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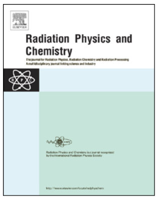

# Angular dependence of response of dosimeters exposed to an extended radioactive source

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## HIGHLIGHTS

- We investigate the exposer angle dependence of dosimeter response to a gamma source.
- Analytical and Monte Carlo analyses show no angular dependence as claimed by others.
- We derive the dose rate formulae taking into account the path length of photons.
- Analytical and Monte Carlo models have been validated using experimental data.

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## ABSTRACT

This study was carried out to investigate the exposure angular dependence of dosimeters response when exposed to the extended gamma source of an irradiation facility. Using analytical and Monte Carlo analysis, we show that dosimeters response has no angular dependence as claimed by a previous study. The dose rate formula we derived takes into account the path length of the photons in the dosimeter. Experimental data have been used to validate our analytical and Monte Carlo methods. Furthermore, the effects on the dosimeters responses in relation to their sizes response of their size and geometry and orientation have been investigated and, within statistical errors, no angular dependence was found.

## 1. Introduction

Industrial $^{60}$Co irradiation facilities are mainly designed for commercial as well as research applications involving products with increasingly more complicated structures. To establish plant operational parameters, such as dose uniformity, source utilization efficiency and maximum and minimum dose rate locations, it is important to know the dose rate distribution inside the irradiation cell. This information is also used to select monitoring locations for routine processing (Kadri et al., 2006; Gharbi et al., 2005) and to set the process for a given range of products within a narrow span of density. Indeed, according to ISO 11137 recommendations (ISO Standard, 2006), sufficient dose mapping must be carried out to identify the highest and the lowest doses received by a product. However, extensive and frequent physical measurements of absorbed dose are expensive, time-consuming and technically demanding. To reduce the huge number of monitoring dosimeters needed for experimental dose rate distribution determination (Farah et al., 2006), analytical methods (Loussaief and Trabelsi, 2007) as well as computer-based models (Kadri et al., 2006; Gharbi et al., 2005; Mannai et al., 2007; Oliveira et al., 2002) can be employed for the analysis of the dose distribution. These methods offer the opportunity to increase the process knowledge base with a little increase in experimental effort and, in certain cases, a long-term decrease in experiments such as dose mapping and routine process dosimetry (Curzio and Allignant, 1996; Saylor and Jordan, 2000; Pina-Villalpando and Sloan, 1998). Thus, modeling methods help in complementing experimental data and add further expansion of the experimental database.

The present work addresses the variation in response of a dosimeter with respect to the angle of incidence of radiation, using both analytical and computer-based models. The results are then compared to experimental data for validation. Indeed angular dependence of dosimeters response is an important issue for some applications (Dong et al., 2011; Gopalani et al., 2003; Tam et al., 1999; Monti et al., 2013; International Atomic Energy Agency and the International Labour Office, 1999). The eventual angular (also known as directional) dependence of dosimeters response may have its origin in the constructional details and physical sizes

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of dosimeters as well as in the energy of the incident radiation. To calculate the absorbed dose in the case of gamma irradiation facility, some previous works (Kadri et al., 2006; Gharbi et al., 2005; Zhu et al., 2010; Computing Radiation Dosimetry, 2002) have circumvented this issue by using spherical dosimeters. This very symmetrical shape allows us to eliminate the angular dependence of the dosimeters. Another work (Loussaief and Trabelsi, 2007), considering the dose as a point quantity, assumed that the dosimeter should allow the determination of the dose within a very small volume (one needs an adequate "point-like dosimeter" to characterize the dose in the vicinity of a given point, Saylor and Jordan, 2000).

Recently, Jemii et al. (2011) have devised an analytical model to calculate the flux rate intercepting a dosimeter film with zero thickness. To determinate this flux, these authors claimed that a $\sin\theta$ term should be introduced in the flux expression to take into account the orientation of the dosimeter. They studied a particular configuration when the dosimeters are parallel to the axis of an extended source and showed that it is equivalent to a unique pencil-like source. The authors compared the flux rate in these two cases (extend and pencil-like sources) and found a less than 1% discrepancy between the two models. Whoever they did not cross-check their results against data or Monte Carlo simulation to validate their findings. In this work, we have performed this comparison and found a large discrepancy between Jemii et al. findings and both data and Monte Carlo simulation. We argue that this discrepancy is due to the non-inclusion of the dosimeter thickness in their calculation and we propose the correct expression of the dose rate formula by taking into account the path length of the photons in the dosimeter. We also investigate in this paper the exposure angular dependence of dosimeters and the effect of dosimeter sizes on the absorbed dose.

## 2. Irradiation facility

The irradiation facility, shown in Fig. 1, consists of an irradiation cell surrounded by concrete shielding including a protective labyrinth, a conveyor system, a control room, a dosimetry laboratory, a warehouse for irradiated and non-irradiated products and refrigerated rooms. The product to be treated is transported inside the irradiation cell using 5 carriers moved by an electromechanical conveyor system fixed on the ground.

