DEVELOPMENT OF A FILM RADIATION DOSIMETER FOR SMALL DOSES

by

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STATEMENT BY AUTHOR

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ABSTRACT

An assembly of Polaroid film and a fluorescent intensifying screen was evaluated as a low level radiation dosimeter. The film response as a function of dose rate, total dose, energy of incident radiation and type of fluorescent screen was studied. The film response was independent of gamma ray energies between 0.37 and 1.33 Mev, but was 5 to 20 times greater for x-rays produced by 1 Mev electron striking a gold target than it was for Co-60 radiation. The film showed a decrease of its sensitivity at very low dose rates. Zinc-cadmium sulfide fluoroscopic screen with type 57 (ASA 3200) film could detect a 10 mr dose from a 10 mr/hr radiation field. Doses between 10 mr and 225 mr were detectable with ASA 3200 film and type 42 (ASA 200) responded to doses between 0.4 r and 2.4 r when exposed to 10 mr/hr radiation fields. The increased sensitivity at high dose rates resulted in a maximum detectable dose on type 57 film of 10 mr from an 1850 mr/hr field.
INTRODUCTION

A great variety of devices have been developed in the last half century to detect and measure radiation. The multiplicity of techniques has been largely due to the varied purposes for which the devices were intended.

Electronic dosimeters exemplified by Geiger-Müller meters and scintillators are inherently complex and are of questionable reliability when subject to rough use. Ionization chambers such as those commonly used in personnel dosimetry are simple devices containing two insulated electrodes with an electrical charge which is dissipated by ionizing radiation. Their disadvantages consist of the requirement of auxiliary equipment for charging and readout, and sensitivity to mechanical shock and humidity changes. Quartz fiber electrosopes are self-reading but retain the problem of shock and humidity response. Thermoluminescent solids are utilized as radiation dosimeters by storing radiation induced disorders which are measured by the quantity of light emitted with the application of heat. They have proved sensitive over a range of 2.5 mrem to 1000 r but require a relatively sophisticated readout device. A chemical reaction induced by ionizing radiation can also be utilized as a radiation dosimeter. The primary problem with these devices has been extending their range to low integrated doses. Aqueous solutions of halogenated hydrocarbons are capable of sensitivities as low as 25 roentgen but ferrous systems such as the Fricke cell are insensitive below the
kilo-roentgen range (Fricke and Morse, 1929). Aqueous iron chemical dosimeter capability was extended to cover the range from 20 r to 2 kr by work on ferric bathophenanthroline at The University of Arizona (Benn, 1965).

Solid chemical dosimeters such as silver phosphate glass are in use. The use of a solid rather than a liquid detector results in a device inherently more rugged. The effect of radiation is to reduce silver ions which results in the glass becoming fluorescent. The fluorescence is proportional to the dose received and may be determined through the use of a photocell and photomultiplier tube.

The most widely used radiation dosimeter utilizes photographic film. Through a suitable choice of films it is possible to use photographic dosimeters to detect total radiation doses from 100 mr to as high as $10^5$ roentgen. The sensitivity and contrast of the film is highly influenced by the developing agents, their age and temperature, and the development time. Because of this the use of film dosimeters requires carefully controlled laboratory processing.

The Polaroid Corporation has recently marketed film having a self-contained developing system. The field readout capability of the system combined with the inherent simplicity of film made the Polaroid an extremely good candidate for investigation as a radiation dosimeter.

This investigation will be concerned with the development of a dosimeter of minimum complexity capable of detecting integral doses ranging from 10 mr to about one roentgen. The system should not be affected by the time period between the exposure and the determination.
of the dose and the desired device should require no auxiliary equipment and be simple to operate.
A photographic film is composed of silver halide grains sus-
pended in a gelatin substrate which is usually supported by a cellu-
lose acetate base. The latent image produced by light activation of
the silver halide renders an entire grain developable with the appli-
cation of suitable reducing agents.

The relation between the light intensity and the exposure time
of the film is described by the degree to which the film follows the
reciprocity law. This law states that the resultant of a photochemical
reaction is dependent only on the product of the light intensity and the
time of exposure and is independent of the magnitude of either quantity.
Photographic films tend to follow the reciprocity law for high intens-
ity light (short exposures) but deviate from it, in the sense of becom-
ing less sensitive, when exposed to light of low intensity. This fact
can be attributed to the unstable nature of the deposited silver and
its recombination with the halide (Morgan, 1944). Figure 1 provided
by the Polaroid Corporation demonstrates reciprocity failure in type 47
film. Note that the region of the greatest rate dependence is approxi-
mately two decades long.

