THE SOLID ANGLE SUBTENDED BY A COLLIMATED DETECTOR AND A NUCLEAR FUEL ASSEMBLY

by

Georgios NICOLAOU *

Laboratory of Nuclear Technology, Department of Electrical and Computer Engineering, School of Engineering, Demokritus University of Thrace, Kimmeria Campus, Xanthi, Greece

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A Monte Carlo procedure is presented to calculate the solid angle subtended between a HPGe collimated detector and a PWR 17 17 fuel assembly. Self-shielding within the assembly is assessed in the case of gamma rays encountered in gamma spectroscopy of spent nuclear fuel. Self-shielding renders a non-uniform 3-D distribution of the radioactivity within the assembly whose extend depends on gamma ray energies of interest. Hence, the solid angle is reduced to an effective one for each of the different energies of interest.

Key words: solid angle, self-shielding, Monte Carlo, nuclear fuel assembly

INTRODUCTION

The management of spent nuclear fuel assemblies after discharge requires knowledge of the nuclear material composition and burnup achieved by the assembly while in a reactor. Gamma-spectroscopy of spent fuel assemblies, in view of analyzing the presence of nuclides such as ^{134}Cs (796, 1365 keV), ^{137}Cs (662 keV), and ^{154}Eu (1275 keV) in the fuel, would allow verification of the content and burnup declared by the operators [1]. Nevertheless, a fraction of the gamma radiation emitted by each fuel rod of the assembly would be absorbed within the rod, due to its high stopping power and, hence, within the assembly. Consequently, an activity ratio, *e. g.* ^{137}Cs/^{154}Eu, used for verification purposes, will be underestimated unless a self-absorption correction of the ^{137}Cs and ^{154}Eu energies used is made.

Self-absorption would effectively render an "apparent" distribution of the nuclides of interest within the assembly with respect to the position of a collimated gamma-spectroscopy detector. This would be due to the difference in path length within the assembly prior to the emergence of gamma rays of interest towards the detector. In this paper, a Monte Carlo approach is presented to determine an effective solid angle subtended by the detector from the assembly, hence considering the self-absorption of the gamma rays within the assembly and their penetration of the collimator edges. The Monte Carlo procedure is based on total variance reduction [2, 3].

* Author's e-mail: nicolaou@ee.duth.gr

MATERIALS AND METHODS

Solid angle determination

For a randomly generated point of disintegration P within a rod in an assembly, with an isotropic emission of gamma rays into a unit radius sphere, the solid angle $\mathrm{d}\Omega$ in spherical co-ordinates is given by

$$\mathrm{d}\Omega \quad \sin\theta\,\mathrm{d}\theta\,\mathrm{d}\alpha \tag{1}$$

where θ and α are the longitudinal and horizontal angles, respectively. The joint probability density distribution $p(\theta, \alpha)$ for the isotropic emission by the point P is

$$p(\theta,\alpha)\,\mathrm{d}\theta\,\mathrm{d}\alpha \quad \frac{\mathrm{d}\Omega}{4\pi} \tag{2}$$

yielding

$$p(\theta) \quad \frac{\sin\theta}{2} \;\; 0 \quad \theta \quad \pi \text{ and } p(\alpha)=\frac{1}{2\pi} \;\; 0 \quad \alpha \quad 2\pi \tag{3}$$

The function $p(\theta, \alpha)$ effectively describes the fraction of the emitted radiation by the source at point P which is within $\mathrm{d}\Omega$.

Following the generation of a disintegration point P, random directions of the gamma rays emitted from the point are generated, intercepting the detector edge. Each direction is associated with a weighting factor W_i which represents the solid angle subtended by the detector from the disintegration point i. Then, the required Ω, for N points of disintegrations and gamma ray directions is

$$\Omega \quad \frac{4\pi}{N} \, {}_{i\;1}^{N} W_\mathrm{i} \tag{4}$$

The self-absorption within the assembly alters the solid angle Ω to an effective solid angle Ω^{eff} where

$$\Omega^{eff} = \frac{4\pi}{N}\sum_{i=1}^{N}(F_{\mathrm{att}} W) \qquad (5)$$

with F_{att} being a correction factor accounting for the self-shielding of a gamma ray emitted by the disintegration point. From the point of disintegration onwards, the procedure is repeated for all fuel rods.

