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# DETERMINATION OF THE SECONDARY ELECTRON EQUILIBRIUM USING AN EXTRAPOLATION CHAMBER

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## Abstract

To ensure that the external personnel dosimetry program conducted by U. S. Department of Energy (DOE) contractors is of the highest quality, the DOE established the Department of Energy Laboratory Accreditation Program or DOELAP. The contractor's dosimetry program is assessed against the criteria set forth for dosimeter performance and the associated quality assurance and calibration programs. Although personnel dosimeters are not processed or calibrated by Fermilab, a proactive quality assurance program is in place to ensure accurate monitoring. This program includes quarterly blind testing of the dosimeters used by personnel.

During the on-site assessment conducted of Fermilab's external dosimetry program during May 1994, an observation with regard to equipment maintenance and calibration was made:

"calibration personnel should probably review the electron secondary equilibrium needs at various irradiation distances from the  $^{137}\text{Cs}$  irradiation systems." The majority of the secondary electrons are generated through interactions of the beam with the collimator. Secondary electrons increase the low energy component of the radiation field, increasing the shallow doses measured. For dosimetric purposes, this increase needs to be defined so appropriate corrections to calculations or modifications to the facility can be made. Prompted by this observation, a study was designed to investigate the electron secondary equilibrium in the facility used for the blind testing by determining the dose equivalent as a function of depth in a tissue-equivalent medium. This presentation summarizes the methodology utilized and results of the investigation.

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## **Introduction**

To ensure that the external personnel dosimetry program conducted by U.S. Department of Energy contractors is of the highest quality, the DOE established the Department of Energy Laboratory Accreditation Program or DOELAP (DOE 1986a,b). The contractor's dosimetry program is assessed against the criteria set forth for dosimeter performance and the associated quality assurance and calibration programs (DOE 1986a). During the onsite assessment conducted of Fermilab's external dosimetry program during May 1994, an observation with regard to equipment maintenance and calibration was made: "calibration personnel should probably review the electron secondary equilibrium needs at various irradiation distances from the  $^{137}\text{Cs}$  irradiation systems." (Dolecek & Mei 1994)

The majority of the secondary electrons are generated through interactions of the beam with the collimator. Secondary electrons increase the low energy component of the radiation field, increasing the shallow doses measured. For dosimetric purposes, this increase needs to be defined so appropriate corrections to calculations or modifications to the facility can be made. Prompted by this observation, a study was designed to investigate the electron secondary equilibrium by determining the dose equivalent as a function of depth in a tissue-equivalent medium in the facility used for blind testing of the personnel dosimeters used on-site. This paper summarizes the methodology utilized and the results of the investigation.

## **Materials And Methods**

The Source Projector Facility<sup>†</sup> is constructed of concrete and consists of an outer control room and an inner irradiation room. Two gamma-ray projectors are operated from the outer room. One

<sup>†</sup> Internal Document. Krueger, F. and J. Larson. Fermilab ES&H Section Source Projector Facility Operating Procedures. April 1993.

of the projectors<sup>‡</sup> contains a nominal 3,700 GBq (100 Ci) <sup>137</sup>Cs source. The other is a dual projector<sup>||</sup> containing two sources with nominal activities of 370 GBq (10 Ci) and 37 GBq (1 Ci) <sup>137</sup>Cs.

The source projectors and collimator are mounted on an elevated rolling stand in the outer room, with their radiation cones directed into the irradiation room through a port. The desired projector is rolled into position on the stand to align with the port for irradiation into the inner room. An instrument/detector positioning carriage is roller-mounted to floor rails along the beam axis inside the inner room. The detector carriage distance from the source may be adjusted remotely from the outer room using a hand crank. The carriage height is readily adjustable by means of a crank-operated elevating mechanism.

For the depth-dose measurements, an extrapolation chamber<sup>¶</sup> was used. The electrode spacing is variable and is adjusted by rotating an aluminum ring which holds the entrance window. There is a reference mark on the ring to allow measurements to be replicated. Plate separations of 0.25 mm, 1.25 mm, 2.23 mm, 3.20 mm and 4.30 mm were used in the collection of data.

