AN IMAGE-CONVERTER TUBE FOR HIGH-SPEED PHOTOGRAPHIC SHUTTER SERVICE

BY

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Summary—A developmental image-converter tube having electrostatic focus, a shutter grid, and electrostatic deflection is described. This tube is intended for multiple-frame photography of high-speed events as short as ten millimicroseconds. Operating characteristics of the tube are described, with emphasis on the low gating-power and deflection-power requirements.

INTRODUCTION

AN image-converter tube is an electron device which provides a visible image of an irradiation pattern incident on its photocathode. Such a tube permits visual observation or photographic recording of optical images produced by nonvisible or relatively nonactinic radiation. In terms of radiation wavelength, the conversion is usually (but not necessarily) from longer to shorter, as, in "snooperscope" types which provide visible images of objects or terrain illuminated by "black" (infrared) light. Image-converter tubes now have many applications in science and industry as well as in the military field. A particularly important application is as shutters in very-high-speed photography.

A developmental image-converter tube designed specifically for high-speed photographic service and having low gating- and deflection-power requirements is described in this paper. The tube has a maximum ultor-voltage rating of 15 kilovolts and a deflection factor of only 75 volts per inch per kilovolt of ultor voltage, and requires a gating voltage of only 17 volts per kilovolt. It uses electrostatic focusing and deflection and is provided with a special P11 phosphor screen capable of resolving better than 22 line pairs per millimeter. Exposure times as short as 10^{-8} second can be achieved without loss of resolution.

Although the use of image-converter tubes as photographic shutters has been previously described,[1-3] the tubes used in this early work

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[1] J. S. Courtney-Pratt, "A New Method for the Photographic Study of Fast Transient Phenomena," *Research*, Vol. 2, p. 287, June, 1949.

[2] A. W. Hogan, "Use of Image Converter Tube for High-Speed Shutter Action," *Proc. I.R.E.*, Vol. 39, p. 268, March, 1951.

[3] F. C. Gibson, M. L. Bowser, C. W. Bamaley, and F. H. Scott, "Image Converter Camera for Studies of Explosive Phenomena," *Rev. Sci. Instr.*, Vol. 25, p. 173, February, 1954.

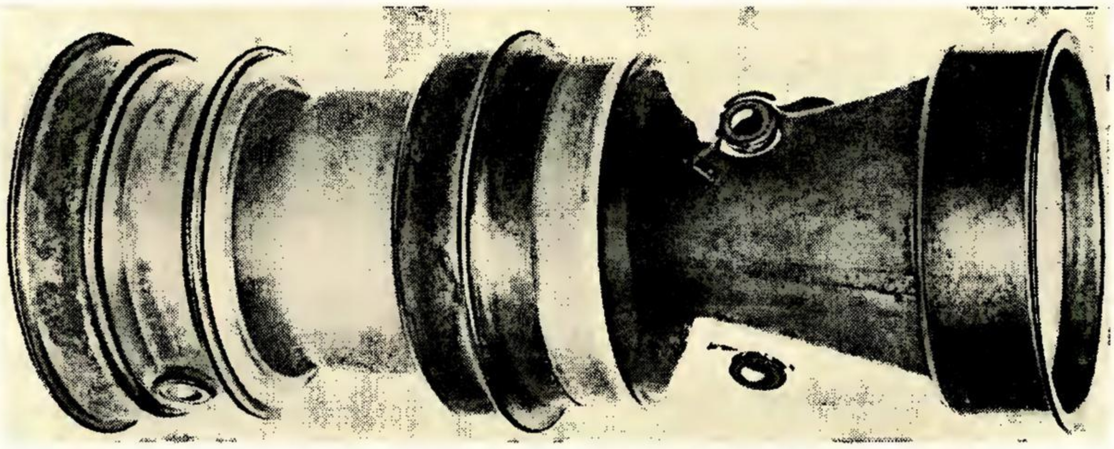

Fig. 1—Photograph of the developmental image-converter tube.

required substantial amounts of gating and deflection power, and, frequently, had been developed for purposes other than shutter service. Not until very recently have tubes designed specifically for shutter service and having low gating- and deflection-power requirements been described.[4]

Design Details

A photograph of the image-converter tube described in this paper is shown in Figure 1, and a cross-sectional drawing is shown in Figure 2. The tube is slightly less than four inches in diameter and is approximately 10 inches long. The circular photocathode is one inch in diameter and has a spherical radius of curvature (as proposed by Morton[5]) of four inches, to minimize curvature of the image field and pincushion distortion.