The irradiation cell is a rectangular chamber ($6\times6$ m$^2$) with high-density concrete walls (1.7 m thick). The source rack is a cylinder of 10.2 cm radius and contains eight $^{60}$Co pencils encapsulated in welded stainless steel with a diameter of 9.7 mm and an overall length of 450 mm. When not in use (Fig. 2(a)), the pencils are stored in a dry storage which consists of a cylindrical shield container of lead (0.39 m radius × 0.7 m high). When in use, the pencils are picked out from the shield container and the source has the form of two vertical cylinders: four pencils on the higher source rack and four pencils on the lower one (Fig. 2(b)). The source activity at the time when dose measurements were realized is ($1.81\pm0.18$) PBq.

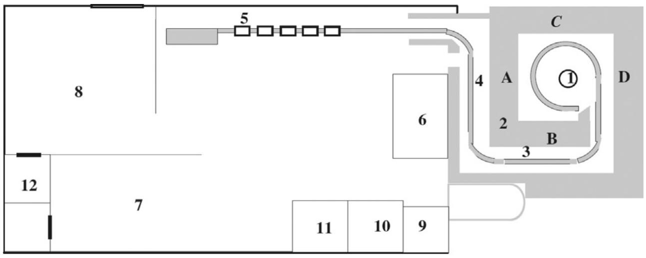

**Fig. 1.** Plane view diagram of the gamma irradiation facility. (1) Source, (2) concrete shielding, (3) transport conveyor system, (4) labyrinth, (5) carriers, (6) control room, (7) outlet storage, (8) inlet storage, (9) dosimetry laboratory, (10) radiation protection, (11) maintenance, and (12) refrigerated rooms.

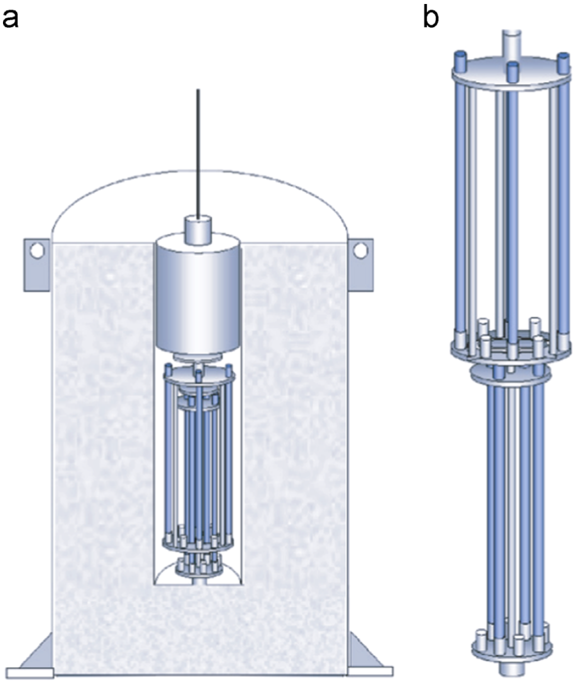

**Fig. 2.** (a) The $^{60}$Co source and the container in the storage position. (b) Details of the stainless steel telescopic source rack (the source is picked out from the shield container).

## 3. Dose measurements

Dose measurements in the irradiation cell were carried out using Red Perspex or Gammachrome dosimeters (Farah et al., 2006; Gharbi et al., 2005; Kadri et al., 2006; Mannai et al., 2007; Loussaief and Trabelsi, 2007). These routine dosimeters are polymethyl methacrylate (PMMA) with an overall uncertainty of 6%, at a 95% confidence level, in the range of 5–50 and 0.1–3 kGy, respectively (ISO/ASTM 51276). These dosimeters are rectangular parallelepipeds of height $h=30$ mm and length $\ell=11$ mm with thickness (width) $w=1.5$ mm for Gammachrome dosimeters and $w=1$ mm for Red Perspex. The determination of the absorbed dose was carried out indirectly through spectrophotometric evaluation (Spectronic Genesys 5 UV-VIS spectrophotometer + Kafer KMF30 thickness gauge+Aer'ODE software, Aer'ODE) of the specific absorbance. The dosimeters are calibrated against Alanine/EPR at the Laboratory of Dosimetry of AERIAL[1] and the absorbed dose is given against water. Dose measurements have been carried out using three PMMA dosimeters for each measurement in order to reduce errors. The dosimeters are placed within the irradiation cell in free air with no additional material around.

## 4. GEANT4 code

GEANT4 is a toolkit that uses object-oriented technology and implemented in the C++ programming language (Agostinelli et al., 2003). It has proved to simulate accurately the passage of particles through matter for a wide range of applications including simulation of high energy and nuclear physics experiments, radiation shielding, medical physics, gamma irradiator design

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[1] www.aerial-crt.com.