The sensitivity of photographic film is also a function of the
wave length of the light to which it is exposed. The inherent sensi-
tivity of plain silver halide emulsions tends to be in the region of
Figure 1. Reciprocity Failure in Type 47 Polaroid Film
400 to 500 m $\mu$. This range of sensitivity can be extended to longer wavelengths by the addition of sensitizing dyes. The dye absorbs the light to which the grain is insensitive. The absorbed energy is then transmitted to the silver halide resulting in photolysis of the latter. Photographic film is sensitized so that its response is as nearly constant as possible over the visible range. The responses of several Polaroid films to artificial daylight are shown in Fig. 2.

The response of photographic film to gamma and x-radiation is linked to the interactions of high energy photons with matter. This interaction can be considered to be essentially the sum of three processes: the photoelectric effect, compton scattering, and pair production. Only Compton scattering and photoelectric effect are significant at the energies of interest here. The process of the photoelectric effect is begun when an incident photon transfers all its energy to an orbital electron. The electron is then emitted from the atom with a kinetic energy equal to the photon energy minus the binding energy of the electron. As the photon energy increases, Compton scattering becomes the primary mode of attenuation. In this process the photon undergoes collision with an orbital electron. The result is a lower energy photon traveling in a new direction and the ejection of the electron from the atom. If the secondary photon does not escape the medium it will undergo succeeding compton scatterings until it is absorbed via the photoelectric effect.

The electrons produced by the above processes induce photolysis in the silver halide grains. Since the photoelectric effect is roughly proportional to the inverse of the cube of the photon energy and the
Figure 2. Spectral Characteristics of Screen and Films
compton effect to the inverse of the first power of the photon energy, it is to be expected that the film response will be energy dependent. Film exposed directly to gamma and x-radiation has been observed to follow the reciprocity law. This has been explained by the high free electron population causing replenishment of any metallic silver lost by the reformation of silver halide (Morgan, 1944).

The greater sensitivity of silver halide to photons in the visible region can be exploited through the use of a fluorescent screen. The electrons produced by the gamma or x-rays incident on the screen result in excitation of the screen phosphors and their emission of visible light. Exposure of the film to the screen will result in an increase in the former's sensitivity. The intensity of the emitted light is proportional to the flux of the incident radiation. The film response is still energy dependent due to the energy dependence of the photon interaction with screen material.

The emission of the screen can be divided into fluorescence and phosphorescence. Fluorescence can be considered to be instantaneous with the incident photon while phosphorescence results from the decay of metastable excited energy states and can often be detected for several hours after exposure of the screen to light. The persistence of the phosphorescence can be utilized to overcome the decreased sensitivity of the dosimeter due to the film's departure from the reciprocity law. If the decay time of the phosphorescence is known, it is possible to choose a time such that the light emitted is of insufficient intensity to result in a detectable film response. A radiation
flux which could not normally produce sufficient screen fluorescence to produce a latent image would then be detectable since the summation of the screen emission from radiation (fluorescence) and that from phosphorescence would produce a light intensity sufficient for a photographic response.

The spectral emission of the screen will not necessarily correspond to the maximum sensitivity of the film as is shown in Fig. 2 for du Pont CB-2 and Polaroid films. Since the spectral response of film is dependent on the sensitizing dyes, spectral optimization of the screen and film can be done in a straightforward manner by the addition of appropriate dyes during manufacture.

Dose Attenuation Through Collimator

It was desired to utilize x-radiation from The University of Arizona's electron accelerator in the study of film response to dose rate and film energy. In order to do this properly the dose rate at the film plane must be known.

The assumption of a point source of x-rays results in the length and cross-sectional area of the collimating hole having no effect on the film plane dosage since the latter is only a function of the distance from the source. Experimental results demonstrated that dose rates considerably lower than those predicted were occurring at the film plane. Further investigations indicated that the source distribution could be better approximated by a plane. The dose at the film plane is then a function of the fraction of the source subtending the solid angle having its origin at the film plane and its magnitude...
limited by the collimator. Since the intensity of the previously considered point source is now the sum of infinitesimal sources spread uniformly over the plane and since only a fraction of this plane contributes to the dose a geometric attenuation occurs which is significantly greater than that due to distance.

Since an ionization probe (Victoreen Model 711) was used to monitor the x-ray dose rates, the attenuation factor would be one which relates the dose rate at the film plane to that recorded by the probe.

