NaI(Tl) Scintillator's Response Functions for Point-like and Distributed Gamma-ray Sources

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Abstract   The response functions of a NaI(Tl) detectors have been estimated using Monte Carlo methods. Response functions were calculated for monoenergetic photon sources (0.05 to 3 MeV). Responses were calculated for point-like sources and for sources distributed in Portland cement cylinders. Calculated responses were used to estimate the detector efficiency for point-like and distributed sources. Samples of cylindrical Portland cement were prepared and exposed to the photoneutron field produced by a 15 MV linac used for radiotherapy. Short half-life radioisotopes were induced and the activity was determined by measuring the pulse-height spectra with a NaI(Tl) γ-ray spectrometer that was calibrated using point-like sources. Instead of doing corrections due to differences between the geometry, material and solid angle of point-like sources used for calibration, and the Portland cement cylinders, the detection efficiency was determined using the ratio between the efficiencies for the point-like and the distributed sources estimated with the Monte Carlo calculations, and the activity of the induced isotopes in cement was obtained.

Keywords: Gamma- ray; Point-like source; Distributed source; NaI(Tl) response; Monte Carlo.

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1. INTRODUCTION

In combination with a multichannel analyzer the NaI(Tl) scintillator is used as a spectrometer in order to obtain the γ rays pulse-height spectrum [6]. The spectrometer efficiency relates the amount of detected photons with the number of photons emitted by the source [5]. To obtain the spectrometer efficiency a calibration procedure is carried out using several certified point-like sources. However, in some situations the gamma sources to be measured are not point-like requiring corrections to account the absorbed and the scattered photons in the source, as well as the solid angle [3, 5, 17, 18].

The neutron-induced activation in a sample depends on the neutron spectrum, the nuclei cross sections, the amount of nuclei and the irradiation time. Neutron activation can be carried out using a nuclear reactor, a neutron generator or using an isotopic neutron source. Linear accelerators for radiotherapy (linacs), working above 7 MV, produce an undesirable field of photoneutrons around the treatment hall. The presence of these photoneutrons becomes a radiation protection issue for the facility; however these neutrons can be used to induce activation [1, 2, 8, 12, 13, 16]. In this work, photoneutrons produced in a linac were used to induce activation of cement samples.

The aim of this work was to calculate the response function and the efficiency of a NaI(Tl) for monoenergetic gamma rays emitted by point-like and distributed, in Portland cement, sources. Efficiencies were used to calculate the induced activity in the concrete samples.

2. MATERIALS AND METHODS

2.1. Monte Carlo calculations

Using the MCNP5 code [19] a 7.62 cm-diameter x 7.62 cm-length NaI scintillator was modeled. The gamma ray sources used for calibration have the radionuclide in the center of a plastic disk, in the model the monoenergetic gamma sources were located in the center of a 2.54 cm in diameter and 0.32 cm thick plastic disk and were sited on a thin polyethylene support as is shown in Figure 1.

For the distributed source another model was designed; here, the source was modeled as a cylinder (2.53 cm-diameter x 1.06 cm-length) made of Portland cement. The Portland cement cell was used as source term where the monoenergetic gamma source was distributed in the cell volume, as is shown in Figure 2. The elemental composition of Portland cement was taken from the literature [9].

The response functions are an important factor for γ-ray spectrum analysis [15]; here, the pulse-height spectra were determined using the tally f8.
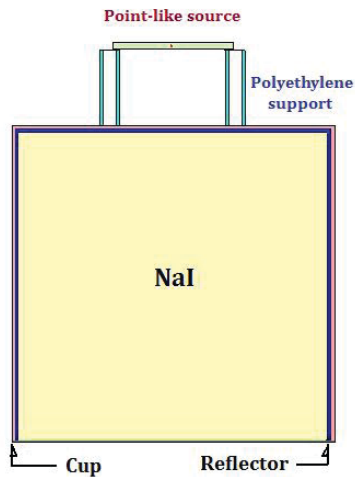
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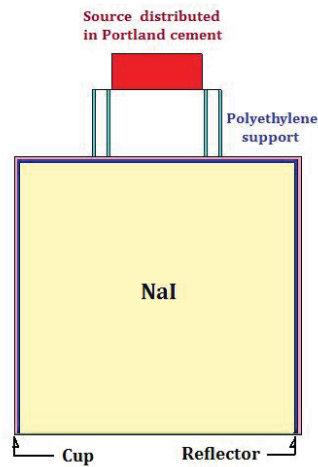**Figure 1:** Monte Carlo model of detector and the point-like source.

