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DOSE RATE AND SPECTRAL MEASUREMENTS FROM PULSED X-RAY GENERATORS

by
E. Tochilin
N. Goldstein

U.S. NAVAL RADIOLOGICAL
DEFENSE LABORATORY

SAN FRANCISCO · CALIFORNIA · 94135

RADIOLOGICAL PHYSICS BRANCH
E. Tochilin, Head

NUCLEONICS DIVISION
C. S. Cook, Head

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ABSTRACT

Typical X-ray spectra from high intensity pulsed X-ray sources were determined by means of an equivalent constant voltage accelerator. The photon energy spectrum for the forward X-ray beam was measured with various X-ray target thicknesses at accelerator voltages of 1.0, 1.5 and 2.0 Mv. X-ray spectra were also obtained from a reflection X-ray target at angles of 7 deg and 45 deg with respect to the X-ray beam at applied potentials of 0.55, 1.0 and 2.0 Mv. The dose rate dependence of thermoluminescent LiF, silver-activated phosphate glass, and dosimetry film was investigated over a range of dose rates extending from 10^4 to 10^{11} rad/sec with three separate flash X-ray systems.

SUMMARY

The Problem

The purpose of this experiment was to provide methods for determining the spectrum and dose rates from pulsed X-ray generators and to evaluate the dose rate response of various dosimeters at these high intensities.

The Findings

X-ray spectra from 0.60, 1.0 and 2.0 Mv pulsed X-ray sources were simulated by measurements made on the Laboratory Van de Graaff. Transmission curves obtained at the Van de Graaff and flash X-ray units were used to establish an identity between the steady state and pulsed X-ray spectra. No dose rate dependence was observed for LiF and CaF_2 thermoluminescent dosimeters and silver-activated phosphate glass up to 10^{11} rad/sec. DuPont 834 film exhibited a dose rate dependence above 5×10^8 rad/sec which corresponds to a delivered dose of 10 rad per pulse.

INTRODUCTION

The past few years have seen the development of high-current pulsed X-ray sources capable of producing instantaneous dose rates exceeding 10^{11} rad/sec with maximum energies extending to 4 MeV.[1-4] By utilizing the electron beam from the higher energy units it is possible to irradiate limited volumes of material with dose rates extending beyond 10^{12} rad/sec. With the electron beam, doses approaching 100,000 rads per pulse become entirely feasible.[4]

One major problem confronting the experimenter is how to make meaningful dosimetric measurements under such conditions. Another problem arising from the use of pulsed X-rays involves the determination of their spectral distribution. In order to achieve maximum X-ray intensity, reflection targets or thin transmission targets are used which results in a significant low-energy component. Since many dosimetry systems used in pulsed beam dosimetry exhibit energy dependence in this energy region, e.g., glass dosimeters and photographic emulsions, it becomes important to establish their energy response for any such exposure condition.

One method of obtaining spectral information on pulsed X-ray beams is to design an identical tube assembly and adapt it to a conventional

electron accelerator. This will produce a steady state version of the pulsed source whose X-ray spectrum can then be analyzed by means of a NaI(Tl) scintillation spectrometer. Many additional beam parameters can be investigated with a properly designed tube assembly--optimum target thickness (transmitted beam) or optimum target angle (reflected beam) for maximum output; changes in beam intensity and spectral distribution due to external absorbers; beam distribution and inverse square relationship at distances close to the target; etc.

Special target assemblies adapted to a 2 MeV Van de Graaff accelerator allowed spectral measurements to be made in the energy range from 0.5 to 2 MeV for both transmission and reflection targets. From this information the physical properties of a pulsed 600 kv X-ray machine (with reflection target) and a pulsed 1 Mv source (with transmission target) were determined, following which the energy and dose rate response of various dosimetry systems were investigated.

Four pulsed sources were made available for this study. These included: a 600 kv X-ray system;[1] two X-ray systems (1 and 3 Mv)* developed for simulation studies;[2] and the Astron pulsed 4 MeV electron accelerator at the University of California Lawrence Radiation Laboratory.[3] When completed the Astron unit will be used as an

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* The 1 and 3 Mv X-ray systems were made available for dose rate measurements by the Physics International Company, San Leandro, California.

experimental thermonuclear power reactor with the pulsed electrons used to confine the plasma and supply the energy required to attain fusion temperatures.[3] For the present study the electrons were stopped in a water-cooled tantalum target attached to the end of the accelerator tube.

STEADY STATE X-RAY MEASUREMENTS

A 2 MeV Van de Graaff electron accelerator was used to provide a steady state equivalent of the 600 kv and 1 Mv flash X-ray units. A target assembly was designed to hold water-cooled tungsten targets at the desired angles to the electron beam. With this arrangement the spectral distribution and intensity of X-rays reflected from the target could be studied for various target angles. The target housing had a 0.15 mm Be window to allow transmission of low-energy X-rays. Measurements were also made with transmission targets in which the target material was placed at the end of the accelerator tube in a plane normal to the beam axis.

