected at a convex mirror. This ideal is realized only approximately in practice, even if the mirror has an accurately spherical surface, the point of focus varying with the height of the ray above the optic axis as shown in Fig. 77. This effect gives rise to geometric distortion in images, and the distortion may be considerable if the incident light falls on a considerable fraction of the mirror area so that the image is formed by axial rays and rays remote from the axis. This distortion is known as *spherical aberration* and can be minimized by restricting the incident light to a small area around the pole of the mirror. The general

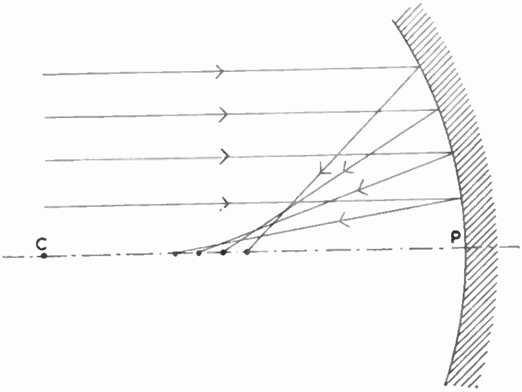

Fig. 77—Spherical aberration of a concave mirror

formula (15) was deduced on the assumption that all rays lie near the axis. An alternative method of minimizing spherical aberration is by use of mirrors with parabolic curvature, for such a surface gives accurate focusing over the entire area of its surface. Unfortunately it is difficult to manufacture parabolic mirrors, and spherical ones must generally be used.

CHAPTER 9

LENSES

9.1 INTRODUCTION

THE first step in televising a scene is the production of an optical image of the scene on the light-sensitive electrode of the camera tube, and for this purpose a lens or a combination of lenses is used; additional lenses may be used in the camera viewfinder. A knowledge of the behaviour of lenses is thus essential to the full understanding of television transmission, and the following pages give an account of the principal properties of single lenses and lens combinations.

This subject, geometric optics, has a larger scope than is immediately apparent, because the devices used to focus electron beams in cathode-ray tubes and camera tubes may also be regarded as lenses; these lenses affect the electron beam in a manner similar to that in which an optical lens affects a beam of light, and for this reason the control of electron beams has been termed *electron optics*. The following pages deal exclusively with optical lenses, and the behaviour of electron lenses is described in Chapter 10.

9.2 CONVEX LENSES

Refraction of Light at a Convex Lens

When a ray of light strikes the surface of a convex lens (Fig. 78) it is deflected towards the normal if, as may generally be assumed, the material of the lens has a refractive index greater than that of the surrounding medium. In other words, when the ray enters

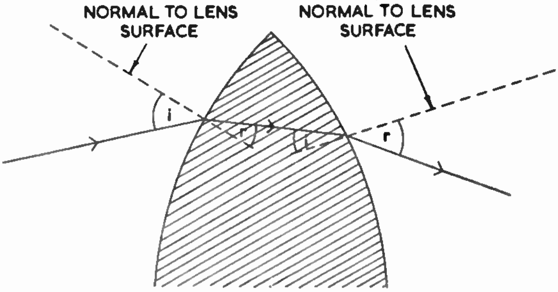

Fig. 78—Refraction of light at the two surfaces of a convex lens

the lens, the angle of incidence ($\angle i$) is greater than the angle of refraction ($\angle r$). When the ray leaves the lens it passes into a less dense medium and is deflected away from the normal. At this boundary the angle of incidence ($\angle i$) is less than the angle of refraction ($\angle r$).

Refraction of Parallel Light at a Convex Lens

When a parallel beam of light falls on a convex lens (Fig. 79), as a result of refraction at the first boundary the light inside the lens is made convergent. Refraction at the second surface further increases the convergence, and the light leaving the lens passes through a point F on the optic axis. F is the image position for an object at infinity and is known as the *focus* or *focal point* of the lens, the distance PF being the focal length. The focal length is related to the radii of curvature of the two spherical surfaces, and the relationship may be deduced as follows.

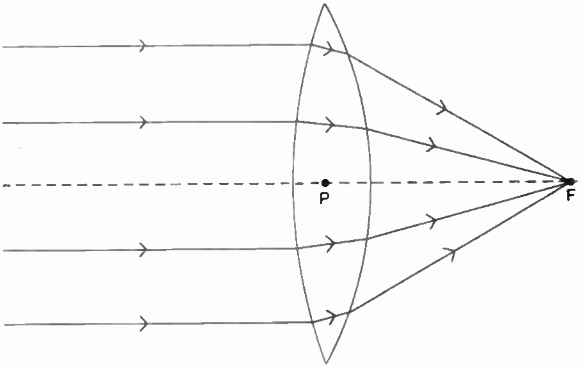

Fig. 79—Refraction of parallel light at a convex lens

Focal Length in Terms of Radii of Curvature

Fig. 80 illustrates a convex lens, assumed to be of negligible thickness. The radii of curvature of the left-hand and right-hand surfaces are R and R′ respectively. O represents a point object on the optic axis, situated at a distance x from the centre of the lens. Applying the general formula (14) to refraction at the left-hand surface of the lens, we have

$$\frac{1}{x} + \frac{n}{x_o} = \frac{n-1}{R} \qquad \ldots \quad \ldots \quad \ldots \quad (20)$$

in which the refractive index of the lens material is taken as n and that of air is taken as unity. Equation (20) gives the distance x_o

of the image I_o which would be formed if all the space to the right of the left-hand surface of the lens were occupied by material of refractive index n. All distances x, x_o and R are positive in this equation.

I_o may be regarded as the object for the right-hand surface of the lens, and as this object is to the right of the refracting surface x is now negative. Stating equation (14) for refraction at the right-hand surface:

$$\frac{-n}{x_o} + \frac{1}{x'} = \frac{1-n}{R'} \qquad \ldots \quad \ldots \quad \ldots \quad (21)$$

Combining (20) and (21):

$$\frac{1}{x} + \frac{1}{x'} = (n-1)\left(\frac{1}{R} - \frac{1}{R'}\right) \qquad \ldots \quad \ldots \quad (22)$$

in which all quantities except R' are positive.

The right-hand side of equation (22) is characteristic of the shape and material of the lens and is termed the *lens power*; its reciprocal is the focal length f. This can be deduced from equation (22) for the focal length is the image distance for an object at infinity. Substituting $x = \infty$ and $x' = f$ in equation (22):

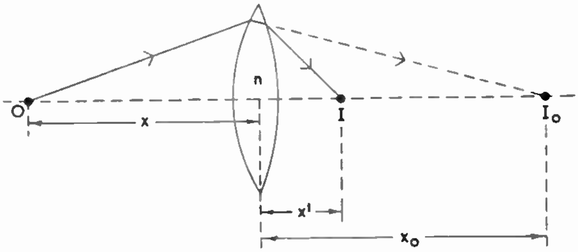

Fig. 80—Formation of an image by a convex lens

$$\frac{1}{f} = (n-1)\left(\frac{1}{R} - \frac{1}{R'}\right) \qquad \ldots \quad \ldots \quad (23)$$

In this expression R' is negative and R positive. Thus provided n is greater than unity f is always positive; for this reason convex lenses are sometimes referred to as *positive lenses*.

For most types of optical glass n is approximately 1·5, and equation (23) may be rewritten:

$$\frac{1}{f} = \frac{1}{2}\left(\frac{1}{R} - \frac{1}{R'}\right) \qquad \ldots \quad \ldots \quad (24)$$

For a symmetrical lens $R' = -R$, and hence $f = R$, that is to say, the focal length is equal to the radius of curvature. If, however, one surface of the lens is flat (such a lens is known as *plano-convex*) either R or R' is infinite, and from equation (24) the focal length is twice the radius of curvature.

Lens Equation

If equations (22) and (23) are combined:

$$\frac{1}{x} + \frac{1}{x'} = \frac{1}{f} \qquad \ldots \qquad \ldots \qquad \ldots \quad (25)$$

an equation which is similar to that for spherical mirrors (17) and applies to convex and concave lenses. Rearranging (25):

$$x' = \frac{xf}{x - f} \qquad \ldots \qquad \ldots \qquad \ldots \quad (26)$$

This equation expresses the image distance x' as a function of the object distance x and the focal length f, and in it both x and f are positive.

Variation of Image Position with Object Position for a Convex Lens

For an object at infinity the image given by a convex lens is at the focus. This is illustrated in Fig. 79 and also in Fig. 81, where O_1 is the object and I_1 its image. If the object is moved nearer the lens so that the light received by the lens is appreciably divergent, the image recedes from the lens as illustrated by O_2 and I_2 in Fig. 81, and when the object is distance f from the lens (O_3), the image (I_3) is at infinity. For objects between infinity and the focus the image is real and behind the lens, but if the object is placed between at a distance less than f from the pole the image becomes virtual and is situated on the same side of the lens as the object. Thus an object at O_4 gives a virtual image at I_4.

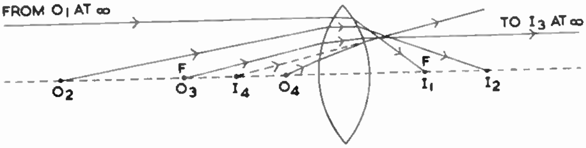

Fig. 81—Variation of image position with object position for a convex lens

This change in the nature of the image when the object distance becomes less than f can be deduced from expression (26); x and f are both positive, and as long as x exceeds f, x' will also be positive. But when x is less than f, x' becomes negative.

The relationship between x and x' is illustrated graphically in Fig. 82; this diagram bears a striking similarity to that for the concave mirror (Fig. 74).

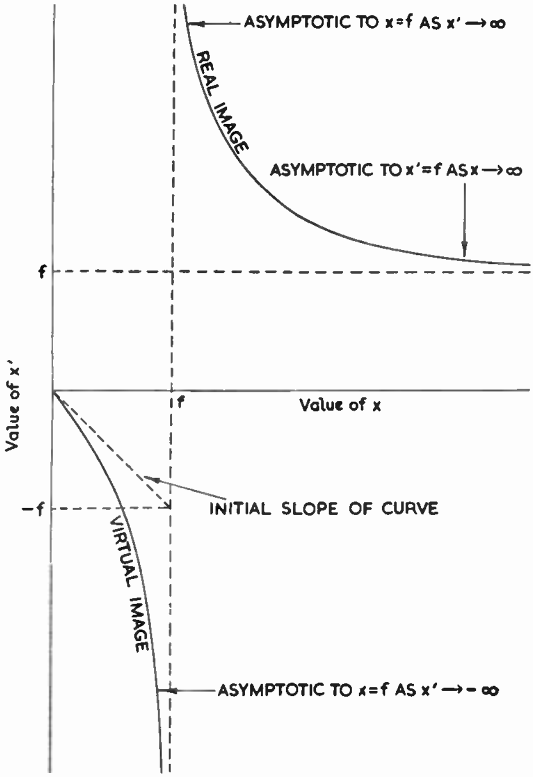

Fig. 82—Curve illustrating the relationship between object and image distance for a convex lens

Image of an Object in a Convex Lens

(*i*) *Real Image*

To find the position of the image of a large object formed by any lens it is usually sufficient to determine the position of the images of the two extreme points of the object. For any given object point the position of the image can be found by drawing in two rays only:

1. The ray travelling parallel to the optic axis; this ray is refracted so as to pass through the focus of the lens.

2. The ray which passes through the centre of the lens; this ray is undeflected because the two lens surfaces are parallel at the centre.

The intersection of these two rays gives the position of the image. This construction is somewhat similar to that used for spherical mirrors on page 141.

In Fig. 83 this construction is used to determine the position of the image of an object AB; the distance of AB from the pole of the lens exceeds f and the image is therefore real.

Ray AD is parallel to the optic axis and, after refraction, passes through F; ray AP passes through the lens centre undeflected and meets DF at A′, which gives the position of the image of A. A similar construction gives the position of B′, the image of B. Thus A′B′ is the position of the image of AB. The image is real, is inverted and is smaller than the object.

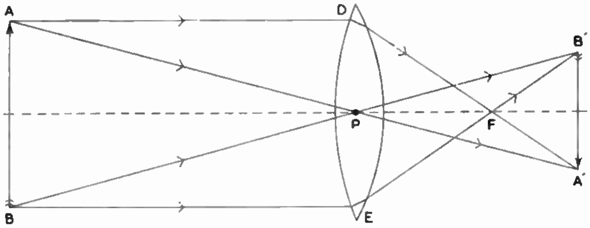

Fig. 83—Geometric construction for the position of a real image in a convex lens

As a numerical calculation we will determine the image position and optical magnification when the object distance is 2 feet and the focal length is 8 inches. For the sign convention adopted, $x = 24$ and $f = 8$. Equation (25) is not convenient for numerical substitution, and the alternative form

$$(f - x)(f - x') = f^2 \qquad \qquad (27)$$

is preferred. On substitution we have

$$(8 - 24)(8 - x') = 64$$
$$(8 - x') = -4$$
$$x' = 12$$

The image is situated 1 foot behind the lens and the magnification is given by x'/x, in this example 12/24, or 0·5 times. A positive sign prefacing the magnification here indicates an inverted image (cf. spherical mirrors).

(*ii*) *Virtual Image*

The construction of Fig. 83 is repeated in Fig. 84 to illustrate the position of the virtual image formed when x is less than f. This diagram uses the same lettering as Fig. 83, and the construction can be followed from the description given above. DF and AP must now be produced in the opposite direction to intersect at A′.

A′B′ is a virtual image, since the rays forming it *appear* to originate from A′B′. The image is upright and larger than the object. Fig. 84 illustrates the use of a convex lens as a magnifying glass.

If the focal length is 6 inches and an object is placed 2 inches from

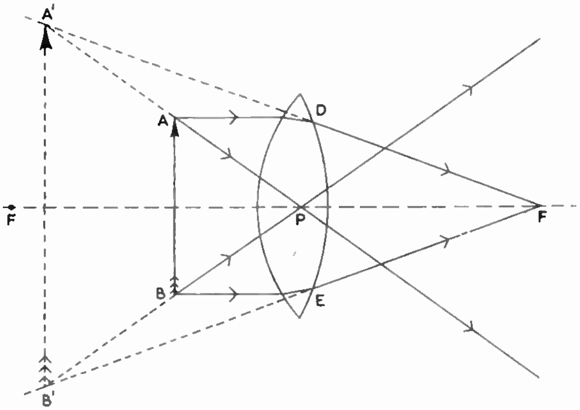

Fig. 84—Geometric construction for a virtual image in a convex lens

the centre of a convex lens the image position can be determined by putting $x = 2$ and $f = 6$ in equation (27):

$$(6 - 2)(6 - x') = 36$$
$$(6 - x') = 9$$
$$x' = -3$$

The image is hence situated 3 inches to the left of the lens and the magnification is given by $x'/x = -3/2 = -1{\cdot}5$ times. The negative sign indicates that the image is upright.

SUMMARY OF PROPERTIES OF A CONVEX LENS

The conclusions of the last few paragraphs may be summarized as follows:

Sign of focal length	Positive
Sign of radius of curvature of incident surface	Positive
Sign of radius of curvature of other surface ..	Negative

In the following table the image is assumed to be on the side of the lens remote from the incident light unless otherwise stated.

This table is similar to that for the concave mirror (page 148).

Position of Object	*Position of Image*	*Nature of Image*	*Magnification*
Between pole and focus	Between pole and infinity on object side	Virtual, upright	Greater than unity
At focus	At infinity	—	Infinite
Between focus and twice focal length	Between infinity and twice focal length	Real, inverted	Greater than unity
At twice focal length	At twice focal length	Real, inverted	Unity
Between infinity and twice focal length	Between focus and twice focal length	Real, inverted	Less than unity
At infinity	At focus	—	Zero

9.3 CONCAVE LENSES

Refraction of Light at a Concave Lens

When a ray of light strikes the surface of a concave lens (Fig. 85), it is deflected towards the normal if, as may generally be assumed, the lens material has a refractive index greater than that of the surrounding medium. In other words, when the ray enters the lens, the angle of incidence ($\angle i$) is greater than the angle of refraction ($\angle r$). When the ray leaves the lens, it passes into a less dense medium and is deflected away from the normal. At the boundary the angle of incidence ($\angle i$) is less than the angle of refraction ($\angle r$).

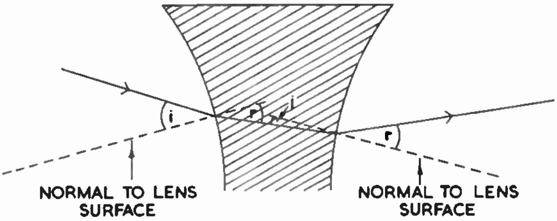

Fig. 85—Refraction of light at the two surfaces of a concave lens

Refraction of Parallel Light at a Concave Lens

When a parallel beam of light falls on a concave lens (Fig. 86) as a result of the refraction at the first boundary, the light inside the lens becomes divergent. Refraction at the second surface further increases this divergence in the light leaving the lens. Thus the light emerging from the lens behaves as if it had originated from a point F on the optic axis and to the left of the lens. F may thus be regarded as the position of the virtual image of an object at

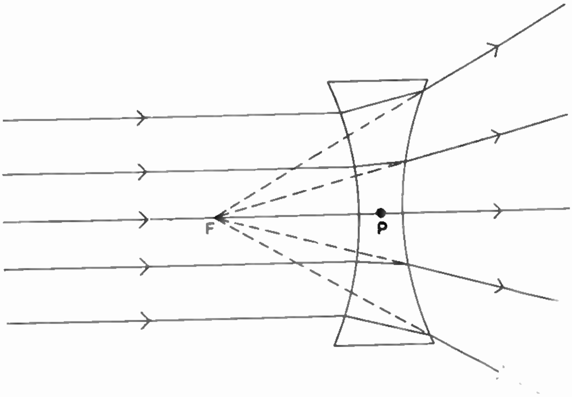

Fig. 86—Refraction of parallel light in a concave lens

infinity and is known as the *focus* or *focal point* of the lens, the distance PF being the focal length.

The focal length is related to the radii of curvature according to equation (20):

$$\frac{1}{f} = (n - 1)\left(\frac{1}{R} - \frac{1}{R'}\right)$$

in which R, the radius of curvature of the left-hand surface, is negative and R', the radius of curvature of the right-hand surface, is positive. Provided n exceeds unity, which is usually true in practice, f for a concave lens is always negative; for this reason concave lenses are sometimes referred to as negative lenses.

For most types of optical glass n is approximately 1·5, and equation (23) may be written

$$\frac{1}{f} = \frac{1}{2}\left(\frac{1}{R} - \frac{1}{R'}\right)$$

For a symmetrical lens $R = -R'$ and $f = R$, that is to say the focal length is equal to the radius of curvature. If, however, one surface of the lens is flat (such a lens is known as *plano-concave*), either R or R' is infinite and from the above equation the focal length is twice the radius of curvature.

Lens Equation

The lens equation

$$\frac{1}{x} + \frac{1}{x'} = \frac{1}{f}$$

holds for concave lenses, but in it f is negative. The equation may be rearranged in the following form:

$$x' = \frac{xf}{x - f}$$

from which it can be seen that for objects on the left of the lens the denominator is always positive and x' is always negative. For very small values of x, x' is approximately equal to x; that is to say, when the object is near the pole, the image is the same distance from the pole and tends in fact to coincide with the object. As object distance is increased the image distance tends to f and the magnification is asymptotic to zero.

Variation of Image Position with Object Position for a Concave Lens

For an object situated at infinity, a concave lens produces an image at the focus. This is illustrated in Fig. 86 and also Fig. 87,

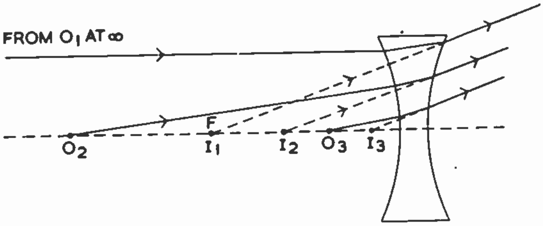

Fig. 87—Variation of image position with object position for a concave lens

in which O_1 is the object at infinity and I_1 the image at the focus. A somewhat nearer object O_2 gives an image at I_2, nearer the pole, and as the object approaches the lens, the image tends to coincide with it. This is illustrated by object O_3, which has an image I_3 only slightly displaced from it.

The relationship between object and image distance is also illustrated by the curve of Fig. 88. The initial part of this has a slope of 45 deg, indicating that the image distance is approximately equal to the object distance provided the latter is small; since the image distance is negative this implies that the image approximately coincides with the object for small object distances.

The curve becomes asymptotic to $x' = -f$ as x approaches infinity, showing that the image position tends to the focus as the object distance is made very great. This curve is similar to that for the convex mirror (Fig. 68).

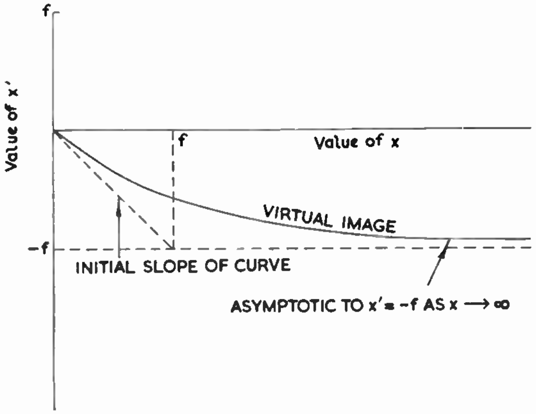

Fig. 88—Curve illustrating the relationship between image and object position for a concave lens

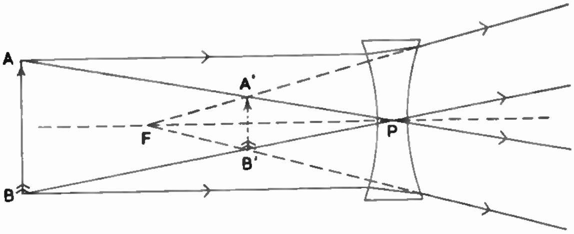

Fig. 89—Geometric construction for a virtual image in a concave lens

Image of an Object in a Concave Lens

The geometric construction of Fig. 83 can be applied to a concave lens as shown in Fig. 89. The lettering is the same as for Figs. 83 and 84 and the construction can be followed from the description on page 155. The image A′B′ is virtual, upright and smaller than the object.

This can be checked by calculation, for suppose the focal length is 10 inches and the object is situated 5 inches from the pole. According to the sign convention, $f = -10$ and $x = 5$. Substituting in equation (27):

$$(-10-5)(-10-x') = 100$$
$$(-10-x') = -6{\cdot}7$$
$$x' = -3{\cdot}3$$

The image is situated 3·3 inches to the left of the lens and the magnification is x'/x, i.e., 3·3/5, or 0·67.

SUMMARY OF PROPERTIES OF A CONCAVE LENS

The conclusions of the last few paragraphs may be summarized as follows:

Sign of focal length of a concave lens ..	Negative
Sign of radius of curvature of incident surface ..	Negative
Sign of radius of curvature of other surface ..	Positive

In the following table the image is assumed to be on the same side of the lens as the incident light.

Position of Object	*Position of Image*	*Nature of Image*	*Magnification*
Between pole and focus	Between pole and focus	Virtual, upright	Less than unity
At infinity	At focus	—	Zero

9.4 LENS COMBINATIONS

Lenses are often used in pairs, and it is necessary to know the effective focal length of a lens combination, such as that shown in Fig. 90, which consists of two convex lenses separated by a distance d. The focal length can be determined by use of equation (25) and by the same argument which was used in deducing this equation. The equation is first used to determine the position of

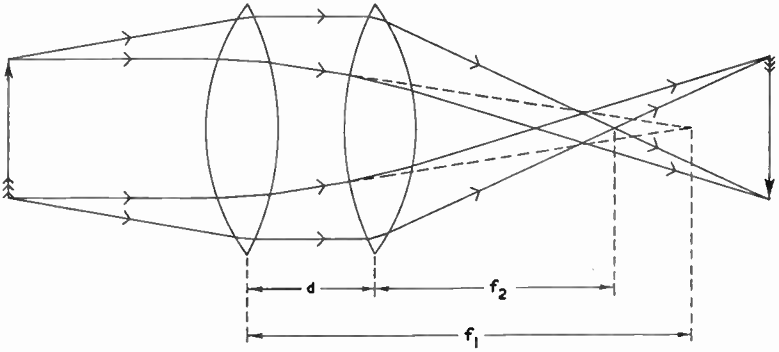

Fig. 90—Simple lens combination

the image formed by the left-hand lens; this image may be regarded as the object for the right-hand lens, and the position of the final image can be determined from a second application of equation (25). If in the expression finally obtained the object distance is made infinite, the distance of the final image from the right-hand lens gives the effective focal length of the combination f as:

$$\frac{1}{f}=\frac{1}{f_1}+\frac{1}{f_2}-\frac{d}{f_1 f_2} \quad \ldots \quad \ldots \quad \ldots \quad (28)$$

in which f_1 and f_2 are the focal lengths of the lenses.

If both lenses are convex, as in Fig. 90, increase in the separation between the lenses increases the effective focal length; but if one lens is convex and the other concave, f_1 and f_2 are of opposite sign, and increase in the separation decreases the effective focal length. If the two lenses are in contact, $d = 0$ and the effective focal length becomes

$$\frac{1}{f}=\frac{1}{f_1}+\frac{1}{f_2} \quad \ldots \quad \ldots \quad \ldots \quad (29)$$

First and Second Principal Points

A lens combination has a definite focal length and could be replaced by a single lens which would behave similarly in respect of image size, nature and position. With a lens system which occupies considerable axial length the term *pole* is difficult to interpret, and measurements of object and image distances are generally made with respect to principal points which are defined as follows. If a parallel beam of light falls on a lens combination from the left, the emergent light is brought to a focus (or appears to diverge from a focus) at F_2 (Fig. 91), known as the *second focal point*, and if the incident and emergent rays are continued inside the lens system they meet to form an equivalent refracting surface

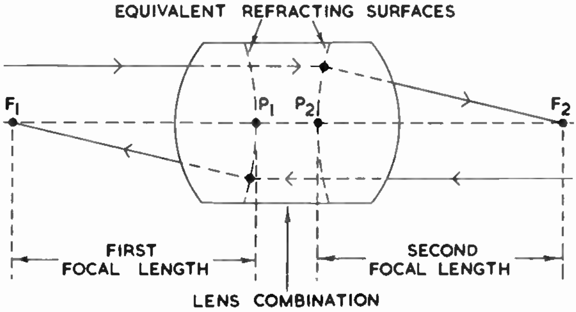

Fig. 91—First and second focal points and principal points

which intersects the optic axis at P_2, the *second principal point*. Similarly if parallel light enters the lens system from the right, it is brought to a focus (or appears to diverge from a focus) at F_1, the *first focal point*, and the equivalent refracting surface meets the optic axis at P_1, the *first principal point*.

The distance between the first principal and first focal points is

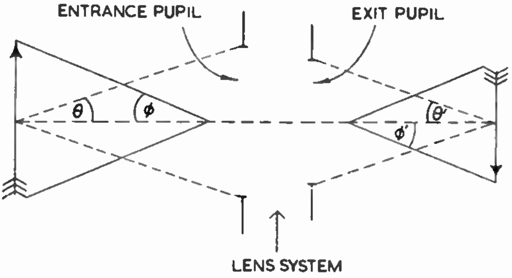

Fig. 92—Distinction between θ, θ', ϕ and ϕ'

the *first focal length*; similarly the distance between the second principal and second focal points is the *second focal length*. Provided the medium to the left and to the right of the lens system has the same refractive index (and this is usually true), the first and second focal lengths are equal. With the same proviso it is also true that the angle ϕ (Fig. 92) made between an object ray and the optic axis at the first principal point is equal to ϕ', the angle between the corresponding image ray and the optic axis at the second principal point. For this reason it is common practice to represent optical systems in a simplified form by showing only the two rays which originate from extremities of the object and pass through the first principal point; however complex the lens system, it is usually represented as a single convex lens and the two object rays are continued through the centre of the lens to become the corresponding image rays, thus ensuring that ϕ equals ϕ', as shown in Fig. 93. This is the way in which the optical systems of the various types of camera tubes were represented in Part II of this book.

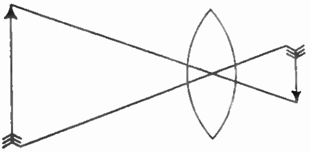

Fig. 93—Simplified method of indicating a lens system

9.5 Limitation of Light Beams

In all lens systems there is some feature known as an *aperture* or *stop* which limits the cross-section of the light beam and controls the brightness of the image. In photographic and television cameras the light is usually controlled by an iris diaphragm, the aperture of which may be varied within wide limits. Such a diaphragm may be situated between two elements in a lens combination as illustrated in Fig. 95 or may be situated before or behind the lens in a single-lens optical system (Fig. 94).

The way in which the stop operates is illustrated in Fig. 94, which shows a convex lens receiving parallel light. If there is no stop the lens is filled with light and all parts of the lens transmit light to the image at F (Fig. 94 (*a*)); when the stop is present only light striking the lens near its centre succeeds in reaching the image space (Fig. 94 (*b*)). The effective diameter of the light beam entering the lens is d_1 in Fig. 94 (*a*) but only d_2 in Fig. 94 (*b*).

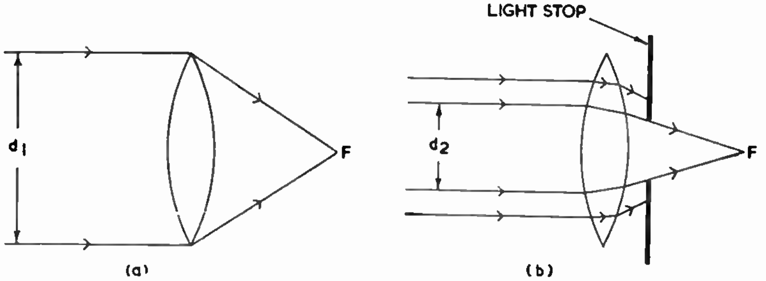

Fig. 94—Effect of a light stop on image illumination. A lens without a stop is shown at (a) and with a stop at (b)

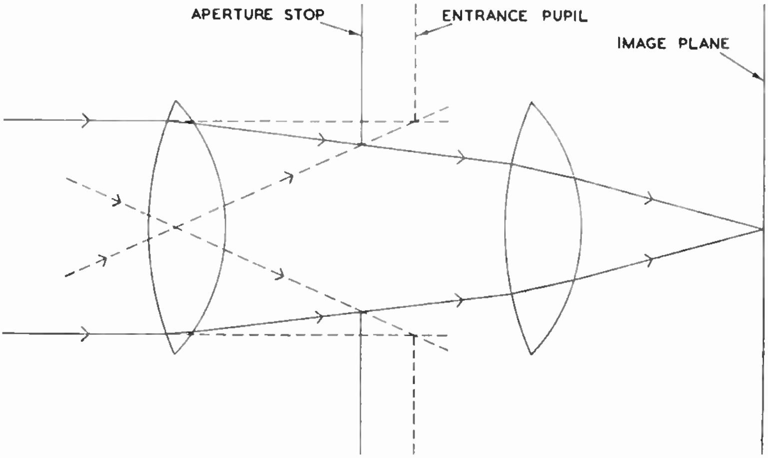

Fig. 95—Entrance pupil of a lens combination

Lenses of long focal length sometimes have no iris diaphragm, and the light cross-section is limited by the rim of the lens itself or by a fixed stop forming an integral part of the lens.

The image of the aperture stop as seen from the object space by all the lenses preceding the stop is known as the *entrance pupil* of the optical system, and, as shown in Fig. 95, is not in general equal to the diameter of the opening of the iris diaphragm. The image of the aperture stop as seen from the image space by all the lenses behind the stop is known as the *exit pupil*. For a single lens without a diaphragm the entrance pupil is equal to the exit pupil and to the diameter of the lens itself.

Aperture Number

The amount of light traversing an optical system of the type used in photographic and television cameras, where the object distances are large, is determined by the diameter of the entrance pupil and is usually expressed by the *aperture number* or *aperture ratio*, which is defined as the ratio of the focal length of the system to the diameter of the entrance pupil:

$$\text{aperture ratio} = \frac{\text{focal length}}{\text{diameter of entrance pupil}} \quad .. \quad (30)$$

This may be rearranged:

$$\text{diameter of entrance pupil} = \frac{\text{focal length}}{\text{aperture ratio}} \quad .. \quad (31)$$

The expression on the right-hand side of equation (30) is usually expressed in the form of a fraction of the type f/n, where n is a number; this fraction is known as an *f-number*. For example, if an iris setting is specified as $f/4{\cdot}5$, the focal length is 4·5 times the diameter of the entrance pupil, and if the lens has a focal length of 6 inches, the diameter of the entrance pupil is $6/4{\cdot}5 = 1{\cdot}33$ inches.

Lenses are usually specified by stating their focal length and maximum aperture number, i.e., the aperture number when the light beam is limited by the maximum diameter of the iris diaphragm or the diameter of the lens itself. For example, a lens for a standard Emitron tube has $f = 6{\cdot}5$ inches and the maximum aperture number is $f/3$; the lens diameter is thus 6·5/3, or approximately 2·2 inches.

The illumination falling on a photographic plate or the light-sensitive electrode of a television camera at the centre of the image field is given by

$$E = \tau B \sin^2 \theta' \quad .. \quad .. \quad .. \quad (32)$$

where E is the illumination in lumens per square foot, τ is the transmission of the lens system (and is equal to unity for a perfect system), B is the brightness of the object in foot-lamberts and $2\theta'$ is the maximum angle subtended by the emergent light at the image plane (Fig. 96).

This expression is derived in Appendix F; it was assumed in the calculation that the object obeys Lambert's law of emission or reflection of light (Appendix C). The expression shows that the illumination on the light-sensitive surface of a photographic or television camera does not depend on the value of θ or the distance of the object but only on the brightness of the object and the slope of the emerging ray. When the object distance is doubled, θ' is halved and the light entering the lens system falls to one-quarter of its original value; the image is, however, only half its original size (i.e., has one-quarter the area) and hence the illumination is the same.

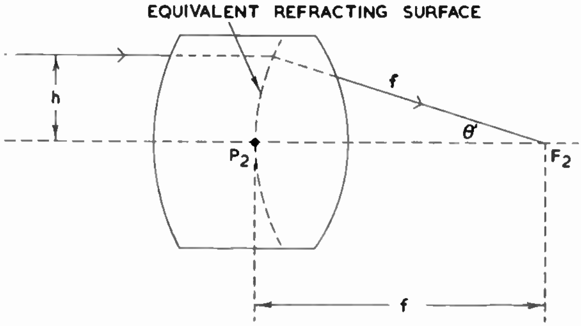

Fig. 96—Calculation of *f*-number of a lens combination

Expression (32) for image illumination includes θ', half the angle subtended by the exit pupil at the image plane. As shown in Appendix F, this angle is related to θ, half the angle subtended by the entrance pupil at the object plane. These angles θ and θ' should not be confused with ϕ and ϕ', which represent respectively the angles subtended by an object at the principal point and the image at the principal point. The distinction is made clear in Fig. 92.

9.6 VARIATION OF ILLUMINATION OVER IMAGE PLANE

The illumination over the image plane is not uniform but has a maximum at the centre of the image and falls off towards the edges of the image. The illumination at any point in an image is equal to $\cos^4 \phi'$ times the illumination at the centre, where ϕ' is the angle between the optic axis and the line joining the point in question to the centre of the lens system. Thus the general expression for the illumination at any point in an image is

$$E = \tau B \sin^2 \theta' \cos^4 \phi' \qquad \ldots \qquad \ldots \quad (33)$$

There are three main causes for this variation in illumination:

(*a*) The distance of a point at the edge of the image from the lens centre is equal to $1/\cos \phi'$ times the distance of the image centre to the lens. Illumination varies inversely as the square of the distance, and thus the illumination at the edge of the image is $\cos^2 \phi'$ times that at the centre. This accounts for a term in $\cos^2 \phi'$ in expression (33).

