Radiation Field of Packages Carrying Spent Co-60 Radioactive Sources - 12437

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ABSTRACT

Among the diverse radioactive sources commonly exploited in medical and industrial applications, Co-60 is increasingly used as strong gamma emitter. Over time, source manufacturers favored Co-60 as opposed to other gamma emitters because its relatively short half-life (5.27 year) that minimizes issues related to the management of disused sources.

Disused Co-60 sources can retain a significant amount of radioactivity (from hundreds of MBq to several GBq) that still poses safety concerns on their handling and transportation. In this context a detailed knowledge of their radiation field would provide the necessary information for taking actions in preventing unnecessary doses to the workers and the population by optimizing transportation procedures and handling operations.

We modeled the geometry and the materials constituting a transportation packaging of a spent Co-60 source which had an original maximum activity of a few GBq and was enclosed in a small lead irradiator. Then we applied a Monte Carlo transport code (MCNP5) for tracking down the gamma photons emitted by the source, including the secondary photons resulting by the interaction of the source photons with the surrounding materials. This allowed for the evaluation of the radiation field inside and outside the packaging, and the corresponding equivalent dose useful for checking the compliance with the regulations and the health risk of possible radiation exposure.

We found that a typical 60-liters drum carrying a spent Co-60 source, enclosed in its original irradiator, with a residual activity of 300 MBq could already overcome an equivalent dose of 0.2 mSv/h on the drum external surface, which is the maximum equivalent dose at any point of the surface for this packaging as prescribed by local regulations. This condition is even more apparent when the source is slightly displaced with respect to the rotation axis of the drum, an easily occurring condition for sources not properly packaged, generating non-compliant hot-spots on the drum surface. As an example, a displacement of 5 cm translates in an increase of 80% in the dose level on the nearest side of the drum. We also found that the equivalent dose is significantly influenced by the scattered source photons and the secondary photons, whose contribution to the radiation field is mainly determined by the package geometry.

The developed model resulted in an important tool for exploring the detail of the radiation field of a spent Co-60 source packaged for transportation allowing to check for compliance with the regulations and to evaluate risks to the workers and the population. It is worth to point out that this modeling approach is completely general and can be applied to a variety of different problems not limited to the transportation of radioactive material.

INTRODUCTION

Since ionizing radiation can modify the physical and chemical properties of the irradiated material it has been used for a variety of applications. In the late '50s, the advent of commercial nuclear reactors made possible the large scale production of radioisotopes and gamma ray emitters like Cobalt-60 became a common radiation source for medical and industrial applications. Co-60 is almost solely used as the gamma radiation source for industrial use now because of its easy production method, its non-solubility in water [1], and short half-life, as opposed to other gamma emitters (e.g., Cs-137, 30.17 years), that minimizes issues related to the management of disused sources.

Radioactive cobalt is produced from natural cobalt which is an element found only in form of the stable isotope Cobalt-59. Small cylinders or pellets made out of almost pure cobalt sintered powder and generally welded in Zircaloy capsules are placed in a nuclear power reactor, where they stay for a limited period (about 18–24 months) depending on the neutron flux at the location. While in the reactor, a Co-59 atom absorbs a neutron and is converted into a Co-60 atom. After irradiation, the capsules are further encapsulated in corrosion resistant stainless steel. At this point the gamma radiation can come through but not the radioactive material itself [1].

Co-60 decays with a half-life of about 5.27 years emitting a negative beta particle. The emitted particle can have energies of 0.31 or 1.48 MeV with the first having a probability of 0.9988. After the beta decay the Co-60 becomes a Nichel-60 in an excited state. The excited Ni-60 immediately decays to the ground state by emitting a gamma photon of 1.1732 MeV followed by another at 1.3325 MeV, or directly a 1.3325 MeV photon, depending on the original beta decay mode.

Given its radiological properties, Co-60 is extensively used for medical applications as source for radiation therapy [2] and it has been proved effective as radiation source for various research activities [e.g., 3]. Industrial applications of gamma radiation include sterilization of health care products, cleaning of water and sewage sludge disinfection, irradiation of food and agriculture products for various end objectives, such as disinfestation, shelf life extension, sprout inhibition, pest control, and sterilization [4]. Moreover, gamma radiation is used for materials modification such as polymerization, polymer crosslinking, and gemstone colorization [5]. Other important applications imply the use of small sources (either in terms of activity and physical dimensions) for density measurements and radiography of thick welded plates.

