THE FARNSWORTH IMAGE AMPLIFIER

I - Introduction

The Image Amplifier tube has evolved from efforts directed toward overcoming the principal limitations in the current methods of transmitting a television image. These limitations will, accordingly, be first considered. Also, since substantially all of the known art is typified by either the Iconoscope or the Image Dissector, only the weaknesses of these two methods will be listed.

Taking first the Image Dissector, its limitations are readily apparent to anyone who has used this system of transmission. It falls short of measuring up to the ideal image transducer in three important particulars. The first of these is that for tubes of the most sensitive variety, namely, those having a solid photoelectric surface, the distance between the lens and the optical image plane (the cathode) is greater than is to be desired, requiring the use of a long focal length lens, with a resultant shallow depth of focus for close-ups.

The second disadvantage of the Dissector system of scanning is that it requires large amounts of power for scanning - 20 to 30 watts in fact - for a horizontal scanning frequency of 13,000 cycles. The most important limitation, however, is the inherent lack of sensitivity obtained with a Dissector tube, even when full use is made of the electron multiplier. The Image Amplifier tube, even in its present state of development, gives a fairly satisfactory solution to all three of these problems.

The difficulties encountered in the use of systems typified by the Iconoscope are of a different nature from those of the Image Dissector, but comparably troublesome. The light sensitivity, while somewhat greater than that of the Image Dissector, still leaves much to be desired. The mosaic surface cannot be made perpendicular both to the scanning beam and to the axis of the optical lens. This makes it necessary to correct the scanning pattern for Keystone distortion. Perhaps the severest limitation to the use of the Iconoscope system is that caused by the spurious shadows that result from the method used in discharging the mosaic, and requiring complex shading networks for their compensation. Also, since the configuration of these shadows depends upon the kind of image focused on the mosaic, an operator must manipulate the shading controls while image transmission is in progress.

The image amplification principle provides a simple solution to these problems also.

To summarize the merits then of the Image Amplifier -

1 - It provides a short optical system, with the image plane perpendicular to the axis of the lens.

2 - Does not require excessive power for scanning.

3 - The electron beam scans the cathode perpendicularly.

4 - There is no shading compensation required.

5 - It promises light sensitivity several orders better than can be theoretically obtained with either the Iconoscope or Dissector.

II - Evolution of the Image Amplifier Principle

The basic idea involved in image amplification is to amplify (or intensify) an electron image before, instead of after, scanning; that is, to provide an amplifier for each picture element, instead of a single amplifier for them all. The advantage of this method is that each amplifier need only respond to picture frequency. If we consider the elemental amplifiers as of the thermionic type, the effective input impedance may be made very high, and the theoretical gain in sensitivity is tremendous. Our first successful, although only partial, application of the Image Amplifier principle, is shown diagrammatically in Figure 1(1).

In this application, a separate thermionic amplifier, or several of the, is provided for each picture element of a single line only. An electron image is created from the optical image to be transmitted, a single horizontal line of which is selected to fall upon the grids of a multiplicity of thermionic amplifiers. The electron image is then deflected at right angles to the single line selected, and at picture frequency. The potential of each grid is thus caused to vary in accordance with the illumination of a vertical line of picture elements, and modulates its plate current accordingly. The plate current of these thermionic amplifiers is directed toward and formed into an electron image in the plane of a second scanning aperture. This amplified electron image, of a succession of lines, is then scanned by deflecting it in a direction parallel to the line, at the desired horizontal frequency.

The construction of the tube for carrying out this process of amplification and dissection is shown in Figures 2 and 3. Figure 2 illustrates the construction of the Image Amplifier element, having the required multiplicity of control grids. This element comprises a refractory insulating tube, having a longitudinal slot form in the side opposite the diaphragm, which carries the scanning slot. This tube is wound with fine wire - 500 to 1000 turns per inch. After the tube is wound, the winding is partially coated with material for insulating it and cementing it to the refractory tube, for example, vitreous enamel. In applying the enamel, that portion of the winding immediately behind the slit in the diaphragm is left bare, as is also that portion covering the slot. After the enamel coating has been baked, a saw-cut is made, extending the length of the tube, to separate the winding into individual discontinuous turns.

A thermionic cathode extends the length of the tube, and is positioned in the slot immediately behind the exposed windings. This cathode is oxide-coated and forms the common cathode for all of the isolated grids. An anode screen is supported immediately in front of the slot.

Figure 3 shows the construction of the complete tube and the position of the image amplifier element, relative to the photoelectric surface and the final scanning aperture.

Referring to Figure 3, the image to be transmitted is focused onto the photoelectric screen. The photo-electrons emitted from the meshes of the screen are accelerated from the photoelectric screen by an anode screen, and then focused magnetically by means of an external solenoid to form an electron image in the plane of the scanning slit. The electrons drawn through the meshes of the free grids by the second anode screen are similarly focused magnetically in the plane of the target.

The low frequency scanning field deflects the electrons in the first half of the tube over the scanning slit, and a high frequency field deflects the electrons over the target in the second half of the tube - there to produce an amplified video current output similar to that which would have been produced by a simple Dissector tube.

The grids of the Image Amplifier are operated free, and assume a biasing potential that is determined by the amount of voltage on the anode screen and the temperature of the cathode.

The improvement in sensitivity over the simple Dissector tube, obtained by this device, is in the final analysis, determined by two factors - the decrease in band-width which the individual grids have to handle (that is, the storage time), and the current amplification obtainable in the elemental thermionic relays. The product of these two factors may be 100 to 1000.

A further advantage is obtainable if an electron multiplier is used instead of the simple target, for since the electrons entering the target originate from a space-charge, more electron multiplication may be used than in the Dissector, without the limit imposed by shot-noise being reached.

An Image Dissector, in which image amplification of the entire image is utilized, is shown in Figure 4. This tube is similar in construction to an ordinary Image Dissector tube. It comprises a solid photoelectric cathode, mounted at one end of the tubular blank, in the opposite of which is mounted a small tubular shield which covers a nickel target, and is pierced by a minute scanning aperture.

In the simple Dissector, an optical image is focused through a transparent window in the end of the blank onto the photoelectric cathode, and an electron image focused magnetically in the plane of the scanning aperture. Scanning is accomplished by sweeping the entire electron image over the aperture.

In the tube, shown in Figure 4, an insulator, made by evaporating insulating material onto a fine mesh screen, is positioned parallel to and fairly close to the cathode(2).

The photoelectric cathode is flooded with infra-red light, so that it emits a current of 25 to 50 microamperes without the optical image on the cathode. When visible light is allowed to shine on the cathode, the current passed by the tube will materially decrease, and may be made to approach zero, depending only on the amount of potential between the cathode and the target shield. It is found, experimentally, that the relay action produced by the visible light is due mostly to wavelengths shorter than the yellow. The operation of the tube is believed to be as follows.

The potential to which the insulator, immediately adjacent an element of the cathode, charges is determined by the wavelength of the incident light. For infra-red light, therefore, the insulator will charge negatively by a small fraction of a volt greater than the cathode. If the voltage between cathode and anode are then adjusted until current just flows, an increase of negative potential on the grid would cause such plate current to decrease. When visible light is allowed to fall on the cathode, the dielectric assumes a higher negative potential, with the result that the current across the tube decreases.