(*b*) The light travelling to a point at the edge of the image passes through the lens aperture at an angle ϕ' to the lens axis and the beam cross-section is $\cos \phi'$ times that which would pass through the aperture along the lens axis. This accounts for a term in $\cos \phi'$ in the above expression.

(*c*) The light reaching a point at the edge of the image falls on the image plane at an angle ϕ' to the lens axis and therefore covers a larger area than it would at the centre of the image. This accounts for a second term in $\cos \phi'$ in the above expression.

Expression (33) gives an optimistic estimate of the relative illumination at the edge of the image field because it neglects the following two factors which also tend to reduce edge illumination:

(*a*) The transmission coefficient τ which was assumed constant in expression (33) is less for light rays passing through the lens obliquely than for rays travelling normally. Oblique rays have a longer glass path and therefore suffer greater absorption than normal rays.

(*b*) Some of the rays travelling obliquely through the lens at, or near, full aperture are partially obstructed by the periphery of some of the lens components, an effect known as *vignetting*. The loss in edge illumination due to vignetting varies with different types of lens and, by careful design, can be almost eliminated. It can always be eliminated by reducing the lens aperture.

Provided the image does not subtend too large an angle at the lens centre, this variation in image illumination is not serious. For example, if the diagonal of the image subtends 20 deg at the lens, the illumination at the corners is $\cos^4 10^\circ = 0{\cdot}94$ times that at the centre; such a small reduction in illumination would not be detectable by the eye. It is usually justifiable to assume that the illumination is uniform over the image area and equal to its value at the centre given by expression (32).

9.7 Light-gathering Capacity of a Lens

(*i*) *When Image Size is Fixed*

For a given image size, i.e., for a particular television camera tube, the aperture ratio of a lens system is a true measure of its light-gathering capacity; this may be shown in the following way. For a perfect lens system the equivalent refracting surface is a sphere of radius f centred on the focal point, and thus in Fig. 96

$$\frac{h}{f} = \sin \theta'$$

where h is the height of the incident ray above the optic axis and θ' is the slope of the emergent ray. If the incident ray just grazes the boundary of the light-limiting aperture, $h = d/2$, where d is the diameter of the entrance pupil, and the above equation may be rewritten:

$$\frac{d}{2f} = \sin \theta' \qquad \ldots \quad \ldots \quad \ldots \quad (34)$$

This is only true for objects so distant from the lens that the light from them may be considered as parallel to the optic axis. From equations (32) and (34):

$$E = \frac{\tau B}{4(f\text{-number})^2} \qquad \ldots \quad \ldots \quad \ldots \quad (35)$$

Thus for a given image size and provided the object distance is great, the illumination of the image depends only on the transmission of the lens, the brightness of the object and the f-number. When one lens is exchanged for another, the image illumination will remain constant provided the lens stops are adjusted to give the same aperture number.

To obtain a practical estimate of the ratio of image illumination to subject brightness, suppose that the aperture number of a lens is $f/8$ and the transmission is 0·80. Substituting in (35):

$$\frac{E}{B} = \frac{0{\cdot}80}{4 \times 8^2} \simeq \frac{1}{300}$$

Thus if the object brightness is 100 foot-lamberts, the image illumination is 0·33 lumen per square foot.

Expression (35) shows that the illumination varies inversely as the square of the f-number; the illumination is thus doubled by decreasing the f-number by $\sqrt{2}$ times and is halved by increasing it by $\sqrt{2}$ times. Thus a lens adjusted to $f/5{\cdot}6$ will give twice the illumination of one set to $f/8$; from the above calculation, if the object brightness is 100 foot-lamberts, a lens of *f*/5·6 will give an image illumination of 0·67 lumen per square foot.

The aperture control of an iris diaphragm is usually calibrated in steps such that each step represents an increase or decrease of aperture ratio by $\sqrt{2}$ times and a corresponding doubling or halving of image illumination. The stops may be marked *f*/1·4, *f*/2·0, *f*/2·8, *f*/4, *f*/5·6, *f*/8, *f*/11, *f*/16 and *f*/22, but intermediate values such as *f*/3·5 and *f*/4·5 are also indicated sometimes. The greatest possible aperture ratio is *f*/0·5; this can be deduced from expression (34), for maximum aperture occurs when $\theta' = \pi/2$ and $\sin \theta' = 1$; the diameter of the entrance pupil is then equal to $2f$ and the aperture ratio is *f*/0·5. In practice lenses are not usually manufactured with an aperture ratio greater than *f*/1·5.

(*ii*) *When Image Size is Not Fixed*

It is sometimes necessary to compare the amount of light transmitted through two lenses of different focal lengths and different *f*-numbers when they are producing images of different size. Such a comparison is necessary in assessing the performances of two different types of television camera tube with different sizes of light-sensitive surface.

For a fair comparison it must be assumed that both lenses give the same field of view, i.e., the value of ϕ (Fig. 92) is the same for both lenses. From this it follows that ϕ' is also the same for both lenses. If for simplicity we assume both images to be at the focal points of their respective lenses, Fig. 92 shows that the width (and height) of the images are in the same ratio as the focal lengths. The image areas are thus directly proportional to the square of the focal lengths. Further information on this topic will be found later under the heading " Angular Field of a Lens System."

The illumination of an image is given by expression (35):

$$E = \frac{\tau B}{4\,(f\text{-number})^2}$$

and the total light flux transmitted through the lens is thus given by

$$F = EA = \frac{\tau BA}{4\,(f\text{-number})^2}$$

where A is the image area. A is, however, proportional to the square of the focal length. Thus

$$F \propto \frac{\tau B f^2}{(f\text{-number})^2}$$

If we assume the lenses to have the same transmission and the objects the same brightness

$$F \propto \frac{f^2}{(f\text{-number})^2}$$

But, from (31)

$$f\text{-number} = \frac{f}{\text{diameter of entrance pupil}}$$

$$\therefore \qquad F \propto (\text{diameter of entrance pupil})^2 \qquad \ldots \qquad \ldots \quad (36)$$

Thus if the image area is always directly proportional to the square of the focal length, the amount of light traversing the lens depends only on the absolute diameter of the entrance pupil. To compare the light-gathering capacity of two lenses with different focal lengths and different relative apertures it is necessary to compare the squares of the absolute diameters of the entrance pupils.

Expression (36) can also be deduced from first principles in the following way. The amount of light received by a given lens from a given point of an object is determined by the solid angle subtended by the entrance pupil at the point in question. Thus if two lenses are situated at the same distance from the object, the light flux entering each is directly proportional to the area of the respective entrance pupil. The object will in fact be composed of a large number of points, and the amount of light received by a lens depends on the number of points included in the lens field of view. If, however, the two lenses have the same angular field and are at the same distance from the object the same number of object points will appear in each lens field, and it will still be true that the amount of light is directly proportional to the area of the entrance pupil, i.e., to the square of the diameter of the entrance pupil.

As a numerical example we will compare the light-gathering capacities of the lens of the standard Emitron tube ($f = 6{\cdot}5$ inches, aperture $f/3$) with that of an image iconoscope ($f = 2$ inches, aperture $f/2$).

The diameter of the entrance pupil is $6{\cdot}5/3 \simeq 2{\cdot}2$ inches for the standard Emitron tube and $2/2 = 1$ inch for the image iconoscope tube. The light transmitted by the standard Emitron lens therefore exceeds that transmitted by the other by a factor of approximately $2{\cdot}2^2$, or nearly 5 times.

9.8 Circles of Confusion

In general a lens forms a three-dimensional image of a three-dimensional object, but for any image plane only the points in one

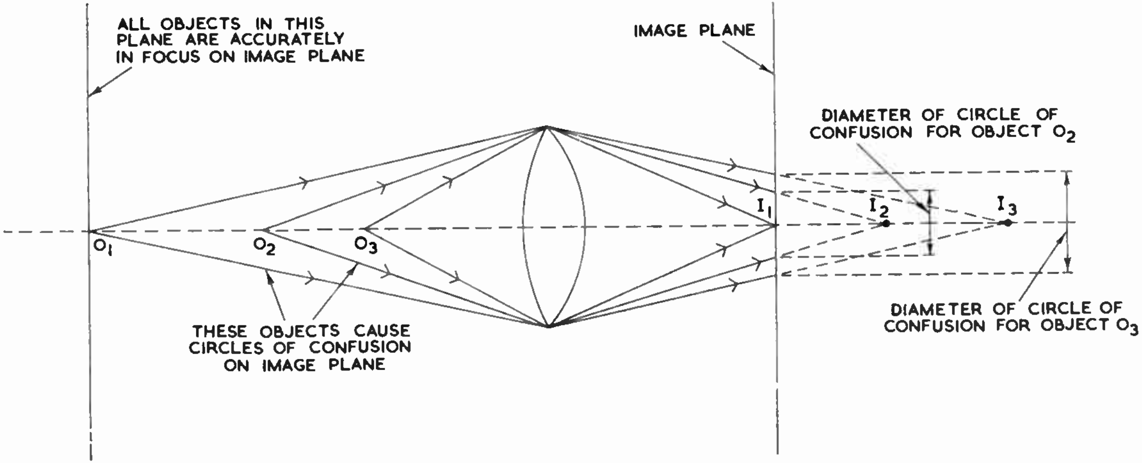

Fig. 97—Formation of circles of confusion

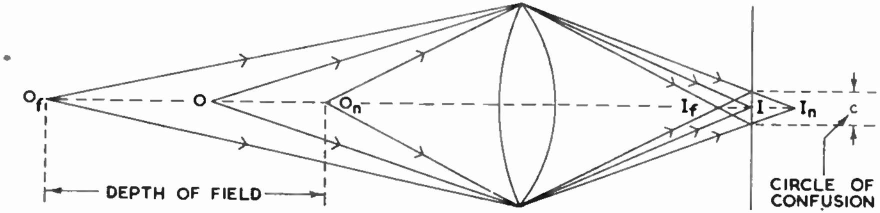

Fig. 98—Depth of field of a lens

particular object plane are accurately in focus. Objects remote from this object plane may not be visible at all in the image or, if they can be seen, are so much out of focus as to be unrecognizable. Objects near the object plane give images which are only slightly blurred, points being reproduced as circles which are known as *circles of confusion.* The formation of a circle of confusion is illustrated in Fig. 97. O_1 is a point object, and the lens forms an image of it at I_1. A plane at right angles to the optic axis at I_1 will form sharp images of all points in a similar plane at O_1. The lens is said to be focused on O_1, and points not in the plane through O_1 will give blurred images. For example, the light from a point object O_2 will, in the absence of the image plane, form a sharp image at I_2, but if the light is intercepted by the plane, the image has the form of a circle of confusion. Similarly a point object at O_3 farther from O_1 forms a larger circle of confusion on the image plane. This illustrates the generalization that the diameters of circles of confusion increase as the object forming them is moved farther from the object plane. If a circle of confusion subtends an angle of less than 1 minute at the eye, it cannot be resolved by the eye and the image appears in focus, but if the circle is larger than the critical value, the image will appear out of focus; in photography the upper limit to the diameter of the circle of confusion is usually set by the requirement that the circle should not be resolvable by the eye. Photographers often take 0·1 mm as the maximum value for a circle of confusion: this subtends an angle of 1 minute at a distance of 12 inches. If, however, it is intended to enlarge a photographic print it is usually necessary to confine the diameter of circles of confusion on the original negative to a smaller value—say 0·025 mm.

In a television system the smallest detail that can be resolved has the size of an element, and the greatest circle of confusion that can be tolerated may be taken as equal to the size of an element on the photo-sensitive electrode of the television camera; in a camera tube having a target 1·4 inches by 1·8 inches, such as the C.P.S. Emitron tube, the circle of confusion is hence 0·0035 inch (approximately 0·09 mm) diameter for a 405-line system. For the standard Emitron tube, which has a mosaic approximately 4 inches by 5¼ inches, the circle of confusion is 0·01 inch diameter.

9.9 DEPTH OF FIELD

The total distance through which an object may move along the axis of a lens before the circle of confusion exceeds the critical value is known as the *depth of field* and is illustrated in Fig. 98.

The image of object O is at I, but if the object moves to O_n (nearer the lens) the image moves to I_n, giving rise to a circle of confusion of diameter c on the image plane through I; if the object moves to the far point O_f the image moves to I_f and gives rise to a circle of confusion of the same diameter in the plane through I. The distance O_nO_f is the depth of field, and it depends primarily on the diameter of circle of confusion that can be tolerated, increasing with increase in circle diameter, but the properties of the optical system also affect the depth of field, as explained later.

If the distance x of an object plane from a lens is related to the distance x' of an image plane according to expression (25), all objects in the object plane give sharp images in the image plane. Object and image distances which are related in this way are termed *conjugate*. If x and x' do not satisfy expression (25) (i.e., are not conjugate, point objects give images in the form of circles of confusion.

Calculation of Depth of Field of a Lens System

If a lens system is adjusted to give an accurately focused image of an object distant x_1 from the lens, the distance d_1 through which the object can be moved towards the lens along its axis before the diameter of the circles of confusion exceeds c is given by

$$d_1 = \frac{cx_1}{Md + c} \qquad \ldots \quad \ldots \quad \ldots \quad (37)$$

where M is the magnification of the lens and d is the diameter of the entrance pupil.

The distance d_2 through which the object may be moved along the lens axis away from the focused plane for a circle of confusion of the same diameter is given by

$$d_2 = \frac{cx_1}{Md - c} \qquad \ldots \quad \ldots \quad \ldots \quad (38)$$

The depth of field is the total distance $(d_1 + d_2)$ through which the object may be moved while keeping the circles of confusion within tolerance:

$$\text{depth of field} = d_1 + d_2 = \frac{2cx_1Md}{M^2d^2 - c^2} \qquad \ldots \quad (39)$$

Equations (37), (38) and (39) are all deduced in Appendix G. The depth of field is directly proportional to the object distance x_1 and is very large at great object distances; normally, therefore, depth-of-field considerations are only important relatively close to the lens. For such small object distances Md considerably exceeds c and equation (39) may be simplified to

$$\text{depth of field} = \frac{2cx_1}{Md} \qquad \ldots \qquad \ldots \quad (40)$$

Depth of Field of Standard Emitron Camera

From (40) we can determine the depth of field for a standard Emitron camera. We shall assume c to be 0·01 inch, x_1 to be 60 inches (5 feet), f to be 6·5 inches and d to be 2·2 inches (equivalent to maximum aperture). The value of M can be obtained from the expression x'_1/x_1, x'_1 being calculated from equation (26). For $x_1 = 60$, x'_1 is 7·29 inches and M is 7·29/60. Substituting in (40):

$$\text{depth of field} = \frac{2 \times 0{\cdot}01 \times 60^2}{7{\cdot}29 \times 2{\cdot}2} = 4{\cdot}5 \text{ inches}$$

This is a very restricted depth of field; it implies, for example, that in an image of a face all features cannot be equally in focus.

The extent to which a television picture can be defocused before the loss of detail becomes obvious to the viewers depends on the nature of the picture; considerably greater defocusing is tolerable in a picture of a human face in close-up than in a reproduction of a resolution pattern containing fine detail.

We shall assume that the greatest circle of confusion tolerable has the size of a picture element, although, on the basis of some subjective tests, de Vore and Iams* suggest that it should have a diameter of $h/200$, where h is the picture height. On this basis the circle of confusion for a 405-line system has a diameter equal to the thickness of two scanning lines.

This calculation shows that very little latitude of object movement along the lens axis is possible with this camera before detail is lost due to the formation of circles of confusion.

Depth of Field of C.P.S. Emitron Camera

We will calculate the depth of field obtained with a C.P.S. Emitron camera for $f = 2{\cdot}5$ inches and an aperture ratio of $f/5{\cdot}6$, values typical of those used in a television studio, and to facilitate comparison with the result for the standard Emitron tube given above the depth of field will be determined for the same object distance, 5 feet. The relative values of focal length and mosaic width are such that the angular field of view is approximately the same as for the standard Emitron. The C.P.S. Emitron tube has

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* H. B. de Vore and H. Iams, " Some Factors affecting the Choice of Lenses for Television Cameras." *Proc. I.R.E.*, Vol. 28, No. 8, August 1940.

a small mosaic, and the value of c mentioned above (0·003 inch) will be used in the calculation. To obtain an approximate result we shall assume the image to be at the focus; M is thus $2{\cdot}5/60$. The aperture d is given by $f/5{\cdot}6 = 2{\cdot}5/5{\cdot}6 = 0{\cdot}446$. Substituting in (40):

$$\text{depth of field} = \frac{2 \times 0{\cdot}003 \times 60^2}{0{\cdot}446 \times 2{\cdot}5}$$

$$= 19{\cdot}35 \text{ inches}$$

For the standard Emitron camera the depth of field was 4·5 inches.

Depth of Field in Television Cameras Generally

Equation (40) shows that the depth of field is directly proportional to the diameter of the circle of confusion and to the object distance but is inversely proportional to the magnification and the diameter of the entrance pupil. In practice, however, these factors are interdependent, and if it is desired to obtain an image of a given size and illumination from an object of given size and brightness the depth of field is the same for all lens combinations. This can be shown as follows.

The magnification is given by x'_1/x, and substituting for x_1 in equation (40) gives

$$\text{depth of field} = \frac{2cx'_1}{M^2 d} \qquad \ldots \qquad \ldots \quad (41)$$

The magnification is determined by the object and image sizes and is fixed. The value of c is also fixed as explained above. Finally the ratio d/x'_1 is also fixed, since it determines sin θ', which, as shown in equation (32), decides the illumination of the image. Thus the depth of field is fixed and is independent of the lens used.

If the image illumination can be sacrificed, greater depth of field can be obtained by decreasing the lens aperture, for the value of d controls the illumination of the image and the depth of field, small apertures giving low illumination but greater depth of field, while large apertures give good illumination but limited depth of field. In a television camera, therefore, the sensitivity of the tube fundamentally decides the depth of field obtainable; if the tube gives an acceptable signal-noise ratio for a low light input the lens may be stopped down to give good depth of field, but if the tube requires considerable light input for an acceptable signal-noise ratio at the output it may be necessary to use maximum aperture, and depth of field is then very limited, as illustrated by the calculation above.

Hyperfocal Distance

To obtain maximum depth of field a lens must be focused on a certain object plane, and the distance of this plane from the first focal point of the lens is known as the *hyperfocal distance* x_h. Depth of field is a maximum when its outermost limit is at infinity. Expressions are deduced in Appendix G for the two limits of the depth of field; they are:

$$\text{outer object distance} = \frac{x_1}{1 - c/Md} \quad \ldots \quad (42)$$

$$\text{inner object distance} = \frac{x_1}{1 + c/Md} \quad \ldots \quad (43)$$

To make the outer object distance infinite, the denominator of (42) must be zero, i.e.,

$$M = \frac{c}{d} \quad \ldots \quad \ldots \quad \ldots \quad (44)$$

The magnification M can be related to the object distance and focal length from equation (26): multiplying this by x_1 we have

$$1 + \frac{x_1}{x'_1} = \frac{x_1}{f}$$

$$\therefore \quad 1 + \frac{1}{M} = \frac{x_1}{f}$$

from which

$$x_1 - f = \frac{f}{M}$$

Substituting for M from (44):

$$x_1 - f = \frac{fd}{c} \quad \ldots \quad \ldots \quad \ldots \quad (45)$$

i.e., hyperfocal distance

$$= x_h = \frac{fd}{c}$$

Since $c/Md = 1$, the inner object distance is, from (43), equal to $x_h/2$, i.e., approximately half the hyperfocal distance. For this adjustment of the optical system the depth of field extends from infinity to half the hyperfocal distance, as shown in Fig. 103.

The hyperfocal distance may alternatively be defined as that object distance for which the circles of confusion in the image plane equal the maximum permissible value when the lens system is focused on infinity; this is also proved in Appendix G. Thus we may say that if a lens system is focused on infinity, the images are in focus (to the extent that the circles of confusion do not exceed a certain value) for all objects lying between infinity and the hyperfocal distance. If, however, the lens system is focused on the hyperfocal distance, images are in focus for all objects lying between infinity and half the hyperfocal distance. This argument can be continued further, for if the lens is focused on half the hyperfocal distance, images are in focus for all objects lying between the hyperfocal distance and one-third of it. In general it is true that if a lens system is focused on a distance x_h/k, where k is any number, images are in focus for all objects lying between $x_h/(k - 1)$ and $x_h/(k + 1)$ as shown in Fig. 100. If the lens is focused on a very near object, say at $x_h/10$, the region of good focus is very restricted because it extends only from $x_h/9$ to $x_h/11$.

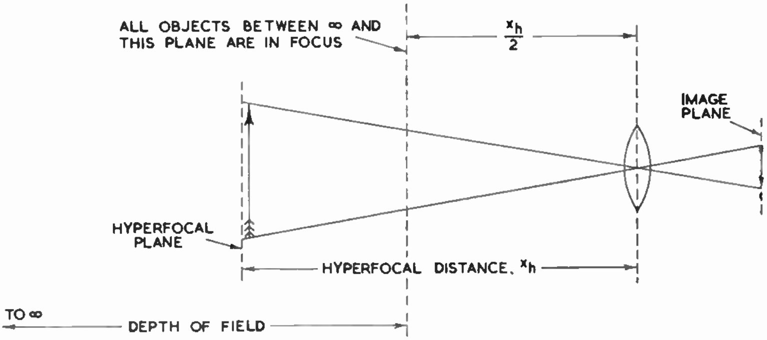

Fig. 99—Depth of field of a lens focused on the hyperfocal plane

Fixed-focus Cameras

When a lens is focused on the hyperfocal plane, all objects lying between infinity and half the hyperfocal distance appear in focus to the extent that the circles of confusion do not exceed a certain value. Such an adjustment of a lens system (illustrated in Fig. 99) is used on fixed-focus photographic box cameras. For example, if the lens has a focal length of 4 inches and an aperture ratio of $f/8$, the entrance pupil diameter is $4/8 = 0{\cdot}5$ inch. If the maximum diameter of the circle of confusion is taken as 0·25 mm (0·01 inch) from (45) the hyperfocal distance is given by

$$\text{hyperfocal distance} = \frac{4 \times 0{\cdot}5}{0{\cdot}01} \text{ inches}$$
$$= 17 \text{ feet approx.}$$

The camera is thus in focus for all object distances between infinity and 8 feet 6 inches from the first focal point.

Hyperfocal Distance for Television Cameras

For a standard Emitron camera the circle of confusion may be taken as 0·01 inch and the lens diameter for maximum aperture as 6·5/3, or approximately 2·2 inches. From equation (45) the hyperfocal distance is given by

$$x_h = \frac{6{\cdot}5 \times 2{\cdot}2}{0{\cdot}01 \times 12} = 120 \text{ feet approx.}$$

The camera is very rarely, if ever, used with object distances as great as this; the normal working distance is very much less, say 1/14th of the hyperfocal distance, and the region of good focus therefore extends from 1/13th to 1/15th of 120 feet, a total range of approximately 16 inches. As suggested by de Vore, a more practical estimate of the region of good focus is obtained by doubling this value. Nevertheless 32 inches is still a very limited range.

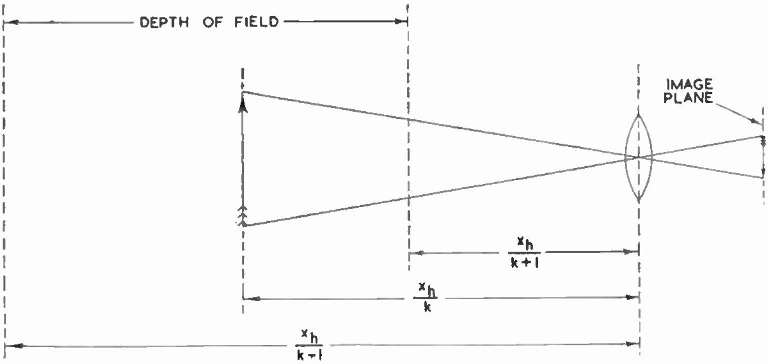

Fig. 100—Depth of field of a lens focused on a plane at a distance of x_h/k from the lens

It is feasible for a more sensitive camera, such as one employing a C.P.S. Emitron tube, to be focused on the hyperfocal plane during normal use. For example, if the lens is of 2·5 inch focal length and is stopped down to $f/8$, the aperture is approximately 0·3 inch diameter and, from equation (45), the hyperfocal distance is given by

$$x_h = \frac{2{\cdot}5 \times 0{\cdot}3}{0{\cdot}003} \text{ inches} = 21 \text{ feet approx.}$$

The camera is thus in focus for all distances between 10 feet 6 inches and infinity. The circle of confusion was taken as 0·003 inch diameter in this calculation, and if this is doubled, as suggested above to allow for the fact that degradation of focus may not be noticed until the circle of confusion has the width of two scanning lines, the C.P.S. Emitron camera may be said to be in focus for all distances exceeding 5 feet 3 inches.

9.10 ANGULAR FIELD OF A LENS SYSTEM

Provided the medium of the object space has the same refractive index as that of the image space, the angle subtended by an image at the second principal point of a lens system is equal to the angle subtended by the object at the first principal point. The relative sizes of image and object can be illustrated as in Fig. 101, which shows two light rays only, those which originate from the extreme points of the object and pass through the centre of the lens system.

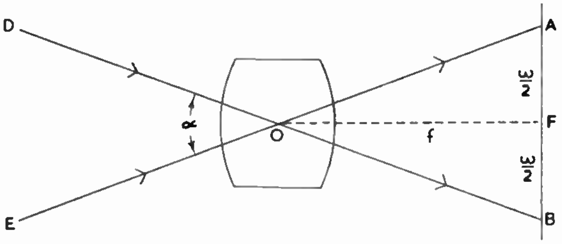

Fig. 101—Calculation of the angular field of a lens system

It is assumed in this diagram that the two principal points coincide; in general the two points do not coincide, but the distance between them is generally small compared with the object and image distances, and the errors resulting from this assumption are usually very small.

Let the image on the light-sensitive electrode (or photographic plate) have a width w and a height h. If the object distance is large compared with the focal length, the image can be assumed to be at the focus. Fig. 101 represents a plan of an optical system, and $\angle$EOD is the angular field of view in the horizontal plane when the object distance is infinite. From Fig. 101:

$$\tan \angle \mathrm{AOF} = \frac{w}{2f}$$

$$\therefore \quad \begin{array}{l}\text{angular field of view} \\ \text{in the horizontal plane}\end{array} = 2 \tan^{-1} \frac{w}{2f} \quad .. \quad (46)$$

For the standard Emitron camera $w = 5{\cdot}25$ inches and

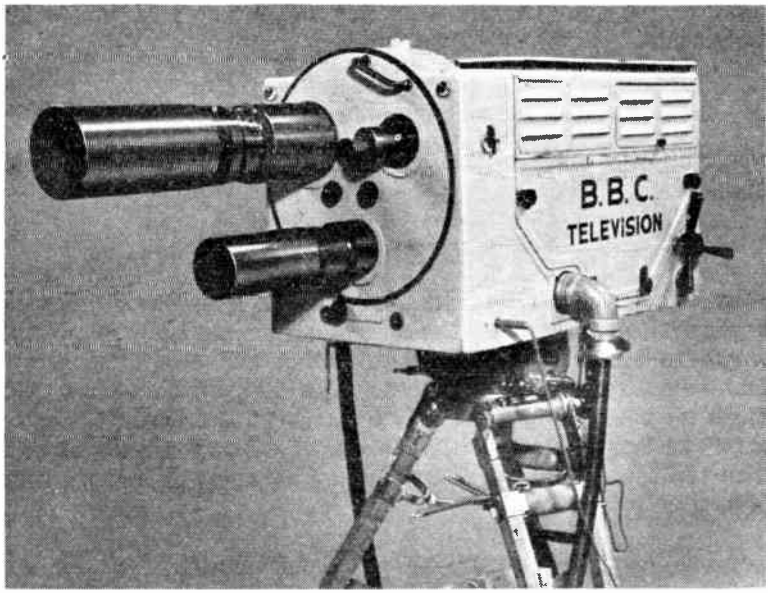

Fig. 102—C.P.S. Emitron camera

$f = 6{\cdot}5$ inches. The angular field of view is hence $2 \tan^{-1} 5{\cdot}25/13 = 2 \times 22 = 44$ deg. It is not often that the angular field of view in the vertical plane is required, but it is given by

$$\begin{array}{c}\text{angular field of view}\\ \text{in the vertical plane}\end{array} = 2 \tan^{-1}\frac{h}{2f} \qquad \ldots \quad (47)$$

The angular field of view in the horizontal plane varies from a maximum of approximately 40 deg required in studio productions to a minimum of, say, 2 deg required in outside broadcasts, for example in a shot of a distant clock tower. For a given camera tube the image size is fixed, and the angular field can be obtained only by correct choice of f; thus television cameras are usually fitted with a turret carrying three or four lenses of different focal lengths, and any lens can be brought into use by rotating the turret. In some cameras the turret can be fitted with any desired selection of lenses; in others a turret containing lenses of short focal length can be exchanged for another turret containing long-focus lenses. A three-lens turret is illustrated in the photograph of a C.P.S. Emitron camera in Fig. 102.

To illustrate the wide variation of focal length necessary to cover the required range of angular fields we shall consider the C.P.S.

Emitron tube, which has a mosaic measuring 1·73 inches by 1·38 inches. Restating (46):

$$f = \frac{w}{2 \tan \alpha/2} \qquad \ldots \qquad \ldots \qquad \ldots \qquad (48)$$

where α is the angle of view. Substituting $w = 1{\cdot}73$ and $\alpha = 40$ in (48):

$$f = \frac{1{\cdot}73}{2 \tan 20} = 2{\cdot}376 \text{ inches}$$

In practice a lens of focal length 2·5 inches is used. To give an angle of view as low as 2 deg requires an extremely long focal length; a repeat of the above calculation for $\alpha = 2$ deg shows that the necessary value of f is nearly 50 inches. Such a lens would make the camera most unwieldy to pan, and the maximum focal length of lenses fitted to television cameras is not usually greater than 17 inches. With such a value of f the angle of view is, from (47), given by

$$\alpha = 2 \tan^{-1} \frac{1{\cdot}73}{34} = 5{\cdot}5 \text{ deg approx.}$$

The bulk of a long-focus lens can be reduced by use of the telephoto principle given later in this chapter; such lenses may have focal lengths equal to two or three times the physical length of the lens mounting. As stated in Part II of this book, in C.P.S. Emitron cameras a more restricted angular view is obtained by use of camera tubes with a smaller mosaic, measuring 1 inch by 0·8 inch, which, with a lens of 17 inch focal length, gives an angular field of view of

$$\alpha = 2 \tan^{-1} \frac{1}{34} = 2{\cdot}5 \text{ deg approx.}$$

In some types of camera tube, notably small image iconoscopes, the photo-cathode is smaller still, being approximately $\frac{2}{3}$ inch by $\frac{1}{2}$ inch. With such a photo-cathode an angular field of 40 deg can be obtained with a lens of approximately 1 inch focal length and of 2·5 deg with a lens of approximately 15 inch focal length; these are shorter focal lengths than are required by larger tubes for a given angular field. Such small tubes are attractive because they make possible the construction of light and compact cameras, but they have disadvantages. For example, they are necessarily of lower sensitivity than larger tubes, because of the smaller photo-cathode area, and thus require larger lens apertures than larger tubes for a given output from a given scene. It is difficult to manufacture lenses of, say, 1 inch diameter having an aperture greater than, say, $f/1{\cdot}9$ without introducing considerable distortion of the image. Thus there is little advantage in reducing photo-cathode size beyond a certain point.

9.11 LENS ABERRATIONS

Practical lenses suffer from a number of defects tending to cause distortion or unwanted coloration of images, and the next few pages give a brief summary of the principal aberrations and the steps that are taken or can be taken to minimize them. These defects are discussed more fully in textbooks on optics, and reference should be made to these for a complete treatment of this subject. Some suitable textbooks are mentioned in the bibliography at the end of this section.

The aberrations listed first are those which are observed with monochromatic light, i.e., light of a single frequency, and those given at the end of the list are observed with white light, being caused by variation with frequency of the refractive index of the lens material.

1. *Spherical Aberration*

Ideally, the rays which originate from one point of an object and pass through a lens system should recombine at a single point in the image space. In practice the rays do not meet at a single point; this is illustrated in Fig. 103, which shows a parallel beam of light incident on a convex lens. The distance from the centre of the lens to the point where the emergent ray cuts the optic axis varies with the height of the incident ray above the optic axis, decreasing with increase in the height of the incident ray. The effect of this on the image of a point object is to surround the image with a faint halo; this is known as *spherical aberration* and is confined to images at the centre of the image field.

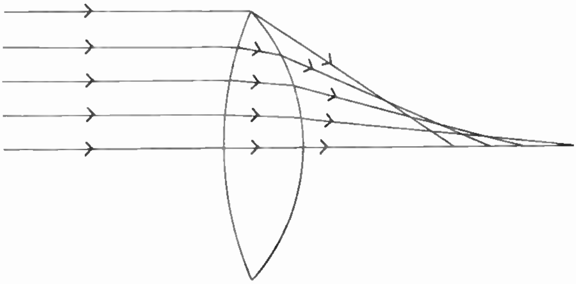

Fig. 103—Spherical aberration in a convex lens

This effect is similar to that which occurs in spherical mirrors (Fig. 77) and can be eliminated, as in a mirror, by giving the refracting surfaces of the lens parabolic curvature. Such surfaces are very difficult to make for small lenses which must be very accurately ground, but parabolic surfaces are used in larger lenses, for example those employed in stage luminaries which are required to produce a sharply defined light beam and not distortion-free images. A lens with parabolic curvature is illustrated in Fig. 104 (*a*); it is very bulky but can be made much more compact by constructing the refracting surface in a number of ridges, as shown in Fig. 104 (*b*). Such lenses are termed *Fresnel* lenses.

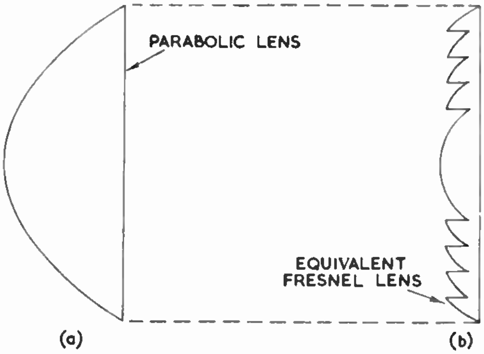

Fig. 104—A lens with parabolic curvature (a) and its Fresnel equivalent (b)

There are several methods of minimizing spherical aberration in lenses with spherical surfaces. It can be reduced by suitable choice of radii of curvature. A given focal length can be obtained from a number of different combinations of radii of curvature, but the particular combination for which the two radii are equal gives minimum aberration in general. But if the object is always at infinity, and if the incident light always falls on the curved surface, a plano-convex lens gives less aberration.

The aberration of a concave lens is opposite in sign to that of a convex lens. Thus when a concave lens is used in conjunction with a convex one the effect of the concave element is to cause the point where the emergent ray cuts the optic axis to recede from the centre of the lens as the height of the incident ray is increased. This provides the basis of a second method of minimizing spherical aberration, for in a combination of a convex and concave element it is possible to arrange for the effective focal length to have the desired value and for the aberrations of the two elements to cancel.

The spherical aberration increases with the height of the incident ray and cannot be corrected for the whole of the lens surface; it can, however, be reduced to a very small value for all apertures up to approximately two-thirds of the maximum. To keep distortion due to spherical aberration at a minimum, lens apertures should always be kept as small as possible.

2. *Coma*

Coma is an effect similar to spherical aberration but occurs in images which do not lie in the centre of the image field; this effect increases with increase in the distance of the image from the centre of the field. The size of an image depends on what part of the lens the rays traverse; rays passing through the centre of the lens form a smaller image than those passing through outer regions of the lens near the rim. Moreover for images remote from the centre of the image field the images are slightly displaced with respect to each other, with the result that an image of a point has the form of a number of overlapping circles of increasing size, the smallest circles being the brightest. The effect is described as a coma because of the similarity of the point image to a comet.

