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AN ELECTRONIC, HIGH-RESOLUTION, X-RAY IMAGING SYSTEM

J. W. Allen
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METALLURGY DIVISION

AN ELECTRONIC, HIGH-RESOLUTION, X-RAY IMAGING SYSTEM

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J. W. Allen and R. W. McClung

ABSTRACT

The need for an electronic-imaging system for high-resolution radiography is discussed with regard to economy and amenability to mechanized processes. An experimental system consisting of an x-ray sensitive Vidicon in a conventional closed-circuit television system is presented as a potential solution to the problem. The operational characteristics of the x-ray sensitive Vidicon, which employs selenium as the photoconductive sensing element, are discussed and data are presented which describes its contrast sensitivity and picture quality. The applicability of this system to practical inspection problems, including its amenability to continuous scanning techniques, is discussed. Recommendations for future improvements of this inspection method are made.

INTRODUCTION

Although the comparatively new nondestructive methods have enormously broadened the horizons of nondestructive testing, a large portion of inspection problems are still best solved by penetrating radiation tests such as film radiography. Also, since the different methods are based on entirely different phenomenological principles, they are inherently most sensitive to discontinuities of different types and orientations, and for many inspections it is very desirable to utilize two or more methods as complementary tests. Thus, penetrating radiation tests and, primarily, film radiography remain one of the most important methods of nondestructive testing.

The major objection to film radiography is its inherent slowness and high cost. Also, it is not at all amenable to automation techniques, and therefore, its application becomes impractical in many production inspection situations. In some applications, fluoroscopy, or televised fluoroscopy, has provided solutions to this dilemma. The resolution available in these methods is not sufficient, however, in many critical applications such as the inspection of nuclear reactor materials. Thus,

in these instances, penetrating radiation inspections are either accomplished by film radiography or not at all.

In recent years, several researchers[1,2,3,4] have experimented with the Vidicon[5] system using x-ray sensitive photoconductors as a means of directly producing televised images of x-ray shadowgraphs. During the past year, the authors have investigated the application of a conventional closed-circuit television system,[6] employing a selenium photoconductor Vidicon, to high-resolution radiographic inspection problems. The purpose of this paper is to present the results of this investigation, describe the potential capabilities of this system, and make recommendations for future development.

The operation of the x-ray sensitive Vidicon is almost identical to that of the conventional light-sensitive tube. The configuration of the Vidicon is shown in Fig. 1 (ORNL-LR-DWG 33248). As illustrated, the photoconductive target layer is scanned with a low-energy electron beam, and a positive potential is maintained on the tube-face side of the layer. Since the resistivity of the photoconductor in the absence of radiation (dark resistivity) is very high ($\sim 10^{15}$ μohm-cm for selenium), only a small portion of the electrons deposited on the photoconductor traverse the layer, and an electron charge builds up on the surface. Upon irradiation, the resistivity of the photoconductor decreases as a function of the radiation intensity, and the resultant electron leakage through the photoconductor leaves a charge replica of the radiation-intensity pattern. As the scanning beam attempts to replenish charge-deficient areas, the small voltage pulses formed across resistor R thus make up the video signals. (A more detailed description is given in Ref. 5.)

RESOLUTION

The resolving abilities of the Vidicon system are determined primarily by the photoconductor properties, the scanning geometry, and the band width

[1] John Jacobs and Harold Berger, "Larger-Area Photoconductive X-Ray Pickup-Tube Performance," Elec. Eng., 158–161 (February 1956).

[2] A. D. Cope and A. Rose, "X-Ray Noise Observation Using a Photoconductive Pickup Tube," J. Appl. Phys., 25(2), 240–242 (February 1954).

[3] L. Heijne, P. Schagen, and H. Bruning, "An Experimental Photoconductive Camera Tube for Television," Philips Tech. Rev., 16, 23–25 (July 1954).

[4] Final Report: Development of a Remote Electronic X-Ray Image Pickup System, Allen B. Du Mont Laboratories, Inc., Passiac, New Jersey.

[5] Paul K. Weimer, Stanley V. Forgue, and Robert R. Goodrich, "The Vidicon Photoconductive Camera Tube," Electronics, 70–73 (May 1950).

[6] This system consists of an RCA-Model ITV-6 television system and a Vidicon of the type 6198 configuration.

