5 To 160 keV Continuous-Wave X-Ray Spectral Energy Distribution and Energy Flux Density Measurements

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Abstract

Techniques developed for measuring the x-ray spectral energy distribution (differential intensity) from a tungsten-target bremsstrahlung x-ray source are reported. Spectra with end-point energies ranging from 20 to 160 keV were recorded. A separate effort to calibrate the dosimetry for the Phillips Laboratory low-energy x-ray facility established a need to know the spectral energy distributions at some point within the facility (previous calibration efforts had relied on spectra obtained from computer simulations). It was discovered that the primary discrepancy between the simulated and measured spectra was in the L- and K-line data. The associated intensity (energy flux density) of the measured distributions was found to be up to 30% higher. Based on the measured distributions, predicted device responses were within 10% of the measured response as compared to about 30% accuracy obtained with simulated distributions.

I. INTRODUCTION

In 1991, the USAF Phillips Laboratory Microelectronics and Photonics Research Branch installed a low energy x-ray facility (LEXR) for use in microelectronics radiation-effects analysis and research. A sketch of the physical layout of the LEXR is provided in Figure 1. The LEXR radiation source is

a Philips MCN-165, tungsten-target bremsstrahlung x-ray tube which generates spectral energy distributions with end-point energies between 5 and 160 keV. The facility provides a convenient, low-cost ionizing-radiation source capable of illuminating objects up to 0.5 m². The primary objective of the work presented here was to measure x-ray spectral energy distributions and the associated intensities within the LEXR, and compare the measured results with simulated results. The secondary objective was to develop spectral measurement techniques which could be readily standardized and employed in confined areas.

Efforts to calibrate the dosimetry of LEXR have been reported previously [1-3]. These efforts demonstrated excellent agreement between the effects observed in Cobalt-60 (⁶⁰Co) and those observed from various x-ray spectral energy distributions generated within the facility. However, comparisons between the measured response of solid-state x-ray detectors and the predicted response (based on simulated distributions) differed by as much as 30%. Since the detectors were accurately calibrated and their responses were accurately measured [4], the computed responses were in question.

A major component in a device's computed response is the incident spectral energy distribution. Calculated and measured spectral energy distributions of x-ray tubes similar to the MCN-16 have been reported in the literature [5,6]. As reported in the earlier work [1-3], Dozier at the Naval Research Laboratory (NRL) calculated the spectrum of the MCN-165 tube using an electron-photon transport code called "TUBE" [7]. Those approximate distributions were computed using x-ray tube parameters obtained from product literature and not engineering design information. Therefore, questions were raised about how accurately the approximate distributions represented the actual distributions incident on the target. To resolve these ambiguities, an effort was initiated to directly measure the spectral energy distributions.

II. APPROACH

There were two experimental phases in this effort. The first phase focused on performing direct spectral energy distribution measurements; the second phase focused on indirect intensity measurements and comparing the measured responses to computed predictions. To measure the spectra and resolve the individual L- and K-lines, a high resolution EG&G ORTEC x-ray spectroscopy system was employed. This system includes a cryogenically cooled high-purity germanium (HPGe) planar detector, a high count-rate pre-

Figure 1: Illustration of LEXR Test Cell

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amplifier, and a computer controlled multi-channel pulse-height analyzer. The HPGe detector has an advertised energy range of 3 to 600 keV.

Precautions are required before making measurements of this sort. The primary difficulty in measuring the output of x-ray tubes is reducing the photon flux to an acceptable level. To prevent the measurement system from saturating due to high photon fluxes, both small aperture collimators and very-low filament currents in the x-ray tube were incorporated. Both of these methods have limitations [8-11]; however, after accounting for these limitations, the desired spectra were measured. The limitations (photon scattering off the aperture and low-current operation of the x-ray tube) and their solutions will be described below.

