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BRIGHTNESS INTENSIFIER STUDY

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Radio Corporation of America Laboratories

MAY 1960

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Radio Corporation of America Laboratories

MAY 1960

Contract AF 33(616)-2631

Project 7072

Task 70827

**AERONAUTICAL RESEARCH LABORATORIES
AIR FORCE RESEARCH DIVISION
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO**

FOREWORD

This technical report was prepared by RCA Laboratories, Princeton, New Jersey, on Contract No. AF 33(616)-2631 under Task No. 70827, "Light Amplification", of Project 7072, "Research on the Quantum Nature of Light". The work was accomplished during the period of 15 September 1954 to 30 November 1956.

This program of research is a sequel to many years of study of the problem of image intensification - a study which includes multi-stage image converter tubes, converter tubes which obtain brightness intensification through fractional magnification and other less conventional systems. This was followed by work on the problem of x-ray image intensification for the Johns Hopkins Hospital under a Navy subcontract which included the investigation of the combination of intensifying screens with the image orthicon principle for viewing the dim image on an external x-ray fluorescent screen and, thus, reaching the photoelectron shot noise limit. Under the research program "Cat Eye" of the United States Air Force, it was concluded by Radames K. H. Gebel, WADC, that the most practical way of achieving an imaging device useful for aeronautical and astronomical purposes which would reach the sought for sensitivity (i.e., be limited by the shot noise of the photoemission from the photocathode at low light levels) would be to use television pickup tube techniques, combined with preamplification using image converter principles and electronic background suppression.

The work was initiated and administered under the direction of the Aeronautical Research Laboratory, Wright Air Development Center. Mr. Radames K. H. Gebel was the Task Scientist.

This report was not released for publication at an earlier date because some of the contents were classified.

ABSTRACT

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The basic limits of vision and image detection are discussed. Experimental results with the direct view intensifier are reported. A general discussion of pickup tube limitations concludes that the image intensifier orthicon is a very suitable pickup tube for a brightness intensifier amplifying a low light scene. Other intensification methods and storage operation of intensifier orthicons are also investigated and discussed. The use of the image intensifier orthicon for optical pulse ranging is suggested. () ←

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I. Introduction

The advantages of being able to see or to form images at light levels below the normal visual threshold are numerous. This is especially true for military applications where the use of active illuminators may be hazardous. Under these circumstances it greatly lengthens the operating day. Furthermore, if the opposition does not have available such a device, he is severely handicapped, both from the security standpoint and from that of limited operating time.

The problem is not new, and a good deal of work has been done on it during the last decade. Direct view image tubes have been built which approach in sensitivity the limit set by electron statistics.¹ Also, television pickup tubes have been built which significantly exceed the sensitivity of commercial camera tubes.²

The purpose of the present contract was to perform researches for the Air Force leading to television pickup tubes employing intensifier techniques and photocathodes with higher primary quantum efficiency, which also have the highest over-all sensitivity. The new tubes should also be capable of good operation under normal daylight conditions.

A study was also to be made of the feasibility of a long range research program on new, better and simpler methods of achieving the intensification necessary to approach the sensitivity limit set by the photon nature of light, thus resulting in more reliable and easily operated tubes.

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1. See "Report on Image Brightness Intensifiers," G.A. Morton, Contract AF33(038)-6413, Sub. 52-63, Rand Corp., July 23, 1953.
 2. See Final Report, "X-Ray Image Brightness Intensification," Contract NObsr-57394(Sub), Oct. 16, 1952 - Feb. 18, 1954.

II. Limits of Vision and Image Detection

Light, like all electromagnetic radiation, interacts with matter as though it were corpuscular in nature. The individual quanta of light are termed photons and the amount of energy each carries is proportional to the frequency of the light. In other words:

$$E = h\nu = hc/\lambda$$

where h is Planck's constant

c the velocity of light

λ the wavelength

ν the frequency.

Therefore, any phenomenon which is based on photoactivity must necessarily be quantized or occur in steps. The ratio of the number of steps to the number of photons incident on the active area is termed the quantum efficiency. For example, if the rate of arrival of photons on a photoelectrically emissive surface is 10,000 per second and the number of photoelectrons emitted 300, the quantum efficiency is 3%.

A consideration of the problem of image recognition shows that it can be reduced to simply that of determining the difference in amounts of light which have fallen on the various areas of the image surface. This concept of image recognition, together with the fact that optical phenomena are quantized, allows the calculation of the fundamental limits of image perception at low light levels. If A and B are two square areas

in the object plane having surface brightnesses B_A and B_B which are imaged by a lens onto the image plane to form squares A' and B' (see Fig. 1), the illumination of these squares will be given by:

$$I_{A'} = B_A \frac{d^2}{4f^2}$$

$$I_{B'} = B_B \frac{d^2}{4f^2}$$

where D is the distance from the lens to the object plane
 d the diameter of the lens
 f the focal length.

The object distance is assumed to be large compared with the focal length of the lens. If h is the length of the side of one of the object squares, then the length of the image square will be

$$h' = \frac{f}{D} h .$$

For white light, there are approximately $\beta = 1.4 \times 10^{16}$ photons per sec. for one lumen light flux; therefore, the rate of photons falling on the two image areas, A' and B' , will be given by:

$$n_{A'} = I_{A'} (h')^2 = B_A \frac{\beta d^2}{4D^2} h^2 \text{ photons/sec.}$$

$$n_{B'} = I_{B'} (h')^2 = B_B \frac{\beta d^2}{4D^2} h^2 \text{ photons/sec.}$$

The number of photons at the two areas in question will depend upon the length of time t over which the observation is made.

(Note: For human vision, this integration period t is the order of 0.1 sec.). If now there are detectors at A' and B' , each with a quantum efficiency γ , the rate of occurrence of photo events will be:

$$n_{A'} \quad \text{and} \quad n_{B'}$$

and the number of events in the integration time

$$N_{A'} = B_A \frac{\sqrt{3} d^2 h^2}{4D^2} \gamma t \quad (1)$$

$$N_{B'} = B_B \frac{\sqrt{3} d^2 h^2}{4D^2} \gamma t \quad (2)$$

If the two rates were absolutely uniform, it should be possible to detect a difference in illumination corresponding to one event. However, the arrival of photons and the production of the events are purely random phenomena and therefore subject to a root-mean-square deviation which is proportional to the square root of the number of events, $(N_{A'} + N_{B'})$. Unless the difference in number during the integration time exceeds the probable deviation by some factor k , it is not possible to determine whether the difference in photo events is simply a statistical fluctuation or due to a real difference in brightness. Therefore, there is a fundamental limit to the difference in brightness which is necessary for recognition of the image. This can be formulated as follows:

$$\Delta N = N_{A'} - N_{B'} \geq k(N_{A'} + N_{B'})^{1/2} \quad (3)$$

$$\Delta B = B_A - B_B$$

from (1) and (2)

$$\Delta B = (N_{A'} - N_{B'}) \left(\frac{\sqrt{3} d^2 h^2}{4D^2} \gamma t \right)^{-1}$$

from (3), for recognition

$$\Delta B \geq k(N_{A'} + N_{B'})^{1/2} \left(\frac{\beta d^2 h^2}{4D^2} \gamma t \right)^{-1}$$

substituting for $(N_{A'} + N_{B'})$ from (1) and (2)

$$\Delta B \geq k(B_A + B_B)^{1/2} \left(\frac{\beta d^2 h^2}{4D^2} \gamma t \right)^{-1/2}$$

This can be expressed in terms of contrast as follows:

$$C = \frac{\Delta B}{B} \quad \text{and} \quad B = \frac{B_A + B_B}{2}$$

$$C \geq k \left(\frac{2}{B} \right)^{1/2} \left(\frac{\beta d^2 h^2}{4D^2} \gamma t \right)^{-1/2}$$

$$C \geq \frac{k}{\sqrt{B}} \frac{2\sqrt{2} D}{dh\sqrt{\beta \gamma t}}$$

Tests on human vision at very low light levels indicate that if the assumption is made of a three to five percent quantum efficiency and a value of 5 be given to the certainty coefficient k , the limitations of human vision can be quite accurately accounted for on the basis of the fundamental statistics of the phenomenon described above. The eye possesses the ability to change the area over which the information is integrated with the amount of light present. At low light, the eye functions as though fairly large areas were operating in unison, thereby increasing the sensitivity of the eye and lowering its definition. The following conclusions can be drawn from the above calculations:

- (1) It is not possible to increase the sensitivity of the eye with any optical device which has the same angular

field of view and effective focal length as the unaided eye.

(2) The sensitivity of the eye can be increased by using a large diameter lens in an optical system with a longer effective focal length and consequent greater magnification and smaller angle of view. (This is the principle on which the night-glass is based and is the consequence of the ability of the eye to integrate large areas at low light levels.)

(3) For a given quantum efficiency γ and certainty coefficient k , the limiting sensitivity of an ideal detector is determined by the absolute area of the objective lens.

As a consequence, if the quantum efficiency of a photoelectric primary surface in any form of image intensifier is essentially the same as the quantum efficiency of the retina of the eye, an electronic brightness intensifier can basically only increase the field of vision of the operator when compared with what can be done with night glasses. A second non-fundamental benefit which can be obtained from a brightness intensifier is that the limiting sensitivity can be achieved without the observer having to be dark-adapted. Finally, if the output of the intensifier is a video signal, it offers the advantage of the viewing element being located in places which are normally not accessible to a human being either through geometry, environment or hazard.

III. Previous Experimental Results with the Direct View Intensifier

During the early 1950's, a good deal of experimental work was done with a direct view image intensifier converter tube. These tubes consisted of a cesium-antimony primary photocathode, having a quantum efficiency of about 10%; and electron lens system which focused the electron image from this cathode onto an intensifying screen; a second lens system focusing the electrons from the intensifying screen onto a second intensifying screen; and a final lens system which images the electrons from the second intensifying screen onto a phosphor viewing screen. A schematic diagram of this tube is shown in Fig. 2.

The intensifier screen consists of a thin transparent supporting member covered on one side with a phosphor screen and on the other with a photocathode as shown in the detailed drawing of Fig. 3. The phosphor and cathode are so chosen that their spectral characteristics are similar. In order to prevent optical feedback from the phosphor to the primary cathode and also to increase the efficiency of the screen, it is coated with a thin aluminum film. Tests on such intensifier screens indicate that one 10-KV electron bombarding the phosphor will cause the release of an average of 10 photoelectrons from the cathode.

The intensifier image tubes which were investigated had, as noted above, two intensifier screens thus giving them a gain of 100 over a simple image tube. Their magnification was approximately one-third, giving an additional brightness gain

of 10 in the case of an extended image. The conversion efficiency of a simple image tube consisting of a cesium-antimony photocathode and a fluorescent viewing screen operated at 10 KV is in the neighborhood of 10 lumens from the screen per incident lumen on the photocathode. The over-all brightness gain of these intensifier tubes was, therefore, of the order of 10^4 ft. lamberts output per ft. candle input. With this degree of intensification, it was possible to see noise in the photoelectron emission from the primary cathode, although the scintillations produced by individual electrons were not recognizable. Thus these tubes approached the theoretical useful gain that can be obtained by intensification of the primary electron image.