The dose received by the probe may be considered to be the summation of the infinitesimal sources that are visible to the probe, or

\[ \int_{\text{probe}} \frac{\partial E}{\partial \Omega} \, d\Omega \]

where \( \varepsilon \) refers to the elemental source strength and \( \Omega \) to the solid angle. Since the probe is unshielded the integral equals that recorded on the monitor. The dose rate at the film plane would be

\[ \int_{\text{hole}} \frac{\partial E}{\partial \Omega} \, d\Omega \]

with the limits of integration determined by the collimator hole. The geometric attenuation factor \( K \) may be defined as:

\[ K = \frac{\int_{\text{probe}} \frac{\partial E}{\partial \Omega} \, d\Omega}{\int_{\text{hole}} \frac{\partial E}{\partial \Omega} \, d\Omega} \quad (1) \]

The parameters of the integrals would be exceedingly difficult to determine so an alternative technique employing the same definition of \( K \) will be used. If the probe is mounted behind the collimator hole and the dose received is integrated over the active volume of the probe,
the resulting quantity will equal the unattenuated dose divided by the geometrical attenuation factor. This may be stated mathematically as:

$$D = K2\pi \int_{0}^{R} D(r)r dr$$  \hspace{1cm} (2)

where $D$ is the dose received by the unshielded probe, $D(r)$ is the dose received through the collimator hole and $R$ is the radius of the probe's sensitive volume.
EXPERIMENTAL PROCEDURE

Polaroid film utilizes a process in which the developing chemicals are an integral part of the film package. This package is composed of film, print paper, and a packet of developing gel. In roll film the gel packet is attached to the edge of the film, while in 4x5 packets it is attached to the edge of the print paper. By passing the assembly beneath a roller the gel packet is broken and the gel evenly spread between the film and print paper. Foreign material beneath the roller or uneven roller pressure will interfere with the development of the exposure. The time between the film coming in contact with the gel and the removal of the print for examination is 10 to 15 seconds.

Roll film was used with a "Graflex Polaroid Land Camera Back" (Cat. No. 9108) which was originally designed to allow the use of Polaroid roll film with a Graflex camera. The device is a Polaroid camera body with the lens assembly removed so that it can be attached to the rear of a Graflex camera. The "Polaroid Land Camera Back" has a small space between the film and the sliding light seal. This space was used as a container for fluoroscopic screens. In order to maintain contact with the film the screens were backed by a block of foam rubber. Each roll of film contained eight exposures of which the first and last were used as controls. In order to prevent the later exposures from having a dose contribution from the earlier ones, the film magazine was protected by a lead brick serving as a shadow shield. When a fluoroscopic
screen was in the camera the film was loaded under illumination from a Kodak Wratten Series OA safelight. The first frame was not exposed to the screen until one hour after loading. This allowed time for any screen phosphorescence to die out.

Polaroid film is also available in packages containing a single 4x5 film, print paper, and gel packet. These are designed for use in a "Polaroid Land 4x5 Film Holder No. 500" which in normal use serves the same function as the Graflex Camera Back previously discussed. The holder was made light tight by covering its face with black opaque paper upon which the screens were mounted.

The several x-ray screens investigated included U. S. Radium Corporation Radilin F and du Pont E-2, CB-2, Par-speed, and Hi-speed. All emitted yellow-green light except par-speed and Hi-speed which emitted blue light. A qualitative analysis of the exposure was facilitated by mounting on the screens a "U" or "X" fashioned from 1/16 inch lead. A more quantitative measure of the dose was achieved by comparing the print with a calibrated Kodak gray scale No. 113 GS 35.

Use of the isotopic sources in the investigation was standardized. The source was elevated one inch from a laboratory work bench and was surrounded on three sides by lead bricks. Isodose lines were plotted at 5, 10, and 20 mr/hr on the remaining side. These lines had approximate radii of 15, 10, and 6 inches respectively. These lines were determined through use of a Johnson model G517-5 monitor. The results were verified with a Jorden model AC-50B-SR-X and a Nuclear Chicago model 2526 dosimeter (calibration and correlation of instrumentation is given in Appendix B).
Total integrated dose measurements utilized as a source a Co-60 solution in a 50 ml volumetric flask. When it was prepared on February 25, 1960, the specific activity of the solution was 3.45 μc/ml, by radioactive decay the activity was reduced to 1.78 μc/ml on February 25, 1965.