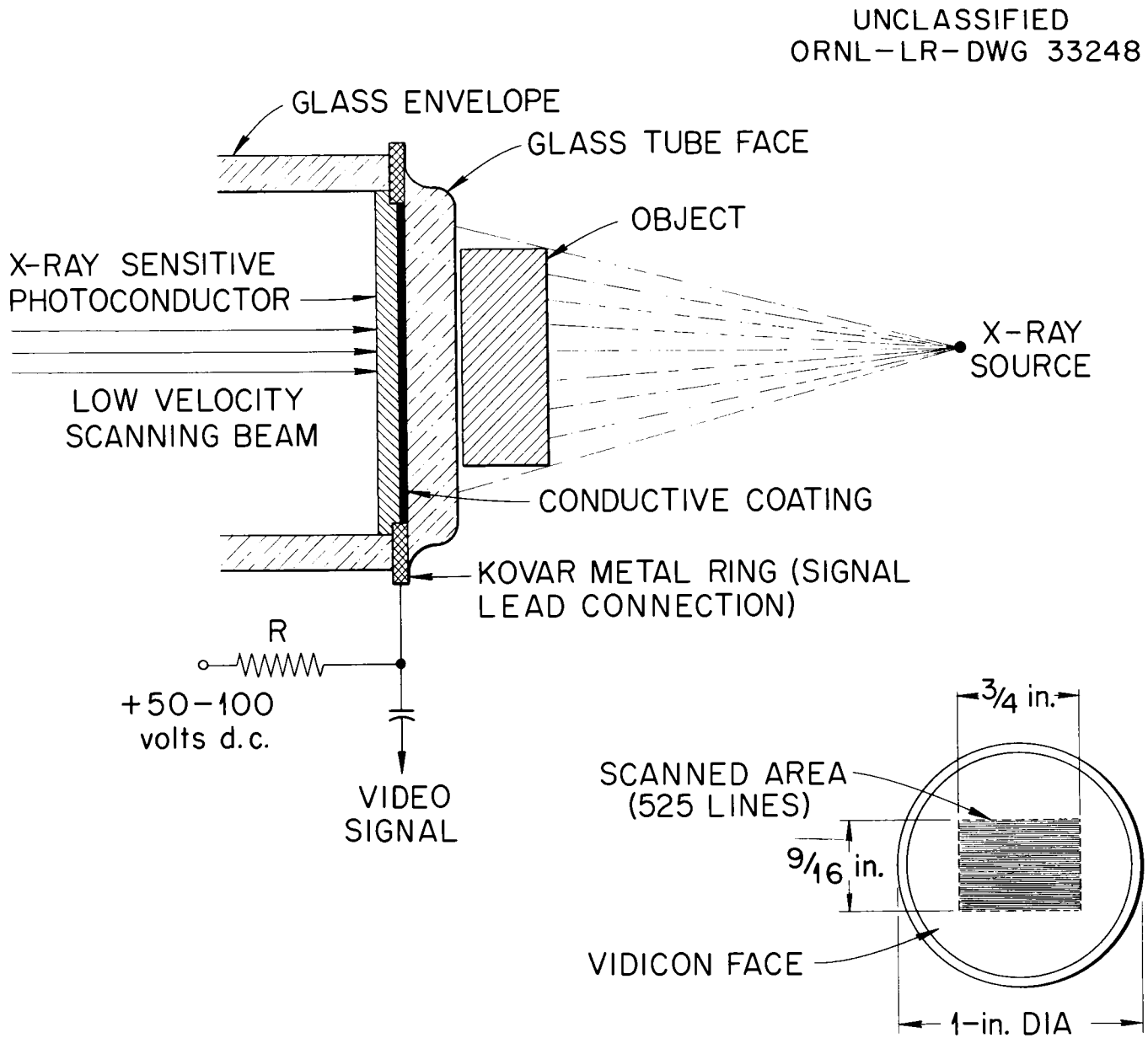

Fig. 1. X-Ray Sensitive Vidicon System.

of the video amplification system. Since the photoconductor layer is of finite thickness, scatter of incident radiation contributes to image unsharpness.[7] Charge leakage can occur in directions other than that of the primary current flow through the photoconductor, and this also contributes to image unsharpness. Thus, the thickness of the layer seems to be a reasonable approximation of the unsharpness. Using this approximation, the unsharpness of the ~ 0.001-in.-thick selenium photoconductor used in this investigation limits the resolution to ~ 0.001 in.

From the illustration of the scanned raster in Fig. 1, it is clear that the unsharpness due to scanning geometry in the vertical direction will be controlled by the distance between scan lines, and for the conventional 525-line television system,

$$U_{vert} = \frac{\text{Raster height}}{525}.$$

The unsharpness in the horizontal direction is determined by the scan rate and the band width of the video amplifying system. In the conventional 525-line, 30 frame/sec system, the active sweep time for one line is ~ 50 μsec, and if the video band width is 8 mc, any one horizontal line may contain 800 distinct picture elements.[8] The resultant horizontal unsharpness for the 3/4-in.-wide raster is therefore ~ 0.001 in.

Since the unsharpness, due to the selenium thickness, and both horizontal and vertical scanning are 0.001 in., the resultant receptor unsharpness may be calculated using Klasens'[9] unsharpness combination formula:

$$U_{receptor} = \sqrt[3]{0.001^3 + 0.001^3} \cong 0.0013 \text{ in.}$$

It should be noted that the unsharpness would not be substantially reduced by reducing the scanned area but it would be increased by increasing the scanned area. The 0.0013-in. receptor unsharpness is comparable to that of Class I radiographic film.

[7] Unsharpness is the measure in inches of the failure of an image to be perfectly sharp.

[8] Jacobs and Berger, Loc. Cit.

[9] H. A. Klasens, "Measurement and Calculations of Unsharpness Combinations in X-Ray Photography," Philips Research Repts., 1(4) 241–249 (August 1946).

The resolving ability of this system is illustrated in Figs. 2 (ORNL Photo 45355) and 3 (ORNL Photo 45350), which are photographs of the television screen for the radiographic parameters indicated. Figure 2 shows the image of a 120-mesh stainless steel screen[10] whose component wire size is 0.002 in. Note that the image indicates that the unsharpness is probably less than 0.002 in., which serves to verify the 0.0012-in. unsharpness approximation for the photoconductive receptor. (The geometrical unsharpness for this exposure was much less than 0.001 in. and therefore was not a contributing consideration.) Figure 3 depicts the image of a 2N175 transistor which is ~ 3/16-in. dia. This illustrates the inherent image magnification possible with such systems. The magnification at the screen in this instance was ~ 12X. Figure 4 (ORNL Photo 45354) is a close-up photograph of the image of the same transistor. The connecting wires shown in this photograph are ~ 0.003-in. dia and the geometric unsharpness is ~ 0.002 in.

RESPONSE

The x-ray response of the Vidicon in terms of signal output per unit input radiation intensity is primarily a function of the thickness of the photoconductor, the absorption characteristics of the photoconductor, the electrical potential on the photoconductor, the frame rate of the scanning beam (which controls the exposure time), and the radiation absorbed in the faceplate glass. Although a detailed discussion of these parameters is beyond the scope of this paper, a brief consideration of their effects is thought to be of value.

For high sensitivity, the photoconductive target should be thick, its absorption cross section high for the entire spectrum of useful x-ray energies, the operating potential high, its cover glass extremely thin, and the frame rate very slow. Obviously, there must be compromises. The thickness must be limited because of resolution considerations, as discussed previously. Also, as the thickness is increased, secondary electron

[10] Donald T. O'Conner, "Fluoroscopy and Electronic X-Ray Image Devices," Chapter 5.8, SNT Handbook of Nondestructive Testing: "The wire-mesh test is a reproducible, simple, and definitive test of resolution for imaging systems."