X-ray spectra were determined by analysis of pulse height spectra from a 10 cm diameter by 10 cm long NaI(Tl) crystal optically coupled to a 12.5 cm diameter photomultiplier tube. The amplified signals from the photomultiplier tube were counted in an hundred-channel analyzer. The X-rays entered the shielded crystal through a lead collimator plug 23 cm long with a 1.27 cm aperture. Reduction of pulse height

distribution to X-ray spectrum followed calculation techniques developed in an earlier investigation.(5) Dose rate measurements were made with a Victoreen thick-wall 25 R thimble chamber calibrated by the Bureau of Standards against Co^{60} gamma rays. Subsequent checks were made with a Cs^{137} standard source (0.66 MeV gamma rays) and with a 250 kv X-ray source for effective X-ray energies ranging from 40 to 155 keV. A calibrated low-energy 25 R thimble chamber served as the X-ray comparison standard.

X-RAY SPECTRA

600 kv pulsed X-ray unit

The 600 kv flash X-ray tube is designed primarily for flash radiography.(1) The cathode consists of a thin cylinder which surrounds a thick conical tungsten anode. Electrons from the cathode impinge on the anode and emit X-rays through a glass window in the direction of the target axis. The conical anode target makes an angle of 7 deg with its central axis (Fig. 1). In order to prolong tube life the unit was operated at 550 kv.

Spectral measurements were made on the Van de Graaff accelerator with the electron beam projected vertically downward and a flat tungsten target positioned at the 7 deg angle. The NaI crystal and Pb collimator were placed in a horizontal position facing the tungsten target. Measurements of the reflected X-ray spectrum for 550 keV

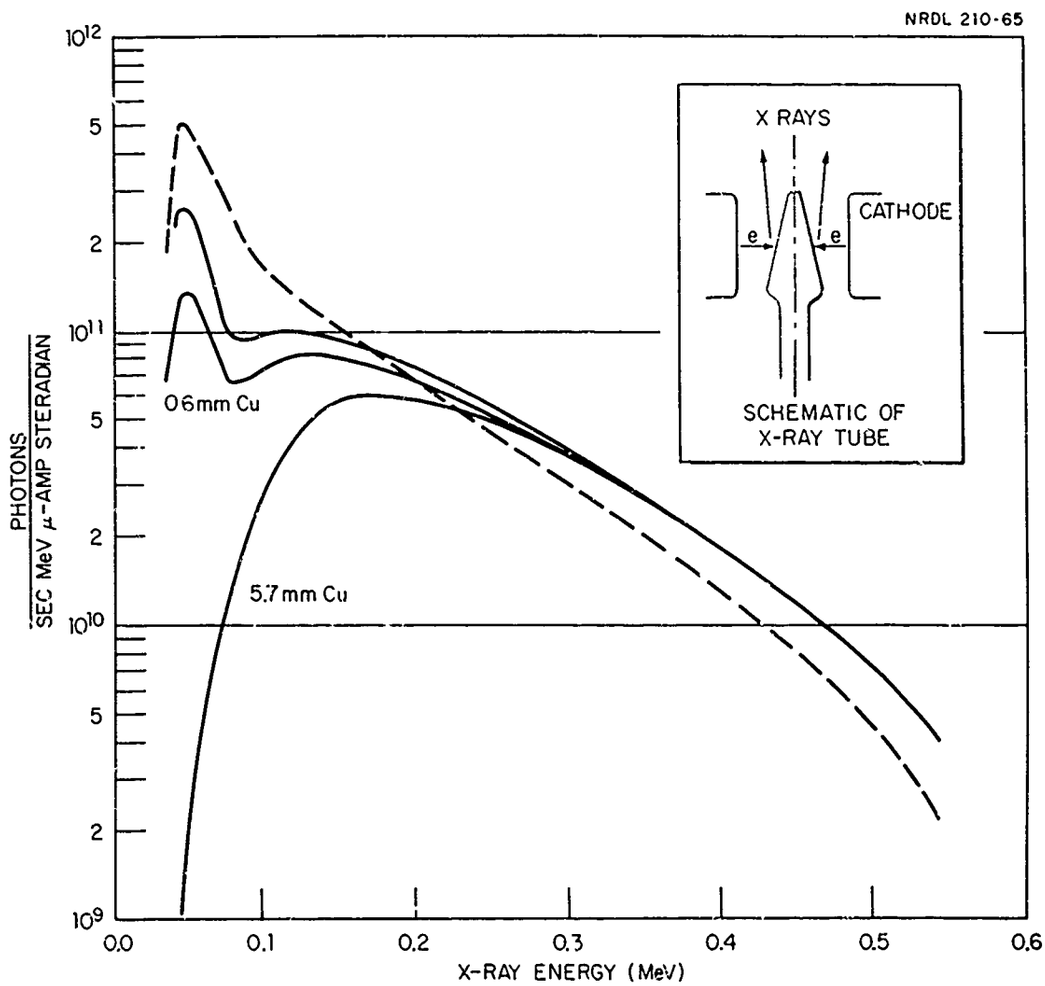

Fig. 1 Comparison of experimental spectra for reflection X-ray targets at 0.55 MV tube potential for targets at two angles (dashed line--45 deg, solid lines--7 deg).