The responses of the photographic emulsion to photon energy and flux are important parameters in evaluating a film as a dosimeter. Gamma radiation from Cr-51, Ag-108 and 110, and Co-60, and $10^3$Kvp x-radiation was used to investigate the energy dependence of the Polaroid film systems as dosimeters. These radiation sources are tabulated with respect to energy and half-life in Table 1. Neutron bombardment of Chromic Nitrate ($\text{Cr(NO}_3\text{)}_3\text{(H}_2\text{O)}_9$) in the TRIGA reactor of The University of Arizona was used to produce Cr-51. The source was not used until 24 hours after removal from the reactor in order to allow the shorter life isotopes such as Cr-55 to decay away. Thermal neutron bombardment of silver nitrate ($\text{AgNO}_3$) was used to obtain the 0.72, 0.62, and 0.43 Mev gamma rays from Ag-108 and the 0.67 and 0.89 Mev gamma rays from Ag-110. The 24 hour wait after neutron bombardment allowed only the gamma rays of the five year half-life isomer of Ag-108 and the 240 day isomer of Ag-110 to contribute to the film dose.

The dose rate due to x-rays produced by a gold target mounted on the one Mev electron accelerator of the Department of Nuclear Engineering, The University of Arizona, was measured with a model 711 Victoreen Remote Area Monitor. In order to monitor continuously the dose rate the sensing element was placed 31-1/2 inches from the centerline of the
Table 1
PHOTON ENERGY AND HALF LIFE OF RADIATION SOURCES

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$\frac{\tau}{2}$</th>
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<tr>
<td>Cr-51</td>
<td>27.8 days</td>
<td>0.32</td>
</tr>
<tr>
<td>Ag-108</td>
<td>5 years</td>
<td>0.72, 0.62, 0.43</td>
</tr>
<tr>
<td>Ag-110</td>
<td>240 days</td>
<td>0.67, 0.89</td>
</tr>
<tr>
<td>Co-60</td>
<td>5.27 years</td>
<td>1.17, 1.33</td>
</tr>
<tr>
<td>X-ray</td>
<td></td>
<td>1000 KV$_p^*$</td>
</tr>
</tbody>
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*KV$_p$ or kilovolt peak refers to the maximum energy of the X-rays resulting from electrons of specified energy striking the target.
x-ray target and its centerline was 2-1/2 inches from the face of the target as is shown in Fig. 3. The decreased dose rate in this position allowed the monitoring of high dose rates in the areas of interest without exceeding the range of the Victoreen instrument. By comparing the beam currents necessary for the same dose rate at a point of interest and at the standard position, it was possible to determine a dose rate ratio. A dose rate of 1000 r/hr 11-1/2 inches from the target required a beam current of .042 ma while .27 ma were required for the same dose rate at the standard position. The ratio therefore is 6.9. Eleven and one half inches was the distance between the source and the film plane. Data on dose rates at different film plane distance are given in Appendix A.

Some of the experiments were designed to determine the dose rate at the film plane through the pinhole and the geometry of the source. These data were necessary for evaluation of the films. A shutter device was constructed which in the open position provided a 1/16 inch square hole 6 inches long. Four inches of this was part of the stationary shield enclosing the 4x5 film holder and the remainder was part of the shutter. If all the radiation were emitted from a point source the device should have been capable of producing a millisecond pulse which would have been recordable on the film. The dose received by the film was not detectable.

Several experiments indicated that the source could be approximated by a plane source. The determination of the resulting geometrical attenuation factor (K) required solution of Eq. (2). The function D(r) was found by placing the Victoreen sensing element behind the shield hole
Figure 3. Orientation of X-ray Source, Sensing Element and Film Holder
and recording the dose rate as the distance between the element's centerline and that of the hole was varied. The radial sensitivity, \( D(r) \), of the element is plotted in Fig. 4. It is seen that the function \( D(r) \) may be considered to be composed of two straight lines, from zero to .125 and from .125 to .318 inches. Therefore from Eq. 2

\[
\frac{D}{K} = \int_{0}^{R} D(r)2\pi rdr = \int_{0}^{.125} D_1\pi rdr + \int_{.125}^{.318} D_2\pi rdr \quad (2b)
\]

and from Fig. 4

\[
D_1 = -.16r + .049 \quad (2c)
\]

\[
D_2 = -.132r + .039 \quad (2d)
\]

Substituting (2c) and (2d) into (2b) results in

\[
\frac{D}{K} = .395 \times 10^{-2} \text{ Kr/hr}
\]

The same beam current results in a dose rate at the unshielded detector of 8.8 Kr/hr. At 11-1/2 inches from the target \( K \) is,

\[
K_{11-1/2} = \frac{D}{.395 \times 10^{-2}} = 2230.
\]

Therefore the dose rate at the film plane 11-1/2 inches from the target is the Victoreen reading at that point divided by 2230. The attenuation factor at 23 inches will differ from the preceding since the film will be able to see a greater fraction of the source area. This fraction will increase with the square of the distance, resulting in the attenuation factor being reduced by a factor of four or \( K_{23} = 558 \). The lack of film response to the millisecond pulses produced by the shutter can thus be explained by the geometrical attenuation. Application of the
Figure 4. Radial Sensitivity of Sensing Element

Radius of Sensitive Volume (R) Equals 0.318 inches

Distance from Centerline (inches)
preceding attenuation factors results in 16 milliseconds being needed for a detectable dose when the accelerator is operated at its rated capacity of 10 ma. Since the shutter could not provide pulses longer than 10 milliseconds, its further use was discontinued.