The detector was mounted on a stand and aligned with the center of the beam at a distance of 1 m from the source. Disks of tissue equivalent plastic were placed in front of the chamber and the current was measured at various thicknesses to develop depth-dose curves. The ion chamber window, constructed of conductive polyethylene, has a nominal density thickness of 2.9 mg cm<sup>-2</sup>, which was added to that of the disks to determine the total density thickness.

<sup>‡</sup> Model 28-10. J.L. Shepherd & Associates, 1010 Arroyo Ave., San Fernando, CA 91340-1822, (818)898-2391.

<sup>||</sup> Model 78-1M. J.L. Shepherd & Associates, 1010 Arroyo Ave., San Fernando, CA 91340-1822, (818)898-2391.

<sup>¶</sup> EG&G, Inc. Extrapolation Ion Chamber -- Model EIC-1 Data Sheet 84. April 1974.

Once the source was raised, the instrumentation was permitted to stabilize in the radiation field. A Keithley Model 610C Electrometer<sup>#</sup> measured the gross charge and its output fed into a Keithley Model 617 Electrometer<sup>\*\*</sup>, used for its data storage capabilities in the voltmeter mode.<sup>††</sup> The Keithley 617 recorded data at 10 second intervals.

## Results

### Depth-dose measurements

The measured current at each density thickness of absorber for the various plate separations was plotted and then fit with two different regression curves. The first curve fit was based on an approach presented by M.J. Scannell (1995). This curve fit is of the form:

$$y = a + bx + \frac{c}{x} \quad [1]$$

where a, b, and c are arbitrary fit parameters. The second fit employed a model which includes an initial dose buildup followed by an exponential falloff:

$$y = a(1 - e^{-bx})(e^{-cx}) \quad [2]$$

again, where a, b and c are fit parameters. In general, the second curve (Equation 2) provides a better fit to the data, as demonstrated by the square of the correlation coefficient. However, given the measurement errors and the lack of absorbers of uniform density thickness between 2.9 mg cm<sup>-2</sup> and 41.4 mg cm<sup>-2</sup>, both equations provide an adequate empirical fit to these data.

<sup>#</sup> Model 610C, Keithley Instruments, Inc., 28775 Aurora Rd., Cleveland, OH 44139, (216)248-0400.

<sup>\*\*</sup> Model 617, Keithley Instruments, Inc., 28775 Aurora Rd., Cleveland, OH 44139, (216)248-0400.

<sup>††</sup> Internal Document. Krueger, F. Operation of Instrumentation Used for Gamma Ray Source Transfer Calibration and Facility Studies. R. P. Note 111. March 1995.

Equations 1 and 2 as fitted to the integrated current data for each separation were used to obtain values for the current at a depth of  $7 \text{ mg cm}^{-2}$  and at a depth of  $1000 \text{ mg cm}^{-2}$ . These calculated values of current at  $7 \text{ mg cm}^{-2}$  and  $1000 \text{ mg cm}^{-2}$  were graphed against plate separation as shown in Fig. 1. Given the physical constraint that at 0 mm plate spacing, there is zero current, each set of calculated values ( $7 \text{ mg cm}^{-2}$  or  $1000 \text{ mg cm}^{-2}$  for Equation 1 or Equation 2) was fit with a linear curve of the form  $y=mx$ . The ratio of the slopes for the  $7 \text{ mg cm}^{-2}$  and  $1000 \text{ mg cm}^{-2}$  curves yields the shallow to deep dose ratio, 1.029 for Equation 1 and 1.037 for Equation 2.