A schematic representation of the equipment configuration used in this work is illustrated in Figure 2. Included in the setup are the MCN-165 x-ray tube, three aligned lead collimators, a 0.025 mm mylar (polyethylene terephthalate) window, and the cryogenically cooled HPGe detector with pre-amplifier. The remainder of the spectroscopy system was installed outside the radiation area and connected to the detector

Figure 2: Illustration of Spectra Measuring Setup

through 10 feet of cable. The measurement system was calibrated to record incident photons in 8,192 energy bins equally spaced between 0 and 200.7 keV (*i.e.*, 24.5 eV/bin = ΔE_i). To obtain a statistically valid sample size in each bin, the minimum "live time" to record a spectrum was set at 1,800 seconds and the "dead time" was limited to 15% of the total measurement time.* If E_i is the lowest energy within bin i , the output of the measurement system is the number of photons, N_i , with energy in the interval $E_i < E < E_i + \Delta E_i$ for $0 < i < 8191$. The data was converted to spectral energy distributions (also known as energy flux density distributions or differential intensities) according to

$$\phi'_i = \frac{N_i E_i}{\Delta E_i A_a t_{\text{int}}} \quad (1)$$

where

ϕ'_i = the i^{th} element of the spectral energy distribution $\phi'(E)$
 ΔE_i = the energy bin width
 A_a = the area of the detector's aperture
 t_{int} = the integration (*i.e.*, live) time

The factors considered in choosing the lead collimator configuration depicted in Figure 2 were: (i) the need to reduce the photon flux and (ii) the need to avoid fluorescence and scatter of x-rays by the collimator material (these could enter the detector and distort the measurement). Collimators 1 and 3 were large aperture structures designed primarily to reduce photon scattering from the lead walls of the radiation cell and collimator 2 was primarily for limiting the photon flux. Collimator 1 was a 5.1 cm slab of lead with a 12.70 mm diameter hole. It was placed within a few millimeters of the x-ray tube exit window. The distance between collimators 1 and 2 was determined by the source-to-detector distance. Collimator 2 (placed 5 mm from collimator 3) consisted of a 12.7 mm thick slab of lead with an entrance aperture 1.8 mm in diameter and an exit aperture 0.34 mm in diameter (see Figure 2). Both apertures had an equal depth (6.35 mm). The dimensions were selected to reduce the photon flux to acceptable levels while obtaining undistorted x-ray spectra. Collimator 3 was actually part of the detector/ pre-amplifier lead shield. It was a 1.27 cm lead wall with a 3.17 mm diameter hole centered 5 mm in front of the detector window.

The 0.025 mm mylar window was used to absorb unwanted low energy photons and electrons that scattered off the interior walls of collimator 2. Calculations showed that the mylar window absorbed more than 75% of the photons with energies below 2.5 keV and more than 95% of the electrons with energies below 40 keV. Also, the mylar served to help align the collimators. A laser beam was directed along the photon path using mirrors. The mylar acted as a partial reflector; when the primary beam illuminated the center of the detector window and the reflected beam was coincident with the incident beam on the mirror, alignment was achieved.

In conjunction with the attenuation achieved by the collimators, low x-ray tube currents (*i.e.*, a few microamps) were used to keep the measurement system's dead time at or below 15 percent. Integrating this approach into the measurement setup required two modifications of the x-ray tube's high voltage power supply. First, to accurately determine the current flowing through the anode, a DC ammeter with nanoampere resolution was installed in the anode's power supply return path. Second, to allow for manual adjustment of the x-ray tube's filament temperature (which in-turn determines the anode current), an adjustable regulated AC source was installed in the tube's filament control circuitry. These modifications were not the final answer. It was found that once the system had been modified to allow microamp anode currents, as the current was lowered into the microamp regime the high voltage on the x-ray tube increased. This effect caused the end-point energy of the emitted spectrum to be greater than expected. The problem was remedied by setting the anode current according to the ammeter and setting the high-voltage to obtain a specific end-

* The measurement time is divided into "live time" and "dead time." Dead time is the fraction of the measurement time when the detector cannot discriminate between photons (*i.e.*, coincident photons). No data is recorded during dead time. Live time is when data is being recorded.

point energy in the measured spectrum. The accuracy of this technique was verified and the results of that verification are described later.