It has been found, experimentally, that an amplification of several thousand is readily obtainable by this method. Also, a storage time of from several minutes down to a small fraction of a second may be obtained. As in the tube shown in Figure 3, an electron multiplier is of greater use in this tube than in the Dissector, since the image electrons originate from partially space-charged saturated regions.

Figure 5 shows a method by which the operation of the light modulator tube of Figure 4 may be improved and its construction simplified. This consists of combining the perforated insulator and the photoelectric screen into one unit, simply by insulating one side of a fine mesh screen and photo-sensitizing the opposite side, but the figure serves to illustrate a more useful type of image amplifier.

In the improved tube, the screen is evaporated with suitable dielectric material (see Figure 6), and then a thin coat of silver sputtered onto the insulator in such a manner that it forms a mosaic surface. Both sides of this screen are photo-sensitized. The image to be transmitted is focused onto the mosaic side of the screen, while the back is flooded with light. A potential difference of a few hundred volts is applied between the cathode and the wall coating. There is copious electron emission from the back of the screen, which, however, is not pulled through the meshes of the screen unless there is illumination on the mosaic side. With light on the mosaic side, the "photo-islands" charge positively in proportion to the illumination, establishing relatively large potential gradients between the front and the back, which serve to draw the electrons from the back through the meshes of the screen in proportion to the illumination on the front. This electron emission is then focused and deflected as in the conventional Dissector tube. Here again, since the image electrons originate from a space-charge cloud, more electron multiplication may be advantageously used than in the simple Image Dissector tube.

This tube has one limitation which has prevented its practical use as yet. The scattered light from the flooding light which penetrates the screen limits the amount of image amplification obtainable. Thus, if the intensity of the flood light is gradually increased, a point is soon reached where the photo-island grids draw all of the current through the meshes, and the light in the image has no effect. Amplifications of well over a hundred have been measured, however. The tube has the further disadvantages that the distance between the optical window and the cathode is too great for a convenient optical system, and the power required to scan is rather more than is desired.

III - Beam Scanning Image Amplifiers

A - Description and Principles of Operation

An electron flood gun may be incorporated in the Image Amplifier Dissector shown in Figure 6 to replace the flooding light for supplying a constant and adequate supply of electrons from the back of the photo-island grid screen. This modification does away with the difficulty experienced from scattered light, and allows the full image amplification gain to be realized, but when an electron gun is used it is more advantageous to confine this to a fine beam and utilize the beam for scanning. This permits less current in the beam, and requires very much less power for scanning. The construction of the tube is then as shown in Figure 8.

As will be seen from Figure 8, the tube comprises an electron gun, for producing a fine pencil of cathode rays, sealed into one end of the tube, and having its anode connected to a metallic film on the inside of the blank. The metallic film extends about nine inches beyond the anode of the gun, into an enlarged section of the blank. Approximately three inches beyond the end of the metallic film, the blank is closed with an optically clear flat window. Sputtered on the inside of this window in a transparent platinum film, connection to which is brought out of the side of the blank.

The photo-island grid screen is positioned approximately an inch from the platinum film, and parallel thereto, with the mosaic side of the screen facing the platinum window.

The photo-island grid is made by evaporating a refractory insulator onto a perforated nickel sheet. The nickel sheet has 400 perforations per square inch, and is approximately .0005 inches thick. There are many possible choices for the insulation material, of which Barium Floride is representative. The insulator should have a low dielectric constant, be highly refractory, and be chemically stable. The thickness of the dielectric should be uniform, and between .0003 and .0005 inches thick.

After the dielectric is evaporated onto the mesh, a thin film of silver is sputtered over it, so that when later formed with

Caesium, it will be a well insulated mosaic. In this respect, no trouble has been experienced from charge spreading, due, most likely, to the fact that the shortest leakage path from each mosaic element is through the holes to the supporting mesh.

A microphotograph, with a magnification of 100, of a small section of a typical photo-island screen, is shown in Figure 10. Part of the dielectric has been scraped off to show the underlying supporting mesh.

Figure 11 is a drawing of the same composite grid. The appearance of a finished tube may be seen in a photograph of Figure 9.

In operation, the tube is connected as shown in Figure 12, with scanning and focusing coils omitted for simplicity. The electron gun is energized with a voltage of from 500 to 1500 volts, and bombards the nickel side of the photo-island grid. Some of the electrons in this beam pass through the meshes of the grid and are collected on the platinum film. About 80% of them, however, strike the metallic nickel to produce secondary electrons. There is a potential difference of from 5 to 50 volts positive on the platinum film, relative to the nickel base of the photo-island screen. This potential is insufficient, however, to draw any of the secondary electrons emitted from the back through the meshes. When an optical image is focused on the mosaic side of the grid, photo-electrons are emitted and drawn to the platinum film, leaving the grid islands charge positively with a charge that increases proportional to product of light intensity and time.

This results in the secondary electrons from the back being pulled through the meshes in an amount which is proportional to the three halves power of the voltage between back and front. It should be noted here that the control of such a grid element is relatively enormous, since the grid is placed only about one-thousandth of an inch from the source of the electrons.

We have then a multiplicity of small thermionic amplifiers, of which only those very near the area bombarded by the scanning beam has an emitting cathode, and scanning is accomplished by moving this cathode source over the back of the grid structure.

The current in the beam need not be more than a few microamperes, since this is quite adequate to give space-charge saturation, for if we consider a beam of elemental size, multiplied by the number of picture elements, our effective cathode emission for the total number of elements becomes the order of an ampere or more.

It will be noted that the elemental grids, although effectively free, are operated positively. It might be expected, therefore, that the grid current drawn by them would be excessive, and that the sensitivity would be decreased, due to the rapid discharge of a grid element, when the scanning beam is in its vicinity. Almost the opposite has been found to be true, experimentally, however, and if too much potential difference is applied between the platinum film anode and the photo-island grid, the beam has nearly no discharge action whatever. Operated in this manner, the tube may have a "memory" of from five to ten minutes, rendering the tube practically useless for transmission of moving objects. Reducing the voltage applied between the platinum film and the grid, improves the speed of response and decreases the sensitivity accordingly. In practice, the voltage is adjusted to be as high as possible, without blurring of the field when the object moves.

It is not necessary that the elemental grids be operated free. They may be connected with the cathode backing by evaporating a suitably thin film of metal through the meshes of the grid from the nickel side until the time constant of the grids has the desired value.

B - Sensitivity

The inherent sensitivity of the Image Amplifier cannot be realized without the addition of another electrode to collect the primary electrons which go through the meshes of the photo-island grid, without striking it, and without the addition of an electron multiplier. A discussion of sensitivity might well be left until these factors were described, but it is advantageous to consider the limitations of the simple beam type tube to indicate the desirability of the two additional elements.

In specifying the sensitivity, it is necessary to specify the storage time, since obviously its sensitivity is proportional to the storage time, and for present purposes this will be taken as one-tenth second, since this is sufficiently short for most purposes.

The total grid to cathode capacitance of a typical tube, using Barium Floride as the dielectric, has been measured to be 6000 micro-microfarads, which gives a total leakage of all of the elements of approximately 15 megohms. If we assume the number of picture elements to be 250,000, the total elemental capacitance becomes 2.4×10^{-14} farads, and the elemental resistance - 3.75×10^{12} ohms.