Under field test conditions, the performance of these tubes in suitable telescopes was about as predicted. The tests were undertaken using a Schmidt objective having a 9" focal length and an effective numerical aperture of the order of 0.9. With these telescopes, the observer could see at light levels where it was impossible to see by direct vision. Compared with good night glasses, the intensifier telescope showed greater sensitivity. With night glasses the observer, of course, had a more limited field of view. However, tests with this equipment indicated that except under very special conditions, the bulk and complexity of the required equipment offset the gain in seeing that was obtained through the increased angle of vision and slightly higher sensitivity. With the night glasses, the observer in general was not seriously handicapped by the limited

field of vision because of the ease with which he could scan the field by turning his glasses. The conclusions from this series of field tests were that the advantages of the device were offset by the disadvantages of weight and complexity and that further development of direct view intensifier tubes was not warranted.

The conclusions arrived at for the direct view intensifier do not, however, apply to a high sensitivity pickup tube giving a video signal. Such pickup tubes can be located at points where it is impractical to have human observers. The high sensitivity enables it to "see" under conditions where seeing would be difficult even with good night glasses. The high angular field as compared to that which can be obtained with night glasses is of primary importance under conditions of remote observation. A very sensitive remote viewing device of this type may have a great many valuable military applications both on the ground and in the air.

IV. General Discussion of Pickup Tube Limitations

The sensitivity of an ideal pickup device would be limited only by the shot noise in the primary photo-effect; for example, either electrons emitted from a surface, as in an image orthicon, or charge carriers produced in a semiconductor, as in a vidicon. Obviously, this requires 100% primary quantum efficiency and also that each primary event be discretely recognizable in the output picture, unobscured by spurious effects. The degree to which both these requirements can be met will enter into the choice of the device.

Over the visual spectral range, the best photoemitters have a quantum efficiency of a few percent with a maximum observed value of about 40 percent. The only inherent noise in this process is due to thermionic emission, which is very small for a number of the photoemitters and can nearly always be reduced by cooling.

Photoconductors are known which have nearly 100% quantum efficiencies in the visual spectral range, but all of them, including those with only modest efficiencies, have large noise effects which completely mask the low light signals. The noise may be of two different types. In the first, some incident light quanta may produce conductivity by a trapping process such that the image persists for many seconds after the light has been removed. In the second, the dark conductivity is simply too high and there is a continuous background noise. The trapping type

of noise is associated with impurity materials or defects in the crystal lattice of the photoconductor. It seems theoretically likely that crystal stability requires a certain density of lattice imperfections which would set a much higher noise level than that of the thermionic emission in the case of photoemitters. For this reason, it seems unprofitable to try to use photoconductivity as the primary pickup process at very low lights.

For the case of a pickup tube with a photoemissive cathode, let us assume that the density of electrons emitted from the surface is $n/\text{cm}^2/\text{sec}$. If now the size of the image area is $H \times L$ and repetition rate is $1/T$ frames per second, the total number of electrons emitted per frame will be $nHLT$. Furthermore, if there are assumed to be m picture elements in the image area, the number of electrons per picture element will be:

$$N_e = \frac{n \cdot H \cdot L \cdot T}{m} .$$

Since the electron emission is a random phenomenon, the root-mean-square deviation of the number of electrons emitted per frame δ would be equal to the square root of the number emitted. Therefore,

$$\delta = \sqrt{\frac{nHLT}{m}} .$$

The limiting signal-to-noise ratio R is, therefore:

$$R \sim \frac{N_e}{\delta} = \sqrt{\frac{nHLT}{m}} .$$

For most pickup devices, some other noise source within the device itself generates fluctuations which are greater than those due to the statistics of the photoelectrons. This noise consequently determines the limiting signal-to-noise ratio of the device and establishes a lower sensitivity than is possible with a device which is limited by the shot noise of the primary photoelectrons. In the case of the image orthicon, it is the statistical fluctuations of the electrons in the scanning beam which sets this limit. If it were possible at low light levels to obtain a large percentage modulation of the scanning beam (i. e., approaching 100%) by the stored charge on the target, it would be possible to reach sensitivities very close to that set by the fluctuations in photoelectrons. However, at low light levels, it is not possible to reduce the beam to this desired low value without introducing excessive lag in the reproduced picture. This is because as target potential decreases and the beam current is decreased, the beam impedance increases and the time constant of the circuit containing the beam impedance and the target capacitance becomes greater than one frame period. If, however, the image current from the photocathode can be increased before storage on the orthicon target (even though its statistics are not improved), it is possible to store charge enough on the target so that the fluctuation in the amplified photoelectron current overrides the fluctuation in the beam current which returns to the multiplier.

Quantitatively the relationships can be estimated as follows:

Let us assume that each photoelectron, because of the action of the intensifier screens and the target secondary electron emission gain, causes the storage of G electrons on the target. The charge stored per second on the target is therefore

$$n_T = GnHL .$$

In order to discharge this stored charge, the beam current must be greater by a term n_d which is independent of the stored charge so that the time constant of discharge remains below a frame period and by a factor b , where $1/b$ is the fractional modulation of the beam. Therefore, the number of beam electrons per second n_b can be expressed as:

$$n_b = b(GnHL + n_d) .$$

Using the argument given above, the signal-to-noise ratio is approximately:

$$R = \frac{\frac{GnHLT}{m}}{\sqrt{\frac{T}{m} [G^2nHL + b(GnHL + n_d)]}} = \frac{\frac{nHLT}{m}}{\sqrt{\frac{T}{m} [nHL(1 + \frac{b}{G}) + \frac{bnd}{G^2}]}}$$

For the conventional image orthicon $G=3$ (approx.) and at low light levels where n is small, the denominator term containing n_d becomes dominant. If the gain factor G is made large, however, the limiting sensitivity of the pickup device is essentially that imposed by the shot noise in the primary photoelectron image, in spite of the poor modulation characteristics of the beam.

In the first line of tubes built, the gain of the two intensifier stages was approximately 100. This is sufficient so that even down to photocathode light values in the region of 10^{-7} ft. candles the limiting noise is the fluctuation in photoelectrons. At the higher light levels and with pictures of fairly high definition, the gain factor does not need to be as large as this for a device approaching limiting sensitivity. This is because as m , the number of picture elements, is increased, it is necessary to increase the number of stored photoelectrons in order to maintain a given signal-to-noise ratio. Therefore, a larger beam current can be used before the beam noise seriously predominates over the photoelectron noise.

A series of intensifier pickup tubes was investigated having a single intensifier target. This was done in order to be able to obtain a better picture under optimum illumination with a given type of photocathode. These tubes, however, will not be able to operate at as low a light level as can the two-stage intensifier tubes. These lower light levels, however, fundamentally limit the resolution of the picture to a definition of under 100 lines per frame. It is thought that the improved picture at slightly higher light levels together with the simplification of the tube may make the one-stage intensifier of greater general utility than the present two-stage tubes.

V. Image Intensifier Orthicons

A. Intensifier Orthicon Type H6198

This tube type was developed under the x-ray contract mentioned in the Introduction and is shown in the photograph, Fig. 4, and schematically in Fig. 5. It consists of a photocathode, two intensifier stages, and an orthicon target which is scanned by a low velocity electron beam. The intensifier stages amplify the electron image which is then stored on the target. The stored charge is removed from the target by the scanning beam. The video signal is obtained from the electrons returning from the target and multiplied by a secondary emission multiplier exactly as is done in the standard image orthicon.

All the tubes of this type which have been made to date were done on an experimental basis and had an external appendage for use in maintaining a good vacuum. In the photograph of Fig. 4 the appendage is in the form of a charcoal trap which required cooling to dry ice temperature or lower during tube operation. Later tubes had an ion-gauge attached at the same point, in place of the charcoal trap, which operated both as a vacuum pump and as a good pressure gauge. Tubes which have been properly pumped and have no leaks do not require any such appendage.

Five tubes of this type were completed and tested. In all of them, the photocathodes were of the antimony-caesium type having approximately an S-11 spectral response. No attempt

was made to prepare any of these tubes with a tri-alkali cathode. Table I summarizes the principal performance characteristics of these tubes.

TABLE I

<u>Tube No.</u>	<u>Cathode Response</u> <u>μa/lumen</u>			<u>Voltage</u>		<u>Resolu- tion</u> <u>TV Lines</u>	<u>Sensi- tivity</u>
	<u>Prim. cath- ode</u>	<u>Int., #1</u>	<u>Int. #2</u>	<u>Lens 1</u>	<u>Lens 2</u>		
H6198-4	5-20	20	20	10 KV	7 KV	350	16
H6198-5	15-20	25	10	12	12	400	>16
H6198-6	40	22	18	13	13	400	60
H6198-7	10	20	16	5	15	screen grainy	<16
H6198-8	12	30	15	target broke before tests could be completed			

The response of the primary cathode (given in column 2 of Table I) is of major importance since its quantum efficiency sets the ultimate limit of the tube performance irrespective of the response of the other two cathodes beyond that required to insure sufficient gain to make photoelectron noise dominate other noise sources in the system. The upper limits to the lens voltages (given in columns 5 and 6) were set by cold discharge from the lens elements. Because of the high sensitivity of this type of tube, even a small amount of cold discharge will degrade its performance. Column 7 gives the optimum resolution in terms of television lines. It is estimated by projecting the image

of a resolution chart onto the cathode and adjusting the light level to give optimum resolution. The threshold sensitivity is given in comparison to the performance of the unaided eye and is the factor by which the illumination must be increased in order to obtain equal recognition of the scene before the camera with the unaided eye. For this test, an F/1.5, 3-inch F.L. objective was employed. This factor turns out to be approximately the same as that by which the intensifier orthicon exceeds the sensitivity of a standard wide-spaced image orthicon.

Two of the five tubes (H6198-7 and H6198-8) were too poor to be of any use even for preliminary test purposes. These tubes were taken apart and the parts salvaged. Tubes H6198-4 and H6198-5 could be used in preliminary tests and were delivered to Wright Field. Tube H6198-6 exhibited quite good performance characteristics both with respect to resolution and sensitivity. The fundamental statistical limitation due to fluctuations of photoelectrons could clearly be reached with this tube in the range of photocathode illumination of 10^{-5} to 10^{-7} lumens per square foot. This tube was also delivered to Wright Field.

B. One-Stage Intensifier Orthicons Type H7215
(With Tri-Alkali Photocathode)

One of the conclusions drawn from the performance of the two-stage Intensifier Orthicons was that the image gain did not need to be as high as their nominal value of 100, since for practical use it is image recognition and not image noise recognition that is desired. This suggested that a single stage tube might be made to function practically as well and be smaller and also simpler both to make and to operate. It would also have fundamentally better definition.

Accordingly, a formal revision was made during the latter part of the contract work, which called for the construction and delivery of two such tubes, incorporating in addition a primary photocathode of the tri-alkali type. This cathode is a recent development of RCA Laboratories,³ and has several times the sensitivity of that of the previously used antimony-cesium type as shown in Fig. 6.

The principal new problem in connection with these tubes was the development of an activation technique for the tri-alkali photocathode suitable to the electron optical structure of the first image section. In order to investigate this, a series of test bulbs was built as shown in Fig. 7. These were processed in sequence with modifications in method as indicated by the preceding tests. A total of eleven such tubes was completed of which three early ones had very poor sensitivities while the remaining ones had values ranging from

3. Sommer, A.H., "New Photoemissive Cathodes of High Sensitivity," RSI 26, 725, July 1955.

80 to 160 microamperes per lumen with five of them having over 100.