The effect can be eliminated from a thin lens by correct choice of lens shape, and usually when a thin lens is corrected for spherical aberration it is also free from coma. Coma cannot be eliminated from a lens combination, but it can be minimized in the same way as spherical aberration by appropriate choice of lens constants.

3. *Astigmatism*

Rays of light from a point object which fail to meet at a single point in the image space are termed *astigmatic*. Thus spherical aberration and coma are both examples of astigmatism, but this term is usually reserved for the distortion of images due to rays striking the lens obliquely. The distortion caused by astigmatism can best be described by reference to the shape of the image of a point object. There is a certain range of image distance within which the image can be said to be in focus and at each end of this range the image has the form of a straight line, the line at one end being at right angles to that at the other. This is illustrated in Fig. 105. At intermediate points within this range the image is elliptical and at one point is circular. This is the circle of least confusion and represents the point of optimum focus.

If the object is a straight line, whether the image is in focus at a given point within the limited range mentioned above depends on the direction of the line. If the image is formed by rays passing through a radius of the lens it will be in focus at one end of the image range, whereas if it is formed by rays passing through an arc of a circle concentric with the lens the image is in focus at the other end of this range.

If the object is a spoked wheel the rim is accurately in focus at one extreme of the image range but the spokes are not; this image point is said to be on the *tangential image surface*. At the other extreme of the image range the spokes are in focus and the rim is not; this image point is said to be on the *sagittal image surface*. Between the tangential and sagittal surfaces there is another surface where the rim and spokes are equally well defined; this is the *surface of least confusion*.

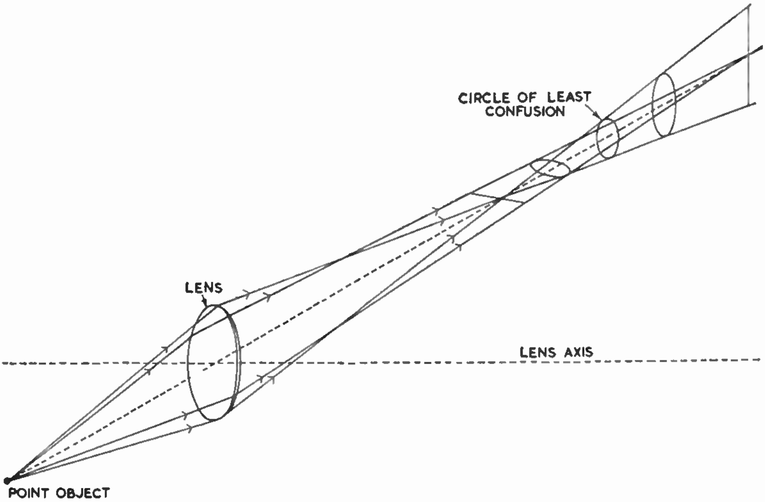

Fig. 105—Illustrating astigmatism

Astigmatism does not exist on the optic axis of a lens system, but it increases rapidly with the obliquity of the incident light. It is usually corrected at the same time as curvature of field as described below.

4. *Curvature of Field*

If a lens is corrected for astigmatism by arranging for the tangential and sagittal image surfaces to coincide, the combined surface is not flat but curved, as shown in Fig. 106. If the image is formed on a flat surface, as in photographic and television cameras, it cannot be equally in focus at all points. This aberration is known as *curvature of field* and is eliminated, together with astigmatism, by arranging for the tangential and sagittal image surfaces to have equal and opposite curvature. The surface of least confusion is then flat and stigmatic. For a single lens, such as that used in a box camera, this can be done by use of an aperture stop of a certain size. For lens combinations it can be achieved, if the lenses are separated, by correct choice of lens constants. A lens combination thus corrected is termed an *anastigmat*.

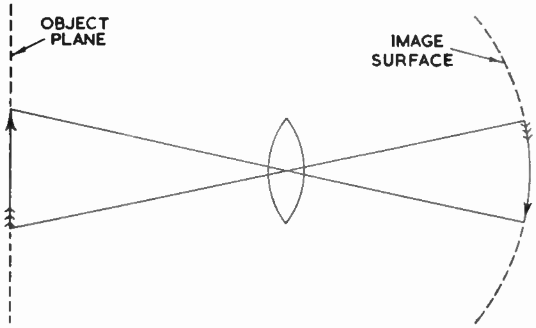

Fig. 106—Curvature of field of a lens

5. *Distortion*

If the magnification of a lens system varies with the distance of an image point from the centre of the image field, the system is said to give distortion. When distortion is present, the image of a rectangular object has sides which curve inwards (pincushion distortion) or outwards (barrel distortion), depending whether the magnification increases or decreases with distance from the centre of the image field. These two types of distortion are illustrated in Fig. 107. Distortion due to variation of magnification is not affected by stopping down the lens system, but in a single-lens system does depend on the position of the stop relative to the lens. Distortion is small in symmetrical lens systems, such as those used in most photographic objectives, in which the stop is situated between two similar elements.

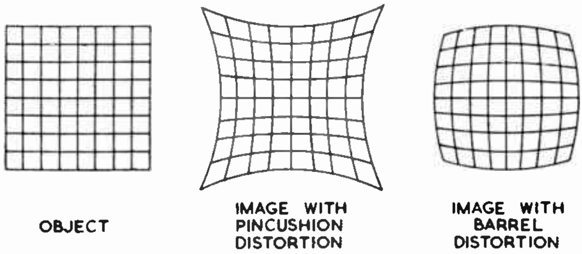

Fig. 107—Pincushion and barrel distortion

6. *Axial Chromatism*

This aberration and that described under (7) are caused by variation with frequency of the refractive index of the lens material and are usually more troublesome than those described under (1) to (5), but any lens used in photography or television must be at least partially corrected for all seven types of aberration.

In general the refractive index of glass increases with frequency, and, from equation (24), the focal length also varies with frequency. Thus if white light falls on a single convex lens the various colours are brought to a focus at different points along the axis, violet light being focused nearest the lens and red light farthest from it, as shown in Fig. 108. Only one colour is in focus on a particular image plane and images are surrounded by coloured borders. The magnitude of this effect can be reduced by decreasing the lens aperture, but both forms of chromatism can be virtually eliminated by the methods described under (7).

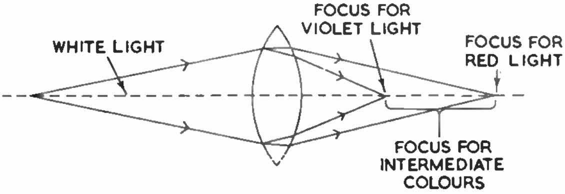

Fig. 108—Axial chromatism

7. *Lateral Chromatism*

The magnification of a lens varies with its focal length and hence with the frequency of the light incident on it. An uncorrected lens thus produces images the size of which vary with their colour. This effect is termed *lateral chromatism*, or sometimes *chromatic difference* of magnification.

Axial and lateral chromatism can be almost eliminated in a two-element lens system by correct choice of lens separation, but if the lenses are in contact the method of elimination is to use materials of different refractive index for the two elements, the refractive indices being correctly chosen. *Achromatic pairs* are commonly constructed with one lens of crown glass and the other of flint glass.

In a monochromatic television system the effect of axial and lateral chromatism is to degrade the definition in reproduced images.

TRANSMISSION OF LENSES

The transmission of a lens has been defined earlier as the ratio of the light passing through the lens to the light incident upon it, and it varies in practice between approximately 0·5 and 0·95. Some of the energy is lost by absorption in the material of the lens, but a larger proportion is lost because light is reflected back from the lens surfaces. The energy lost at each reflection is equal to $(n - 1)^2/(n + 1)^2$ of the incident energy, where n is the refractive index of the lens material. If $n = 1{\cdot}5$ the energy lost is 0·04 of the incident energy, and if, as in a complex lens combination, there are many reflecting surfaces the overall loss due to reflection can be serious. This reflection has a further disadvantage, namely, that light returning along its incident path after reflection from a lens surface may be reflected again at another surface and ultimately reach the image space. Here the light is usually scattered over the image plane and has the effect of degrading shadows and reducing contrast.

BLOOMED LENSES

One way of reducing the reflection at lens surfaces is by coating them with a very thin film of silica or evaporated fluorite. This film behaves as a quarter-wave matching section inserted between one medium (air) and another (glass) of different refractive index and minimizes loss due to reflection at the glass surface; this may be compared with the use of a quarter-wavelength of cable to match two transmission lines of differing characteristic impedance. The analogy is a very close one, and the lens coating should, for perfect matching, have a refractive index n_3, where

$$n_3 = \sqrt{(n_1 n_2)} \qquad \ldots \qquad \ldots \qquad \ldots \quad (49)$$

in which n_1 is the refractive index of the first medium and is equal to unity if this medium is air and n_2 is the refractive index of the second medium. For transmission-line matching the equivalent expression is

$$Z_3 = \sqrt{(Z_1 Z_2)}$$

where Z_1 is the characteristic impedance of the first transmission line,
Z_2 is the characteristic impedance of the second transmission line
and Z_3 is the characteristic impedance of the inserted quarter-wave section.

Complete elimination of reflection by this means is only possible for a single wavelength and for a particular angle of incidence; nevertheless this process can improve the transmission of a lens system by as much as 40 per cent and leads to much better contrast in images by reducing scattered light. Lenses treated in this way are termed *coated* or *bloomed* and have a characteristic blue appearance. Great care should be taken in cleaning these lenses because the coating is extremely thin: $\lambda/4$ at 4,500 Ångström units is approximately 5×10^{-6} inch.

OPTICAL FILTERS

When a photographic or television camera is oversensitive to a particular band of light frequencies the spectral response can be corrected by use of a suitable light filter, which is usually placed in front of the camera lens. A great variety of filters is available; some designed to transmit a narrow band of frequencies centred around a particular value (these are termed *monochromatic* filters), others to transmit all the visible spectrum except for a narrow band of frequencies. It is sometimes desirable to absorb all visible frequencies to the same extent, and for this purpose neutral filters are available.

Some filters consist of a thin film of gelatine containing appropriate dyes and mounted between two sheets of glass; others consist of a sheet of coloured glass. To prevent distortion the glass used in filters must be of optical quality, i.e., the sides must be plane parallel.

On a clear summer day the light input to a television outside broadcast camera may be excessive even when the lens aperture is reduced to its minimum value. On such occasions neutral filters are used to reduce the light input; it is essential to use such filters with a camera tube such as the C.P.S. Emitron, which is unstable for light inputs exceeding a certain value. Typical values for the transmission of such filters are 0·1 and 0·01.

9.12 PERSPECTIVE DISTORTION

In television programmes originating at a studio, the angular field of the camera lens can be made any desired value within wide limits by suitable choice of focal length. The lens should, however, be chosen with care, because the perspective of the reproduced image will appear distorted unless the angle subtended by the scene at the camera is approximately equal to the angle subtended by the reproduced image at the viewer's eyes. In outside broadcasts it frequently happens that this condition cannot be observed because the angular field is fixed by the width of the scene and the distance of the camera from it; in such circumstances any perspective distortion must be tolerated.

Some indication of the angle subtended by a receiving viewing screen at the viewer's eyes can be obtained as follows.

At short viewing distances the line structure of a television picture is obvious and distracts attention from the content of the picture; on the other hand, if the picture is viewed from a long distance the line structure is not seen, but the picture loses definition because details are too small to be resolved at the eye. The optimum viewing distance is that at which the line structure just cannot be resolved; at this distance the thickness of each line subtends an angle of approximately 1 minute at the eye. If the picture contains L lines, the height of the picture subtends $L/60$ deg at the eye and the width of the picture subtends $aL/60$ deg, where a is the aspect ratio. If $L = 405$ and $a = 4/3$, the angle subtended by the picture width at the optimum viewing distance is 9 deg. The use of vertical spot-wobble on the viewing screen does not invalidate this argument; although spot-wobble makes it impossible to see the line structure at close viewing distances it is still true that the finest detail has the same dimensions as the line thickness.

If the lens of the television camera is chosen to give an angular field of 9 deg in the horizontal plane, the reproduced picture is a true representation of what the eye would see at the camera position. If the camera lens is chosen to give a wider view—say 40 deg—the reproduced picture contains all the objects which would be seen by a viewer at approximately four times the camera distance and contained within an angular field of 9 deg. The perspective of the picture is thus distorted; the scene appears to have greater distance between foreground and background than exists in fact. This distortion can be put to good effect if it is desired to give the impression of great depth to a shallow scene, but the method has disadvantages because people walking towards the front or the back of the scene at a normal speed appear to be moving unnaturally quickly in the reproduced scene.

If the camera lens is chosen to have a narrower view—say 3 deg—the reproduced picture contains the objects which would be seen by a viewer at approximately one-third the camera distance and contained within an angular field of 9 deg. The perspective of the picture is again distorted, for the scene appears to have a shorter distance between foreground and background than exists in fact. People walking towards the front or the back of the scene at a normal speed appear to be moving unnaturally slowly in the reproduced scene. This effect is a very familiar one, for it is frequently noticed in television programmes or films of cricket matches; the pitch must, of course, be viewed from a great distance, and a lens of long focal length is essential. If the camera is situated nearly in line with the wickets, batsmen appear to take a very long time to run the length of the pitch. Even more graphic of this foreshortening effect of long-focus lenses are pictures taken at a racecourse of horses galloping towards the camera; in spite of their exertion the horses appear to be making very little progress along the course.

The previous few paragraphs may be summarized thus: to obtain a realistic impression of perspective, a picture must subtend approximately the same angle at the viewer's eye as the original scene subtended at the camera lens. This point can be illustrated by reference to Figs. 109 and 110 which are reproductions of the same photograph, Fig. 109 being three times the size of the other in linear measure. If page 193 is held approximately 10 inches from the eye and the two photographs are studied, it will be noted that Fig. 109 has the more natural appearance of the two; the reason is that the angle subtended at the eye by Fig. 109 at this distance is more nearly equal to that subtended by the original scene at the camera than that subtended by Fig. 110.

If, however, Fig. 110 is viewed at approximately 3 inches distance it subtends at the eye approximately the same angle as the original scene at the camera and the perspective appears more natural than that of Fig. 109. A convex lens is normally necessary to enable readers with average sight to focus their eyes on an object as close as 3 inches.

Nature of Perspective Distortion

The term *perspective distortion* which has been used to describe the unnatural appearance of photographs viewed from the wrong distance is an unfortunate one because it suggests, quite wrongly, that the effect may be due to some defect in the lens. In fact, the distortion would be present even if a perfect lens could be used to take the photograph.

" Steep Perspective "

Fig. 111 illustrates another effect which is observed when a lens is focused on a very close object and the scene contains a receding plane. The distorted appearance of the car is not due to the photograph being viewed from the wrong distance, because the angular field here is no different from that in Fig. 109; the distortion in this photograph is due to the " steep perspective," i.e., to the fact that the optical magnification for nearby objects such as the right-hand wheel and lamp is several times that for more distant objects such as the windscreen or the rear wing. This effect is hardly noticeable in Fig. 109 because in this more distant view the optical magnification

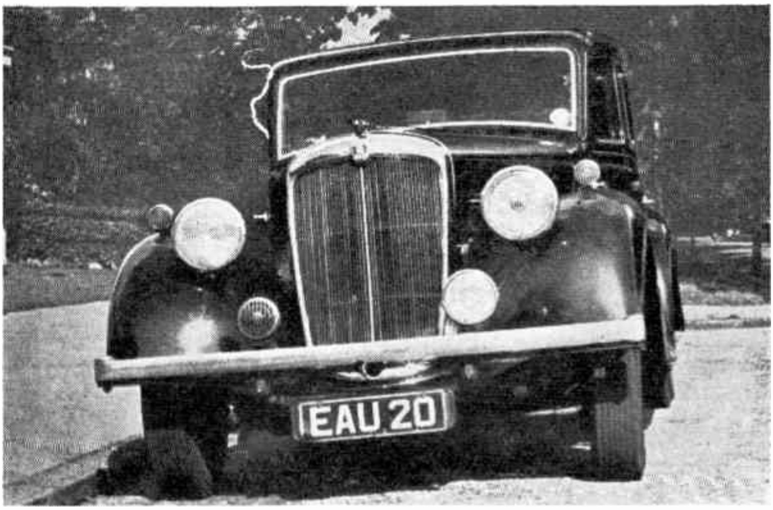

Fig. 109—Viewed at a distance of approximately 10 inches, the perspective in this photograph appears natural. Fig. 110 (Right)—A reproduction of Fig. 109 scaled down to approximately one-third the size

Fig. 111—The same car taken from a nearer viewpoint

for the front of the car does not greatly differ from its value for the rear of the car. This effect differs from that described previously under the heading " Perspective Distortion " because it is independent of the angular field of the lens; steep perspective can be just as troublesome in pictures taken with narrow-angle lenses as in those taken with wide-angle ones and is caused by taking too close a viewpoint.

Techniques used to take Close-up Views

There are two techniques which may be adopted to give close-up views of part of a scene; one is to use a medium- or wide-angle lens and to move the camera up to the centre of interest in the scene; the other is to use a lens of long focal length which restricts the angular field of view of the camera to the desired degree. Of these two alternatives the first is, in general, preferable because it enables the same lens to be used for distant and close-up shots. The angular field of the lens therefore remains constant irrespective of whether the shot is a distant or near one. In studios, therefore, and in some outside broadcasts, where it is possible to have the television cameras mounted on dollies to make them mobile, close-up views are obtained by moving the camera rather than by changing lenses. This technique has the advantage that any perspective distortion experienced by viewers by virtue of their distance from the screen applies equally to distant and close-up shots.

If the lenses of different focal lengths are used to control the field of view, viewers (who normally stay at a fixed distance from their screens) receive pictures in which the degree of perspective distortion will change when the lens in the camera is changed. Though undesirable, this is not a very objectionable effect; this is fortunate because, in outside broadcasts, television cameras must often be fixed in position at some distance from the scene to be televised, and close-up views can be obtained only by use of long-focus lenses.

9.13 CHOICE OF LENSES FOR A TELEVISION CAMERA

The choice of a lens for a television camera is affected by a number of factors which will now be discussed; some of these factors have already been mentioned in earlier pages but will be repeated here for completeness.

When a particular television camera tube is to be used to transmit a particular scene, the characteristics of the lens required are decided by the following considerations:

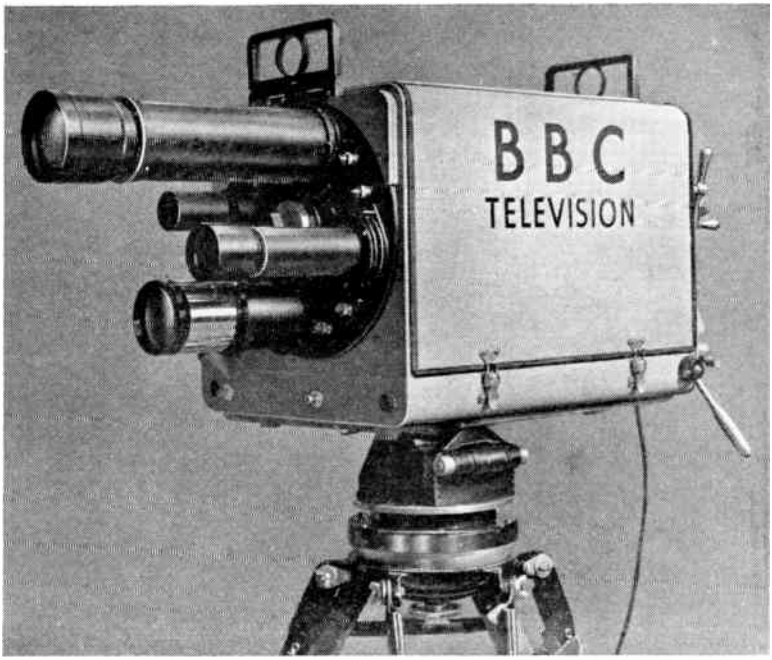

Fig. 112—An image iconoscope camera with a four-lens turret

(*a*) the size of the light-sensitive electrode of the tube,
(*b*) the sensitivity of the tube,
(*c*) the angle of view required, and
(*d*) the brightness of the scene.

The sensitivity of the tube is measured by the light input necessary to give a specified signal-noise ratio at the camera output, the noise of the tube itself and of the following vision-frequency amplifier being taken into account.

The focal length necessary is determined by the width w of the light-sensitive electrode of the tube and the required angle of view according to equation (48), which may be written in the form

$$f = \frac{w}{2} \cot \frac{\alpha}{2} \qquad \ldots \quad \ldots \quad \ldots \quad (50)$$

If the width of the light-sensitive electrode is large, as in an iconoscope, very large focal lengths will be necessary to give narrow angles of view. The distance between a lens and its image always exceeds its focal length, and to enable images to fall on the light-sensitive electrode, lenses must be supported in mountings which project from the front of the camera. A long mounting is required for a lens of long focal length and makes the camera inconvenient and cumbersome to handle. It is advantageous, therefore, to have camera tubes with small photo-sensitive surfaces, although even with these, as has already been pointed out, difficulties are experienced in obtaining very narrow angles of view, and telephoto lenses are sometimes used to obtain a smaller lens mounting. An image iconoscope camera fitted with a four-lens turret is illustrated in Fig. 112. This shows the size of the mountings required by lenses of long focal length.

From a knowledge of the camera-tube sensitivity and the area of the photo-sensitive surface, the illumination E required to give a worthwhile picture can be calculated. This, together with the scene brightness B, decides the aperture ratio of the lens according to equation (35):

$$E = \frac{\tau B}{4(f\text{-number})^2}$$

in which τ is the transmission of the lens and will be taken as 0·8. This may be rearranged:

$$f\text{-number} = \frac{1}{2}\sqrt{\left(\frac{\tau B}{E}\right)} \qquad \ldots \qquad \ldots \quad (51)$$

This expression gives the minimum aperture necessary for successful results and shows that it is directly proportional to the square root of the scene brightness and inversely proportional to the square root of the tube sensitivity. Large values of f-number are desirable not only to reduce lens aberrations but also to give good depth of field. If the tube sensitivity is limited, as in the iconoscope, high values of f-number can only be obtained by having large values of scene brightness, which in turn imply high illumination; according to McGee,* a mosaic illumination of 4 foot-candles is necessary for a very good picture from a standard Emitron tube. Even with an illumination of 200 foot-candles this requires an aperture ratio, from (51), of

$$f\text{-number} = \frac{1}{2}\sqrt{\left(\frac{0{\cdot}8 \times 200}{4}\right)} = 3{\cdot}16$$

in which the highlight brightness B is taken as equal to the incident illumination. As already shown, an aperture ratio of $f/3$ results in very limited depth of field.

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* J. D. McGee, "A Review of Some Television Pick-up Tubes." *Journal I.E.E.*, Vol. 97, No. 50, November 1950.

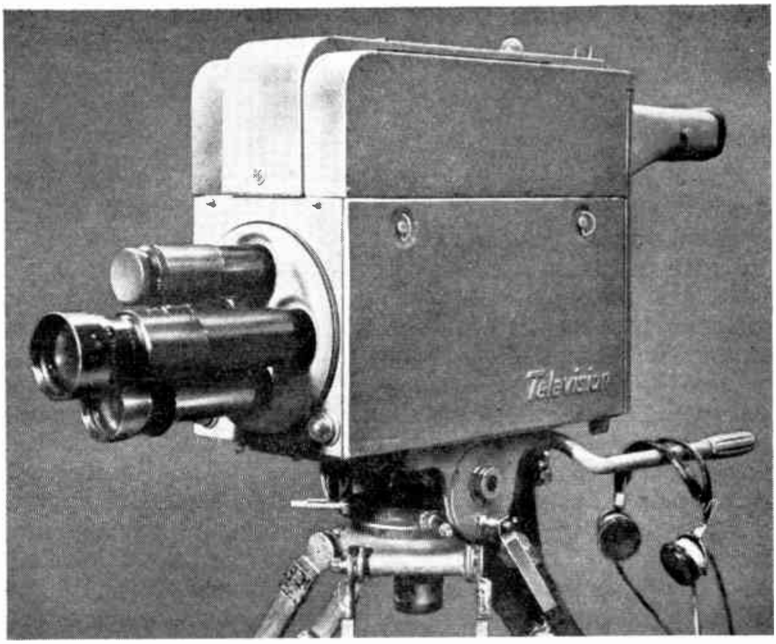

Fig. 113—An image orthicon camera with a four-lens turret

With the more sensitive tubes, such as the C.P.S. Emitron, lower illumination can be used and greater depth of field obtained. For example, McGee* quotes the C.P.S. Emitron as requiring 0·05 foot-candle of mosaic illumination for very good pictures. If we assume a scene illumination of 30 foot-candles, the aperture becomes:

$$f\text{-number} = \frac{1}{2}\sqrt{\left(\frac{0{\cdot}8 \times 30}{0{\cdot}05}\right)} \simeq 11$$

With this aperture and mosaic illumination, results are satisfactory provided no gamma-correction circuits are employed. When such circuits are used the signal-noise ratio is impaired and mosaic illumination greater than 0·05 foot-candle is necessary to give a satisfactory signal-noise ratio. When gamma correction is used, therefore, somewhat larger apertures than *f*/11 will probably be required with incident studio illumination of 30 foot-candles.

If the tube is used out of doors on a clear summer day the scene brightness will be considerably greater, possibly as much as 5,000 foot-lamberts, and the camera will need to be stopped down to the

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* J. D. McGee, "A Review of Some Television Pick-up Tubes." *Journal I.E.E.*, Vol. 97, No. 50, November 1950.

minimum iris setting; possibly some neutral filters will also be required to keep the illumination of the mosaic to reasonable proportions.

9.14 APERTURE CONTROL OF TELEVISION CAMERAS

For a given scene brightness the illumination on the light-sensitive electrode of a television camera depends only on the aperture ratio of the lens system; this is shown by equation (35). In a lens turret, if all the iris diaphragms are operated by a single control, it is advantageous to arrange for the relative apertures of all lenses to be equal. The operator can then switch from one lens to another without touching the aperture control. This can be successfully carried out for lenses of relatively short focal length having reasonably small diameters, but a difficulty arises when long-focus lenses are used. For example, a lens of 17 inch focal length with a relative aperture of $f/4{\cdot}5$ has a diameter of nearly 4 inches, and any increase in aperture would necessitate a bulky and heavy lens mounting. To keep the lenses a reasonable size, lenses of long focal length usually have an aperture of less than $f/4{\cdot}5$ or $f/5{\cdot}6$, and it is impossible to gang the iris control (if any) of such a lens with those of other lenses which may have a maximum aperture of $f/1{\cdot}9$.

The size of long-focus lenses and their mounts can be judged from Fig. 113 which illustrates an image orthicon camera with a four-lens turret.

9.15 VARIATION OF ILLUMINATION OVER IMAGE PLANE IN A TELEVISION CAMERA

In deriving expression (51) it was assumed that the illumination of the light-sensitive electrode of a television camera is uniform and equal to that at the image centre. As already shown (page 167), this is a justifiable assumption provided the image does not subtend too large an angle at the lens. It is, however, quite common for wide-angle lenses in television cameras to embrace an angular field of 45 deg, and for such lenses the variation of illumination over the image may be appreciable. To illustrate this we will consider the extreme case of an image which subtends an angle of 45 deg at the lens centre, and will calculate the ratio of the illumination in a corner to that at the centre of the image.

The ratio of image width to focal length is, from (46), given by

$$\frac{w}{f} = 2\tan\frac{\alpha}{2} = 2\tan 22{\cdot}5 = 0{\cdot}8284$$

If the aspect ratio of the image is 4 : 3, the diagonal is 5/4 times the width and the ratio of the diagonal to the focal length is 0·8284 × 5/4 = 1·0355. From (44) the diagonal subtends an angle, at the centre of the lens, of 2 $\tan^{-1}$ 1·0355/2 = 2 $\tan^{-1}$ 0·5178 = 54·7 deg. The line joining a corner of the image to the lens centre thus makes an angle ϕ' of approximately 54·7/2 = 27 deg with the optic axis and, as shown in expression (30), the ratio of the illumination at a corner to that at the image centre is directly proportional to $\cos^4 \phi'$, which in this example is equal to 0·64. For such an illumination ratio the corners of the image will be appreciably darker than the centre; this effect is not particularly serious, however, because it is only appreciable with wide-angle lenses, and even with these is not very important because the viewer's interest is usually concentrated on the centre of the image.

9.16 FOCUSING OF TELEVISION CAMERAS

A standard Emitron camera normally has a single lens which is moved towards or away from the camera tube to effect focusing; in other types of camera using image iconoscope, C.P.S. Emitron or image orthicon tubes, which are fitted with lens turrets, it would be inconvenient to move the turret and focusing is effected by moving the television tube along the axis of the lens in use. Since the lenses in a turret are of different focal length, the focus control has usually to be operated after each change of lens, but some lens mountings are fitted with a prefocusing facility. In this, provision is made for a particular lens to move longitudinally in its mounting, and it can be so positioned that when the turret is rotated from one particular lens to the prefocused lens the picture is automatically in focus and consequently no movement of the focusing control is necessary.

Racking Distances in Television Cameras

The distance through which a camera tube must be moved to effect focusing depends fundamentally on the size of the photo-sensitive surface of the tube. This can be shown in the following way. The camera is usually designed so that, for all lenses, it can be focused on any object distance between infinity and a certain inner distance. For an object distance of infinity the image distance is f, the focal length; for an object distance of x the image distance x' is given by equation (26), thus:

$$x' = \frac{xf}{x - f}$$

The range of image distances is thus given by

$$\frac{xf}{x-f} - f = \frac{f^2}{x-f} \quad \ldots \quad \ldots \quad \ldots \quad (52)$$

Normally the inner object distance x is large compared with f and the range of image distances for which provision must be made is approximately f^2/x. For a given inner limit x the racking distance is directly proportional to the square of the focal length of the lens used. As shown by equation (48), the focal length is directly proportional to the width of the light-sensitive surface for a given angular field. Thus the racking distance is directly proportional to the square of the width of the light-sensitive surface.

For a camera tube such as the C.P.S Emitron, which has a mosaic 1·8 inches in width, a racking distance of the order of 1 inch is necessary to cover an adequate range of object distances with a long-focus lens, but for camera tubes with very small photo-cathodes, such as a very small image iconoscope, the racking distance is very small and for a wide-angle lens may be as little as 1/200th inch. Thus the focusing mechanism must be capable of moving the tube with precision through distances as small as 1/1,000th inch; this requires a carefully designed focusing control with very little backlash.

9.17 Lens Hoods

Under ideal conditions a lens should receive light only from the scene on which it is focused; if any additional light enters the lens from other light sources surrounding the scene the contrast in the image can be materially reduced. Unless precautions are taken it is very easy for unwanted light to enter a lens system at oblique angles of incidence and reach the image space by internal reflection at the lens surfaces; this is particularly likely to happen in a

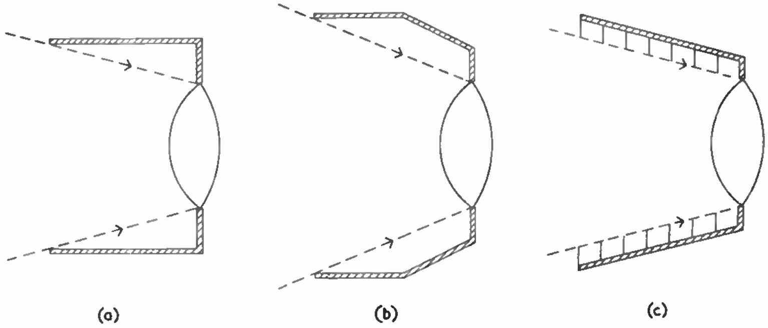

Fig. 114—Three types of lens hood

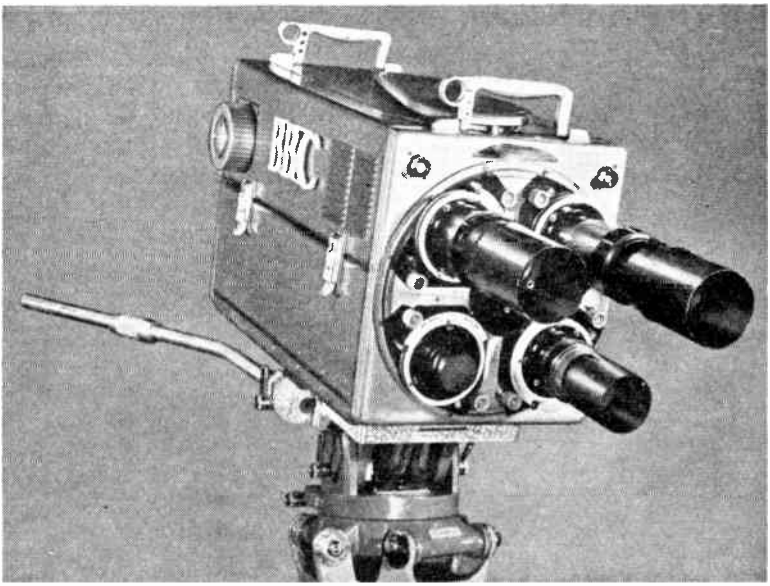

Fig. 115—An image orthicon camera with a four-lens turret

television studio, where very bright lighting is used. To prevent loss of contrast due to this cause, lenses are usually fitted with hoods of circular or rectangular cross-section mounted in front of the lens so that their axis coincides with that of the optical system as shown in Fig. 114. If the lens has a short focal length and is intended to give a wide-angle view, a parallel-sided hood would need to be so short to avoid cutting off the light from the edges of the scene that its efficiency would be low; a flared form (Fig. 114 (*b*)) is used instead. The interiors of lens hoods must be non-reflecting and are usually given a black matt finish; sometimes they are lined with black velvet. An alternative method of preventing reflection from the inside walls of hoods is by the provision of a series of vanes mounted at right angles to the hood surface as shown in Fig. 114 (*c*).

The provision of hoods results in some operational inconvenience because they inevitably add to the length of lens mountings and to the weight of the camera. Moreover the hoods on long-focus lenses may be in the field of view of short-focus lenses in the same turret; frequently this difficulty can only be solved by removing the hoods when not required.

These lens hoods can be seen in the photograph of an image orthicon camera in Fig. 115.

9.18 Telephoto Lenses

To obtain a narrow viewing angle a lens with a long focal length is necessary. Single lenses with long focal lengths are inconvenient for use in photographic or television cameras because the distance between the lens and its image must always be greater than the focal length; to obtain a narrow viewing angle, therefore, a very long and inconvenient lens mounting is necessary. Telephoto lenses provide one solution to this difficulty because they have a long focal length, but the distance between the lens and the image, known as the *back focus*, may be short.

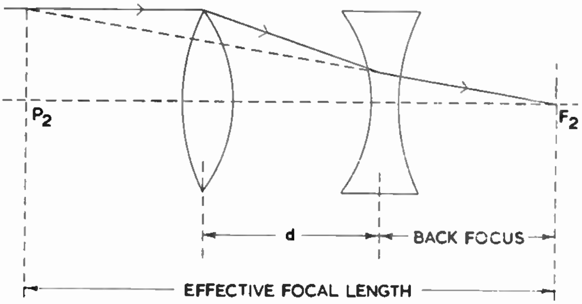

Fig. 116—Telephoto lens combination

A telephoto lens is a combination of a front convex lens and a back concave lens (Fig. 116), the separation being less than the focal length of the convex lens. The focal length of such a combination is given by equation (28):

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

where f_1 is the focal length of the convex lens,
f_2 is the focal length of the concave lens,
d is the separation.

As an example, let $f_1 = +10$ inches, $f_2 = -10$ inches and $d = 5$ inches. From (28) $f = 20$ inches.