A calibrated x-ray diode (XRD), known as the Secondary-Electron MIXed-Radiation Dosimeter (SEMIRAD), was used to provide an indirect "measure" of the intensity (Figure 3).

Figure 3: SEMIRAD X-Ray Diode

Photons incident on the diode's aperture interact with the surface of the gold film on the cathode and generate secondary electrons. The electrons are collected on the anode, establishing a current described by the equation:

$$i_d = A_a \int_0^{E'} \phi'(E) S(E) dE \quad (2)$$

where

i_d = Diode current [μA]

A_a = Aperture area [cm^2]

$\phi'(E)$ = Calculated or measured spectral energy distribution $\left[\frac{keV}{keV \cdot cm^2 \cdot s} \right]$

$S(E)$ = Diode sensitivity data $\left[\frac{\mu C}{keV} \right]$

E' = End - point energy of $\Phi'(E)$ [keV]

A Keithley 617 Electrometer was used to measure this current.

The calibration of this diode was performed by the SAIC-DNA x-ray calibration facility in Albuquerque, New Mexico. Fourteen different elements were used to provide bremsstrahlung-induced K-fluorescent monochromatic x-rays ranging from 5.4 keV to 101.0 keV. The response of the XRD to those monochromatic x-rays were used to produce the calibration curve shown in Figure 4. The two discontinuities in the curve occur at the L- and K-shell absorption energies of gold. The XRD current can be computed by performing a piece-wise integration of Equation (2) using this data.

Figure 4: SEMIRAD X-Ray Diode Calibration Curve

III. RESULTS

Spectra were measured in the LEXR test cell through 50 cm and 82 cm of air for seven end-point energies between 20 keV and 160 keV. Examples of the absolute measured spectra and corresponding calculated spectra (superimposed) are illustrated below in Figures 5 through 7. The measured data presented in these figures was collected as described immediately following Figure 2 and scaled as described by Equation (1). The units of $\phi'(E)$ are given in Equation (2). The TUBE code output is $\hat{\phi}(E)$ where

$$\hat{\phi}(E) = \text{The normalized spectral energy distribution} \left[\frac{keV}{keV \cdot sr \cdot e^-} \right] \quad (3)$$

and

sr = steradians

e^- = electron

$\hat{\phi}(E)$ was converted to $\phi'(E)$ according to [2]:

$$\phi'(E) = \hat{\phi}(E) * \frac{i_{tube}}{e \cdot d^2} \quad (4)$$

where

i_{tube} = The x - ray tube anode current [μA]

d = The distance between the tube and the target [cm]

e = The electron charge, $1.6 \times 10^{-13} \mu C$

The units of the data and the conversion of the TUBE data are described in detail in the earlier work [2].

Figure 5 and 6 show spectra with end-point energies of 50 keV and 100 keV that are incident on the detector after 50 cm of air, respectfully. Figure 7 shows similar plots, except the end-point energy is 140 keV after 82 cm of air. All of the spectra were plotted as absolute differential intensity versus photon energy. The total number of photons counted by the detector in each of the measured spectra were 11,306,590 for the 50 keV, 16,474,130 for the 100 keV, and 39,561,300 for the 140 keV.

Figure 5: Comparison of Calculated and Measured 50 keV Spectra after 50 cm of Air

Figure 6: Comparison of Calculated and Measured 100 keV Spectra after 50 cm of Air

Figure 7: Comparison of Calculated and Measured 140 keV Spectra after 82 cm of Air

The measured and calculated spectral continua in each of the three plots agree closely. The measured and calculated energy locations for the major tungsten L- and K-lines also agree closely (8 to 10 keV for the L-lines and 60 to 70 keV for the K-lines). However, major differences were noted in the intensities of the L- and K-lines and in the number of those lines. The magnitudes of the measured L- and K-lines are greater than the magnitudes in the calculated "lines." Also, the number of lines in each measured spectrum was greater than the number of lines in each associated calculated spectrum. In the theoretical spectra, three of the primary L-lines and two of the primary K-lines are presented. In the measured spectra, seven L-lines and four K-lines were detected. These two differences were noted in all the measurements.