On the basis of the activation tests, the processing of three pickup tubes was then carried out. Fig. 8 is a photograph of this type of tube and Fig. 9 is the schematic diagram. Each tube initially had an ionization gauge attached as an appendage which was tipped off after the testing was nearly complete. The individual results with these tubes were as follows:

Tube No. H7215-1

Due to an accident during processing, the sensitivity of the first photocathode was very poor and, in addition, the tube had a small leak which it was not possible to stop. Because of the poor sensitivity, the low-light performance was never good during tests. The tube was finally delivered to the Wright Field Laboratory as a mechanical sample.

Tube No. H7215-2

This was the best of the three tubes built and its performance came up fairly well to expectations.

Sensitivity of 1st cathode = 100 microamps. per lumen

Image intensification ~ 10x at 15 KV

High light resolution = 450 lines over center area

At cathode illuminations of 10^{-5} ft. candles, the resolution was about 200 lines, which is quite close to that of the best two-stage tubes where the resolution is clearly noise limited by the emission from the first photocathode.

There was never any indication of vacuum difficulty and the tube was delivered to the Wright Field Laboratory for further testing and use.

Tube No. H7215-3

This tube suffered from poor control at one point in the activation of the first photocathode and came out with a rather low sensitivity.

Sensitivity of 1st cathode = 30 microamps. per lumen

Image intensification ~ 12x at 12 KV

High light resolution = 450 lines over center area

The low-light performance of this tube was inferior to that of the preceding one by just about the ratio of their cathode sensitivities. The tube remained stable in respect to vacuum over a period of several weeks and was also delivered to the Wright Field Laboratory for testing and use.

VI. Investigation of Other Intensification Methods

A. General Considerations

Paralleling the construction of the intensifier orthicons mentioned in the preceding section, a long range research was initiated, aimed toward improving and simplifying the intensifier pickup tube. The approach taken was to develop a single target structure which performed both the functions of intensification and charge storage. Its gain should be sufficient so that each electron striking it from the image side would produce a recognizable signal on its beam scanned side. One promising method of achieving this seemed to be by use of the principle of bombardment-induced conductivity in a semiconductor.

A number of semiconductors have been reported in the literature as exhibiting this property, such as selenium⁴, zinc sulphide, arsenic tri-sulphide and antimony tri-sulphide⁵. Tests have been made showing that when thin layers of these materials are bombarded by 10 or 15 KV electrons, several hundred electrons may be excited in the material for each arriving electron. These excited electrons can be drawn through the material as a conduction current. The gain that can be obtained depends upon the bombarding energy, thickness of the material, voltage across the material, and the type of semi-

4. Pensak, L.; "Electron Bombardment Induced Conductivity in Selenium," Phys. Rev. 79, 171, 1950.

5. Ansbacher, F. and Ehrenberg, W., "Electron-Bombardment Conductivity of Dielectric Films," Proc. Phys. Soc. A. 64, 362, 1951.

conductor used. Fig. 10 shows the behavior of an amorphous selenium layer deposited on an aluminum film when bombarded from either side.

An intensifier pickup tube target based on this principle might take the form shown in Fig. 11, which corresponds to the "back-bombardment" case. The semiconductor is supported on a thin layer of conducting glass. This glass is chosen to have a resistivity of the order of 10^{11} ohm-cm. Its conductivity is low enough so that the lateral leakage is small, yet high enough so that charges accumulated on one side can be drawn to the other. The semiconductor, which is selenium in the experimental tube shown, is coated on the other side by a thin film of aluminum. Electrons from the primary photocathode penetrate the aluminum film and enter the semiconductor where they excite conduction electrons. The scanning beam scans the other side of the thin glass, bringing its potential down to cathode potential and maintaining it there as the equilibrium state. The aluminum film is made positive with respect to the cathode and consequently with respect to the scanned side of the glass. When the semiconductor is not bombarded, its conductivity is extremely low so that very little current flows through it to the semiconductor interface. Any charges which are on this face are drawn through the glass to the scanned side. When the semiconductor is bombarded, a current flows between the aluminum film and the glass semiconductor interface causing charges to accumulate there. These charges are

drawn through the conducting glass and form the stored charge which is eventually removed by the scanning beam and gives rise to the video signal.

Another method of making such a target is illustrated in Fig. 12. Here the supporting member is a fine-mesh metal screen upon which a thin plastic film is deposited. A conducting layer of aluminum is evaporated upon the cellulose and then the semiconductor is deposited upon the aluminum. The bombarding electrons pass through holes of the screen, the plastic film, the aluminum layer and enter the semiconductor where they produce the many conduction electrons. The scanning beam deposits charge directly upon the semiconductor, otherwise the action of this target is the same as that of the one just described.

A different type of intensifier target also offers a possible solution and must be explored. It is shown diagrammatically in Fig. 13 and consists of a thin glass supporting membrane coated with a transparent conducting layer upon which is deposited a photoconductive layer, the surface of which is exposed to a low velocity scanning beam. The other side of the supporting glass is coated with a phosphor layer which is aluminized. In operation, the high velocity image electrons pass through the aluminum film and produce light in the phosphor layer. This light in turn produces charge carriers in the photoconductive layer which change its surface potential as set by the scanning beam, just as in the bombardment-induced conductivity type of target. Calculations indicate that if a

photoconductive quantum efficiency of near unity is obtained, such a target should produce a gain of one hundred at 10 or 15 KV.

B. Experimental Results

Two pickup tubes were built having bombardment-induced conductive targets of the type shown in Fig. 11 with selenium as the active material. The tube design is shown schematically in Fig. 14. The reason for choosing selenium rather than some of the other materials was that it had been reported as functioning at a greater thickness and hence the capacity of a picture element could be made less. Thus the scanning beam efficiency would be improved at low excitations, as discussed previously with respect to the orthicon target.

A preliminary test was first made by forming an Sb-Cs photocathode in a bulb in which there was selenium present in order to check cathode stability. No significant change in sensitivity was observed with age.

Both of the pickup tubes had sliding internal evaporators for the selenium which could be kept cool during the initial outgassing tube bake. When the selenium was evaporated to form the target, it was found to diffuse badly around shadowing objects and had to be driven off the photocathode area by heating it locally. The photocathodes formed in both tubes had low sensitivity and deteriorated steadily on standing, contrary to the test bulb result mentioned above. The target in one of the tubes (H6584-1) broke completely out of its frame during processing so that no scanning tests were possible. The other

tube (H6584-2) was operated in the camera for several days before the photocathode failed completely. A test picture was reproduced having about 200-line resolution but the lag effects were great and quite complicated. For example, a picture was put onto the photocathode and left for several seconds until the reproduced image was steady. The cathode picture was then turned off and the reproduced image faded out after several seconds. Upon illuminating the photocathode again, with uniformly distributed light, the previous image reappeared momentarily. This reappearance could be made to repeat a number of times by turning on and off the uniform light. The intensifier gain was not measured but was not very great up to 10 KV.

It was then decided that testing of the target materials could be done better with a bombarding gun type of tube rather than with one requiring a photocathode. Fig. 15 shows a schematic diagram of the tube designed for this purpose, which was given the type number H6901. The entire gun end of the tube was operated at a negative potential which was variable from 0 to 20 KV with respect to ground.

1. Target Test Tubes of Type H6901 with Preformed Targets as in Fig. 12

Three tubes of this type were built with selenium targets. In each case the aluminum film was 0.1 micron thick and the selenium layer was 10 microns thick. It was not possible to bake these tubes adequately during exhaust because

of selenium migration and reaction with the aluminum film. One tube was soft and another cracked so that neither could be tested. The third tube showed no B-I-C effect until the bombarding beam was so intense that it caused permanent change in the target. In view of all the experiences with selenium targets, this material does not appear to be very promising.

One tube was built with a preformed ZnS target of 0.1 micron thickness deposited upon an aluminum film of the same thickness. This tube showed a B-I-C effect but there was a lag of several minutes in following changes in the pattern and also the gain was very low. The leakage currents to the target were large and unsteady, due to the high potentials at the bombarding gun and focusing electrodes and hence no gain measurements were made.

Two tubes were built having one-half of the target area coated with As_2S_3 , each to about 1 micron thickness. The aluminum film was again 0.1 micron thick. In both tubes each material showed the B-I-C effect with a time lag of several seconds. The gain of the As_2S_3 layer was better than the Sb_2S_3 layer. It was possible to measure the gains in one of these tubes and a maximum value of 25 was found for As_2S_3 .

One tube of this type was built and tested which had a target consisting of simply a 0.1 micron thick aluminum film on an orthicon glass target about 2 microns thick. No B-I-C effect was observed with it.

2. Pickup Tubes with Phosphor-Photoconductor Targets

Some experimental work being done elsewhere in RCA Laboratories indicated a very high photoconductivity effect in a multiple layer initially made as $\text{Bi}_2\text{O}_3 + \text{PbO} + \text{O}$ and later as just $\text{PbO} + \text{O}$. One of these materials, together with a high efficiency ZnS:Ag phosphor material, was made into targets as shown in Fig. 13. Three intensifier pickup tubes with the type number H6946, as shown in Fig. 14, were built using those targets. The photocathode was of the Sb-Cs type in each tube. One of the tubes became soft due to a leak and no tests were made. In another tube the $\text{PbO} + \text{O}$ layer crumbled off from most of the target area due to some mechanical and thermal shocks. An image was obtained from the remaining coated area of the target, but it showed a gain of less than unity and also a several second time lag. The third tube suffered from a contamination of the $\text{PbO} + \text{O}$ layer, which had a dark gray color instead of its normal light yellow color. The sensitivity was very poor, presumably because of this, but a picture was obtained with strong light. The resolution was about 300 lines and the picture showed only slight lag.

This long-range work is only in its very early initial stages and much more work, particularly of a more basic nature, must be done before positive answers can be obtained. It is felt, however, that this initial exploration has given valuable information as to methods of procedure.

VII. Storage Operation of Intensifier Orthicons

A series of experiments was carried out to investigate the storage characteristics of the present type intensifier orthicons. These tests consisted of allowing the charge from the intensified electron image to store on the target for a controlled length of time. During the storage period, the beam is biased off. At the end of the storage period, the beam is allowed to sweep the target for one or two frames and the resulting picture is reproduced on the monitor kinescope. The cycle is then repeated.

The test equipment for this study consists of the standard monitor system with a keying circuit to control the scanning beams of the pickup tube and viewing tube. The keying circuit employs a univibrator which is activated by a manually controlled switch (the control can be also put on a timer) and triggered by the sweep circuit. The univibrator has two positions, one which allows the two beams to be on for one frame, the second allowing them to remain on for two frame periods. A circuit diagram of the keying circuit is shown in Fig. 16.

Initial tests with this system show that the target in tube H6198-6 is capable of integrating charge over a period of from five to ten seconds. Beyond this, the charge image begins to deteriorate, presumably by the lateral spread of charge along the target surface. These tests are to be continued and photographic recording of the reproduced image will be used instead of attempting to use direct observation.

VIII. Optical Pulse Ranging

One of the interesting possible applications of the image intensifier orthicon is in the solution of the pulse ranging problem. Some thought has been given to this application and the preliminary estimates appear to be quite favorable.