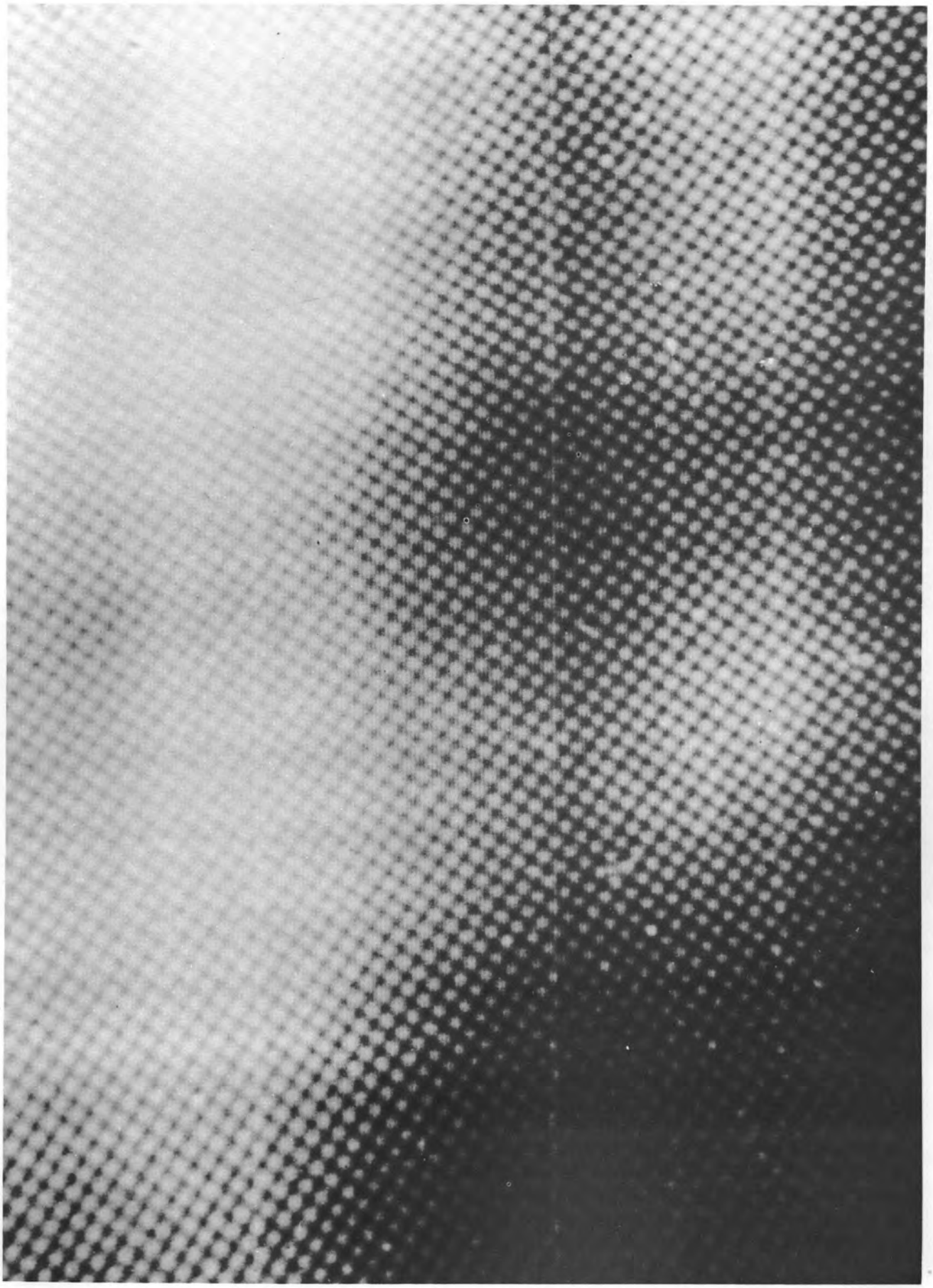

Fig. 2 (ORNL Photo 45355) Image of a 120-Mesh Stainless Steel Screen, 150 kv Constant Potential, 20 ma. Source to receptor distance equals 13 in.

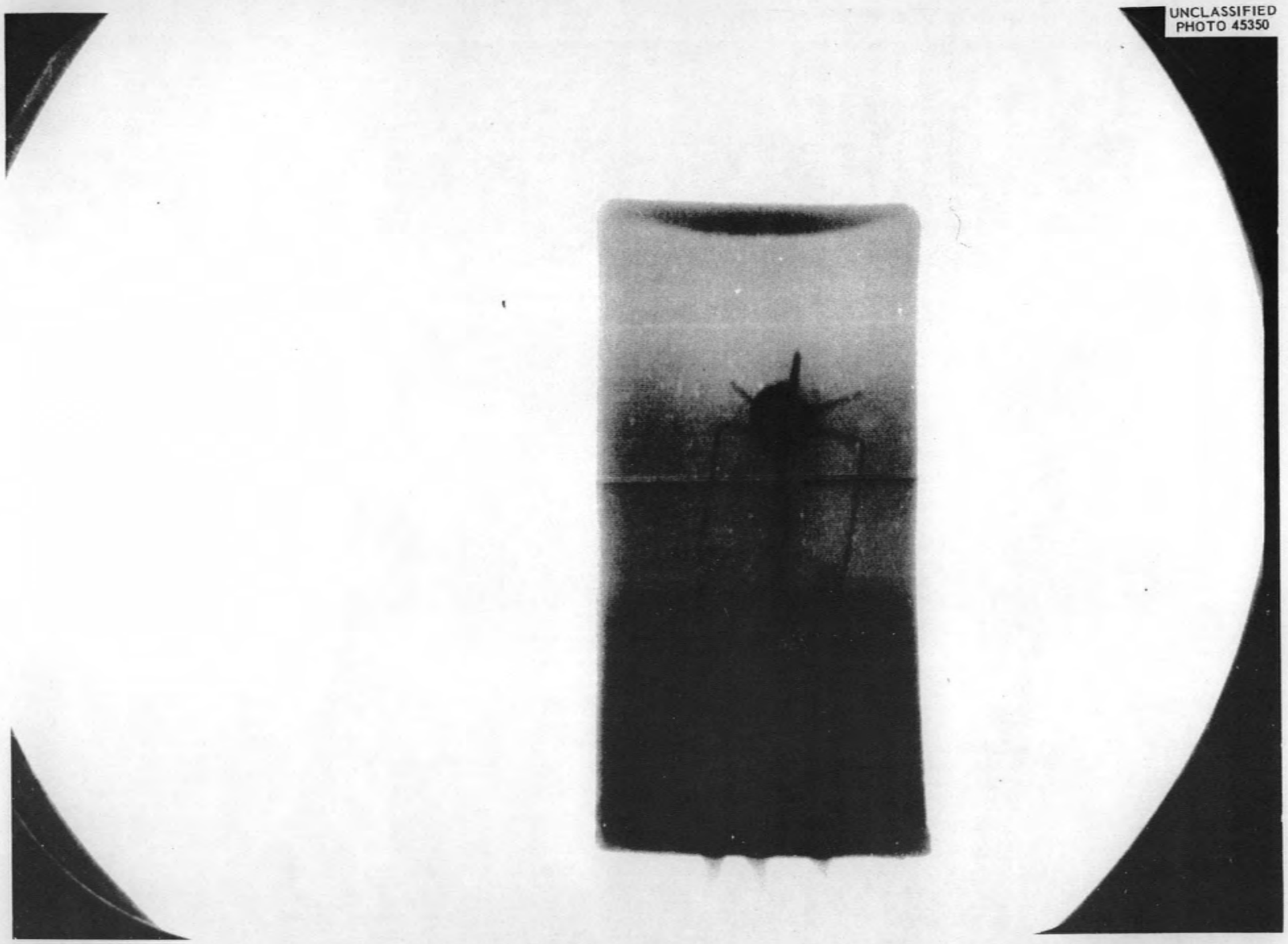

Fig. 3. Image of a 2N175 Transistor Which is ~ 3/16-in. Dia, 150 kv Constant Potential, 20 ma. Source to receptor distance equals 13 in.