electrons were made with the beam passing through the 0.15 mm Be filter and with additional filters of 0.6 mm and 5.7 mm of Cu. In addition the beam traversed 2.2 m of air and 0.25 mm of Al covering the NaI crystal. The resultant spectra are shown as solid curves in Fig. 1 while the dashed curve is the spectrum for a 45 deg reflection target. The unfiltered beam is a typical continuous X-ray spectrum rising to a broad maximum around 100-130 keV. Accompanying the continuous distribution is the characteristic radiation for tungsten photons at around 60 keV arising from the transition of excited atoms to lower energy levels. The 0.6 mm Cu filter selectively reduces the intensity at the expense of lower energies and shifts the population maximum of the continuous spectrum to a higher energy. With a 5.7 mm Cu filter the 60 keV tungsten line is almost completely eliminated while the dose rate is reduced by a factor of two. Additional curves comparing the spectral response of reflection tungsten targets positioned at 7 deg and 45 deg for 1 and 2 MeV electrons are presented in Figs. 2 and 3.

Another method of determining spectral distribution is the attenuation method described by Greening[6] which is based on the analysis of attenuation curves. A modified version of this technique was used by Bouchard[7] to estimate the energy spectrum from a similar 600 kv flash X-ray system. Using film as a detector, absorption curves with different filter materials were obtained. The measured optical densities were then compared with expected values from an initially

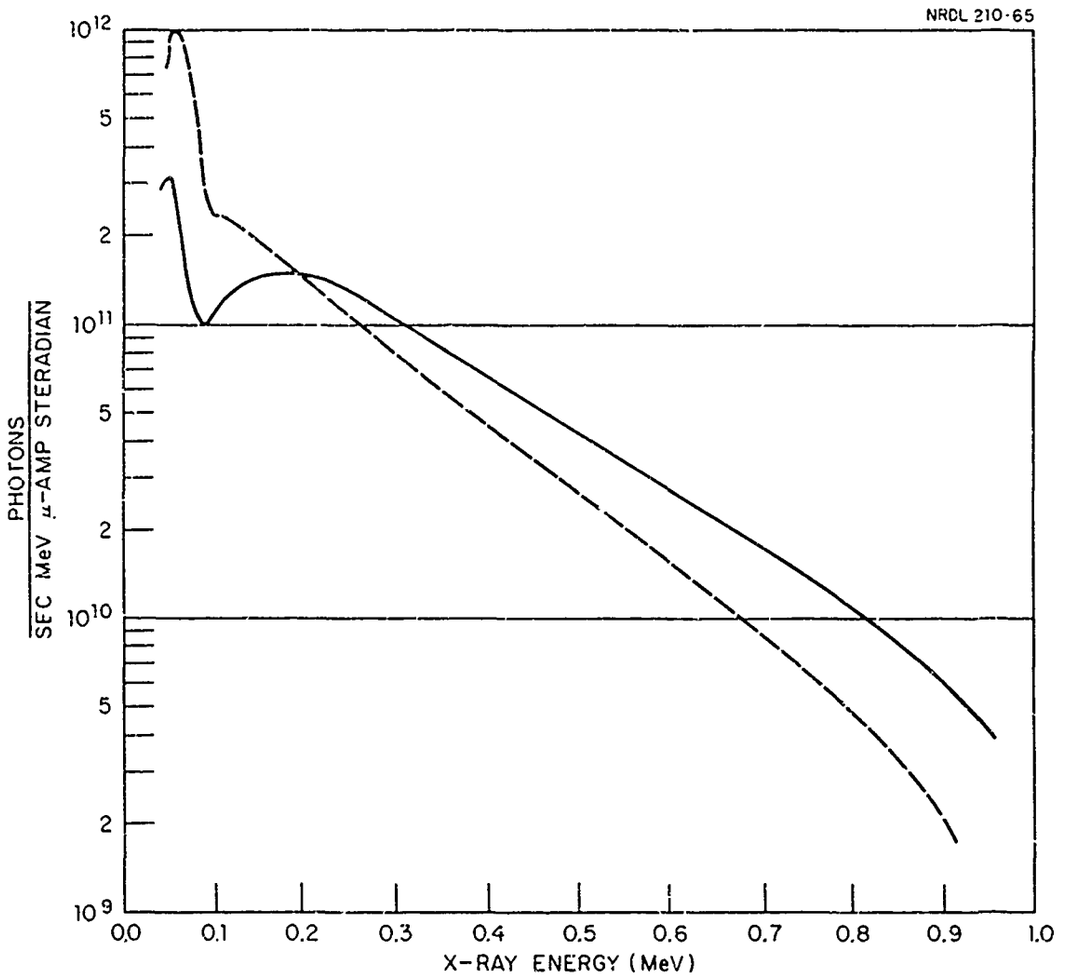

Fig. 2 Comparison of experimental spectra for reflection X-ray targets at 1.0 Mv tube potential for targets at two angles (dashed line--45 deg, solid line--7 deg).

