Radioactivity Determination of Sealed Beta-Emitting Sources by Surface Dose Measurements and Monte Carlo Simulations

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1. Introduction

The radiation detection systems employed in radioactivity calibration laboratories have changed considerably over the past sixty years. Advancements in the areas of material science, electronics, and computer technology have contributed to the development of more sensitive, reliable, and user-friendly laboratory instruments. The four primary radiation measurement systems considered to be necessary for the modern radionuclide measurement laboratory are gas-flow proportional counters, liquid scintillation counters, Si spectrometer systems, and Ge spectrometer systems. [1]

A national institute of standards recognized by BIPM (Bureau International des Poids et Mesures) use these detector to measure the radio-activity. However, these measurement systems have some limitation. For a gas-filled detector, the source size should not be larger than that determined by the counter geometry and the measurements are limited to sources with the activities of less than 20,000 Bq. [2] A liquid scintillation detector can only be used to measure an activity of liquid mixture isotope.[3] Therefore it can't be used to measure activities of sealed sources. Further it is quite difficult to measure a radioactivity of beta-isotope accurately due to self-absorption and scattering. In particular an radioactivity generated by a nuclear reactor is approximately calculated by using target material compositions, cross-sections, and neutron flux, which is determined upon operating parameters within the nuclear reactor. However, the results from this approach involve a high uncertainty,

We develop a Monte Carlo applied radioactivity determination for beta sources. It is based on an assumption that the surface dose rate is proportional to the activity of beta-source. The calibration constant was defined as the ratio of the surface dose to activity. The calibration constant was derived by comparing measurement and simulation. We simulated a beta-source and a detector to evaluate the surface dose rate and several correction parameters using a Monte Carlo tool. The extrapolation ion-chamber was used to measure the surface dose rate for a standard source. The Sr/Y-90 standard source is calibrated by NIST used for this study.

2. Material and Methods

2.1 Standard Source

A NIST traceable source was used to measure a surface dose rate and calculate calibration constant. The active material is uniformly distributed over the surface of Stainless Steel foil and sealed in an aluminum mounting ring under a 0.9 mg/cm^2 aluminized Mylar window for Sr-90. The Nature of source activity was evaporated Salts on Stainless Steel (0.254 mm thickness). And active diameter is 20 mm. The overall source diameter is 25.4 mm and 3.18 mm thick. Contained radioactivity is 4.077 kBq at reference date (1-Feb-12, 12:00 PST). The total uncertainty of source at the 99% confidence level is 3.1%. All measured dosimetry data were corrected for radioactive decay of Sr-90 between the measurement date and reference date

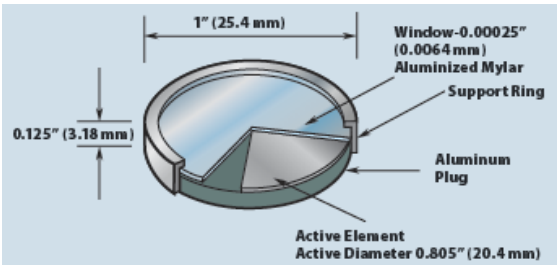


Fig.1 Schematic Diagram of Sr-90 Standard Source

2.2 Extrapolation chamber (EC)

The reference dose rate was determined using an extrapolation ionization chamber (Bohm extrapolation chamber, PTW, Germany). An extrapolation chamber (EC) can vary its ionization volume to a vanishingly small amount. In the extrapolation chamber measurements, the spacing between the entrance foil and the collecting electrode (i.e., chamber air gap) was varied in the range of 3.0, 5.0, 7.0, and 9.0 mm. The range of 0.6 MeV electrons in air is approximately 200 cm, which is about 2000 times the maximum chamber air gap of 9 mm. The absorbed dose rate in water, Dw, was determined from the slope of the linear fitting (i.e.,

