

AN ABSTRACT OF THE THESIS OF

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From the time when fluoroscopic screens were first used there have been scattered references to reduction in their light output due to age, use, etc. References are scarce and usually devoid of quantitative data. A long-range program has been set up in an effort to arrive at some meaningful information.

A group of 24 fluoroscopic screens were used in this study, 12 each from two manufacturers. All screens were of the zinc-cadmium sulfide phosphor type mounted on plastic backing material. The screens were divided into test groups and subjected to exposure of X-ray, sunlight, incandescent lamps and fluorescent lamps. Test conditions were so designed that they could be related to some realistic exposure to which the screen in a diagnostic unit might be subjected.

To determine their relative condition, measurements of the

light output of all the screens were taken on a monthly basis. These measurements were made under controlled conditions utilizing a specially-constructed special X-ray unit and a direct-reading light meter employing a photomultiplier tube as the detector. By use of a direct-reading instrument calibrated in foot-lamberts, measurements were made independently of the sensitivity of the observer's eye and required no time-consuming matching of brightness. Calibration of the light meter was maintained by use of a regulated brightness source.

Where possible, old fluoroscopic screens were tested to compare their light output efficiency with that of a new screen.

A Study of the Deterioration of X-ray
Fluoroscopic Screens

by

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A STUDY OF THE DETERIORATION OF X-RAY FLUOROSCOPIC SCREENS

I. INTRODUCTION

Purpose of Study

The human eye is sensitive to a very limited range of the electromagnetic spectrum. Radiant energy that does not directly affect the eye can often be converted to the visible range through the process of luminescence. A luminescent material is one that will absorb energy and subsequently re-emit this energy completely or partially as visible light. Luminescence is particularly significant to the field of X-ray in that the fluorescence of a barium platino-cyanide screen in the vicinity of a covered gas discharge tube was directly responsible for Roentgen's discovery of X-rays.

The barium platinocyanide screen used by Roentgen would be considered very unsatisfactory by present-day standards. This type of fluorescent screen was prepared by evaporation from an aqueous solution. The finely powdered material was suspended in water, the mixture was then poured evenly upon the supporting plate and the water was allowed to evaporate. Water of hydration is contained in the crystal structure when prepared in this manner. This water functions as a foreign molecule in the crystal matrix and is responsible for the observed luminescence. Barium platinocyanide screens

were very expensive and subject to loss of the loosely-bound water of hydration when exposed to dry atmosphere, heat or radiation. Upon removal of this water, the barium platinocyanide loses its fluorescent capabilities.

The development of modern fluoroscopic screens took a number of years. This development (see section II) has led to the almost universal use of zinc sulfide and cadmium sulfide phosphors for fluoroscopic screens. Screens produced from this type of phosphor are much superior to those of early times. Their luminescence spectrum closely matches that of the human eye. They show very little lag or afterglow and are not subject to early deterioration as were the barium platinocyanide screens.

It has been reported that the luminescent efficiency of a modern fluoroscopic screen will also decrease with age and use. Factors such as exposure to high radiation levels, or extended exposure to fluorescent light and sunlight may accelerate this reported aging process. As the luminescent efficiency is decreased, the radiologist would have to operate the X-ray machine at higher output levels in order to obtain the same image brightness level on the fluoroscopic screen. This operation at higher output levels in turn leads to higher exposure rates to both the radiological personnel and the patient.

This study will attempt to establish and quantitate some of the

factors that may contribute to the deterioration of X-ray fluoroscopic screens. With this information, it may be possible to make some recommendations for the correct use of the screens so that deterioration will be kept to a minimum. This information would also provide some basis on which reasonable guides for the acceptability or non-acceptability of X-ray fluoroscopic screens might be established, based upon the age of a screen or the amount and type of use it has had.

Fluorescent Deterioration Reported

There has been very little quantitative information concerning the permanent deterioration of the luminescent capabilities of fluorescent screens. While working with calcium tungstate, CaWO_4 , intensifying screens Coltman, Ebbighausen and Alter (1947) observed that the portion of the screen that had been exposed to X-rays was somewhat fainter. They classified this deterioration of luminescence as screen "fatigue." In their experimentation the screen had been exposed to 80 kilovolt X-rays filtered by one-half millimeter of copper and one millimeter of aluminum and the X-ray tube was operated at 20 milliamperes. The screen was mounted over a two-inch square hole in a sheet of 1/8-inch lead. This lead shield and screen were mounted over the open end of an X-ray protective cone of unspecified dimensions. The screen was exposed for a period of

about six and one-half hours under the above mentioned conditions.

The reported measurements indicated that the exposed portion of the screen was about eight percent fainter than the outer portion that had been protected from the high exposure levels by the 1/8-inch lead shield. This observation indicates that a deterioration of calcium tungstate may be expected from extended exposure to X-rays of a typical diagnostic energy. The luminescent process in the inorganic calcium tungstate crystal is similar to that observed in zinc-cadmium sulfide-type phosphors, so a similar effect might take place for this phosphor.

Some information has been reported concerning the deterioration of zinc sulfide and cadmium sulfide phosphors exposed to various types of radiation. Curie (1963) states that daylight will produce a blackening of zinc sulfide and more so of cadmium sulfide. He attributes this darkening to the production of free metal atoms. The mechanism is a photochemical process which breaks the atomic bond holding the atom in the crystal lattice; the metal becomes colloidal and the damage is irreversible.

A more complete study of the blackening of zinc and cadmium sulfide phosphors when exposed to visible light has been reported by Gordon, Seitz and Quinlin (1939). From their work and others they drew the following conclusions concerning photoluminescent zinc sulfide:

- A. Only sulfides that are photoluminescent will darken appreciably under the influence of ultraviolet radiation. In the preparation of these crystals, they were first precipitated from an aqueous solution and then heat treated. The heat treatment, consisting of one hour in a 950°C oven, was necessary to render the phosphor luminescent. The effect of this heat treatment was the introduction of neutral zinc or cadmium atoms into the crystal lattice. These interstitial atoms, which are not part of the regular crystal lattice, create luminescent centres. Only after the heat treatment had caused the introduction of these interstitial atoms was ultraviolet radiation capable of producing any appreciable darkening of the phosphor.
- B. They were able to further correlate the darkening of the phosphor with the presence of the luminescent centres by subjecting the crystals to high pressures. Under normal conditions the interstitial atoms were thought to be in thermodynamic equilibrium with their surroundings; the pressure would cause a condition of unbalance allowing the interstitial atoms to precipitate out. When this occurred, the phosphor lost its capability to fluoresce and no further appreciable darkening occurred.

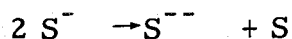
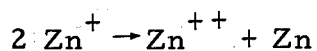
C. Moisture was found to accelerate the darkening process by a factor of a thousand or more over that experienced in a dry environment. Zinc-cadmium sulfide contained in an evacuated quart container was exposed to a mercury vapor lamp for a period of 2,000 hours. No appreciable darkening was observed during this period. A similar sample, exposed to the same light source but in a super-saturated atmosphere, became very dark in less than one-half hour.

In the process of photoluminescence, an electron is first raised to the conduction band by the absorption of energy from the incident light photons. This freed electron will either recombine with a luminescent centre producing fluorescent light, or will become trapped. In a vacuum the trapped electron in time, can gain sufficient thermal energy and escape the trap. In the presence of moisture, the negative charge of the trap would attract a positive ion and render the trap stable. The positive ions are postulated to be zinc ions of dissolved zinc sulfide in the situation where pure water is present. The concentration of ions would be much greater if a good electrolyte were present and, in fact, Gordon, Seitz and Quinlin (1939) found that exposure of the phosphor while in a sodium chloride solution would cause the darkening to proceed at a faster rate than that observed for pure water.

In phosphor excitation, an electron is raised to the conduction

band leaving a free positive hole in the valence band. This hole will migrate in the crystal and, upon reaching the surface, will act like singly-charged sulfur atoms attracting negatively-charged ions from the solution. According to this description, the interior of the zinc-sulfide crystal should be left unaltered in the final state since the centres are not depleted during blackening but act as catalysts. This is borne out by the fact that centre concentration can be of the order of 10^{-4} or less, than the concentration of the ordinary atoms in the crystals, but decomposition of greater than ten percent of the atoms can be obtained.

The creation of free zinc and sulfur may be looked upon as the electrolysis of zinc sulfide by the electromotive force created by the ionic crystal structure. Gordon, Seitz and Quinlin (1939) have postulated that the following process may be plausible:



Under the correct conditions, the above process is reversible ($\text{Zn} + \text{S} \rightarrow \text{ZnS}$). They found that a slightly darkened sample of zinc sulfide reverted to its original state if left in the dark. This reversal also required a moist condition and was accelerated by the presence of an electrolyte.

The decomposition products have been analyzed and consist mainly of free zinc and sulfur with traces of H_2S , SO_2 and

hydrosulfuric acids. The compounds can be explained by the presence of water. Some of these products, for example the free zinc and sulfur, may revert back to their original state as a ZnS crystal, but this may not always be a 100 percent reversal. Other products formed, such as H_2S and SO_2 , may not be capable of ever reverting to their original state.

In summary, Gordon, Seitz and Quinlin (1939) have shown that under the influence of light, moisture and pressure zinc and cadmium sulfide crystals will darken. If the process is not 100 percent reversible, which is usually the case, the overall effect would be a permanent darkening of the luminescent material. Even for the 100 percent reversible process, there is no assurance that the material would be returned to its original crystal lattice state, in which case the luminous efficiency might be expected to change.

The luminescent process can be subdivided according to the excitation process. Photoluminescence occurs when the material, usually of crystalline structure, is excited by the absorption of light. It may be assumed that each quantum of light excites one electron. According to quantum theory, the quantum $h\nu$ must be exactly identical with the energy difference ΔE between the ground state and the particular excited state. The frequency of the emitted luminescent radiation is dependent upon the energy difference between the ground and excited state and is uniquely determined for a particular

material.

For excitation by ionizing radiation, X-rays, gamma rays, electrons, etc., the situation is somewhat more complicated. Cathodeluminescence deals with luminescent excitation by cathode rays, electrons such as used in cathode-ray tubes, etc. X-ray excitation will first involve a photoelectric, Compton or pair production reaction producing charged particles that will act like the cathode rays. Each particle penetrates into the solid losing energy in collisions with the electrons of the crystal and thus causing the excitation of a number of secondary electrons. The nature of the luminescence is the same for both types of excitation, the energy of the luminescent radiation being determined solely by the energy states of the material.

Very little has been reported concerning the possible deterioration of zinc sulfide type phosphors under the influence of X-ray exposure. In X-ray excitation, although the primary radiation consists of photons, the excitation is due to the fast secondary electrons. X-ray excited luminescence approaches more nearly cathodeluminescence than it does photoluminescence. A consideration of the results obtained from the studies involving cathode luminescence should give some insight into the possible effects due to X-rays.

Due to its vast utilization in the electronic image tube in recent years, cathodeluminescence has been studied by a number of

investigators. In cathodeluminescence, the ionizing particle, the electron, passing through the phosphor excites or ionizes the crystal atoms; this excitation is followed by the visible emission of fluorescence. Cathode ray excitation is accompanied by a strong perturbation of the entire crystal lattice; even electrons in the inner atomic shells may be excited by the incident particles. This process is much more complex than that taking place in photoexcitation where only the valence and conduction bands are considered.

The radiative transition process whereby the visible photons are released is usually independent of the mode of excitation, for example in cathodeluminescence, the same emission spectrum is obtained as in photoluminescence. Some difference will arise in the conversion efficiency, the value of efficiency being less for ionizing radiation than for photoexcitation by ultraviolet light. This variation between photoexcitation and cathode-excitation is greatest for particulate radiation of high specific ionization and of high excitation density.

Curie (1963) states that zinc and cadmium sulfide subjected to electron bombardment slowly blackens and the luminescent efficiency decreases. He states that this effect is, in part, due to the production of non-radiative recombination centres.

Smith, Potter and Aven (1960) noted the effect of humidity on the deterioration of electroluminescent panels. They postulated that

this effect is due at least in part to the rotation of the sulfide grains produced by the internal electric field of the dielectric and this in turn leads to a lowering of the luminescence efficiency.

For higher-energy ionizing radiation there is the possibility of producing lattice defects and interstitial atoms in the crystal matrix (Kulp and Kelley, 1960). This requires an energy of about 8.7 electron volts in cadmium sulfide corresponding to a minimum threshold energy of 115 thousand electron volts for the bombarding electrons. In zinc sulfide, the minimum value is probably about 15 electron volts. When the energy is greater than this minimum threshold value, new centres are created.

This effect is probably of little consequence for the normal fluoroscopic screen; these screens are predominantly zinc sulfide and, for the normal diagnostic range of 60 to 150 thousand electron volts, the minimum threshold energy is not exceeded. If screens with a substantial concentration of cadmium sulfide are used, it might be reasonable to expect some shift in the spectrum.

II. LUMINESCENCE AND THE FLUOROSCOPIC SCREEN

Historic Development of X-ray Fluorescent Screens

The first detailed study of fluorescence was made by Sir George Gabriel Stokes (1852a, b; 1853a, b). According to his obituary notice, carried in the proceedings of the Royal Society, Lord Rayleigh (1903) states that Stokes' work on what is now called fluorescence was the most far reaching of his experimental discoveries.

Various reports of the phenomenon now known as fluorescence can be found in the literature well before the investigations of Stokes (Harvey, 1944). In 1575 Nicolo Monardes reported that a solution prepared from the extract of a Spanish wood, a solution used as a treatment for kidney disease, appeared bluish when exposed to sunlight. The bluish hue of this yellow solution was also reported by Sir Isaac Newton, but neither understood the significance of their observation. In 1833 Sir David Brewster reported that an alcohol solution of chlorophyll prepared from green plant leaves showed a bright light of a blood red color when exposed to light contrasting with the green color of the solution (Stokes, 1852). Brewster's explanation was that an internal dispersion of some unknown substance was responsible for the observed red color.

Sir John Herschel discovered that a weak solution of quinine

sulfate, which appeared transparent and colorless when viewed by the transmitted light, exhibited a peculiar blue hue in a portion of the fluid when exposed to light (Stokes, 1852b). Herschel observed that when the fluid was illuminated by a beam of ordinary daylight, the blue hue was produced in only a very thin stratum of the solution adjacent to the incident light beam. His investigations showed that the blue light produced was unpolarized, and the transmitted beam was incapable of producing the effect in a second container of the quinine solution. A beam of light modified in such a manner was termed "epipolized" by Herschel. Brewster found some of Herschel's observations difficult to explain, in particular that the whole or a great portion of the dispersed beam was unpolarized, whereas a beam reflected from suspended particles might be expected to be polarized by reflection. From the general identity attending the two phenomena, Brewster was led to conclude that epipoly was merely a particular case of internal dispersion.