Since the simple tube does not embody an electron multiplier, our first consideration must be the amount of output necessary to override the thermal agitation noise in the first resistor of the external amplifier. A practical value of this resistor is 2000 ohms, so that for a band-width of 3 megacycles, the thermal noise will be approximately 8 micro-volts(3). An output voltage of 10^{-4} volts will, therefore, be taken as the minimum allowable signal out of the tube, giving a current of approximately 0.05 microamperes as the required average signal component.

We now need to find the amount of voltage which must be developed on the photo-islands to give this change in current. This is a constant that is very difficult to measure, but our best experience indicates that one volt on the mosaic will result in approximately one microampere change in the current when the scanning beam is sharply focused, or, in other words, we shall require 0.05 volts to develop the required signal output. This means an average photo-current from the image of 3.3×10^{-9} amperes. Thus, we have a current amplification of fifteen times - but this is all signal current - so that the tube is fifteen times as sensitive as if simple storage of the charge were utilized.

The sensitivity of the mosaic surfaces practically obtainable so far is of the order of one microampere per lumen. We, therefore, shall require a minimum illumination of 3.3×10^{-3} lumens in the optical image to give a satisfactory noise free output.

However, we must first examine other sources of interference within the Image Amplifier itself. The possible sources of such noise are four-fold:

1 - The shot effect of the current leaving the elemental grid.

2 - The thermal agitation of the elemental grid resistance to ground.

3 - The shot-noise from the secondary electrons drawn through the meshes.

4 - Noise produced by irregularity of the number of electrons passing through the meshes of the grid as the beam scans across it.

Computation shows that the shot-noise fluctuation, due to the element grid current, is of the order of 7.5×10^{-4} volts, as against 5×10^{-2} volts signal. This component may, therefore, be neglected.

To find the thermal agitation at room temperature we may use the formula(4) -

$$\frac{\overline{E_v^2}}{\overline{E_T^2}} = 19.4 \text{ iR} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

From this relation we find that the thermal agitation amounts to approximately 0.9 of the shot-noise. We may, therefore, neglect the fluctuation noise caused by the thermal agitation in the elemental grid to ground resistance.

We cannot compute the shot-noise produced by the secondary electron cloud in back of the grids without knowing the extent of space-charge saturation, but from experience with ordinary thermionic tubes, we know that this component may be made as small as necessary by the establishment of a sufficiently dense space-charge. Experimentally, no trouble has been experienced from fluctuation noise traceable to this cause.

The interference produced by the irregularity of the number of electrons passing through the meshes of the grid as the scanning beam moves across it, represents the limiting factor in the simple tube shown in Figure 8. When no means is provided for collecting these primary electrons to keep them from flowing in the output circuit, it is necessary that the component of signal current be at least 10% of the total beam current. Thus, if the beam current is 5 microamperes, the signal component must be at least 0.5 microamperes. Or, in other words, the sensitivity of the tube is reduced approximately 10-1 over what could be utilized if the primary electrons were kept out of the work circuit. Tubes, therefore, have been developed to accomplish this result.

The fluctuation voltage present on the elemental grids, that is produced by both thermal agitation and shot irregularities of the photo-current, has a maximum frequency component in the neighborhood of 10 cycles per second, and this frequency component is not passed by the external video frequency amplifiers. Also, there is little or no shot-noise in the amplified current. We may, therefore, use an electron multiplier to increase the sensitivity of the tube by a factor of 20-100 times. The improved types of Image Amplifier tubes, therefore, incorporate an electron multiplier tube.

C - Combination of the Image Amplifier with an Electron Multiplier

Figure 13 shows an Image Amplifier, in which is incorporated a highly effective four-stage electron multiplier. The first three stages are small cube shaped silver boxes, approximately 1 cm. long on a side. One face of each cube is open, and an adjacent face open, but covered with a fine mesh tungsten screen. The cubes are mounted with the open face of one closely adjacent to the screen covered face of another, as is illustrated by the figure.

The fourth stage is a sheet of silver, 1 cm. square. The whole multiplier is covered by a metallic shield, which is open at the top to allow the electrons to enter the first stage. The photo-island grid is mounted approximately four inches from the end of a tubular blank. Parallel to the grid, on the mosaic side, and closely adjacent thereto, is positioned an anode screen of fine open mesh knitted tungsten screen. In front of this anode screen, the blank is metallized, and connection to the metallic film brought out through the side of the blank. The electron multiplier is mounted in a side tubulation, approximately three-fourths of an inch from the end of the blank. The blank is closed with a flat optically clear window. Behind this window, and closely parallel thereto, is positioned a second tungsten mesh screen, similar to the anode screen.

The tube is connected as shown in Figure 14. Connections to the Image Amplifier portion of the tube are the same as those of the tube shown in Figure 8. The multiplier shield is maintained positive, by one hundred volts or so, with respect to the anode screen.

FOOTNOTES ON

THE FARNSWORTH IMAGE AMPLIFIER

(1) U.S. Patent #2,085,742

(2) There are better ways to construct this particular tube, but this construction serves better to illustrate the principles of operation.

(3) See, for example, G.L. Pearson - Physics - Vol. 5 - Number 9 - Page 243.

(4) G.L. Pearson reference already cited.

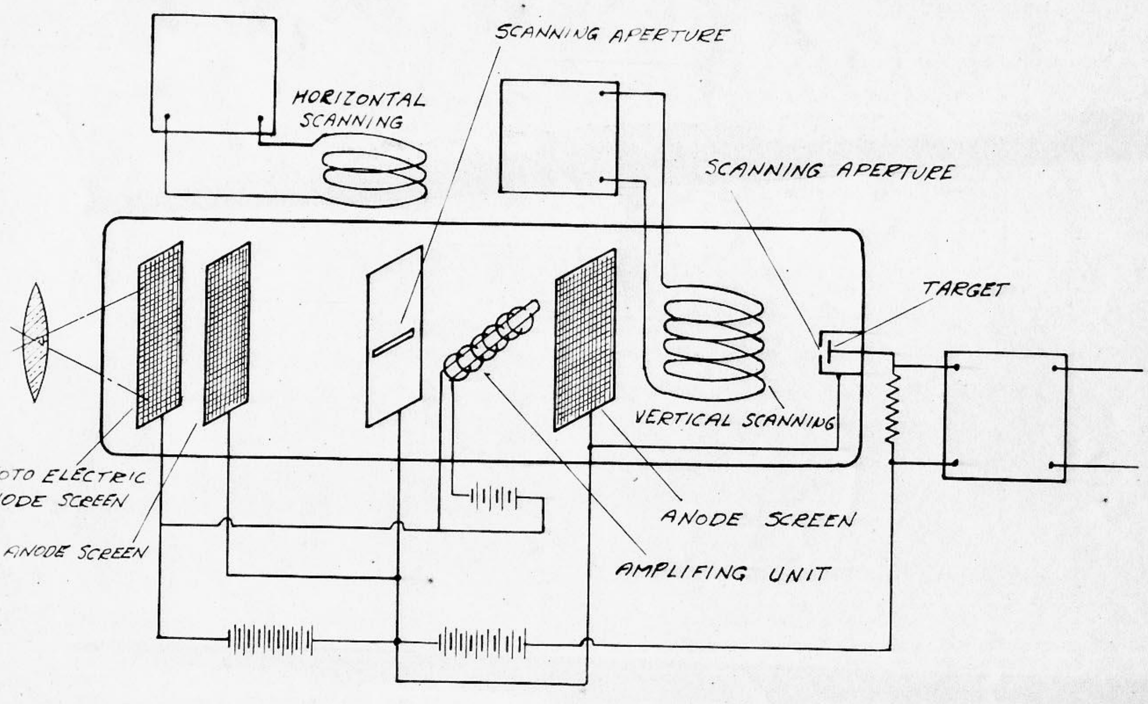
SCANNING APERTURE
HORIZONTAL SCANNING
SCANNING APERTURE
TARGET
VERTICAL SCANNING
PHOTO ELECTRIC CATHODE SCREEN
ANODE SCREEN
ANODE SCREEN
AMPLIFING UNIT