The determination of the attenuation factor was based on the idealized case of a uniform plane source. The actual case is more accurately described as a plane source containing a localized region of relatively high intensity surrounded by a region of fairly uniform intensity. Since the attenuation factor was defined as the ratio of the dose received by the unshielded detector to that received through the shield hole the error in the actual distribution is cancelled out. It is believed that the determination of the attenuation factor is probably accurate to within a factor of two.

Dose rate data using pulses greater than 2 seconds necessitated the use of a brick shield between the x-ray target and the entrance to the shield hole as seen in Fig. 3 to prevent exposure of the film during startup of the accelerator. Operational procedure consisted of bringing the accelerator up to the desired beam current, electromechanically removing the bricks and after the film is exposed for the desired length of time scrambling the accelerator. The scrambling of the accelerator was essentially instantaneous but times of approximately two minutes were needed to build up to the desire beam current. The use of control films demonstrated that no detectable dose was being received during the run-up of the beam current under these conditions. These films were placed in the shield and the operating procedure
followed up to the point of removing the bricks, at which time the accelerator would be scrambled and the films developed.

The 4.5 curie Co-60 source available at the Department of Nuclear Engineering was of sufficient strength to duplicate the dose rate studies done with the accelerator. Duplication of dose rates allowed comparison of the film's response to the spectral differences of Co-60 and x-radiation. The 4x5 film holder was mounted on a fiberboard base on which was mounted a handle to facilitate fast placement and removal. Variation in dose rate was achieved by varying the source to film plane difference. Dose rates were obtained through use of a Nuclear Chicago Model 2511 Survey Meter for dose rates less than 2.5 Kr/hr.
RESULTS AND DISCUSSION

The sensitivity of the film dosimeter was greatly increased through the use of fluorescent screens. The degree of sensitization was dependent on the spectra and intensity of the light emitted from the screen. This intensity dependence was a result of reciprocity failure of the film. The higher cross-sections associated with low energy photons result in the dosimeter being less sensitive to high energy gamma radiation. The dose capability of the screen is dependent on all of the preceding and therefore will vary greatly with them.

Intensifying Screens

The optimum sensitivity of the dosimeter is dependent upon matching the absorption spectra of the film to the emission spectra of the screen. It is seen in Fig. 2 that the maximum sensitivity of types 42, 47 and 57 Polaroid films occurs at 4360 and 5800 Å while type 410 is most sensitive at 4500 and 5800 Å. The spectral distributions result from the fact that Polaroid film is intended for photographic use and therefore is designed to be most sensitive over the visible region. Zinc cadmium sulfide screens exemplified by du Pont E-2 and CB-2, and US Radium Corporation Radilin F emit light at the proper frequency and with sufficient intensity to provide the amplification necessary to record the specified integrated doses. The spectral emission of du Pont E-2 and CB-2 has a peak at 5300 Å.
Further improvement of the matching could be achieved through the addition of dyes to the film emulsion or additives to the screen. Observation of Fig. 2 indicates that optimum matching of the film and screen would result in approximately a fourfold increase in dosimeter sensitivity. A negligible increase in the sensitivity results from the combination of Polaroid film with du Pont Par-speed and Hi-speed intensifying screens. This was to be expected since medical x-ray screens normally emit blue or ultraviolet light and are coupled with emulsions which are extremely sensitive in these regions.

The zinc cadmium sulfide screens exhibited both fluorescence and phosphorescence. No phosphorescent effect was detected when the screen was exposed to dose rates of the order of 10 mR/hr. All the emission could then be taken as to occur instantaneously (fluorescence) with the incident radiation. Substantial phosphorescence did occur after exposure of the screen to visible light. The effect was most evident with Radilin F and was detectable with a one-half hour exposure of type 57 film (ASA 3200) up to 9 hours after exposure of the screen to 40 foot-candles of fluorescent light. Although no film response was found 12-1/2 hours after the screen's exposure to light, an increase in the sensitivity of the dosimeter was noted.