For a large class of pulse ranging problems, particularly those in which some degree of reconnaissance is involved, the use of imaging techniques is highly desirable. The basic arrangement of an imaging optical pulse ranging system is shown in Fig. 17. The pulsed light source can be turned on at a pre-assigned time and then extinguished abruptly at the end of a given interval. Similarly, the image pickup camera, normally biased off, can be turned on abruptly upon application of a control signal. The control signal is supplied from the pulsed source through a variable delay line.

The simplest cycle of operation is one where the light source is turned on for a period long compared to the range under consideration and then extinguished abruptly at time $T=0$. A delay line is set to retard the control signal for an interval T_1 at which time the pickup device is turned on. The pickup device remains on for an interval again long compared to the range involved. With this cycle of operation, the reproduced image shows the foreground in complete darkness out to a distance $X_1 = T_1 \frac{c}{2}$, where c is the velocity of light.

The effective illumination on the scene rises from zero at a distance X_1 to a maximum at $2X_1$ beyond which the illumination falls again. By controlling the value of the delay line, the illuminated region can be made to approach or recede from the pickup point. Obvious modifications of this cycle can restrict the illuminated region to a band rather than from an arbitrary distance to infinity.

Eq. 1 in Fig. 17 gives the distance in terms of the time setting on the delay line, while Eq. 2 gives the light energy reaching the pickup device in lumen seconds in terms of the radiation from the source, the gain of the searchlight, the F-number of the optical system of the pickup device and the distance.

The first essential of the pickup device is that it be capable of being gated on and off very rapidly. The techniques for gating image tubes have been worked out in considerable detail in connection with high speed photography. Inasmuch as image sections based on the principles used in the ordinary image tube are employed in the intensifier orthicon, the gating problem can be considered as solved.

The briefest estimate made with the aid of Eq. 2 will show that extraordinarily severe demands are placed on the sensitivity of the pickup device. Even where the sensitivity is limited by the statistical fluctuations of the fundamental electrical processes involved, the range obtainable will be relatively short if the image has to be based on a single light

flash. However, if the imaging device can store the information of a number of flashes in addition to having very high sensitivity, practical ranges can be obtained. Both of these conditions are satisfied by the intensifier orthicon.

For pulse ranging, the intensifier orthicon is gated by applying the appropriate potentials to the focusing electrode of the first image section. The focusing electrode used for gating is carried on a flange which extends through the glass thus permitting a symmetrical connection to a coaxial transmission line which can be charged negative to bias the tube off and then discharged through a spark to apply a positive square wave to the electrode to bias the tube on. This technique is similar to that used in millimicrosecond flash photography with image tubes made for this purpose.⁶

With the aid of Eq. 2 given in Fig. 17 and the performance data given on the intensifier orthicon, it is possible to make an estimate of the ranges obtainable. The estimate shown in Fig. 18 assumes that the pulse light source has an intrinsic brightness of 10^7 candles per square centimeter and an area of $1/10$ square centimeter. It is surrounded by a parabolic reflector which concentrates the light into a beam having an angular spread of 36° , thus giving a gain factor of 100. Under these circumstances, the maximum range is 1 kilometer to the near edge of the illuminated region and 2 kilometers to the point of maximum illumination where a single flash

6. Saxe, R.F. and Chippendale, R.A., "Millimicrosecond Exposures by Image Tubes," Brit. Jour. Appl. Phys. 6, 336, 1955.

per frame is used. However, because of the storage properties of the system, a series of many pulses per frame will, of course, increase the operating range. Assuming a frame rate of 30 cycles per second for the pickup device, if the above source is pulsed at a rate of 100 per second, the maximum range obtainable will be 6×10^3 meters which would be a very practical working distance. It should be pointed out that the frame rate of the pickup system may be much lower than 30 per second. With targets of the type used in tubes that are being investigated at present, storage times of 5 to 10 seconds are feasible and frame periods up to this length of time might be used.

It may be said that while no tests have as yet been made on the intensifier orthicon as a pickup device for pulse ranging, the measured performance characteristics of the tube indicate that it should be very practical for this application.

