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Characterization of photon-emitting wide area reference sources

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ABSTRACT

A procedure has been developed to calibrate photon-emitting wide area reference sources in terms of activity, surface emission rate and uniformity considering the requirements introduced by the recent revision of ISO standard 8769. The method makes use of a large volume NaI detector with a cross table scanning system, a radiography system and it applies Monte Carlo techniques to assess the surface emission rate. The method was successfully applied to sources of ^{241}Am, ^{57}Co, ^{137}Cs and ^{60}Co. In addition, problems with definitions and the practical use of standard ISO 8769:2010 are highlighted.

1. Introduction

Wide area reference sources are commonly used to calibrate contamination monitors with respect to surface emission rates and activities. Usually the source efficiency, i.e. the ratio of the number of emitted particles or photons to the activity, is unknown and largely depends on the manufacturing process or on filters that are used. In particular, there is special interest in photon-emitting wide area sources with filters to remove X-ray and electron contributions.

The procedures to measure the surface emission rate and the activity of alpha- and beta-emitting sources are well established at national metrology institutes. The determination of the activity is more challenging because the source efficiency will vary from source to source even if sources of the same type are compared (Janßen and Thieme, 2000). However, calibration methods exist and are applied regularly (Janßen and Klein, 1994; Janßen and Klein, 1996; Švec et al., 2006).

The recent revision of ISO standard 8769 (ISO, 2010) tightened the criteria to classify wide area sources in terms of uniformity and also prescribes measurement procedures to assess the uniformity. These changes require a new experimental approach because, until now, no national metrology institute has been able to certify class 1 photon-emitting wide area reference sources. The work presented here is based on a calibrated NaI detector to determine the source activity and an autoradiography system to measure the activity distribution. Simulation techniques were used to evaluate the resulting photon surface emission rate to overcome experimental problems of measuring the emission rates directly.

2. Calibration procedure

2.1. Definitions

In ISO standard 8769:2010 the uniformity is defined as the relative experimental standard deviation of the photon surface emission rates of portions of the active area of the source, each portion having the same size of 5 cm^2 or less. Further constraints on the shape and the arrangement of these portions are not given, but bearing in mind that knowledge about uniformity and distribution of the photon emission rates should enable the user of a wide area source to calibrate contamination monitors smaller than the source itself, it seems reasonable to divide the active area of the source into subareas that resemble the original shape. Quadratic sources with an active area of 10 cm × 10 cm are commonly used and will be considered in the following. The concept and the procedures presented can, however, be easily transferred to rectangular sources with different dimensions. Following these deliberations a source with an active area of 100 cm^2 is divided into 25 quadratic portions with an area of 4 cm^2 each.

Defining subareas to describe a wide area source implicitly assumes that the activity is homogeneously distributed within these subareas. Depending on the manufacturing technique, this premise may be far from reality, because incorporating the radioactive material into an anodized aluminum foil, drop deposition or printing the source using an inkjet technique will affect the source properties in different ways. The same is true of the simulation or the experiment described later where each subarea is sampled by a limited number of point-like activity spots, the mean of which is attributed to the whole subarea.

The ISO standard defines the surface emission rate as the number of photons above a given energy emerging from the face of the source or its window per unit time. This definition is

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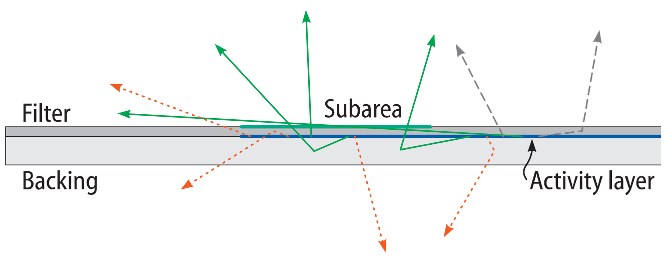

Fig. 1. Definition of the surface emission rate. All photons leaving the source via the front face of a single subarea (solid lines) contribute to the surface emission of that subarea irrespective of the origin of the initial photon. Photons emitted from the backing or the edges (dotted lines) are not taken into account.

straightforward for alpha- and beta-emitting sources without a filter layer but becomes complicated for photon-emitting sources which include a filter with a thickness of up to 1 mm. The inner structure of the source is not accessible to the user, and thus, the "face of the source" is the surface of the filter, which implies that it does not coincide with the activity layer. We decided that a useful definition of the surface emission rate of the whole source must be transferable to subareas of the source in a consistent way so that it can be calculated by summing over all subareas. This is in contrast to the ISO standard stating "Because of possible edge effects and contributions from neighbouring areas, the total emission rate for the source cannot be determined from the summation of emission rates from the individual areas."