FIG. 1

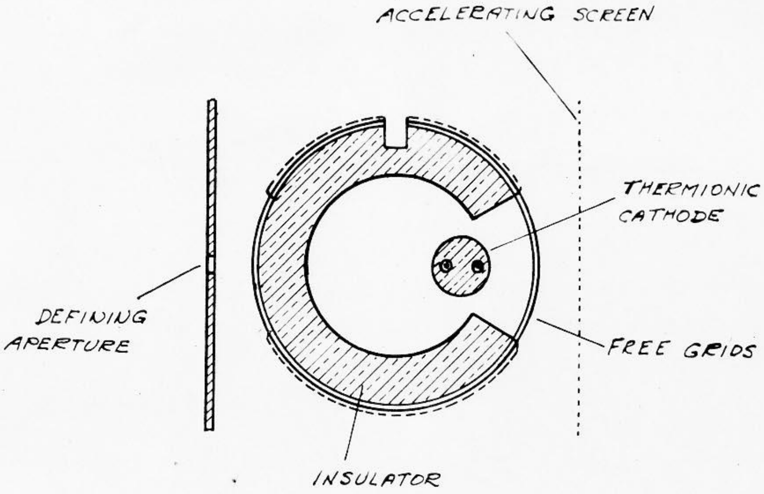
ACCELERATING SCREEN
THERMIONIC CATHODE
DEFINING APERTURE
FREE GRIDS
INSULATOR

FIG. 2

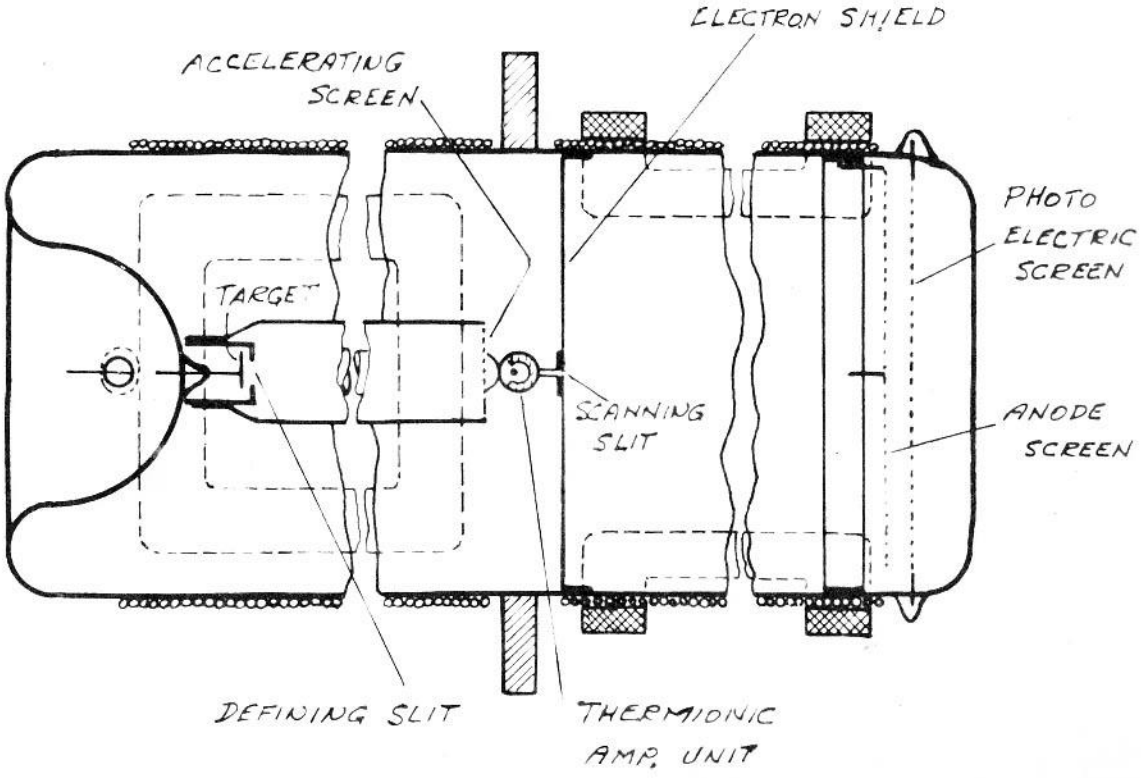
ELECTRON SHIELD
ACCELERATING SCREEN
PHOTO ELECTRIC SCREEN
TARGET
SCANNING SLIT
ANODE SCREEN
DEFINING SLIT
THERMIONIC AMP. UNIT