Stokes had been working with polarized light from various sources and became interested in the observations of Brewster and Herschel. Stokes found many of their explanations difficult to accept; in particular, what rays were capable of producing the blue hue in a quinine solution and why their capability was so quickly extinguished resulting in the production of only a thin stratum at the interface of the incident light beam and the solution. After considerable

experimentation, Stokes was able to show that the process is not due to internal dispersion of suspended particles, but is instead similar to phosphorescence. He suggested the term fluorescence be used to describe the phenomenon (1853a, p. 4).

In my former paper I suggested the term fluorescence, to denote the general appearance of a solution of sulfate of quinine and similar media. I have been encouraged to give this expression wider signification, and henceforth instead of true internal dispersion, I intend to use the term fluorescence which is a singular word not implying the adoption of any theory.

Stokes also worked with a number of other fluorescent materials. Of particular significance were the platinocyanides of calcium, barium and strontium which he reported to fluoresce in different shades of green (1853a).

Lenard, while working with gas discharge tubes, was the first to discover that it was possible to produce luminescence in fluorescent materials outside a Crooks' tube. Roentgen's discovery of X-rays was really an extension of Lenard's work. Roentgen discovered that, in fact, some visually undetectable type of radiation was produced in the discharge of a Hittorf or Crooks' tube. This invisible radiation was able to penetrate optically-opaque material and excite certain fluorescent materials.

The fluorescent screen that Roentgen used in making his discovery consisted of barium-platinocyanide crystals deposited on a cardboard backing. This type of fluorescent crystal had been

studied by Stokes and subsequently used by many experimenters of that time in their investigations of the gas discharge phenomenon. By present day standards, these barium platinocyanide screens would appear very poor. They were prepared by precipitation from an aqueous solution onto some backing material such as cardboard to give structural support. Screens prepared in this way contained loosely-bound water of hydration, which in turn was responsible for the crystals ability to fluoresce. These screens were very expensive and subject to deterioration. The water of hydration contained in the crystal was easily lost under the influence of heat and dry atmospheric conditions. As previously mentioned, the loss of this water would render the crystal nonfluorescent. Although having many drawbacks, barium platinocyanide screens were used exclusively for a number of years in fluoroscopic screens. Their yellow-green fluorescence closely matched the visual response of the eye.

The great interest generated by Roentgen's discovery of X-rays renewed the study of the fluorescent process and the search for new and better fluorescent crystals. One of the first to take up this study of fluorescence was Thomas A. Edison. From January to March of 1896 he investigated more than 8,000 different materials. His basic interest had been in trying to develop a new electric lamp. Edison found more than 1,800 different materials would fluoresce to some degree, but found calcium tungstate to be the best.

He found this material to be much superior to barium platinocyanide; it was relatively stable and had a light output about six times greater.

Edison's practical nature and creative mind led him to try and utilize his discoveries concerning fluorescent materials. He reported in Century Magazine (1896)

When the X-ray came up, I made the first fluoroscopic using tungstate of calcium. I also found that this tungstate could be put into a vacuum chamber of glass and fused to the inner walls of the chamber; and if the X-ray electrodes were let into the glass chamber and a proper vacuum was attained, you could get a fluorescent lamp of several candle-power. I started in to make a number of these lamps, but I soon found that the X-rays had affected poisonously my assistant, Mr. Dally, so that his hair came out and his flesh commenced to ulcerate. I then concluded it would not do, and that it would not be a very popular kind of light; so I dropped it.

Edison's fluoroscope consisted of a box, curved at one end to fit closely over the forehead and eyes; at the other end a thin layer of calcium tungstate was spread on a stiff backing material. By placing the object to be viewed between the X-ray tube and the fluorescent screen a shadow image could be observed. This apparatus was first shown to the public at the Electrical Exhibition of 1896 held at the Grand Central Palace in New York City. The fluoroscope was demonstrated as part of Edison's exhibit and was set up so the public could view their own bones.

Edison prepared his crystal calcium tungstate by fusing

together anhydrous sodium tungstate and calcium chloride. This mixture was then spread on a backing material using collodion as a binder. The firm of Aylsworth and Jackson; located in Orange, New Jersey, manufactured these screens on a commercial basis for Edison. These screens were reported to have considerable fluorescent lag and would deteriorate rapidly (Glasser, 1933), but they were an improvement over barium platinocyanide and were thus considered very satisfactory for the times.

Spectral studies have shown that calcium tungstate fluorescence lies predominantly in the blue-violet region of the spectrum. This characteristic has precluded its use as a fluoroscopic screen since the eye's response to this portion of the spectrum is low. Its spectral response corresponds quite closely to that of a photographic emulsion and calcium tungstate is the predominant phosphor used for X-ray intensifying screens.

The X-ray intensifying screen has developed mainly around the discovery of calcium tungstate by Edison. In the early days the Germans were quite active in the manufacture of screens. One screen made of willemite, natural zinc silicate, was produced under the name "Astral Fluorescent Screens." Natural zinc silicate was quite scarce and artificially-produced crystals were soon used in the production of these screens. Zinc silicate was not entirely satisfactory; its yellow-green fluorescence did not closely match the

optimum film response spectrum and also showed extreme lag. Another German firm produced a screen known as a "Gehler Folie" from Scheelite, natural calcium tungstate. These screens were exported to the United States in large numbers prior to the First World War.

When it became difficult to obtain screens from the European manufacturers, a number of United States products became available. In 1912 Dr. Herbert Threlkeld Edwards produced a screen of calcium tungstate which was relatively fast and of good quality. A year later the Snook-Roentgen Manufacturing Company introduced the Snook "Lagless Intensifying Screen." This screen, developed by Carl V. S. Patterson then working for the Snook concern, was similar to the Threlkeld Edwards screen.

Patterson, who had left Snook to form his own company, introduced an improved calcium tungstate screen in 1916. This screen had a much finer grain and showed very little lag. In 1918, Patterson also developed the double-screen technique to be used with the new duplitized film having an emulsion on both sides of the base.

A number of other firms have been involved in the production of intensifying screens at one time or another. Eastman Kodak introduced their first screen in 1922 and Buck X-Ograph Company; St. Louis, Missouri, marketed a screen in 1924. Today, the two main producers of fluoroscopic and intensifying screens are the

United States Radium Company, who market their product under the name Radelin, and Dupont whose involvement in the production of this product stems from their acquisition of the Patterson Screen Company.

The development of the modern fluoroscopic screen proceeded somewhat independently of the intensifying screen due to different design criteria. As pointed out by Levy and West (1925, p. 404-406), a screen that is to be used for visual examination must exhibit certain characteristics:

- A. "The intensity of illumination of the fluorescent screen, when excited by X-rays, should be as great as possible."

The visual impression of brightness is dependent on the spectral content of the excited fluorescence. To be most efficient, this excited fluorescence should correspond to the spectral sensitivity of the human eye. The maximum response of the human eye corresponds to a wavelength of about 5,550 Angstroms. The yellow-green fluorescence of barium platinocyanide lies in this region of maximum spectral sensitivity. Its sensitivity was one reason for its utilization as a phosphor in fluoroscopic screens until 1914 when Patterson introduced the first cadmium tungstate screen for fluoroscopy.

- B. "The definition which can be described as the screen ability

to show fine detail without blur, should be high."

To obtain this fine detail, the fluorescent crystals must be small in size and of a relatively thin deposition layer. The phosphors used in early screens were ground to produce small crystal size. This procedure would cause an appreciable reduction in their luminescent capability.

- C. "The screen should show very little afterflow or lag since a faint trace of the previous image on the screen will lead to confused and blurred results."

Before Levy and West (1933) developed a method of producing zinc sulfide phosphor with little afterglow, this characteristic of zinc sulfide prevented its use as a fluorescent crystal in fluoroscopic screens. An interesting development prior to Levy and West's work was reported by I. Seth Hirsch (1926) in which he specifically utilized the inherent afterglow of a fluoroscopic screen in a device capable of image storage. In Hirsch's apparatus, a screen with extreme lag was used on which an image could be stored for subsequent examination. The screen was so constructed that it could be heated with an electrical element at some time after the exposure. Heating would cause the thermal release of a large number of electrons

from their trapping centres with the subsequent production of a bright visible image.

Except for special applications, the lag of a fluorescent screen is considered an undesirable quality.

D. "The screen should be sensitive to hard radiation."

When X-radiation is incident on matter, the soft, low-energy radiation will be attenuated to a greater degree than will the higher energy portion of the spectrum. This effect will cause a shift in the effective energy of the beam to a higher value. In a fluoroscopic examination, the patient will act as an attenuator and the spectral distribution of the beam incident in the fluoroscopic screen will be shifted to a higher effective energy. To be most efficient, the fluoroscopic screen should be more sensitive to higher energy radiation. Zinc silicate is one example of a fluorescent matter whose response decreases with increasing energy.

E. "The screen contrast should be good."

Contrast which can be described as the density difference observable between different parts is dependent upon the color of fluorescent emission and the amount of scatter in the screen. Here again, to be most effective the excited fluorescence should as nearly as possible

correspond to the spectral sensitivity of the eye.

F. "The screen should be durable and undergo little deterioration."

As previously described, the deterioration of the fluorescent capabilities of barium platinocyanide, as a result of the loss of water of hydration, was an unfavorable characteristic in its use as a phosphor for fluoroscopic screens. But, due to the fact that its spectral response was closely matched to the characteristic sensitivity of the human eye, barium platinocyanide was used predominantly for fluoroscopic screens until 1914. In June of that year, Patterson introduced the first cadmium tungstate screen. This screen, known as a type A, was not subject to early deterioration as was barium platinocyanide. When this type of screen was prepared so that a small grain effect would be produced, by using very small crystals or thin deposition layers, an objectionable loss of brilliance occurred with an apparent color change to a more bluish hue.

The development of zinc sulfide type phosphors by Levy and West (1933) caused a change to the use of this type of crystal phosphor in fluoroscopic screens. They were able to develop techniques for producing zinc sulfide with little afterglow. By varying the

proportions of other components, they were able to change the spectral response of the phosphor. The final substance arrived at was zinc-cadmium sulfide. The desired characteristics of an ideal fluorescent screen for visual examination, as outlined by Levy and West (1933), were most nearly met by this material. Since 1933 this type of crystal phosphor has been the primary material used in fluoroscopic screens.

The Luminescent Process in Inorganic Crystals

The basis of an inorganic phosphor is a pure, insulating crystal which is made luminescent by the addition of a small number of impurity atoms. These additional atoms occupy interstitial, or substitutional, positions in the crystal matrix lattice.

Figure 1 shows an energy-band diagram for luminescent inorganic crystal. The narrow energy levels which exist in the atom in free space are broadened into bands by the fields due to surrounding ions. These bands in an insulator are filled and, although the electrons in these bands may move freely from ion to ion, the total state of motion cannot be altered by an electrical field and electrical conduction cannot take place. Some distance above the filled valence band there is an empty band, C, corresponding to the state of a freed electron. This is known as the conduction band. If an electron is raised from the valence band to the conduction band, the movement

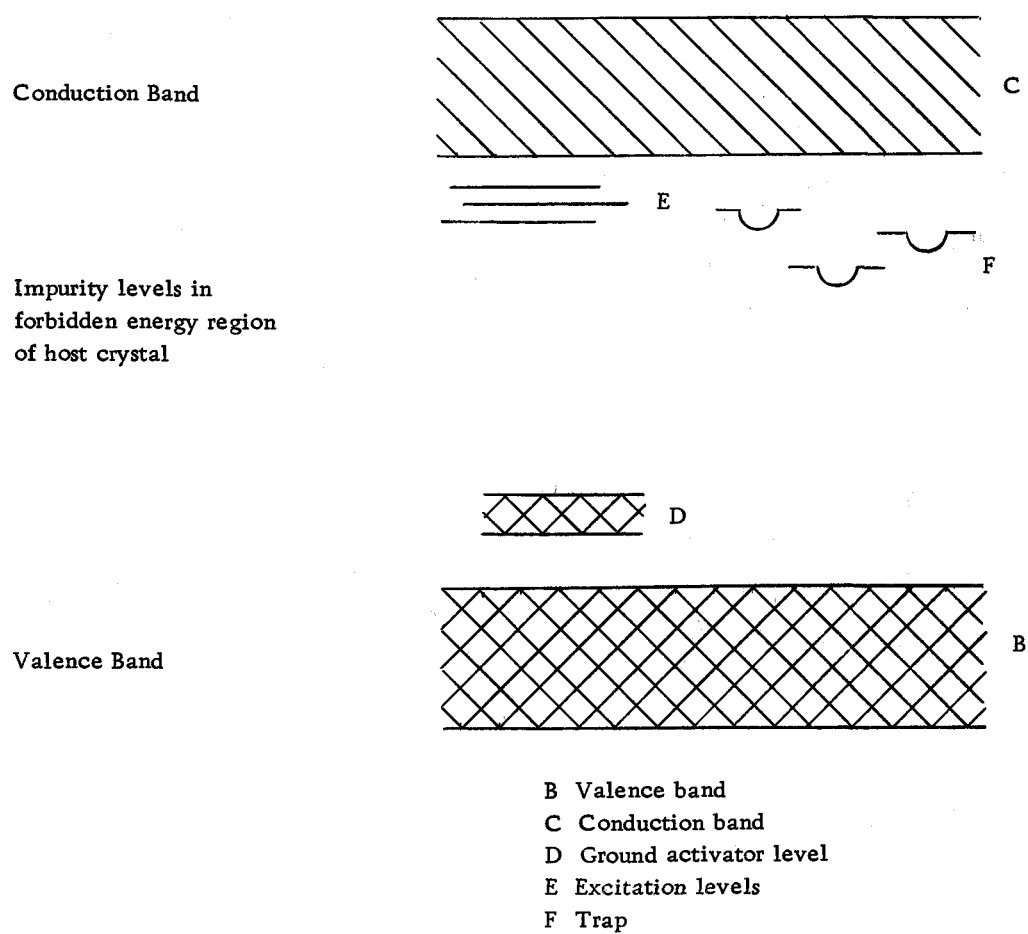


Figure 1. Energy-band diagram for luminescent inorganic crystal.

of the electron in C and the positive hole in B can give rise to a current. This phenomenon is known as photoconduction.

Impurity atoms, or lattice irregularities, give rise to localized electron states such as D, E and F with narrow energy levels which may occur in the forbidden region between the conduction and valence band of the host crystal. These positions are known as centres. Electrons moving in the vicinity may occupy these positions.

The centres are of three main types: (1) Luminescent centres in which the transition to the ground state is accompanied by the emission of a photon. For ZnS, Cu or Ag atoms are commonly used to create this type of centre. (2) Quenching centres in which radiationless loss of energy can occur; Fe and Ni are examples of elements that will create quenching centres. (3) Electron traps which have metastable levels from which the electron may return to the conduction band by acquiring thermal energy from the lattice vibrations.