Also, as the end-point energy of the measured spectra was extended to the upper voltage limit of the x-ray tube, K-lines from other metals began to appear. In the 140 keV measured spectrum (Figure 7), a K-line for silver (22.16 keV) appeared. Detailed information on the design of the tube was not available during the work presented here. However, that information is of significant value both in improving the fidelity of the TUBE simulation and in understanding the source of the stray lines mentioned above. Therefore, future work will attempt to clarify the design of the tube, both by obtaining additional information from the manufacturer and by using simulation experiments.

Indirect intensities (in terms of XRD current) for most of the measured spectra, including those in Figures 5 through 7, are presented in Figures 8 and 9. Plotted are the XRD currents as a function of x-ray tube current for several x-ray tube anode voltages. Figure 8 shows the diode currents recorded at x-ray end-point energies of 50 and 100 keV through 50 cm of air. Figure 9 shows the diode currents measured at end-point energies of 30, 50, 100 and 140 keV through 82 cm of air. Marked on each plot are the points where a corresponding spectrum measurement was made. The black dots on each curve represent the average of six distinct measurements. These curves demonstrate that the measured XRD currents (a function of the intensities) are a linear function of the x-ray tube current.

$$i_d = A_a \int_0^{\infty} \phi'(E) S(E) dE = A_a i_{tube} \int_0^{\infty} \hat{\phi}(E) S(E) dE \quad (5)$$

where

$$\begin{aligned} i_d &= \text{Diode current} \\ i_{tube} &= \text{X-ray tube filament current} \\ \phi(E) &= \text{Current-normalized differential intensity} \\ &= \frac{\phi'(E)}{i_{tube}} \end{aligned}$$

This linearity indicates that the differential intensity is directly proportional to tube current throughout the measured range. That is, $\phi'(E) = \phi(E) \cdot i_{tube}$ for all tube currents measured here.

Figure 8: X-Ray Diode Current versus X-Ray Tube Current at 50 cm for 50 and 100 keV Spectral End-Points

IV. DISCUSSION

Figure 9: X-Ray Diode Current versus Tube Current at 82 cm for Spectral End-Point Energies between 30 keV and 140 keV

Tabulated data showing the measured and predicted XRD currents for different x-ray energies at 50 cm and 82 cm in air are presented in Tables I and II. The measured flux intensities were obtained directly from the SEMIRAD x-ray diode. The two calculated flux intensities, one using simulated incident spectra and the other using measured incident spectra were obtained through numerical integration [1,2]. The integral equation for determining the calculated flux intensity was provided previously in Equation (2).

Comparing the two calculated intensities with the XRD measurements shows that the predicted flux intensities obtained using measured spectra were within 10% of the measured values. The predicted intensities using simulated (TUBE) spectra were 10 to 30% lower than the measured values.

Past work has shown that approximately 80 percent of the radiation-dose deposited in a typical integrated circuit from a filtered tungsten-target x-ray tube can be attributed to photons from the L-line fluorescence portion of the x-ray tube's spectral energy distribution [12]. That, coupled with the fact that the magnitude of the L-lines is about an order-of-magnitude higher than the adjacent continuum suggests that the most important spectral information for calculating the response of a device is the L-lines.