FIG. 3

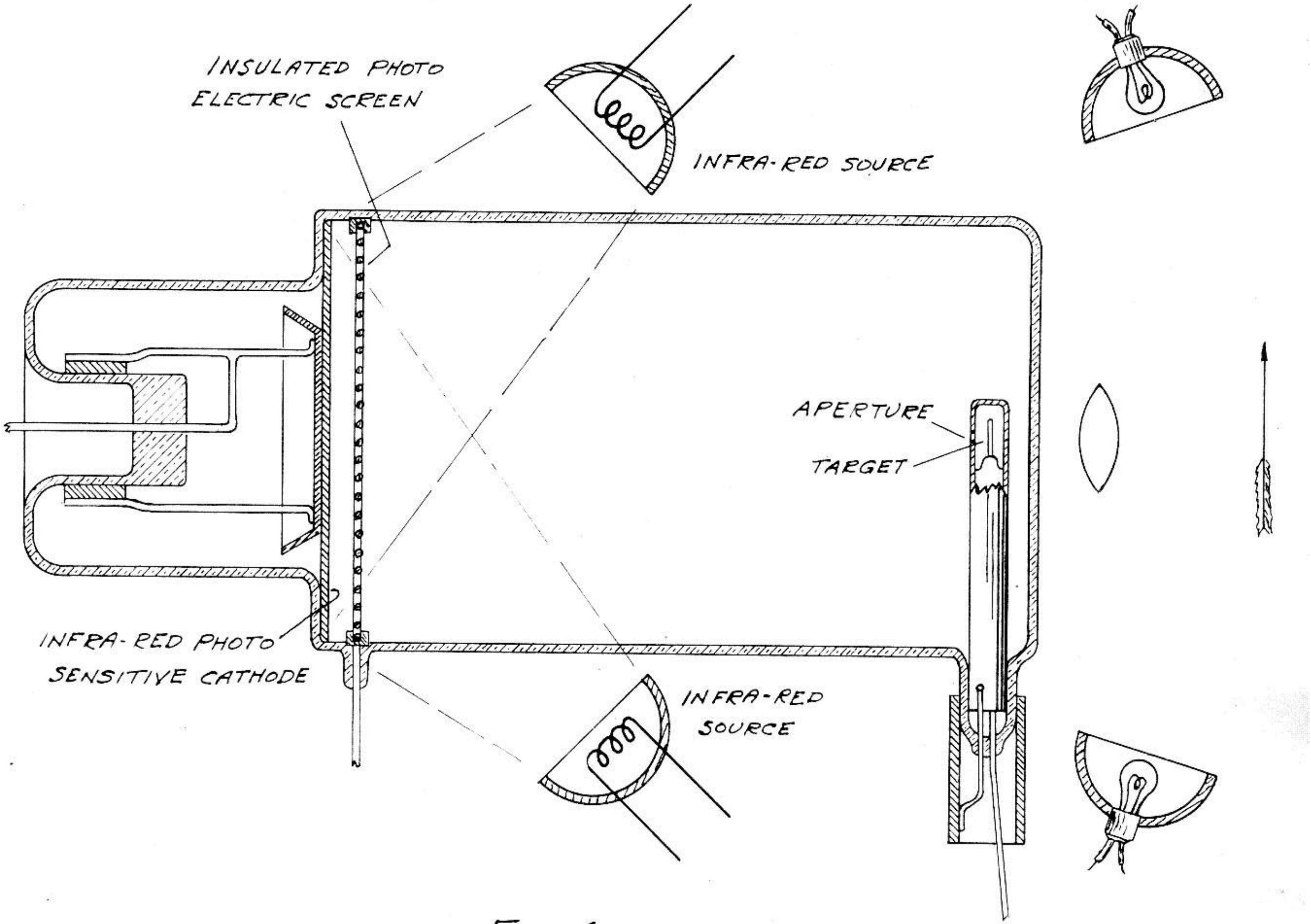
INSULATED PHOTO
ELECTRIC SCREEN
INFRA-RED SOURCE
APERTURE
TARGET
INFRA-RED PHOTO
SENSITIVE CATHODE
INFRA-RED
SOURCE

FIG. 4

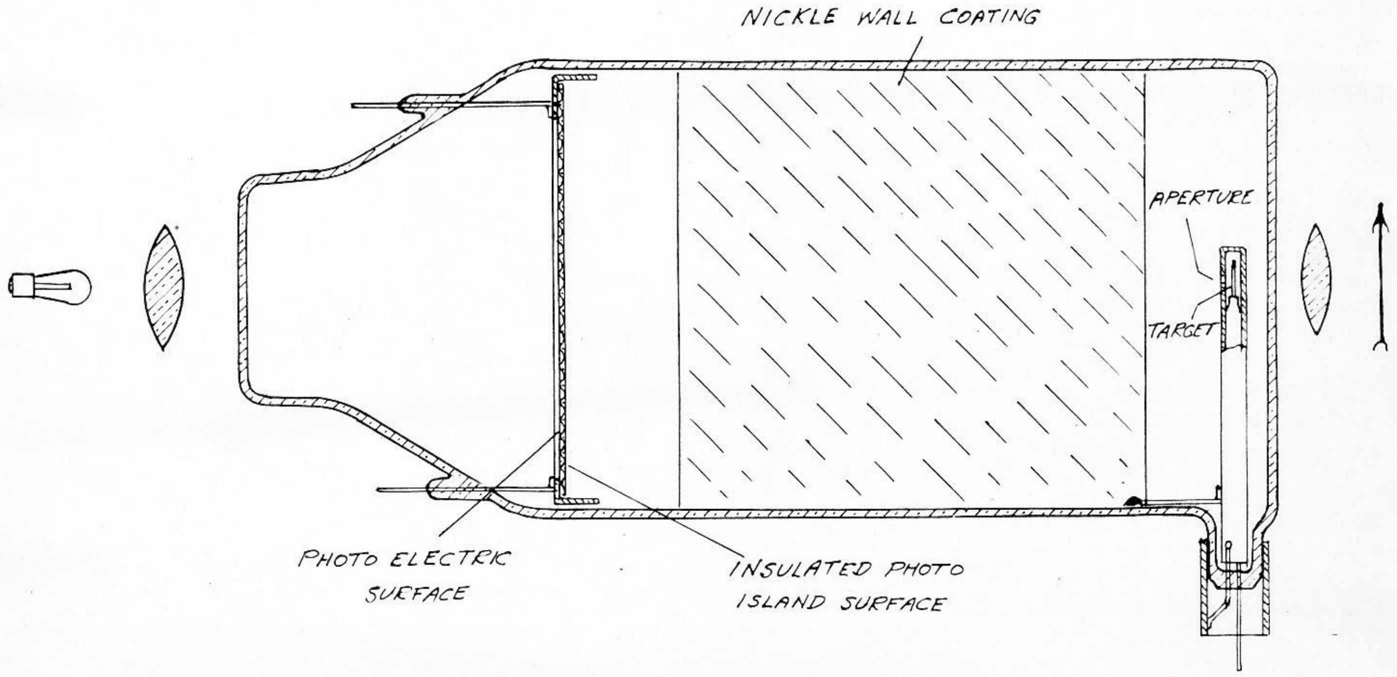
NICKLE WALL COATING
APERTURE
TARGET
PHOTO ELECTRIC SURFACE
INSULATED PHOTO ISLAND SURFACE