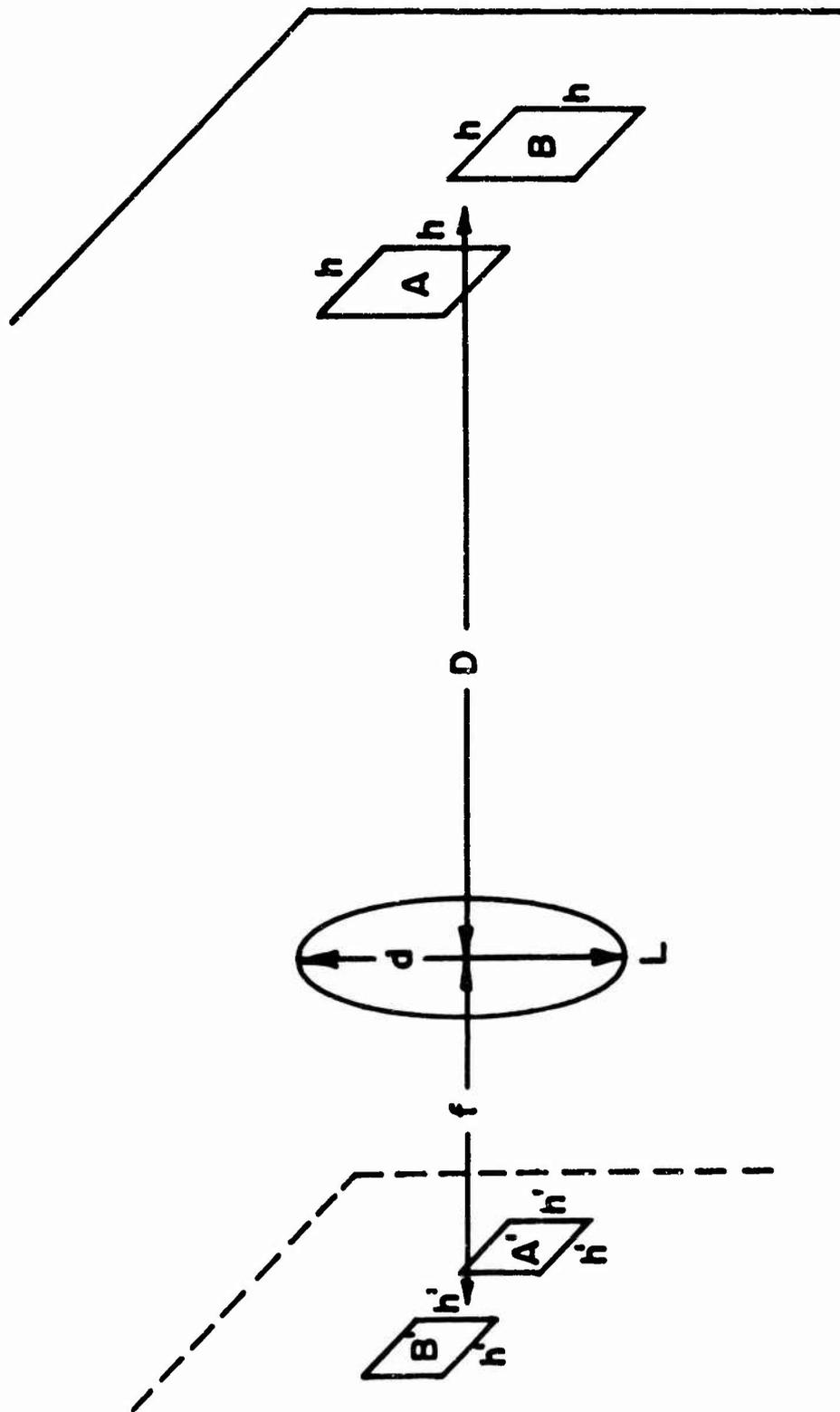


Figure 1. Optical Imaging Diagram

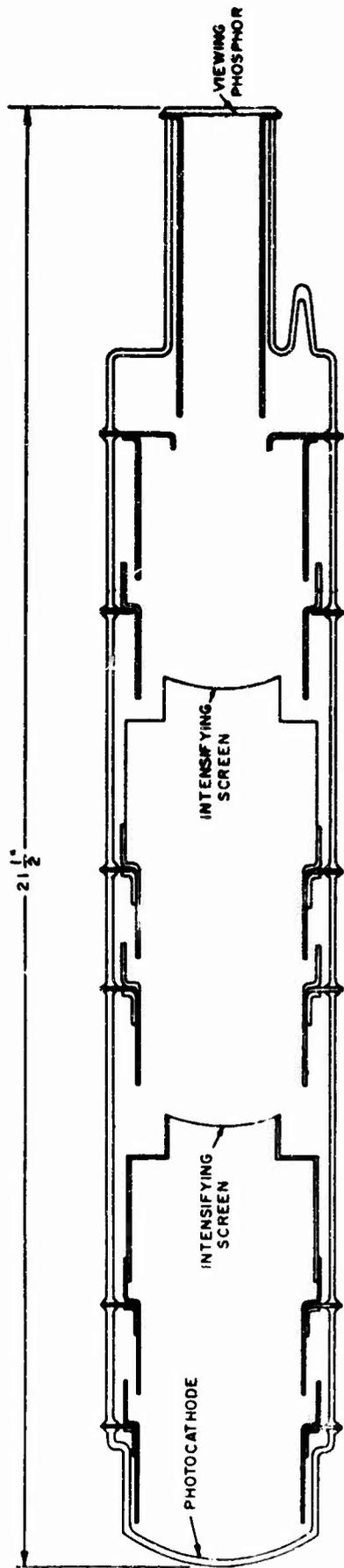


Figure 2. Direct View Image Intensifier

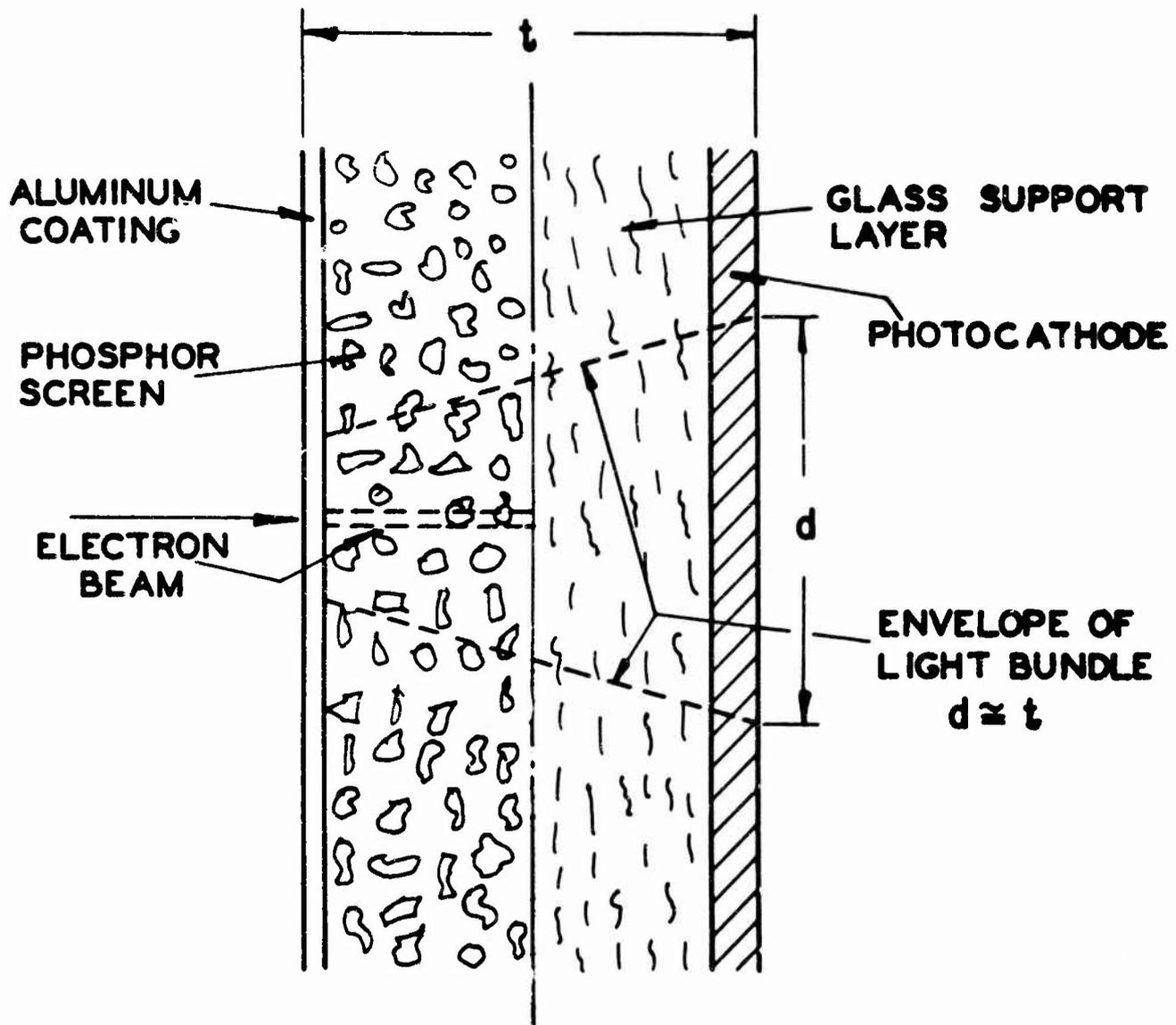


Figure 3. Intensifier Screen



Figure 4. Intensifier Orthicon

INTENSIFIER ORTHICON

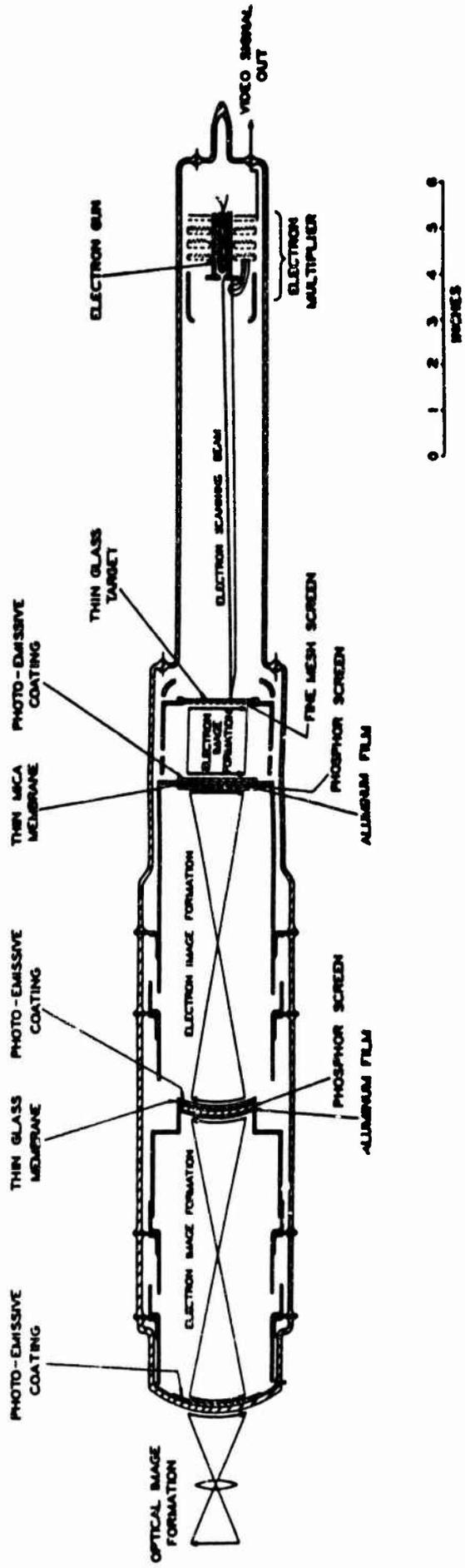


Fig. 5

Figure 5. Intensifier Orthicon (Schematic)