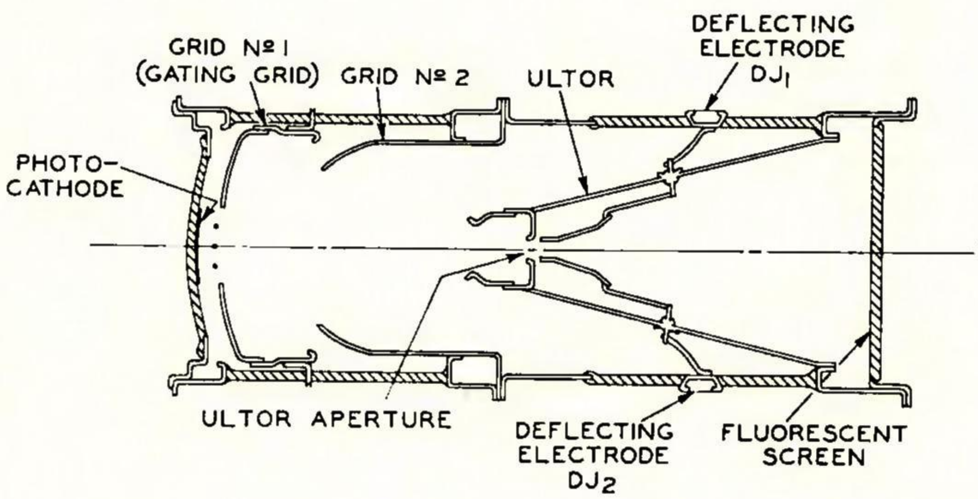

Fig. 2—Cross-sectional drawing of the developmental tube.

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[4] B. R. Linden and P. A. Snell, "Shutter Image Converter Tubes," *Proc. I.R.E.*, Vol. 45, p. 513, April, 1957.

[5] G. A. Morton and E. G. Ramberg, "Electron Optics of an Image Tube," *Physics*, Vol. 7, p. 451, December, 1936.

Grid No. 1, grid No. 2, and the ultor comprise an electrostatic converging lens which produces on the fluorescent screen an inverted electron image of the photocathode illumination pattern. The magnification obtained is 0.75. The pair of electrostatic deflecting plates permits positioning of a series of displayed images so that none overlaps a preceding image.

Image Formation and Focusing

The position of the electron image on the tube axis is determined by the point at which the electron paths converge. These paths, in turn, are determined by the convergence of the internal electric field, or the related potential distribution along the axis. The normal potential distribution (approximate) along the axis for a focused electron image in the center of the screen is shown in Figure 3 by the solid

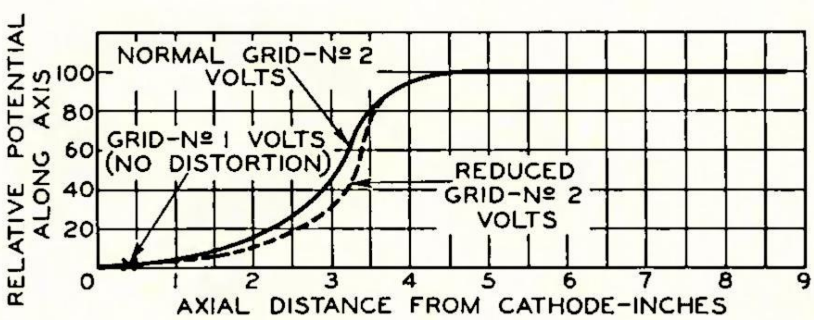


Fig. 3—Approximate potential distribution along the tube axis required to provide a focused electron image on the fluorescent screen. Solid curve: normal distribution; dashed curve: effect of a reduction in grid No. 2 voltage.

curve. The convergence of the electric field at a point of specified potential is proportional to the curvature of the potential-distribution plot (d^2V/dZ^2) at that point. As shown by the dashed curve in Figure 3, a reduction in the potential applied to grid No. 2 increases the curvature of the potential-distribution plot. Consequently, if the field produced by the normal potential distribution is not sufficiently convergent to provide a focused image at the screen, the image may be moved back towards the apex of the ultor by a reduction of the potential applied to grid No. 2.