"extrapolation curve"), i.e., the change of the ionization chamber current (I) vs chamber

air gap thickness (t). All readings were normalized to a reference temperature, 20˚C, and pressure, 101.325 kPa. The absorbed dose rate in water was given as below:

$$\dot{D}_w = \frac{\left(\frac{w}{e}\right) S_{w,\mathrm{air}}}{\rho_0 a} \left(\frac{\Delta I}{\Delta t}\right)_{t\to 0} k_{\mathrm{back}} \qquad (1)$$

where (W/e) = the mean energy required to produce an ion pair in dry air divided by the elementary charge (33.83 ± 0.06 J/C), $S_{w,air}$ = the ratio of the mean mass-collision stopping.[5]

power of water to that of air, □0 the density of air (1.2047 kg/m3) in the reference condition, a = the area of the collecting electrode (7.0685 cm2), k_{back} = a correction factor, $(\Delta I/\Delta t)_{t\to 0}$ = the rate of change of current (I) with the distance (t), i.e., the extrapolation chamber electrode's air gap. The ionization currents were obtained in the Charge mode of the electrometer (UNIDOS, PTW, Germany) for each air gap and two voltage polarities (±300 V). And Measurement time is 100 seconds. Figure 2 shows the measurement setup for the Sr-90 standard source using the extrapolation chamber. A custom-made guide system housed both the extrapolation chamber and the applicator. The guide system allowed the applicator to be placed precisely at the specified distance from the detector (EC) and to align the applicator with the central axis of the chamber. Owing to this guide system, the measurements were repeated at five different SDDs (source-to-detector distance) of 5,7, 9 and 11 mm within 0.1 mm precision.

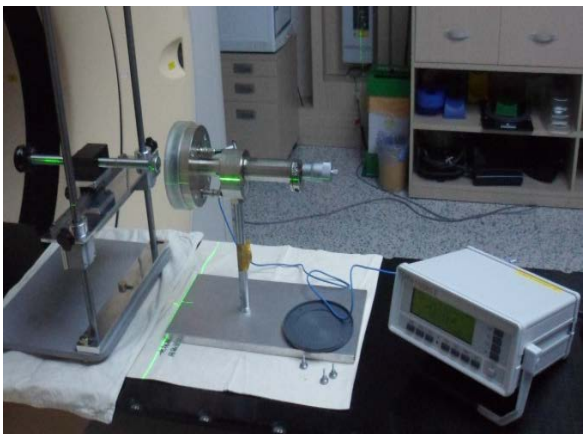


Fig. 2 Measurement setup for Sr-90 standard source dosimetry using extrapolation chamber dosimetry with guide system

2.3 Monte Carlo simulations

Monte Carlo simulations were carried out using the MCNP5 code from the Los Alamos National Laboratory. The MCNP code employed an improved electron transport algorithm of ITS 3.0 (Integrated Tiger Series Version 3.0. We assumed that the source activity was uniformly distributed in the entire volume of absorbent disk. Photons and electrons were tracked until they reached the cutoff energy of 1 keV. The MCNP5 simulations were carried out for the applicator placed on the top of a cylindrical water phantom that has a 2 cm radius and 1.5 cm height (Fig. 3). The pulse height tally (*F8) of MCNP was used for dose calculations in voxels (0.5 × 0.5 × 0.005 mm3) shown in Fig. 3. The *F8 tally card describes energy distribution of pulses created in a detector. In order to reach statistical errors less than 1.5% for any voxels of interest in the simulation geometry, 8×10^7 histories were run in coupled electron=photon mode on a Linux cluster (2.67 GHz×24 CPUs) for approximate 12 h of computer time. The energy spectrum of beta particles emitted from the applicator was changed, since beta particles were moderated by metallic encapsulation. The change in the energy Spectrum was calculated with the surface flux tally (F2) of MCNP5 using the tally energy card (En). The energy range of 0–2.21 MeV was separated into 22 bins with the same interval (0.1 MeV). The energy spectrum was calculated at 0.25 mm depth in water from the surface of applicator. The extrapolation chamber detector efficiencies for various SDDs were determined by the Monte Carlo simulations using the Surface current tally (F1). The detector efficiency was defined as the ratio of particles emitted from the source to particles arrived at the detector. The cell of cylindrical type with a 30 mm diameter and 0.1 mm thickness was set at five different distances from the applicator in air.