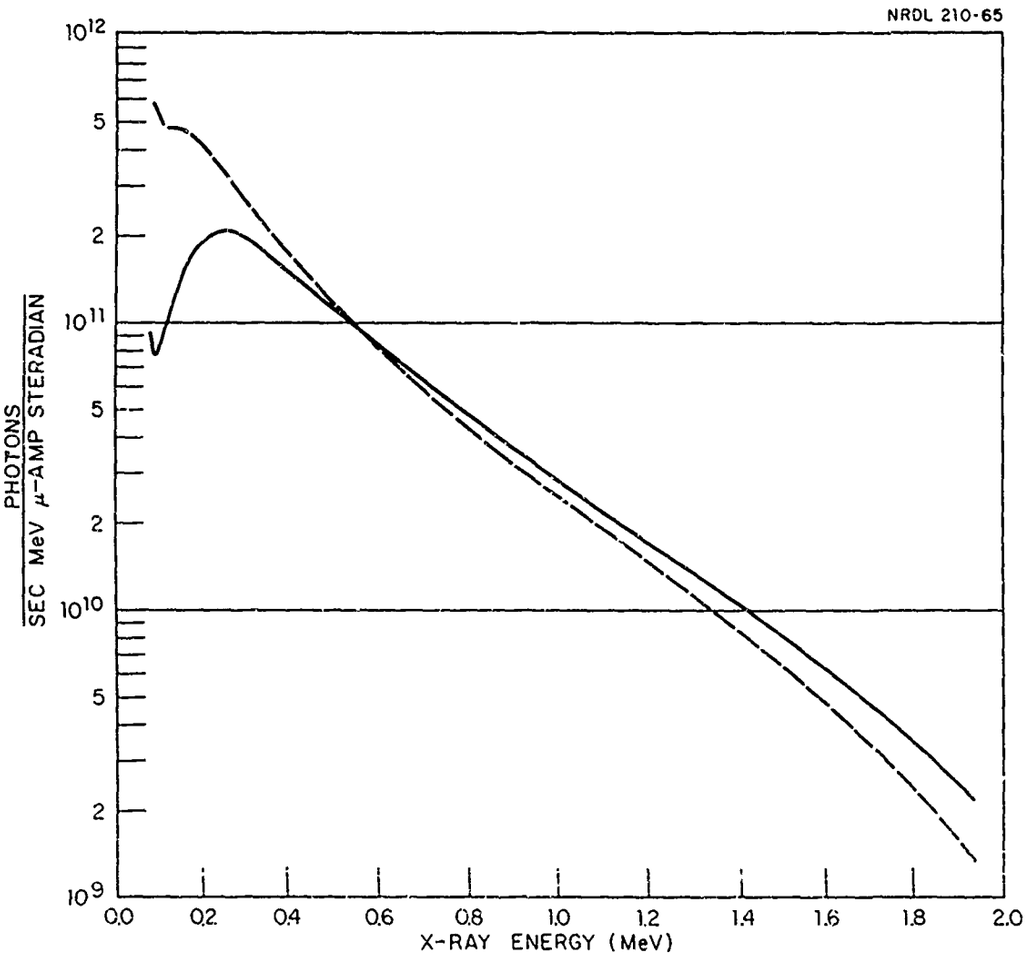

Fig. 3 Comparison of experimental spectra for reflection X-ray targets at 2.0 Mv tube potential for targets at two angles (dashed line--45 deg, solid line--7 deg).

assumed photon energy spectrum. The proposed spectrum was then successively modified in such a manner that the spread in experimental and calculated results was reduced to less than 10 percent. The resultant spectrum, with a 1.6 mm Cu filter, showed a broad maximum between 200-300 keV which is in contradiction with our present measurements. It is of interest to note that the first approximation spectrum for Bouchard's analysis, a calculated continuous spectrum based on Kramers' formula[8] was quite similar to our measured distribution with the 5.7 mm Cu filter.

The attenuation method was used in our measurements to establish an identity between the steady state and pulsed X-ray spectrum. Copper transmission curves obtained at the Van de Graaff and at the flash X-ray unit were found to be identical for thickness greater than 0.6 mm. A combination of measurements with ionization chambers and thermoluminescent LiF dosimeters were used to obtain data for the pulsed beam. Ionization chambers were used only at dose rates where recombination effects were not significant. A more rapid attenuation of the pulsed beam was observed over the initial portion of the transmission curve which indicated the presence of low-energy electrons in addition to the 550 keV component. This condition was observed for three separate tubes. One possible explanation is that the tube was not holding its original vacuum and was therefore "gassy." For this reason it may be preferable to operate with enough filtration to

eliminate any undesirable soft X-ray component not directly attributable to the primary electron beam.

One Mv pulsed X-ray unit

The 1 Mv pulsed X-ray tube used a transmission tungsten target backed by 6.4 mm of aluminum with the plane of the target normal to the electron beam. The tube could be readily dismantled which allowed a variation in thickness of target material.