Simulation of fuel assembly

The geometry simulated in order to assess self-absorption within the assembly and its effect on the solid angle it subtends with a collimated detector is shown in fig. 1. A PWR 17 × 17 square fuel assembly with rods containing heavy material and surrounded by cladding is considered (tab. 1) [4]. The detection system comprises a HPGe detector with diameter and height of 7.3 cm and 5.79 cm, collimated by a Pb borehole collimator with diameter and length of 0.5 cm and 15 cm. The assembly is placed symmetrically in front of the detection system, with its axial central axis perpendicular to the central axis of the system. Hence, the field of view of the collimated detector contains the mid part of the fuel assembly with a flat burnup and 3-D radioactivity distribution [5].

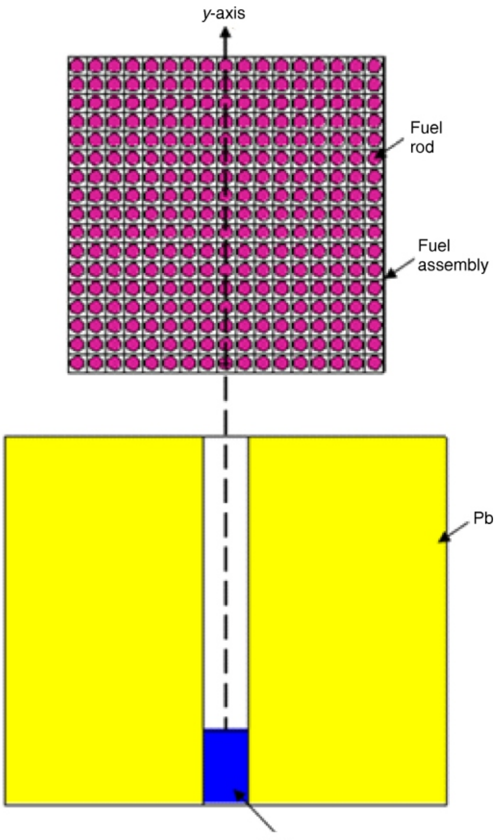

Figure 1. A cross-sectional view of the geometrical configuration comprising the collimated HPGe detector and the fuel assembly

Table 1. Physical description of the fuel assembly considered

PWR assembly	
Assembly type	17 x 17 pins square array
pin pitch [mm]	12.6
Fuel pin rod	
active length [m]	3.66
pellet diameter [mm]	9.5
clad material	Zr
clad thickness [mm]	0.57

RESULTS AND DISCUSSION

Gamma rays of different energies emitted by the assembly are absorbed within it to a different extent prior to their emerging towards the detector. This renders a 3-D radioactivity within the assembly which depends on gamma ray energies. Hence, the solid angle subtended between the 3-D radioactivity distribution and the collimated detector differs in accordance with the extend of the self-absorption of gamma rays. Self-absorption within the assembly is twofold: (a) within the fuel rod of origin of the gamma rays, and (b) within the assembly itself, due to the shielding of these gamma rays from rods on their path towards the detector, issues which are examined and assessed. Self-absorption effectively reduces the geometric solid angle between the assembly and the collimated detector to an effective solid angle (Ω^{eff}) which is sought.

Self-absorption has firstly been assessed within a fuel rod, with the first one along the central axis-*y* of the array being considered (fig. 1). Gamma rays with energies 662-1365 keV encountered in gamma spectroscopy of spent nuclear fuel due to ^{134}Cs, ^{137}Cs and ^{154}Eu are assumed emitted by the rod. The effect of self-absorption was examined comparing the number of photons at the detector in cases of the rod with heavy material surrounded by cladding and as a void structure. The decrease in the number of photons due to self-absorption ranges between 25 % and 3 % for 662 keV and 1365 keV gamma rays, respectively. Hence, a significant self-shielding within a rod is observed at the lower energy of interest of 662 keV.