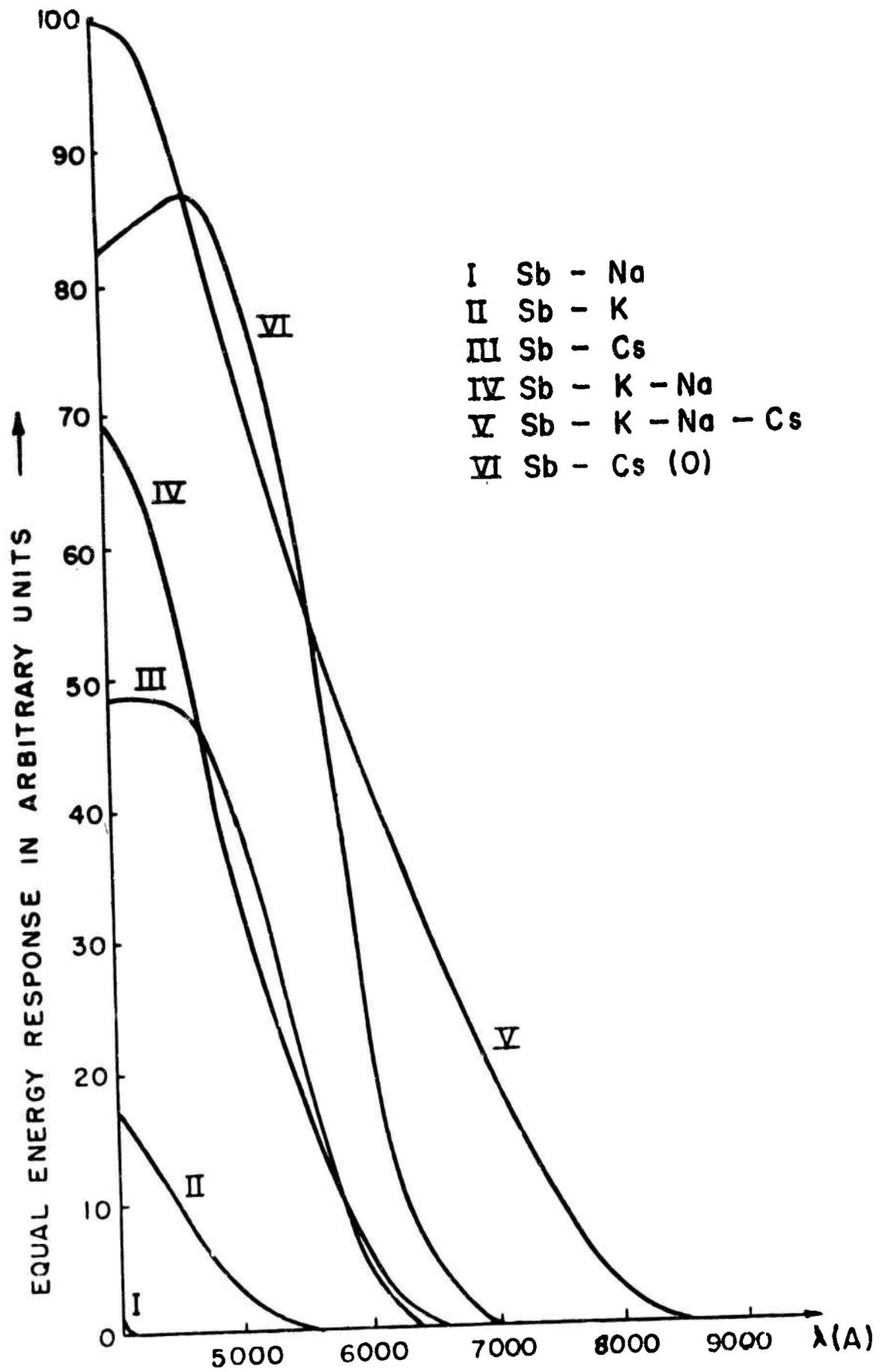


Figure 6. Comparative Sensitivity of Photocathodes

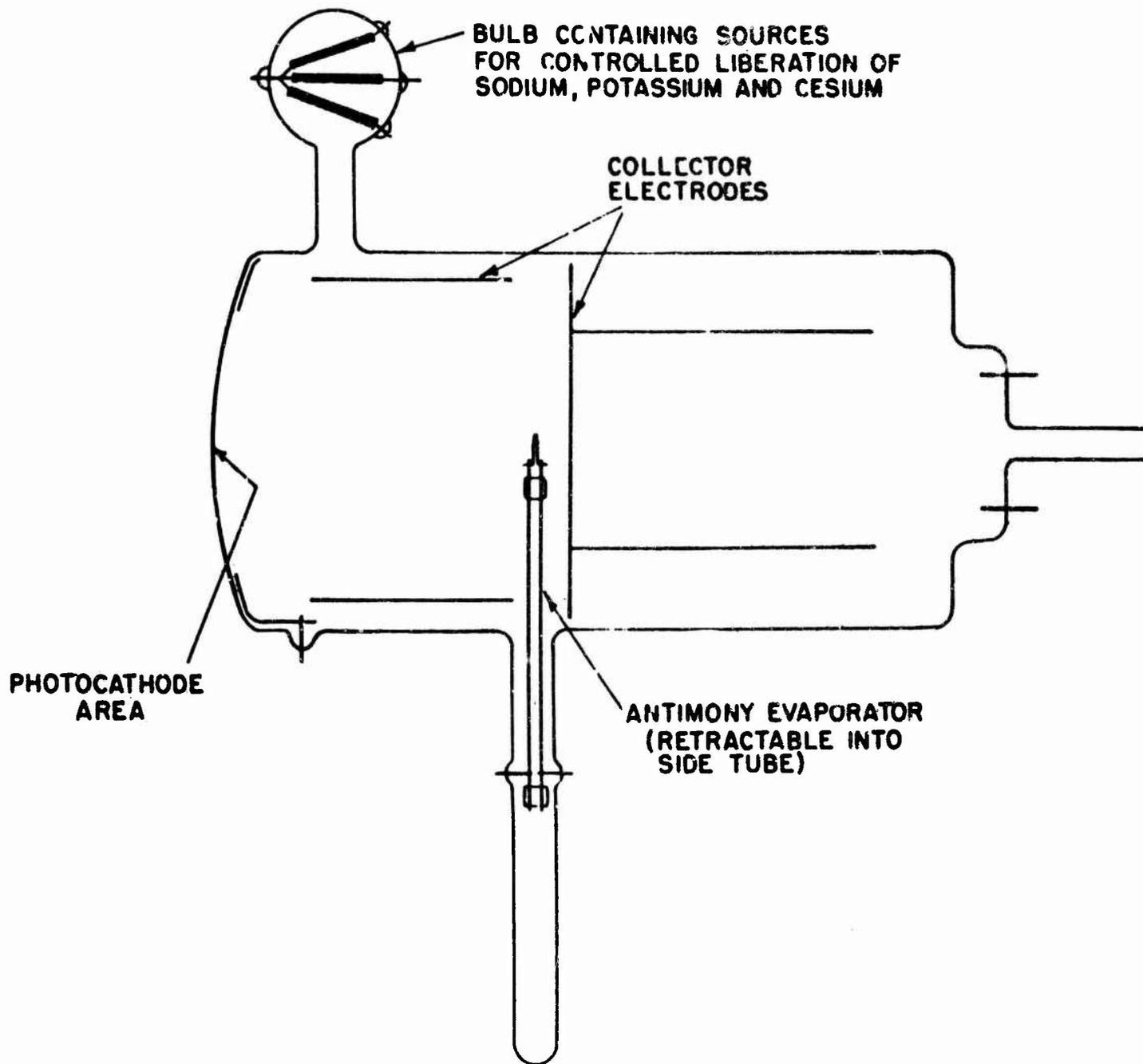


Figure 7. Response Curves of Photocathodes

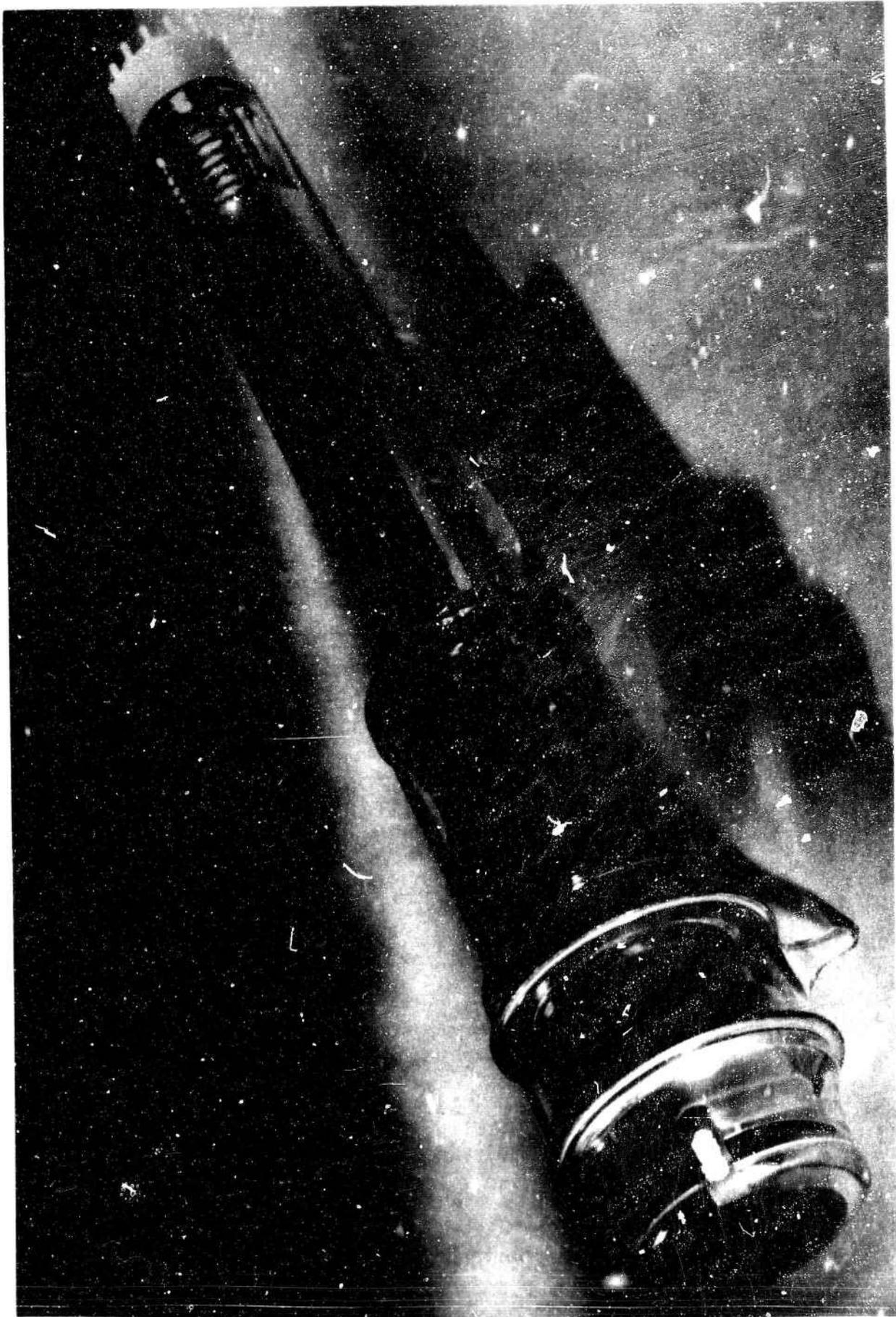


Figure 8. One-Stage Intensifier Orthicon.

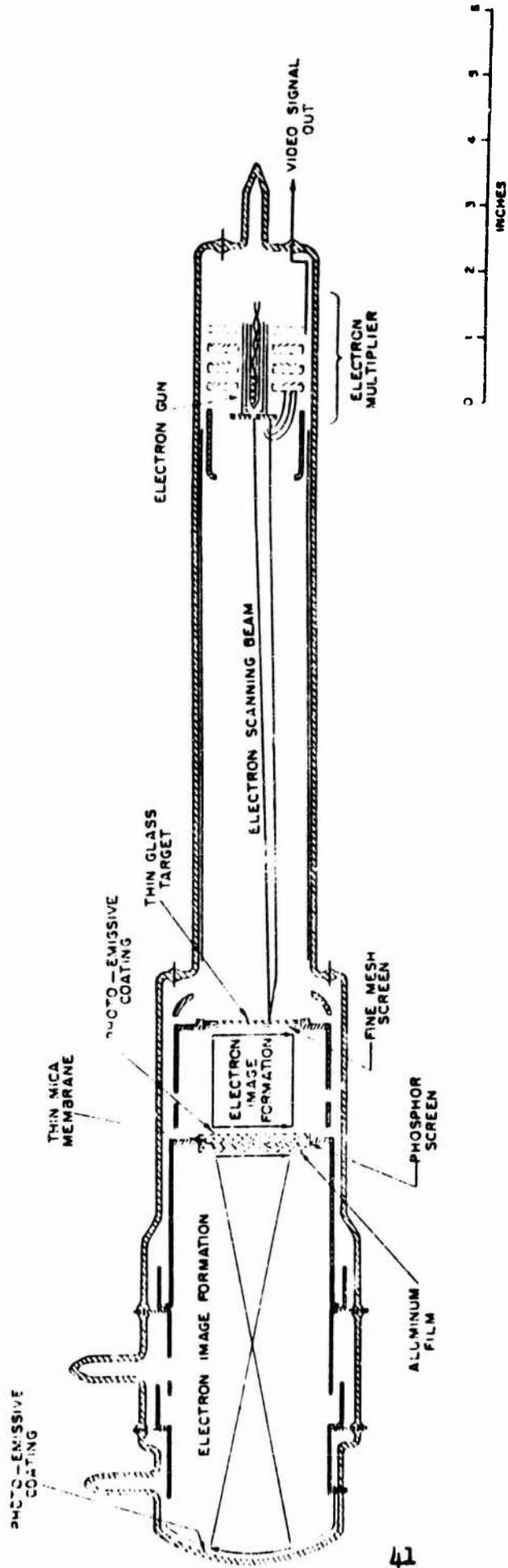


Figure 9. One-Stage Intensifier Orthicon (Schematic)

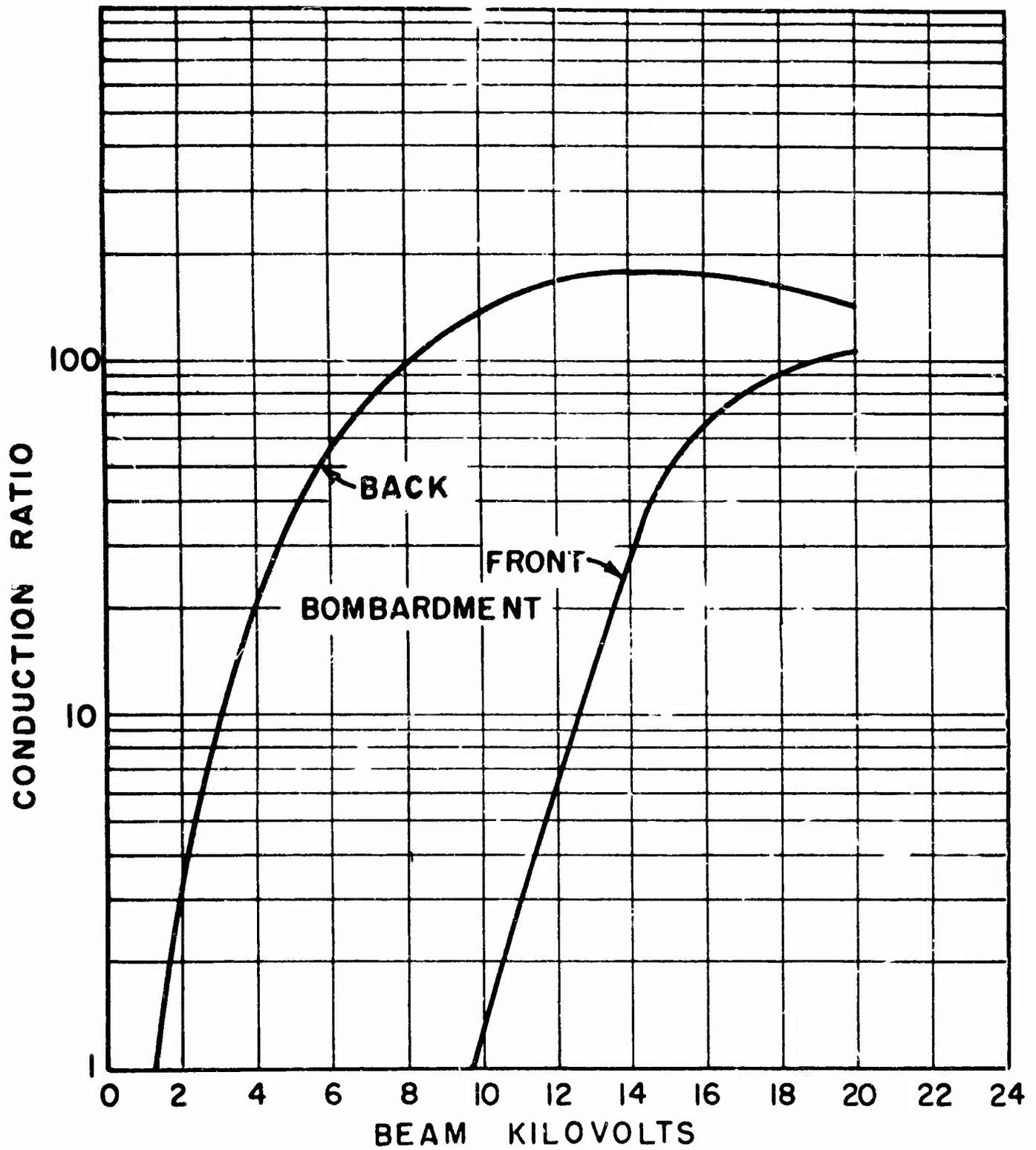


Figure 10. Induced Conductivity in Selenium.