The gating grid (grid No. 1) is placed close to the photocathode. It is normally operated at a small positive potential with respect to the photocathode (indicated in Figure 3 by an "X"). For complete suppression of cathode emission the gating grid must be supplied with a negative bias voltage sufficient to provide a negative voltage gradient at every point on the cathode. If the gating grid contained simply a single large aperture, a large bias voltage would be required for cutoff.

The cutoff bias can be substantially reduced, however, by the use of fine wires across the grid aperture, and, with a sufficiently fine mesh, can be made as small as 2 or 3 volts, i.e., equal to the maximum energy with which electrons leave the photocathode. A mesh of such fineness, however, degrades the electron image, and, therefore, is not desirable. In the developmental tube a cutoff voltage of only —4 volts per kilovolt of ultor voltage is achieved by the use of three wires across the gating-grid aperture. This voltage is satisfactorily small in relation to the normal gating-grid operating voltage (approximately 12 volts per kilovolt of ultor voltage), and is not substantially reduced by the use of closer grid-wire spacing.

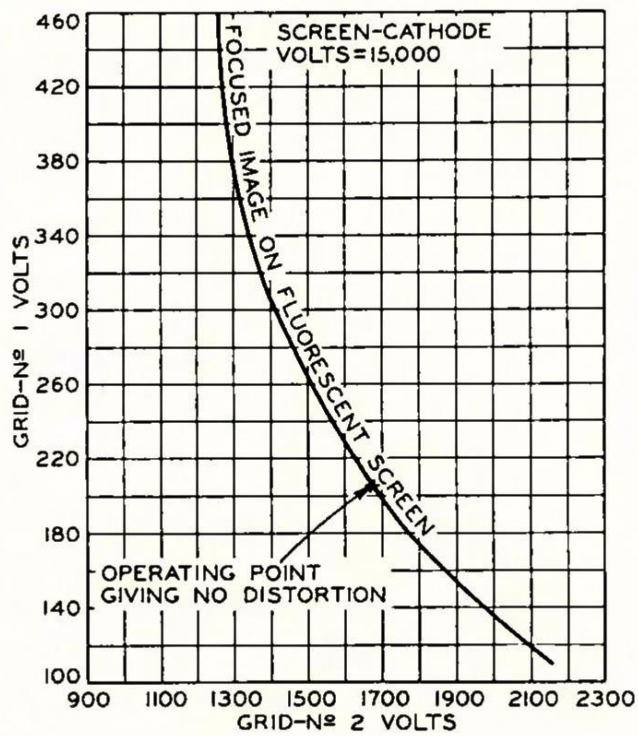


Fig. 4—Loci of grid No. 1 and grid No. 2 voltages which provide a focused electron image on the fluorescent screen. Point X indicates only combination of grid voltages for which there is no scattering of beam electrons by the cross wires of grid No. 1.

The gating grid voltage, like grid No. 2 voltage, is effective for controlling the convergence of the electron-lens system. As shown in Figure 4, for a wide range of grid No. 2 voltages, there are corresponding grid No. 1 voltages which will provide a focused image in the center of the screen. However, unless the potential applied to grid No. 1 is the same as the potential that would exist at the plane of the grid aperture in the absence of the grid cross wires, the resulting field will be distorted in the vicinity of the grid wires, and will not have the axial symmetry required for good imaging. There is, consequently, only one combination of grid No. 1 and grid No. 2 potentials which