Figure 2: Monte Carlo model of detector and the distributed source.

Responses were broadened using the Gaussian energy broadening feature of tallies in the aim to match the calculated with the measured pulse-height spectra [6, 14, 4]. Calculated pulse-height spectra of monoenergetic point-like sources were used to calculate the net areas under the photopeaks. The net area-to-emitted photon ratio was used to estimate the point-like sources efficiency ($\varepsilon_{P,MC}(E)$) in function of the photon energy. The same procedure was applied to estimate the efficiency of the distributed sources ($\varepsilon_{CC,MC}(E)$).

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The amount of histories in the Monte Carlo calculations was large enough to have uncertainties less than 0.1%. Efficiencies calculated with Monte Carlo were used to obtain the efficiency in the measurements of the activated cement samples using Equation 1 [11].

$$\varepsilon_{CC}(E) = \varepsilon_P(E) \; \frac{\varepsilon_{CC,MC}(E)}{\varepsilon_{P,MC}(E)} \tag{1}$$

In Equation 1, $\varepsilon_{CC}(E)$ is the efficiency of the cement cylinder samples, $\varepsilon_{CC,MC}(E)$ is the cement cylinder efficiency calculated with Monte Carlo, $\varepsilon_{P,MC}(E)$ is the efficiency for point sources calculated with Monte Carlo, and $\varepsilon_P(E)$ is the efficiency measured with the certified point-like sources. The $\varepsilon_P(E)$ was measured using the photons emitted by ^{22}Na, ^{137}Cs and ^{60}Co sources with activities traceable to NIST with uncertainties less than 3%.

2.2. Preparation, irradiation and measuring the concrete samples

Three cylindrical cement samples (2.53 ± 0.01 cm-diameter and 1.06 ± 0.04 cm-length) were prepared by mixing water and commercial Portland cement using a 0.45 water-to-cement ratio. Samples have a mean density of 2.1 ± 0.1 g/cm^3. Each cement sample was allocated to 3 m from the 15 MV linac head attached to one of the bunker walls. The sample was 90° from the photon beam, as is shown in Figure 3.

At the irradiation site the neutron spectrum the two largest components are thermal and fast neutrons. The linac was set to deliver 12 Gy to the isocenter
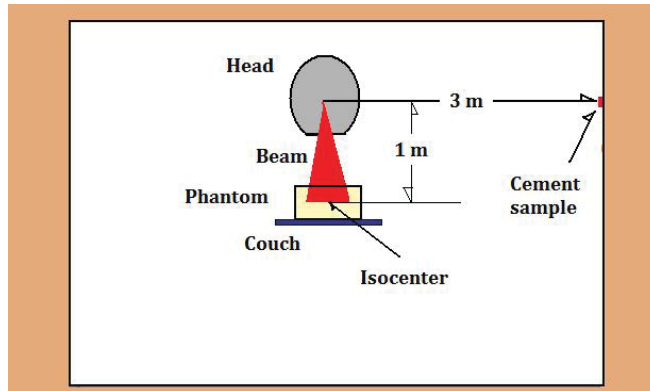

Figure 3: Irradiation setup.

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(3 Gy/min) that was to 100 cm from the center of the linac head. The isocenter was 5 cm-depth of a 30 cm x 30 cm x 15 cm solid water phantom using 20 cm x 20 cm field [1, 2]. During the linac operation photoneutrons are produced inducing the neutron activation of linac head, air, and items inside the room [8, 12, 13, 16].

Once the linac was off the induced activity in the cement sample was measured with a gamma ray spectrometer with a 7.62 cm Ø x 7.62 cm NaI(Tl). The spectrometer was previously calibrated using ^{22}Na, ^{137}Cs and ^{60}Co point-like calibrated sources. The calibration setup was carried out as the Monte Carlo model shown in Figure 1. These sources were also used to obtain the relationship between the channel number and the photon energy.

The linac operation conditions were the same when each cement sample was irradiated. The unique difference was the cooling time. During the irradiated cement samples, for each observable photopeak the region of interest was defined and the counts were corrected due to background using the same region of interest. The background pulse-height spectrum was measured for 24 hours. The net count rate was used to calculate the induced activity using the Equation 2 [10].

$$A = \frac{N \lambda e^{\lambda t_c}}{\varepsilon_{CC} \ p_\gamma \left(1 - e^{-\lambda t_i}\right)\left(1 - e^{-\lambda t_m}\right)} \tag{2}$$

In this equation A is the saturation activity, N represents the net counts under the photopeak, λ is the decay constant of the induced radionuclide, t_c, ti, and tm are the cooling, irradiation and measuring times respectively, pγ is the gamma-ray emission probability (branching ratio), and ε_{CC} is the efficiency calculated with Equation 1.