Disused Co-60 sources can retain a significant amount of radioactivity (from hundreds of MBq to several GBq) that still poses safety concerns on their handling and transportation. In this context a detailed knowledge of their radiation field would provide the necessary information for taking actions in preventing unnecessary doses to the workers and the population by optimizing transportation procedures and handling operations. Here we modeled a transport packaging of a typical disused Co-60 source for characterizing its radiation field and consequently checking the compliance with the regulations and the health risk of possible radiation exposure.

METHOD

We modeled in details the geometry and the materials constituting a typical transportation packaging of a spent Co-60 source that could have been used, for example, in industrial density measurements. Such a source had an original maximum activity of a few GBq and is enclosed in a small lead irradiator. The packaging is constituted by a drum which includes the irradiator suspended in a filling made of

polyethylene chips. The whole packaging is surrounded by air. The drum is a truncated cone with a capacity of 60 liters made of 5 mm-thick iron. To simulate the polyethylene chips, the internal volume of the drum was filled with polyethylene assuming a density of 0.5 g/cm^3 to take into account the air that fills the gaps between the chips. The irradiator was modeled by a lead sphere with a radius of 7 cm and a concentric spherical cavity of 2.5 cm in diameter where the Co-60 source is placed. The adopted source is an isotropic point source emitting gamma rays at 1.1732 and 1.3325 MeV with the expected probability. The irradiator has been displaced by 5 cm with respect to the rotation axis of the drum. This is an easily occurring condition for sources not properly packaged.

Then we applied a Monte Carlo photon transport code for tracking down the gamma photons emitted by the source, including the less energetic secondary photons resulting by the interaction of the source photons with the surrounding materials. This allowed for the evaluation of the three-dimensional radiation field inside and outside the packaging, and the corresponding equivalent dose useful for checking the compliance with the regulations and the health risk of possible radiation exposure. The code adopted was A General Monte Carlo n-Particle Transport Code, Version 5 (MCNP) [6]. MCNP is a general-purpose Monte Carlo n-particle code that can be used for neutron, photon, electron or coupled neutron/photon/electron transport. For photons, it takes into account of incoherent and coherent scattering, fluorescent emission after photoelectric absorption, absorption in pair production with local emission of annihilation radiation, and bremsstrahlung [7]. The volume occupied by the packaging, and its surroundings, is divided in small rectangular cells whose larger dimension is approximately 4.7 cm. The contribution of each transported photon is tallied in each cell in terms of track lengths, thus the average flux in each cell is estimated from the track length density [6]. The average flux is then converted to equivalent dose using the 1977 ANSI/ANS [8] and ICRP-21 [9] photon flux-to-dose rate conversion factors [6].

Italy acknowledged EURATOM directives 80/836, 84/467, 84/466, 89/618, 90/641 and 92/3 under D. Lgs. 230/95 stating that under any circumstances an individual of the population cannot receive an equivalent dose exceeding 1 mSv per year. This requirement translates into a maximum contact dose of 0.2 mSv/h on the external surface of a packaging in case of transport of a 60 liters drum containing a sealed radioactive source such as Co-60. This amount of equivalent dose is therefore the reference value on which the following considerations are based.

RESULTS

The Monte Carlo simulation was stopped after having tracked the history of 1x10^9 photons generated by the source. This number of tracked source photons allows for an average relative uncertainty of 1% associated with the results. The total equivalent dose associated with the calculated radiation field is illustrated in Figure 1. The color bars refer to the specific case of a 300 MBq Co-60 source transported in the packaging, a typical value of residual activity for a disused commercial Co-60 source.

Given the energy of the source photons, the main interaction with the surrounding materials is by means of Compton scattering. Upon interaction, each photon loses some energy and might change direction. The scattered and less energetic photons have a higher probability of ionizing atoms by photoelectric effect. The emitted photoelectrons are promptly stopped by the surrounding atoms generating bremsstrahlung photons with lower energies, compared to gamma rays, that are about 75 keV (hard X-rays) with a rate of 2 photons per source photon. The distribution of these photons clearly depends on the distribution of their generating material that, in this specific case, is the package itself (Figure 1d).

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With reference to Figure 1a, the arrows indicates the presence of a hot-spot on the drum surface. The total equivalent dose in this point of the packaging exceeds 0.2 mSv/h. In Figure 2 the spectrum (0.05 MeV in sampling) of the hot-spot identified on the drum surface is reported, and the total equivalent dose is the area below the curve. The total equivalent dose takes therefore into account all the photon energies, including bremsstrahlung and scattered photons. The former mainly contribute to the energies ranging from 0 to 0.15 MeV, while the latter from 0.15 to 1.30 MeV. Their contribution to the total dose is not negligible resulting in 0.12 mSv/h (57% of the total equivalent dose), with the X-ray components contributing with 1.4 μSv/h. Direct source photons escaping the packaging contributes to the total dose with 0.09 mSv/h (43% of the total equivalent dose).