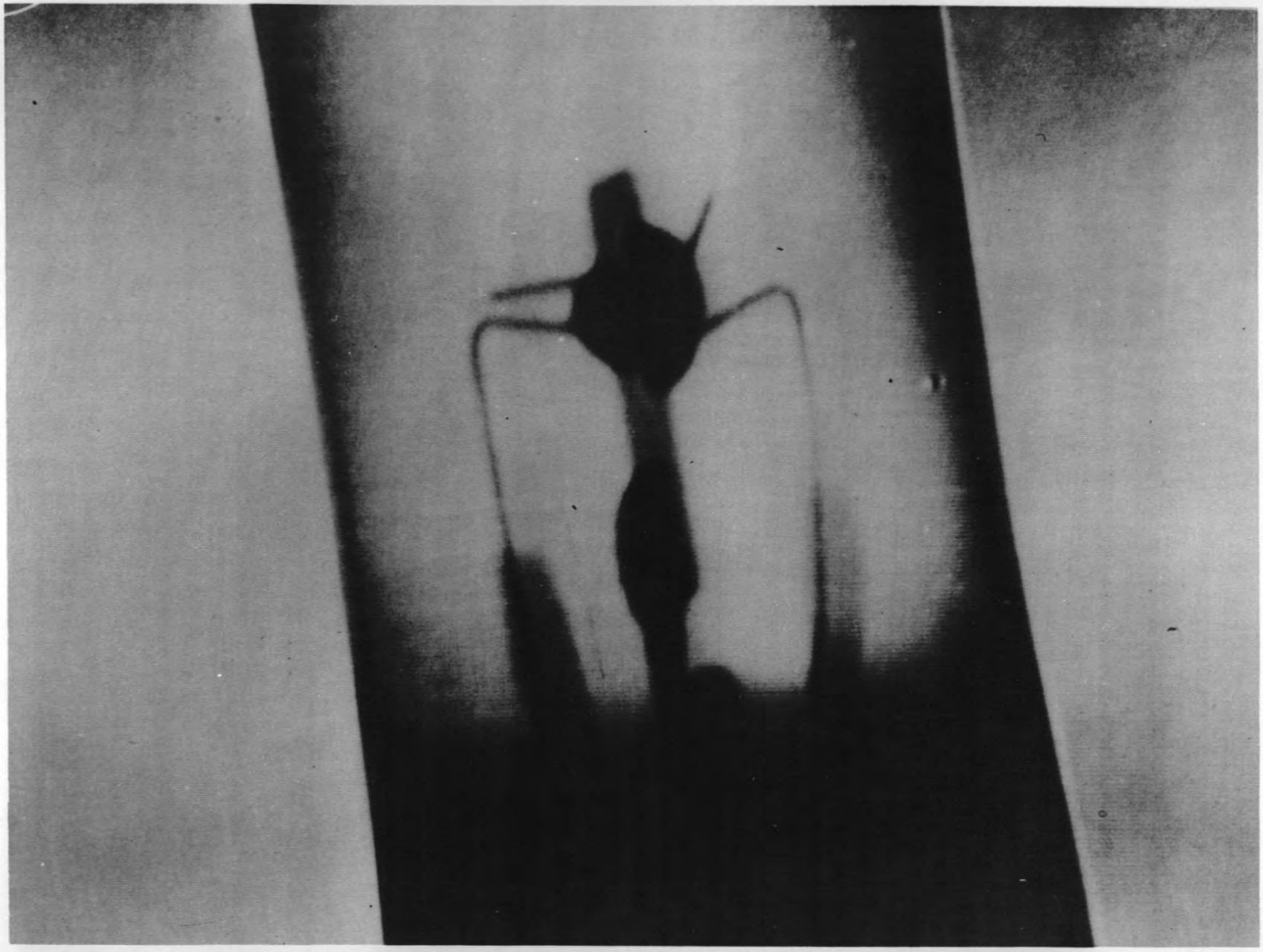

Fig. 4 (ORNL Photo 45454) Close-up Photograph of Image of Transistor, 150 kv Constant Potential, 20 ma. Source to receptor distance equals 13 in.

emission from the photoconductor[11] occurs at lower operating potentials. The emission of secondary electrons from the photoconductor produces a negative image which is much inferior in quality to the positive image. Since the sensitivity increases with operating potential on the photoconductor, an optimum thickness exists for a given material. For selenium this optimum appears to be about 0.001 in.

As previously described, the effect of radiation is to decrease the resistivity of the photoconductor (by increasing the number of conduction electrons) and thereby discharge the electrons deposited by the scanning beam. Thus, the photoconductor is electrically equivalent to an RC circuit[12] in which the resistance varies with the incident radiation intensity, and the discharge time constant accordingly varies from a few tenths of a second to a few microseconds, depending on the radiation intensity. In the many applications in which it would be desirable to use the Vidicon system, the fields are moderate in intensity, and the discharge time constant is rather long. Thus, the photoconductor does not completely discharge in the normal 1/30-sec interval between successive scans of the electron beam, and the sensitivity could be increased by decreasing the frame rate. The flickering which occurs at low frame rates could be largely eliminated if a storage tube presentation was used instead of the conventional CRT display.

In the Vidicon used in this investigation, the selenium target is ~ 0.001 in. thick, and the faceplate glass (Boro-silicate glass) is ~ 0.020 in. thick. Its sensitivity has been measured to be 78, 96, and 81 electrons per incident photon for constant potential x-ray machine energies of 100 kv, 200 kv, and 300 kv, respectively. Assuming 6% absorption in the faceplate and 15% absorption in the selenium at 100 kv[2], the sensitivity at 100 kv is ~ 550 electrons per absorbed photon.

The x-ray sensitivity of this selenium Vidicon is illustrated more completely in Fig. 5 (ORNL-LR-DWG 33474), which is a graph of the photoconductor current as a function of the incident radiation for three different x-ray voltages. The almost equal response of the Vidicon to 100, 200, and 300 kv is not surprising if it is considered that the

[11] Final Report: Development of a Remote Electronic X-Ray Image Pickup System, Allen B. Du Mont Laboratories, Inc., Passiac, New Jersey.

[12] An electrical circuit composed of resistance and capacitance is characterized by exponential discharge rates.