The back focus can be calculated as follows. If the object is at infinity, the convex lens gives an image 10 inches behind the lens, i.e., 5 inches behind the concave lens. This image can be regarded as a virtual object for the concave lens, and the position of its image may be obtained by substituting in equation (25), due regard being paid to signs. Putting $x = -5$ and $f = -10$ in equation (25) gives x' as 10 inches, i.e., 10 inches behind the concave lens. Thus the effective focal length of the combination is 20 inches but

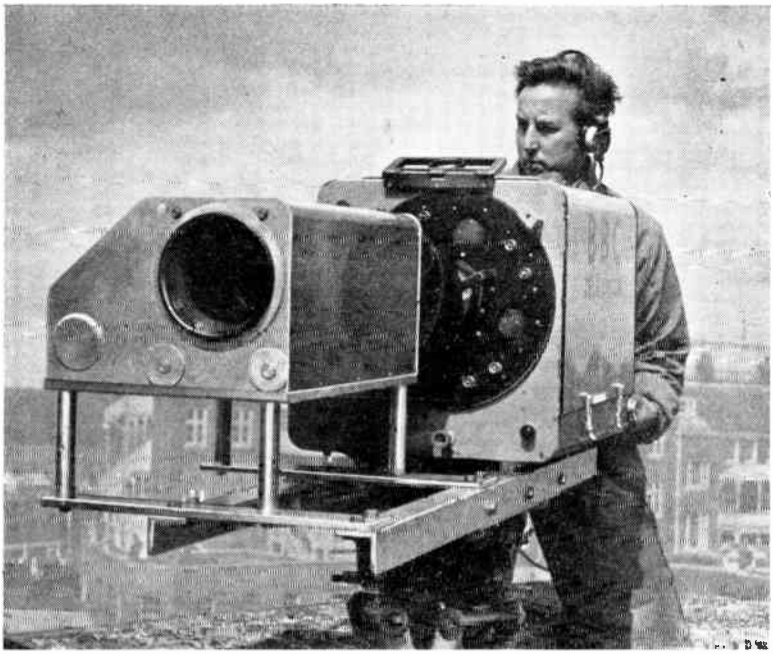

Fig. 117—Prototype zoom lens

the back focus is only 10 inches and the principal points lie considerably ahead of the lenses as shown in Fig. 116. The ratio of focal length to back focus is known as the *telephoto magnification* and in this example is 2·0. The length of the lens mounting is, however, equal to the back focus plus the separation and is 15 inches. If the above calculation is repeated in general terms it is easily shown that the telephoto magnification is given by $f_1/(f_1 - d)$.

The focal length of a telephoto lens can be varied by altering the separation between the lenses, but the spherical aberration also varies with the separation, and it is preferable to keep the separation fixed at that value for which spherical aberration was corrected.

9.19 Zoom Lenses

A zoom lens is a lens combination of which the effective focal length can be varied while the image distance remains constant. When a zoom lens is used with a television camera, operation of the zoom control alters the angular field of the lens and a viewer of the reproduced image has the impression that the camera is moving away from or towards the scene. Thus, provided the range of focal length is sufficient, a zoom lens can be used for wide-angle and narrow-angle shots and can take the place of a lens turret. It has the advantage over a turret that the viewing angle can be changed without momentarily losing the picture but is less convenient in that it occupies more space longitudinally; it is, however, not so wide or so heavy as a turret.

Some zoom lenses are used in place of the normal camera lens or lens turret, but others have been made which are used in addition to a camera lens. Both types of zoom lens consist fundamentally of two fixed outer lenses on the same axis as a number of inner lenses which are moved longitudinally and differentially by the zoom control. By suitable design the inner lenses are so moved that the effective focal length of the combination varies, the back focus remaining constant, as the zoom control is operated. To keep the image illumination constant the lens must also be designed so that the aperture ratio is independent of the setting of the zoom control. The aberration of the zoom control lens is kept to a minimum by balancing the aberrations of the positive and negative elements, but relative changes in the positions of these elements upset the balance, and to keep the overall aberration low the extent of movement of the inner elements and thus the variation in focal length must be limited. For this reason the range of focal length of the zoom lens is limited to approximately 5 : 1, and a lens might cover the range from 4 inches to 20 inches.* A photograph of a prototype zoom lens is given in Fig. 117.

9.20 TELEVISION CAMERA VIEWFINDERS

Television and photographic cameras are equipped with a viewfinder, a device which gives an image of the field of view of the camera and enables the operator to position the camera so that only wanted parts of a scene appear in the reproduced image. In very simple cameras, such as photographic box cameras, the viewfinder consists of a small lens and a plane mirror inclined to give an optical image on a miniature ground glass screen, a mask being used to limit the viewfinder field to that of the camera lens.

A television camera is frequently in use for long periods, during which it may be situated close to a scene or at some distance from it. It is usually necessary to adjust the focus of the camera optical system many times during its period of use because of movements of artists or objects in the scene, particularly if a number of different lenses are used; to facilitate such adjustments the viewfinder of a television camera is designed to indicate not only the field of

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* H. H. Hopkins, " A 5 : 1 Television Zoom Lens." *Proceedings of the I.E.E. Television Convention* 1952, Paper No. 1353.

view of the camera lens but also whether the camera optical system is accurately in focus. To this end the viewfinder itself is made focusing.

Standard Emitron Viewfinder

There are a number of ways in which such a viewfinder may be designed; in one example, provided by the standard Emitron camera, the viewfinder consists of a lens which focuses an image of the scene on a ground glass screen as shown in Figs. 118, 119 and 120. The viewfinder lens has the same focal length and diameter as that associated with the camera tube and is mounted with its axis parallel to that of the camera lens and on the same holder; both lenses therefore move together when the focus control is adjusted. The viewfinder screen is positioned in the same plane as the camera-tube mosaic, and if the focus control is adjusted to bring the viewfinder image into focus, the image on the mosaic must also be in focus. The viewfinder image is, of course, upside down and laterally inverted, but camera operators soon become accustomed to this; it may prove a slight disadvantage, however, when an operator who is experienced with this form of viewfinder has to operate a camera with an electronic viewfinder in which the image is not inverted.

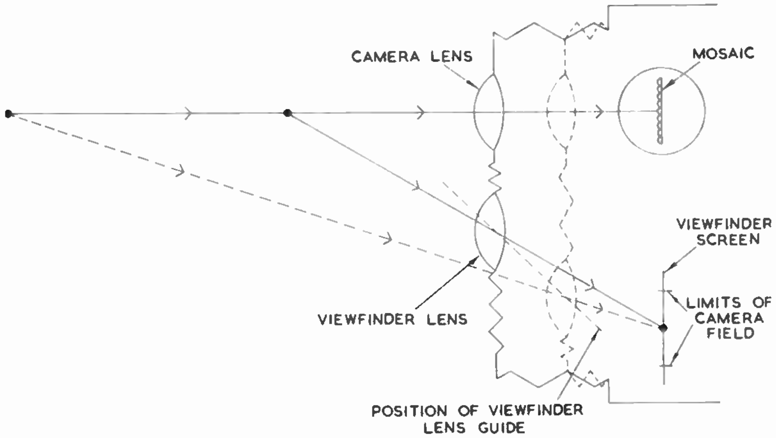

Fig. 118—Viewfinder of a standard Emitron camera

The camera field must be in the same position on the viewfinder screen irrespective of object distance. To achieve this the straight line passing through the centre of the viewfinder screen and the centre of the viewfinder lens must intersect the axis of the camera lens at the point on which both lenses are focused. The viewfinder lens must therefore be capable of moving laterally away from or towards the camera lens as both lenses are moved longitudinally by the focusing control, the arrangement being such that the lenses move apart while they are moved back to focus a distant object.

For a given object distance the setting of the focus control depends on the focal length of the lens used; if, therefore, the camera and viewfinder lenses are changed for others of different focal length, the relationship between lateral and longitudinal movements of the viewfinder lens must be altered. The lateral movement of the viewfinder lens can be accomplished by a stud which is mounted on the lens holder and engages with a slot inclined at an angle to the lens axis; in such an arrangement the angle between the slot and the lens axis can be varied to suit the focal length of the lenses in use.

Advantages and Disadvantages of Standard Emitron Viewfinder

A viewfinder of this type has a number of useful features in addition to the essential requirements of indicating the camera field and camera focusing; for example, if the viewfinder screen is made larger than the mosaic, the angular field of the viewfinder is larger than that of the camera lens. This is a help to the camera operator, for if the camera-lens field is marked on the viewfinder screen, the operator can see what objects will come into the field of view of the camera lens when the camera is moved. Without such a facility the operator must look along the camera to estimate how far the camera can be moved before unwanted objects or scenes come into the view of the camera lens; it is quite possible for essential action in the programme to be lost or for the camera lens to go out of focus while the operator's attention is removed from the viewfinder.

A second advantage of this optical type of viewfinder is that the depth of field of the viewfinder can be made more limited than that of the camera lens, enabling the camera operator to notice degradation of focus before it becomes noticeable to the viewers. This facility is obtained by having a larger aperture for the viewfinder lens than for the camera lens. The viewfinder aperture is, however, normally greater than the camera-lens aperture for reasons unconnected with viewfinding; the lens of an optical viewfinder is usually used at large aperture to give a bright image, whereas with a sensitive camera tube the camera lens is generally stopped down to give good depth of field and to minimize lens aberrations. The degree to which the camera lens can be stopped down depends on the sensitivity of the camera tube; the sensitivity of the standard Emitron tube is so limited that it is usually necessary to operate

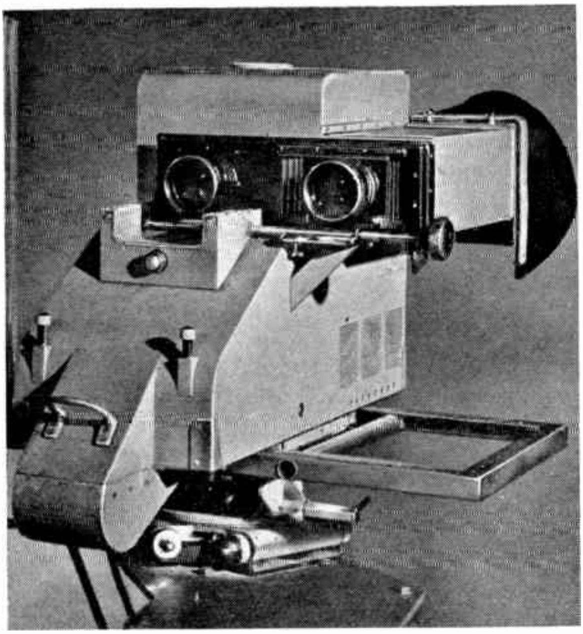

Fig. 119—Standard Emitron camera (front view)

Fig. 120—Standard Emitron camera (rear view)

the camera lens at full aperture. Thus the depths of field of viewfinder and camera lens are equal and all the advantages of the viewfinder are not realized with this tube.

In the simple form shown in Fig. 118 the optical viewfinder does not add greatly to the weight or the bulk of the camera, but it may do so if arrangements are incorporated for the simultaneous changing of camera and viewfinder lenses, and this possibly constitutes the greatest disadvantage of this form of viewfinder.

In general, optical viewfinders have a number of advantages; they give good indication of camera focus (particularly if the camera tube is sensitive, permitting its lens to be stopped down) and can be designed to give a larger field of view than the camera lens. An advantage not mentioned earlier is that such viewfinders give coloured images, and it is easier to detect the optimum focus position for a coloured image than for a monochromatic one, such as that obtained from an electronic viewfinder, where the contrast due to colours is absent. At the expense of some complexity in the equipment, optical viewfinders can be designed for use with a camera equipped with a lens turret.* The most serious disadvantage of the optical viewfinder is that a fair scene illumination is necessary to give a reasonably bright image; for this reason such viewfinders are generally used only with studio cameras. If such a viewfinder is used on an outside broadcast it is possible that the light from a poorly lit scene may be inadequate to give a good image in an

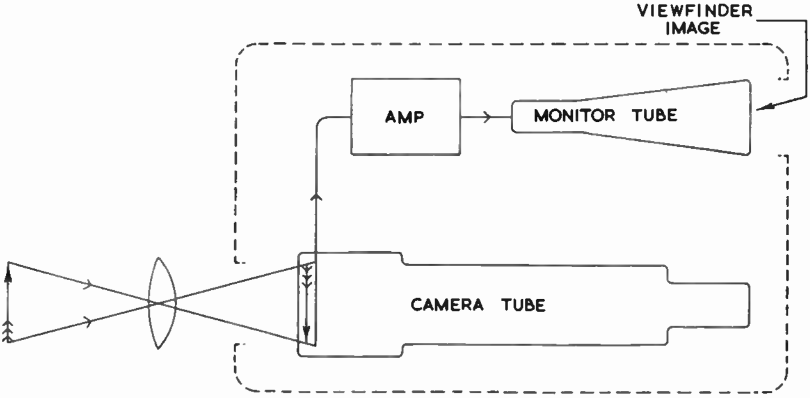

Fig. 121—An electronic viewfinder

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* See, for example, T. Worswick and J. L. Bliss, " Design Features of a Television Camera with a Single-lens Optical Viewfinder." *Proceedings of the I.E.E. Television Convention* 1952, Paper No. 1313.

Fig. 122—Rear view of image iconoscope camera showing viewfinder hood

optical viewfinder though quite adequate to produce an acceptable picture from a sensitive camera tube.

Electronic Viewfinders

Cameras more sensitive than an iconoscope generally have a viewfinder consisting of a small cathode-ray tube fed via amplifiers from the camera-tube output (Fig. 121). These can be seen in the two television cameras illustrated in Figs. 122 and 123. This electronic form of viewfinder overcomes a number of the disadvantages of the optical viewfinder; for example, no separate lens system is required for the viewfinder, and the camera lens mounting can be designed without regard to viewfinder requirements. Moreover, provided the camera tube can produce a satisfactory signal-noise ratio at its output, the viewfinder image can be made as bright as desired even if the scene brightness is low. Electronic viewfinders have, however, a number of disadvantages; for example, they do not show degradation of optical focus as readily as optical viewfinders. To keep camera bulk at a minimum the viewfinder cathode-ray tube must be small (say 3 inches in diameter), and it is more difficult to detect variation of camera focus by inspection of the small images from such a tube than from the larger images of television receivers or the coloured images of optical viewfinders. Clearly it is most important that the electrical focus of the viewfinder tube should be kept in very accurate adjustment. Fortunately the chances of the optical system of a sensitive camera going out of focus are more remote than with less sensitive cameras because the lens of a sensitive camera can be stopped down to give a large depth of field. A second disadvantage of an electronic viewfinder is that its field of view cannot without great difficulty be made appreciably greater than that of the camera lens: thus the viewfinder gives no indication of what objects will come into view when the camera is moved. Thirdly, electronic viewfinders necessarily add to the size and weight of the camera, which must accommodate not only the viewfinder tube but also its e.h.t. supply unit, time-base generators and amplifiers. It is quite convenient, however, to accommodate all the equipment associated with the viewfinder in a unit which can be detached from the camera whenever the services of the viewfinder can be dispensed with.

9.21 Optical Systems in Projection Television

In the majority of television receivers the picture is produced on the face of a cathode-ray tube which is viewed directly or by reflection at a plane mirror. Receivers of this type can be produced at a reasonably low cost provided that the pictures are small enough to be accommodated on the face of a cathode-ray tube not exceeding about 12 inches in diameter, but the cost of the tube increases sharply and receivers become correspondingly expensive when larger pictures are required.

Cathode-ray Tube

One way out of this difficulty is by optically enlarging a small bright image produced on the face of a small cathode-ray tube. In projection receivers which use such a principle a picture measuring 18 inches by 14 inches can be obtained from a cathode-ray tube with a face diameter of 2·5 inches, the light being projected on to a translucent screen. Alternatively the light can be projected on to a reflecting screen external to the cabinet: by this means a picture measuring 48 inches by 36 inches can be obtained. The tube is conventional in design but must be made to close tolerances, because the spot where the beam meets the face must be very small in order to build up a picture of several hundred lines in a small area. The light liberated from the cathode-ray tube may finally cover an area nearly 100 times that of the picture on the tube face (several hundred times for external projection): thus the picture on the tube face must be very bright. To this end an

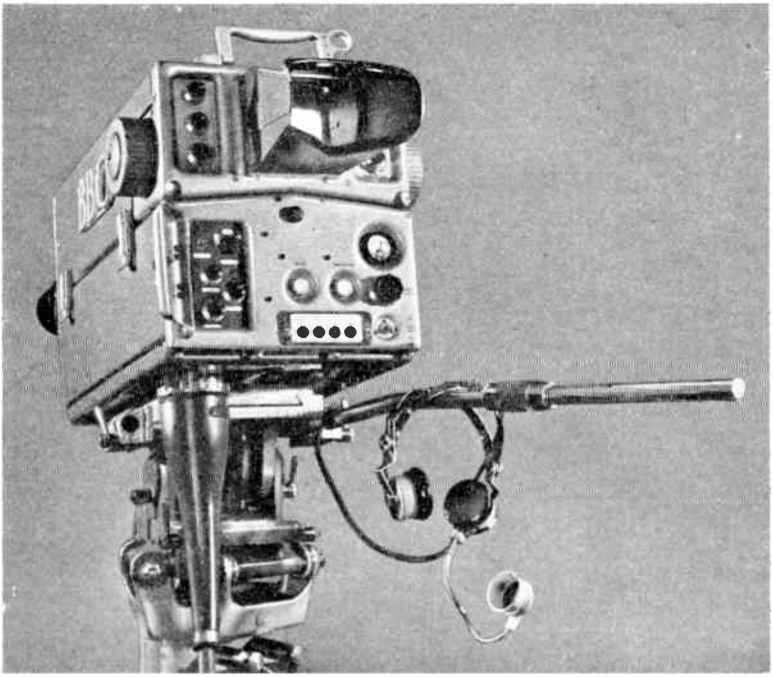

Fig. 123—Rear view of an image orthicon camera showing a portion of the view-finder screen through the hood

e.h.t. supply of the order of 25 kV is necessary, and the tube face is backed with a thin skin of aluminium. This improves the brightness of the image by reflecting forward light which would otherwise be lost in the interior of the tube. It also improves the contrast of the image by making the face more opaque to light developed inside the tube and stabilizes the screen potential by improving its conductivity. The metal backing also prevents the screen being blackened by bombardment by heavy negative ions, being relatively impervious to these, though transparent to electrons.

Optical System

The small bright image produced by the cathode-ray tube can be enlarged by a lens system or a spherical mirror system, but the latter is generally used because it enables the optical system to be made very compact, as illustrated in Fig. 124. This is a modified form of the optical system developed by Schmidt for use in astronomical telescopes, but the light path is folded to save space. Light from the tube face is reflected at a concave mirror which is placed at a distance between the focal length and radius of curvature from the face, this being the condition for producing a magnified real image (see page 146). The reflected light strikes a plane mirror which is inclined at 45 deg to the tube axis and contains a hole

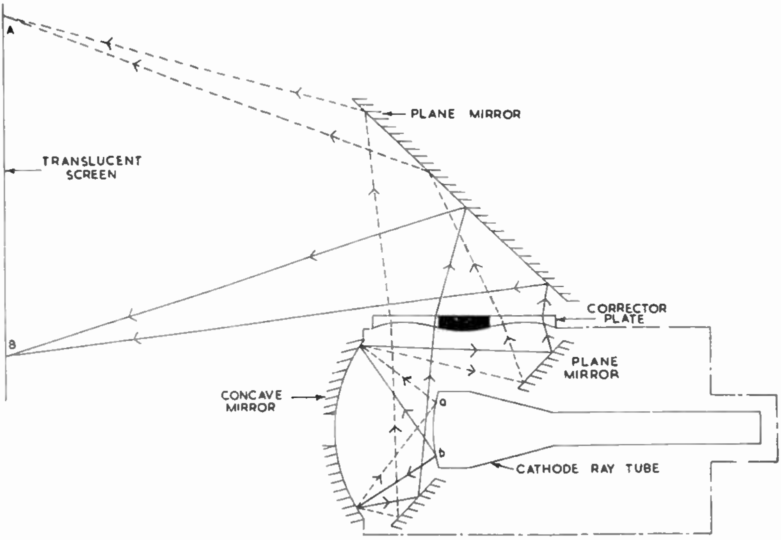

Fig. 124—Optical system used in projection television receivers

just large enough to accommodate the tube face. After reflection at the plane mirror, the light passes through a corrector plate and strikes a second plane mirror to form an image on the translucent receiving screen.

The diagram shows how light from points a and b on the tube face are brought to a focus at points A and B, respectively, on the translucent screen; the beam from any particular point on the tube face is out of focus at the first plane mirror and is spread over its surface, as indicated in the diagram. Thus the light loss due to the hole in the first plane mirror is the same for beams from any point on the tube face and the image is uniformly illuminated.

The area around the pole of the concave mirror must not be used in forming the final image because it returns light from the face of the cathode-ray tube back to the tube face, where it is scattered and degrades contrast in the final picture. The outer area of the concave mirror is therefore used: this gives rise to considerable spherical aberration and a corrector plate is necessary to minimize it. The spherical aberration produced by a concave mirror is illustrated in Fig. 125 (*a*): this shows that rays of light originating from a point source are brought to different focal points, depending on what part of the mirror they strike. Rays reflected at points on the mirror at some distance from the pole are focused nearer the mirror than rays reflected at points near the pole. The aberration could be corrected by a plate of spherical form, but the corrector would need to be of considerable thickness and expensive. By use of an aspherical surface the corrector can be made thin as shown in Fig. 125 (*b*). The centre of the corrector is parallel-sided and the focal point for rays reflected near the pole of the concave mirror is therefore unaffected: the outer area of the corrector has plano-concave form and brings rays reflected at the outer area of the concave mirror to the same focal point as rays reflected nearer the pole of the mirror. The slope of the surface of the corrector plate shown in Fig. 125 (*b*) can be reduced by combining with it a plano-convex lens to give the shape shown in Fig. 125 (*c*). This reduces the throw of the optical system but simplifies manufacture of the corrector plate.

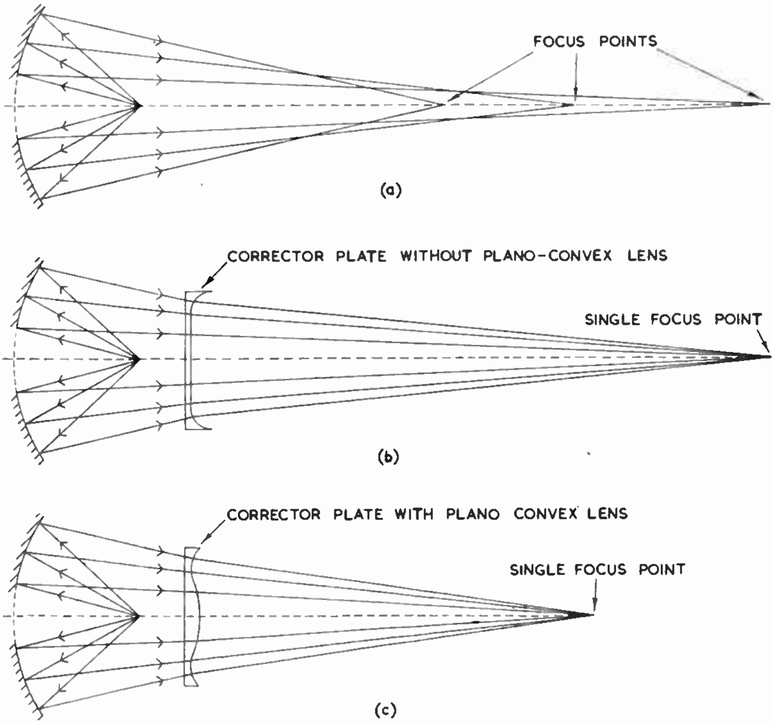

Fig. 125—Correction of spherical aberration in projection television system

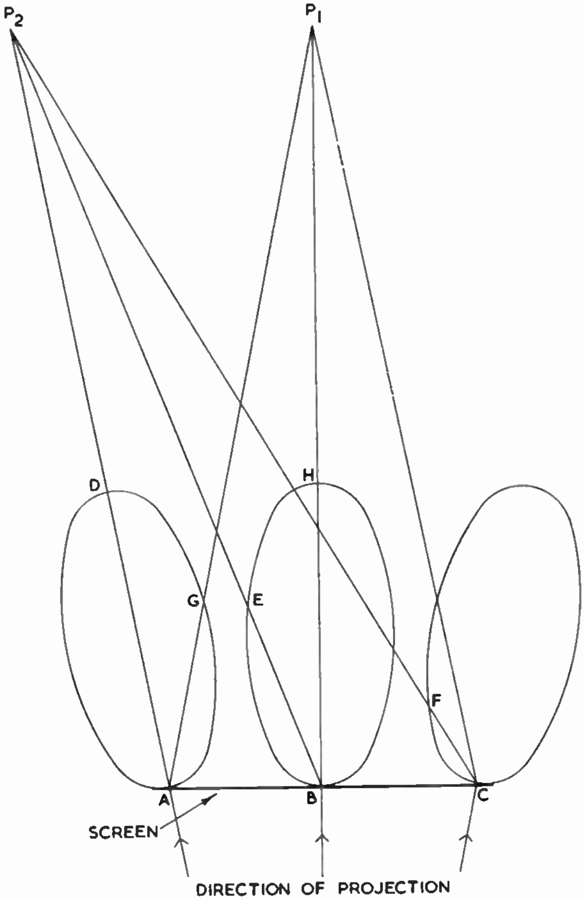

Fig. 126—Distribution of light in the horizontal plane from a simple diffusing surface

Glass aspherical surfaces are difficult to manufacture and one type of corrector plate is made of transparent gelatine by a most ingenious method described by Rinia, de Gier and van Alphen.* Very briefly, a negative mould is made for the corrector but the variations in depth of contour are exaggerated by a chosen factor. The mould is heated and a solution of gelatine in water is poured in, the mould being closed by a plane sheet of glass which excludes excess solution. After the mould has cooled, the glass plate is

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* H. Rinia, J. de Gier and P. M. van Alphen, " Home Projection Television.' Part I, Cathode-ray Tube and Optical System. *Proceedings I.R.E.*, pp. 395–400: Vol. 36, No. 3, March 1948.

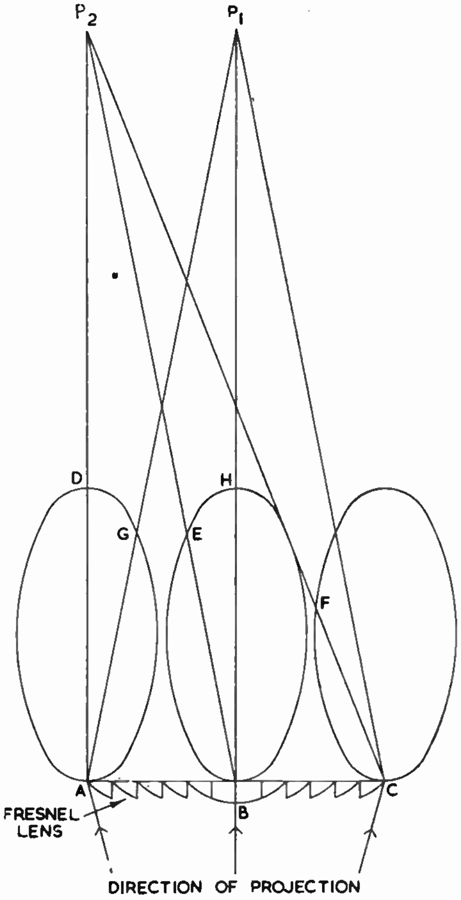

Fig. 127—Distribution of light in the horizontal plane from a screen backed by a Fresnel lens

removed with the gelatine adhering to it and the gelatine is allowed to set. During setting the solution shrinks due to loss of water, but it does not wrinkle because the shrinkage takes place only in a direction at right angles to the glass plate: it was this observation which made the method possible. When the gelatine has dried, it presents a hard surface which can be cleaned, but the corrector is robust because it is mostly of glass. By varying the water content of the gelatine solution the shrinkage can be controlled and correctors of different optical powers, suitable for various throw distances, can be produced.

Viewing Screens

The viewing screen was originally a sheet of plane ground glass, the picture being projected on one side and viewed from the other. Such a screen is not very efficient, however, because there is a serious loss of illumination at one side of the screen when it is viewed obliquely. This is illustrated in Fig. 126, which shows the polar diagram of light radiated in the horizontal plane from a plane ground glass screen. Maximum light radiation occurs along the direction of projection and this results in non-uniform light distribution when the screen is viewed from a point such as P_2. The light received from the near side of the screen is a maximum, being measured by length AD, but that received from the far side is much less than this, being measured by length CF. This effectively limits the horizontal viewing angle to between 20 and 30 deg. A viewer positioned on the axis of the screen at a point such as P_t will notice a slight falling-off of illumination towards the edges of the picture, the light from the edge being measured by AG while that from the centre is given by BH.

Some of the light reaching the screen is wasted because it is radiated at appreciable angles to the normal, and an improvement in efficiency can be obtained by using a less optically dense screen on which vertical rulings have been made. This gives improved horizontal radiation and increases efficiency by nearly 50 per cent.

A further improvement in the performance of the screen can be obtained by shaping the rear into a Fresnel lens as shown in Fig. 127. This has the effect of refracting light received at angles to the normal at the rear of the screen and redirecting it so that maximum radiation leaves the screen in a normal direction. This considerably reduces the variations in illumination over the surface of the screen and gives an effective viewing angle of approximately 60 deg, more than double that of a plane screen. A screen with a Fresnel lens and vertical rulings can give a light gain up to eight times that available from a simple diffusing surface.

CHAPTER 10

ELECTRON OPTICS

10.1 INTRODUCTION

THE action of television camera tubes is dependent on an electron beam which is focused on the target and deflected so as to cover it in a series of scanning lines; at the other end of the television chain a somewhat similar process occurs in the cathode-ray tubes used to display television images. The ability to focus and deflect electron beams to produce a desired pattern on a screen plays a very important part in television engineering, and this chapter is devoted to the fundamental principles which decide the behaviour of electrons subjected to electric and magnetic fields. We shall show that electrons travelling in the region containing such fields experience deflections comparable with those of a ray of light in a region containing different transparent media. This analogy between the behaviour of electron beams and light beams is very useful: an electron beam can be focused by means of coils carrying direct current or by systems of charged conductors; no matter which means is adopted, the resultant magnetic or electric field can be regarded as a lens, and its effect on the electron beam can be calculated from the laws governing optical lenses described in the previous chapter. Because of the similarity between the behaviour of electron beams and light beams, the study of electron motion in the presence of electric and magnetic fields has been termed *Electron Optics*. Only the basic features of the subject are given here; for more detailed information reference should be made to the bibliography at the end of this book.

10.2 INTENSITY AND POTENTIAL OF AN ELECTRIC FIELD

An electric field is a region between two charged conductors in which an electric charge experiences a force. This force is present whether the charge is stationary or moving with respect to the field (cf. an electron in a magnetic field). The force acting on a unit charge at any point in an electric field is known as the electric field strength or intensity ϵ. This is a vector quantity because force has magnitude and direction, and in diagrams of electric fields it is usual to represent the direction of the intensity at any point by arrowed lines, the number of lines in a given area indicating the magnitude of the intensity. Such a diagram is Fig. 128, which illustrates a uniform electric field between two parallel conducting plates, one of which is maintained at a steady potential with respect to the other. The direction of the field is from the positive to the negative plate, because this is the direction in which a positive charge would be urged. The force on an electron in this field is $e\epsilon$ and is in the opposite direction to the field because the electron charge e is negative.

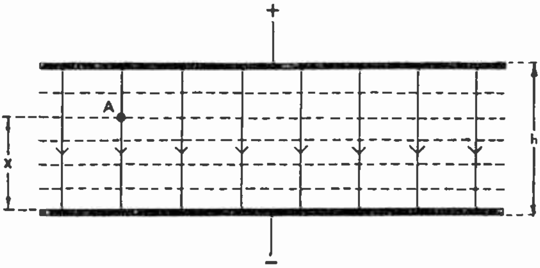

Fig. 128—A uniform electric field. Intensity is shown by solid arrowed lines and equipotential surfaces by dotted lines

It is usual in electron optics to represent stationary electric fields by indicating the electric potential at various points instead of showing the lines of intensity. Potential is a scalar quantity having magnitude only and is equal to the work done in bringing a unit charge from a point at some reference potential to the point in question. The work done is independent of the length and direction of the path taken between the two points.

For example, if a unit charge is moved from the negative to the positive plate in Fig. 128, the work done is given by

$$\text{force} \times \text{distance} = \epsilon h$$

where h is the perpendicular distance between the plates. This is therefore the potential V of the positive plate with respect to the negative plate.

$$\therefore \quad V = \epsilon h \qquad \ldots \qquad \ldots \qquad \ldots \quad (53)$$

from which ϵ, the intensity at any point between two parallel plates, is given by V/h, i.e.,

$$\text{intensity} = \frac{\text{difference in potential}}{\text{distance}}$$

For example, if the potential difference between the two plates in Fig. 128 is 1,000 volts and the separation 5 cm, the intensity is $1{,}000/5 = 200$ volts per centimetre. Intensity is a differential quantity and is measured by the rate of change of potential with distance; it may be compared with the gradient of a hill, which is measured by the rate of change of height with distance.

From expression (53) the potential of point A in Fig. 128, measured with respect to that of the negative plate, is equal to ϵx. The potential is thus directly proportional to x and is the same at any point in a plane parallel to the negative plate and at a distance x from it. Such a plane is termed an *equipotential surface*, and a number of such surfaces are shown in dotted lines in Fig. 128.

A conducting surface must be an equipotential surface. If any difference of potential exists between two points on the same conductor, current flows from one point to the other; provided the potential difference is not maintained by external sources of e.m.f., the current continues to flow until the potentials at the two points are equal. Thus in Fig. 128 the two conducting plates may be regarded as the initial and final equipotential surfaces, i.e., the surfaces which define the boundary of the field.

Electric fields are frequently represented by a series of equipotential surfaces, usually drawn for equal increments in potential. Sometimes, as in Fig. 129, the surfaces are labelled with their particular value of potential.

No work is done in moving a charge along an equipotential surface. Thus there cannot be any component of electric intensity along such a surface, and at any point in an electric field the intensity is always at right angles to the equipotential surface at that point.

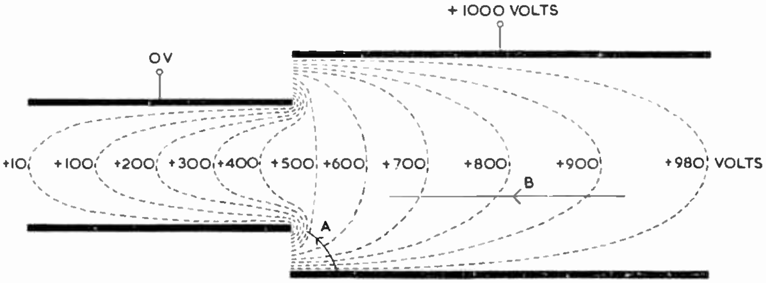

Fig. 129—Equipotential surfaces in the neighbourhood of two charged coaxial cylinders

This is illustrated for a uniform parallel field in Fig. 128, but the statement is universally true and in Fig. 129 is illustrated for the electric field between two charged coaxial cylinders. The cylinders are themselves the initial and final equipotential surfaces.

The difference in potential δV between two equipotential surfaces is equal to the work done in moving a unit charge from one surface to the other. As before, the work is independent of the path taken and the charge may be moved in any direction. The work is given by $\epsilon\delta x$, where ϵ is the average value of the intensity between the surfaces *measured in the direction of the chosen path* and δx is the distance through which the charge is moved along that path.

$$\therefore \quad \delta V = \epsilon\delta x$$

from which
$$\epsilon = \frac{\delta V}{\delta x}$$

If the unit charge is moved from one surface to the next along the perpendicular to the surfaces, the expression $\delta V/\delta x$ gives the field strength, i.e., the maximum intensity: but if the path makes an angle θ to the normal, the expression gives the component of the field along the chosen path.