The energy-band picture of an ideal crystal cannot account for all the excited states of the solid. It has been shown that besides the excited states in which the free electron and hole are produced, there exists the possibility of lower energy excited states, such as E, for which photoconduction does not take place (Leverenz, 1950). These states constitute a neutral unit or bound state. These bound electron hole pairs are known as excitons or exciton states; this may correspond to the excited state of an impurity atom or some normally bound

excited state.

Photoconducting states are of primary interest for crystals such as ZnS. Excitation raises electrons from the valence band or from the activator centres into the conduction band of the crystal. Between the valence band and the conduction band lie the impurity centres.

The recombination centres for electrons and holes are characterized by an effective cross-section σ_e for electron capture and σ_t for hole capture. A centre is a luminescent centre if the probability of radiative emission P_r is greater than that for nonradiative emission P_{nr} .

$$P_r \gg P_{nr}$$

A centre is a quenching centre if the opposite is true. In ZnS:Fe, ZnS:Ni, ZnS:Co the impurities create quenching centres and their introduction into the crystal matrix results in a substantial reduction in luminescence. Elements such as Ag, Cu and Mn are commonly used to produce activation centres. Electron traps and electron donors show a large capture probability for conduction electrons, but transition from them to the valence band is almost forbidden. Electrons residing in traps cannot usually drop to the ground level directly but, instead, must first be given sufficient energy to be raised to the conduction band and subsequently drop to the valence band or activator centre. If the level is normally empty,

it constitutes an electron trap; if normally occupied, it is a donor level.

ZnS:Ag and CdS:Ag are both primarily photoconducting crystals (Figure 2). According to the description by Curie (1963), excitation raises electrons from the valence band or from the luminescent centres into the conduction band of the crystal. Between the valence and conduction bands we have to consider the recombination centres, donor levels and electron traps.

Luminescence can be either fluorescence or phosphorescence. According to the earlier definitions, fluorescence is light emission that does not persist for any considerable length of time following excitation. For example; an often seen value for the limit of this persistence is $\tau < 10^{-8}$ seconds. Under this classification, phosphorescence is luminescence which persisted longer than the selected differentiating time.

A more exact distinction between fluorescence and phosphorescence can be made by reference to the process taking place (Pringsheim, 1943). Under this classification, fluorescence is due to the spontaneous transition of a molecule from its excited state to a lower energy level. The mean life of this process depends only on transition probability; in most cases it is very short, $\tau < 10^{-7}$ seconds, but can be delayed up to one second. This process is practically independent of temperature. The characteristic feature of

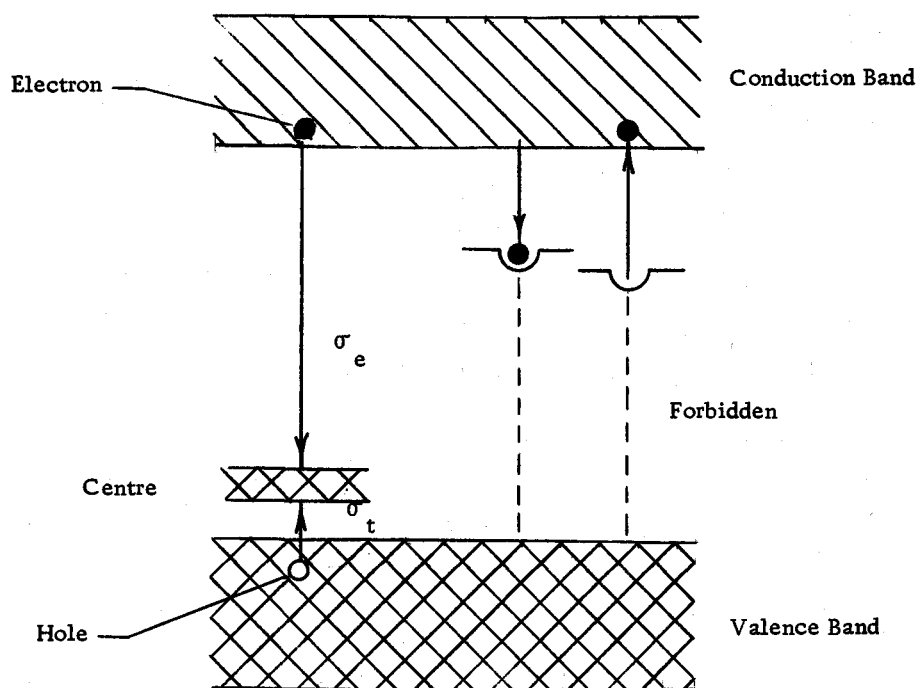


Figure 2. Photoconducting crystal.

phosphorescence is that the excited electron does not immediately emit light by returning to the ground state, but passes instead into a metastable or quasistable state known as a trapping centre. This trapping site lies slightly below the excited energy level so that once the electron is trapped, energy must be supplied to remove it from the centre. This energy can usually be gained thermally. Once the electron has been removed from the trap to the excited state, it can then return to the ground state with light emission accompanying this transition, or the electron may be retrapped. Phosphorescence is a temperature-dependent phenomenon and will occur within a short time, if the trap depth is shallow or the temperature is relatively high. If the temperature is low, the transition will occur at a relatively slow rate or be completely "frozen in."

We can distinguish two types of fluorescent processes: monomolecular, associated with first-order kinetics; and bimolecular, associated with second-order kinetics.

If the probability that in time, dt , an electron returns to the ground state with the emission of light is given by:

$$-a dt$$

where a is a constant for the crystal at a given temperature; and n is the number of electrons in the excited state at time, t :

$$\text{which gives } \frac{dn}{n} = -a dt$$

$$n = n_0 e^{-at}$$

$$\text{and since } I = \frac{dn}{dt}$$

$$\text{then } I = I_0 e^{-at}$$

As previously stated, the luminescence of most inorganic crystals depends upon the presence of impurity or activator atoms which establish centres in the forbidden energy band of the crystal. The probability of recombination is proportional to the number of these available centres:

$$\frac{dn}{n} = -a n dt$$

and so, n , decreases hyperbolically with time,

$$n = \frac{n_0}{(1 + n_0 a t)}$$

the luminescence decay then being given by:

$$I = \frac{dn}{dt} = a n^2$$

thus

$$I = \frac{I_0}{(1 + at)^2}$$

where

$$a = \sqrt{I_0 a}$$

thus in the bimolecular case, decay becomes more rapid as the excitation intensity is increased.

The above kinetics applies exactly only to fluorescence since its derivation does not consider the intermediate process of trapping. For a particular crystal matrix, the observed luminescence is often a combination of monomolecular and bimolecular schemes with one or the other predominating.

In the case of sulfide phosphors of the type ZnS:Cu, the short duration emission seems to involve first of all a monomolecular decay with a lifetime characteristic of transitions in isolated atoms, and finally an approximately bimolecular decay with a lifetime of the order of 10^{-5} seconds due to electrons, previously liberated, recombining with emission centres. All this is followed by a slower decay (10^{-4} to 10^{-2} seconds) with complex kinetics and which is really a short period phosphorescence due to traps of 0.3 or 0.4 eV in depth. Finally, there follows a relatively long period of phosphorescence (Curie, 1963).

It is a characteristic of many inorganic phosphors for their luminescent response, when excited by X-rays, to increase as temperature is decreased. An electron in the valence band can enter a luminescent centre by thermal activation. The electron previously removed from the centre to the conduction band can no longer return to this centre, but instead can recombine via some other defect; quenching centre for example. The same transition of an electron from the valence band to an activator level can occur by the absorption

of an optical photon; i. e., optical quenching due to infrared radiation (Curie, 1963).

Phosphor Preparation and Measurement of Luminescence

The action of a specific activator atom on the luminescent spectral emission of ZnS crystals has been shown by Leverenz (1940). The peak wavelength of the luminescent emission band occurs in the following order for a cubical ZnS crystal:

| | | |
|--------|--------------------------|-----------|
| ZnS:Ag | - 4,550 Å ^o , | (2.73 eV) |
| ZnS:Zn | - 4,700 Å ^o , | (2.64 eV) |
| ZnS:Cu | - 5,280 Å ^o , | (2.35 eV) |
| ZnS:Mn | - 5,910 Å ^o , | (2.1 eV) |

The major visible luminescence is as previously described due to the transition of an electron in the conduction band to an activator level. This can diagrammatically be shown for the specified ZnS crystals in Figure 3.

In this simplified energy-level picture at least two possibilities have been ignored: electrons might fall from the conduction band to normally unoccupied impurity levels, such as E_I^* , before making the transition to the lower energy states; secondly, the electron might be raised initially to the discrete, unoccupied level. Electrons raised to these band excitation states are not free to move throughout the crystal. A specific example of this type of transition is shown by the ZnS:Mn phosphor whose luminescence is primarily due to

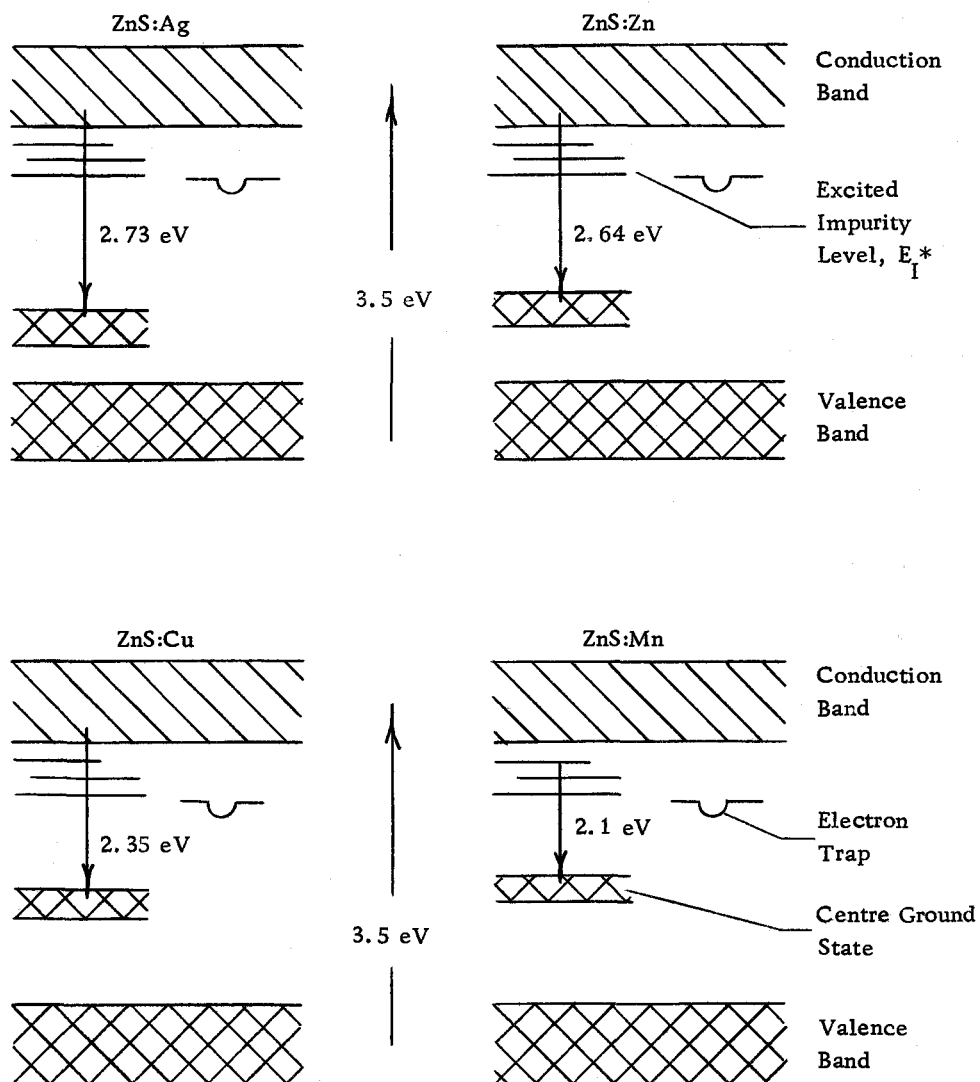


Figure 3. Effect of different activator atoms in a zinc sulfide crystal matrix.

E_I^* - see page 32.

transitions within bound excitation states.

In all cases where luminescence is of importance the measurement of luminescent efficiency must be considered. There are three ways of defining the efficiency of a luminescent light source: (1) Luminous efficiency; the ratio of the total light output to the energy input without questioning which part of this energy is absorbed by the luminescent material or lost by reflection, transmission or by any other process. (2) Energy yield, ϕ ; the ratio of the energy of the luminescent light, in ergs or watts per second, to the energy absorbed by the luminescent material. (3) Quantum yield, Q ; the ratio of the number of photons absorbed by the luminescent material to the number of photons contained in the emitted light.

The effect of the specific spectral distribution of a particular phosphor on its luminescent efficiency has been graphically demonstrated by Leverenz (1940). In the lower curves of Figure 4 are shown the relative energy versus wavelength for ZnS and ZnCdS phosphors. It can be observed that on an energy basis, the ZnS is the most efficient.