FIG. 5

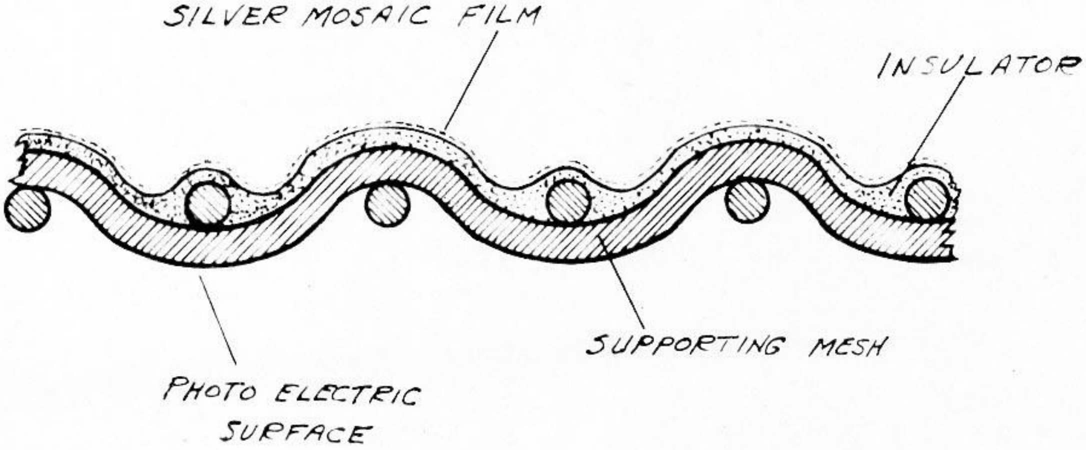
SILVER MOSAIC FILM
INSULATOR
SUPPORTING MESH
PHOTO ELECTRIC SURFACE

FIG 6

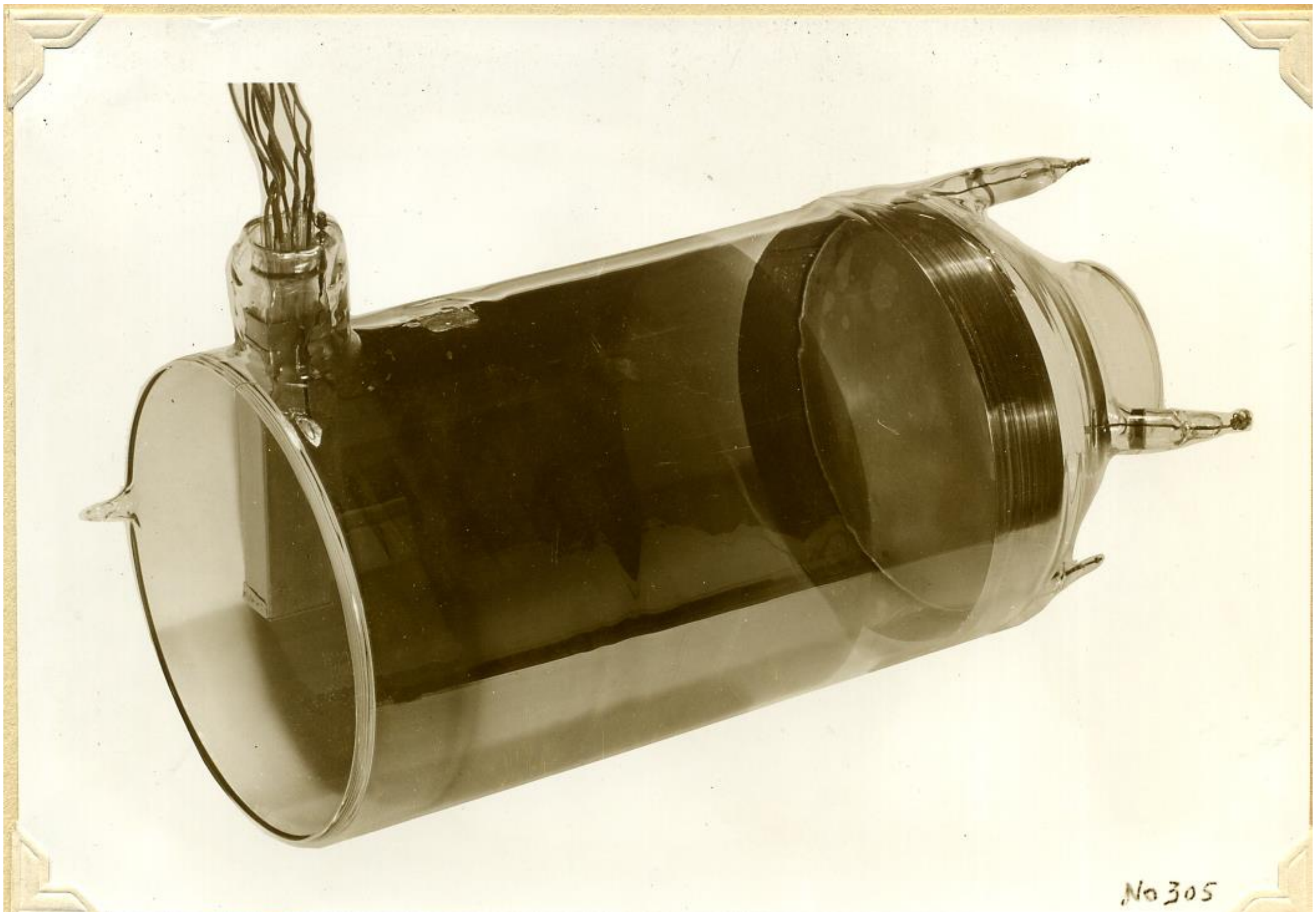

Figure 7

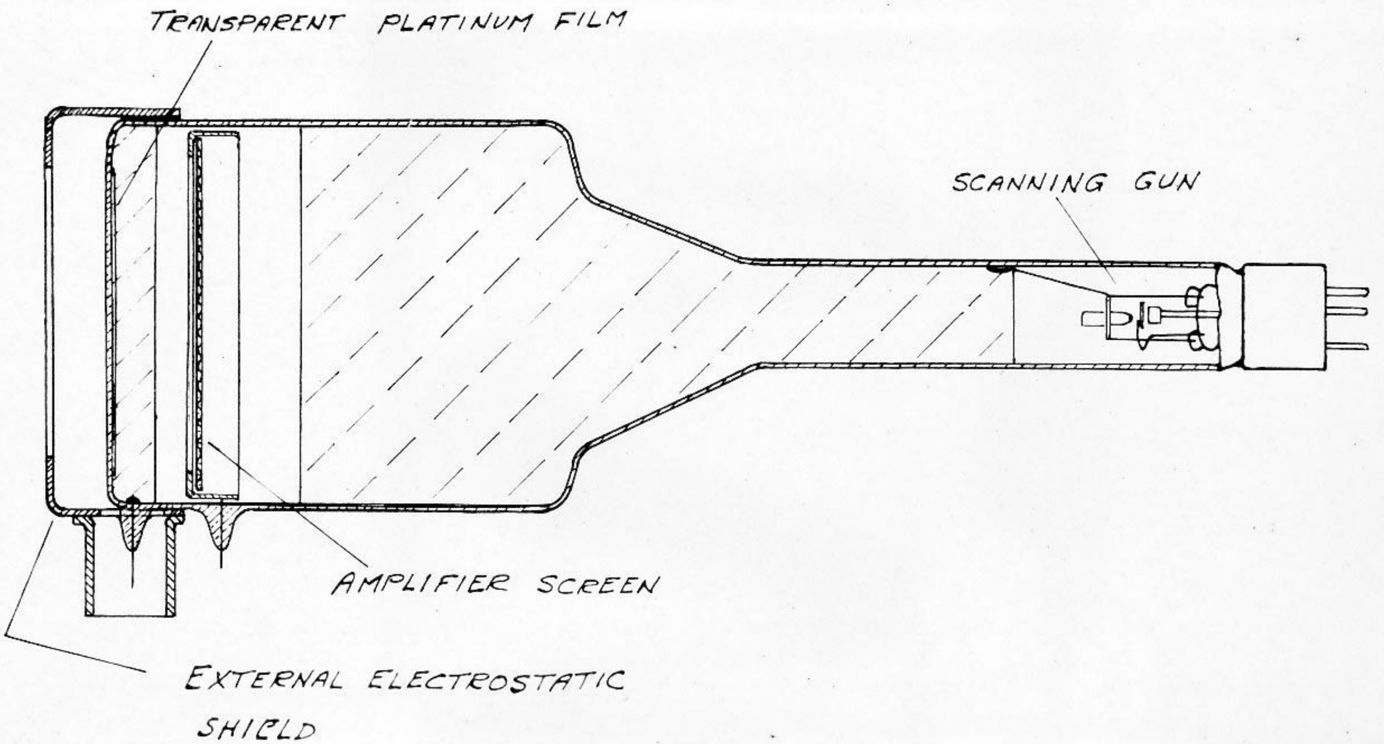
TRANSPARENT PLATINUM FILM
SCANNING GUN
AMPLIFIER SCREEN
EXTERNAL ELECTROSTATIC SHIELD