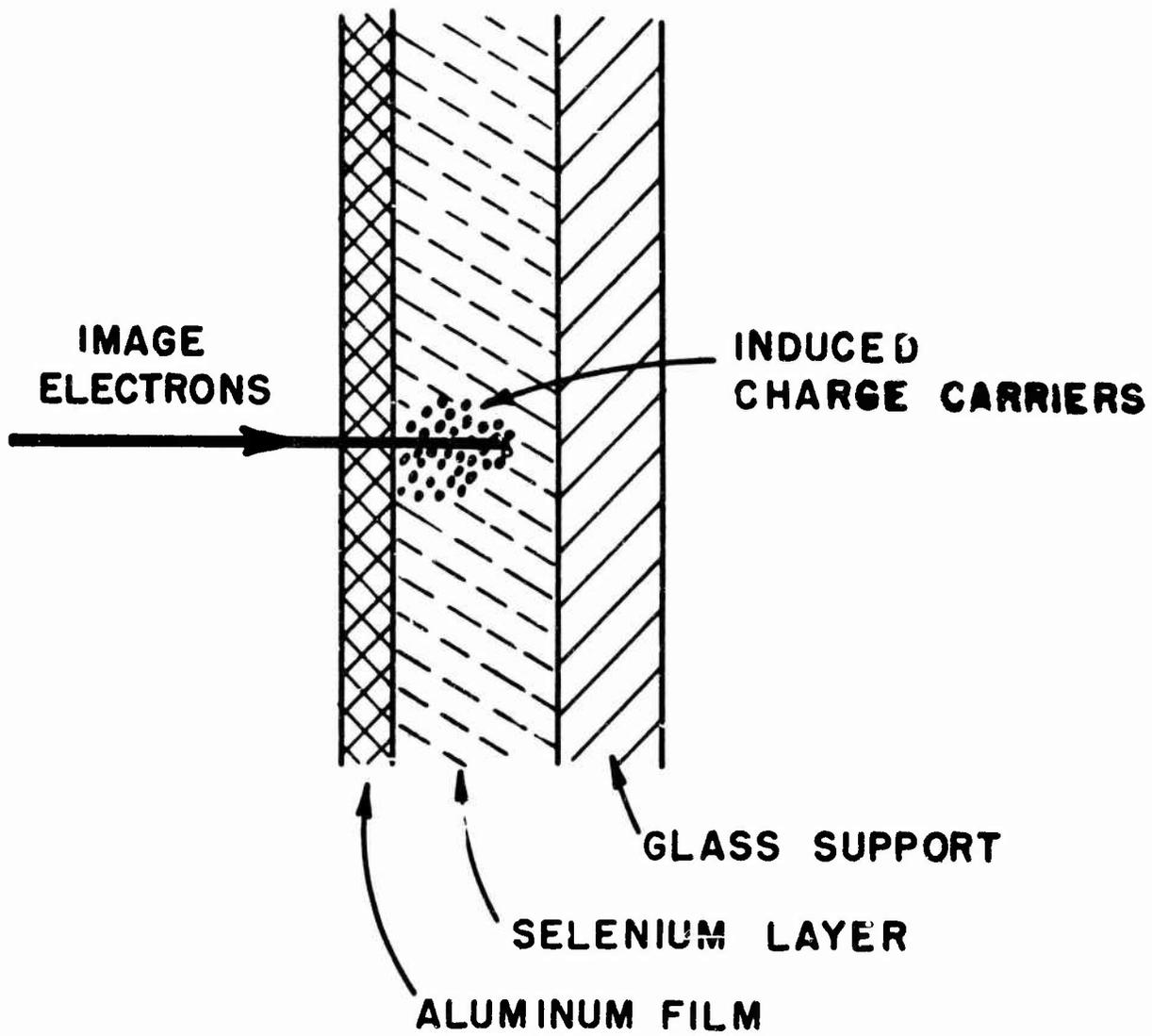


Figure 11. Bombardment-Induced Conductivity Intensifier Target

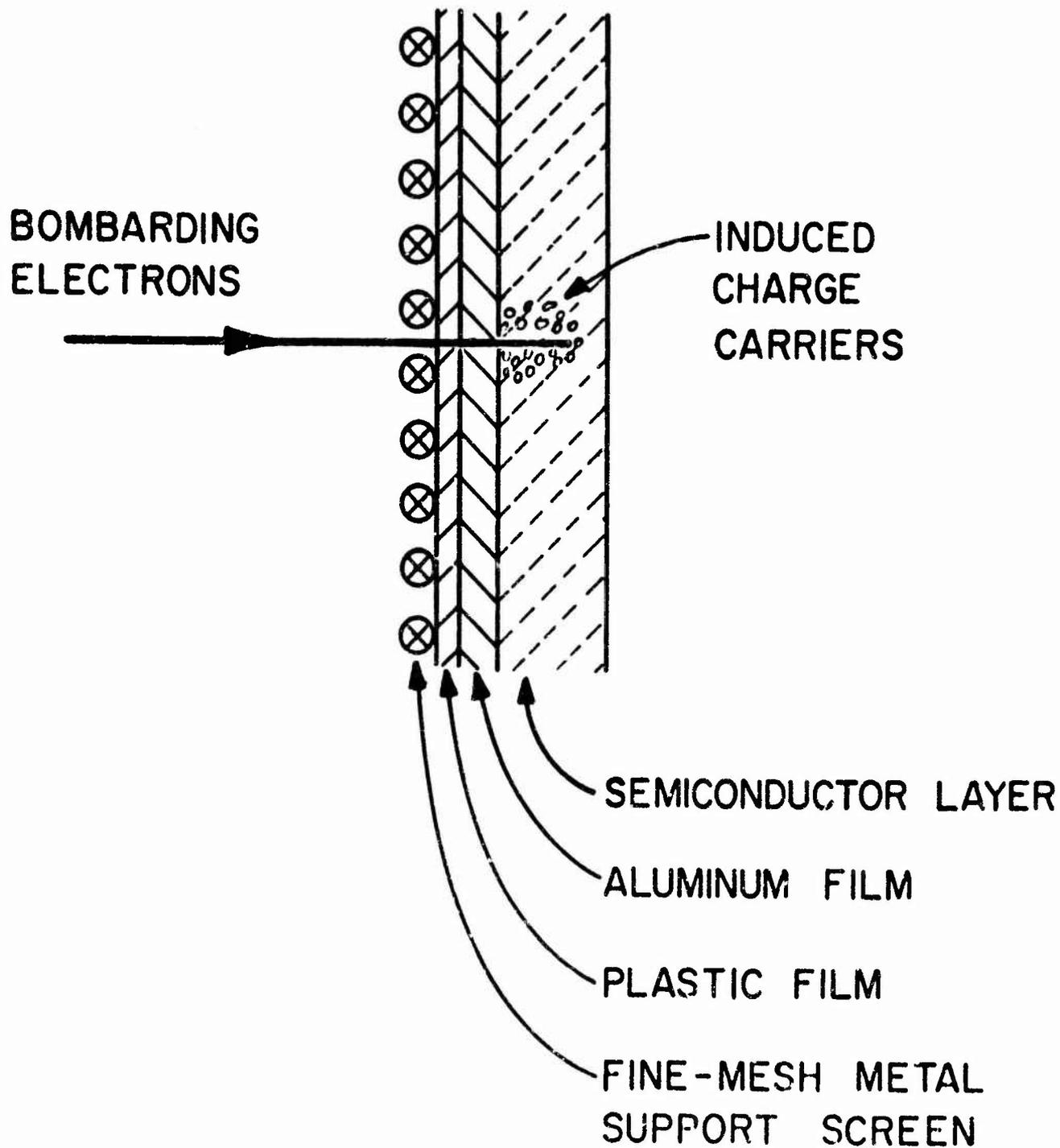


Figure 12. Bombardment-Induced Conductivity Target

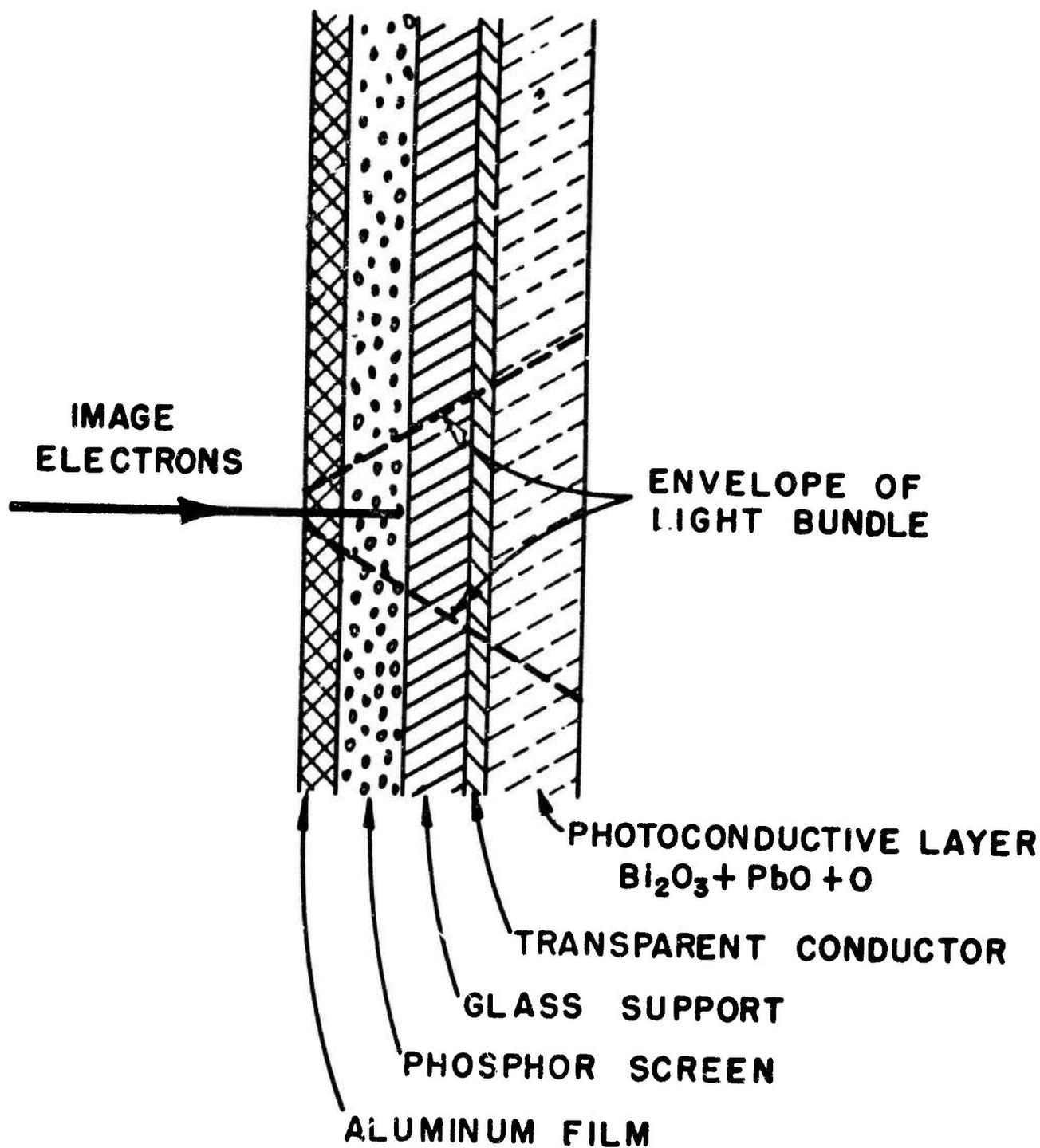


Figure 13. Photoconductivity Intensifier Target

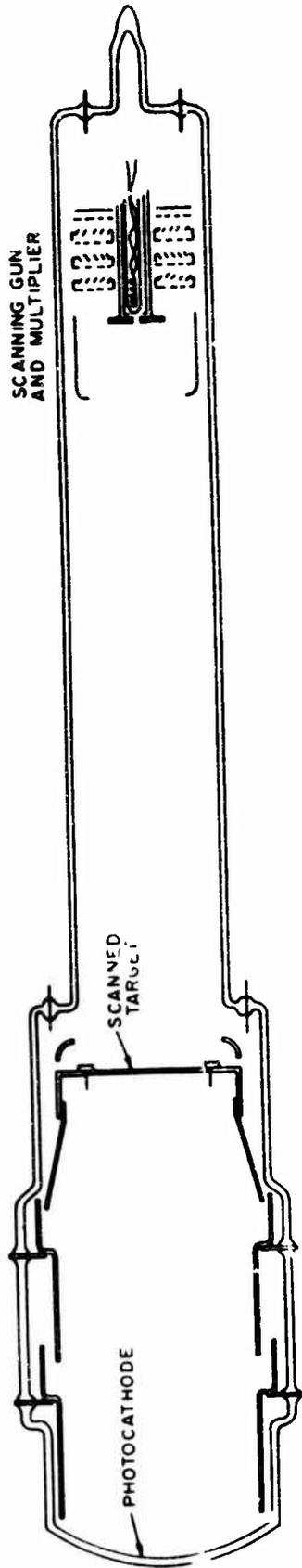


Figure 14. Intensifier Pickup Tube

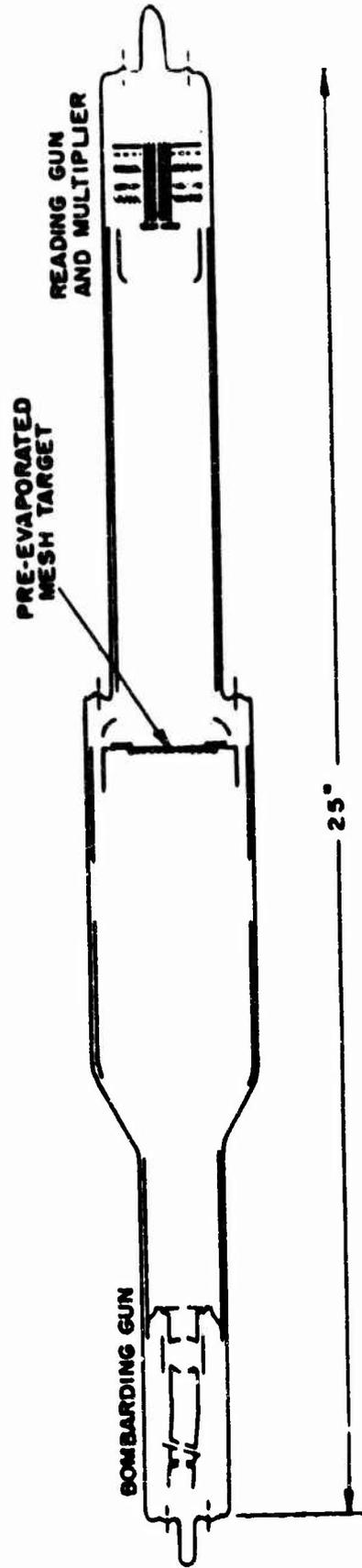
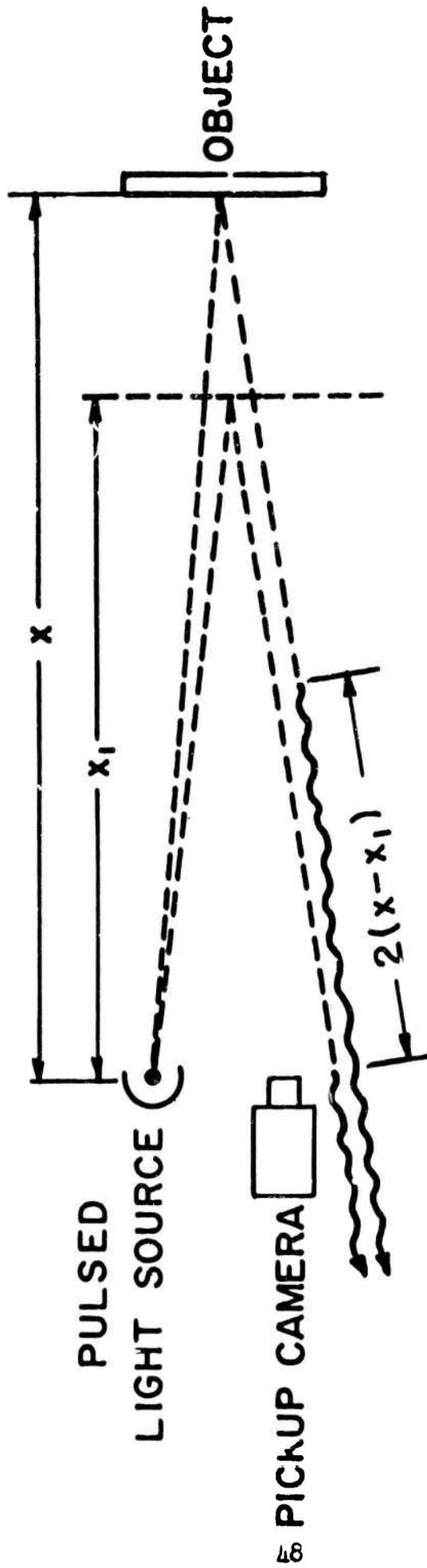


Figure 15. B.I.C. Intensifier Orthicon Test Tube



Eq. 1 $x_1 = \frac{cT_1}{2}$