An experiment with 1 MeV electrons was conducted with the Van de Graaff to determine the effect of target thickness on X-ray spectrum and dose rate. Measurements were made with tungsten target thicknesses varied from 0.127 to 0.508 mm with and without backing of 1 cm of aluminum and also with additional copper filters 0.56 and 1.88 mm thick. The Al backing had little effect on the measured spectrum other than to reduce the intensity by approximately 20 percent over all energies. Figure 4 shows spectra obtained with target thicknesses of 0.127, 0.254, and 0.508 mm. The lower two curves in Fig. 4 show the effect of additional copper filters. Characteristics X-rays for tungsten are seen to exist even for a thick target (0.508 mm of tungsten) but may be eliminated by adding a copper absorber. Figures 5 and 6 show similar spectra obtained with transmission tungsten targets of various thicknesses for 1.5 and 2 Mv tube potential.

Characteristic X-rays from the tungsten target were not resolved for the 2 Mv spectra of Fig. 6 as was the case at lower energies.

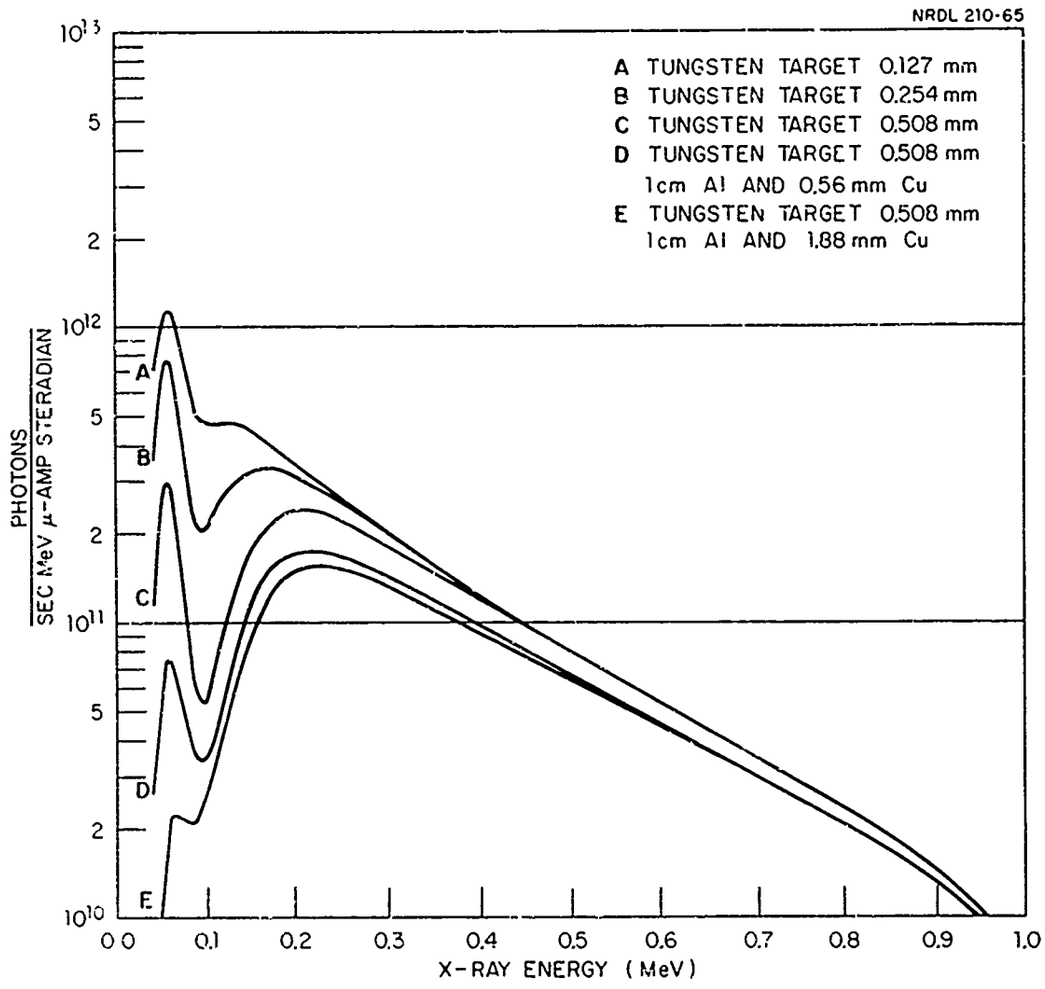

Fig. 4 Comparison of experimental spectra for transmission X-ray targets of various thicknesses at 1.0 Mv tube potential.