FIG. 8

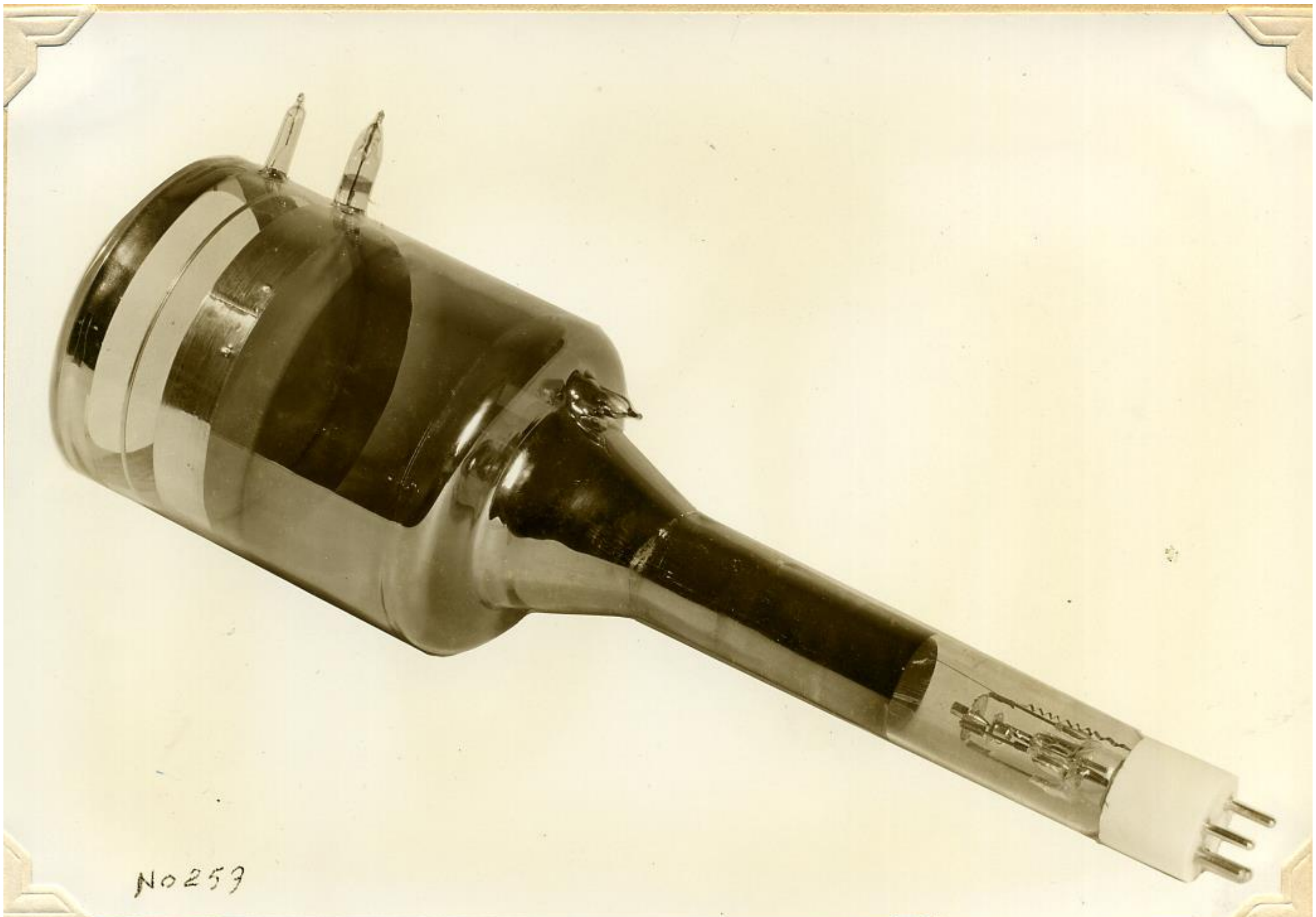

Figure 9

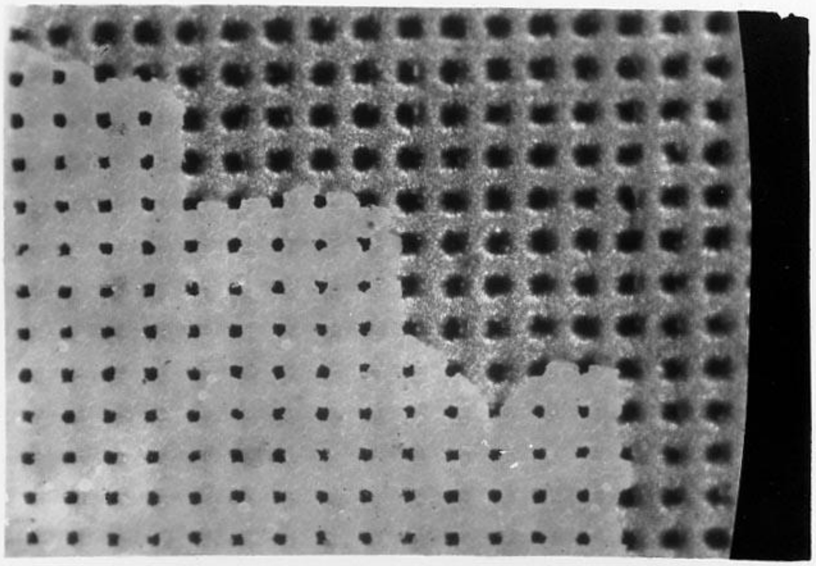

Figure 10

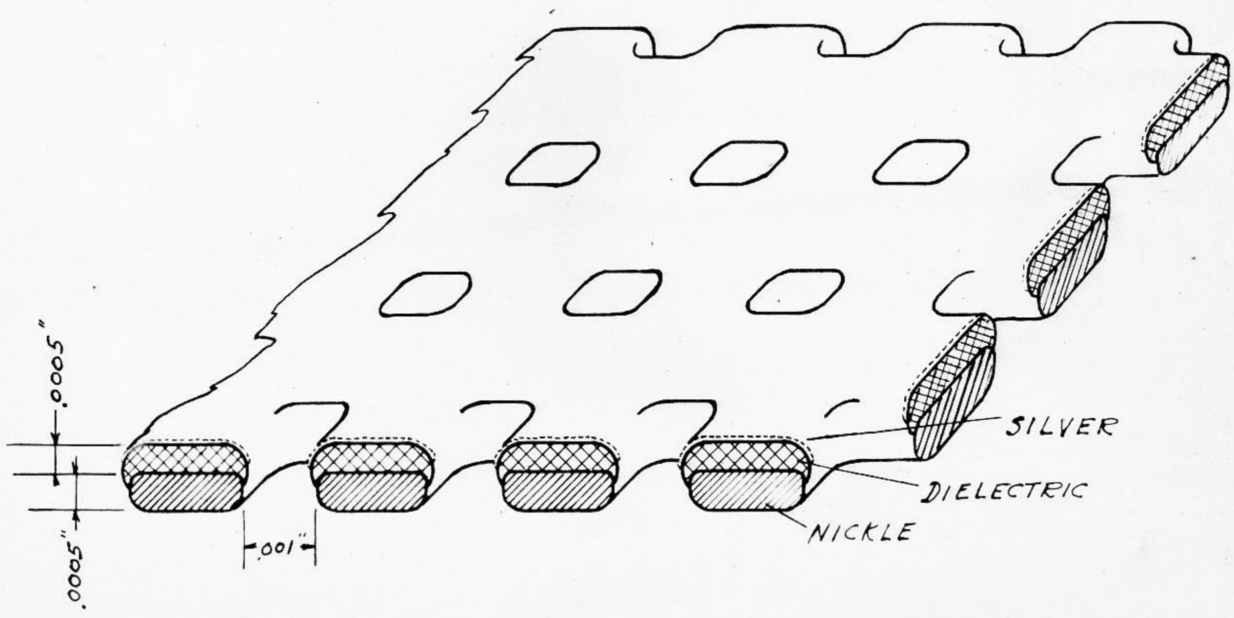

FIG. 11

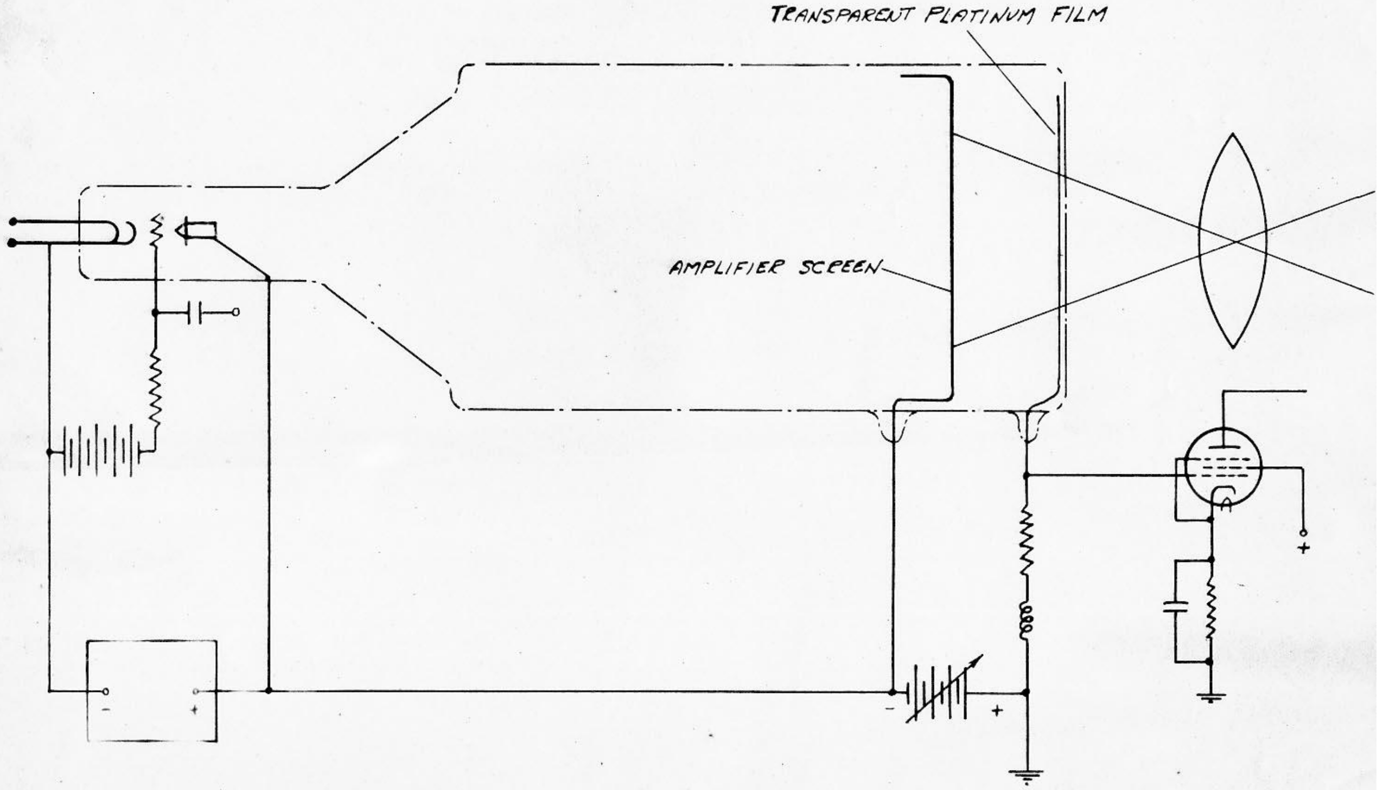