Eq. 2 $L_p = \frac{EG}{4\pi} \cdot \frac{1}{4F^2} \cdot \frac{2(x-x_1)}{x^2 c}$

Figure 17. Imaging Optical Pulse Hanging System

$$\text{Eq. 2: } L_p = \frac{EG}{4\pi} \cdot \frac{1}{4F^2} \cdot \frac{2(x-x_1)}{x^2 C}$$

ASSUME: $L_p = 10^{10}$ lumen sec./cm.²

$$\frac{EG}{4\pi} = 10^8 \text{ candles}$$

$$\frac{1}{4F^2} = 10^{-1} \quad (F \approx 1.5)$$

MAXIMUM ENERGY AT $x = 2x_1$

HENCE $2x_1 = 10^{10}$ cms. = 2 kilometers

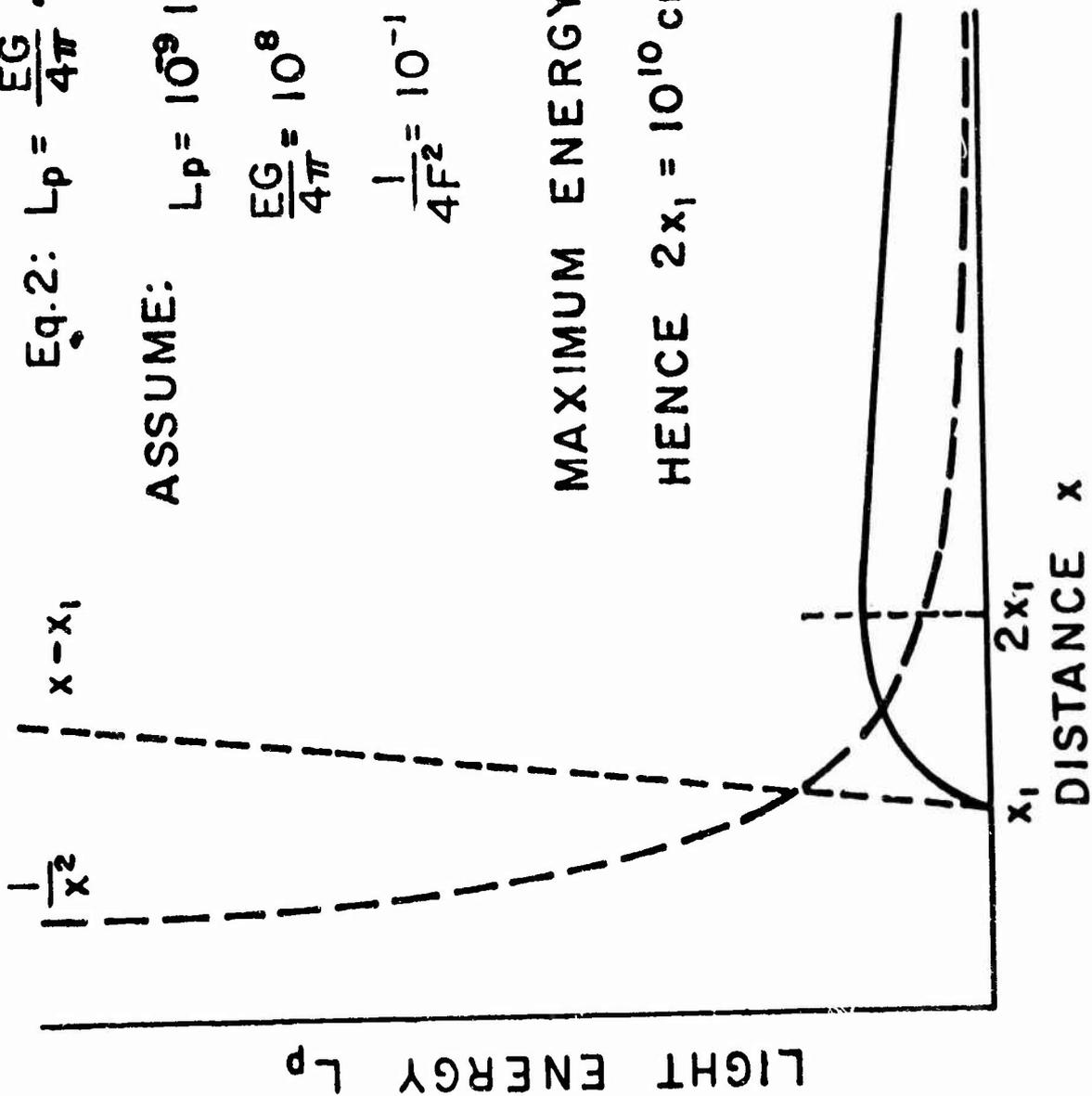


Figure 16. Effective Light Energy versus Distance Relation in Pulse Ranging System