The increased sensitivity of the dosimeter after exposure of the screen to light can be attributed to the presence of a threshold light intensity for film response. This threshold arises from the film not following the reciprocity law. The intensity of the phosphorescence from the light exposure was below the threshold level as was the
fluorescence from the incident radiation, but the summation of the two was sufficient to produce a latent image.

Of the screens investigated only du Pont E-2 was sufficiently sensitive in a 10 mr/hr field to detect a 10 mr dose on ASA 3200 film without any amplification from phosphorescence. This screen was composed of 25-30 μ grains of zinc cadmium sulfide mounted on a 10 mil polyester backing. The intensifying factor, defined as the ratio of the dose necessary to produce the same film response without a screen to that with a screen, was found to be 11 when the film was exposed to Co 60 radiation. The composition of CB-2 and E-2 were identical except for the coating weight of the phosphor layer. The greater weight of the layer on the E-2 screen increased the probability of photon interaction and therefore increased the sensitivity. Since high resolution was the limiting factor on the coating weight for medical fluoroscopy it is believed that a further increase in the sensitivity is possible by increasing the thickness of the phosphor. This would be limited by reduced emission due to absorption and scattering through a thick screen.

Dose Rate

The rate dependence of type 57 film coupled with an E-2 screen is shown in Fig. 5 and is seen to be greatest for exposures greater than 38 seconds or conversely for dose rates less than 950 mr/hr. After allowing for the energy dependence of the screen good correlation was found between gamma and x-ray film responses as a function of dose rate. This would be expected if the rate effect is due to the intensity
Figure 5. Dose Rate Dependence of an Assembly of E-2 Screen and Polaroid Film
of light emitted by the screen. Comparison of Fig. 5 with the rate
dependence of the film alone shown in Fig. 1 shows that the region of
greatest non-linearity is in both cases approximately two orders of
magnitude wide. This would again indicate that the rate dependence is
due to a threshold light intensity of film response.

It is seen in Fig. 5 that the response tends toward linearity
for exposures less than 40 seconds. This plateau region was also the
most sensitive, having a maximum detectable dose of 10 mr. Note that
the maximum detectable dose for dose rates in the order of 10 mr/hr was
225 mr while the minimum detectable dose in this region was 10 mr.

Energy Dependence

The energy dependence between 0.37 and 1.33 Mev was investigated
with Cr 51, Ag 108 and 110 and Co-60. It is seen in Fig. 6 that the
film response is essentially independent of photon energy in this range.
Comparison of the exposures shown in Fig. 7 indicates that the film-
screen assembly is approximately 10 times more sensitive to x-rays
produced by bombarding a gold target with one Mev electron than it
is to Co-60 gamma rays. This result is not unexpected due to the great
difference between the energy spectra of x-rays and gamma rays. The
accuracy in the determination of the energy dependence is directly re-
lated to the determination of the x-ray dose rate at the film plane.
The determination of the dose rate at the film plane was considered to
be accurate within a factor of two. The screen may therefore be between
5 and 20 times more sensitive to these x-rays than to Co-60 gamma rays.
Figure 6. Gamma Ray Energy Dependence of Type 57 Polaroid Film with E-2 Screen
Figure 7. Sensitivity Variation Between X-rays and Gamma Rays of Type 57 Polaroid Film with E-2 Screen
Total Dose

The response of a photographic emulsion to radiation is normally presented graphically as a plot of the logarithm of the dose versus the density of the image. The curve is referred to as the characteristic curve. The density is defined as the logarithm of the ratio of the incident light to the transmitted light. This definition is only useful when studying a negative but the Polaroid process results in the production of a print without a true negative. The use of a grey scale which was calibrated in reflection density facilitated quantitative definition of the film exposure and therefore the construction of characteristic curves. The graininess of the higher speed films and the natural bluish tint of Polaroid film added a degree of subjectivity to the comparison with the grey scale. For this reason both reproductions of the prints and the corresponding characteristic curves are shown in Figs. 8 through 14. No characteristic curve of type 410 film is presented since the prints were too grainy to allow worthwhile comparison with the grey chart.