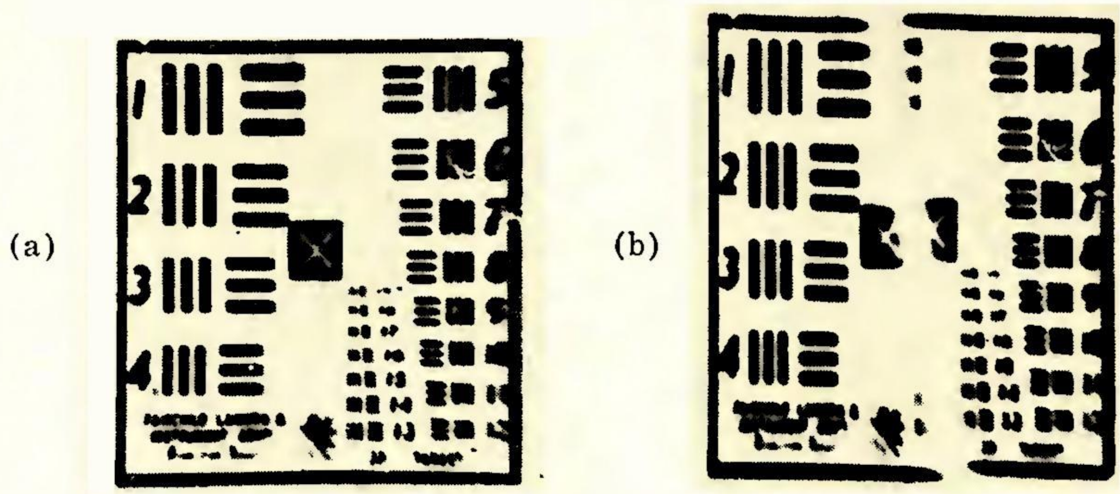


Fig. 5—(a) Focused, undistorted image produced when proper voltages ar applied to grids No. 1 and No. 2; (b) segmented image produced whei grid No. 1 and grid No. 2 voltages do not have the proper values.

provides an undistorted as well as focused image on the screen. A any other combination of grid voltages, the cross wires of grid No. cause scattering of the electrons in their immediate vicinity and con sequent distortion of the image. Figure 5a shows the appearance o the image when the proper voltages are applied to grids No. 1 and 2 Figure 5b shows how a focused image may be broken into segment when these voltages do not have the proper values.

Deflection

The electric field of the electrostatic lens used in the developmenta tube is essentially a radial field which directs the electrons toward the apex of the ultor, where the beam diameter becomes very small It is practical, therefore, to employ a simple electrostatic deflectio system using internal deflecting plates. Because the diameter of th beam at the crossover point (the ultor aperture) is only about 0.12 inch at an ultor voltage of 10 kilovolts, and is even smaller at highe ultor voltages, the deflecting plates can be closely spaced so as to obtai high deflection sensitivity. The spacing used in the developmental tub

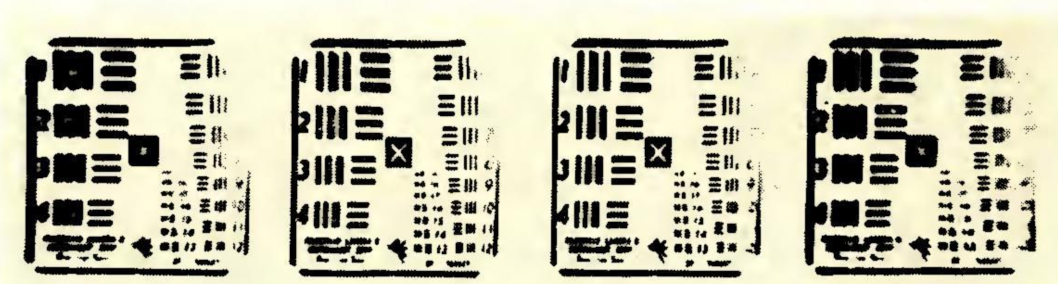


Fig. 6—Linear display of sequential frames of the same test pattern obtaine by application of suitable potentials to the electrostatic deflecting plates

is 0.15 inch, providing a deflection factor of only 75 volts per inch per kilovolt of ultor voltage.

Figure 6 shows four images of the same resolution chart displayed in a linear array by the application of suitable voltages to the deflecting plates. The quality of these images indicates that wide-angle deflection can be achieved without serious loss of resolution or distortion. Figures 7 and 8 show resolution and distortion (relative magnification), respectively, as functions of deflection.