The expression $\delta V/\delta x$ again shows that intensity is the rate of change of potential with distance. This is a useful result, for if an electric field is indicated by a series of equipotential surfaces drawn for equal increments of potential, the intensity will be greatest in those regions where the surfaces are most crowded. For example, in Fig. 129 the intensity is greater at A than at B.

A similar result holds for a map with equal-height contours; hills have maximum slope at the points where the contours are most crowded.

10.3 Behaviour of an Electron in a Uniform Electric Field

(*a*) *When the Initial Electron Velocity is Parallel to the Field*

An electron in a uniform electric field of intensity ϵ experiences a force $e\epsilon$ which acts in the opposite direction to the electric field, i.e., the force is in the direction of increasing positive potential. The motion of the electron under this force can be deduced from Newton's law:

$$F = ma$$

from which
$$\epsilon e = ma \qquad \ldots \quad \ldots \quad \ldots \quad (54)$$

where F = the force acting on the electron,
m = mass of the electron
and a = acceleration of the electron.

If the electron is initially at rest and the force acts for a time t, the velocity v acquired at the end of this time is given by

$$v = at$$

and substituting for a from (54):

$$v = \frac{\epsilon e}{m}t \qquad \ldots \quad \ldots \quad \ldots \quad (55)$$

The distance d moved by the electron during this time is given by

$$d = \tfrac{1}{2}at^2$$

$$= \frac{e\epsilon}{2m}t^2 \quad \ldots \quad \ldots \quad \ldots \quad (56)$$

Substituting for t from (55):

$$ed = \frac{mv^2}{2\epsilon}$$

from which $\tfrac{1}{2}mv^2 = d\epsilon e$

From (53), $d\epsilon$ is equal to the potential difference V through which the electron has moved.

$$\therefore \quad \tfrac{1}{2}mv^2 = eV \quad \ldots \quad \ldots \quad \ldots \quad (57)$$

Thus the kinetic energy $\tfrac{1}{2}mv^2$ acquired by the electron is equal to the product of its charge and the potential difference through which it has moved. The velocity acquired by an electron which has moved from rest through a potential difference of V is, from (57), given by

$$v = \sqrt{\left(\frac{2eV}{m}\right)} \quad \ldots \quad \ldots \quad (58)$$

and is thus proportional to the square root of the potential difference.

The mass of an electron is 9·107 × 10^{-28} gramme and its charge is 4·77 × 10^{-10} absolute electrostatic unit. If these values are substituted in (58) we have

$$v = 5{\cdot}96 \times 10^7\sqrt{V} \text{ centimetres per second} \quad \ldots \quad \ldots \quad (59)$$

where V is in volts.* This shows that a very small voltage can produce enormous electron velocities; for example, if V is put equal to 1 μV in expression (59) v is 5·96 × 10^4 centimetres per second—approximately 1,300 miles per hour! In spite of this high velocity the kinetic energy of the electron is low because of the minute mass.

For an accelerating potential of 2 kV, such as is used on the final anode of small cathode-ray tubes, the electron velocity calculated from expression (59) is approximately 2·7 × 10^9 centimetres per second, just less than one-tenth the velocity of light. This result is approximate because expression (58) holds only for electron velocities, which are small compared with that of light. If the electron velocity is appreciable compared with that of light, the electron behaves as though its mass is greater than that of a stationary electron, and this apparent increase in mass becomes greater as the electron velocity approaches that of light. In calculating

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* 1 volt = 1/300 absolute electrostatic unit of potential.

electron velocities attained with accelerating potentials greater than approximately 2·5 kV, allowance must be made for the increase in mass.

Expression (57) shows that the kinetic energy of an electron can be expressed in electron-volts, and expression (59) shows that electron velocities can be stated in terms of volts, a velocity of V volts being that attained by an electron moving from rest through a potential difference of V volts.

If an electron enters an electric field with a velocity v_0 (corresponding to a potential V_0) parallel to the field, its final velocity v after moving through a potential difference V is given by

$$\tfrac{1}{2}m(v^2 + v_0^2) = e(V + V_0) \quad .. \quad .. \quad .. \quad (60)$$

which corresponds to expression (57). By putting $V = -V_0$ in (60) we can see that the kinetic energy of the electron is reduced to zero: thus if an electron enters a retarding field of sufficient magnitude it will be brought to rest. If the retarding field is still stronger, the electron will, after stopping, be accelerated backwards along its incident path.

(*b*) *When the Initial Electron Velocity is at Right Angles to the Field*

The shape of the path traced by an electron which enters an electric field at right angles is of great practical importance because this occurs in cathode-ray tubes and television camera tubes with electrostatic deflection.

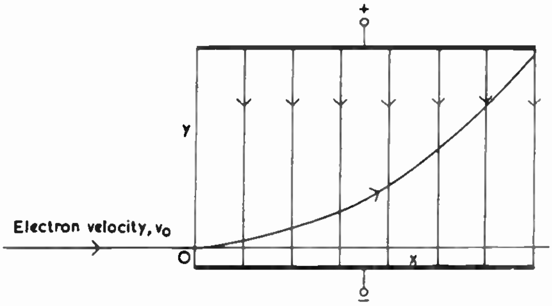

Fig. 130—Path of an electron after entering an electric field at right angles

Suppose the electron has an initial velocity v_0 parallel to the x-axis (Fig. 130) and that the point O, where the electron enters the vertical field, is the origin of Cartesian co-ordinates.

As soon as the electron enters the field it experiences an upward force in the direction opposite to that of the arrows and this gives rise to a vertical component of velocity which is independent of the horizontal motion. Thus the electron motion has two components and takes the form of the curve shown.

The horizontal component of velocity of the electron is unaffected by the electric field and is described by the equation

$$x = v_0 t \quad \ldots \quad (61)$$

The vertical component of velocity is described by equations (54) to (58).

From equation (56):

$$y = \frac{e\epsilon}{2m} t^2 \quad \ldots \quad (62)$$

Eliminating t between (61) and (62):

$$y = \frac{e\epsilon}{2m} \cdot \frac{x^2}{v_0^2} \quad \ldots \quad (63)$$

But, from (58):

$$v_0^2 = \frac{2eV_0}{m}$$

where V_0 is the potential through which the electron has moved prior to entering the deflecting field.

Substituting for v_0^2 in (63):

$$y = \frac{1}{4} \cdot \frac{\epsilon x^2}{V_0} \quad \ldots \quad (64)$$

Since ϵ and V_0 are constants, this may be rewritten:

$$y = \text{a constant} \times x^2$$

which shows that the electron path has the shape of a parabola. The slope of the parabola at any point (x, y) is given by

$$\frac{dy}{dx} = \frac{1}{dx} \cdot \frac{\epsilon x^2}{4V_0}$$

$$\therefore \quad \frac{dy}{dx} = \frac{\epsilon x}{2V_0} \quad \ldots \quad (65)$$

(*c*) *When the Initial Electron Velocity is at an Angle θ to the Field*

If an electron enters an electric field obliquely as shown by the solid curve in Fig. 131, its initial velocity v_0 can be resolved into two components $v_0 \cos \theta$ parallel to the field and $v_0 \sin \theta$ at right angles to it. The effects of the field on these two components can be considered separately.

As explained above, the component $v_0 \cos \theta$ is uniformly increased if the electron is proceeding in the direction of increasing positive potential. The component $v_0 \sin \theta$, at right angles to the field, gives rise to a parabolic path as pictured in Fig. 130. If the two motions are combined, the resultant path has a shape such as that shown in Fig. 131. The shape approximates to a straight line when θ approaches zero.

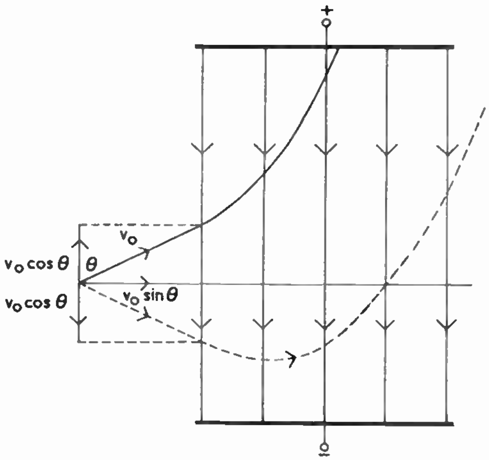

Fig. 131—Paths of an electron entering an electric field at a small angle

The dotted line in Fig. 131 shows the path taken by an electron when the component of velocity parallel to the field is opposite to the direction of increasing positive potential. This component is reduced to zero and then reversed, giving a path curved as shown by the dotted line in the figure.

10.4 BEHAVIOUR OF AN ELECTRON IN A UNIFORM MAGNETIC FIELD

A magnetic field is a region in which a magnetic pole experiences a force, and the force acting on a unit pole at any point in the field is known as the magnetic field strength H at that point. This is a vector quantity because force has magnitude as well as direction, but in diagrams of magnetic fields it is usual to represent the direction of the field at any point by arrowed lines, the number of lines shown in a given area indicating the magnitude of the field in that area.

A conductor carrying a current and situated in a magnetic field experiences a force which acts at right angles to the magnetic field and to the conductor; the magnitude of this force is proportional to the field strength, the current, the length l of the conductor included in the field and the sine of the angle θ between field and current. In Fig. 132 the magnetic field is assumed at right angles to the plane of the paper, acting downwards into it. F (in dynes) is given by

$$F = \frac{1}{10} HIl \sin \theta \quad \ldots \quad \ldots \quad \ldots \quad (66)$$

where H is in oersteds, I in amps and l in centimetres.

The force (in dynes) on a moving electron is given by

$$F = -\frac{1}{10} Hve \sin \theta \quad \ldots \quad \ldots \quad (67)$$

where H is in oersteds, v in centimetres per second and e in coulombs.

For a given direction of current or electron velocity the force on an electron is in the opposite direction to that experienced by a conductor carrying a current. The relationship between the directions of field, electron velocity and force is explained in Appendix H and is illustrated in Fig. 133, in which the lines of magnetic intensity are assumed to be at right angles to the paper and pointing down into it.

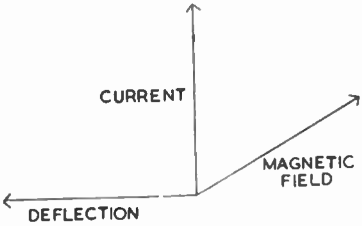

Fig. 132—Force on a current-carrying conductor in a magnetic field

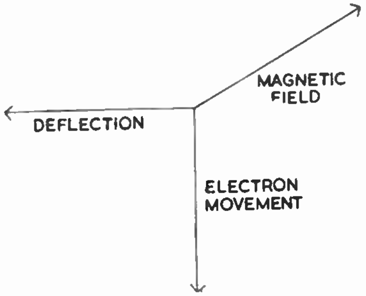

Fig. 133—Force on an electron moving in a magnetic field

From expression (67), there is no force on a stationary electron ($v = 0$). In this respect the effect of a magnetic field on an electron differs from that of an electric field, in which a stationary electron does experience a force.

(*a*) *When the Initial Electron Velocity is Parallel to the Field*

If an electron enters a magnetic field in a direction parallel to the field, $\theta = 0$ and, from expression (14), there is no force on the electron, which thus moves through the field at a uniform rate equal to the initial velocity and in the same direction. Expressed differently, the electron path does not cut the lines of magnetic intensity, and no deflecting force acts on the electron.

(*b*) *When the Initial Electron Velocity is at Right Angles to the Field*

Expression (67) shows that the deflecting force on an electron moving in a magnetic field is a maximum when $\theta = 90$ deg, i.e., when the electron path is at right angles to the lines of magnetic intensity. In Fig. 134 the arrow v_1 represents the initial direction of the electron and H represents the direction of magnetic intensity, which is assumed to be at right angles to the page and acting down into it. Interaction between v_1 and H produces a downward deflecting force F_1 as shown, and under the action of this force the electron path is curved downwards. Thus after the electron has been in the field for a short time the instantaneous direction of its velocity is as shown by the arrow v_2.

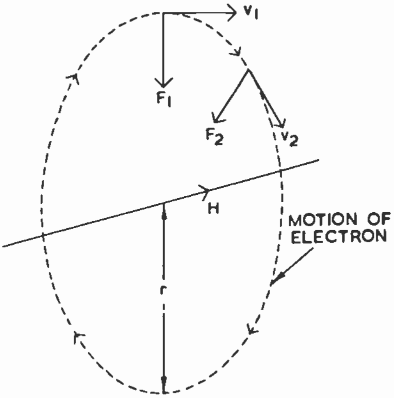

Fig. 134—Circular motion of an electron in a magnetic field

This deflection of the electron path immediately produces a corresponding change in the direction of the deflecting force, which always acts at right angles to the instantaneous direction of the electron velocity and to the magnetic field. Thus, when the velocity is in the direction indicated by v_2, the direction of the deflecting force is given by F_2. Under the stimulus of this force the electron path is bent even more steeply downwards, and this in turn causes a further change in the direction of the deflecting force.

As a result of these continual changes in the direction of the electron velocity and the corresponding changes in the direction of the force, the electron pursues a circular path of radius r as shown in Fig. 134. The electron rotates in this path continuously at a constant speed equal to the initial velocity v_1 on entering the field; the magnetic field does not alter the magnitude of the electron velocity but only its direction.

The radius of the circle described by the electron can be evaluated by equating the magnetic deflecting force with the centripetal force due to the circular motion:

$$Hev = \frac{mv^2}{r}$$

from which

$$r = \frac{mv}{He} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (68)$$

Substituting $m = 9{\cdot}107 \times 10^{-28}$ gramme, $e = 1{\cdot}59 \times 10^{-20}$ absolute electromagnetic unit* and $v = 5{\cdot}96 \times \sqrt{V}$ centimetres per second (expression 59), we have

$$r = 3{\cdot}37 \frac{\sqrt{V}}{H} \text{ centimetres}$$

where V is the potential difference in volts through which the electron has moved in acquiring its velocity v and H is the magnetic field strength in oersteds. From (68) the radius of the electron orbit is increased by increasing V or by decreasing H.

The time T taken for the electron to describe one complete circle is obtained by dividing the circumference of the circle by the velocity:

$$T = \frac{2\pi r}{v}$$

Substituting for r from (68):

$$T = \frac{2\pi m}{eH}$$

Substituting for m and e, we have*

$$T = \frac{0{\cdot}355 \times 10^{-8}}{H} \text{ second} \quad \ldots \quad \ldots \quad (69)$$

in which H is in oersteds. Thus the periodic time does not depend on the velocity of the electron.

(c) *When the Initial Velocity is at an Angle θ to the Field*

If an electron enters a magnetic field along a line making an angle θ with the lines of magnetic intensity, the component $v \cos \theta$ is parallel to the field and is unaffected by it. The component $v \sin \theta$ is at right angles to the field and results in a circular motion of radius $(mv \sin \theta)/He$, as shown by expression (68). This radius is $3{\cdot}37 \sqrt{V} \sin \theta / H$ centimetres, in which V is in volts and H in oersteds. The combination of the linear and circular motion is to cause the electron to describe a helical path as shown in Fig. 135.

---

* In these two substitutions it is necessary to state the electron charge in electromagnetic units because H is normally expressed in these units.

The pitch of the helix is given by the product of the longitudinal velocity ($v \cos \theta$) and the periodic time T (expression 69):

$$\text{pitch of helix} = Tv \cos \theta$$

$$= \frac{2\pi mv \cos \theta}{He}$$

Expressing T as in expression (69) and v as in expression (58):

$$\text{pitch} = \frac{21{\cdot}2\sqrt{(V \cos \theta)}}{H} \text{ centimetres} \qquad .. \quad (70)$$

in which V is in volts and H in oersteds.

If θ is small, $\cos \theta$ is approximately unity and the pitch is given approximately by $21{\cdot}2 \sqrt{V}/H$ centimetres, where V is in volts and H in oersteds. Where θ is small, the pitch does not vary very greatly with θ: this is important in magnetic focusing, for if a number of electrons with different velocities enter a magnetic field at one point, the velocities making different but small angles to the field, they will describe helices of different radii but the same pitch: moreover they will all take the same time to describe the helices and all meet at one point after having described each complete loop. Points of focus therefore occur at intervals equal to the pitch along a line parallel to the magnetic field.

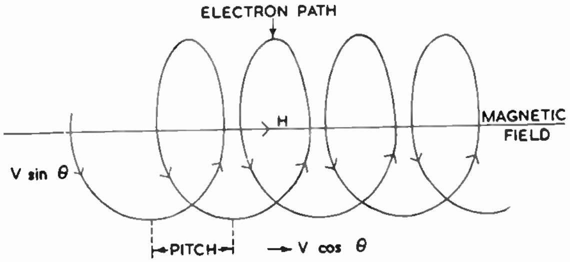

Fig. 135—Path of an electron entering a magnetic field at a small angle

10.5 BEHAVIOUR OF AN ELECTRON IN COMBINED ELECTRIC AND MAGNETIC FIELDS

The behaviour of an electron in a region where electric and magnetic fields coexist is difficult to determine except in certain simple examples. The only instance of such combined fields mentioned in this book occurs in the line-deflection system of the orthicon television camera tube, and this example will be examined in detail. The tube has a magnetic field parallel to its axis and an electric field at right angles to the axis as shown in Fig. 136; electrons enter the combined field parallel to the tube axis.

If there were no electric field, electrons would pass through the magnetic field in a straight line parallel to the axis and at constant velocity; since the electron velocity does not cut the field there is no lateral deflecting force. When the electric field is present the electron acquires a vertical component of velocity which cuts the magnetic field to produce a further lateral deflecting force on the now obliquely moving electron.

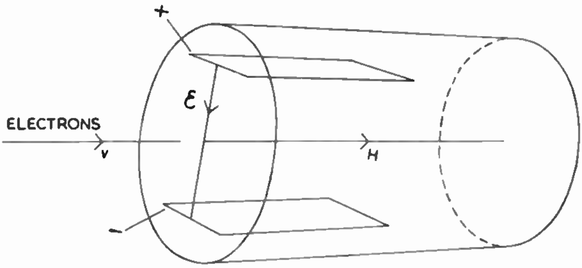

Fig. 136—Orientation of magnetic and electric fields in orthicon camera tube

Suppose the fields and the initial electron velocity have the directions shown in Fig. 137; to simplify the following explanation the longitudinal velocity *v* of the electron will be initially neglected. This velocity causes a uniform longitudinal movement of the electron along the tube axis and can be taken into account after the shape of the lateral motion has been deduced.

On entering the field the electron experiences a vertical accelerating force due to the electric field, but the vertical component of velocity produced by this force is small at first and the lateral deflecting force due to the magnetic field (which is proportional to the vertical component of the electron velocity) is correspondingly small. Initially, therefore, the electron tends to move vertically upwards in the direction of increasing electric potential. As the vertical velocity increases, the lateral deflecting force due to the magnetic field also increases and the electron path bends over to the right as shown in Fig. 137.

As the electron velocity changes direction the deflecting force due to the magnetic field also changes direction, since this force is always at right angles to the field and to the instantaneous velocity. This process is similar to that described on page 226, and the electron tends to take a circular path, with the result that the direction of electron velocity changes from vertically upwards to horizontal and

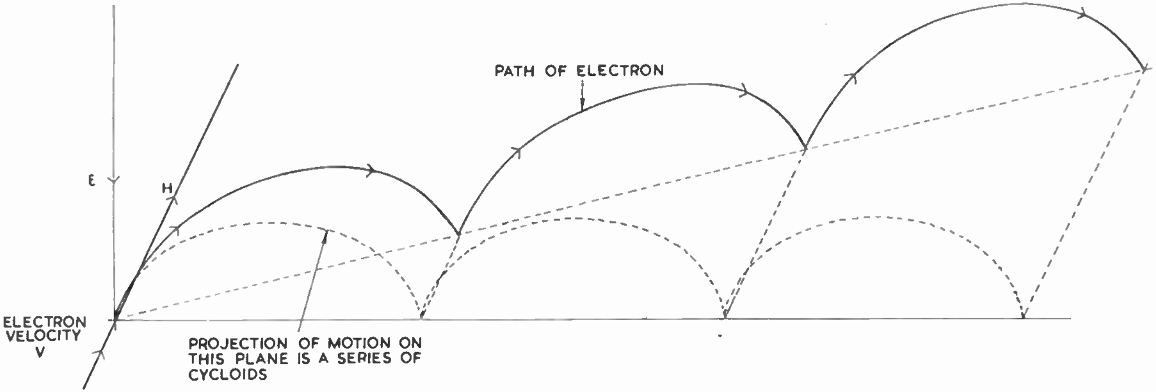

Fig. 137—Path taken by an electron in combined electric and magnetic fields

then to vertically downwards: at the same time the direction of the force due to the magnetic field which was initially to the right changes to downwards and finally to the left. The downwards velocity of the electron is reduced to zero by the electric field, which continuously exerts an upwards accelerating force on the electron. As the electron slows down, the magnetic force decreases and the lateral velocity becomes less. The electron velocity reaches zero when the electron is at a position on the same horizontal level at which it entered the fields. The electron velocity is zero only for an instant and under the influence of the vertical accelerating force moves upwards again, and the cycle of events just described continues as long as the electron is subject to both fields.

If the longitudinal velocity of the electron is neglected, the electron path is a series of cycloids* in a plane at right angles to the magnetic field as shown in Fig. 138. When the longitudinal velocity is added to this motion, the resultant electron path takes the shape shown in Fig. 137.

The time taken to describe each cycloid is independent of the electric field and inversely proportional to the magnetic field strength H; the amplitude of the cycloids is directly proportional to the electric intensity and inversely proportional to H. These results should be compared with the corresponding ones for an electron entering a magnetic field at right angles.

If the direction of the electric field is reversed, the electron moves downwards instead of upwards and the lateral deflecting force due to the magnetic field is initially to the left, i.e., the lateral displacement of the electron is in the opposite direction to that shown in Fig. 137.

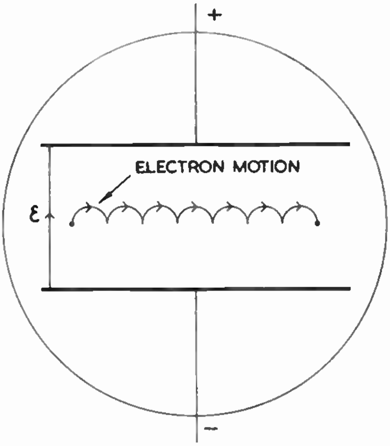

Fig. 138—Projection of electron motion in orthicon tube on a plane normal to the tube axis

The direction of lateral displacement of the electron in Figs. 137 and 138 depends only on the directions of the magnetic and electric fields and not on the direction of the initial velocity of the electron. Thus in these two diagrams the lateral displacement is to the right no matter whether the electron is initially stationary, proceeding

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* A cycloid is the path traced out by a point on the circumference of a circle when the latter rolls along a straight line.

downwards into the paper or upwards out of the paper. The direction of displacement is thus unaffected by reversing the initial electron velocity; this point is further elaborated on page 269.

10.6 ANALOGY BETWEEN ELECTRON BEAMS AND LIGHT BEAMS

An electron moving in a region of constant potential V_1 travels at a constant velocity v_1 proportional to $\sqrt{V_1}$. If it crosses a boundary into another region of constant potential V_2 (greater than V_1) its velocity increases to v_2 (proportional to $\sqrt{V_2}$) and, as shown in Fig. 139, its direction also changes, being deflected towards the normal. This change in direction is brought about by the electric intensity at the boundary between the two regions; the intensity is in the direction of the normal and causes a downwards accelerating force on the electron which increases its vertical component of velocity.

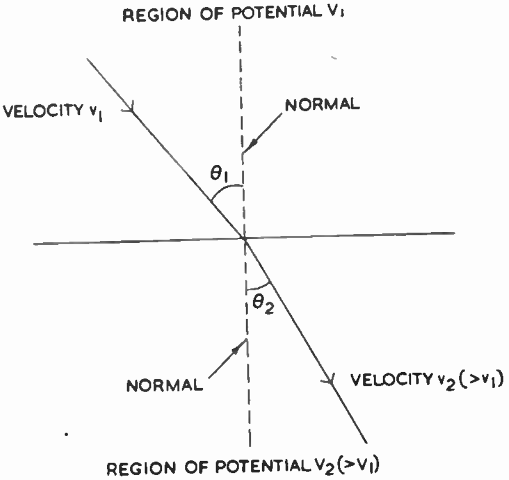


Fig. 139—Path of an electron passing from a region of potential V_1 to another of greater potential V_2

If V_2 is less than V_1, the electron is subjected to a vertical decelerating force as it crosses the boundary, with the result that the vertical component of velocity is reduced and the electron path is deflected away from the normal in the lower medium. Irrespective of the relative values of V_1 and V_2, the horizontal component of electron velocity does not change as the electron crosses the boundary: therefore

$$v_1 \sin \theta_1 = v_2 \sin \theta_2 \quad .. \quad .. \quad .. \quad (71)$$

Fig. 139 may be compared with Fig. 140, which illustrates a ray of light travelling with a velocity v_1 in a medium of refractive index n_1 and crossing a boundary into a medium of refractive index n_2 in which the light velocity is v_2. Rewriting Snell's law (expression (13) in Chapter 8) in terms of θ_1, θ_2, n_1 and n_2, we have

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{n_2}{n_1}$$

$$\text{i.e.,} \quad n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad .. \quad .. \quad .. \quad (72)$$

which is similar to expression (71). A comparison between these two expressions shows that the factor which is equivalent to refractive index in electron optics is electron velocity or $\sqrt{}$(potential), and an electron passing from one region to another of greater potential is deflected towards the normal in the same way as a beam of light is deflected in passing from one medium to another of greater refractive index.

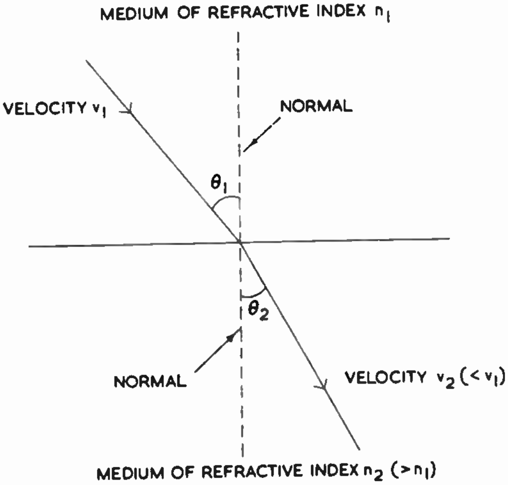


Fig. 140—Path of a light ray passing from a medium of refractive index n_1 into another of greater refractive index n_2

This analogy compares changes in direction of propagation of light rays with changes in direction of propagation of electron beams. The former changes are expressed in terms of refractive index and the latter changes in terms of electron velocity (or region potential). The velocity of light is not taken into account in the comparison, and in Fig. 139 the electron path is deflected towards the normal because its velocity is *greater in the lower region*, whereas in Fig. 140 the light path is deflected towards the normal because the velocity is *less in the lower medium.*

If the lower region has a lower potential than the upper, the electron is slowed down as it crosses the boundary and is deflected away from the normal as shown in Fig. 141. This compares with the deflection of a light beam on passing from one medium into another of smaller refractive index. If in Fig. 141 the difference in potential is made sufficiently great, the vertical component of the electron velocity can be reversed; this process is best illustrated by a drawing in which the two regions of constant potential are separated by an appreciable distance, as shown in Fig. 142. The lines of electric intensity are not confined in this drawing to an

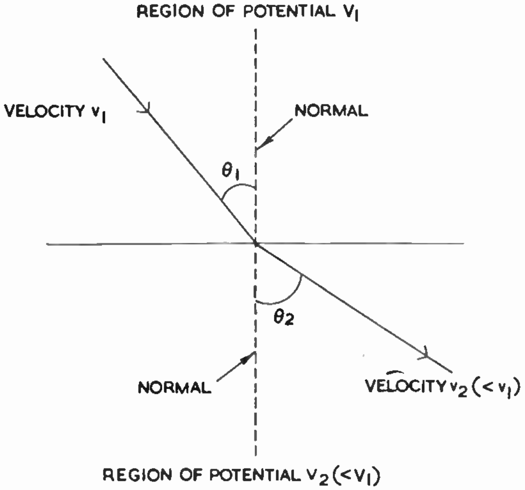


Fig. 141—Path of an electron beam passing from a region of potential V_1 into another of slightly lower potential V_2

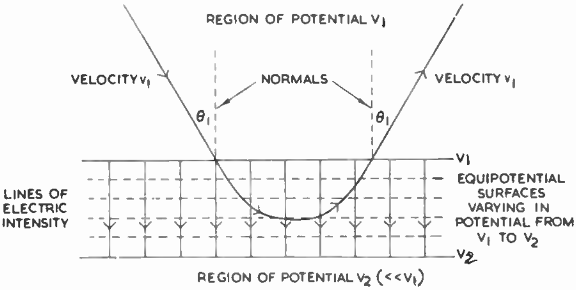


Fig. 142—Path of an electron beam passing from a region of potential V_1 into another of considerably lower potential V_2

infinitely thin boundary as in Figs. 139 and 141 but occupy a boundary zone. When electrons enter this zone they penetrate for a distance before the vertical motion is arrested and are then accelerated back into the upper medium, as shown in Fig. 142. They enter the upper medium with the same velocity v_1 that they had originally and make the same angle θ_1 with the normal.

The lines of intensity in the boundary zone are parallel to the normal to the zone surfaces and are lines of maximum voltage gradient. The condition for electron reflection is

$$e(V_1 - V_2) > \tfrac{1}{2}mv_1^2 \cos^2 \theta_1$$

This behaviour can be compared with regular reflection of a light beam, for if in expression (72) n_2 is put equal to $- n_1$ we have

$$\sin \theta_2 = - \sin \theta_2$$

from which

$$\theta_2 = - \theta_1$$

This shows that the angle of reflection is equal to the angle of incidence: the negative sign is in agreement with the sign convention adopted in Chapter 8.

Fig. 142 shows an electron being reflected obliquely at the boundary between two regions, but, of course, normal reflection can also occur if an electron approaches such a boundary along a path at right angles to the boundary. The electron slows down in the boundary zone, is brought momentarily to rest, and is then accelerated back along its initial path. These are the conditions which exist near the target of low-velocity television camera tubes.

Conditions such as those pictured in Figs. 139 and 141, in which the change from one region to another takes place within a very small distance, are very common in optics where a definite surface usually separates the two media. Such conditions are, however, very rare in electron optics, for here the change from one region to another is gradual, as shown in Fig. 142, and an electron must travel an appreciable distance in moving from one to the other. A typical example is given in Fig. 143, which may be regarded as a more practical version of Fig. 139. This diagram shows an electron entering an electric field, which is indicated by equipotential surfaces and is assumed to be the boundary zone between two regions of constant potential. The electron experiences an accelerating force in the direction of increasing potential and undergoes continuous refraction in the field, taking the curved path shown. As mentioned earlier, the path of the electron is parabolic if the electric field is uniform and if the electron enters it parallel to the equipotential surfaces, i.e., at right angles to the field. The direction in which the electron is deflected is towards the normal to the equipotential surfaces if the electron is moving from a region of low to a region of high potential: this is true irrespective of the shape of the equipotential surfaces and is a useful result which can be used to distinguish between convergent and divergent electron lenses.

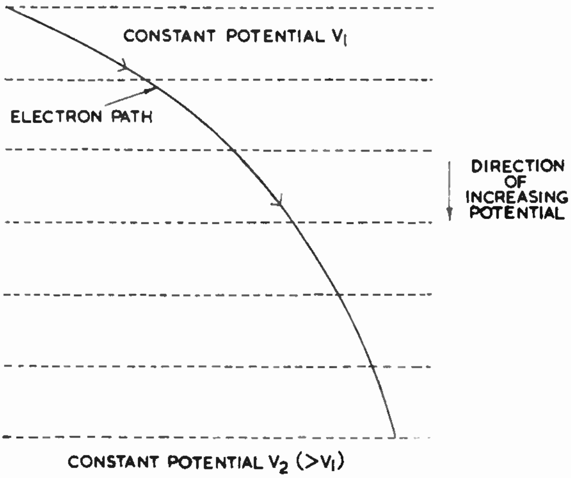


Fig. 143—Electron undergoing continuous refraction in an electric field

10.7 FUNDAMENTAL PROPERTIES OF ELECTRON LENSES

The next few pages are devoted to the properties of electrostatic and magnetic electron lenses, and these will be described in terms of their geometric optical equivalents. There are, however, a number of features in which electron lenses differ from light lenses, and these are of such fundamental importance that they will be given first.

1. In light lenses there is usually a definite number of refractions at surfaces between media of different refractive index and the light travels in straight lines between any two successive refractions: in electron lenses refraction is a continuous process and the electrons pursue curved paths.
2. Light lenses are usually bounded on both sides by the same medium, and the lens behaviour can be expressed in terms of one value of focal length which holds for light travelling along the axis in either direction: in electron lenses the final medium is usually different from the original (its properties in

this case being dependent on values of potential), and two focal lengths, one for each direction, are necessary in calculating lens behaviour.

3. The focal length or the power of an electron lens can be varied over a wide range by varying the potential of the electrodes or the current through the coils. Thus electron lenses are much more flexible than their optical equivalents for which the focal length is fixed.

4. Many light lenses are thin compared to the focal length, and measurements of object and image distances can be made from the lens centre; the length of an electron lens is often comparable to (and sometimes greater than) the focal length, and measurements must be made from the principal points of the lens, as explained in Chapter 9.

5. The path of a light beam is not affected by the presence of other light beams in the vicinity, but there is a force of repulsion between neighbouring electron beams (due to the negative charges of the constituent electrons) which can give rise to aberrations for which there is no equivalent in light lenses. In addition, magnetic lenses can produce another aberration not observed in light lenses; this takes the form of a distortion in which straight lines are reproduced in the shape of an elongated letter S; this is described more fully on page 259.

10.8 ELECTROSTATIC LENSES

A practical electrostatic lens of the type used in cathode-ray tubes has an optical equivalent containing several convex and concave elements. Such compound lenses will be described later, and we shall first consider the electron lens illustrated in Fig. 144 (iv). Such a lens has limited practical application, but because of its simplicity it provides a good introductory illustration of the fundamental principles of electron lenses.

Aperture Lenses

Any arrangement of electrodes having rotational symmetry about an axis can be used as an electron lens, and one of the simplest types is the aperture lens which is formed when a plate b, having a circular hole, is situated in a uniform electric field and is mounted parallel to the two plates a and c, giving rise to the field (Fig. 144 (iv)). The aperture plate may be connected to either of the field-forming plates or to a source of intermediate potential.

If plate b is not present, the field between a and c is uniform and the equipotential surfaces can be represented by a series of equally spaced lines parallel to each other and to plates a and c as shown in

Fig. 144 (i). If plate b has no aperture, and is placed between a and b as shown in Fig. 144 (ii), its introduction does not affect the electric field, but the plate takes up a potential intermediate between that of plates a and c, the value of this potential depending on its position. For example, if plate b is placed midway between plates a and c, the potential it acquires is the arithmetic mean of that of plates a and c.