The combined effect of self-absorption within a fuel rod emitting gamma rays and their shielding from rods on their path towards the detector is now assessed. The series of rods with heavy material and cladding along the central axis-y of the detection system is considered (fig. 1). Each rod in turn, from the 1st to the 9$^{\mathrm{th}}$ along the central axis-*y* is considered radioactive, rendering from none up to 8 rods of shielding for each rod position, respectively. In each case, the number of photons at the detector is calculated for gamma ray energies of 662 and 1365 keV. The variation in the number of photons for an increasing number of shielding rods is shown in fig. 2. Each curve has been normalized to the corresponding value, due to the first rod

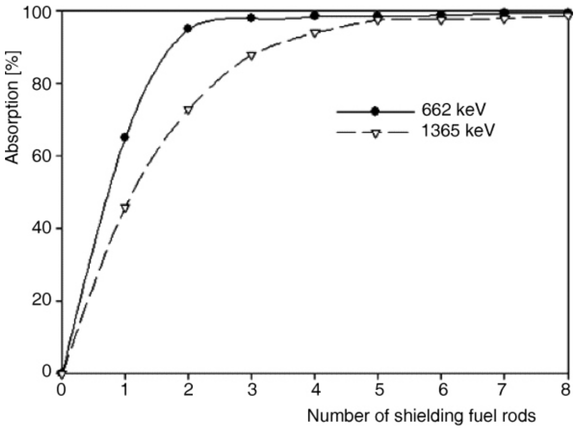

Figure 2. Absorption of 662 keV and 1365 keV through different number of fuel rods

with zero shielding. In the case of 662 keV photons, only the first 2 rods along axis-y contribute significantly as there is more than 97.5 % absorption beyond them. In the case of 1365 keV photons, up to 5 rods contribute. For verification purposes, these results were compared with results obtained experimentally in a hot cell facility, via gamma spectroscopy of actual spent fuel rods from a PWR [6]. The outcomes of the simulations carried out in this work and the experimental work are in agreement.

The above argument is now extended over the whole 17 17 array of fuel rods, at this point considered to be radioactive. Self-absorption and shielding would render a smaller radioactive 3-D distribution with decreasing gamma ray energy. This yields different Ω^{eff} subtended between the assembly and the collimated detector, with the ratio of Ω^{eff} between the cases corresponding to 1356 keV to 662 keV ($^{134}Cs/^{137}Cs$) being 2.26.

Further work to assess the effect of self-absorption and shielding on Ω^{eff} for collimators of different hole diameter and length is in progress. Furthermore, the approach will be developed for a BWR spent fuel assembly whose axial burnup variation is not flat. Finally, measurements on assemblies will be performed to test the procedure.

CONCLUSION

A Monte Carlo procedure has been presented to calculate the solid angle subtended between a HPGe collimated detector and a PWR 17 17 fuel assembly, taking into consideration the self-shielding within the assembly of the emitted gamma rays encountered. Although the effect of self-absorption is small for the 1365 keV of ^{134}Cs, it is rather significant in the case of 662 keV gamma rays of ^{137}Cs. Consequently, their ratio without a self-absorption correction would be overestimated. A correction factor of 0.44 would be required for the particular geometrical set-up of the assembly and the collimated detector simulated in this study.

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Јоргос НИКОЛАУ

ПРОСТОРНИ УГАО ОБРАЗОВАН КОЛИМИСАНИМ ДЕТЕКТОРОМ И СКЛОПОМ НУКЛЕАРНОГ ГОРИВА

Приказана је Монте Карло процедура за прорачун просторног угла између HPGe колимисаног детектора и горивног склопа 17   17 PWR реактора. Процењено је самозаклањање у горивном склопу за гама зрачење које се сусреће у гама спектрометрији утрошеног нуклеарног горива. Самозаклањање доприноси неуниформној 3-D расподели радиоактивности унутар горивног склопа чији домети зависе од енергије разматраног гама зрачења. Отуда је просторни угао редукован на ефективни угао за сваку енергију од интереса.

Кључне речи: просторни угао, самозаклањање, Монте Карло, склоп нуклеарног горива