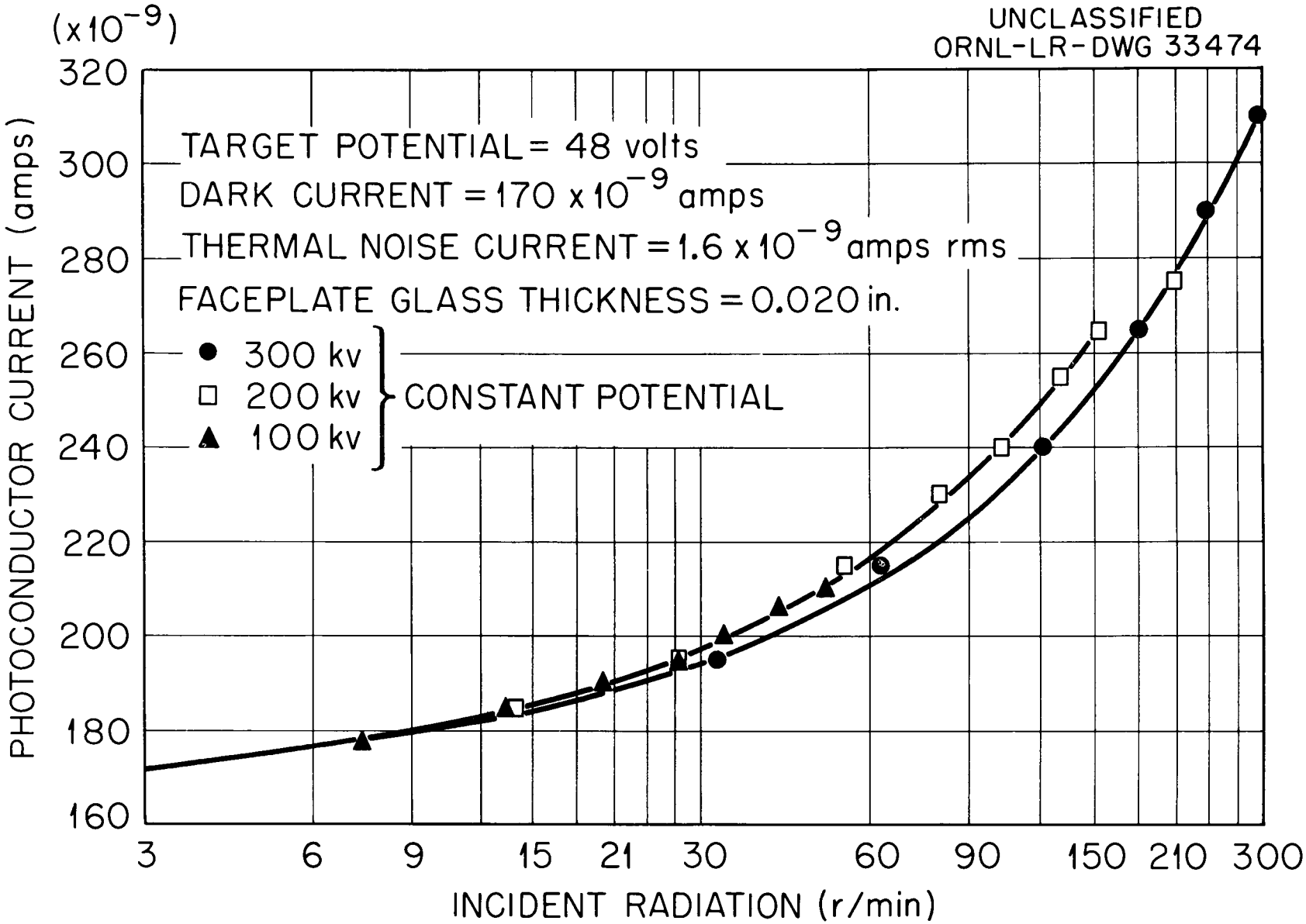

Fig. 5. Vidicon Photoconductor Current vs X-Radiation Intensity.

spectrum of energies in the unfiltered x-ray tube output is very wide and that the total beam intensity per x-ray tube milliampere increases rapidly with the tube voltage.

It is probable that greater sensitivity can be achieved using a higher density material such as lead monoxide for the photoconductor. Also, investigation[13] has shown that heavy-metal photoelectron emitters placed immediately in front of the photoconductor increase the sensitivity considerably.

RADIOGRAPHIC CONSIDERATIONS

The radiographic sensitivity of the selenium Vidicon system has been investigated using aluminum and stainless steel. Figure 6 (ORNL-LR-DWG 33476) is a graph of Vidicon current as a function of aluminum subject thickness for the parameters indicated. It has been established that the CRT screen brightness varies linearly with the Vidicon signal current over an adequately wide range. Therefore, any linear brightness scale can be substituted for the current ordinate on this graph by the appropriate adjustment of the television brightness and contrast controls.

It is generally agreed[14] that the minimum perceptible change in brightness in the range of 1- to 250-ft candles is 1.6% of the brightness. Thus, the minimum perceptible change in subject thickness from the Vidicon system assuming a gradient of one (or for fluoroscopy in this brightness range) should be:

$$(1) \quad \% S = \frac{1.6}{\mu x}$$

in which,

μ = linear absorption coefficient

x = thickness.

For radiographic film this relation becomes:[15]

[13] Final Report: Development of a Remote Electronic X-Ray Image Pickup System, Allen B. Du Mont Laboratories, Inc., Passiac, New Jersey.

[14] C. F. K. Mees, The Theory of Photographic Process, 803–805 (MacMillan Company, 1942).

[15] Donald T. O'Conner, "Fluoroscopy and Electronic X-Ray Image Devices," Chapter 5.8, SNT Handbook of Nondestructive Testing.

