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A THEORETICAL STUDY OF THE ATTENUATION OF PHOTONS IN GHANAIAN SERPENTINE SHIELDS

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ABSTRACT

The thicknesses of three serpentine rocks located at Anum, Peki-Dzake and Golokwati in Ghana were calculated using a 1-D transport code ANISN/PC. The attenuation of 21-photon energy groups in the range 10 keV - 13 MeV were investigated. Calculation is done using S_6 angular quadrature in a spherical geometry and P_3 scattering order. The spatial flux and energy distributions of photons were determined for the local serpentine shields. The results were compared with those obtained from foreign serpentines and known materials presently used for radiation shielding. The trend of results and computed parameters such as relaxation length and transmission indicate that the local serpentines exhibit good photon attenuation properties.

Keywords: photons, transport theory, attenuation, relaxation length

INTRODUCTION

Concrete of 10% water content which is used to surround the pressure vessel of thermal reactors loses more than half of its water content when temperatures exceed 90°C[1]. This causes deterioration of its mechanical and attenuation properties. Thus, the concrete must be cooled and maintained at temperature of 50°C [2]. This has led to design of shields to be complex with expensive cooling systems.

A more suitable material for radiation shielding which can be used instead of concrete is serpentine. It consists of a hydrous magnesium silicate with water of hydration ($3MgO.2SiO_2.2H_2O$). The rock also contains iron, calcium and aluminium oxides [3]. Serpentine has advantage over concrete because it has a higher percentage of water content than concrete. Investigations have shown that it is suitable for shelding neutrons due to its large water content [4,5]. An additional advantage it has over concrete is that it loses its water of crystallisation at temperatures exceeding 480°C. For the reasons stated above, it can find its use in the design of shields which could withstand high temperatures without any appreciable loss of water and the provision of ducts in the shield for cooling could be avoided.

In this study, theoretical calculations were carried out using the PC version of ANISN [6]. Multigroup crossection set for 21- group gamma structure were generated for the different elements in the shields.

This paper presents the calculation results of the various shields. The variation of the spatial flux and energy spectra of fast photons (γ-rays) emitted from a point in spherical shields of water, stainless steel, concrete and serpentines were investigated. The computed relaxation lengths and transmission of local serpentines were also compared with those obtained for different shields.

THEORY

In a steady-state radiation field, the net rate at which particles are lost in an element must exactly be balanced by the rate of secondary or source particles which are introduced into the volume. Transport equation or linearized Boltzmann equation is used to determine the particle distribution in space $\underline{r}$, direction $\underline{\Omega}$ and energy E. The corresponding steady state equation is

$$\left(\underline{\Omega}.\nabla + \Sigma_t\right)\phi(\underline{r},\underline{\Omega},E) = \int_0 dE' \int \Sigma_s(\underline{r},\underline{\Omega}' \rightarrow \underline{\Omega}, E' \rightarrow E)\,\phi(\underline{r},\underline{\Omega}',E')\,d\underline{\Omega}'dE' + \underline{S}(\underline{r},\underline{\Omega},E') \qquad (1)$$

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where

$\phi(\underline{r},\underline{\Omega},E')$ = the expected number of particles per unit area per unit time at $\underline{r}$ with energies in unit energy about E and moving in a unit angle about $\underline{\Omega}$.

$S(\underline{r},\underline{\Omega},E)$ = the number of source particles emitted in dV about r travelling in a cone of direction $d\underline{\Omega}$ about $\underline{\Omega}$ with energies between E and E+dE.

$\Sigma_s(\underline{r},\underline{\Omega}'\rightarrow\underline{\Omega}',E'\rightarrow E)$ = macroscopic scattering crossection which is the probability that the particles at position $\underline{r}$ with energy E' travelling in direction Ω' scatter into dE about E and into the cone of direction $d\underline{\Omega}$ about $\underline{\Omega}$.

The transport equation is solved analytically for limited cases only. For estimation of particle flux it is approximated by solving it numerically as it is of the case in ANISN code. The differential transfer crossection can be expanded by a truncated Legendre polynomial series in the form

$$\Sigma_s(\underline{r},E\rightarrow E,\mu_o) = \sum_{\ell=0}^{L} \frac{2\ell+1}{2}\Sigma_s^{(\ell)}(\underline{r}',E'\rightarrow E)P_\ell(\mu_o) \qquad (2)$$

where

μ_o is the angle between the incoming and outgoing directions in the scaterring process ($\mu_g = \underline{\Omega}.\underline{\Omega}$).