DISCUSSION

In the example illustrated in this work, a small Co-60 source inside its irradiator and properly packaged in a drum for transport, presents a hot-spot on the drum surface if the irradiator is displaced of just few centimeters with respect to the rotation axis of the drum. A Monte Carlo simulation provided a complete description of the radiation field in the volume surrounding the packaging as a function of photon energy showing that a significant contribution comes from source photons scattered by the package itself.

As an example, the Transport Index (TI) [10] of this packaging was calculated, resulting in a value of 0.5 (Figure 2). This value is low when compared to the regulations [10], however suggests that an individual just 1 meter afar from the packaging receives, in a few hours, a dose comparable to that received with a radiograph [11]. This might be the case of the driver of a truck transporting the packaging, in particular when a number of packages are transported at the same time.

It is important to notice that the results presented in this work are general, and can be appropriately scaled to represent the radiation field of similar geometries with gamma sources of different activity. However, this quick application of a Monte Carlo simulation provides useful insights in the process of preparing a packaging for transport. This simple model suggests that this approach can be efficient for screening a number of packaging configurations and flagging those potentially not compliant with regulations, that will require a more thorough care in the packaging process. Furthermore the knowledge of the details of the radiation field can be useful for optimizing the geometry of the transport cargo, and becomes essential when a variety of packaging are transported or stored, in order to prevent hazardous situations during their handling, and hence preventing unnecessary doses to the workers and the populations.