If plate b is connected to a source of potential which differs from that naturally acquired by the plate by virtue of its position in the field, the plate divides the field into two uniform fields of unequal intensity as shown in Fig. 144 (iii). This diagram illustrates the relative intensity when plate b is made more positive than its natural potential. The field between plates a and b is of greater intensity than that between b and c, as shown by the crowding of the equipotential surfaces on the left of the diagram. In general the intensity of the field in the region ab is given by

$$\epsilon_{ab} = \frac{V_a - V_b}{d_1} \quad \ldots \quad \ldots \quad \ldots \quad (73)$$

and in the region bc by

$$\epsilon_{bc} = \frac{V_b - V_c}{d_2} \quad \ldots \quad \ldots \quad \ldots \quad (74)$$

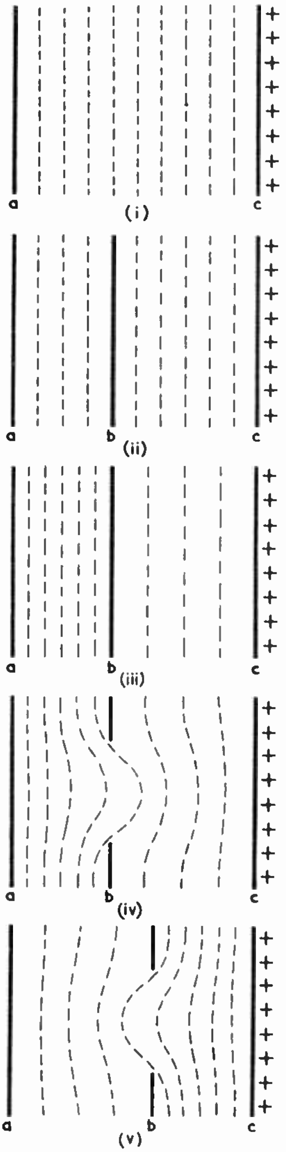


Fig. 144—Field between two plates a and b. (i) With no intermediate plate; (ii) with intermediate plate c at its natural potential; (iii) with plate c more positive than in (ii); (iv) as (iii) but with aperture in plate c; (v) with an aperture plate biased negatively with respect to its natural potential

where V_a = potential of plate a,
V_b = potential of plate b,
V_c = potential of plate c,
d_1 = distance between plates a and b,
and d_2 = distance between plates b and c.

When there is an aperture in plate b, and if the fields on either side are unequal, the equipotential surfaces representing the stronger field project through the opening as shown in Fig. 144 (iv). The distribution of this field can be deduced from Figs. 144 (ii) and 144 (iii), because on the axis of the aperture the field tends to take up the distribution of Fig. 144 (i) (i.e., the distribution when plate b is missing or at its natural potential), whereas at points remote from this axis the distribution approximates to that of Fig. 144 (iii) (when plate b has no aperture).

Fig. 144 (v) shows the distribution of field when the aperture plate is made more negative than its natural potential; the equipotential surfaces now project through the aperture in a direction opposite to that shown in Fig. 144 (iv). Again the distribution can be deduced from first principles: on the axis of the aperture the spacing of the equipotential surfaces approximates to that obtained without an aperture plate, and at points remote from this axis the spacing approximates to that obtained if plate b has no aperture.

The electric field near the aperture in Figs. 144 (iv) and 144 (v) can bend the paths of electrons in a manner similar to that in which a light lens bends the paths of light rays.

In general an aperture lens may be defined as one formed near an aperture separating two uniform fields. There is no reason why one of these fields should not have zero intensity; this can be obtained in Figs. 144 (iv) or 144 (v) by connecting plate b to plate a or plate c, and for sake of simplicity in the following account of aperture lenses it will be assumed that the field on one side of the aperture is zero.

Divergent Aperture Lens

Fig. 145 represents a divergent aperture lens: it may be regarded as a special case of the lens of Fig. 144 (iv) when $V_b = V_c$. Electrons enter the lens from the left and are accelerated in the direction of increasing potential; in crossing the equipotential surfaces they are deflected towards the normal to these surfaces as shown in Fig. 146. Thus a parallel beam of electrons entering the lens becomes divergent by refraction in the region of the curved equipotential surfaces. In the space between b and c the electrons pursue straight

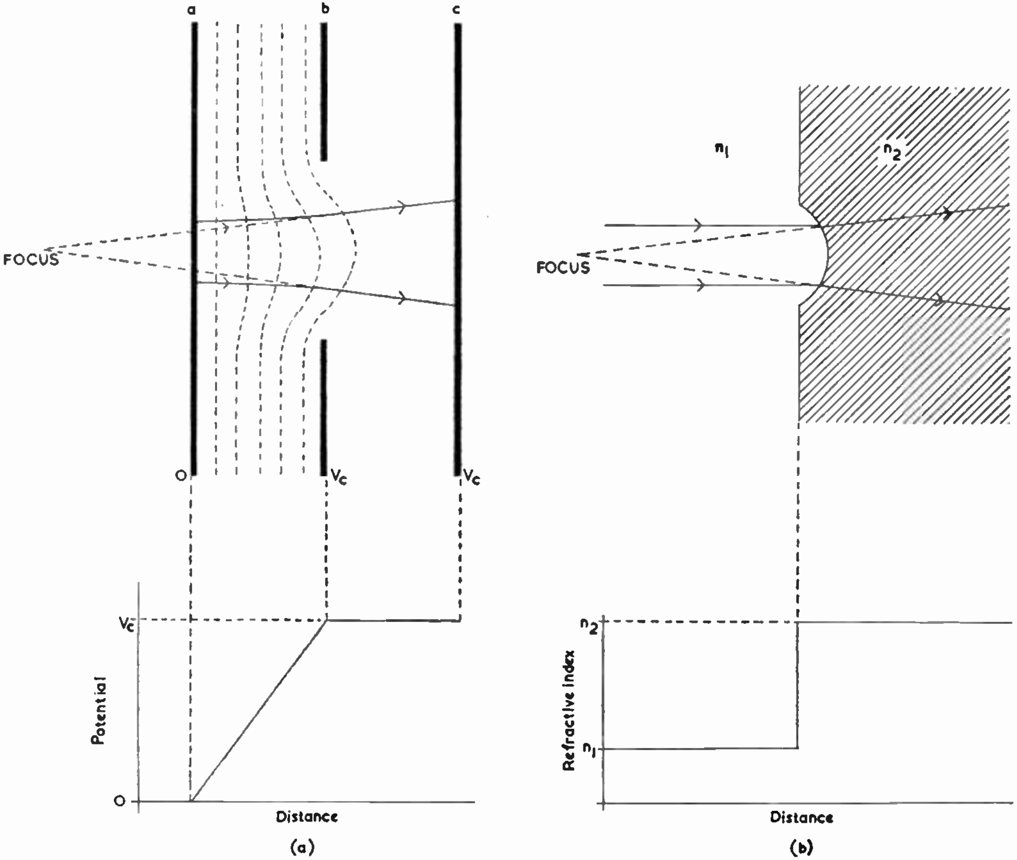


Fig. 145—A divergent aperture lens (a) and its optical equivalent (b)

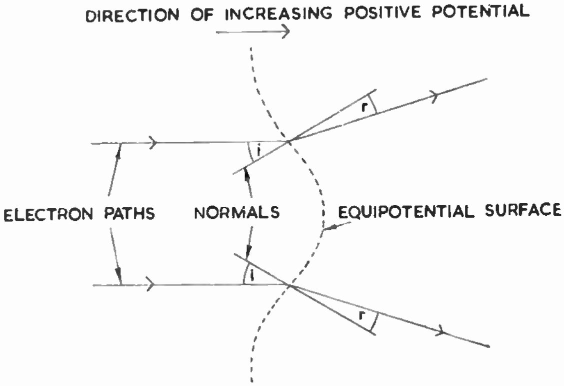


Fig. 146—Deflection of electron beam in the electron lens of Fig. 145a

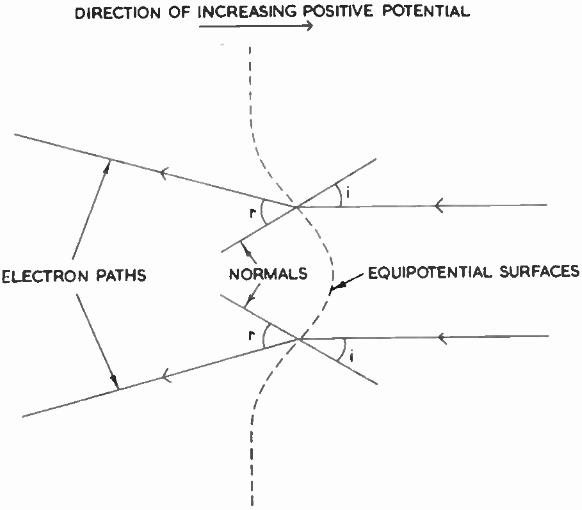
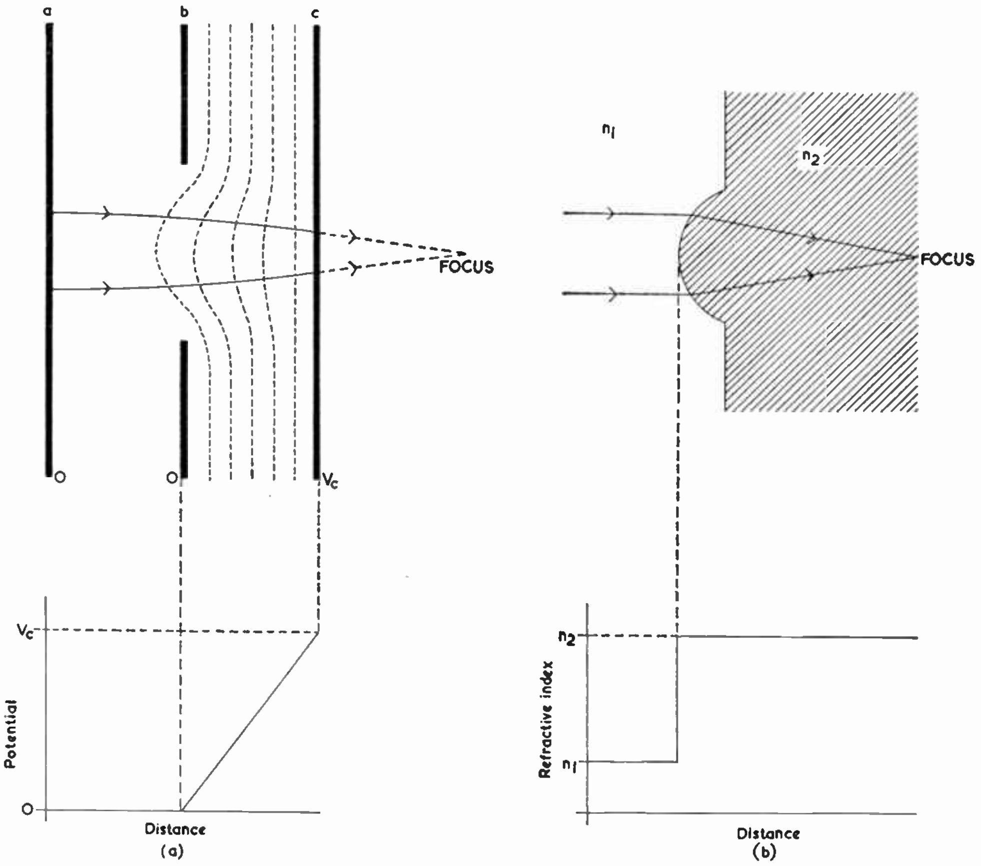


Fig. 147—Deflection of an electron beam in the lens of Fig. 145a when electrons are proceeding in the opposite direction

paths which, if produced backwards, meet at the focus of the electron lens.

This electron lens is similar to a concave light lens in that it makes a parallel beam divergent; a concave lens is not, however, a true analogue, because such a lens has the same initial and final medium whereas the final region in Fig. 145*a* has a potential of V_e, which is positive with respect to the initial potential of zero. The corresponding optical system is shown in Fig. 145*b* and consists of

Fig. 148—A convergent aperture lens (a) and its optical equivalent (b)



a concave depression in the surface of a dense optical medium; the similarity between this diagram and Fig. 145*a* is very striking.

If the direction of the electron beam is reversed in Fig. 145*a* the electrons meet a retarding electric field and, if they are to arrive at plate a, must have an initial velocity great enough to enable them to overcome the deceleration of the field. As shown in Fig. 147, the electrons now meet convex equipotential surfaces and in crossing them are deflected away from the normal ($\angle r > \angle i$) because the electrons are proceeding into a region of decreasing positive potential. Thus the aperture lens is divergent for electrons passing through it in either direction; similarly the optical lens system of Fig. 145*b* is divergent for light passing through it in either direction.

Convergent Aperture Lens

A convergent aperture lens is illustrated in Fig. 148*a*. The field has a distribution similar to that of Fig. 144 (v), and electrons moving up the potential gradient meet convex equipotential surfaces. In crossing these surfaces the electrons are deflected towards the normal ($\angle i > \angle r$) and a parallel incident beam becomes convergent as shown in Fig. 149. The optical analogue of Fig. 148*a* is shown in Fig. 148*b*; it consists of a convex bulge on a block of material in a medium of smaller refractive index.

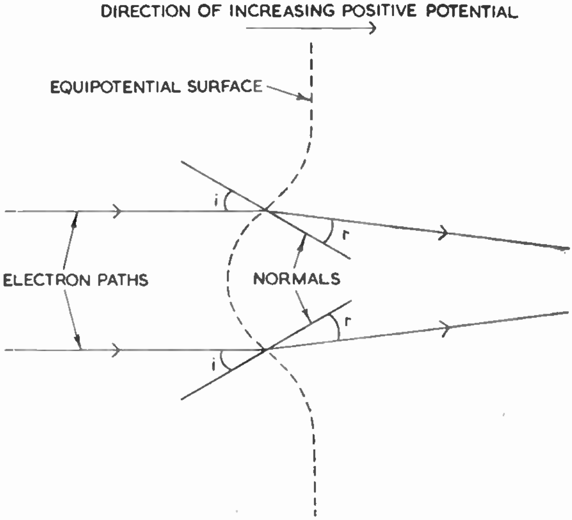


Fig. 149—Paths of electrons in the lens of Fig. 148a

By an argument similar to that advanced above in respect of

Fig. 145*a* it can be shown that the aperture lens of Fig. 148*a* is also convergent when the electrons enter the lens in the opposite direction; this behaviour is similar to that of the optical analogue of Fig. 148*b*, which is also convergent when the direction of the light beam is reversed.

From Figs. 145 and 148 two rules can be deduced for determining the nature of the electron lenses. They are of universal application and are as follows:

1. If the electrons move in the direction of increasing potential and if the equipotential surfaces they are approaching are concave (as in Fig. 145), the effect of these surfaces is to make the beam divergent; conversely if the surfaces are convex their effect is to make the beam convergent.

   In other words, when the electrons move in the direction of increasing potential, the shape of the equipotential surfaces is also the shape of the front surfaces of the components in the equivalent optical lens system.

2. If the electrons move in the direction of decreasing potential and if the equipotential surfaces they are approaching are concave, the effect of these surfaces is to make the beam convergent; conversely if the surfaces are convex (as in Fig. 147) their effect is to make the beam divergent.

Cylinder Lens

The anodes of cathode-ray tubes are usually in the form of metal cylinders or (and these have the same effect) conductive coatings deposited on the inside walls of the tube. These electrodes are used to focus the electron beam on the screen and are equivalent to convex light lenses.

Fig. 150*a* illustrates a lens formed by two cylinders of unequal diameter, the smaller (which we shall call the first cylinder) having a potential V_1 which is less than V_2, the potential of the second cylinder. Electrons are assumed to be travelling in a divergent beam centred about the common axis of the cylinders and in the direction of increasing positive potential.

The field between the cylinders has the form indicated by the equipotential lines in Fig. 150*a*. The electrons first meet convex equipotential surfaces which, as explained above, serve to make the beam convergent, but near the space between the two cylinders the equipotential surfaces become concave and the beam tends to diverge again. The effect of the first section of the lens is, however, greater than that of the second, and the overall effect of the lens is convergent. Cylinder lenses are generally convergent because the electrons have a lower velocity in the first part of the lens than in

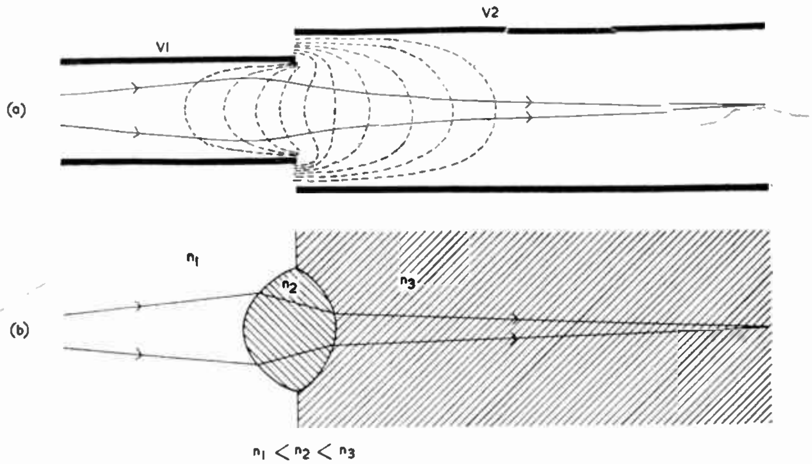


Fig. 150—A cylinder lens (a) and its optical equivalent (b)

the second and thus suffer greater deflection for the same force. The optical analogue of Fig. 150*a* is shown in Fig. 150*b*.

Calculations on such lenses are complicated because the length is long compared with the focal lengths: thus object and image positions must be expressed with reference to two principal points and two focal lengths, as shown in Fig. 151. The significance of these points is explained in Chapter 9.

The focal lengths of a cylinder lens depend on:

1. The magnitude and the ratio of the cylinder potentials.
2. The ratio of the cylinder diameters.
3. The spacing between the cylinders.

If the potentials of both cylinders are increased, the ratio remaining constant, the electric field becomes stronger and the lens more

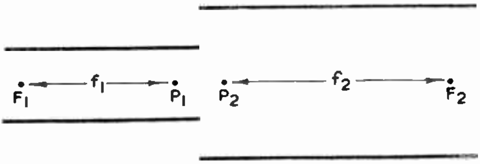


Fig. 151—Principal points and focal points of a cylinder lens

convergent; in other words, the focal lengths decrease as the potentials are raised. The ratio of the first to the second focal length depends on the ratio of the potential of the first cylinder to that of the second. Thus if the potentials of both cylinders are doubled, both focal lengths decrease but their ratio remains unchanged.

In general the focal lengths increase (i.e., the lens becomes weaker) as the ratio of the diameter of the second cylinder to that of the first cylinder increases; the lens is also weakened if the spacing between the cylinders is increased.

Immersion Lens

Immersion lenses are used to concentrate the electrons liberated from a cathode into a beam, i.e., their function is to fire electrons into lenses of the type described previously; the name arose because the object (cathode) is so near the electric field constituting the lens that it may be regarded as immersed in it.

In the electron lenses described above it was assumed that electrons entered the electric field with a reasonably high velocity, high enough in some instances to enable them to penetrate a retarding field. Such conditions do not occur near the cathode of a cathode-ray tube because electrons are liberated from it with very low velocities and in the electron lenses used to concentrate the emission a strong accelerating field is required very near the cathode. Immersion lenses usually consist of two plates which have apertures and may be extended in the form of cylinders as shown by the dotted lines in Fig. 152, where C represents a cathode, G a control grid and A an anode. If the potential of C is taken as zero, that of G is approximately the same or slightly negative but A has a high positive potential. The field between G and A is very much stronger than that between G and C and penetrates the hole in G to within a very small distance of C; in other words, the attraction of the anode is not entirely offset by the repulsion of the control grid in spite of the greater distance of the anode. By increasing the negative potential of G it is possible to neutralize the attraction of the anode and to suppress the electron beam completely; thus the potential of the control grid can be varied to control the density of the electron beam.

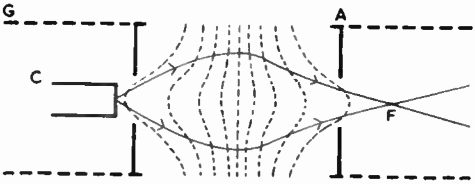


Fig. 152—Typical immersion lens

The field of the immersion lens has the form shown by the equipotential lines in Fig. 152 and is very similar to that of the two-cylinder lens of Fig. 150*a*; the optical analogue has the form shown in Fig. 150*b*. An immersion lens is of extremely high power and electrons entering it are brought to a focus within a very short distance, leaving the lens in a divergent beam.

The electrons meeting at F may be said to form an image of the cathode, but it is a very small image (i.e., the magnification of the lens is less than unity). The remaining electrodes in the electron gun of a cathode-ray tube are designed to give an image of F on the screen and may have the form of a two-cylinder lens of which A in Fig. 152 may be one element.

Symmetrical Lens

In the electron lenses described above, the final region has a different (usually higher) potential from the initial region, and in this respect the lenses differ from light lenses. It is possible, however, to design an electrostatic lens in which both initial and final regions have the same potential; such lenses are termed symmetrical, and an example is illustrated in Fig. 153. This particular type of lens is sometimes termed " univoltage " because the centre electrode (or the two outer electrodes) may be connected to the gun cathode and only one positive potential is then required by the lens. Although such lenses have greater application in electron microscopes than in television equipment, they are mentioned here to show how close the resemblance to light lenses can be. The univoltage lenses have the property that their focal lengths are equal for both directions. The focal lengths are very short and do not vary very greatly with variations of the electrode potentials.

The lens has the form of three parallel plates, each with a circular hole; the outer plates have the same potential, and the centre one is made positive or negative with respect to them.

Fig. 153 shows a symmetrical lens with a positively charged central electrode. Electrons entering the lens as a beam parallel to the axis first meet convex equipotential surfaces of successively increasing potential and are deflected towards the axis; the field near the first aperture is thus equivalent to a positive lens. Near the central aperture the equipotential surfaces have concave curvature, but the potential is still increasing and the electrons in this region are deflected away from the axis, the field here having the effect of a negative lens. When the electrons pass through the central aperture they enter a region where the equipotential surfaces are convex and the potential is decreasing; the effect of this field is still that of a negative lens and the deflection experienced near the

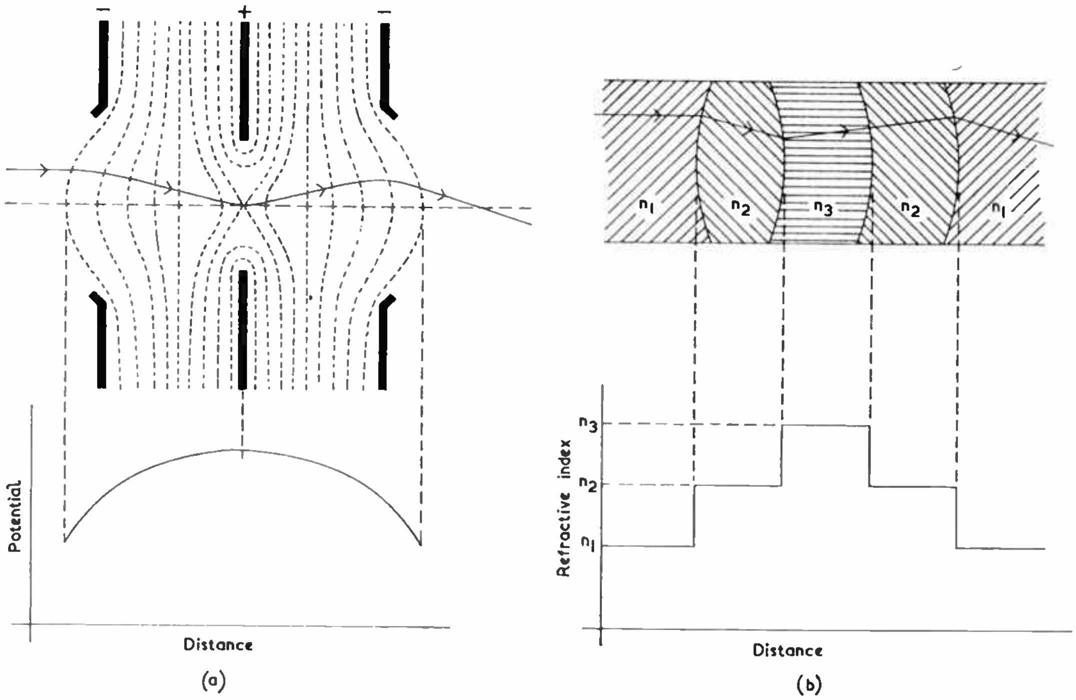
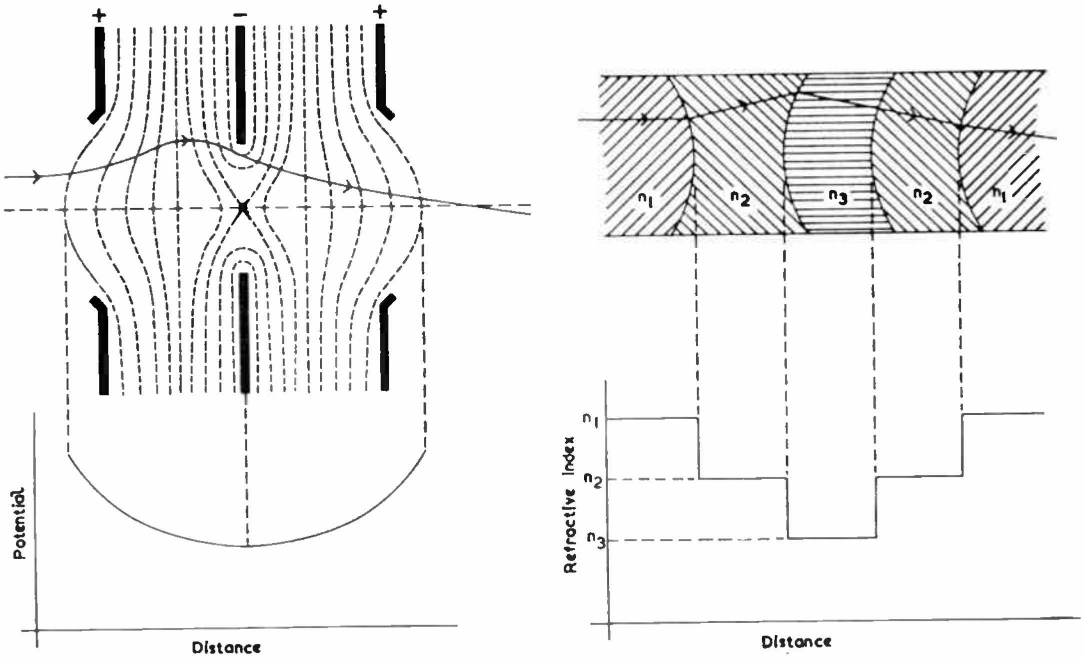


Fig. 153—A symmetrical electron lens with a positively charged centre electrode (a) and its optical equivalent (b)



(a) (b)

Fig. 154—A symmetrical electron lens with a negatively charged centre electrode (a) and its optical equivalent (b)

first aperture is completely neutralized, with the result that electrons are now proceeding away from the axis. Near the third aperture the equipotential surfaces are again concave and the potential is decreasing; the field here has the effect of a positive lens and cancels the effect of the central parts of the lens, the electrons leaving with a deflection towards the axis. The overall effect of the lens is thus positive. The optical equivalent of the electron lens is shown in Fig. 153*b*.

It might be thought that if the central electrode of a symmetrical lens were made negative with respect to the other electrodes, the resulting electric field would have the effect of a negative lens, but in fact such a lens is still convergent as shown in Fig. 154. There is only one type of electron lens which can be made convergent or divergent by alteration of potentials, and this is the aperture lens (page 237). The equipotential surfaces in Fig. 154*a* have the same shape as those in Fig. 153*a*, but the potential at the lens centre has a minimum in Fig. 154 and a maximum in Fig. 153.

If the path of an electron beam is traced through the equipotential surfaces of Fig. 154, it will be found that the field near the first aperture is divergent, that near the second central aperture is convergent, and that near the final aperture is again divergent. As in Fig. 153, however, the effect of the negative plates predominates and the overall effect of the lens is positive.

10.9 Magnetic Lenses

Electron beams can be focused by the magnetic fields of coils carrying direct current or of permanent magnets, but the analogy between magnetic and light lenses is not so obvious as between electric and light lenses. In general there are two types of magnetic lens, one employing a long magnetic field, usually produced by a solenoid carrying d.c., and the other using a short magnetic field which can be produced by a short coil carrying d.c. or by a permanent magnet. The mechanism of the focusing effect is quite different in these two lenses; in the long lens both object and image are in a region of the same field strength (which may be compared with refractive index) and focusing is brought about by the axial field: in the short lens the object and image are both well out of the field and focusing is almost entirely due to the radial components of the magnetic field. The distinction between the axial and radial components of a magnetic field is made clear in Fig. 155, which represents in a simplified form the field due to a current-carrying coil of helical form. The direction of the magnetic field at any point P is, of course, indicated by the direction of the line of magnetic intensity passing through the point; this field can be resolved into two components, one parallel with the coil axis (axial component) and the other at right angles to the coil axis (radial component).

Long magnetic lenses are used for beam focusing in the C.P.S. Emitron camera tube and for beam and image focusing in the image

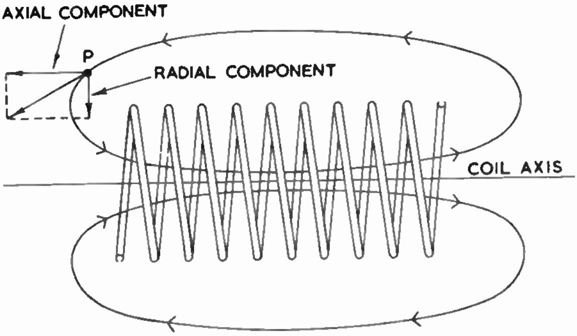


Fig. 155—Axial and radial components of a magnetic field

orthicon tube. Short magnetic lenses are used in the image sections of camera tubes of the Super-Emitron type and in cathode-ray tubes used for picture reproduction.

Long Magnetic Lens

Fig. 156 shows in perspective one type of coil which can be used to form a long magnetic lens. Such a coil is usually represented in diagrams as shown in Fig. 157, where the shaded rectangles represent a longitudinal section through the focusing coil, which

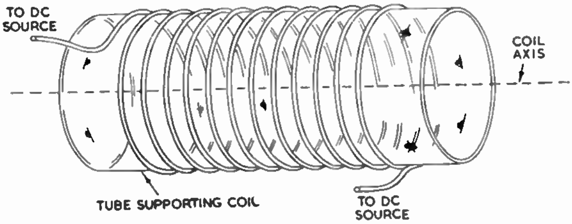


Fig. 156—Perspective drawing of the focusing coil of a long magnetic lens

produces a uniform magnetic field parallel to the coil axis. Fig. 157 illustrates the use of a long magnetic lens in a C.P.S. Emitron camera tube.

Electrons leave the electron gun as a divergent beam subtending an appreciable angle at the cathode, but the gun anodes contain a number of aperture plates which intercept electrons with appreciable radial components of velocity. Thus the electrons leaving the gun have velocities which are either parallel to the magnetic field or else make very small angles with it. The behaviour of electrons entering a magnetic field in this manner was discussed on page 227; if the initial velocity of an electron makes an angle of θ with the tube axis, the velocity component $v \cos \theta$ is parallel to the field and is unaffected by it, giving the electron a uniform axial movement along the tube. The component $v \sin \theta$ is at right angles to the field and produces a circular motion of radius $(mv \sin \theta)/eH$ and of periodic time $2\pi m/eH$. If the axial component of velocity were zero the electron would describe circles in a plane at right angles to the axis, but when the axial component is finite the electron describes helices with an amplitude proportional to $v \sin \theta$ about an axis parallel to the tube axis.

Provided θ is small, all electrons take the same time to describe each loop of the helix, and thus, if the electrons enter the magnetic field at one point on the tube axis, they all meet again at another point after describing each complete loop. Points of focus therefore occur at regular intervals along the axis of the tube as shown in Fig. 157; the spacing of the foci is equal to the product of the longitudinal velocity $v \cos \theta$ and the periodic time $2\pi m/He$ and is equal to $(2\pi mv \cos \theta)/He$; provided θ is small $\cos \theta$ is approximately unity and the spacing is approximately $2\pi mv/He$. In practical units this spacing is given by:

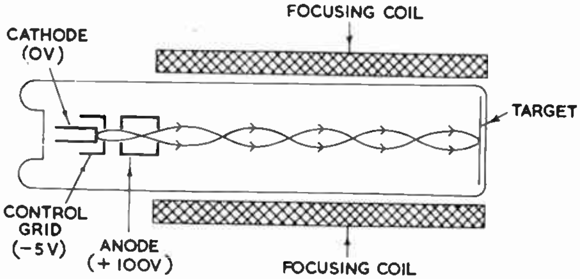


Fig. 157—A long magnetic lens

$$\text{spacing} = \frac{21 \cdot 2 \sqrt{V}}{H} \text{ centimetres}$$

where V is the accelerating potential in volts and H is the magnetic field strength in oersteds (see expression (70)).

As a numerical example we will calculate the spacing of the focal points in a C.P.S. Emitron camera tube for which V is approximately 300 volts and H is approximately 50 oersteds.

Substituting in the above expression:

$$\text{spacing} = \frac{21{\cdot}2 \times \sqrt{300}}{50} = 7{\cdot}2 \text{ centimetres}$$

With this spacing there are three points of focus between the gun and the target.

The projection of the electron motion on a plane at right angles to the tube axis (i.e., the path of an electron as seen by an observer situated behind the cathode) is a circle which passes through the point of entry of the electron into the lens; for convenience we shall assume this point of entry to coincide with the axis of the tube. The position of this circle, relative to the tube axis, depends on the direction of the electron velocity when the electron enters the lens. If the velocity is inclined upwards at an angle θ (Fig. 158) to the tube axis, the radial component is directed vertically upwards and the centre O_1 of the circle representing the projection of the electron motion on a plane

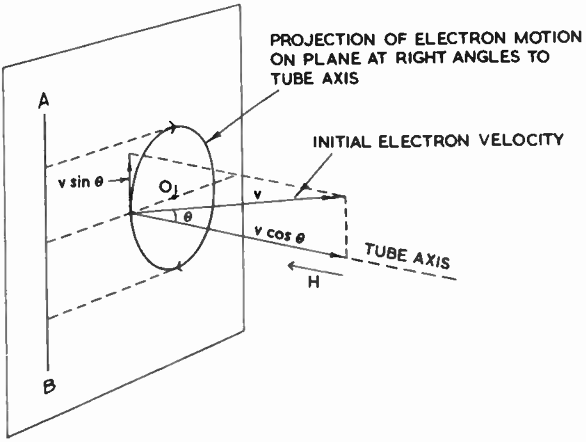


Fig. 158—Typical projection of electron motion on a plane at right angles to the tube axis in a long magnetic lens

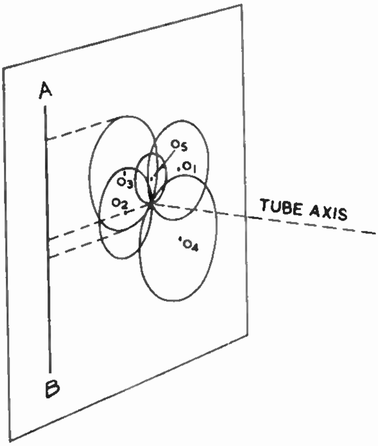


Fig. 159—Typical projections of electron motion on a plane at right angles to the tube axis in a long magnetic lens

at right angles to the tube axis is on the horizontal passing through the tube axis as shown in Fig. 158. Similarly for an electron initially inclined downwards, the corresponding circle has a centre O_2 (Fig. 159) on the same horizontal line but on the other side of the axis, the circumference still, of course, passing through the tube axis. The electron velocities are distributed at random and the circles may have any diameter within a certain range. The centres of the circles may also be situated in any position with respect to the tube axis; the circumferences must, however, pass through the tube axis. A few typical circles are shown in Fig. 159.