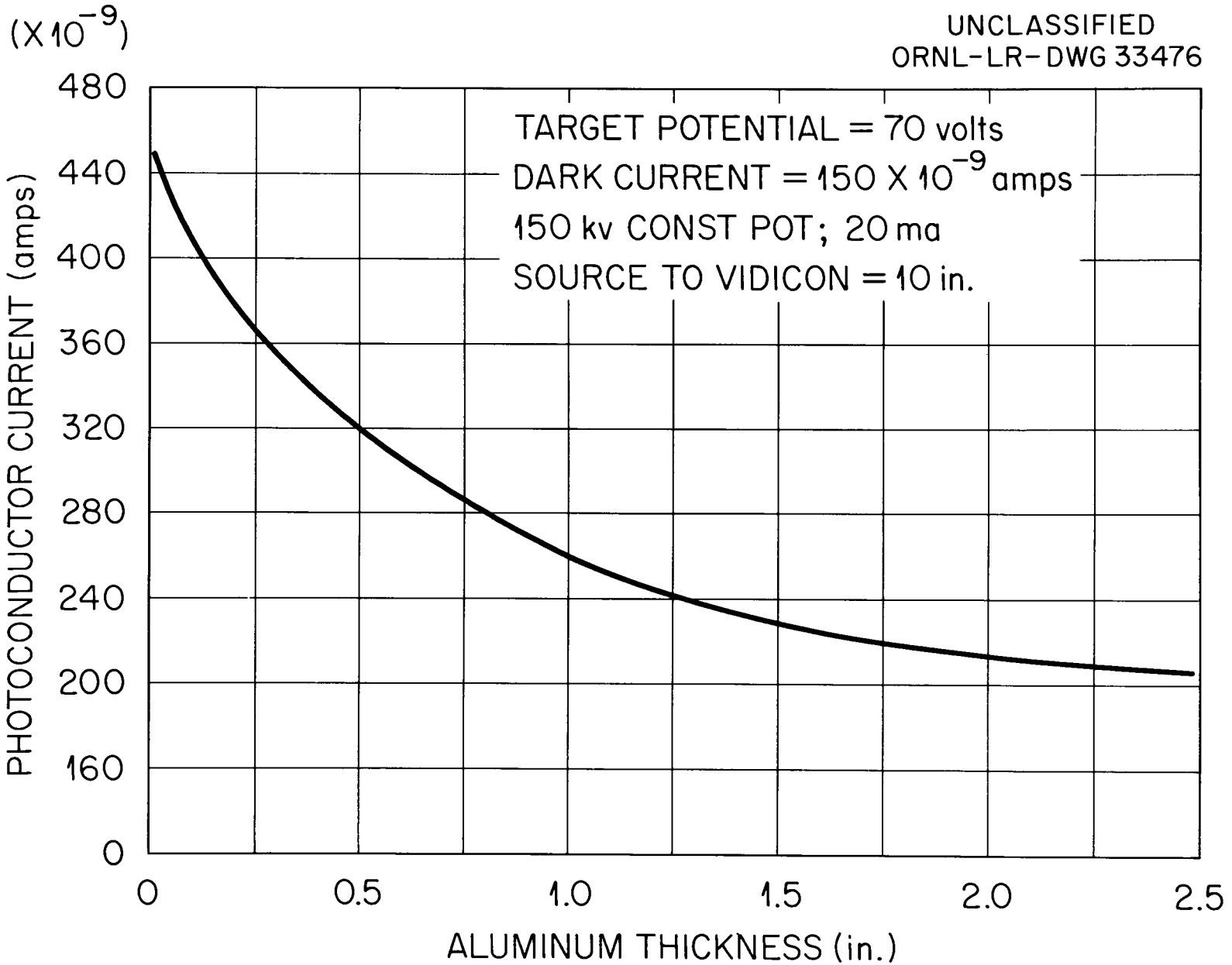

Fig. 6. Vidicon Photoconductor Current vs Aluminum Thickness.

(2) $\% S = \frac{1.6}{m\mu x}$

in which,

m = the film gradient.

In order to determine the applicability of this system to radiographic problems, the comparison of Fig. 7 (ORNL-LR-DWG 33475) was made between the contrast sensitivity available with Class I radiographic film and with this system. Shown in this illustration are constant density curves relating the contrast sensitivity to aluminum thickness for 150-kv constant potential x-rays. The indicated points on the graph are observed penetrameter sensitivities from the Vidicon system and are comparable to the film curves having greater sensitivity than that described by the curve for density equals 0.5 and less than that described by the curve for density equals 2. Since the penetrameters contained holes, the diameter of which were 1, 2, and 4 times the thickness, and all holes were visible in the image, the points on the graph represent detail sensitivity as well as contrast sensitivity. It is interesting to note that for Class I film density equals 0.5, the gradient is 1.0, such that equations (1) and (2) are identical. Since the observed sensitivities fall below the film density equals 0.5 curve in Fig. 7, it is clear that the system exhibits a gradient > 1. The factors controlling this gradient have not been explored sufficiently to allow conclusions or generalities.

Figure 8 (ORNL Photo 45351) is a photograph of the television screen showing an 0.009-in.-thick aluminum penetrameter and an 0.125-in.-thick aluminum plate. The photograph clearly reveals the 0.009-in., 0.018-in., and 0.036-in.-dia holes in the penetrameter. The penetrameter was placed between the plate and the Vidicon face to minimize the geometric unsharpness, since the system rather than the subject was being studied. The contrast of the direct image was enhanced slightly by the photographic process to compensate for reduction in quality caused by reproducing, projection, etc. By capitalizing upon the gradient of the photographic film, contrast sensitivities much greater than those indicated in Fig. 7 have been obtained.

From a cursory examination, it might be concluded that the small effective receptor area (9/16 in. x 3/4 in. as considered here) would seriously limit the applicability of this system to practical inspection

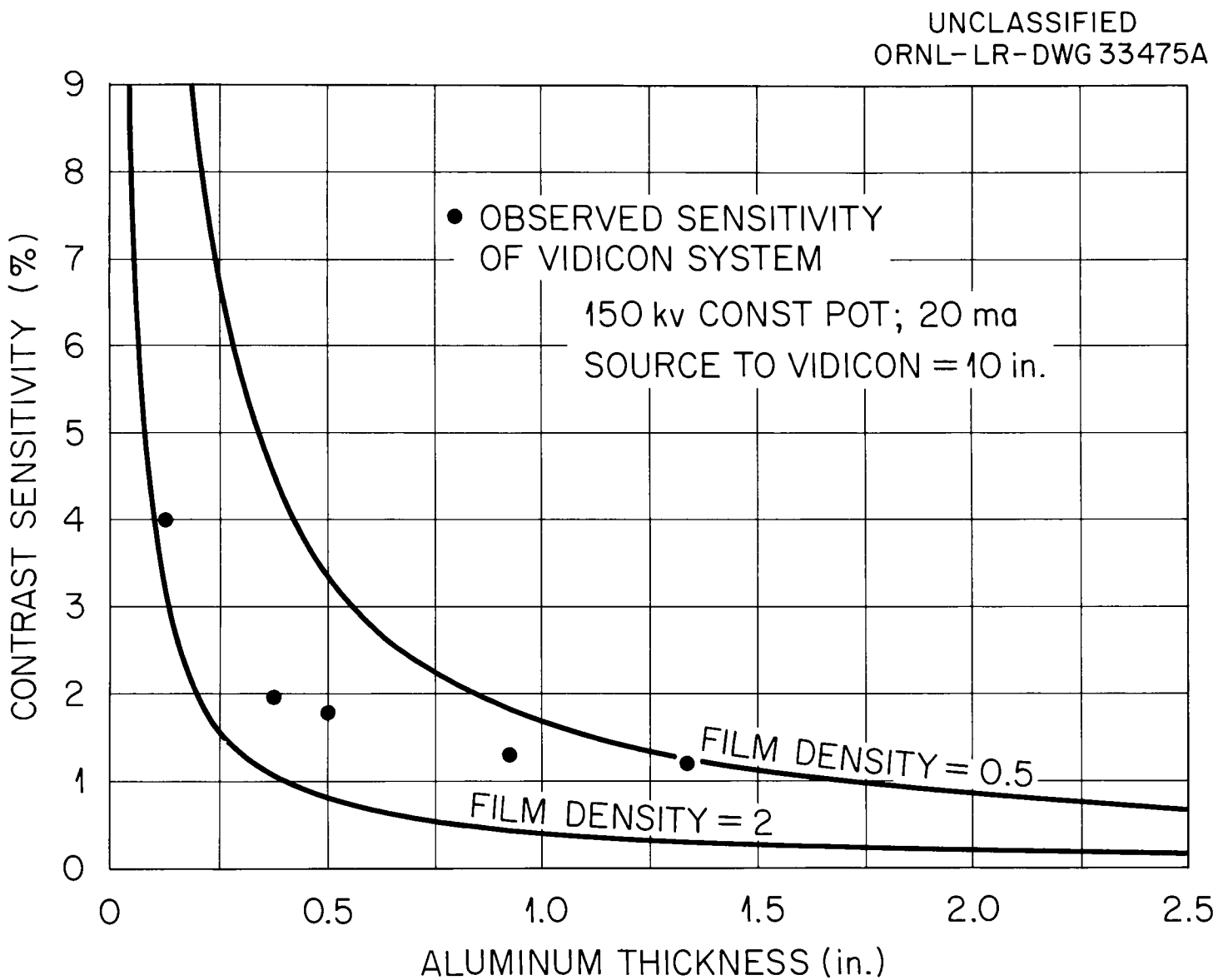

Fig. 7. Comparison of Contrast Sensitivity of Vidicon System, and Class I Film Radiography vs Aluminum Thickness.