### Estimation of absorber thickness

The majority of the shallow dose seen by the detector is due to secondary electrons produced by Compton scattering off the collimator and source holder. The betas originating from the radioactive decay of the source are ranged out by the source holder, with some bremsstrahlung production. The secondary electrons can be described as being similar to a beta radiation source with a continuous spectrum, with a maximum energy given by the Compton edge. Thus, the maximum energy of a secondary electron is very close to the gamma ray energy emitted from the  $^{137}\text{Cs}$  source, 0.6616 MeV. It has been experimentally observed that the transmission curve for beta radiation emitted from a source is best fit by an exponential curve (Knoll 1979):

$$\frac{I}{I_0} = e^{-\mu t} \quad [3]$$

Because the transmission is described by an exponential, eliminating all of the secondary electrons is impractical. It is possible to reduce the number of secondary electrons such that their contribution to the shallow dose is negligible. This can be achieved by arbitrarily assuming a ratio for  $I/I_0$  of 0.001 or 0.1%. The absorber thickness that would achieve this ratio is estimated to be  $0.254 \text{ g cm}^{-2}$  (2.76 mm polyethylene). An alternative way to estimate the absorber thickness is to use an empirical formula to determine the range of the particles (Shleien 1992):

$$R = 0.412E^{1.265-0.0954\ln E} \quad [4]$$

OR

$$R = 0.542E - 0.133 \text{ [Feather's Rule]} \quad [5]$$

Using these equations, the absorber thickness is estimated to be 0.240 g cm<sup>-2</sup> or 0.226 g cm<sup>-2</sup>, respectively. These are comparable to the value determined using Equation 3.

Any amount of shielding would also be expected to attenuate the deep dose. Through interpolation, the mass attenuation coefficient for a <sup>137</sup>Cs gamma ray in polyethylene is found to be 0.0885 cm<sup>2</sup> g<sup>-1</sup> (Shleien 1992). By introducing an additional 0.254 g cm<sup>-2</sup> of polyethylene into the beam, the gamma absorbed dose rate and hence, the deep dose rate, would be expected to decrease by approximately 2%.

### Conversion between integrated current and absorbed dose rate

For comparison, the absorbed dose rate was calculated from this data. Measurements had already been performed using NIST traceable instrumentation and sources to determine the exposure rate of the <sup>137</sup>Cs source used in this experiment. Calculation of the absorbed dose rate is dependent upon a number of factors: the effective area, the plate separation, the density of air, the ionization potential, the relative mass stopping power of tissue to air and the current generated by the chamber. The charge collected was corrected for temperature and pressure differences by employing the ideal gas law. The correction for humidity was negligible. These factors are related by the Bragg-Gray principle:

$$D\left(\frac{\text{Gy}}{\text{s}}\right) = \frac{S * W\left(\frac{\text{J}}{\text{C}}\right)}{\rho\left(\frac{\text{kg}}{\text{mm}^3}\right) * A(\text{mm}^2) * d(\text{mm})} * \frac{Q(\text{C})}{t(\text{s})} \quad [6]$$

where D = dose rate

S = relative mass stopping power

W = ionization potential

r = density of air at NTP (22°C and 1 atm)

A = effective area of the chamber plate

d = plate separation

Q = charge collected by the chamber

t = integration time

$$\frac{S * W}{\rho * A * d}$$

For a given plate separation,  $\rho * A * d$  is a constant. NCRP Publication 112 provides a value for S equal to 1.13 (NCRP 1991). W was taken to be 35 J C<sup>-1</sup> based on information in Knoll (1979).

Using the measurements at 2.9 mg cm<sup>-2</sup>, the absorbed dose rate at each of the various turns can be derived. A linear extrapolation to 0 mm plate spacing results in an absorbed dose rate of 215.79 mGy hr<sup>-1</sup>. For comparison, the source strength as measured using the NIST traceable instrumentation and then correcting for decay was 199.89 mGy hr<sup>-1</sup>.

## Discussion

The dose rate obtained using the extrapolation chamber and that measured by NIST traceable instruments are about 8% different. This is partially explained by the fact that the NIST traceable instruments have walls sufficiently thick enough to shield out all of the betas and low energy x-rays and measurably attenuate the gammas. Another explanation may lie within the values chosen for W and S in calculating the dose conversion factors. The range of values for W are from 33.85 J C<sup>-1</sup> to 35 J C<sup>-1</sup> depending upon the reference; the range of values for S are from 1.13 to 1.15. These calculations used the extremes for both W and S. This may account for approximately 3% and about 2% of the discrepancy, respectively. The center of the detector was