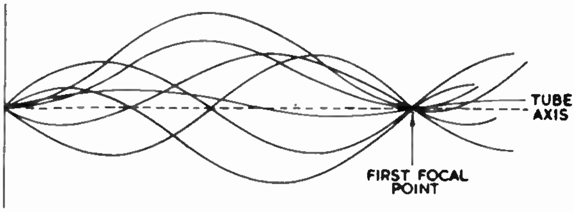


Fig. 160—Typical projections of electron motion on a plane passing through the tube axis of a long magnetic lens

The projection of the helical path on a plane passing through the tube axis (i.e., the path of an electron as seen by an observer situated at the side of the tube) is a sine wave with an amplitude proportional to $v \sin \theta$, the axial length occupied by each cycle being proportional to $v \cos \theta$. The position of this sine wave relative to the projection of the tube axis depends on the initial direction of the electron velocity; if the initial velocity is inclined upwards (θ in Fig. 158) the corresponding circle is situated to one side of the axis and the projection of electron motion on a vertical plane such as AB is symmetrically positioned about the projection of the tube axis. If the circle lies above the tube axis (circle O_5 in Fig. 159), the corresponding sine wave also lies entirely above the projection of the

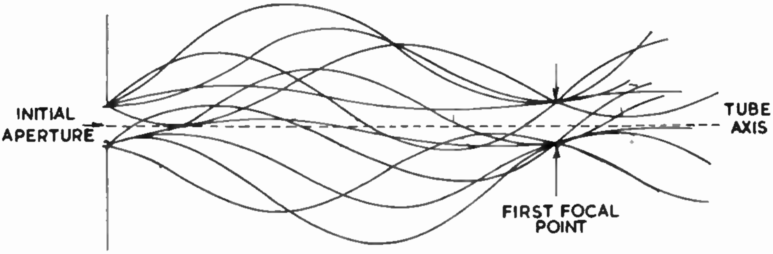


Fig. 161—Electron paths in a long magnetic lens when the orifice has appreciable dimensions

tube axis. Thus the curves representing the projection of the electron motion on a plane passing through the tube axis are sine waves, all with the same pitch, so disposed about the tube axis that any fraction of the curve may lie above or below the axis. A few typical curves are given in Fig. 160.

It has so far been assumed that all electrons enter the long magnetic lens at one point, but in practice electrons enter the lens through an orifice with appreciable dimensions. Each electron, after describing one complete revolution of its particular helical path, arrives at a point on the same axial level at which it entered the lens. Thus the electrons, having described one revolution, occupy instantaneously an area approximately equal to that of the original orifice; an attempt has been made to show this in Fig. 161.

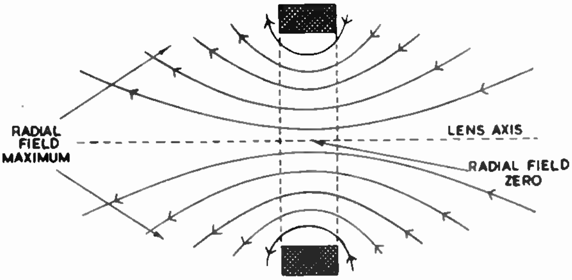


Fig. 162—Magnetic field due to a short coil without a shroud

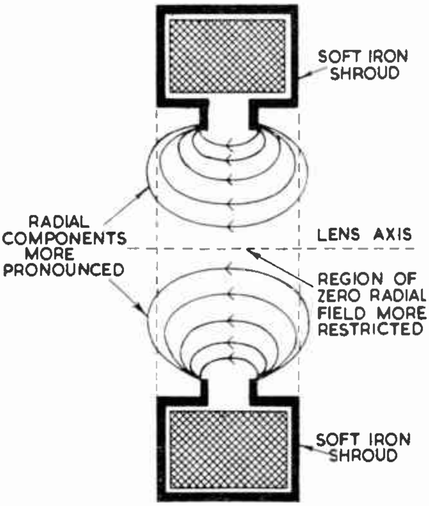


Fig. 163—Magnetic field due to a short coil with a shroud

Thus each of the succession of images formed by a long magnetic lens is approximately equal in size to the original object; the images are, however, usually displaced through a small angle with respect to the object.

Short Magnetic Lens

The magnetic field due to a short coil carrying d.c. has the form illustrated in Fig. 162; it may be considered as constant for a short distance along the coil axis but diverges rapidly outside this distance, having pronounced radial components except near the centre of the coil. As it is the radial field components which give rise to the focusing action, a lens of this type can be made stronger (i.e., the focal length can be reduced) by enclosing the coil in a soft-iron shroud as shown in Fig. 163; this restricts the length of the axial field and exaggerates the radial components.

The action of the lens can be considered to take place in three stages; the first occurring at the entrance pupil where the radial field is strong, the second at the lens centre where the axial field predominates, and the third near the exit pupil where the radial field is again very strong.

(*a*) *First Stage*

Consider an electron entering the lens from a point O with a velocity v at an angle θ to the lens axis as shown in Fig. 164. When the electron enters the magnetic field it experiences a force which is at right angles to its velocity and to the field; thus in Fig. 164 the force is at right angles to the plane of the paper and tends to deflect the electron in this direction. When it does so, however, the electron cuts across the axial component of the magnetic field and generates a radial force directed towards the axis of the lens.

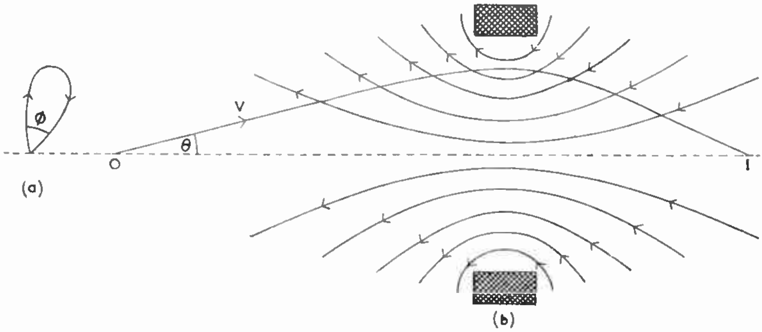


Fig. 164—A short magnetic lens. The projection of the electron path in a plane at right angles to the lens axis is shown at (a) and in a plane through the axis at (b)

Under the action of these two forces the electron begins to rotate about the lens axis and the angular velocity attained depends on the magnitude of the radial field component. This increases with increase in distance from the lens axis, being zero at the axis and a maximum near the coil. Thus the angular velocity of the electron is approximately proportional to its initial displacement from the axis when it entered the lens; it is thus greater for large values of θ than for small.

(*b*) *Second Stage*

As the electron approaches the centre of the coil, the radial field component decreases and the axial component increases. Interaction of the angular velocity of the electron with the axial field gives rise to a force directed towards the lens axis, and this reduces the radial component of velocity $v \sin \theta$ to zero and reverses it, causing the electron to move towards the lens axis as it approaches the lens centre. The extent of this deflection is proportional to the angular velocity of the electron and is greater for electrons with large values of θ than for those with small values.

(*c*) *Third Stage*

As the electron enters the second region where the radial field predominates (on the right of the plane of the coil in Fig. 164) the radial component of electron velocity is substantially unaffected, since it is parallel to the field, but the longitudinal component of

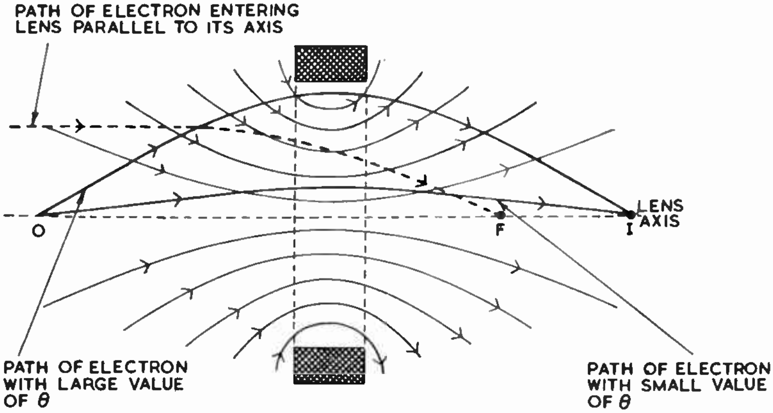


Fig. 165—Two electron paths in a short magnetic lens

the electron velocity reacts with the radial field to produce a rotation of the electron as described above. This rotation is, however, in the opposite direction because the radial field on the right of the coil is in the opposite direction to that on the left. Hence electrons leave the lens with a radial component of velocity directed towards the axis, and this is approximately proportional to the displacement of the electron from the axis when it entered the lens. Provided the disposition and intensity of the magnetic field are suitably adjusted, all the electrons diverging from O will recombine at I; two typical electron paths are illustrated in Fig. 165.

In an ideal lens the magnetic field is symmetrical about the plane of the coil and the rotation of the electron produced on the right of the coil exactly cancels that produced on the left-hand side; in a practical lens, however, there is usually some residual rotation of the image.

Fig. 164*b* shows the path of an electron projected on a plane which rotates with the electron about the lens axis at an angular velocity equal to that of the electron and which in general is not constant as the electron passes through the lens. Fig. 164*a* shows the projection of the electron path on a plane at right angles to the lens axis; it shows how the rotation increases to a maximum as the electron approaches the centre of the coil and is then reduced as the electron leaves the coil. The residual rotation is ϕ, and the image is rotated through an angle ϕ with respect to the inverted position which is normal for a convex lens.

Focal Length of a Short Magnetic Lens

Magnetic lenses of this type may be compared with symmetrical electrostatic lenses and are always positive. The focal length is given by

$$f = K \frac{VR}{(NI)^2} \qquad \ldots \qquad \ldots \qquad \ldots \qquad (75)$$

where I is the current in the coil,
N is the number of turns on the coil,
R is the radius of the coil,
V is the potential corresponding to the electron velocity,
and K is a constant depending on the shape of the coil and to what extent it is shrouded.

The focal length is inversely proportional to the square of the current in the coil; thus the current can be reversed in direction without effect on the sign or magnitude of the focal length.

10.10 ABERRATIONS OF ELECTRON LENSES

Electron lenses can suffer from all the aberrations encountered in optical lenses (listed in Chapter 9) and from some further aberrations which are peculiar to electron lenses. Coma, curvature of field and astigmatism are not usually troublesome in electron lenses, and the chief aberrations requiring correction are spherical aberration, chromatic aberration and distortion.

The presence of spherical aberration is indicated by a loss in definition of images formed on the lens axis and is caused by failure of all the refracted rays from a point object to meet at a single point. Although this aberration is chiefly caused by the shape of the equipotential surfaces, it can also be caused by the mutual repulsion of the electrons in the emergent beam; this tends to make the beam diverge and spoils the focus. In electrostatic lenses this aberration can be minimized by increasing the potentials on the electrodes; this also gives a brighter image and enables a smaller aperture to be used. Alternatively, the aberration can be reduced by use of lenses with specially shaped electrodes which give equipotential surfaces with a shape nearer to the ideal.

Chromatic aberration is distortion caused by electrons passing through a lens with different velocities, and may be due to the different initial velocities with which electrons are released from the cathode. Chromatic aberration can be minimized by use of accelerating voltages so large that the initial velocities are negligible compared with them.

Although pincushion and barrel distortion occur in electron lenses, a more serious form of distortion is the rotation of images formed by magnetic lenses. If all points in the image were rotated through an equal angle with respect to the corresponding object points, this distortion would not be serious; unfortunately points near the edge of the image are usually rotated through a greater angle than points near the centre. Thus straight lines passing through the centre of the object field are reproduced in the image in the form of an elongated S. This form of distortion can be minimized by constructing magnetic lenses in the form of two coils, through which direct current is passed in opposite directions. Image rotation cancels, but the focusing effect, which depends on the square of the current (as shown in expression (75)), is additive.

10.11 DEFLECTION OF ELECTRON BEAMS

The previous pages have described the methods used to focus an electron beam on a target and have shown that electric or magnetic lenses can be used for this purpose. In order to scan a target the electron beam must be focused on it and must, in addition, be deflected so as to traverse the target in the desired manner. In general, electron beams can be deflected by electric or magnetic fields; electric deflection was used in early television receivers and is still used in cathode-ray oscilloscopes, but magnetic deflection is now almost universal in television camera tubes and television receivers.

Electric Deflection

Electric deflection is illustrated in Fig. 166. The beam is passed through a uniform electric field between two parallel conducting plates, the beam cutting the field at right angles. The beam describes a parabolic path between the plates and emerges at an angle α to the initial direction. Let the perpendicular distance between the plates be a, their length in the initial direction of the beam be b, and the distance from the centre of the plates to the screen be l.

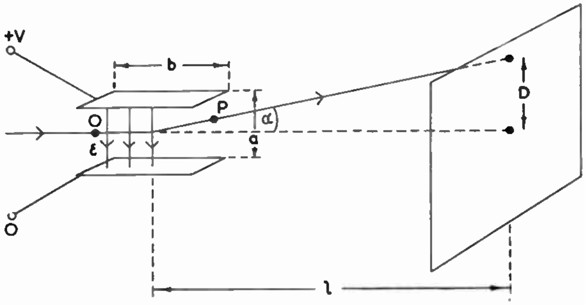


Fig. 166—Electric deflection of an electron beam

From (65), the slope $\mathrm{d}y/\mathrm{d}x$ of the parabolic path at a point (x, y) is given by $\epsilon x/2V_0$. If the point O be taken as origin, the slope at point P after the beam has travelled a distance b is $\epsilon b/2V_0$. But $\epsilon = V/a$, where V is the deflecting p.d. between the plates.

$$\therefore \quad \frac{\mathrm{d}y}{\mathrm{d}x} = \frac{Vb}{2aV_0}$$

Provided the angular deflection α is small:

$$\frac{\mathrm{d}y}{\mathrm{d}x} = \tan\alpha \simeq \frac{D}{l}$$

where D is the displacement of the beam on the target.

$$\therefore \quad D = \frac{Vlb}{2aV_0} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (76)$$

from which

$$\frac{D}{V} = \frac{lb}{2a} \cdot \frac{1}{V_0} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (77)$$

The value D/V is known as the *deflection sensitivity*; it is equal to the deflection of the beam on the screen (usually given in millimetres) for a p.d. of 1 volt applied between the deflecting plates. For a particular cathode-ray tube b and a are constant, and as shown in expression (77) the deflection sensitivity is inversely proportional to the final anode voltage V_0. For this reason deflection sensitivities are often expressed in the form d/V_0 millimetres per volt, where d is the deflection sensitivity and V_0 is the final anode potential. For example, the deflection sensitivity of a particular cathode-ray tube is given as $785/V_0$ millimetres per volt; if the final anode potential is 1,000 volts the deflection for 1 volt applied between the plates is 0·785 millimetres.

Expression (77) shows that the deflection sensitivity is directly proportional to the length of the plates and the distance of the plates from the screen but is inversely proportional to the distance between the plates. The expression is approximate because it was assumed that the field between the plates was parallel whereas in fact it tends to spread at the edges, as shown in Fig. 167. This effect is known as *fringing*.

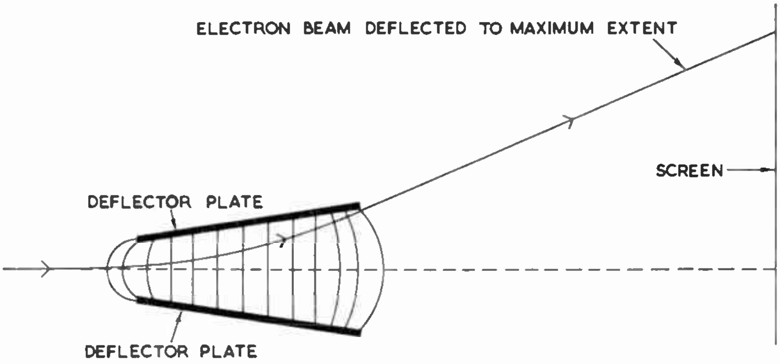


Fig. 167—Typical arrangement of plates for electric deflection

For a given final anode voltage, the deflection sensitivity can be increased by increasing l, but an upper limit is imposed on l by the difficulty of focusing a very long beam. The sensitivity can also be increased by increasing the length b of the plates or by decreasing a, their spacing, but if b is increased or a decreased beyond a certain limit the beam strikes the trailing edge of the plates and fails to reach the screen. The required maximum angular deflection of the beam determines the minimum value of the ratio of a/b which can be used.

A slight increase in deflection sensitivity can be obtained by setting the plates at a small angle to each other so that the spacing increases in the direction of the screen as shown in Fig. 167; for a given maximum angular deflection of the beam this expedient enables the average spacing to be reduced to less than the value for parallel plates, thus increasing sensitivity.

Most cathode-ray tubes and television camera tubes employ two deflection systems, one deflecting the beam in a direction at right angles to the deflection produced by the other. When electric deflection is used, two pairs of plates are required, and these are usually mounted in tandem, one pair being nearer the screen than the other. From expression (77) it follows that the deflection sensitivity of the plates nearer the screen must be less than that of the other pair; in practice the ratio of the sensitivities may be as large as 2 : 1.

Magnetic Deflection

Electron beams can also be deflected by the magnetic field of a coil placed outside the tube and arranged, as shown in Fig. 168*a*, with its axis at right angles to that of the tube. The deflection is in a direction at right angles to the coil axis and the tube axis. To give a more intense and more uniform field at the centre of the tube the coil is usually in the form of two halves which are connected in series and are situated on either side of the tube. The coils are sometimes of rectangular section and saddle-shaped so as to fit the tube closely as shown in Fig. 168*b*; alternatively they may have iron cores and be shaped as in Fig. 170*a*.

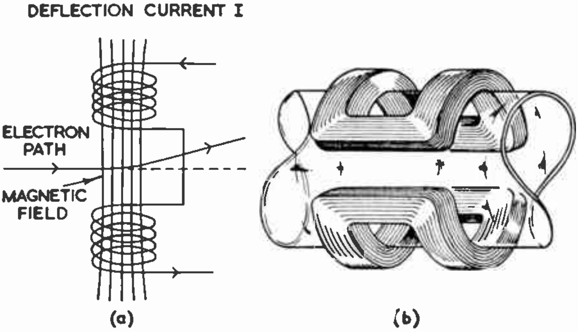


Fig. 168—Magnetic deflection is illustrated at (a) and a practical form of coil construction at (b)

A beam of electrons with a velocity v centimetres per second behaves as a current of $-ev$, and when such a current cuts a magnetic field H at right angles the beam experiences a deflecting force Hev.

From Newton's laws this force produces an acceleration a at right angles to the field and to the electron velocity, where

$$a = \frac{Hev}{m} \qquad \ldots \quad \ldots \quad \ldots \quad (78)$$

where m is the electron mass. If the magnetic field occupies a length b of the tube, this acceleration persists for a time b/v and the beam is deflected through a distance d given by

$$d = \tfrac{1}{2}at^2$$

Substituting for a and t:

$$d = \frac{Heb^2}{2mv} \qquad \ldots \quad \ldots \quad \ldots \quad (79)$$

The electron paths before and after deflection are straight lines which when produced meet at a point O, the centre of the magnetic field as shown in Fig. 169. If the angle of deflection is α:

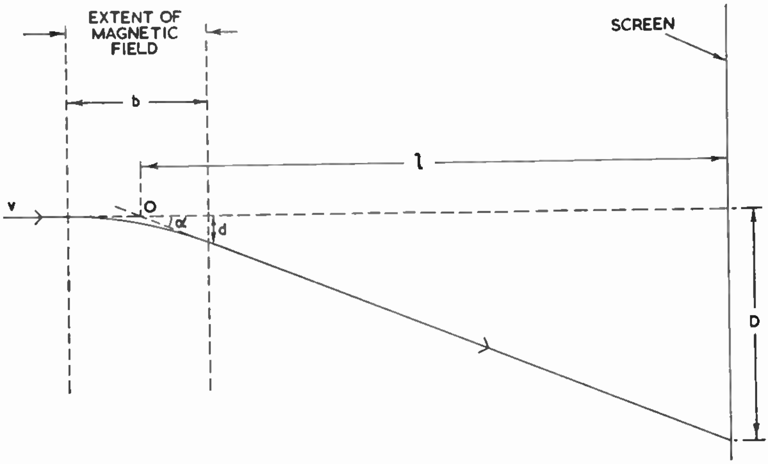


Fig. 169—Magnetic deflection of an electron beam

$$\tan \alpha = \frac{d}{b/2} = \frac{D}{l}$$

and substituting for d from (79):

$$D = \frac{lHeb}{mv}$$

But, from (58):

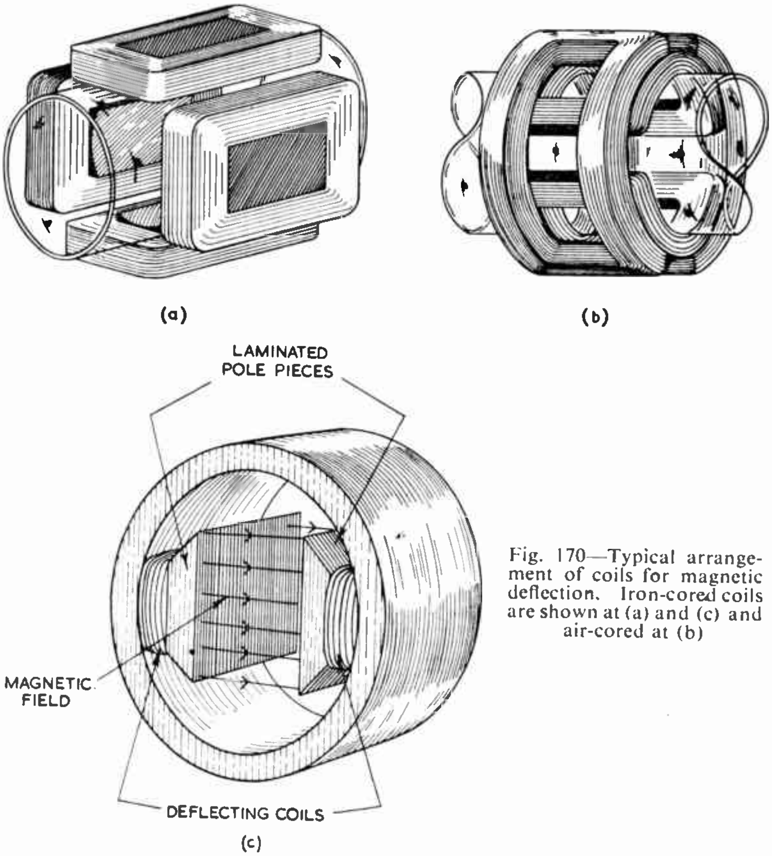


Fig. 170—Typical arrangement of coils for magnetic deflection. Iron-cored coils are shown at (a) and (c) and air-cored at (b)

$$v = \sqrt{\left(\frac{2eV_0}{m}\right)}$$

Substituting for v:

$$\frac{D}{H} = bl\sqrt{\left(\frac{e}{2mV_0}\right)} \quad \ldots \quad \ldots \quad \ldots \quad (80)$$

Thus the deflection sensitivity, i.e., the deflection (usually expressed in millimetres) for a field of 1 oersted, is directly proportional to the length of the deflecting field and to the distance of the screen from the field centre; in these respects magnetic and electric deflections are similar. Expression (80) also shows that the magnetic deflection sensitivity is inversely proportional to the square root of the accelerating voltage V_0; electric deflection sensitivity is inversely proportional to V_0. For this reason magnetic deflection is preferred to electric deflection in cathode-ray tubes, such as those used in television receivers, where high accelerating voltages are necessary.

At one time magnetic deflection was used only at low frequencies because of the difficulty of designing deflecting coils with low-power losses at high frequencies, but the difficulty has now been overcome and magnetic deflection at frequencies of the order of 10 kc/s can be achieved.

To obtain magnetic deflection in two directions at right angles, as is required in television camera tubes and television receivers, four coils are used, one pair to produce a horizontal magnetic field (for vertical deflection) and the other pair to produce a vertical field (for horizontal deflection). There is, however, no need for the two pairs of coils to be mounted in tandem as electric deflecting plates; the four coils may be grouped around one particular section of the tube as shown in Fig. 170. For this reason cathode-ray tubes for magnetic deflection are shorter than those for electric deflection, a consideration of some importance in television receiver design, where the tube has to be accommodated within a cabinet. The deflection system commonly used in television receivers is similar to that of Fig. 170*b* with a soft-iron cylinder surrounding the coils to decrease the external field and increase the deflecting fields.

There are a number of different forms of magnetic deflecting coils, and that illustrated in Fig. 170*c* may be regarded as a development of the arrangement of Fig. 170*a*, in which an iron path is provided for the magnetic field external to the tube. For simplicity Fig. 170 shows arrangements for beam deflection in one direction only (usually frame deflection); the space at the top and bottom of the iron cage can be used to accommodate air-cored line-deflector coils. The iron ring surrounding the deflecting coils considerably reduces the external field and increases the efficiency of the deflecting system. To minimize losses in the core due to eddy currents the core is built up of laminations in the same way as a transformer core.

The extended pole-pieces in Fig. 170*c* are provided to give a uniform magnetic field throughout the cross-sectional area of the tube. The same effect can be obtained, without using extended pole-pieces, by grading the winding of the deflector coils; one method is to construct each of the pairs of coils in, say, three sections of different diameters which are arranged concentrically. Provided the number of turns in each section is correctly chosen such coils give a better approximation to a uniform field than single-section coils.

Alternative Forms of Magnetic Deflecting Coils

In the magnetic deflecting systems so far described, each pair of coils has a common axis which intersects the axis of the tube;

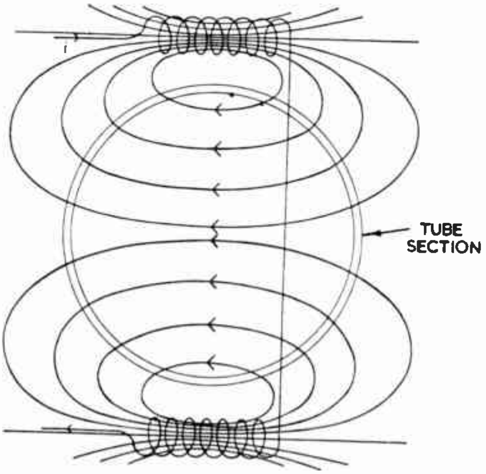


Fig. 171—Alternative arrangement of magnetic deflecting coils

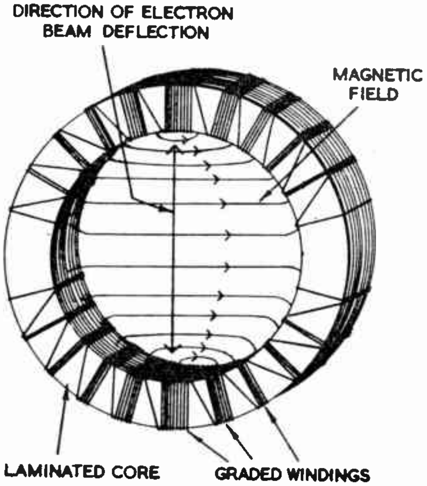


Fig. 172—A practical arrangement of magnetic deflecting coils using the principle of Fig. 171

but there is an alternative arrangement, illustrated diagrammatically in Fig. 171, in which the axes of each pair of coils are parallel and do not intersect the tube axis.

Fig. 172 illustrates a practical arrangement of coils; the two coils are wound as toroids on a laminated ring-shaped core. If the coils are uniformly wound the magnetic field tends to be crowded at the centre of the tube. A more uniform field can be obtained by using a non-uniform winding. the effective spacing between adjacent turns being a maximum at the ends of each winding and gradually decreasing to a minimum at the centre as shown in Fig. 172. Coils for line and frame deflection can be wound on the same ring core; since each pair of coils occupies the whole length of the core, one pair of coils must be wound on top of the other.

10.12 ELECTRON-BEAM DEFLECTION IN THE PRESENCE OF AN AXIAL MAGNETIC FIELD

In a number of types of camera tube, focusing is carried out by a long magnetic lens occupying most of the length of the tube and deflection is achieved by plates, or more commonly coils, situated within the focusing coil. In the neighbourhood of the deflection system, the electron beam is subjected to an axial magnetic field and a transverse electric or magnetic field. The mechanism of electric and magnetic deflection in the presence of an axial magnetic field differs from that described above; the foregoing description applies to cathode-ray tubes in which no axial field is used. The difference brought about by the additional magnetic field will be made clear in the following descriptions.

Electric Deflection

The behaviour of an electron projected into a combined magnetic and electric field of the type used in the orthicon camera tube was

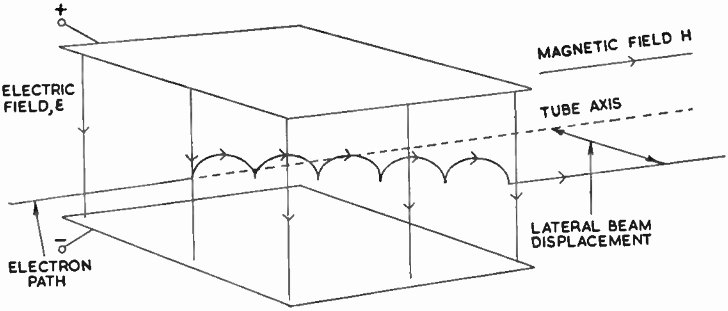


Fig. 173—Electric deflection in the presence of an axial magnetic field

described on page 228. The magnetic field is parallel to the tube axis, the electric field is at right angles to it, and an axial electron beam entering the combined field describes a series of cycloids in a plane parallel to the lines of electric intensity (vertical in Fig. 173) but inclined to the axis of the tube as shown.

The direction of beam displacement is at right angles to the lines of the electric field and to those of the magnetic field and can be reversed by reversing either field. For a given magnetic field the

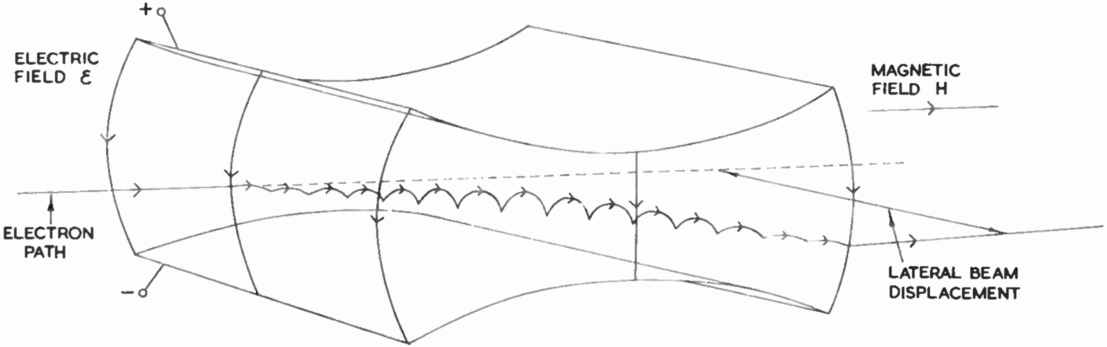


Fig. 174—Path taken by an electron between orthicon deflecting plates

deflection is directly proportional to the electric field strength. The beam leaves the electric field at a point laterally displaced from that at which it enters the field, and the direction in which the beam moves on leaving the field depends upon its instantaneous velocity at the boundary. At one point during each cycloid the vertical and horizontal components of velocity are zero, and if the beam is at such a point when it reaches the electric field boundary it will leave the field parallel to the tube axis, i.e., parallel to its initial direction but laterally displaced from it. The effect of the combined field is thus to displace the beam laterally through a distance directly proportional to the strength of the electric field. This form of electric deflection is employed to give orthogonal scanning in the orthicon camera tube, i.e., to ensure that the beam always approaches the target at right angles irrespective of the deflection. (The necessity for orthogonal scanning is explained in Chapter 5.) To achieve this it is essential that the beam leaves the electric field when its components of velocity at right angles to the axis are zero; in other words, the beam must describe an integral number of cycloids between the plates. The period of each cycloid depends only on the magnetic field strength (the amplitude of the cycloids depends on the electric field strength), and for a given electron velocity (determined by the final anode potential) the axial magnetic field can be adjusted to ensure this condition.

One particular value of magnetic field will eliminate lateral components of velocity for electrons leaving the electric field with a certain axial velocity. The axial velocity is not the same, however, for all the electrons in the beam; the slow and fast ones do not perform an integral number of cycloids and leave the electric field with appreciable lateral components of velocity; this causes bad focusing and degrades contrast in reproduced images. These unwanted velocity components can be minimized by using plates curved as shown in Fig. 174. This shape avoids the more abrupt discontinuity in electric field which occurs with parallel plates (Fig. 173) and provides a field which rises to a maximum at the centre of the plates and falls away on either side. Thus the amplitude of the cycloidal motion increases from zero to a maximum at the centre of the plates and then falls to a very low value as the electrons approach the boundary of the electric field: any lateral components of velocity are very small when the beam leaves the plates.

The direction of beam displacement between the plates depends upon the directions of the magnetic field and the electric field but not on the initial velocity of the electron beam. For example, if the beam travelling towards the target of a camera tube is displaced *upwards* by deflector plates (assuming electric frame deflection is used), and this is repelled by the target, the return beam will also be deflected *upwards* by the deflector plates.

To summarize: the effect of the axial magnetic field is to rotate the direction of electron-beam displacement through 90 deg; with such a field the electron beam experiences a deflecting force at right angles to the lines of the electric field. Without an axial magnetic field the deflecting force is parallel to the electric field. Moreover in orthogonal scanning the beam emerges from the electric field parallel to but displaced from its initial direction. In a tube without an axial magnetic field the beam suffers a permanent deflection between the plates and leaves them in a direction making an angle with the initial beam direction. As a corollary, in an orthicon camera tube the width of the deflecting plates must be at least equal to that of the target, but in a tube without an axial magnetic field the deflecting plates may be considerably smaller than the screen.

Magnetic Deflection

Most low-velocity camera tubes use magnetic deflection, and the electron beam is focused by a long magnetic lens. In the neighbourhood of the deflection system the beam is subjected to an axial magnetic field due to the focusing coil and a transverse magnetic field due to the deflecting coil as shown in Fig. 175. These two fields may be regarded as the components of a single field of strength $\sqrt{(H_T^2 + H_A^2)}$ which is inclined at an angle α to the tube axis, where $\tan \alpha = H_T/H_A$, H_T being the transverse and H_A the axial field. The electron beam from the gun is initially parallel to the tube axis and enters this field at an angle α to the lines of intensity. The behaviour of electrons entering a parallel magnetic field at an oblique angle was discussed on page 227, where it was shown that the electrons take a helical path about the axis parallel to the magnetic field. Thus the beam entering the region of the combined field is deflected through an angle α as shown in Fig. 175 and performs helices about an axis parallel to the lines of intensity of the resultant field.

After leaving the region occupied by the transverse magnetic field, the beam is subjected to the axial field only, and it enters this field at an angle α. The beam is again deflected through an angle α and now performs spirals around a line parallel to the tube axis. After this deflection the beam is parallel to the axis of the tube again, and the effect of the two magnetic fields is thus to displace the beam laterally in the direction of the transverse field without permanently altering its direction. The lateral displacement is directly proportional to the transverse magnetic field and is reversed by reversing this field. The chief merit of this form of deflection is that it compels the electron beam to approach the target always at right angles; this is necessary to achieve orthogonal scanning which is required in low-velocity camera tubes.

A significant feature of this type of deflection is that the direction in which the beam is displaced is reversed when the initial electron velocity is reversed; as an illustration, if a beam travelling towards the target of a camera tube is deflected *upwards* by the field of the magnetic frame deflection coils, a return beam travelling towards the cathode is deflected *downwards*. A beam repelled by the target thus retraces its outgoing path. In this respect magnetic deflection differs from electric deflection, in which the return beam is displaced in the same direction as the outgoing beam.