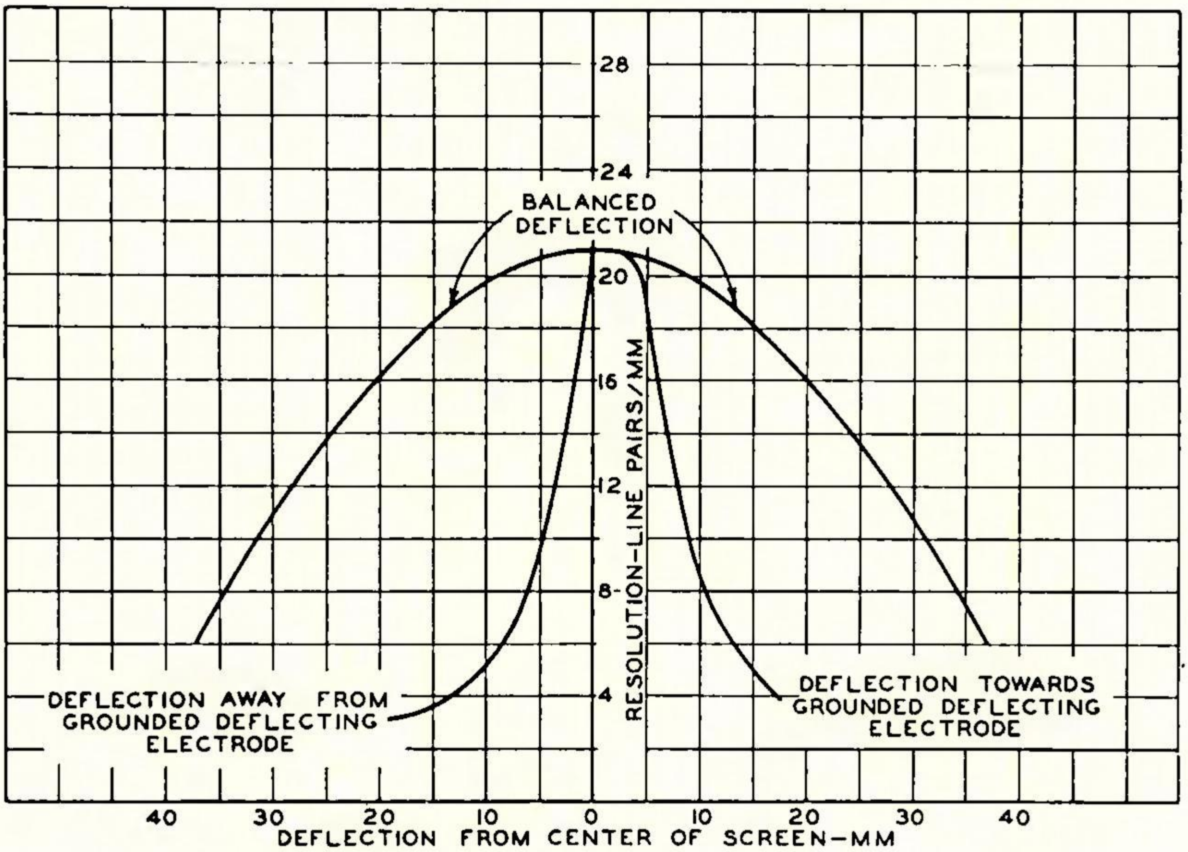


Fig. 7—Resolution of the developmental tube as a function of deflection distance.

Conversion Gain

The phosphor screen used in the new tube is a P11 type, specially prepared to have a very fine grain and high resolution capability. The screen is also very efficient, being capable of converting as much as 10 per cent of the incident beam energy into useful radiant energy. The aluminum film which backs the screen provides the following advantages:

1. It increases the useful light output of the screen by sending back through the screen light emitted towards the inside of the tube.

2. It prevents light feedback from the fluorescent screen to the photocathode, and thus prevents the loss of contrast which would otherwise result.

