FIELD MEASUREMENTS OF BETA-RAY SPECTRA INSIDE NUCLEAR GENERATING STATIONS USING A SILICON DETECTOR COINCIDENCE TELESCOPE

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INTRODUCTION

Beta radiation is now recognized as a significant radiation safety problem in the personal dosimetry of weakly penetrating radiations. The use of "thick" dosimeters (eg., typically 100 mg cm^{-2}) for beta dosimetry requires, therefore, the application of beta correction factors which correct for the under-response of these dosemeters to low-energy betas. The estimation of these beta correction factors requires in-turn some knowledge of the beta-ray energy spectrum impinging on the dosemeter. In acknowledgement of this requirement, and to improve the accuracy of beta ray personal dosimetry in their nuclear power installations, Ontario Hydro initiated a study in the 1990s aimed at the characterization of beta radiation fields in CANDU reactor typical working conditions.

In the first stage of this effort, a two-detector coincidence telescope, based on a thin (97 μm) silicon detector (dE detector) and a thick (2 cm) plastic scintillator (E detector), was used (1). The use of a 97 μm thick silicon detector allowed us to achieve a lower energy coincidence threshold of 125 keV. This telescope was used to measure approximately thirty beta radiation fields in CANDU nuclear generating stations (2). Monte Carlo calculations were then used to estimate beta correction factors for the LiF-TLD elements in the Ontario Hydro TL dosimeters (3). Due to the poor energy resolution and noise characteristics of the plastic scintillator, the spectrometer coincidence efficiency decreased rapidly below 500 keV reaching a value of only approximately 15% at 125 keV. These low energy characteristics were judged insufficient, since the Monte Carlo calculations (3) showed that it is exactly the energy region below 500 keV for which the electron depth-dose distributions vary extremely rapidly, thereby contributing to the large and uncertain values of the beta correction factor. Furthermore, the measured beta spectra, corrected crudely for the loss in coincidence efficiency below 500 keV, showed an approximately exponential electron fluence intensity that increased with decreasing electron energy, implying that the deduced beta correction factors could be very significantly underestimated due to the uncharted electron energy region between 60 keV (the minimum electron energy which penetrates to a skin depth of 7 mg cm^{-2}) and 125 keV. Other serious difficulties arose when measurements were attempted in areas, for example a reactor containment vault, which required encapsulation of the spectrometer in plastic to prevent radioactive contamination. The encapsulation in plastic without adequate ventilation or cooling led to an increase in the temperature and leakage current of the front silicon detector, resulting in a rapid increase in noise level and consequently to an uncontrolled increase in the chance coincidence rate.

Based on these considerations a two- or three-element detector coincidence telescope based exclusively on silicon detectors, and cooled thermoelectrically when encapsulated was constructed and tested with the following significant advantages.

SYSTEM PERFORMANCE

1. The lower energy coincidence threshold (front dE detector, A = 40 μm) is 70 keV (60% efficiency) compared to 125 keV (15% efficiency) for the silicon/plastic

spectrometer. Slightly higher but still improved coincidence thresholds are obtainable with 72-μm and 97-μm thick detectors.

2. The coincidence efficiency decreases from 100% for electron energies below 100 keV to 250 keV depending on the choice of thickness for the front detector A compared to 500 keV for the plastic spectrometer. For the 40-μm detector the coincidence efficiency is 100% over the entire range of energies above 100 keV. For the thicker dE detectors the loss in coincidence efficiency is far more moderate below 250 keV than the loss in coincidence efficiency for the plastic spectrometer.

3. An important figure of merit (FOM) of the spectrometer is the rejection factor against photons, R_p, where

$$Rp = N_1/(N_t - N_c). \qquad (1)$$

N_1 is the singles counting rate in the thick energy detector , N_t is the total coincidence counting rate, and N_c is the chance coincidence rate. R_p is defined in this manner for a pure incident photon fluence and is essentially a measure of the reduction in the photon count rate due to operation of the coincidence requirement.

The photon rejection ratios are also significantly improved compared to the silicon/plastic spectrometer. For ^{133}Ba, in the two-element mode, the photon rejection ratio is 1600:1 compared to 360:1 for the silicon plastic spectrometer. In the three-element mode, the photon rejection ratio for ^{60}Co photons is approximately 2000:1 compared to 225:1 for the plastic spectrometer.