Peckham (1949) has demonstrated by use of a psychometric technique to determine the visual performance of a screen, that the resolving power of fluoroscopic screens at various contrast and brightness levels, the optimum composition for a fluoroscopic screen. A phosphor ratio of 55 parts zinc sulfide to 45 parts cadmium

1. ZnS:Ag
2. Zn(50%)-Cd(50%)S:Ag
3. Zn(20%)-Cd(80%)S:Ag

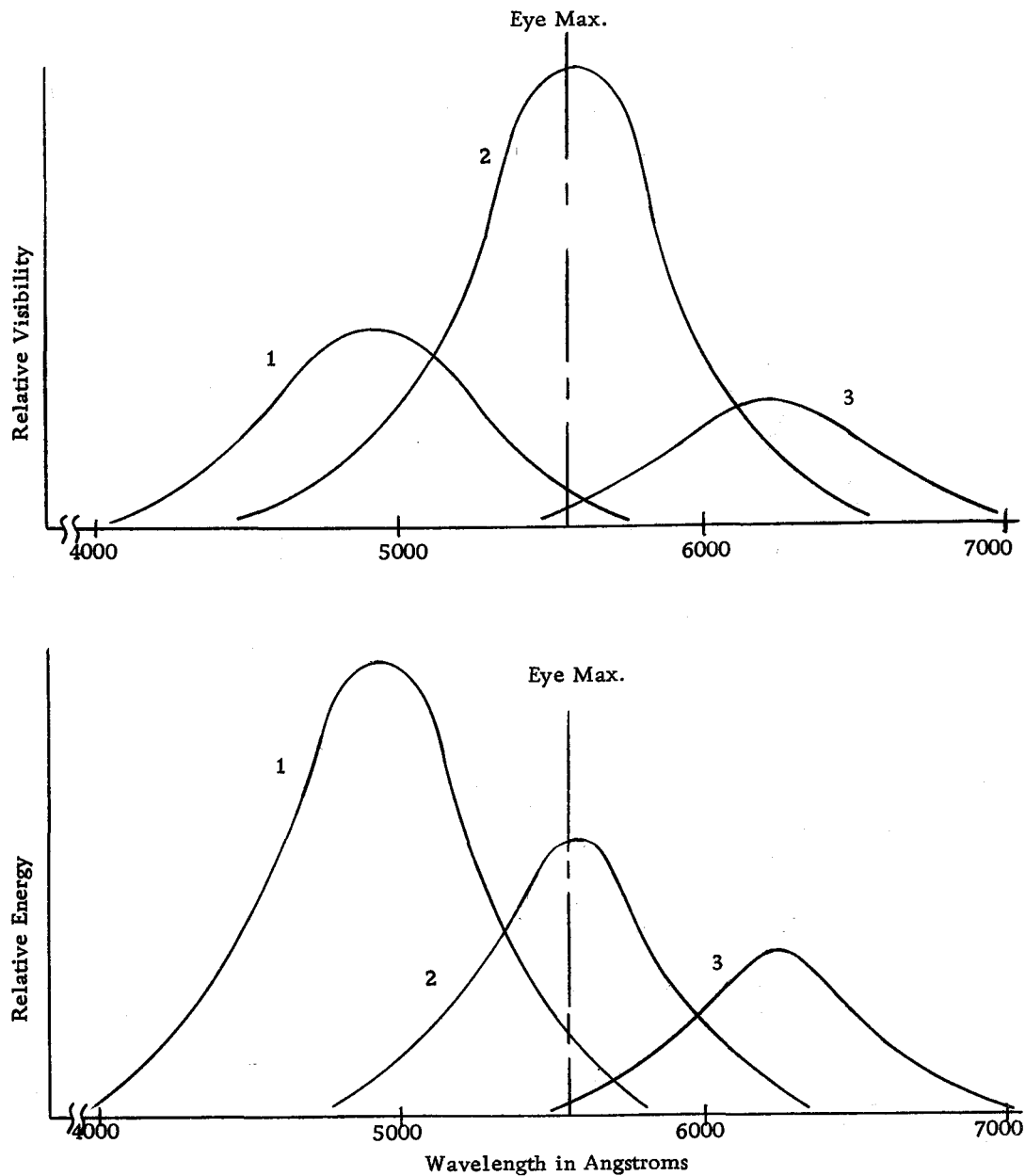


Figure 4. Spectral distribution of energy and relative visibility for ZnS:Ag; Zn(50%)-Cd(50%)S:Ag; and Zn(20%)-Cd(80%)S:Ag.

sulfide was found to be optimum. An increase in phosphor thickness will result in greater light output. This greater thickness also results in a reduction of the resolving power of the screen due to scatter of the light in the thicker phosphor layer. For the screens studied, he found a thickness of 0.0125 inches to be optimum.

III. MATERIALS AND METHODS

Special X-ray Unit

A special X-ray unit was designed and constructed for this study. The intent was to have a self-shielded unit in which exposure conditions, similar to those found in a conventional fluoroscopic unit, could be obtained, and for which the geometry would be fixed so that reproducible results could be obtained over a long term study.

The apparatus, see Figures 5, 6 and 7 employs a General Electric Maximar 100 X-ray unit housed in a shielded enclosure constructed of lead bonded to plywood. The tube head sits in the shielded enclosure with the beam port facing upward. The controls are mounted on the exterior of the shielded enclosure. The Maximar 100 unit has a continually-variable kilovoltage control with a maximum of 100 kilovolts peak. A current stabilizer with six-position switch is built into the unit so that non-fluctuating current settings from one-half to five milliamperes can be obtained.

The internal dimensions of the unit are shown in Figure 7. A piece of fluoroscopic table top is mounted 20 inches above the focal spot and the focal screen distance is 30 inches. Two small doors allow access to the area directly above the table top position so that various thicknesses of tissue-equivalent material may be placed in



Figure 5. Special X-ray unit with "Brightness Spot Meter" mounted on adapter.



Figure 6. Special X-ray unit with front panels open and screen exposure holder intercepting the beam.

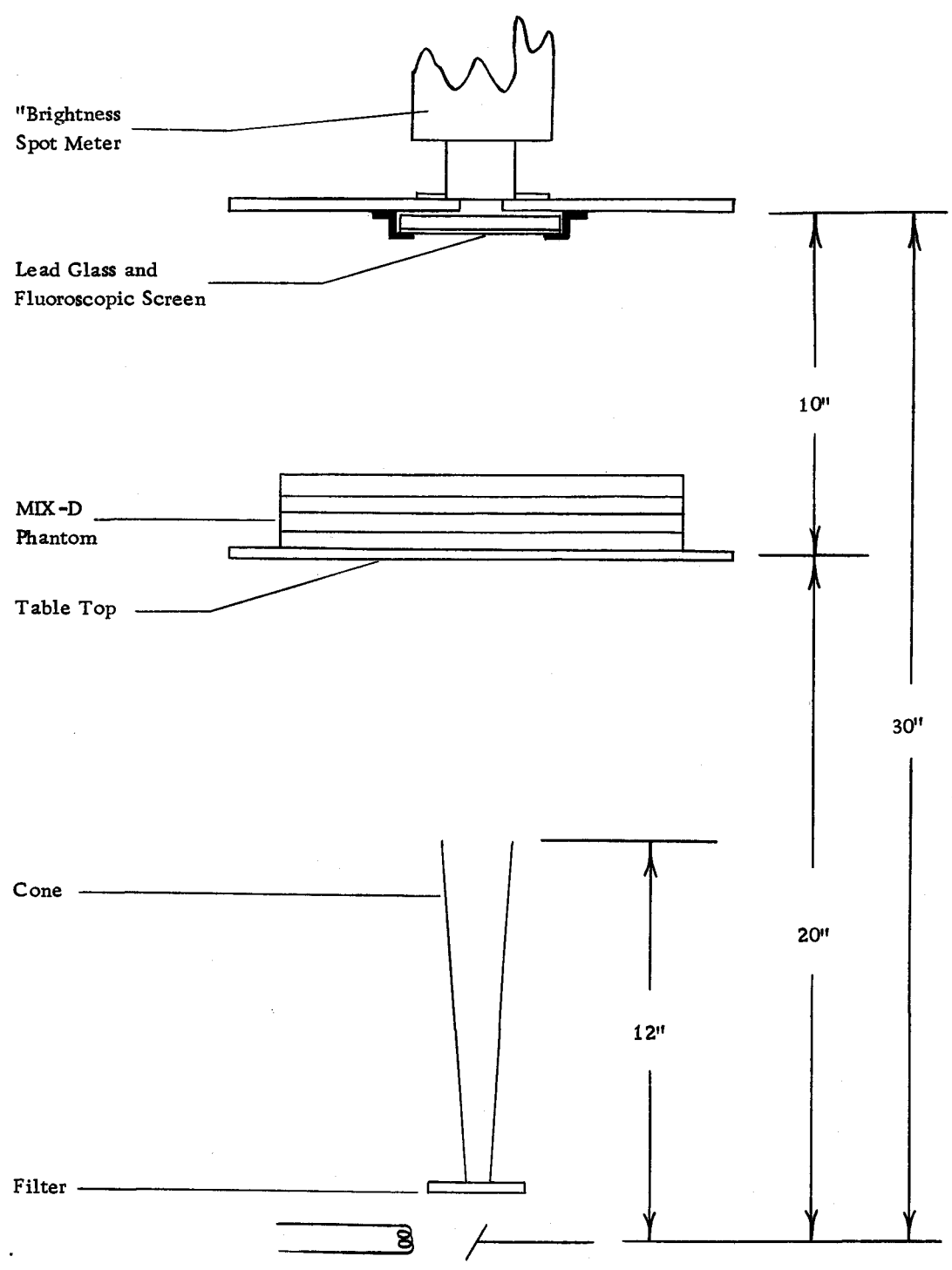


Figure 7. Geometry of special X-ray setup.

the primary beam at this site where the patient is normally positioned. The fluoroscopic screens are mounted ten inches above the table top. When the unit is to be used for fluorescent light measurements a special adapter, constructed of 1/16-inch steel, is used to hold the detector portion of the "Brightness Spot Meter" and one of the five by seven inch fluoroscopic screen assemblies consisting of a fluoroscopic screen with lead glass and cardboard backing. This adapter provides a light tight coupling between the screen and light meter so that measurements of screen luminescence can be made in the convenience of a fully-lighted room. When the X-ray unit is used to irradiate the screens as part of the controlled test exposure, a second adapter is used. This adapter holds four of the five by seven inch fluoroscopic screen assemblies consisting of a screen with lead-glass cover and cardboard backing.

When the table top access doors are open, a panel hinged at the base may be opened to allow access to the tube head. This is to allow ease in changing the filters and cones used with this unit. The doors and head-access panel are interlocked with the control to prevent operation of the unit when they are open.

The Maximar 100 X-ray unit has a two millimeter thick beryllium window tube for which the equivalent aluminum thickness is less than 0.1 millimeters. An additional 2.5 millimeter aluminum filter was placed in the beam at the filter position on the tube head.

Measurements made with a Victoreen 25R condenser chamber at the table top at 100 kVp gave a unique half-value layer of 3.38 millimeters of aluminum and a homogeneity coefficient of 0.884 (Trout, Kelley and Lucas, 1960, 1962).

The measured exposure rate per minute at the table top is shown in Figure 8. All values of exposure rate are seen to be less than ten Roentgens per minute, the maximum exposure rate recommended by the National Council on Radiation Protection and Measurement (USNBS, 1961).

When measurements of the luminescent response of the fluoroscopic screens are made, three sheets of one-half inch thick MIX-D (Jones and Raine, 1949), a tissue-equivalent phantom material, is placed at the table top position. The measured exposure rate per minute at the screen position is shown in Figure 9. These measurements were made with a 25R Victoreen condenser R-meter. The filtration was as specified above and a cone, limiting the beam to a five centimeter diameter at a distance of 30 centimeters from the focal spot, was used.

Fluoroscopic Screens and Exposure Conditions

Twenty-four fluoroscopic screens, 12 each from two different manufacturers, to be known as type I and type II, constituted the test population. These screens were five by seven inches in size and

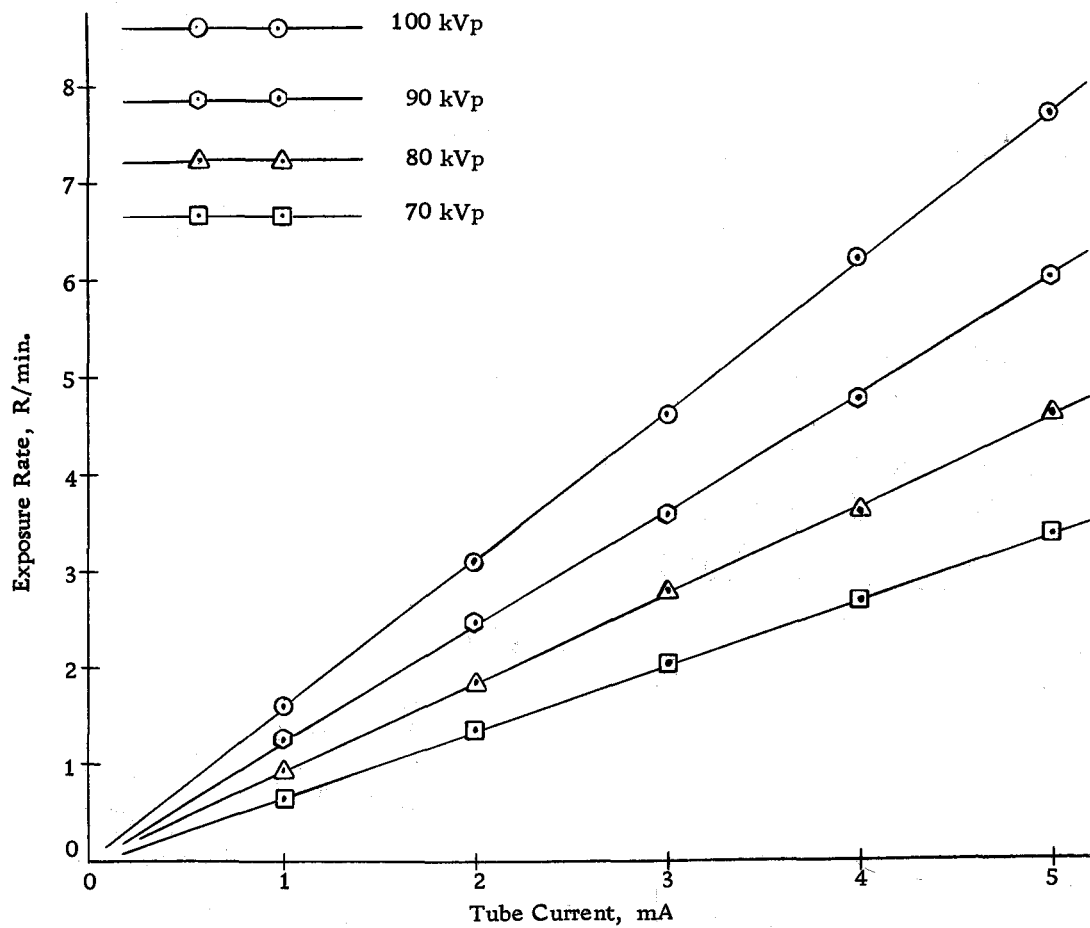


Figure 8. Table top exposure rate versus tube current for special X-ray unit.