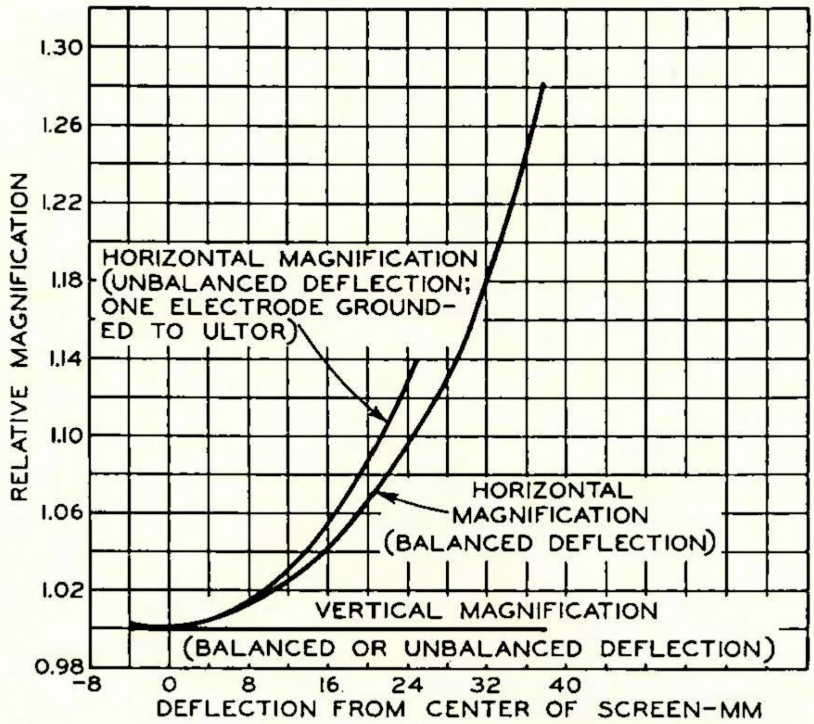


Fig. 8—Distortion (relative magnification) of the electron image as a function of deflection distance.

3. It prevents the illumination on the photocathode from being transmitted directly through the tube to the fluorescent screen and thus avoids possible exposure of photographic films during intervals when the gating grid is biased beyond cutoff.

Figure 9 shows the spectral emission characteristic of the P11 phosphor screen and the spectral sensitivity of the S11 photocathode. Effective application of the tube requires a knowledge of the ratio of output radiant energy to incident radiant energy. This ratio, commonly called the conversion gain, depends on the spectral distribution

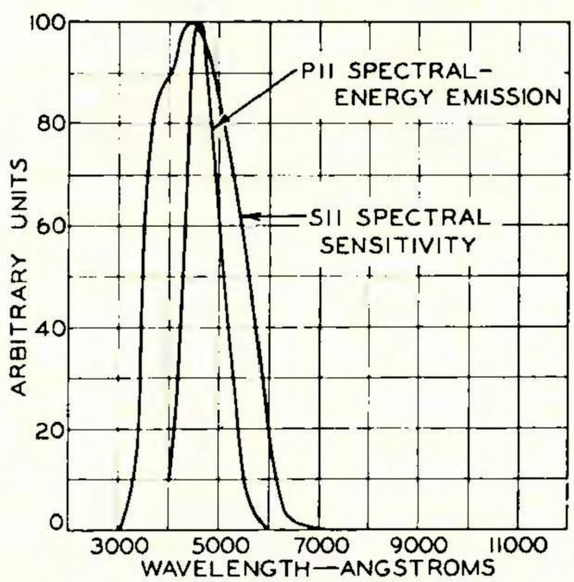


Fig. 9—Spectral characteristics of the photocathode and fluorescent screen used in the developmental image-converter tube.

CONVERSION GAIN OF TYPICAL IMAGE CONVERTER TUBE
HAVING S-11 CATHODE RESPONSE AND P11 PHOSPHOR

Radiation on Cathode (Wavelength = 4400 Å)	Cathode Emission (Sensitivity = 0.024 μa/μw)
1 μwatt	0.024 μampere

Energy Delivered to Screen (Screen Voltage = 10 KV)	Screen Radiation (Screen Efficiency = 10 per cent)	Conversion Gain
240 μwatts	24 μwatts	24

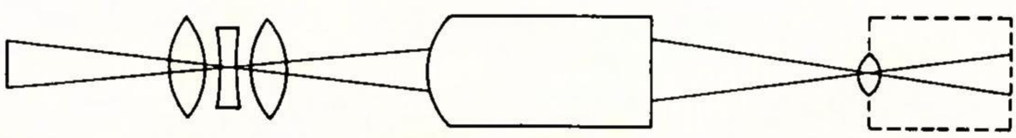
Fig. 10—Calculation of conversion gain at the wavelength of maximum photocathode sensitivity.

of the incident light. The expected conversion gain for illumination having the wavelength of maximum photocathode sensitivity (4400 Å) can be easily calculated from the relations shown in Figure 10. A typical photocathode sensitivity of 30 microamperes per lumen (0.024 microamperes per microwatt at 4400 Å) is assumed. The conversion gain for illumination of any other wavelength can be calculated by multiplying the corresponding relative sensitivity on the S11 response curve by the conversion gain at 4400 Å.