Multigroup model treats the energy dependance by dividing the entire energy range of interest into a finite number G of energy intervals g=1,2,3,..., G. Thus, for anisotropic scattering, the multigroup equations corresponding to equation (l) becomes

$$\underline{\Omega}.\nabla\phi_g(\underline{r},\underline{\Omega}) + \Sigma_{tg}\phi(\underline{r},\underline{\Omega}) = \sum_{\ell=0}^{L}\sum_{g'=1}^{G}\int d\underline{\Omega}'\left(\frac{2\ell+1}{2}\right)\Sigma_{sg'\rightarrow g}^{(\ell)}(r)P_\ell(\mu_o)\phi'(\underline{r},\underline{\Omega}) + \underline{S}_g(\underline{r},\underline{\Omega}) \qquad g=1,2,3,\ \ldots,\ G \qquad (3)$$

where

$\phi_g(\underline{r},\underline{\Omega})$ is the group angular flux:

$$\phi_g(\underline{r},\underline{\Omega}) = \int_{E_g}^{E_{g+1}}\phi(\underline{r},E,\underline{\Omega})dE \quad \text{and } \phi_g = \int_{\Omega}\phi_g d\underline{\Omega} \text{ is the total flux.}$$

The multigroup cross-sections $\Sigma_{tg'}$, $\Sigma_{sg'\rightarrow g}$ are flux weighted cross-sections averaged over the energy intervals:

$$\Sigma_g(\underline{r}) = \frac{\int_g \Sigma(\underline{r},E)\phi(\underline{r},E)dE}{\phi_g(\underline{r})}$$

and

$$\Sigma_{sg'\rightarrow g}^{(\ell)}(r) = \frac{\int_g dE\int_{g'}\Sigma_s(\underline{r},E'\rightarrow E)\int_{4\pi}\phi(\underline{r},E',\underline{\Omega}')P_\ell(\mu_o)dE'd\Omega'}{\int_{g'}\int_{4\pi}\phi(\underline{r},E',\underline{\Omega}')P_\ell(\mu_o)dE'd\underline{\Omega}'}$$

The shields studied in this work are of spherical geometry for which the streaming term can be expressed and when substituted into equation (3) becomes

$$\frac{\mu}{r^2}\frac{\partial}{\partial r}\left[r^2\phi_g(\underline{r},\mu)\right] + \frac{1}{r}\frac{\partial}{\partial\mu}\left[(1-\mu^2)\phi_g(\underline{r},\mu)\right] + \Sigma_{tg}\phi_g(\underline{r},\mu) = \sum_{\ell=0}^{L}\left(\frac{2\ell+1}{2}\right)\sum_{g'=1}^{G}\Sigma_{sg'\rightarrow g}^{(\ell)}(r)P_\ell(\mu)\int_{-1}^{1}\phi_g(\underline{r},\mu')P_\ell(\mu') + \underline{S}_g(\underline{r},\mu) \qquad (4)$$

Next, the scalar flux is approximated by quadrature formua. The angular variable is discretized into a number of discrete directions. The angular fluxes are calculated using a set of μ values and carrying out all integrations by a quadrature scheme so that

$$\int_{-1}^{1} f(\mu)d\mu = \sum_{m=1}^{M}\mu_m f(\mu_m) \qquad (5)$$

Accordingly, the discrete ordinate quadrature set Ω_m and w_m weights are selected to discretise the transport equation. The approximate value of the integral is

$$\int_{\underline{\Omega}}\phi(\underline{r},\underline{\Omega})d\underline{\Omega} = \sum_{m=1}^{M}\phi(\underline{r},\underline{\Omega}_m)w_m \qquad (6)$$

The quadrature weights w_m and μ_m form part of the data for the problem. The solution has to satisfy two principles of (i) physical symmetry and (ii) the arrangement of discrete directions on latitudes on the unit sphere. Lathrop and Carlson [7] have the details on the discrete ordinate angular quandratures.

For this work, we have applied the reflection boundary condition which is commonly used. The condition assumes that particles are reflected at the surface with angle of incidence equal to the angle of reflection. Mathematically, it is expressed as

$$\phi(\underline{r}_s,\underline{\Omega},E) = \phi(\underline{r}_s,\underline{\Omega}^*,E) \qquad \underline{\Omega}.\underline{n} < 0 \qquad (7)$$

where

$$\underline{\Omega}^*.\underline{n} = -\underline{\Omega}.\underline{n}; \qquad \underline{\Omega}\times\underline{\Omega}.\underline{n} = 0$$

The transport equation (5) is discretized into a discrete phase-space cell, resulting kinto a system of algebraic equations at the discrete mesh points r_j; Ω_m for each energy group, g.

$$\underline{\underline{A}}\,\underline{\phi} = \underline{\underline{B}}\,\underline{\phi} + \underline{\underline{S}} \qquad (8)$$

where

$\underline{A}$ is the matrix representing the streaming-collision operator ($\underline{\Omega}.\nabla + \Sigma$); $\underline{B}$ is matrix representing the group inscattering term and $\underline{S}$ represents the source term (external, plus group-to-group scattering).

The numeical solution of the algebraic equations are in ref.(6)

MATERIALS AND PROCEDURE FOR CALCULATION

The spatial flux and energy distribution of fast γ-ray spectra behind different thicknesses of water, stainless steel, concrete and serpentines from Ghana, Libya and Japan were computed using the multigroup discrete ordinate code ANISN/PC (CCC-0514).