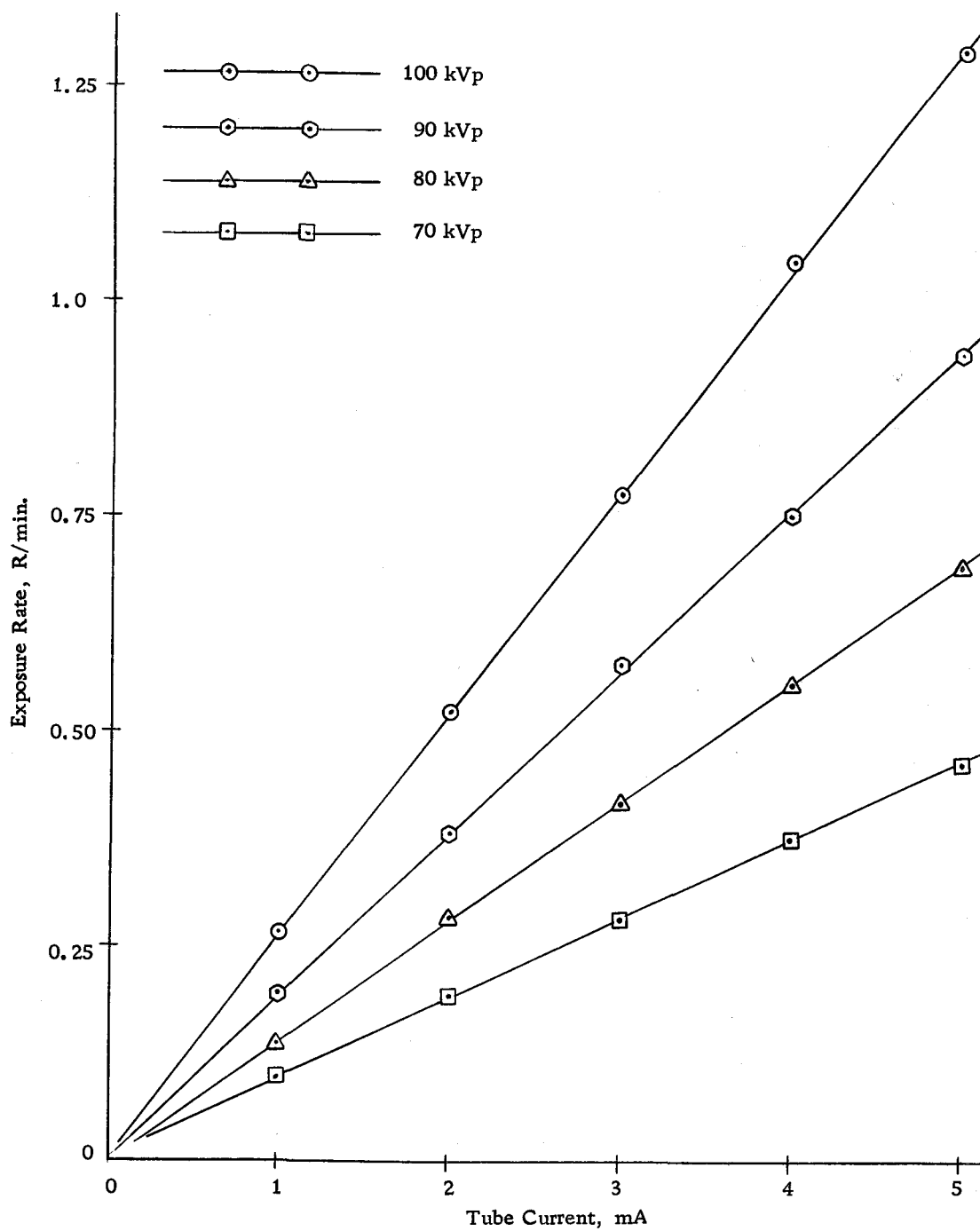


Figure 9. Screen exposure rate versus tube current with three sheets of one-half inch thick MIX-D in the beam.

consisted of zinc-cadmium sulfide phosphor mounted on a plastic support backing.

The manufacturers of both screens state that certain factors may cause a deterioration of the phosphor material. Specifically, manufacturer I states that the phosphor material from which his screens are made will discolor when exposed to ultraviolet radiation and should not be exposed to direct sunlight, bright daylight, ultraviolet or fluorescent lamps. He, therefore, recommends that these screens be covered at all times when not in use. Manufacturer II states that normal exposure to X-radiation does not damage the screens; but, since prolonged exposure to ultraviolet radiation of certain wavelengths may cause discoloration and reduce efficiency, it is recommended that exposure to light be kept to a minimum.

To establish and quantitate the effect of some of these factors, the population of test screens was divided into six groups, each group containing two type I screens and two type II screens. The division of the screens is shown in Table 1. Each of the test conditions listed was chosen to investigate one of the agents reported or suspected of cause screen deterioration. All test conditions were designed to represent an exposure to the screen that could be interpreted in some realistic manner. For example, the exposure of the screens to sunlight, fluorescent light and tungsten lamps was made through lead glass. All radiation exposures were also made with the screens

placed next to lead glass so that backscatter conditions would be the same as those experienced by a fluoroscopic screen in an actual diagnostic unit.

Table 1. Division of fluoroscopic screen test population.

| Exposure Condition | Type I | Type II |
|---|------------|---------|
| A. Control | 2 | 2 |
| B. Busy diagnostic exposure | 2 | 2 |
| C. High radiation exposure | 2 | 2 |
| D. Fluorescent light exposure | 2 | 2 |
| E. Tungsten light exposure | 2 | 2 |
| F. Sunlight exposure | 2 | 2 |
| total of 24 five by seven inch fluoroscopic screens | | |
| | 12 type I | |
| | 12 type II | |

Test conditions were as follows:

- A. Control group; four screens kept in a darkened storage box at room temperature. These screens were retained at the laboratory and exposed to X-rays only when periodic measurements of the fluorescent output of all the screens were made.
- B. Busy Diagnostic Exposure group; four screens exposed to 1,000 milliamperere minutes per week. This exposure was made with the experimental X-ray unit operated at 100 kilovolts peak and five milliamperes for which the exposure

rate was 1.1 Roentgens per minute. As previously described, the unique half-value layer at 100 kilovolts with 2.5 millimeters of aluminum added was 3.38 millimeters of aluminum and the homogeneity coefficient equal to 0.884. Four sheets of one-half inch thick MIX-D, a tissue-equivalent phantom material, were placed in the primary beam at the table top position between the X-ray tube and exposed fluoroscopic screens. An external interval timer attached to the X-ray machine turned the unit on and off for sequential 15 second periods. This was done to reproduce the short periodic exposures a fluoroscopic screen would experience under actual diagnostic conditions. When exposed, the fluoroscopic screens were positioned between a sheet of lead glass and a black cardboard backing.

- C. High Radiation Exposure group; four screens exposed to 1,000 milliamperere minutes per week with no tissue-equivalent material in the beam. This exposure would represent the exposure received by a fluoroscopic screen continually subjected to an unattenuated direct beam.

This exposure was made with a General Electric Maxitron 300 X-ray unit operated at 100 kilovolts peak and 20 milliamperes. The filtration was equivalent to 2.5 millimeters of aluminum at the specified operating potential.

As in the busy diagnostic exposure, the screens were placed on lead glass and exposed through a cardboard backing material, and at an 80 centimeter target-to-screen distance the exposure rate was 23 Roentgens per minute. Exposures were made once each week with no further attempt to fractionate the exposure.

- D. Fluorescent Light Exposure group; four screens continually exposed to fluorescent light. The test was set up in a room having no windows so that no external source of light would affect the test. The room contained two fluorescent light fixtures, each having four 40-watt daylight-type fluorescent tubes. One type I and one type II screens were placed on a table top 31 inches from the floor and 75 inches from the light fixture. The level of illumination at this position was measured with a Weston Master III exposure meter and found to be 39 foot-candles. The two remaining screens in the test group were placed at a position 11 inches from the center of the fluorescent tubes. The measured illumination at this point was 300 foot-candles.

The spectrum of a daylight fluorescent lamp is shown in Figure 10. Since light incident on all the fluoroscopic screens must pass through a sheet of lead glass, this factor must be considered. The transmission characteristics of

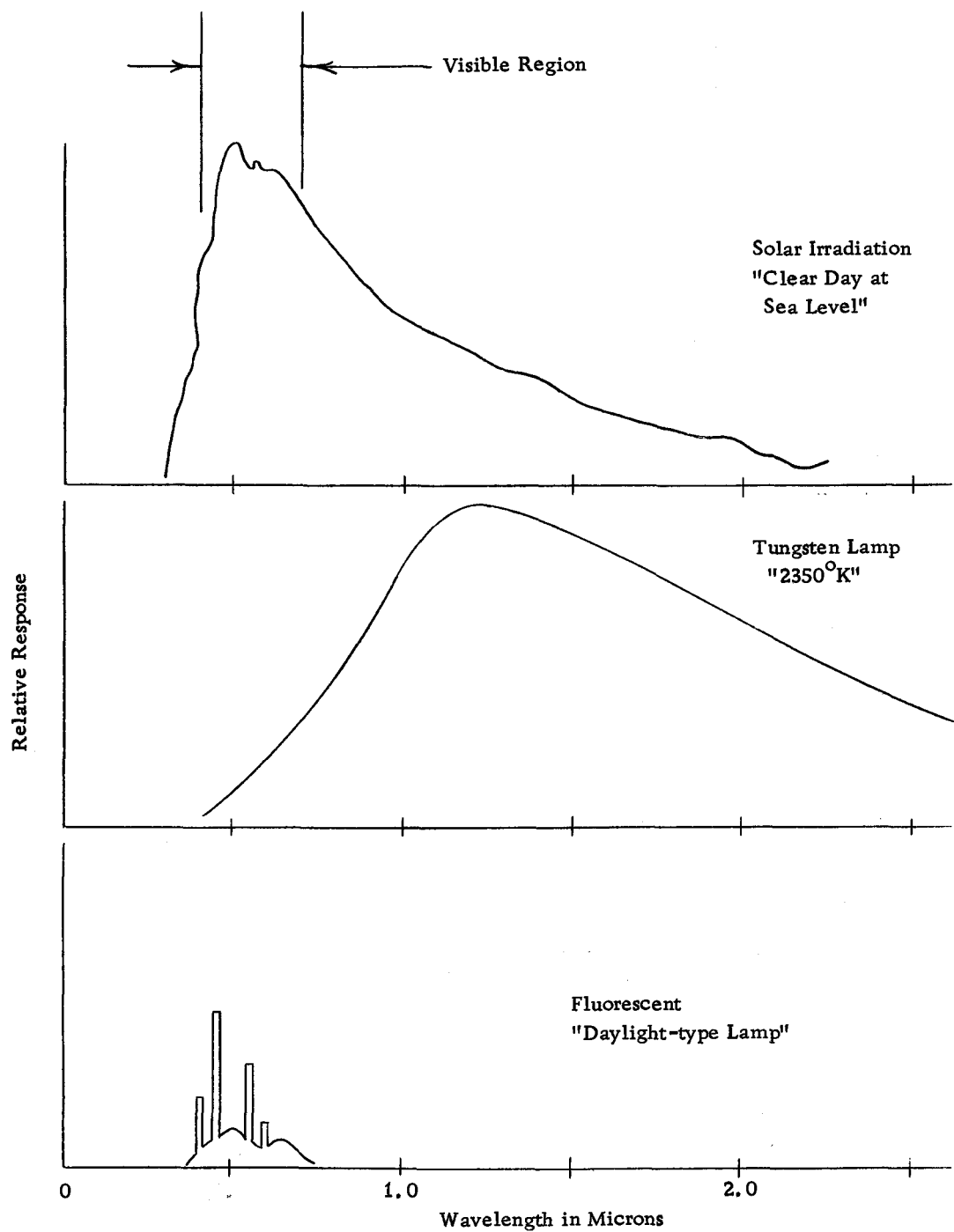


Figure 10. Typical light spectra from solar irradiation at sea level, tungsten lamp and daylight-type fluorescent lamp.

the glass would limit the ultraviolet portion of the spectrum. The normal recommended illumination levels, for a well-lighted room suitable for reading, range from 30 to 70 foot-candles. With these levels in mind, the measured illumination level of 39 foot-candles at the table top position could be considered a normal illumination level that an uncovered screen might be exposed to. The 300 foot-candle illumination level would be from five to ten times normal.

- E. Tungsten Light Exposure group; four screens exposed continually to four 60-watt tungsten lamps operated on a nominal 110 volt line. Two screens, one type I and one type II, were placed seven inches from the lamps. The illumination level measured with the Weston Master III exposure meter was 300 foot-candles, a level five to ten times normal. Two screens at a distance of 21 inches from the lamps received an illumination of 100 foot-candles.
- F. Sunlight Exposure group; four screens exposed to direct sunlight in Las Vegas, Nevada. The screens, placed between a sheet of lead glass and a black cardboard backing, were sealed in a thin plastic bag to prevent possible damage due to moisture, sand, etc. The four screens comprising this test group were placed in an unshaded area and exposed

to direct sunlight. Data on the number of hours of sunlight per day was obtained from the local U. S. Weather Bureau Station.

The Weather Bureau utilized a pyranometer to obtain values for the number of hours of sunlight per day. The pyranometer is a thermal-response device consisting of two thermocouples connected in series with opposing polarities (Johnson, 1954). A disk with a reflecting surface is connected to one thermocouple and another disk with a black surface is connected to the second. When sunlight is incident on the device, a signal is generated due to the higher temperature of the absorbing black surface. The temperature of the reflecting surface is an indication of the ambient conditions and would be equal to that of the black surface if no radiant energy were incident on it. The pyranometer measures only the flux scattered by the sky on a unit area normally to the sun at the earth's surface. A shield prevents direct sunlight from striking the instrument so that diffuse sky radiation is measured.

Brightness Spot Meter

Light level measurements were made with a Photo Research Corporation Spectra "Brightness Spot Meter," Model UB-1-1/2^o (Figure 11). This meter is a direct-reading instrument eliminating



Figure 11. Spectra "Brightness Spot Meter" showing power supply, regulated brightness source and detector mounted on adapter.

the error inherent in techniques employing the visual matching of brightness levels. Light is picked up by an f-1.9 objective lens. A partial reflecting mirror located in the interior of the lens system directs a portion of the light downward to a sensing photomultiplier tube. Output from the photomultiplier tube is fed to the input grid resistor and range-selector circuit of a three-stage DC electrometer tube amplifier. The output signal is indicated on a microammeter calibrated in foot-lamberts brightness.

The Spot Meter has an optical acceptance angle of $1\text{-}1/2^{\circ}$. The minimum range full scale is 0.01 foot-lamberts and the minimum detectable brightness 0.0001 foot-lamberts. Calibration is maintained by use of a regulated brightness source supplied by the same manufacturer. According to the manufacturer's specifications, this source of nine foot-lamberts has a rated variation of plus or minus one percent when operated from a 95 to 130 volt 60-cycle line.