Prototype

A dosimeter composed of an intensifying screen and Polaroid film would be very similar to the modified 4x5 film holder utilized in the experimental work. It is required that the screen be movable in order that it be in contact with the film during exposure and the film and print paper be in contact during development. The system design to achieve this is shown in Fig. 15. The assembly of print paper, gel packet, and film is fastened in the inner envelope. The first step in developing
the exposure is the removal of the screen from between the print paper and the film by sliding the middle envelope the required amount. Passage of the packet beneath a spring loaded, rubber surfaced roller is all that is required for development.
Figure 8. Film Response of Type 57 Polaroid with E-2 Screen to Co-60 Radiation
Figure 9. Characteristic Curve of Type 57 Polaroid Film with E-2 Screen
Figure 10. Film Response of Type 47 Polaroid Film with E-2 Screen to Co-60 Radiation
Figure 11. Characteristic Curve of Type 47 Polaroid Film with E-2 Screen
Figure 12. Film Response of Type 42 Polaroid Film with E-2 Screen to Co-60 Radiation
Figure 13. Characteristic Curve of Type 42 Polaroid Film with E-2 Screen
Figure 14. Film Response of Type 410 Polaroid Film with E-2 Screen to Co-60 Radiation
Figure 15. Prototype Radiation Dosimeter Employing Polaroid Film and a Fluorescent Screen
CONCLUSIONS

Times between the exposure and development of the film of up to ten days were found to have no effect on the film's response.

It is seen from Fig. 7 through 13 that the combination of Polaroid film and E-2 intensifying screen allows the determination of doses ranging from 5 mr to over 2 roentgens thus exceeding the 10 mr to 1 roentgen requirements. Doses between 225 and 438 mr lie between the upper range of type 57 (ASA 3200) and the lower range of type 42 (ASA 200). This gap should easily be filled by utilization of type 37 (ASA 400) Polaroid film. Unfortunately, this film was not available for investigation. The upper limit of detection can be extended by a factor of 10 through use of film without a screen. Use in the same packet of film with and without an intensifying screen is only practical if a 1/4 inch screenless zone is provided around the film section not exposed to the screen. This is done to minimize light leakage from the screen to the film. If the film was a composite of films of several speeds the required dose capability would be achieved without a size limitation and with a minimum of complexity.

The preceding dose range capabilities are only applicable if the dose rates are of the order of 10 mr/hr. Higher dose rates would result in altered characteristic curves owing to the rate dependence discussed earlier. The screen film combinations that were investigated were too sensitive at high dose rates to detect a dose of one roentgen.
Further investigation in this area should indicate the techniques necessary to achieve the desired dose range. Related work would be the determination of the characteristic curves for films exposed to dose rates corresponding to the plateau of the rate curve.

Capabilities of the system as a neutron detector should be determined. One packet might then serve as both a neutron and a gamma dosimeter. No investigation was made of the effect of temperature on film exposure or development. Knowledge in these areas would indicate future applicability of the system.
APPENDIX A

Table A-1

EFFECT OF DISTANCE FROM X-RAY TARGET ON DOSE RATE

<table>
<thead>
<tr>
<th>Distance from Source</th>
<th>Current</th>
<th>Dose Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>45-5/8 inches</td>
<td>0.092 ma</td>
<td>0.2 Kr/hr</td>
</tr>
<tr>
<td>23 inches</td>
<td>0.026 ma</td>
<td>0.2 Kr/hr</td>
</tr>
<tr>
<td>11-1/2 inches</td>
<td>0.008 ma</td>
<td>0.2 Kr/hr</td>
</tr>
<tr>
<td></td>
<td>0.042 ma</td>
<td>1.0 Kr/hr</td>
</tr>
</tbody>
</table>

Position of Victoreen Probe with Respect to the X-ray Target

The overall view is shown on Fig. 3. The probe was 31-1/2 inches from the centerline of the x-ray target. The centerline at the probe intersected the centerline of the source 2-1/2 inches behind the face of the latter. With the probe in this standard position a current of 0.27 ma was required to record a dose rate of 1 Kr/hr. The ratio of the dose rate at the standard position to the uncollimated dose at 11-1/2 and 23 inches is then:

\[
\frac{D_{11-1/2}}{D_{\text{standard}}} = \frac{0.27}{0.042} = 6.43
\]

\[
\frac{D_{23}}{D_{\text{standard}}} = \frac{0.27}{0.13} = 2.08
\]

The dose rates at the film plane are then

\[
D_{11-1/2} = \frac{6.43 \times D_{\text{standard}}}{2230}
\]

\[
D_{23} = \frac{2.08 \times D_{\text{standard}}}{558}
\]
APPENDIX B
DOSIMETER CALIBRATION AND CORRELATION
LIST OF EQUIPMENT

Kodak Paper Grey Scale No. 113 GS 35
Eastman Kodak Company, Rochester, New York

Victoreen Remote Area Monitor; Model 711, Serial 229 Sensing Element;
Model A 747 A, Serial 147, Accuracy ±20%, Built-in calibration source, Linear gamma response within ±10% between .08 and 1.2 Mev; Range: 10 r/hr to 10⁴ r/hr
Victoreen Instrument Company, Cleveland, Ohio.