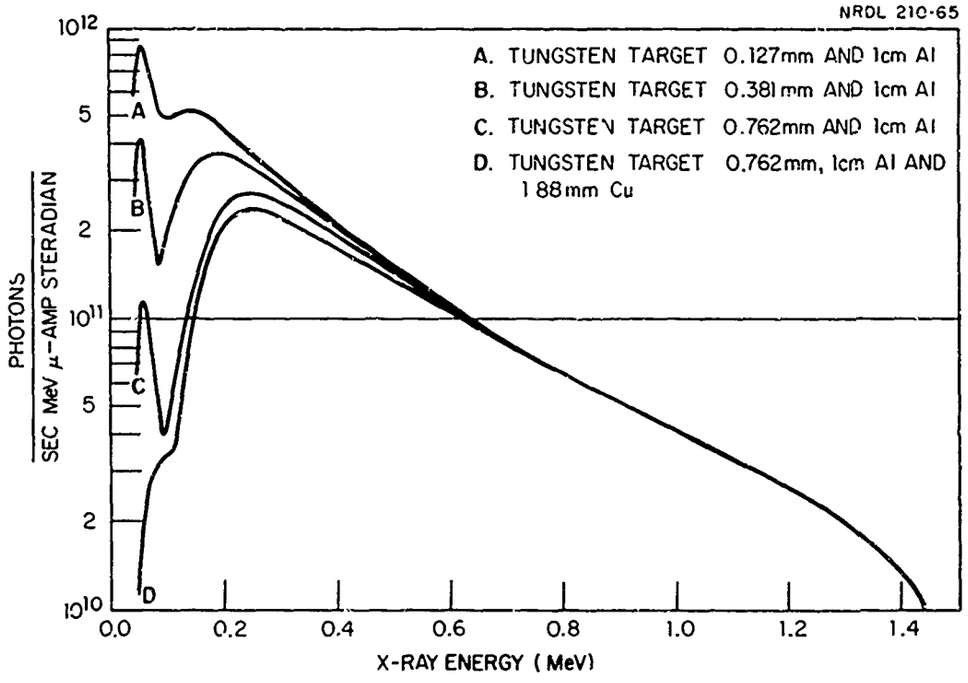

Fig. 5 Comparison of experimental spectra for transmission X-ray targets of various thicknesses at 1.5 Mv tube potential.

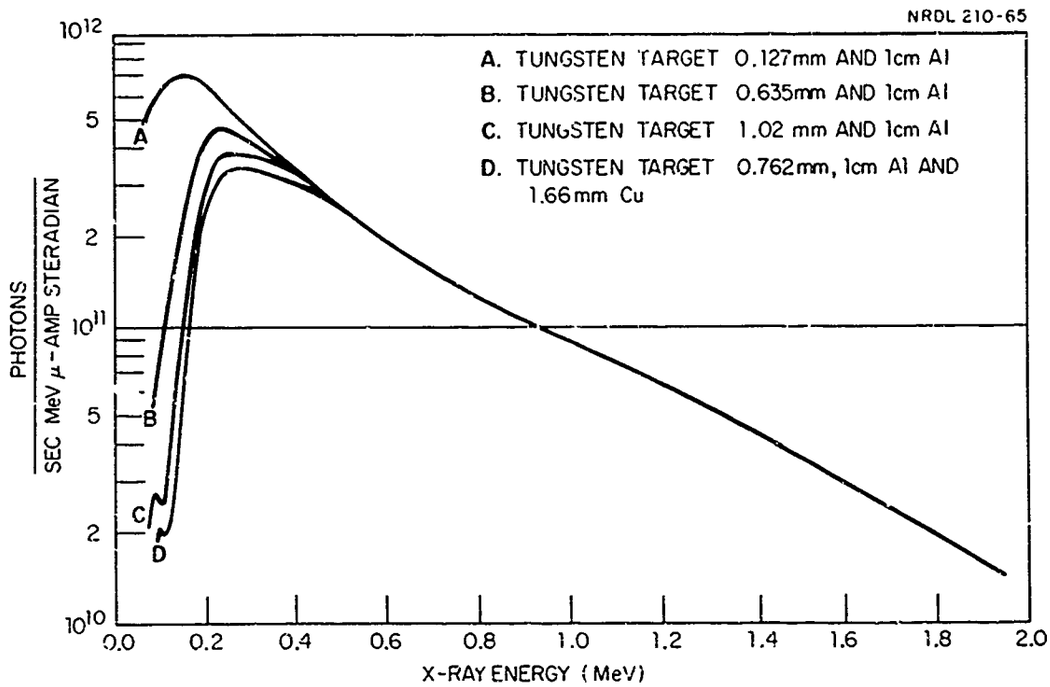

Fig. 6 Comparison of experimental spectra for transmission X-ray targets of various thicknesses at 2.0 Mv tube potential.

The magnitude of this component may be estimated by reference to Edelsack, et al., where X-ray spectra from thick gold targets were determined for electrons of 1.0, 1.5, and 2.0 MeV.[5]

Doses associated with the measured spectra were found to decrease exponentially with increasing target thickness. From an inspection of Fig. 4 one sees that the 0.508 mm tungsten target eliminates a large component of low-energy X-rays originally transmitted through 0.127 mm of tungsten. The overall spectral attenuation corresponded to a 25 percent decrease in dose rate. The additional 1.88 mm of copper which essentially eliminates the 60 keV tungsten line produces an additional 10 percent reduction in dose. Table 1 gives the exposure in R per ma-min at one meter for transmission targets of various thicknesses at 1.0, 1.5, and 2.0 Mv tube potentials.