To measure luminous intensity, the photo tube S-4 response characteristic has been modified by insertion of a Wratten 106 filter to simulate the International Commission on Illumination, luminous response curve. The C.I.E. values mentioned are the variation of photopic luminous efficiency with light wavelength as established for the human eye by the International Commission on Illumination (USNBS 1962, p. 3). The C.I.E. luminosity response and response of the Spot Meter are shown in Figure 12. As pointed out by the

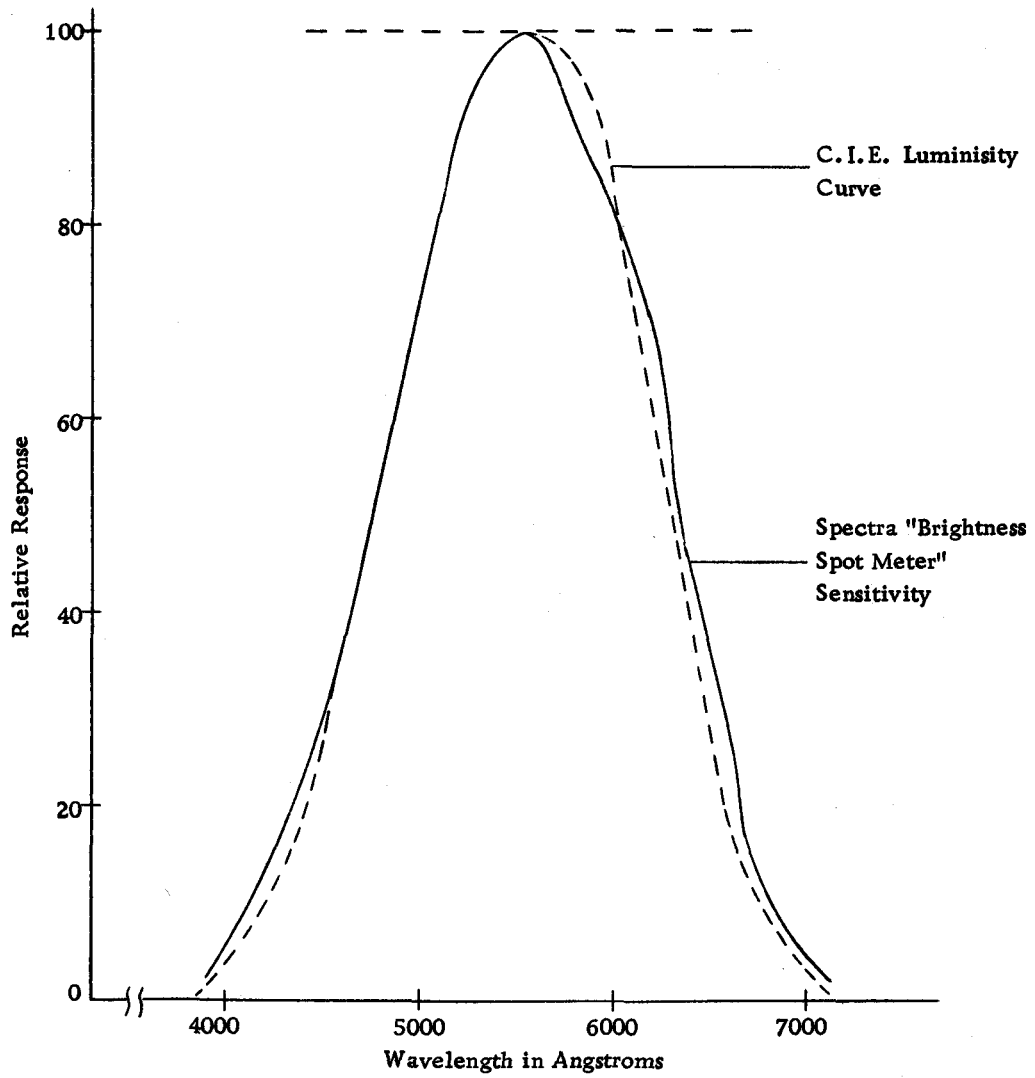


Figure 12. Comparison of C.I.E. luminosity curve and Spectra "Brightness Spot Meter" sensitivity.

manufacturer of the Spot Meter, there are two limiting factors in producing an instrument capable of performing this transition exactly: First, the difficulty in producing the dye composition for the filter such that it will correct an S-4 detector characteristic to simulate the C. I. E. tristimulus values exactly. Secondly, the spectral characteristics of the detectors vary one from the other; thus necessitating individual correction filters for each instrument.

At the light levels experienced under conventional fluoroscopy, the response is that of the scotopic eye. No correction has been made for this difference since the appropriate correction filters were not available.

Luminescent Response of Fluoroscopic Screens

Measurements of the luminescent response, light output versus Roentgen exposure, was found to be a linear function over the range of exposure values used in this study. This is in agreement with Henny and Chamberlain (1944). They reported that for a type B Patterson fluoroscopic screen a linear relationship exists between exposure at the screen and the corresponding brightness for exposure levels up to three or four Roentgens per minute. It was shown in Figure 9 that at 100 kilovolts peak and five milliamperes, the maximum operating values of the experimental X-ray unit, and with three sheets of MIX-D in the beam, the measured exposure rate at

the screen was less than one and one-half Roentgen per minute.

Figure 13 shows the characteristic response of a type I and type II fluoroscopic screen. The linear relationship between light output and exposure can be seen. These curves represent the average characteristic response of both types of screens at 70 and 100 kilovolts. The 12 type II screens have an average light output response about 18 percent greater than the 12 type I screens. Variation among screens within each group of 12 was observed to be about plus or minus five percent.

Data Acquisition and Statistical Analysis

At intervals of about one month throughout the duration of the study, measurements of the characteristic light output response of all the fluoroscopic screens were taken. These measurements were made at 70 and 100 kilovolts peak and at each voltage six readings were taken; one at one-half, one, two, three, four and five milliamperes. The relationship between exposure rate and luminescent light output is shown in Figure 13. For the range of exposure rates used in this study it has been shown that screen luminescence is a linear function of exposure rate.

The equation which describes the relationship between x , the exposure rate and the mean of y , the luminescent light output of the screen is called the regression equation of y on x . The line of

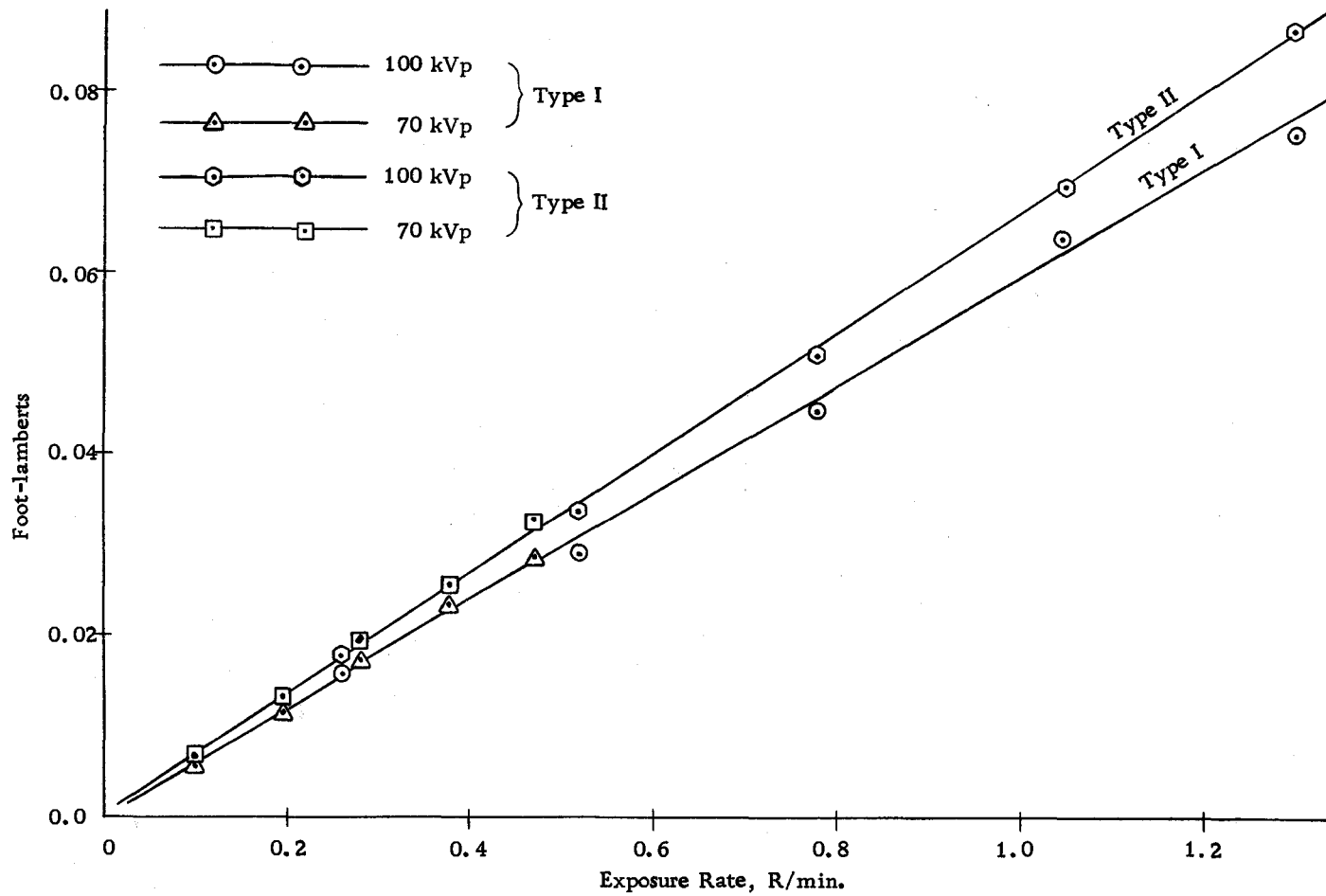


Figure 13. Foot-lamberts versus exposure rate for type I and type II fluoroscopic screens at 70 kVp and 100 kVp.

regression of y on x can be expressed by the equation: $\mu_{y \cdot x} = \alpha + \beta(x - \bar{x})$. Alpha (α) is the mean of the array of y at x equals \bar{x} where \bar{x} is the mean of x . The quantity β is the rate of change of the mean of y with respect to x and is called the regression coefficient of y on x . In geometrical terms, it is the slope of the regression line.

For each set of points describing the luminescent light output at a specific voltage and time, a linear regression analysis was performed. This analysis was carried out on the Control Data Corporation Model 3300 digital computer operated by the Oregon State University Computer Center. From each regression curve the light output, when excited by an exposure rate of one-half Roentgens per minute, was determined. From Figure 9, it can be seen that the screen exposure rate is one-half Roentgen per minute at 1.8 milliamperes when operating at 100 kilovolts peak and 5.3 milliamperes when operating at 70 kilovolts peak.

IV. EXPERIMENTAL RESULTS

The results obtained in the study of the deterioration of X-ray fluoroscopic screens are presented in Figures 14 through 21. These curves show the luminescent light output measured in foot-lamberts as a function of the exposure received by the screens for the particular parameter studied. The luminescent light output values plotted were obtained from the linear regression curve at an exposure level of one-half Roentgens per minute.

Figures 14 and 15 show results for the sunlight exposure group. During the study, one of the type I screens was damaged. The protective plastic bag in which it was exposed broke open allowing the screen to get wet in a rain shower. This condition caused the screen to turn a gray-black color and its light output dropped about 80 percent. This effect of moisture is in agreement with findings of Gordon, Seitz and Quinlin (1939) previously described concerning the action of moisture on a zinc-cadmium sulfide phosphor. Because of this accident, the results shown for the sunlight exposure group are based upon the three remaining screens. None of the information concerning the damaged screen has been included in the results.

Figures 16 through 19 show the results obtained for the fluorescent and tungsten light exposure. For these figures a level of 50 foot-candles has been assumed to represent the illumination that

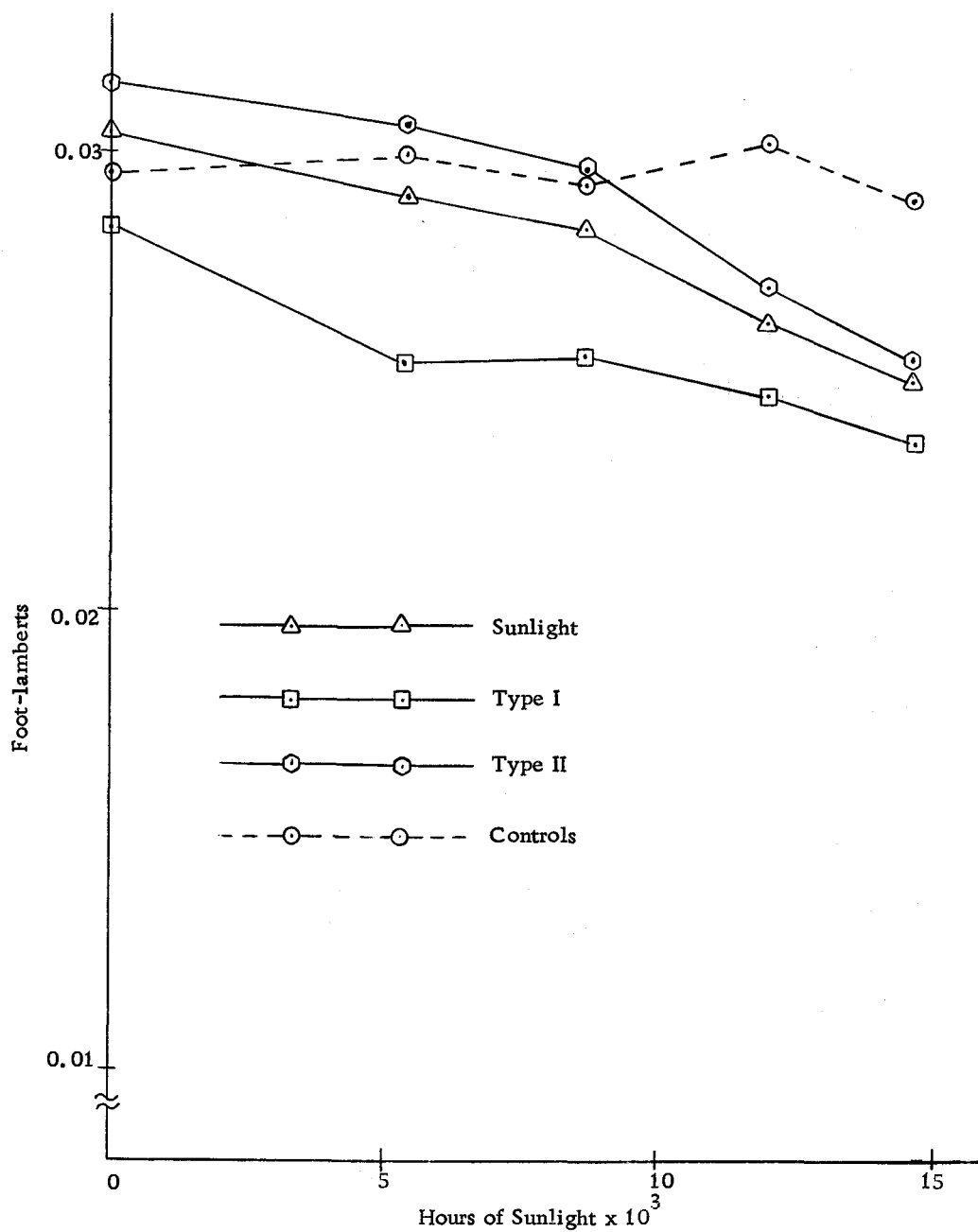


Figure 14. Response of screens exposed to sunlight excited by one-half Roentgen per minute at 100 kVp versus the number of hours of sunlight.