This entails that the definition includes only photons emerging from the source through the filter above the active area but does not include photons emerging through the edges, thus reducing the solid angle of accepted photons to a value of less than 2π, depending on the filter thickness (Fig. 1). It should also be noted that the surface emission rate can only be defined for a massless environment because effects of scattering, for example off shielding material, will modify the surface emission rate as well as the angular and energy distribution of the emitted photons.

2.2. Determination of uniformity and activity distribution

To determine the activity distribution or to calculate the uniformity U of a wide area source, a position sensitive detector—which also includes imaging plates—or a masking device is required. In contrast to alpha- and beta-emitting sources, a significant crosstalk from neighboring subareas into the subarea under study is observed when measuring photon-emitting sources. The ISO standard requires that the contribution of those neighboring subareas shall be less than 5%, which, however, can hardly be achieved. Even for a masking device made of 50 mm of lead with an aperture of 20 mm × 20 mm, the constraint laid by the ISO standard cannot be fulfilled. For ^{60}Co, the contribution of neighboring subareas was found to be more than 500% and even for ^{241}Am using imaging plates, it is about 6%. Therefore, another method was developed to reconstruct the true activity distribution from scanning the wide area source with a masking device or from data collected by digital autoradiography acting as a "position sensitive measurement system". For this purpose the response of the detection system to a reference source with an active area of 20 mm × 20 mm embedded into the same backing and filter material like the wide area source is measured. It is now possible to measure a set of 81 efficiencies $\varepsilon_{x'-x,y'-y}$ that describe the response of the detector placed at position (x',y') to the reference source at position (x,y). Writing the observed count rates of the large area source while scanning the whole active area with a step size of 20 mm as a vector $\vec{N}$ with 25 components and assuming an activity distribution with a_i being the percentaged partial activity in subarea i, the following equation can be formed

$$\vec{N} = \hat{\varepsilon}\cdot\vec{a}\cdot A = \underbrace{\begin{pmatrix} \varepsilon_{0,0} & \cdots & \varepsilon_{80,-80} \\ \vdots & \ddots & \vdots \\ \varepsilon_{-80,80} & \cdots & \varepsilon_{0,0} \end{pmatrix}}_{25\times25\text{ matrix elements}} \times \begin{pmatrix} a_1 \\ \vdots \\ a_{25} \end{pmatrix} \cdot A \quad (1)$$

with A being the overall activity of the source. Eq. 1 can also be transferred to an experimental condition where a position sensitive detector with a source in fixed position is used.

This is a linear system of equations and can be solved analytically by using Cramer's rule to determine the partial activities $\vec{a}\cdot A$ of the source. It will have one single solution, if the condition $\det(\hat{\varepsilon}) \neq 0$ is fulfilled, which was true of all measurements made so far. It should be noted that results worsen for $\det(\hat{\varepsilon}) \to 0$, which corresponds to an experimental condition, where the aperture device is not efficient in masking the part of the source that should not be measured. The validity of the solution was also confirmed by using the Microsoft Excel Solver tool (Solver, 2000) minimizing the difference between the calculated and the observed activity distribution. It yielded the same results within the numerical precision of the algorithm. With the known activity distribution the uniformity relating to activity U_A can be calculated.

2.3. Determination of activity

To determine the activity without *a priori* knowledge about the activity distribution requires a detector significantly larger than the source to be calibrated and this detector must have a uniform response across its active area. These requirements can hardly be met with photon sensitive gamma detectors like germanium detectors or inorganic scintillators. Detectors that are affordable and readily available are always a compromise in terms of detection efficiency, size and cost and need to be calibrated with respect to their spatial response.

Assuming an activity distribution with a_i being the percentaged partial activity in subarea i, the expected count rate $\dot{N}$ of a wide area source positioned centrally below the detector can be expressed as

$$\dot{N} = \sum_{i=1}^{25} \dot{N}_i = A \sum_{i=1}^{25} \varepsilon_i a_i \quad (2)$$

with ε_i being the position-dependent detection efficiency for a given nuclide. Using a calibrated detector and knowing the activity distribution a_i the source activity A can be determined.

2.4. Determination of surface emission rate

The photon surface emission rate of a point source with higher photon energies and little self-absorption can easily be calculated from the activity, the photon emission probabilities and corrections to take absorption effects into account. The situation becomes more complex for area sources where the required backing material and filter cause significant absorption and scattering. Thus, the surface emission rate is derived from a known activity distribution by means of detailed Monte Carlo simulations which yield conversion factors c_{ij} that translate the activity within each subarea of the source to the resulting surface emission rate in the j-th subarea ϕ_j. The total surface emission rate Φ can now be calculated as

$$\Phi = \sum_{j=1}^{25} \phi_j = \sum_{j=1}^{25} \sum_{i=1}^{25} c_{ij} a_i A \quad (3)$$