Table 1. Roentgens per ma-min at one meter for transmission X-ray targets of various thicknesses at 1.0, 1.5, and 2.0 tube potential

Additional Filtration		Tube Potential					
		1 Mv		1.5 Mv		2 Mv	
mm Al	mm Cu	mm W	R	mm W	R	mm W	R
10	-	0.127	97	0.127	249	0.381	550
10	-	.254	81	.508	213	.635	506
10	-	.508	71	-	-	1.02	469
10	1.66	-	-	-	-	1.02	431
10	1.88	.127	75	.127	213		

DOSE RATE STUDIES

The dose rate response of silver-activated phosphate glass,* thermoluminescent LiF** and dosimeter film were initially studied with pulsed X-rays from the Astron accelerator. Under normal operation the Astron beam was pulsed five times a second. This time interval was sufficiently long so that the dose from each pulse was completely resolved by each dosimeter system prior to the arrival of the next burst of X-rays. At the higher dose rates a small number of runs were also made with single pulses.

Beam current was monitored by taking a photograph of an oscilloscope trace from a single pulse made at the end of each run. Integrating the pulse area gave the charge which averaged 20 μcoulombs per pulse delivered over a period slightly greater than 0.35 μsec. The pulse shape was rectangular over the first 0.1 μsec after which it decreased linearly to zero. The average pulse time was assumed to be 0.3 μsec during this exposure period.

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* These included the high-Z and low-Z fluorod glasses manufactured by Bausch and Lomb, Inc., Rochester, New York, and the low-Z fluorods and glass plates manufactured by Tokyo Shibaura Electric Co., Ltd., Tokyo.

** Manufactured by the Harshaw Chemical Co., Cleveland, Ohio.

The horizontal accelerator tube was about 3 m above the floor and at least 5 m from the nearest wall in a large concrete building. In order to minimize scattered radiation for auxiliary equipment in the area the X-ray target was surrounded by a 5 cm thick lead housing. A 5 cm diameter aperture placed directly in line with the horizontal electron beam and 20 cm ahead of the Ta target restricted the transmitted X-ray beam to a 14 deg cone. The X-ray dose rate was determined with a microcalorimeter positioned on the beam axis 188 cm from the target. The microcalorimeter has been described in a separate report.(9) Absorbed dose was determined over a series of seven 1-min runs. The dose rate thus obtained was 54.6 carbon rad/min or 62 R/min at an average current of 100 μamps (100 μcoulombs/sec). For an average current of 1 μamp the output at 1 meter would be 2.2 R/min which is in agreement with other data in the literature.(10)

Dose rate measurements were monitored with Sievert type ionization chambers.*(11) They were chosen because of the small separation between central cathode and outer wall which is necessary in order to attain sufficient field strength to achieve saturation at high dose rates. The chambers are cylindrical in shape, about 5 mm in diameter and 2 cm long. With a charger-reader designed to apply a 600 v potential to the chambers a full scale reading of about 250 rad was

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* Manufactured by Alderson Research Laboratories, Long Island City, New York.

obtained. A second 150 v charger-reader gave a full scale reading of 50 rad.

Having determined the X-ray output at one point the dosimeters were then calibrated at this distance. Dose rate dependence of the various systems was studied by assuming an inverse square relationship over the distance between 10-400 cm and observing how well the individual dosimeter response followed this predicted relationship. An additional check on output was provided by the Sievert ionization chambers. Figure 7 shows the dose rate response of silver-activated phosphate glass, photographic emulsion (DuPont types 555 and 834) and thermoluminescent LiF over dose rates extending from 5×10^3 to 2×10^7 rad/sec. Over this range the three dosimetry systems are essentially independent of dose rate.

The accuracy of these measurements was difficult to assess but probably was within ± 10 percent for all exposures. Each run consisted of dosimeters placed at two distances with the front group of dosimeters positioned so as not to shield the ones further back. All runs were at a constant beam current; the total dose received for each run being determined by exposure time. For dose rates below 10^5 rad/sec beam intensity was reduced by means of a 2-in. thick Pb absorber. Normalization was achieved from the average reading of five Sievert ionization chambers which were exposed at each point. Two LiF and glass dosimeters and one film dosimeter were exposed along with the Sievert chambers.