Figure 10 shows an expanded view of the L-lines extracted from the 50 keV spectrum in Figure 5. The measured data includes at least 7 data points for each L-line. The TUBE data, on the other hand, provides the continuum, as plotted in the figures, and also the energy flux density (intensity) of each of the L- and K-lines (*i.e.*, the integral with respect to energy of the curve from the beginning of a line to the end of that line) and the location of the line. For the sake of plotting the data, the lines were depicted as triangles using equidistant points on the continuum as endpoints of the line with the magnitude chosen to satisfy the intensity equation. To ensure an accurate comparison of the lines obtained from each source (*i.e.*, the measured and simulated data), the data plotted in Figure 10 was integrated to compute the total energy flux density of each of the curves. This calculation showed that the intensity of the measured spectrum is 18.8% greater than the intensity of the simulated spectrum. This difference explains the data shown in Tables I and II and confirms that the measured L-line intensities are greater than those obtained from the TUBE simulations. Therefore, using the measured spectral data will result in a more accurate calculation of the actual dose deposited in the target.

Table I: Comparison of Measured X-Ray Diode Response with Predicted Response Based on TUBE Spectra (Simulated) and Measured Spectra (Measured) at 50 cm

X-Ray Tube		XRD Current				
Voltage (kV)	Current (μ A)	Measured (pA)	Predicted (Simulated)	Percent Difference	Predicted (Measured)	Percent Difference
50	4.0	0.070	0.054	22.8	0.071	-1.4
100	2.6	0.080	0.058	27.5	0.078	2.5

Table II: Comparison of Measured X-Ray Diode Response with Predicted Response Based on TUBE Spectra (Simulated) and Measured Spectra (Measured) at 82 cm

X-Ray Tube		XRD Current				
Voltage (kV)	Current (μ A)	Measured (pA)	Predicted (Simulated)	Percent Difference	Predicted (Measured)	Percent Difference
20	230	0.230	0.208	9.6	0.246	-7.0
30	55.0	0.153	0.130	15.0	0.167	-9.2
50	24.0	0.130	0.118	9.2	0.141	-8.5
80	15.0	0.128	0.115	10.2	0.130	-1.6
100	13.0	0.130	0.115	11.5	0.125	3.8
120	11.5	0.125	0.103	17.6	0.116	7.2
140	14.5	0.170	0.127	25.3	0.158	7.1
160	14.0	0.175	0.126	28.0	0.161	8.0

Figure 10: Comparison of Calculated and Measured L-Lines from 50 keV Spectra

The relationship of spectral energy distribution and intensity as a function of x-ray tube current is crucial in this effort. It is generally accepted that spectral energy distribution emitted from a bremsstrahlung source operating at a fixed anode voltage is independent of tube current—only the intensities will change and should scale directly with the tube current. Spectral distribution measurement techniques developed in this effort were able to prove that the anode voltage can be accurately set and held constant for different tube currents.

The SEMIRAD X-ray Diode used in this effort was an excellent detector for investigating the dependency of source intensities on x-ray tube current. The operation of the SEMIRAD depends on the collection of secondary electrons alone; hence, recombination effects do not occur. As a result, the SEMIRAD will not saturate due to charge recombination at high dose rates [13]. The dose rates encountered in this work are well within the operating range of the XRD employed; therefore, the diode currents measured here will depend only on the incident spectral energy distribution throughout the entire operating range of the x-ray tube.

The collaborating diode data presented here is an essential part of this work. Without it to show that the spectral energy distributions are directly proportional to the x-ray tube current over the entire operating range, there would be no experimental evidence to support the belief that the spectra measured at low tube currents would be valid at higher tube currents.

V. SUMMARY/CONCLUSION

Past work has shown that the measured ionizing dose delivered by photons of 30 keV and above to test samples in the LEXR was 10 to 30% higher than predictions. Since the measured values were made with calibrated dosimetry, the predictions were questioned. The work in this paper resolved this question. Spectral energy distributions with end-point energies ranging from 20 to 160 keV incident on a detector at different locations within the LEXR recorded larger responses than indicated by simulation. Higher intensities in the actual L- and K-lines were a major factor. Replacing the simulated

spectra with the measured spectra in the dosimetry calculations for the above facility resulted in agreement to within 10 percent of measured.

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