It is worth to point out that this modeling approach is completely general and can be applied to a variety of different problems not limited to the transportation of radioactive material.
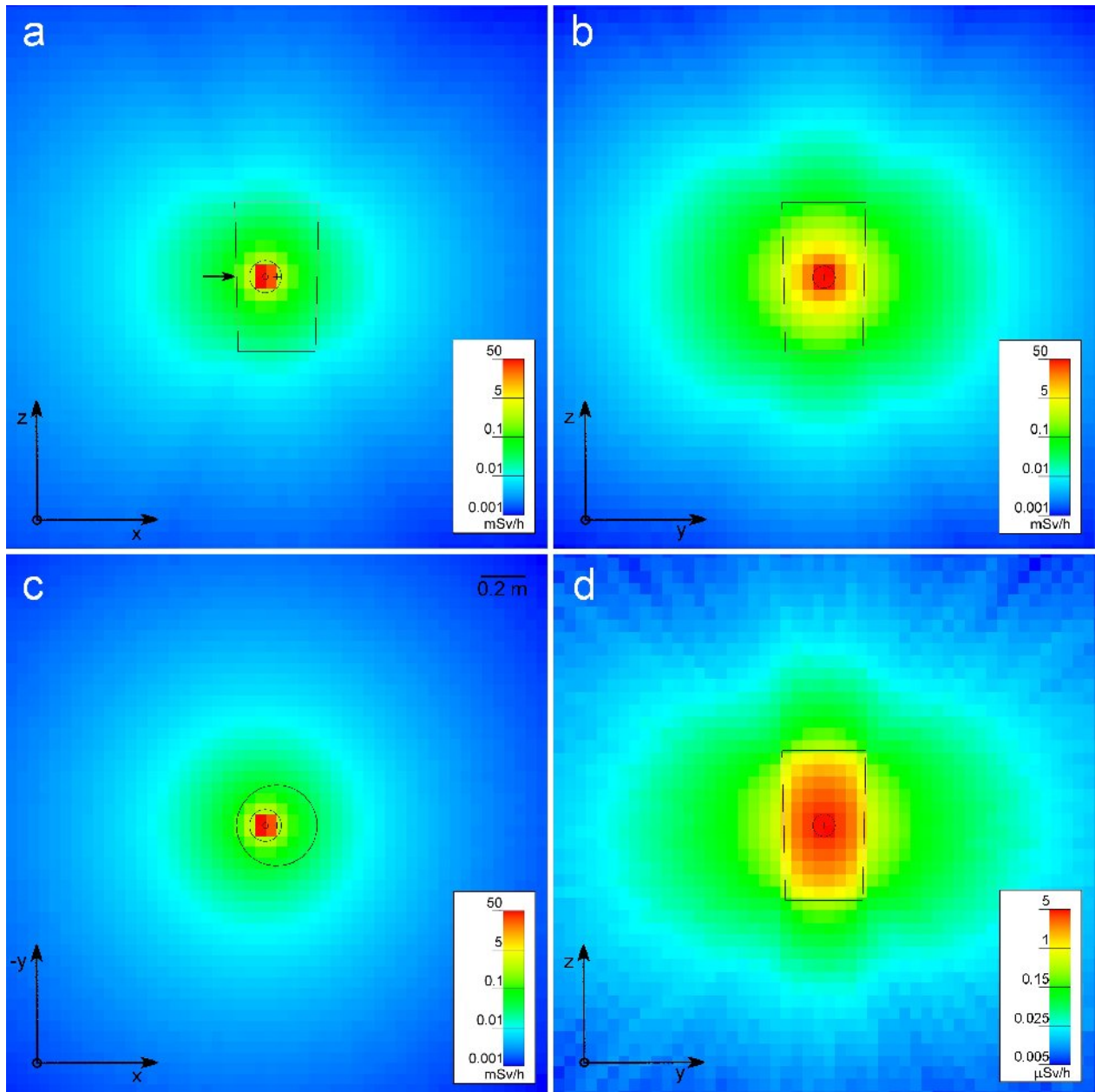
Fig 1. (a)(b)(c) Orthogonal projection of the radiation field (expressed in total equivalent dose) generated by a transport packaging with a 300 MBq Co-60 source. Drum is represented by the truncated cone drawn with a black line. The irradiator is represented by the black circle. (d) XZ plane of the equivalent dose field for photon energies ranging from 50 to 100 keV, which dominated by bremsstrahlung photons. The photon distribution follows the geometry of the drum.
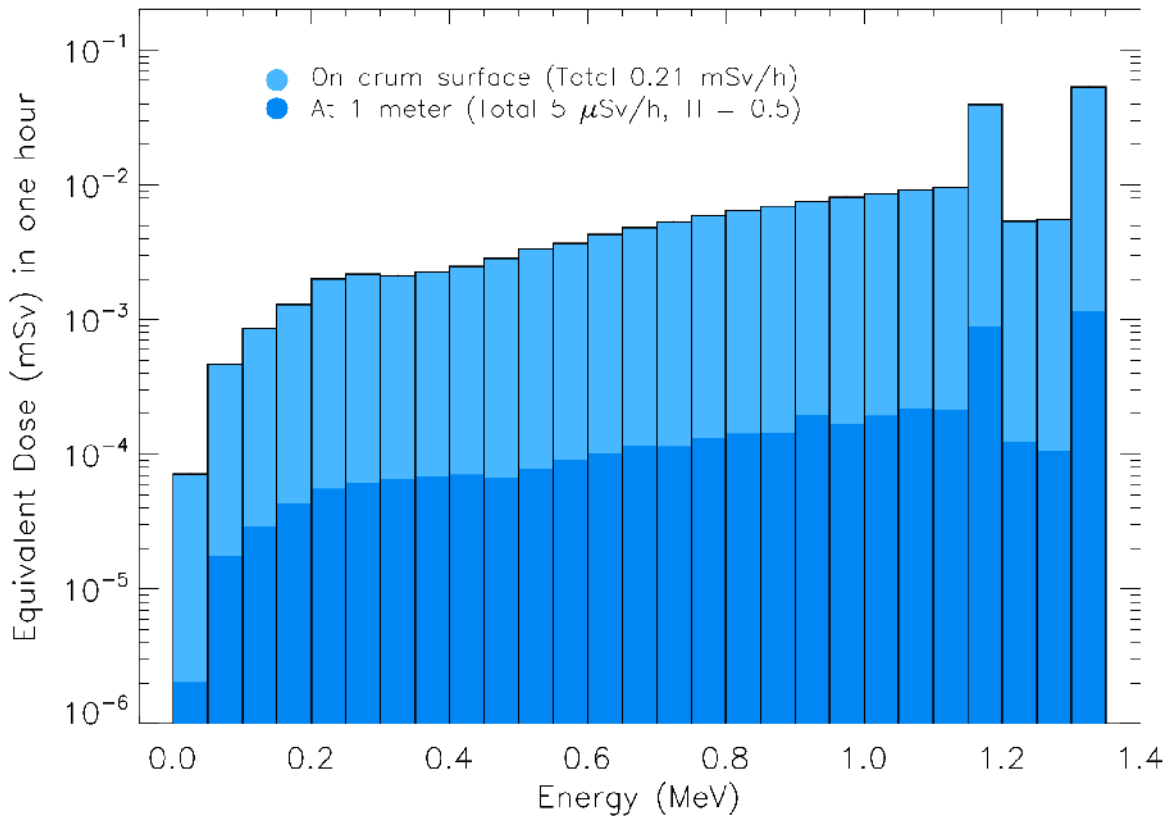
Fig 2. Energy spectrum of the radiation (expressed in total equivalent dose) corresponding to the hot-spot found on the drum surface (see text) and at 1 meter from it. The total equivalent doses are represented by the colored areas.

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