FIG. 12

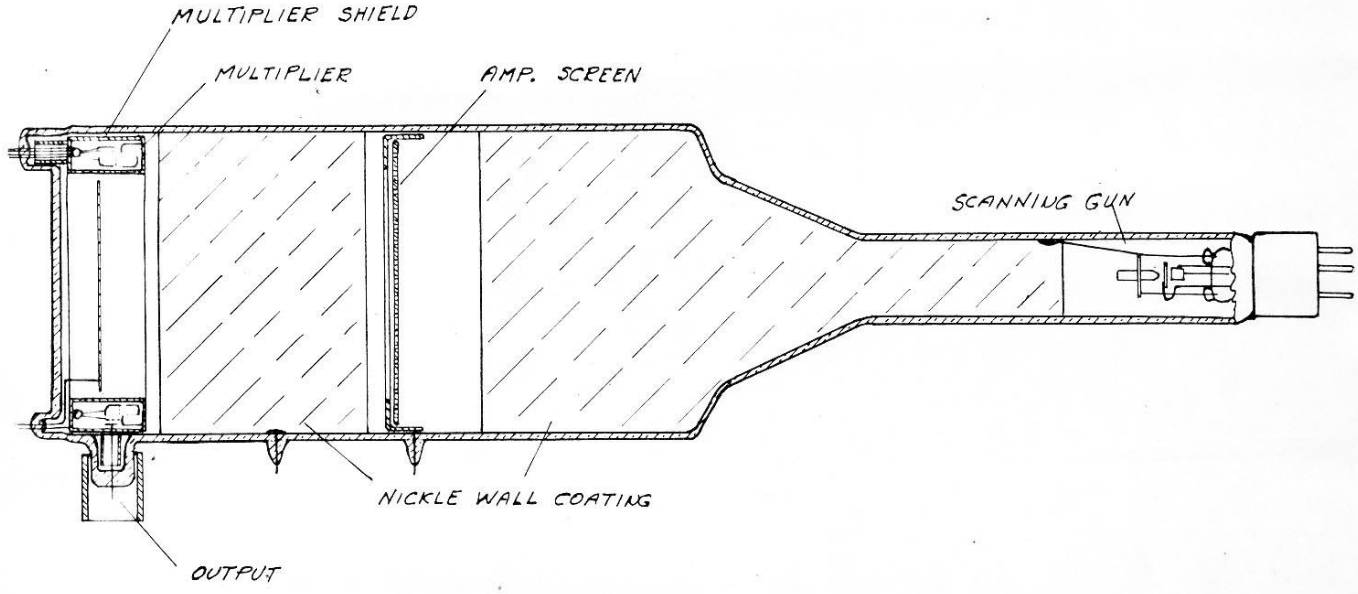
MULTIPLIER SHIELD
MULTIPLIER
AMP. SCREEN
SCANNING GUN
NICKLE WALL COATING
OUTPUT

FIG. 15

FOOTNOTES ON

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