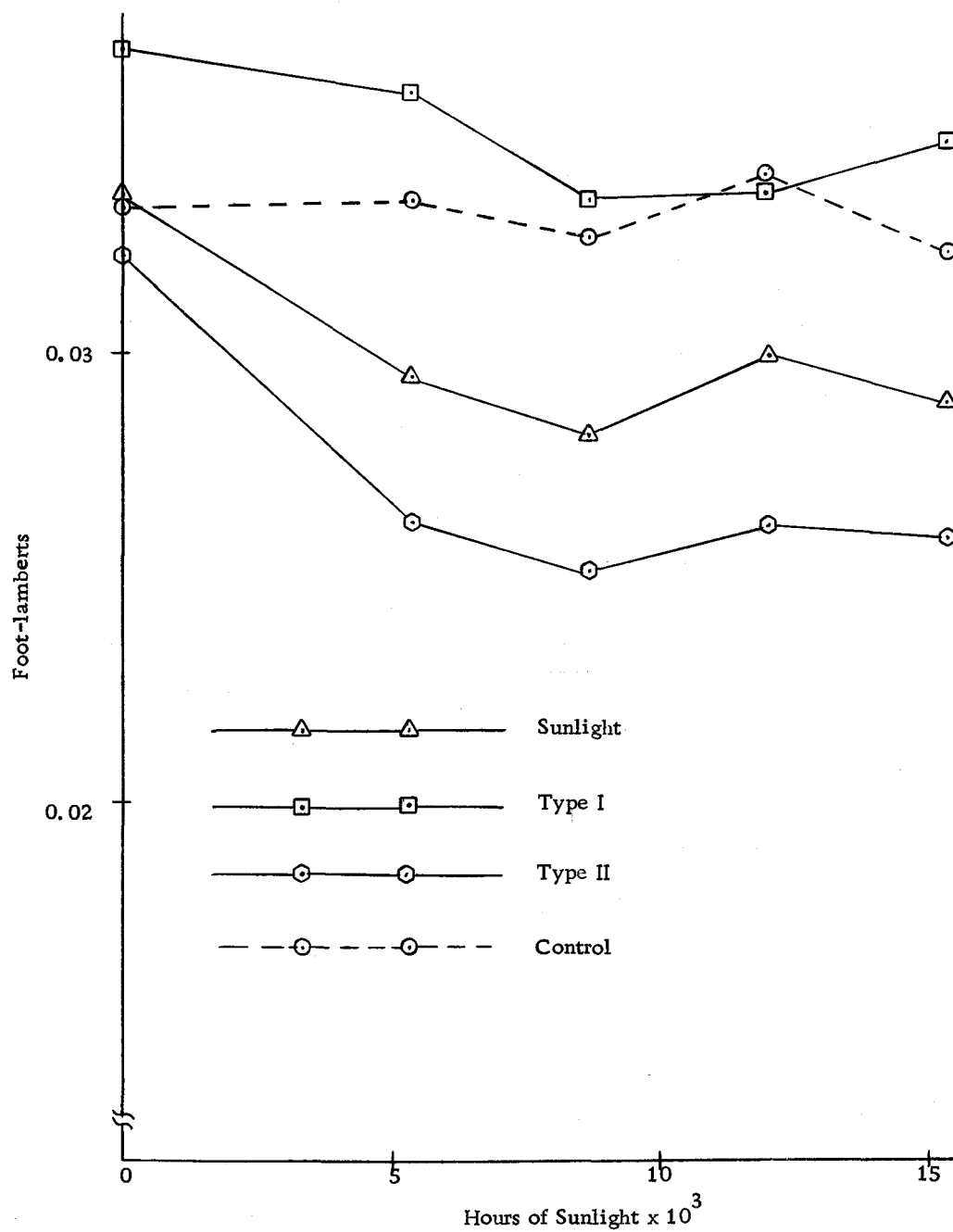


Figure 15. Response of screens exposed to sunlight excited by one-half Roentgen per minute at 70 kVp versus the number of hours of sunlight.

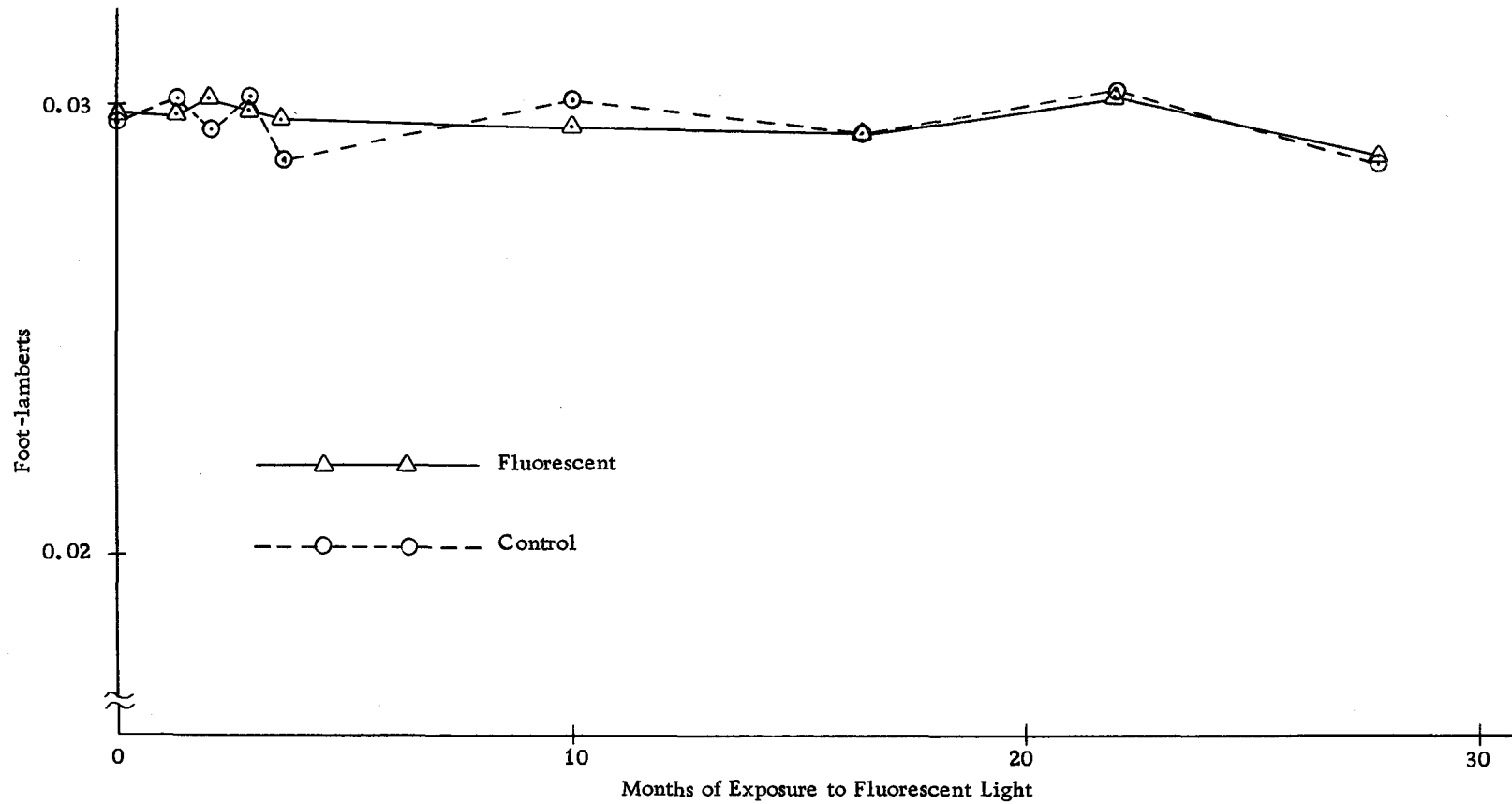


Figure 16. Response of screens exposed to fluorescent light excited by one-half Roentgen per minute at 100 kVp versus adjusted months of exposure to fluorescent light.

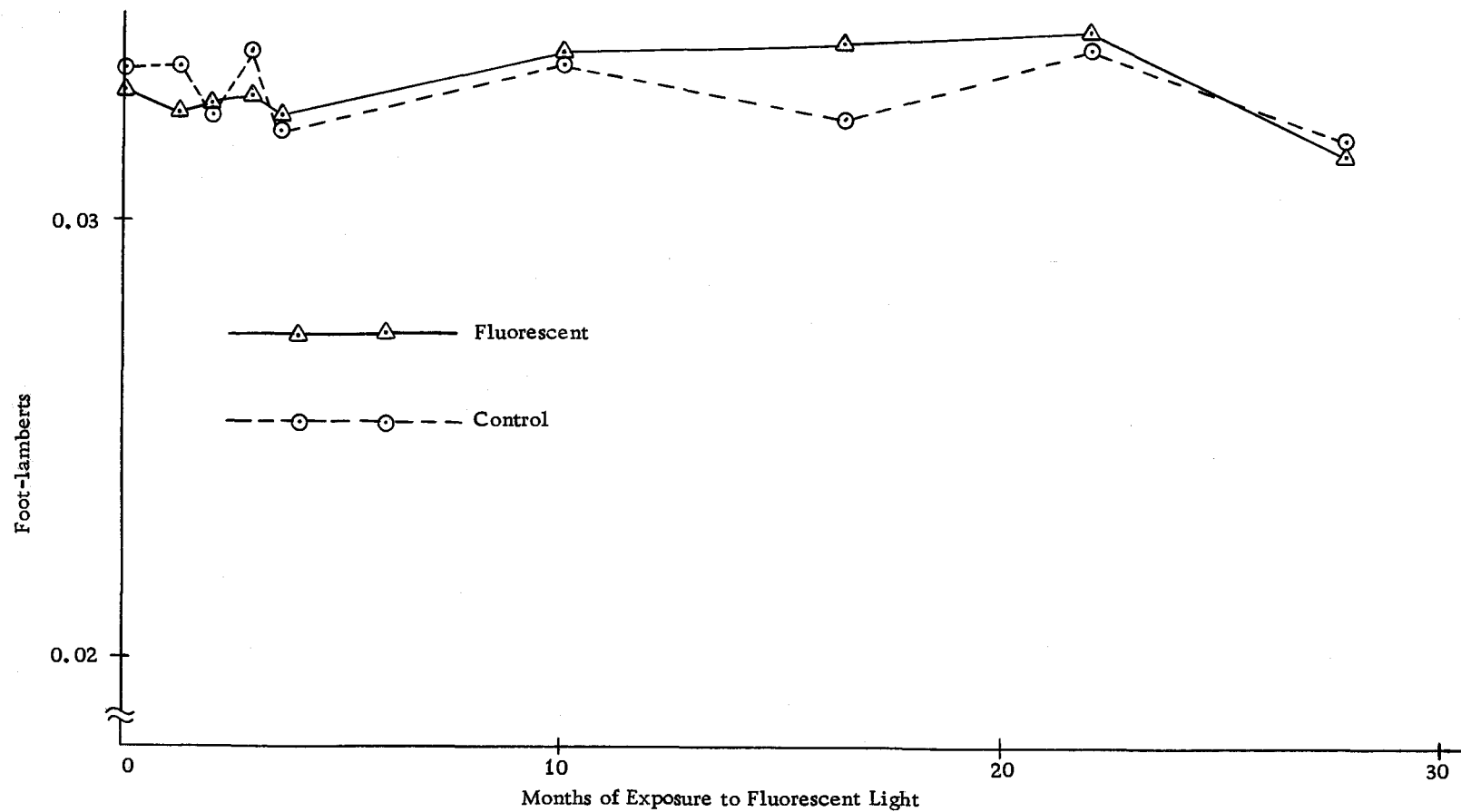


Figure 17. Response of screens exposed to fluorescent light excited by one-half Roentgen per minute at 70 kVp versus adjusted months of exposure to fluorescent light.

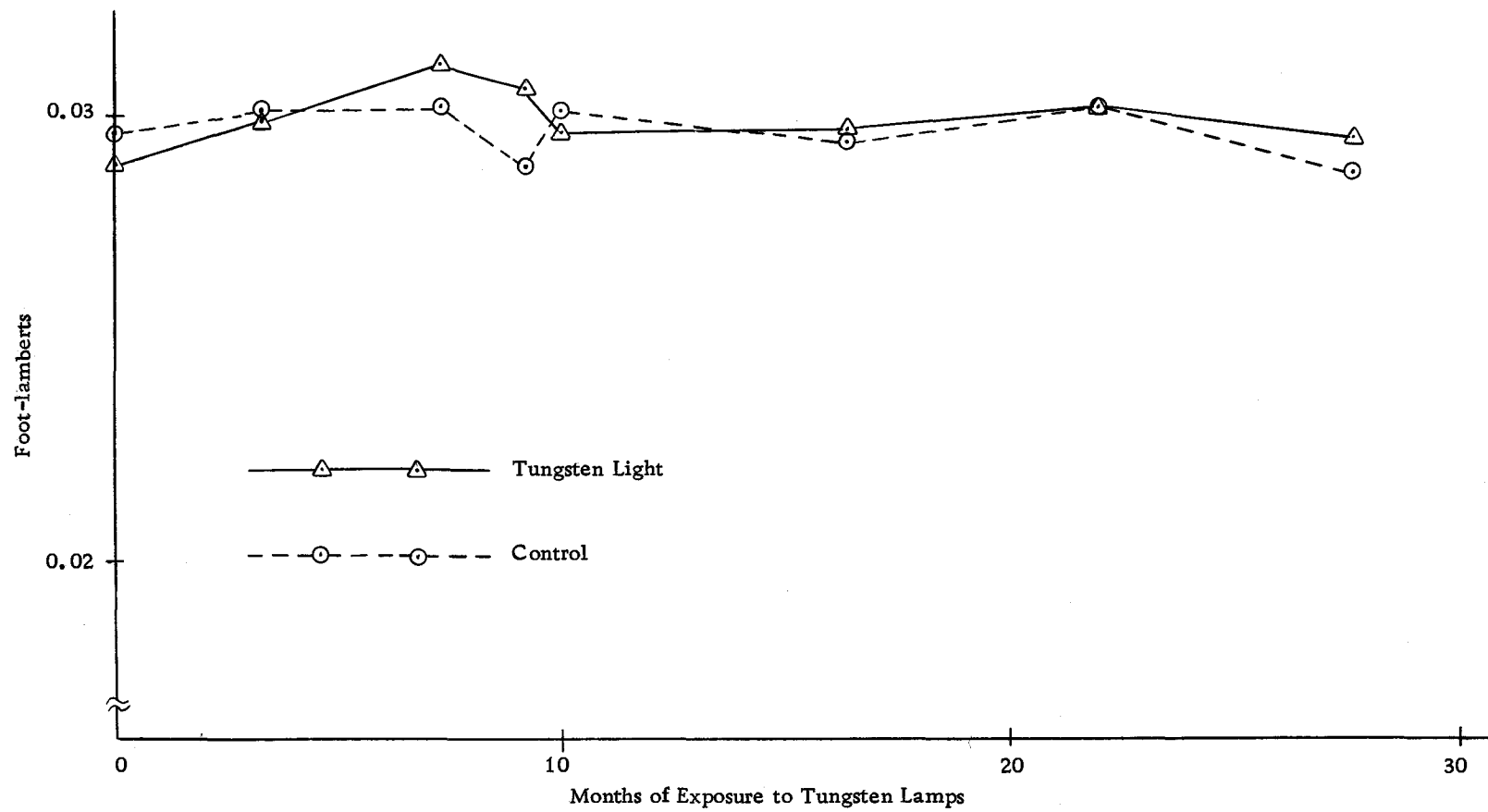


Figure 18. Response of screens exposed to tungsten light excited by one-half Roentgen per minute at 100 kVp versus adjusted months of exposure to tungsten lamps.