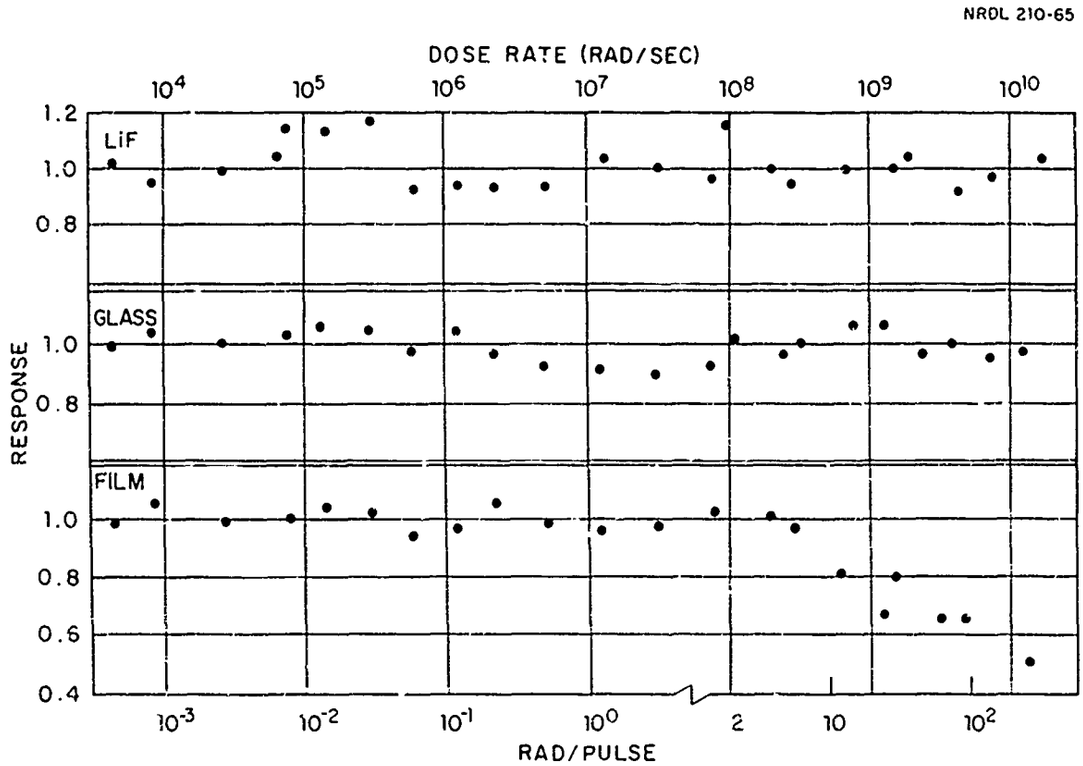

Fig. 7 Relative dose rate response of thermoluminescent LiF, silver-activated phosphate glass, and dosimetry film.

Dose rate studies for the silver-activated phosphate glass and thermoluminescent LiF dosimeters were extended to the 1 Mv pulsed X-ray source where dose rates of 1.7×10^{10} rad/sec were obtained 2.75 cm from the target. A dose of 350 rad per pulse was delivered at this dose rate. Once again measurements were made using inverse square to obtain dose rates from 10^{8} to 1.7×10^{10} rad/sec over the distance between 2.7 and 24 cm. The results are shown also in Fig. 7 and indicate no dose rate dependence for the glass and LiF dosimeters. Previous measurements by Karzmark, et al., with the LiF dosimeter showed no dose rate dependence from 5×10^{2} to 2×10^{8} rad/sec.[12] On the other hand a dose rate effect is clearly indicated for DuPont type 834 dosimeter film for dose rates in excess of 5×10^{8} rad/sec which corresponds to a delivered dose of 10 rad per pulse.

Using somewhat modified exposure conditions at the 3 Mv pulsed X-ray source it was possible to extend measurements with LiF and glass to dose rates over 2×10^{11} rad/sec (4500 rad/pulse) with no indication of dose rate effects (within $\pm$ 10 percent). CaF_2 thermoluminescent dosimeters exposed under the same conditions also showed no dose rate effects up to 10^{11} rad/sec.*

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* The CaF_2 dosimeters were furnished for exposure and read by Harry Diamond Laboratories personnel, U.S. Army Materiel Command, Washington, D.C. They were manufactured by Edgerton, Germeshausen and Grier, Inc., Santa Barbara, California.

A further check on the dose rate from the 3 Mv pulsed X-ray machine was made with a microcalorimeter positioned 10 cm from the target.[13] The average dose for a pulse of 2×10^{-8} sec was about 500 R. Simultaneous measurements made with the microcalorimeter and LiF dosimeters gave the same value within an experimental error of 5 percent. The independent intercomparison further established the lack of dose rate effects for the systems under study.

The behavior of integrating ionization chambers exposed to either high intensity continuous radiation or to instantaneous pulses of radiation may be determined from generalized saturation curves developed by Boag.[14] Instantaneous pulses are those whose duration is short compared with the time required for complete ion collection in the chamber, which is the order of milliseconds. Because solid state dosimeters of the type described have such excellent response characteristics to pulsed radiation it becomes a routine matter to construct a response curve for any ionization chamber. However, in some instances it may be desirable to fit a single point to the saturation curves presented by Boag and thereby obviate the need for additional measurements. The dose rate response as predicted from Boag's data has generally been found to be greater than that obtained experimentally. The difference can be accounted for if the empirical constant m given by Boag as 15.9 is increased to an average value of 36.7 as determined by Greening by analysis of the experimental results

of seven different workers.[15] It is of interest to note that the value of $\underline{m}$ obtained by Greening in reviewing the original experimental data of Boag was at variance with his published value but in good agreement with the average number.

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14 KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, roles, and weights is optional.