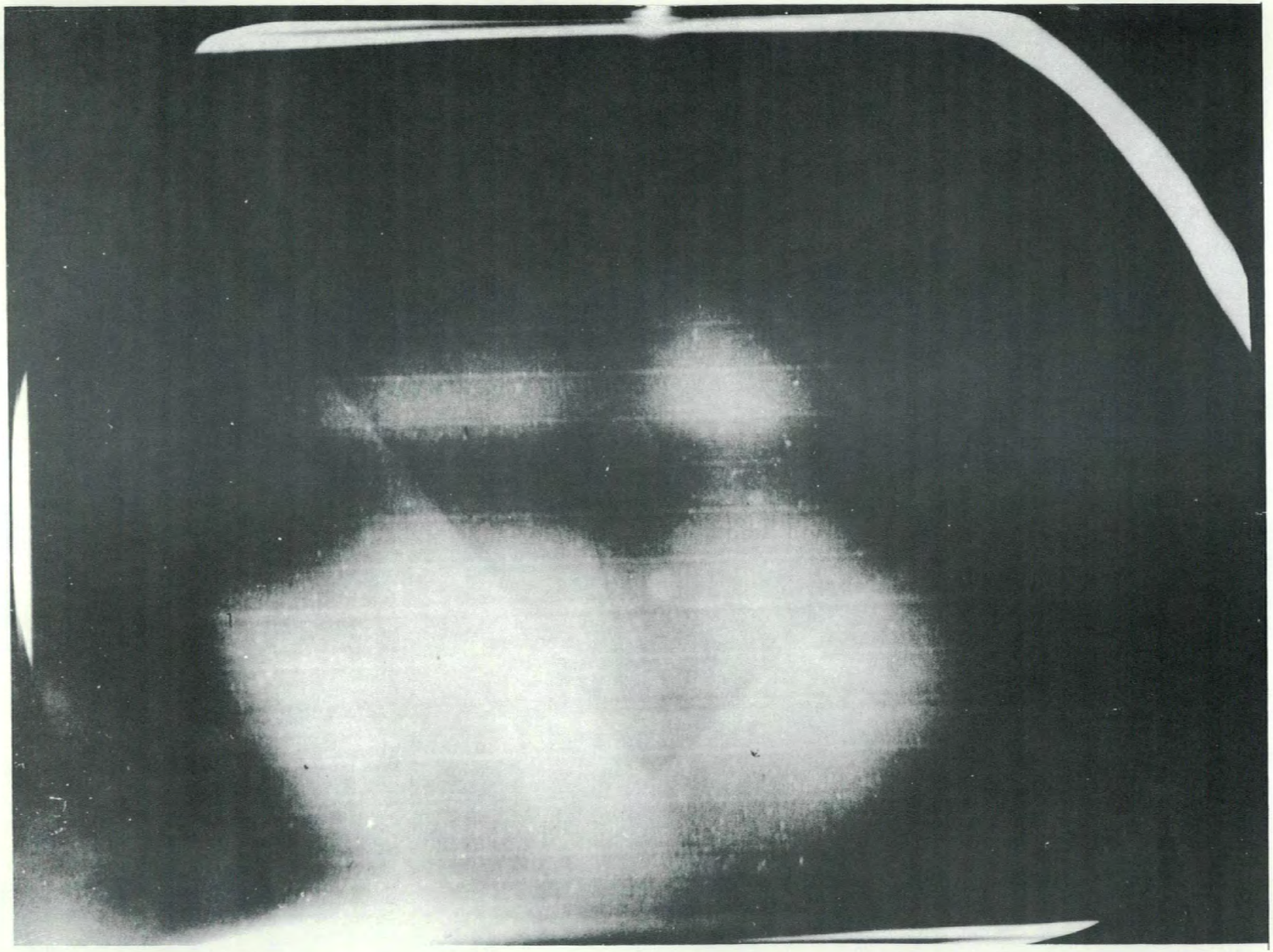

Fig. 8 (ORNL Photo 45351) Image of 0.009-in. Penetrameter on 1/8-in.-Thick Aluminum, 150 kv Constant Potential, 20 ma. Source to receptor distance equals 13 in.

situations. Consider, however, that the radiographic film reader cannot examine crucially an area much larger than this at any one instant. If it is also considered that this system is very amenable to the continuous scanning of the subject under test, the small receptor area presents no significant handicap. Thus, the application area of this type system becomes evident: it is readily amenable to the high-resolution inspection of small parts which can be mechanically scanned. The greatest saving of inspection time and cost would, of course, be affected in situations in which many parts of identical geometry were to be inspected.

PICTURE QUALITY

In the preceding sections, it has been shown that the resolving ability of this system is excellent and that the available sensitivity is adequate for many radiographic-inspection problems. An additional factor which must be considered is the clarity with which information is presented. This concerns the random noise which is brightness modulated on the CRT screen along with the picture information and the presence of anomalies in the photoconductor which produce bothersome picture images.

There are two primary sources of noise present in the x-ray sensitive Vidicon system: the noise due to the thermal agitation of electrons at the video amplifier input and x-ray photon noise. The thermal noise is dependent upon the temperature, the video amplifier input resistance (Vidicon signal plate output resistance), and the band width of the video amplifier. At normal temperature, with the normal input resistance for Vidicon of 5×10^4 ohms, and assuming a band width of 8 mc, the thermal-noise current at the amplifier input is $\sim 1.6 \times 10^{-9}$ amp rms. This noise current will be constant and independent of the operational parameters of the system.

The x-ray photon noise has been investigated by Cope and Rose[16] and the noise current found to vary according to

$$(I_n^2)_{av} = 2eGI$$

[16] A. D. Cope and A. Rose, "X-Ray Noise Observation Using a Photoconductive Pickup Tube," J. Appl. Phys., 25(2), 240–242 (February 1954).

in which,

$(I_n^2)_{av}$ = mean squared noise current per unit band width

e = electron charge in coulombs

G = number of electron carriers produced per absorbed x-ray photon

I = net signal current produced by the absorbed radiation.

It can easily be shown that in most practical instances, the photon noise will be predominant over the thermal noise. For example, consider a net Vidicon current of 20×10^{-9} amp produced by a 100-kv x-ray beam. Using the previously determined figure of 550 electrons per absorbed photon, the rms-noise current is 4.6×10^{-9} amp. Thus, in this instance, the photon-noise current is approximately three times greater than the thermal-noise current. The number of electrons per photon increases rapidly with the x-ray energy, and therefore, the photon noise increases with the x-ray energy. The rms-photon noise current varies with the square root of the signal current, and the signal current varies in approximate linearity with the x-ray intensity. Therefore, the best signal-to-noise ratio is obtained with the greatest possible beam intensity and lowest x-ray energy compatible with radiographic considerations.