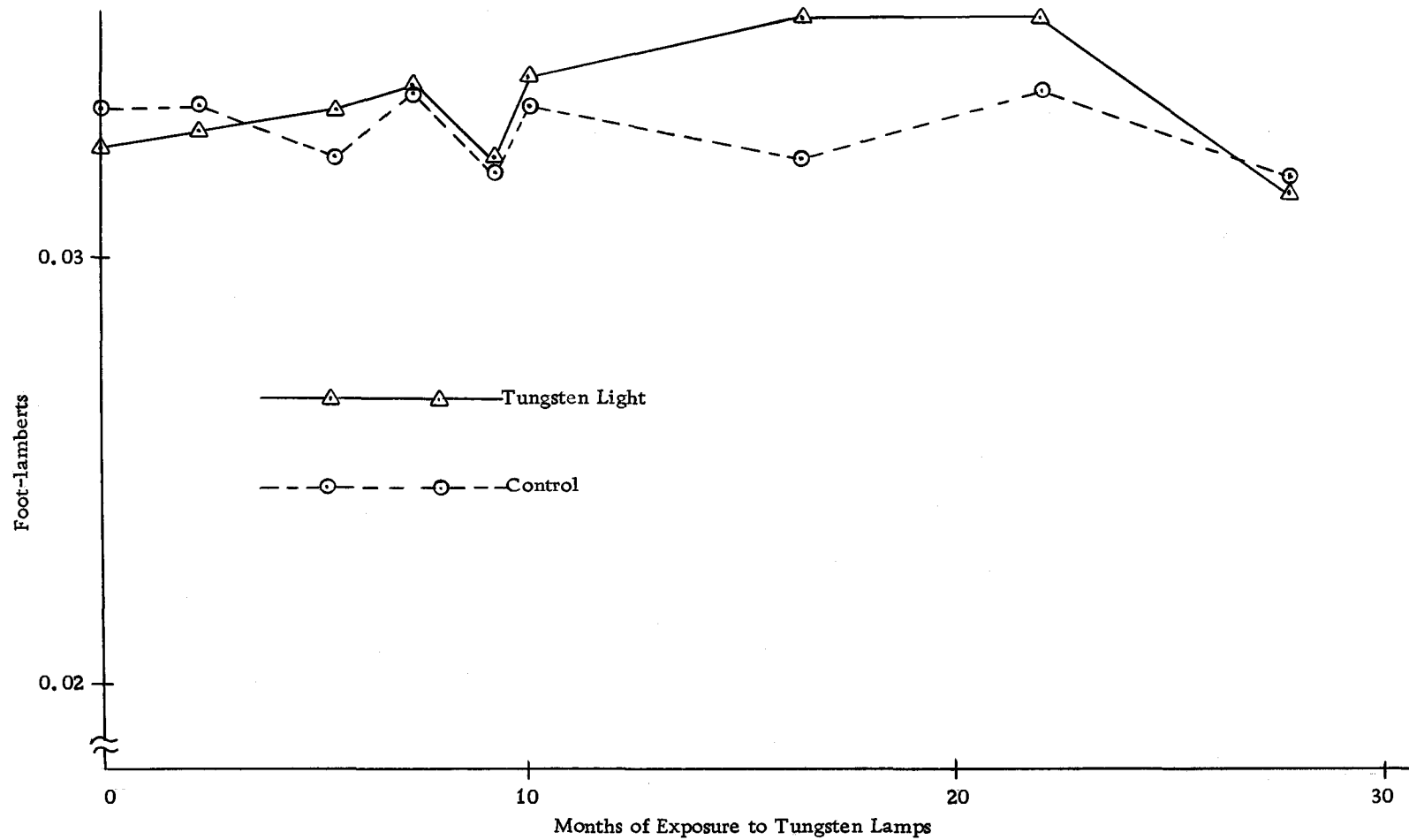


Figure 19. Response of screens exposed to tungsten light excited by one-half Roentgen per minute at 70 kVp versus adjusted months of exposure to tungsten lamps.

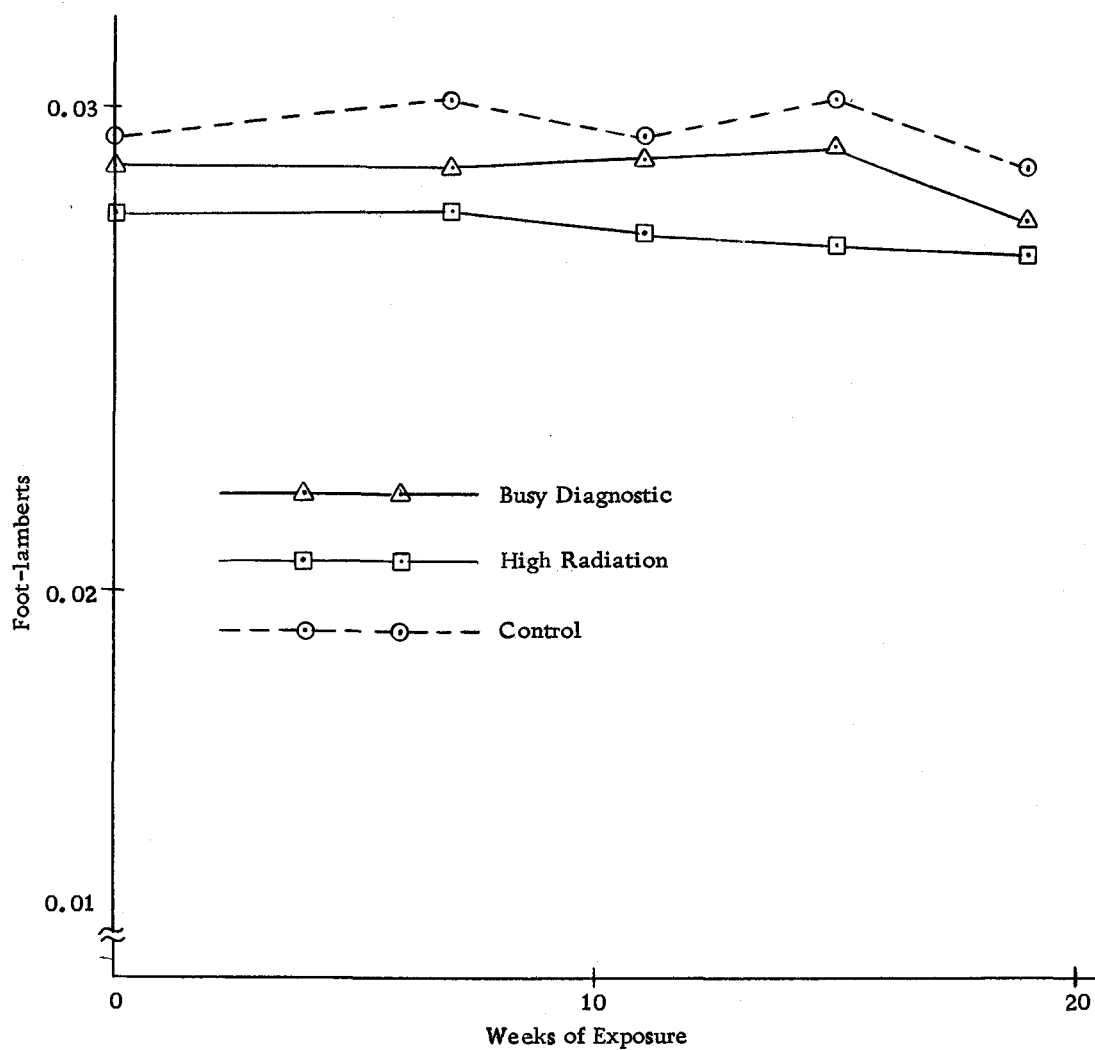


Figure 20. Response of screens exposed to radiation excited by one-half Roentgen per minute at 100 kVp versus weeks of exposure.

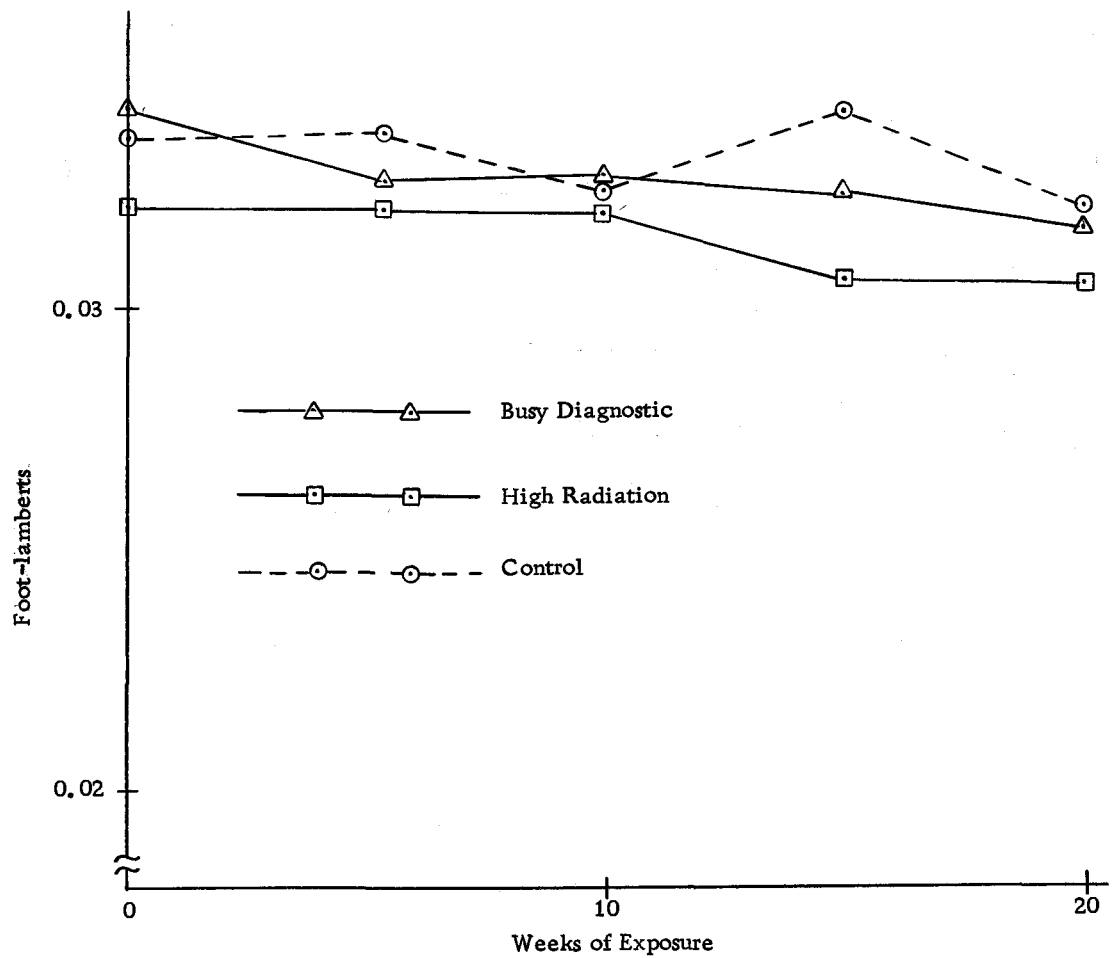


Figure 21. Response of screens exposed to radiation excited by one-half Roentgen per minute at 70 kVp versus weeks of exposure.

might be found in a well-lighted room. Using this value, the illumination of the test screens have been adjusted to months of exposure to this level. A 24-hour day and 30-day month have also been assumed for this extrapolation of the illumination level.

Figures 20 and 21 show the relative condition of the busy diagnostic and high radiation test groups as a function of the number of milliampere minutes of exposure received.

Measurements of the light output of a number of old fluoroscopic screens were taken. The results of these measurements, together with the readings taken on some new screens, are shown in Table 2. The values shown for a and b represent the average for the initial readings obtained for the 12 type I and 12 type II screens at the start of the screen deterioration study. Screens c and d, both Patterson B-2 screens, were the only old screens tested for which a reasonable age and history of use could be established. Both screens were 20 years old and had only been used a few times for diagnostic purposes at the time they were originally purchased. During this 20-year span, both screens had been protected from exposure to light.

Table 2. Luminescent response of a number of old fluoroscopic screens.

| Screen | Luminescence measured at 100 kVp, 5 mA (1.29 R/min) | Luminescence measured at 70 kVp, 5 mA (0.46 R/min) |
|---------------------------------|---|--|
| a. Average of 12 type I | 0.075 foot-lamberts | 0.029 foot-lamberts |
| b. Average of 12 type II | 0.087 " | 0.031 " |
| c. Patterson B-2 (20 years old) | 0.074 " | 0.027 " |
| d. Patterson B-2 (20 years old) | 0.067 " | 0.026 " |
| e. Patterson B-2 | 0.072 " | 0.028 " |
| f. Patterson B-2 | 0.067 " | 0.026 " |
| g. Patterson B-2 | 0.071 " | 0.027 " |
| h. Patterson B | 0.041 " | 0.017 " |
| i. Patterson B | 0.033 " | 0.014 " |

V. SUMMARY AND CONCLUSIONS

All aspects of this study have been so designed that a long term investigation can be conducted with as little variation in the experimental parameters as possible. The geometry of the special X-ray machine is fixed so that measurements and exposures are already made at the same position. In addition, the unit is used exclusively for this study. A long term calibration can be maintained on the "Brightness Spot Meter" by use of the regulated brightness source.

The results of this study indicates that with the exception of the screens exposed to sunlight, no significant variation has been observed in the luminescent response of the different test groups over that observed for the controls. A definite deterioration in their luminescent response can be seen in the screens exposed to sunlight. An average decrease of about 15 percent has occurred for these screens over that of the controls during the period of the study.

The measurements made on old fluoroscopic screens indicate that their luminescent response is less than that of a new fluoroscopic screen. No definite conclusions can be made about the possible deterioration of these screens since with the exception of the two 20 year old screens, the age and history of exposure is not known. In addition, the unavailability of a screen produced at the same time as the older screens for which little or no deterioration had occurred prevents a direct comparison of deterioration.

The information in this report contains only initial findings. Studies must be continued in order to establish meaningful information relative to the long-range deterioration of fluoroscopic screens.

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