Photon source is assumed to be located in the centre of a sphere for any shield. Calculation is done in energy groups within the range of 10keV-13MeV as shown in Table 1. with a fixed source in the first mesh. For spherical geometry S_6 angular quandrature and anisotropic scattering by Legendre expansion up to order P_3 was applied. The entire thickness of any shield under investigation was divided into a number of mesh intervlas each of 1 cm thick. The number densities of water, stainless steel used in the computation can be seen in Table 2.

The densities of the Ghanaian serpentines from Anum (SGA), Peki-Dzake (SGP) and Golokwati (SGG) [8] were determined to be 2.59 g/cc. The chemical compositions of the local serpentines listed in Table 3 were used to compute the number densities of elements listed in Table 4. along side with those from Libya, (SL) [9] Japan, (SJ) [10] and concrete (C) [11] presently employed for radiation shielding.

Microscopic crossections were taken from FLUNGP.LIB master library [12] using the utility program LMOD to create library files for various elements constituting the shields.

RESULTS AND DISCUSSION

The photon fluxes with energies within the range (10keV-13MeV) passing through 10cm and 30cm shields were computed. Fig.1 is an illustration of the trend of results for a Ghanaian Anum Serpentine (SGA) in comparison with shields of water, concrete and stainless steel. Comparison of results of the local serpentinie with foreign serpentines and concrete is shown in Fig.2. Similar trend of results was followed by the two other local serpentines from Peki-Dzake and Golokwati. Details of results are contained in the report of Akaho et al.[13]. From the plot in Fig.1 it can be seen that for energy less than 1MeV, the spectra for water, concrete and stainless steel are different from that obtained for the local serpentines. However, the shape of curves is similar when energy exceeds 1MeV. It can be observed from Fig.2 that all serpentines, local and foreign have similar shape for all the energy range studied. Within this range the concrete yields lower number of photons with slight differences in values. The effect of the shield thickness on the form of the gamma energy spectrum was investigated. The illustration of the effect can be seen in Fig.3 where one observes that the form of the gamma spectrum remains the same as the layer thickness increases. The number of photons in different energy groups reduces with increasing thickness of the shields.

The attenuation of group 1 gamma photons for the Ghanaian serpentines was compared with shields presently in use in Figs.4-6. It can be observed that apart from water, the local serpentines are inferior to stainless steel and concrete.

Figs. 7-15 represent the behaviour of the attenuation of energy groups 10, 15, and 21 in serpentines and concrete. The plots for energy group 10 show that concrete is the most efficient among the materials studied for thickness exceeding 15cm. However, it is the least efficient material for thickness less than 15cm. The attenuation property of the Ghanaian Anum Serpentine (SGA) is worse than the Libyan one (SL) but better than the Japanese serprntine (SJ). The Ghanaian Peki-Dzake (SGP) and Golokwati one (SGG) have almost the same attenuation capability as the Libyan shield for thickness greater than 15cm. From Figs.10-12 it can be observed that the local serpentines from Peki-Dzake and Golokwati exhibit attenuation characteristics than the Libyan and Japanese ones. The Anum deposit has inferior attenuation property than the Libyan one but it is superior to the Japanese serpentine. The attenuation of the serpentine shields for energy group 21 as compared with that of concrete in Figs 13-15 show that concrete has the best gamma attenuation property followed by the Ghanaian and next the Libyan serpentines and then the Japanese one.

From the calculated relaxation lengths for the different shields it was found that the attenuation is not exponenetial for any shield thickness investigated. Therefore, the relaxation lengths are expected to vary from point to point in the medium. For selected thickness of shields the relaxation lengths were computed using the relationship:

$$\frac{1}{\lambda} = \frac{-d \ n\phi(x)}{dx} = - \frac{1}{\phi(x)} \frac{d\phi(x)}{dx} \quad (9)$$

where

λ is the relaxation length of the shield material and $\phi(x)$ is the flux at the distance x.

Tables 5 and 6 contain the list of the relaxation lengths for 15cm and 30cm respectively for the different shields. The results show that apart from concrete the Ghanaian Golokwati serpentine (SGA) has the smallest relaxation length suggesting that it is the best among the serpentines for attenuation of γ-rays. This is followed by the local Peki-Dzake serpentine (SGP). The Libyan serpentine (SL) is more efficient than the Ghanaian Anum serpentine (SGA). The Japanese one is the least effective shield among the tested serpentines.

Finally, the transmission which is defined as the right hand side current, J^+ multiplied by the surface area of the shield was determined for the different shields. Table 7 shows a list of the values for the various shields. The values obtained for spherical water, stainless steel and concrete shields are consistent with those reported by Maiorino [12]. The smaller the value the better is the material for gamma radiation shielding. Consequently, it