Application

Figure 11 shows schematically the complete optical system of an image-converter camera, and the brightness gain achieved under typical operating conditions. If the scene observed is sufficiently distant so that the effective magnification (M) of the objective lens is very small, the brightness gain may be as much as four times that shown in Figure 11.

In most cases the loss of light in the objective lens used to form an



SCENE BRIGHTNESS = B	LENS F:No. (f/d) = 2.0 TRANSMISSION (T) = 80% MAGNIFICATION (M) = 1	IMAGE CONVERTER TUBE CONVERSION GAIN (G) = 24 MAGNIFICATION (m) = 0.75	CAMERA

ILLUMINATION ON TUBE	SCREEN BRIGHTNESS	BRIGHTNESS GAIN
$E = \frac{BT}{4(f/d)^2(1+M)^2} = \frac{B}{80}$	$B' = \frac{EG}{m^2} = \frac{43B}{80}$	$\frac{B'}{B} = \frac{TG}{4(f/d)^2(1+M)^2 m^2} = 0.5$

Fig. 11—Block diagram of image-converter camera system, and calculation of brightness gain.

optical image on the photocathode of an image-converter tube is great enough to cancel most of the energy gain achieved in the tube itself. For applications requiring the highest possible image brightness the objective lens should, therefore, have the largest possible aperture preferably f:1.1 or larger. The conversion gain of the image-converter tube itself can be increased by operation at higher ultor voltage. Although the developmental tube has a tentative maximum ultor-voltage rating of 15 kilovolts continuous, it has improved design features which permit the use of ultor voltages up to 30 kilovolts where a pulse-type ultor-voltage supply is used.

The principal hazard involved in operation at an ultor voltage higher than 15 kilovolts is internal breakdown, with resulting discharges which may destroy the photocathode or scatter cesium through the interior of the envelope. The most common cause of internal breakdown is the accumulation of a high positive charge on the interior of the glass envelope in a region where the envelope is sealed to a negative electrode. The resulting field gradient is generally steep enough to produce field emission from the negative electrode, thereby initiating an internal discharge, which recurs periodically at a rate depending on the time required for the positive charge on the envelope to reach the field-emission value. The effects of such breakdowns may be minimized by the use of external impedances which will limit the resulting current through the tube to a safe value. However, even though the discharge current is limited in this manner the repeated dispersal of cesium throughout the tube increases the tendency towards breakdown.

Because a finite time is required for the positive charge on the envelope to reach a significant value, the danger of breakdown at higher-than-rated ultor voltages can be minimized by the use of a pulse-type ultor-supply circuit. With such an arrangement all adjustments may be made at a lower ultor voltage (15 kilovolts), and the voltage then raised to as much as 30 kilovolts for periods up to a second. It is important to limit the capacitance across the high-voltage supply circuit to assure that, if breakdown does occur, the energy dissipated within the tube during the resulting discharge is not great enough to cause damage.

The stiff-wire leads used in earlier tubes for the external connections to the gating grid and the deflecting plates were occasionally responsible for corona. This difficulty is avoided in the developmental tube by the use of recessed-cavity caps.

Exposure Time

In practice, the shutter speeds attainable with the new tube are limited by the ability of the external circuitry to supply good squarewave pulses of sufficiently short duration. With perfect pulse-forming circuits, the minimum exposure time is limited by electron transit time. Electrons are defocused if they are not beyond the influence of the gating grid when its voltage returns to the cutoff value at the end of the gating pulse. The calculated transit time of electrons between the cathode and ultor for 15 kilovolts on the ultor is approximately 5×10^{-9} second. Loss of resolution will probably become noticeable, therefore, at exposure times in the order of 10^{-8} second, and become progressively worse as exposure time is decreased.

Acknowledgments

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