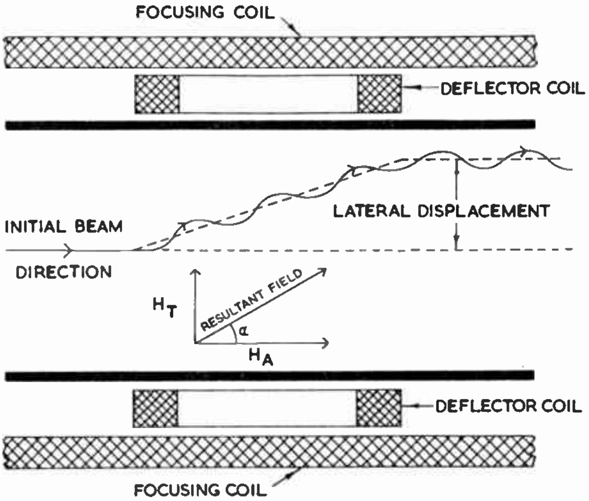


Fig. 175—Magnetic deflection in the presence of an axial magnetic field

This form of magnetic deflection differs from that in the foregoing description (where no axial field is used) in that the beam is deflected in the direction of the transverse field, i.e., towards one of the saddle deflecting coils and not at right angles to the transverse field as in a tube without an axial field. Moreover, when an axial field is present there is no permanent deflection of the beam, which emerges from the transverse field parallel to but laterally displaced with respect to its initial direction. In a tube with magnetic deflection but no axial field the emergent beam makes an angle with the initial beam.

APPENDIX A

APERTURE DISTORTION IN TELEVISION CAMERA TUBES

IN a camera tube of the iconoscope or orthicon type the limiting resolution is determined by the shape and cross-sectional area of the scanning beam at the point where it meets the mosaic and by the granular structure of the mosaic itself. The first of these two factors is in practice more important than the second because it is usually impossible to reduce the cross-sectional area of the electron beam to less than a certain minimum value, whereas mosaics can be manufactured with a very fine structure; in practice the cross-section of the beam may cover 10 or 12 cells of the mosaic. The effect of finite beam cross-section is to cause a high-frequency loss in the camera output, thus impairing definition in reproduced images. The way in which this distortion arises may be explained as follows:

Fig. A1(a) shows part of a light image on a mosaic and contains an abrupt transition from black to white. If the scanning beam is of infinitely small cross-section the output of the tube jumps instantaneously as the beam crosses the line of demarcation, the waveform having the shape shown in Fig. A1(b). Such a steep wavefront contains harmonics, extending theoretically to an infinitely high value.

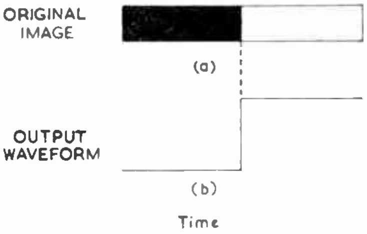
In practice, however, the beam has appreciable dimensions and takes a finite time to cross the boundary between black and white. At the instant when the beam rests half on the black and half on the white part of the image, the tube output is intermediate between that corresponding to black and that for white. The output waveform has the shape shown in Fig. A2(b) and the reproduced image has the appearance shown in Fig. A2(c).

A waveform such as that shown in Fig. A2(b) does not contain so many high-frequency components as that of Fig. A1(b) and the effect of the finite beam cross-section is thus to attenuate the high-frequency output of the camera. The effect is described as aperture distortion and is important only where a change from one tonal value to another takes place within a very short distance, i.e., when the undistorted output would contain high-frequency components. If, along the scanning lines, the tonal values change slowly with distance, the camera output portrays the change accurately because no high-frequency components are necessary.

If an image contains very fine detail it is possible that a transition from black to white and back again to black may take place within the area occupied by the scanning beam. In this case the output of the camera at the instant when the beam covers the detail is an integral of the amount of light which has fallen on this particular area of the mosaic since it was last scanned; the result is that this detail is not portrayed in the camera output at its correct amplitude or its correct waveform.

Aperture distortion also occurs in cathode-ray tubes during reproduction of images because the spot on the screen has appreciable area. This appendix is, however, confined to the distortion produced in television camera tubes.

Fig. A1—Output obtained when scanning beam has infinitely small dimensions



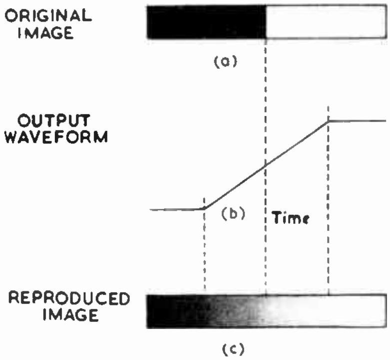


Fig. A2—Output obtained when scanning beam has appreciable dimensions

The extent of the high-frequency loss due to aperture distortion can be quantitatively assessed as follows:—Suppose the light image on the mosaic is such that the tonal value along a particular line follows a sinusoidal law; this may be expressed thus:

$$y = k + \sin 2\pi\frac{x}{\lambda}$$

where y is the tonal value at a distance x from the origin and λ is the distance corresponding to one complete cycle of tonal value.

The constant k must be introduced because the tonal value cannot have a negative value for any value of x; k must therefore be equal to or greater than 1 and for convenience will be taken as 1.

$$\therefore \quad y = 1 + \sin 2\pi\frac{x}{\lambda}$$

and the curve of y plotted against x is given in Fig. A3.

The scanning beam is assumed to be of uniform density and rectangular cross-section, having a dimension l in the direction of scanning and b at right angles to the scanning lines. Further, we shall assume that b is the width of the scanning lines; this implies that the beam completely discharges the mosaic in every picture period. A rectangular beam cross-section is assumed because it considerably simplifies the mathematics of the following analysis. In an actual camera the scanning beam is most likely to have a circular cross-section with maximum density at the centre and for this reason the conclusions reached in the analysis are only approximately realized in practice.

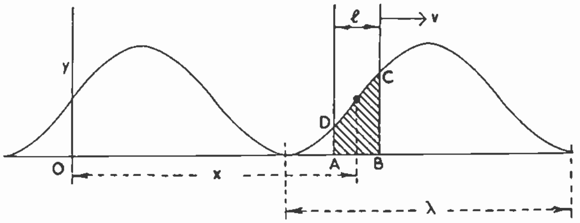


Fig. A3—Illustrating sinusoidal variation of tonal value

At a time t the centre of the beam is assumed to be at a distance x from the origin and the beam scans the mosaic with a velocity v. Thus

$$x = vt$$

The camera output at any instant is directly proportional to the amount of light which has been received by that area of the mosaic occupied by the scanning beam during the previous picture period. The output is thus proportional to the beam cross-section and the tonal value, i.e., to lby. Since b is constant the camera output may be taken as directly proportional to ly, that is to the area ABCD in Fig. A3; this is the area included between the ordinates at $x + l/2$ and $x - l/2$ and beneath the curve of y plotted against x. As the scanning beam moves along the x axis at a velocity v the included area (tube output) varies continuously between a maximum and a minimum.

$$\text{Area} = \int_{x - l/2}^{x + l/2} y.dx$$

$$= \int_{x - l/2}^{x + l/2} \left(1 + \sin 2\pi \frac{x}{\lambda}\right) dx$$

$$= \left[x - \frac{\lambda}{2\pi} \cos 2\pi \frac{x}{\lambda}\right]_{x - l/2}^{x + l/2}$$

$$= l + \frac{\lambda}{\pi} \sin 2\pi \frac{x}{\lambda} \sin \frac{\pi l}{\lambda}$$

$$= l\left(1 + \frac{\lambda}{l\pi} \sin \frac{\pi l}{\lambda} \sin 2\pi \frac{x}{\lambda}\right)$$

$$\text{But } \frac{2\pi x}{\lambda} = \frac{2\pi f x}{v} = 2\pi f t = \omega t$$

$$\therefore \text{ area } = l\left(1 + \frac{\lambda}{\pi l} \sin \frac{\pi l}{\lambda} \sin \omega t\right) \quad \ldots \quad \ldots \quad (81)$$

The output of the camera is directly proportional to this area. There are two terms in this expression; the first is a steady or d.c. component and the second a component which varies sinusoidally with time. This second term is the only alternating component present in the output which is therefore undistorted.

Amplitude of alternating output

$$= \frac{\lambda}{\pi} \sin \frac{l\pi}{\lambda} = l \frac{v}{fl\pi} \sin \frac{\pi l f}{v} = l \frac{\sin \theta}{\theta} \quad \ldots \quad \ldots \quad (82)$$

where $\theta = \pi l f / v$ and is directly proportional to frequency for given values of v and l. Thus, for a given scanning speed and beam cross-section, the frequency response of the camera tube can be plotted in decibels from the expression

$$\text{response} = 20 \log_{10} \frac{\sin \theta}{\theta}^{*}$$

---

* The expression $(\sin \theta)/\theta$, where θ is proportional to frequency, gives the frequency response obtained in a number of scanning processes. For example, see *Sound Recording and Reproduction*, page 215, by J. W. Godfrey and S. W. Amos. (Iliffe and Sons, Ltd., 1952.)

This curve is plotted in Fig. A4. At low frequencies θ is small and $(\sin \theta)/\theta$ is approximately unity but as frequency (and θ) is increased $(\sin \theta)/\theta$ falls and reaches zero when $\theta = \pi$ radians. The curve is reasonably level, however, up to a value of θ of 1·2 radians where the loss is 2 db. Zero output occurs when $\sin \theta = 0$, i.e., when $\theta = \pi$ radians. This occurs when

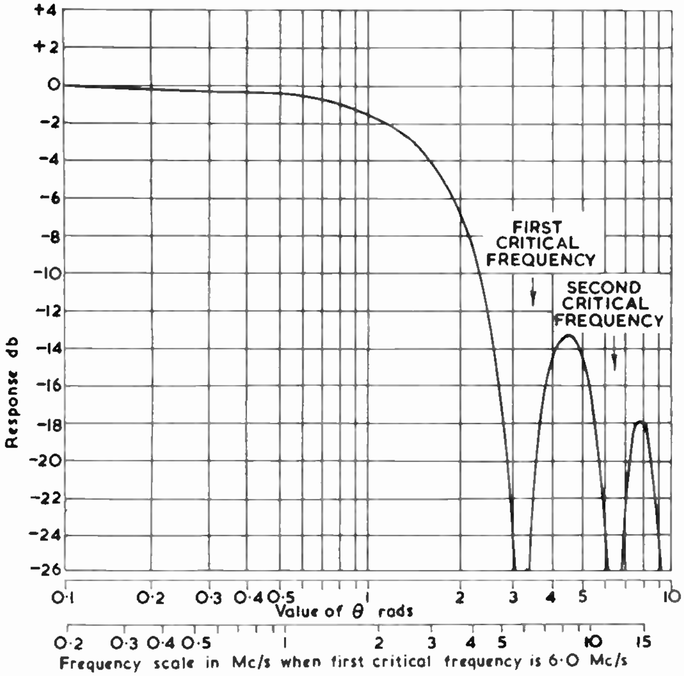


Fig. A4—Curve of $20 \log_{10} \frac{\sin \theta}{\theta}$

$$\frac{\pi l f}{v} = \pi$$

$$\therefore f = \frac{v}{l}$$

The frequency (v/l) at which zero output occurs is known as the *first critical* or *extinction* frequency and for a given scanning speed is inversely proportional to l, i.e., to the cross-sectional area of the scanning beam. To maintain a good high-frequency response and minimize aperture distortion the extinction frequency must be made as high as possible; this requires a low value of l and necessarily entails a low output, as shown in equation (82). On the other hand a large value of l gives a large output but the extinction frequency is low and aperture distortion considerable.

For a given value of λ (i.e., for an image detail of a given size) there is an optimum value of l given by

$$l = \frac{v}{2f}$$

This can be deduced from expression (82), for the output of the tube is a maximum when $\sin \theta = 1$. This occurs when $\theta = \pi/2$, that is when

$$l = \frac{v}{2f}$$

Let the picture contain L lines and the beam be of square cross-section of side l where $l = b =$ width of the scanning lines. Then l is equal to h/L where h is the height of the image on the mosaic.

The width w of the image is ha' where a' is a value of the aspect ratio in which allowance has been made for the effect of the suppression periods as explained in Chapter 2.

Therefore the length of one scanning line $= ha' = lLa'$.

In one picture period the beam scans L lines, a total length of lL^2a', and in one second the total distance travelled by the scanning beam is $Pa'L^2l$ where P is the picture frequency. This is equal to the velocity v of the scanning beam,

$$\therefore v = Pa'L^2l$$

The first extinction frequency is given by v/l, i.e.,

$$\text{first extinction frequency} = \frac{v}{l} = \frac{Pa'L^2l}{l} = Pa'L^2$$

It was shown in Chapter 2 that the highest frequency which must be transmitted in order to portray detail of the size of an element is given by $Pa'L^2/2$; this is one-half the first critical frequency. If $P = 25$, $L = 405$ and $a' = 1{\cdot}516$ the extinction frequency is given by

$$f = Pa'L^2 = 25 \times 1{\cdot}516 \times 405^2 = 6{\cdot}22 \text{ Mc/s.}$$

If the extinction frequency is known the frequency response of the camera tube can be obtained directly from Fig. A4. To do this, a logarithmic frequency scale in which the length of one cycle equals that for θ is placed along the horizontal axis so that the extinction frequency coincides with a value of θ of π radians. This has been done in Fig. A4 for an extinction frequency of 6·0 Mc/s (approximately correct for the British television standards) and it can be seen that the response is -2 db at 2·2 Mc/s and -4 db at 3·0 Mc/s. There is little point in transmitting frequencies in excess of $Pa'L^2/2$, since this is approximately the highest value which is necessary to transmit detail of the size of an element. The shape of the response curve up to $\theta = \pi$ radians is similar to that of a low-pass filter and can be equalized by a suitable network up to a frequency corresponding to, say, $\theta = 2$ radians.

An interesting feature of aperture distortion is that the attenuation caused by a symmetrical beam section (e.g., a rectangular or round section) is not accompanied by any phase shift. If the scanning spot is unsymmetrical, however, phase shift does occur; an example of this is provided by the flying-spot scanner where the effective aperture is the area of the spot together with that of the comet tail caused by afterglow of the screen material. If afterglow is appreciable, the aperture is unsymmetrical and phase distortion results.

The first extinction frequency is not the limiting frequency generated by a camera tube, for when θ exceeds π radians $(\sin \theta)/\theta$ again has a finite value and a maximum response occurs when $\theta = 3\pi/2$ radians. This is a negative maximum (since $\sin 3\pi/2 = -1$) but the sign is not indicated in an attenuation curve such as Fig. A4. Another frequency of zero output, known as the second critical frequency, occurs when $\theta = 2\pi$ radians and this is followed by a second maximum (positive) when $\theta = 5\pi/2$ radians. The response continues to an infinitely high frequency, critical frequencies occurring whenever θ is a multiple of π radians and maxima occurring whenever θ is an odd multiple of $\pi/2$ radians. The maxima are of progressively less amplitude as frequency increases, as shown in Fig. A4 in which the first two maxima are plotted.

APPENDIX B

UNITS OF ILLUMINATION AND BRIGHTNESS AND THEIR EQUIVALENTS

FOR the sake of simplicity, only the British units of illumination and brightness were defined in Chapter 7, but units based on the metric system are also extensively used. These units are defined in this appendix and the interrelations between the various units are given in detail.

Illumination

An illumination of 1 lumen per square metre is known as 1 *lux* (sometimes termed a *metre-candle*), and an illumination of 1 lumen per square centimetre is 1 *phot*. The phot is rather a large unit, and its submultiple the *milliphot* (equal to 10^{-3} phot) is frequently used for expressing low values of illumination. The relationships between the foot-candle, lux, phot and milliphot are as follows:

1 foot-candle = 1 lumen per square foot
= 10·76 lux
= 1·076 milliphots

1 lux = 1 lumen per square metre
= 0·0929 foot-candle
= 0·0001 phot
= 0·1 milliphot

1 phot = 1 lumen per square centimetre
= 10,000 lux
= 929 foot-candles

1 milliphot = 0·001 phot
= 10 lux
= 0·929 foot-candle

Brightness

A perfectly-diffusing surface which radiates a total of 1 lumen per square centimetre is said to have a brightness of 1 *lambert*. This is a large unit, and its submultiple the *millilambert* is often used for measuring low values of brightness. It was shown in Chapter 7 that a brightness of 1 candle per square foot is equivalent to π foot-lamberts; from this it follows that a brightness of 1 candle per square centimetre is equivalent to π lamberts. This and other equivalents are given in the list below:

1 lambert = 1 lumen per square centimetre
= 0·3183 candle per square centimetre
= 2·054 candles per square inch
= 929 foot-lamberts

1 foot-lambert = 1 lumen per square foot
= 1·076 millilamberts
= 0·00221 candle per square inch
= 0·000343 candle per square centimetre
= 0·001076 lambert

1 millilambert = 0·001 lambert
= 0·929 foot-lambert

1 candle per square centimetre
= 3·1416 lamberts
= 2,919 foot-lamberts

1 candle per square inch
= 0·487 lambert
= 487 millilamberts
= 452 foot-lamberts

1 candle per square foot
= 3·1416 foot-lamberts
= 3·382 millilamberts

APPENDIX C

LIGHT FLUX RADIATED FROM A PERFECTLY-DIFFUSING SURFACE

THIS determination is based on Lambert's law, which states that the luminous intensity of a uniformly-diffusing surface in a direction making an angle θ to the normal is directly proportional to cos θ. In Fig. C1 the intensity is a maximum and equal to I along the normal OA and is zero along the surface CD. If the length OA is chosen to represent I and a circle of diameter OA is described about it, the length OP of any chord at an angle θ to the normal represents the intensity in that direction.

To determine the total flux radiated by the surface, consider the area swept out by an elementary arc EF as it rotates about the axis OA in Fig. C2. The length of the arc is $r.d\theta$, its radius of rotation is r sin θ, and the area swept out in one revolution is thus $2\pi r^2$ sin $\theta.d\theta$. The elementary solid angle $d\omega$ subtended by this surface at O is given by area/radius², i.e.,

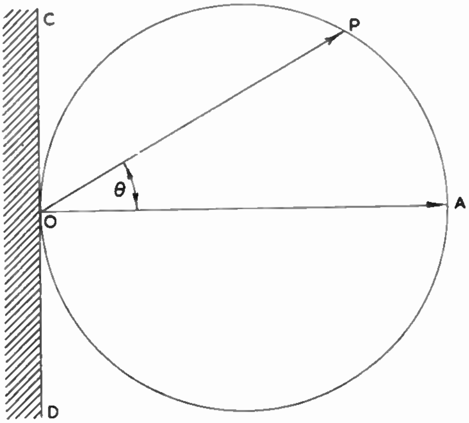


Fig. C1—Radiation from a uniformly diffusing surface

$$d\omega = 2\pi \sin \theta . d\theta$$

The intensity along OP is I cos θ, where I is the normal intensity. The luminous flux dF contained within this solid angle is given by

$$dF = I \cos \theta . d\omega$$

and substituting for $d\omega$:

$$\begin{aligned} dF &= 2\pi I \sin\theta \cos\theta . d\theta \\ &= \pi I \sin 2\theta . d\theta \end{aligned}$$

The total flux emitted by the surface is obtained by integrating this expression from $\theta = 0$ to $\theta = \pi/2$:

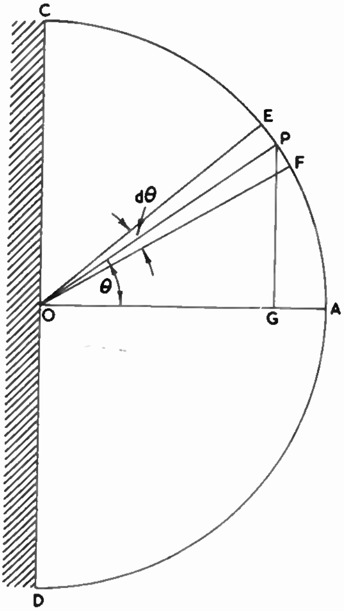


Fig. C2—Determination of total flux radiated

$$\begin{aligned} F &= \int_0^{\pi/2} \pi I \sin 2\theta . d\theta \\ &= \pi I \end{aligned}$$

Thus the total flux emitted by a surface with a normal intensity of I candles is πI lumens.

APPENDIX D

GENERAL FORMULA FOR REFRACTION AT A SPHERICAL SURFACE

FIG. D1 illustrates an object O giving a ray of light OA which falls on a spherical boundary between two media of refractive index n and n'. The ray is refracted to form an image at I. According to the sign convention set out on page 134, the distances x, x' and R in Fig. D1 are positive; from this it follows that the angles θ, θ' and α are also positive.

The angles i, r, θ, θ' and α are so small that their sines and tangents are approximately equal to the angles themselves. If these angles are small, the foot B of the perpendicular from A on the optic axis will practically coincide with P, the pole of the spherical surface, and

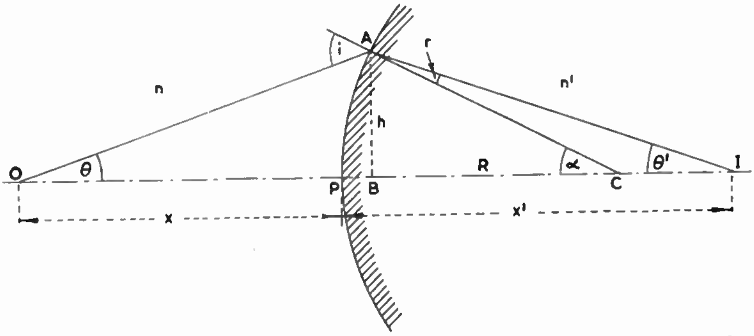


Fig. D1—Derivation of a general formula for refraction at a spherical surface

$$\theta \simeq \frac{h}{x}, \quad \theta' \simeq \frac{h}{x'}, \quad \alpha \simeq \frac{h}{R} \quad \ldots \quad \ldots \quad (83)$$

For small values of i and r Snell's law becomes

$$\frac{i}{r} = \frac{n'}{n} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (84)$$

From Fig. D1 $i = \theta + \alpha$ and $r = \alpha - \theta'$.

$$\therefore \quad \frac{i}{r} = \frac{\theta + \alpha}{\alpha - \theta'}$$

Substituting for i/r from (84) and θ, θ' and α from (83):

$$\frac{n'}{n} = \frac{\dfrac{h}{x} + \dfrac{h}{R}}{\dfrac{h}{R} - \dfrac{h}{x'}}$$

Rearranging:

$$\frac{1}{x} + \frac{1}{R} = \frac{n'}{n} \cdot \frac{1}{R} - \frac{n'}{n} \cdot \frac{1}{x'}$$

From which

$$\frac{n}{x} + \frac{n'}{x'} = \frac{n' - n}{R}$$

APPENDIX E

MAGNIFICATION OF A CONVEX MIRROR

THE expression for the magnification of an optical system can be proved fairly simply for a convex or concave mirror or for either type of lens, but it may be necessary to allow for the fact that some of the factors x, x' or R may be negative. To avoid this complication the expression is derived here for a convex mirror, for which all three factors are positive.

Fig. E1 illustrates the formation of the image of a large object AB in a convex mirror. The image is A′B′, and magnification M is given by A′B′/AB. Triangles ABC and A′B′C are similar

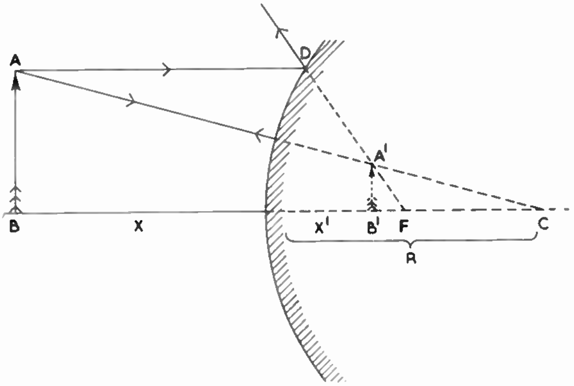


Fig. E1—Magnification of a convex mirror

$$\frac{A'B'}{AB} = \frac{B'C}{BC}$$

$$\therefore \quad M = \frac{B'C}{BC} = \frac{R - x'}{R + x}$$

From expression (15) on page 135:—

$$R = \frac{2x'x}{x - x'}$$

Substituting for R:

$$M = \frac{\dfrac{2x'x}{x - x'} - x'}{\dfrac{2x'x}{x - x'} + x}$$

This reduces to

$$M = \frac{x'}{x}$$

APPENDIX F

ILLUMINATION AT AN AXIAL POINT OF A LENS SYSTEM

THIS appendix is adapted, by permission, from *Principles of Optics*, by Hardy and Perrin. (Copyright 1932. McGraw-Hill Book Company Inc.)

Fig. F1 illustrates an optical system which is represented by its entrance and exit pupils only and produces an image at I of an object O assumed for convenience to be circular.

Let O be divided into annular rings of radius *r* and width *dr*.

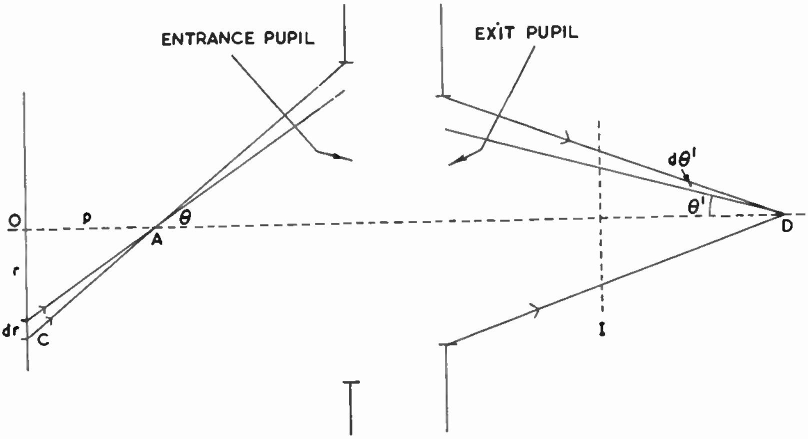


Fig. F1—Illumination at an axial point of a lens system

The illumination *dE* at A, a point on the optic axis, due to an elementary ring of the object is given by

$$dE = \frac{dI}{p^2 \sec^2 \theta} \cos \theta \quad .. \quad .. \quad .. \quad (85)$$

where *dI* is the luminous intensity of the ring in the direction of A and $p^2 \sec^2 \theta$ is the square of its distance from A. If the source obeys Lambert's law

$$dI = 2\pi r \, dr \, B \cos \theta$$

in which *B* is the brightness in candles per unit area of the source and $2\pi r\, dr$ is the area of the ring; this follows from equation (8) of Chapter 7. Substituting for dI in (85):

$$dE = \frac{2\pi r\, dr\, B \cos^2 \theta}{p^2 \sec^2 \theta} \quad \ldots \quad \ldots \quad \ldots \quad (86)$$

But
$$r = p \tan \theta$$
$$\therefore \quad dr = p \sec^2 \theta . d\theta$$

Substituting for r and dr in (86):

$$dE = 2\pi B \sin \theta \cos \theta . d\theta$$

The illumination at A due to the area of the source within the angle θ is given by

$$E = \int_0^\theta 2\pi B \sin \theta \cos \theta . d\theta$$
$$= \pi B \sin^2 \theta$$

In a perfect lens system all the light passing into the entrance pupil emerges from the exit pupil, and the illumination at D, the image of A, bears the same ratio to that at A as the area of D to the area of A; the area ratio is proportional to the ratio of $\sin \theta'$ to $\sin \theta$. Thus the illumination at the axial point D is given by

$$E' = \pi B \sin^2 \theta'$$

where B is in candles per unit area. If B is in foot-lamberts (see page 128) and if the transmission of the lens system is τ:

$$E' = \tau B \sin^2 \theta'$$

which shows that the illumination at an axial point depends only on the transmission of the lens system, the brightness of the object and the angle subtended at the point by the exit pupil.

APPENDIX G

DEPTH OF FIELD

THE relationship between the depth of field, lens aperture and the diameter of the circle of confusion will be deduced from Fig. G1. For the sake of simplicity this illustrates a single-element lens, but the results deduced in this appendix are of general application.

The position of the image plane is chosen so that the object O is accurately in focus at I. If the object is moved through a distance d_1 to O_n, the image moves to I_n, giving a circle of confusion of diameter c on the plane through I.

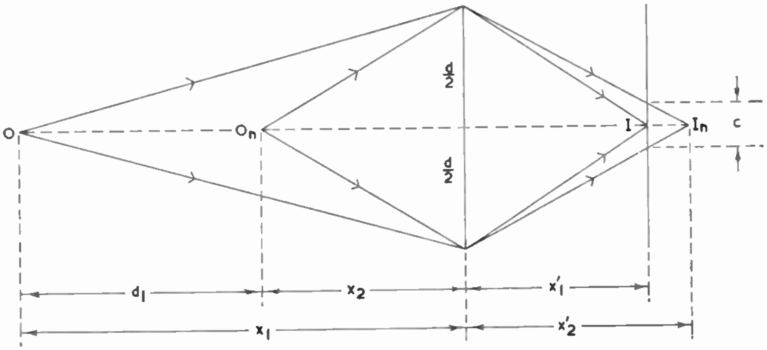


Fig. G1—Calculation of depth of field

From equation (26):

$$\frac{1}{x_1}+\frac{1}{x'_1}=\frac{1}{f} \qquad \ldots \quad \ldots \quad \ldots \quad (87)$$

and

$$\frac{1}{x_2}+\frac{1}{x'_2}=\frac{1}{f} \qquad \ldots \quad \ldots \quad \ldots \quad (88)$$

Equating (87) and (88):

$$\frac{1}{x_2}-\frac{1}{x_1}=\frac{1}{x'_1}-\frac{1}{x'_2}$$

from which

$$\frac{x_1-x_2}{x_1 x_2}=\frac{x'_2-x'_1}{x'_1 x'_2} \qquad \ldots \quad \ldots \quad \ldots \quad (89)$$

But $x_1 - x_2 = d_1$ and, from similar triangles in the image space of Fig. G1, $x'_2 - x'_1 = cx'_2/d$. Substituting in expression (89) and rearranging:

$$d_1 = \frac{cx_2}{d \cdot \dfrac{x'_1}{x_1}} \quad \dots \quad \dots \quad \dots \quad (90)$$

But $x_2 = x_1 - d_1$ and $x'_1/x_1 = M$. Substituting in (90) and rearranging:

$$d_1 = \frac{cx_1}{Md + c} \quad \dots \quad \dots \quad \dots \quad (91)$$

If the object is moved to a far distance O_f, distant d_2 from O, the image is formed between I and the lens, giving rise to a circle of confusion of diameter c. By a proof similar to the above it may be shown

$$d_2 = \frac{cx_1}{Md - c}$$

The depth of field is the total distance through which O may be moved for a circle of confusion no greater than c and is given by

$$\text{depth of field} = d_1 + d_2 = \frac{cx_1}{Md + c} + \frac{cx_1}{Md - c} = \frac{2cx_1Md}{M^2d^2 - c^2}$$

The inner object distance for a circle of confusion of diameter c is given by

$$\text{inner object distance} = x_1 - \frac{cx_1}{Md + c} = \frac{x_1}{1 + c/Md}$$

Similarly

$$\text{outer object distance} = x_1 + \frac{cx_1}{Md - c} = \frac{x_1}{1 - c/Md}$$

Equation (90) may be rewritten in the form

$$x_1 - x_2 = \frac{cx_2x_1}{dx'_1}$$

and on division by x_1 this becomes

$$1 - \frac{x_2}{x_1} = \frac{cx_2}{dx'_1}$$

If x_1 is infinite, $x'_1 = f$ and the expression becomes

$$1 = \frac{cx_2}{df}$$

$$\text{i.e.,} \quad x_2 = \frac{fd}{c}$$

$$= \text{hyperfocal distance}$$

In words, if the lens is focused on infinity an object at the hyperfocal distance gives an image in which the diameter of the circles of confusion is c.

APPENDIX H

FORCE ON AN ELECTRON MOVING IN A MAGNETIC FIELD

THE force on a current-carrying conductor situated in a magnetic field is given by equation (66) on page 225:

$$F = \frac{1}{10} HIl \sin \theta$$

and the corresponding relationship for the force on an electron moving in a magnetic field is expressed by equation (67):

$$F = -\frac{1}{10} Hve \sin \theta$$

These two equations show that, to experience the same force as an electron travelling with a velocity v along the same path in the same field, the current I in a conductor l centimetres long must be given by $Il = -ev$. If the conductor is made one centimetre in length we have

$$I = -ev$$

This value of I represents the current which in a conductor *of unit length* experiences the same force as an electron moving with a velocity v; this is sometimes expressed by the statement that an electron of velocity v is equivalent to a current of $-ev$. The negative sign implies that the electron experiences the same force as a current ev moving in the opposite direction to the electron along the same path (of unit length) in the same field. This point is illustrated in Figs. 132 and 133 in Chapter 10, in which, for convenience, the current and electron flow is assumed to be at right angles to the field.

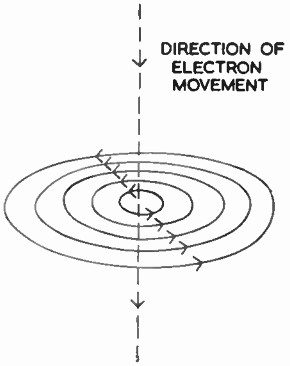


Fig. H1—Magnetic field due to a moving electron

A number of rules and mnemonics have been devised to illustrate the relative directions of field, current and deflection, but when they are used to deduce the direction of deflection of an electron beam, the current direction must be taken as opposite to that of electron flow. This may result in confusion in applying these rules to problems in electron optics, and no rules were therefore quoted in Chapter 10.

When necessary it is possible to deduce the direction of deflection of an electron beam in a magnetic field from first principles by remembering that the magnetic field set up by a moving electron is a series of circles with the path as centre, the direction of the magnetic force being anti-clockwise when viewed in the direction of electron movement. This is illustrated in Fig. H1, in which it is assumed that the field is viewed from above.

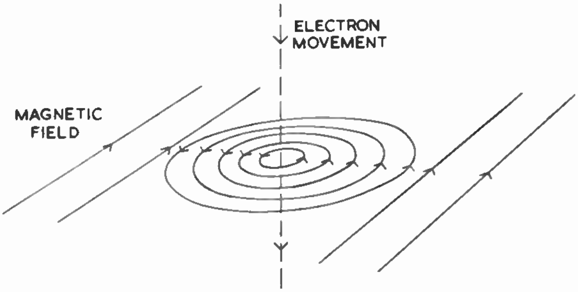


Fig. H2—Field due to a moving electron superimposed on a parallel magnetic field

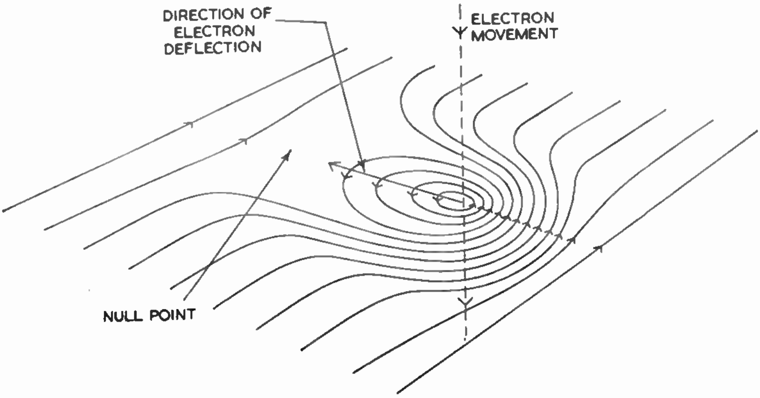


Fig. H3—Composite field due to an electron moving through a uniform magnetic field

If the electron moves across a magnetic field directed into the paper as shown in Fig. H2, the lines of force due to the electron and field are in the same direction on the right of the electron path but opposite in direction on the left. As a result the fields redistribute themselves as shown in Fig. H3, the lines being crowded on the right of the electron path but farther apart on the left. At one point on the left the two fields cancel, giving a null point at which there is no magnetic force. This implies that the magnetic field is stronger on the right of the diagram than on the left, and as a consequence the electron experiences a force directed towards the left, i.e., towards the null point, as shown in Fig. H3. The relative directions of electron movement, field and force agree with those in Fig. 133. There is, of course, no need to go through all the stages of this argument every time the direction of deflection is required; it may be assumed that the deflection is always directed from the point where the lines of force travel in the same direction towards the point where the lines are in opposite directions.

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