3. RESULTS

3.1. Monte Carlo calculations

In the Figure 4 are shown the NaI response functions for point and concrete distributed sources in function of photon energy. As the photon energy is increased the photopeaks are wider. This behavior is in agreement with the typical NaI(Tl) resolution [5].

The calculated and measured efficiencies are shown in Figure 5. The uncertainties in the calculated efficiencies are 1% while the measured efficiency is 4%. The continuous lines are the fitted functions.

The counting efficiency is lower for the distributed sources due to photon absorption and photon scattering in the cement matrix.

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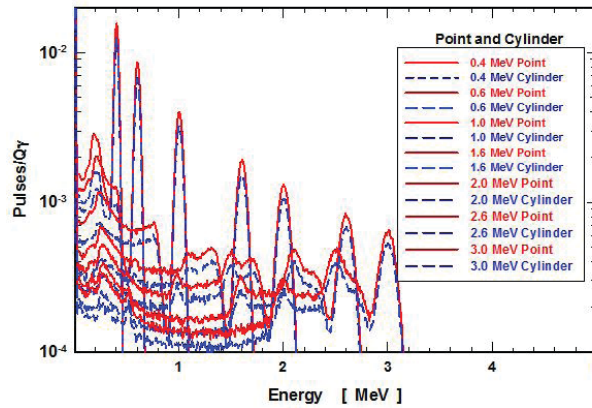V.M.
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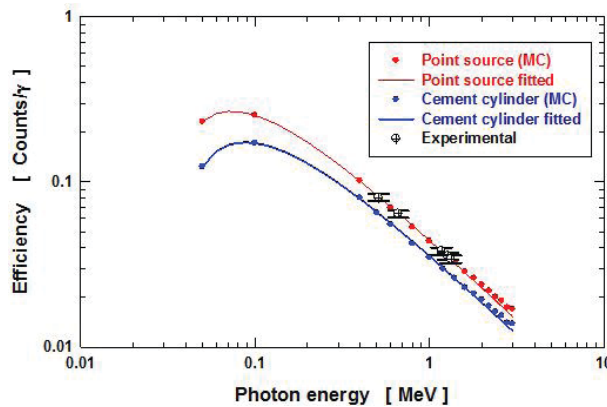**Figure 4:** Response functions for distributed and point-like monoenergetic γ-ray sources.

Figure 5: Calculated and measured efficiencies.

3.2. Activation induced in the concrete samples

In the concrete samples three photopeaks were identified: 846, 1368 and 1778 keV produced by ^{56}Mn, ^{24}Na, and ^{28}Al having half-lives of 2.58 h, 14.96 h and 2.24 min respectively [5].

The activity of each radioisotope, of the three cement samples, was used to calculate the mean value. The elemental composition of cement Portland has aluminum and sodium as major components. Manganese is not reported as a major component however; in the preparation of Portland cement standards

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the National Bureau of Standards reported the presence of Mn as a minor constituent [7].

The average activities of cement Portland samples were 0.1543 ± 0.0199 Bq/g for ^{56}Mn, 0.5021 ± 0.1893 Bq/g for ^{24}Na, and 1.977 ± 0.2804 Bq/g for ^{28}Al. These radioisotopes have been also reported in other linacs facilities [13, 8].

4. CONCLUSIONS

Using Monte Carlo methods the response functions and the efficiency of a NaI(Tl) were estimated for monoenergetic gamma sources. Calculated efficiencies were used to determine the detection efficiency for cement cylinders that were activated by the photoneutrons produced by a 15 MeV linac for radiotherapy. The Monte Carlo efficiencies allow making corrections due to the differences in the solid angle and account the scattering and absorption of photons in the Portland cement. Photoneutrons in the linac bunker induced activation in cement samples where ^{56}Mn, ^{24}Na, and ^{28}Al were produced. The average specific activity induced in the cement samples were 0.1543 ± 0.0199 Bq/g for ^{56}Mn, 0.5021 ± 0.1893 Bq/g for ^{24}Na, and 1.977 ± 0.2804 Bq/g for ^{28}Al.

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