It would appear according to the relative size of the noise current as compared to the net Vidicon current that this would be the limiting factor which would make it impossible to obtain adequate contrast sensitivities. Were it not for the fact that the noise signals are random in nature, as compared to the ordered image signals, the x-ray sensitive Vidicon system would be impractical. However, since they are random, they merely act to reduce the maximum observable contrast sensitivity and, to a lesser degree, the resolution. The demonstrated attainments of resolution and contrast sensitivity suffice to illustrate the feasibility of this system for many high-resolution applications in spite of the noise levels.

One of the primary disadvantages of selenium as a photoconductor material is the presence of anomalies in the layer. The photoconductor is placed on the glass signal plate in an amorphous state by sublimation. Small areas of the layer transform to the crystalline state as the tube ages. This process has been observed to be accelerated by high ambient temperatures and high operating potentials. The transformed areas have a much lower resistivity than the amorphous surrounding and produce bright spots on the viewing screen. This effect is shown in Fig. 9 (ORNL Photo 45352), which is a photograph of the television screen showing the image

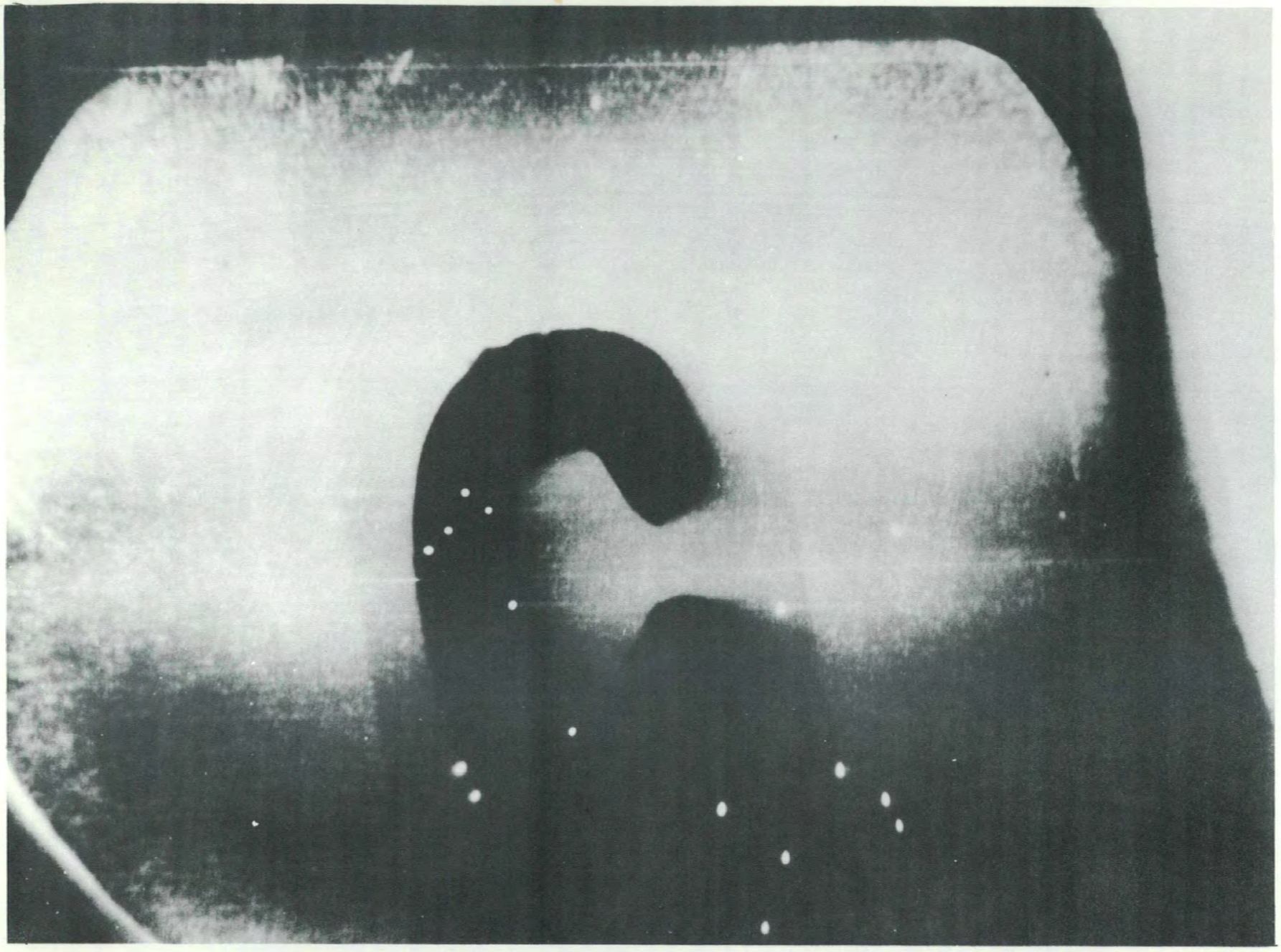

Fig. 9 (ORNL Photo 45352) Image Formed on a Vidicon Containing Transformed Areas in the Photoconductor.

of an old tube which has transformed badly. A small lead number was used for reference, and the vertical gray band was produced by its plastic backing. The bright spots and other markings are in evidence and clearly detract from the radiographic usefulness of this tube.

CONCLUSIONS AND RECOMMENDATIONS

The small-area photoconductor Vidicon system for x-ray viewing has resolving power not equaled by any other known system except Class I film radiography. The contrast sensitivity available with the selenium photoconductor Vidicon system is adequate for many applications, although its usefulness is limited to high-intensity fields (in the range of 50 r/min and greater at the photoconductor). The instability of the selenium photoconductor and its low x-ray absorption, at the higher x-ray energies, indicate a need for further research and development on this type system.

The following recommendations are made toward producing a superior system:

1. The use of materials exhibiting higher x-ray absorption should be explored. (Some other materials including lead monoxide[17,18] have already been explored.)

2. Efforts should be made to obviate secondary electron emission from the photoconductor, which would allow higher operating potentials.

3. The use of heavy-metal photoelectron emitter plates[17] in front proximity to the photoconductor for increased sensitivity at higher x-ray energies should be further investigated.

4. The use of low-absorption faceplates to replace glass plates for low x-ray energy work should be explored.

5. Development efforts should be undertaken which would allow longer exposure time to improve the sensitivity at low field intensities. As mentioned previously, a possible approach to this problem would be the use of image storage methods which would obviate flickering of the image and allow variable exposure time.

[17] John Jacobs and Harold Berger, "Larger-Area Photoconductive X-Ray Pickup-Tube Performance," Elec. Eng., 158–161 (February 1956).

[18] Final Report: Development of a Remote Electronic X-Ray Image Pickup System, Allen B. Du Mont Laboratories, Inc., Passiac, New Jersey.

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