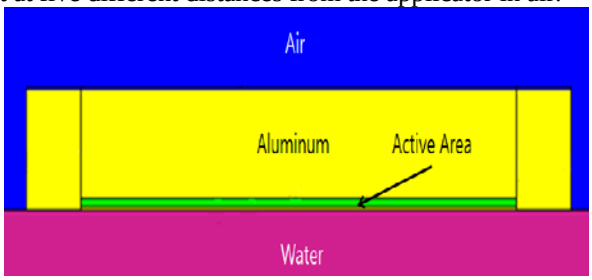
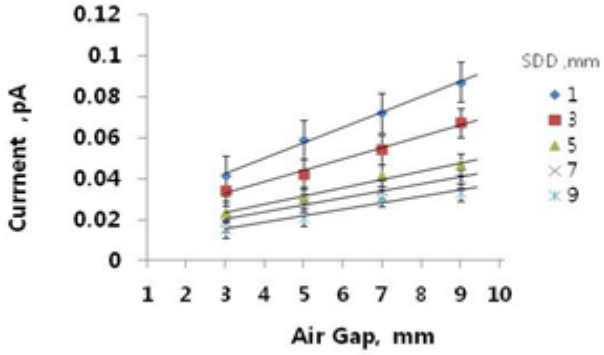


Fig.3 Schematic (cross-sectional) view of Sr-90 standard source for MCNP simulations.

3. RESULTS

The extrapolation curves of Fig. 4 were obtained by plotting the mean values of measured ionization currents as a function of the air-gap thickness between two chamber electrodes for various SDDs. The curves show a linear behavior for the air-gap thickness between 3.0 and 9.0 mm. All R-square values for this linear fitting were over 0.9. The current at the surface was obtained by extrapolating the curve to the air-gap thickness for various SDDs. By using this extrapolation curve, it was possible to determine the reference dose rate of the Sr/Y-90 Standard source. The rate of current change as the air-gap thickness approached zero was determined.

The rate of current change was converted into the absorbed dose rate to water using Eq. (1). The average energy of betas at the outer surface of the applicator was determined to be 0.9346 ± 0.133 MeV. The stopping power ratio (Sw,air) was approximately 1.1256 ± 0.003 for the average energy. The detector efficiencies for seven SDDs were calculated to correct the reference dose rates (Table 1). These corrected reference dose rates for seven SSDs were averaged, yielding a reference dose rate of 4.15×10^{-5} cGy/s. And calibration factor that dose rate was divided activity was calculated. It was 1.19×10^{-8} cGy/s·Bq for MC, 1.21×10^{-8} cGy/s·Bq for Monte Carlo Simulation.



SDD (mm)	Current (pA/mm)	Detector Efficiency	Corrected Reference Dose rate (cGy/s)
5	0.0044	0.43	4.46^{-05}
7	0.0036	0.37	4.08^{-05}
9	0.0029	0.32	4.01^{-05}
11	0.0015	0.16	4.07^{-05}
Mean			4.15^{-05}

4. Discussion and Conclusions

There was about 1.7% difference in the reference dose rates measured by the two techniques. These difference and relative errors were comparable to those of other studies. [6] It should be noticed that the area of collecting electrode was nine times larger than that of radiation field. If the diameter of the source is smaller than the area of collecting electrode, the source should be located at a sufficiently large distance from the detector surface so that the radiation field at the detector surface was larger than the area of collecting electrode. In addition, beta particles from the applicator interact with materials (e.g., air) between the applicator and the detector. Therefore, the number of betas detected by an extrapolation chamber differ that emitted from the applicator. In this study, the rate of change of current was measured at four distances between the extrapolation chamber and the source. The correction factor for a given geometry (denoted as detector efficiency) was calculated by the MC simulations to convert the rate of change of current to the reference dose rate for a unit activity. We demonstrated that the method developed in this study could accurately determine the radioactivity of beta-source. For the further validation, a test source will be produced by HANARO. The activity of it will be determined by using the calibration constant. The determined activity will be cross-calibrated by NIST.

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