The beta-ray spectrometer described herein, incorporating photon rejection ratios of up to 2000:1, represents a significant improvement in the "state-of-the-art" in beta ray spectroscopy in the intense photon fields often encountered in reactor radiation environments. The spectrometer has been used to measure over 40 field spectra in CANDU reactors (5) ands the details of these measurements and the calculated beta factors using depth dose distributions based on Monte Carlo calculations for these spectra are described in the following.

BETA-RAY MEASUREMENTS

A total of forty two measurements were carried at three sites operated by Ontario Hydro, the Pickering, Bruce B and Darlington Nuclear Generation Stations. The measurements were carried out on various fuelling machine and boiler room components and smears from various working areas, in various detector configurations and at various source-detector distances. These sources are representative of components that working personnel come into direct contact during clean-up and maintainance procedures. The spectra are generally featureless with the relative intensity of the electron fluence increasing roughly exponentially with decreasing electron energy. The maximum energy varies between 1200 keV and 3500 keV, with an average energy of approximately 550 keV. This behaviour is apparently typical of a mixed fission-product spectrum. The threshold energy of the various spectra varies between 70 keV and 150 keV. Filtered spectra, through various layers of protective clothing, show no significant changes in shape in the important low-energy region, the main effect of the filtration being a reduction in the maximum energy of the spectra. Thus, although low-energy betas in the primary spectrum are absorbed by the protective clothing, multiple scattering and attenuation of the higher-energy electrons replenishes the supply of low-energy electrons, resulting in an essentially unaltered spectrum in the low-energy region. This observation goes against the common dogma that protective clothing reduces superficial dose via absorption/removal of low-energy electrons. This will be true only in the absence of high-energy electrons which continually replenish the supply of low-energy electrons.

CALCULATION OF BETA CORRECTION FACTOR

Beta correction factors were calculated for all the measured beta-energy spevctra, for both the 100 mg cm-2 and 240 mg cm-2 skin and extremity dosimeters, in both perpendicular and isotropic geometries. It is interesting to compare the average beta correction factors obtained using the silicon spectrometer with those obtained using the plastic spectrometer. The beta factors are increased by 19% for the skin chip and by 11% for the extremity dosimeter respectively, indicating that low-energy electrons (between 60-125 keV and not detected by the plastic spectrometer) lead to a measureable, but not dramatic, increase in the beta correction factors.
Averaging over all the beta correction factors for the skin dosemeter yields 2.33 ± 0.83 compared to the current value of 1.74 used by Ontario Hydro. Averaging over all the beta correction factors for the extremity dosemeter yields 3.73 ± 1.38, compared to the current value of 2.0 used by Ontario Hydro. Our measured values are, therefore, 34% (skin chip) and 87% (extremity dosemeter) higher than the current beta correction factors used by Ontario Hydro in their dosimetry program. It is intuitively more reasonable to expect that the working place environment (and averaged over the movements of the radiation worker) produces an effective near-isotropic radiation field for a "chest-worn" or an extremity dosimeter. In this case the more appropriate beta correction factor for the "skin" chip would be 2.73 ± 0.77 and for the extremity dosimeter 4.42 ± 1.17. These values are 57% and 120% greater, respectively, than the current values used by Ontario Hydro.

CONCLUSIONS

The very large spread in beta correction factors clearly indicates the need for a dosimetry system based on thinner detectors for both the "skin" chip and the extremity dosemeters. With the currently used thickness of 100 mg cm^{-2} and 240 mg cm^{-2} used by Ontario Hydro, the appropriate beta correction factors vary by approximately one order of magnitude depending on the source of the radiation field, the angular distribution of the radiation field, the source - TLD distance, etc.... The only practical method to reduce these large uncertainties is to adopt detector thicknesses as low as possible and still consistent with other dosimetric requirements such as minimum detectable dose, ruggedness, etc... To demonstrate the benefits of decreased thickness we have calculated the beta correction factors for representative and extreme spectra for 40 and 20 mg cm^{-2} chips. These particular thicknesses were chosen to correspond to commercially available LiF-TLDs. The benefits of decreased thickness are dramatic. The average value of the beta correction factor decreases from 4.80 for a 240 mg cm^{-2} chip to 1.29 for a 20 mg cm^{-2} chip. In addition, the spread in beta correction factors also dramatically decreases, from 4.80 ± 2.1 (44%) for the 240 mg cm^{-2} chip to 1.29 ± 0.1 (8%) for the 20 mg cm^{-2} chip. Clearly a 20 mg cm^{-2} chip of high sensitivity is the optimum choice for superficial dose estimation due to beta rays.

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