Nuclear Chicago Beta-Gamma Survey Meter
Accuracy ±10%
Linear gamma response within ±10% between .05 and 2 Mev
Model 2526, Serial 1275; Range: 0-0.25, .25, 2.5 r/hr
Model 2511, Serial 713; Range: 0-2.5, 25, 250 r/hr

Nuclear Chicago Model 2588 Serial 2 Calibration Source for Models 2526 and 2511 survey meters. Accuracy ±10%
Nuclear Chicago Corporation; Chicago, Illinois

Johnson Survey Meter Model GSM-5
Range 0, .2, 2, 20 mr/hr;
Wm. B. Johnson and Associates, Montville, N. J.

Jordan Survey Meter, Model AC-50B-SR-X, Serial 829
Accuracy ±15% within temperature range of -10°C to +150°F
Uniform response to gamma rays from 80 Kev to 1.2 Mev
Range .05-50 mr/hr, .05-50 r/hr
Jordon Electronics; Alhambra, California

Table B-1

CALIBRATION OF 2526 AND 2511 SURVEY METERS WITH MODEL 2588
CALIBRATION SOURCE

<table>
<thead>
<tr>
<th>Attenuator Position</th>
<th>Model 2511 Calibrated Source (r/hr)</th>
<th>Survey Meter (r/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>243</td>
<td>247</td>
</tr>
<tr>
<td>4</td>
<td>83.5</td>
<td>83.5</td>
</tr>
<tr>
<td>3</td>
<td>16.65</td>
<td>16.6</td>
</tr>
<tr>
<td>2</td>
<td>7.6</td>
<td>7.6</td>
</tr>
<tr>
<td>1</td>
<td>1.46</td>
<td>1.45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Attenuator Position</th>
<th>Model 2526 Calibrated Source (mr/hr)</th>
<th>Survey Meter (mr/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2410</td>
<td>2410</td>
</tr>
<tr>
<td>4</td>
<td>840</td>
<td>830</td>
</tr>
<tr>
<td>3</td>
<td>158</td>
<td>155</td>
</tr>
<tr>
<td>2</td>
<td>77</td>
<td>77</td>
</tr>
<tr>
<td>1</td>
<td>16</td>
<td>14.9</td>
</tr>
</tbody>
</table>
Figure B-1. Calibration of 2526 and 2511 Survey Meters with Model 2588 Calibration Source
### Table B-2

CORRELATION OF VICTOREEN MONITOR WITH NUCLEAR CHICAGO SURVEY METERS THROUGH USE OF 4.5 CURIE CO-60 SOURCE

<table>
<thead>
<tr>
<th>Victoreen Monitor</th>
<th>2511</th>
<th>2526</th>
</tr>
</thead>
<tbody>
<tr>
<td>41 r/hr</td>
<td>46 r/hr</td>
<td>off scale</td>
</tr>
<tr>
<td>31 r/hr</td>
<td>32 r/hr</td>
<td>off scale</td>
</tr>
<tr>
<td>8.1 r/hr</td>
<td>9.1 r/hr</td>
<td>off scale</td>
</tr>
<tr>
<td>2 r/hr</td>
<td>1.8 r/hr</td>
<td>off scale</td>
</tr>
<tr>
<td>off scale</td>
<td>2.07 r/hr</td>
<td>1.7 r/hr</td>
</tr>
<tr>
<td>off scale</td>
<td>1.5 r/hr</td>
<td>1.15 r/hr</td>
</tr>
<tr>
<td>off scale</td>
<td>1.0 r/hr</td>
<td>0.71 r/hr</td>
</tr>
<tr>
<td>off scale</td>
<td>0.5 r/hr</td>
<td>0.3 r/hr</td>
</tr>
</tbody>
</table>

### Table B-3

CORRELATION OF THE JOHNSON, NUCLEAR CHICAGO, AND JORDON SURVEY METERS THROUGH USE OF A 1.78 μC/ml CO-60 SOURCE

<table>
<thead>
<tr>
<th>Johnson</th>
<th>2526</th>
<th>Jorden</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 mr</td>
<td>10.3 mr</td>
<td>9 mr</td>
</tr>
<tr>
<td>20 mr</td>
<td>22 mr</td>
<td>25 mr</td>
</tr>
</tbody>
</table>
Figure B-2. Correlation of Victoreen Monitor with 2511 and 2526 Survey Meters
SELECTED BIBLIOGRAPHY


Fricke and Morse, Phil. Mag., 7, 129, (1929).

