TWO LAYERED SHIELDING SYSTEM FOR A CALIFORNIUM-252 NEUTRON SOURCE

SISTEMA DE BLINDAJE BICAPA PARA UNA FUENTE DE NEUTRONES DE CALIFORNIO-252

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Abstract

A theoretical approach was used to calculate an inside layer of paraffin to moderate neutrons generated by a 20 MBq Californium-252 (Cf-252) source and subsequently an outside layer of lead to shield the gammas being produced in the paraffin. Materials are evaluated in terms of moderating power, absorbing ability, cost limitation and material availability. The results showed that the combination of thickness of 45.7 *cm* of paraffin with 7.05 *cm* of lead permits the meet the safety requirement to the planned dose limit outside of shielding.

Keywords: Neutron shielding, Removal cross section, Californium-252 (^{252}Cf), Dose equivalent rate.

Resumen

Una aproximación teórica fue utilizada para calcular una película de parafina utilizada para moderar neutrones de una fuente de Californio-252 (Cf-252) y una película posterior de plomo que sirve de blindaje a los rayos gammas producidos en la parafina. Los materiales son evaluados en términos del poder moderador, la habilidad de absorbción, limitaciones de costo y disponibilidad del material. Los

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resultados muestran que una combinación de un espesor de 45.7 *cm* de parafina con 7.05; *cm* de plomo permite satisfacer los requerimientos de seguridad para el límite de dosis por fuera del blindaje.

Palabras clave: Blindaje para de neutrones, sección eficaz, Californio-252 (^{252}Cf), rata de dosis equivalente

Introduction

The objective of this work is to design a shielding system that will reduce the nominal radiation dose received from the ^{252}Cf source to as reasonably low a level as possible. To achieve the limit of 1 $\mu Sv/h$, we will have to make several key design decisions. These include: whether to shield gamma rays with the same unit used to shield neutrons, what materials to use, and what geometry to implement. To reach these decisions, we will have to focus on several design constraints, which include radiation emitted from fissioning nuclei in core (both neutrons and gammas) and releases of secondary gamma rays on paraffin layer.

Materials and Methods

^{252}Cf emits neutrons as a result of spontaneous fission. About 3.1% of decay of ^{252}Cf is via spontaneous fission, giving nearly 6-8 gamma rays and an average of 3.75 neutrons. This values correspond to [1]:

- Neutron emission rate of 2.314334×10^6 $neutrons/s$ per μg , the neutron average energy is $\bar{E} = 2.1\ MeV$.
- Photon emission rate of 1.3×10^7 $photons/s$ per μg with a gamma average energy of $\bar{E} = 2.3\ MeV$.

The dose rate are:

[1] Take from http://www.hightechsource.co.uk/Legacy/Resources/Californium-252.pdf at September 2014

- Neutron dose rate of 23 mSv/h @ 1m per μg.
- Equilibrium gamma exposure rate of 1.36 mSv/h @ 1m per μg.

First layer: Paraffin

For neutron shielding, paraffin wax is used to slow neutrons to thermal energies. Paraffin wax is a saturated aliphatic hydrocarbon of the methane series having the general formula C_nH_{2n+2} with the value of n being typically about 25 (eg. Chemical formula $C_{30}H_{62}$). We have selected paraffin wax as the shielding material as it is enriched with hydrogen and due to its easy availability and high scattering cross sections.

Properties of the paraffin are listed in the following table. Scattering cross section refers to scattering and absorption cross section is the probability that the neutron after termalization could be absorbed when approaching the nuclide.

density $[g/cm^3]$	0.89
molar mass density $[g/mol]$	422.8
%C	85.22
%H	14.78
absorption microscopic cross section [barns]	hydrogen $\sigma_a^H = 0.3326$ carbon $\sigma_a^C = 0.0035$
scattering microscopic cross section [barns]	hydrogen $\sigma_s^H = 82.01$ carbon $\sigma_s^C = 5.55$
Half- value layer [cm]	3.2 for neutrons of 1 MeV 6.9 for neutrons of 5 MeV
Calculated total macroscopic cross section $[cm^{-1}]$	$\Sigma_t = 0.142\ cm^{-1}$

TABLE 1. Parameters of Paraffin. The values of microscopic cross sections are taken of [1] for neutrons in paraffin. The HVL values are taken of [2]

Due to the relative masses of the neutron and the carbon nucleus the carbon is ineffective in slowing down neutrons and the bigest contribution is from H atoms. The number of molecules per unit volume (cm^3) in the paraffin is:

$$n = \frac{N_A \rho}{M_A} = \frac{6.02 \times 10^{23} \cdot 0.89}{442.8} = 1.21 \times 10^{21} \; molecules/cm^3$$

Each molecule of paraffin wax contains about 62 H atoms and 30 C atoms. Therefore the number of atoms of H per cm^3 is $n_H = 7.5 \times 10^{22} \; atoms \; H/cm^3$ and the number of atoms of C per cm^3 is $n_C = 3.63 \times 10^{22} \; atoms \; C/cm^3$.
The scattering macroscopic cross section is:

$$\Sigma_s = 7.5 \times 10^{22} \cdot 82.01 \times 10^{-24} + 3.63 \times 10^{22} \cdot 5.55 \times 10^{-24} = 6.35 \; cm^{-1},$$

The absorption macroscopic cross section is:

$$\Sigma_a = 7.5 \times 10^{22} \cdot 0.3326 \times 10^{-24} + 3.63 \times 10^{22} \cdot 0.0035 \times 10^{-24} = 0.025 \; cm^{-1},$$

The total macroscopic cross section can be calculated using $\Sigma_t = \Sigma_s + \Sigma_a = 6.375 \; cm^{-1}$, but this value does not have into account the oil content of the paraffin.
The thickness of any given material where 50% of the incident equivalent dose rate has been attenuated is known as the half-value layer (HVL). The HVL is expressed in units of thickness (cm). Aygün and Budak [3] have calculated the HVL for seven different paraffin wax samples exposed to 4.5 MeV neutrons and the results ranging from 6.82 cm ($\Sigma_t = 0.1016 cm^{-1}$) for paraffin with 0.75% oil concentration to 3.51 cm ($\Sigma_t = 0.1977 cm^{-1}$) for paraffin with 13.5% oil concentration. Using interpolation of the half-value layers of neutrons of HVL= 3.2 cm for neutrons of 1 MeV and HVL= 6.9 cm for neutrons of 5 MeV reported by [2, 3], the HVL for neutrons of 2.1 MeV is approximately 4.89 cm and therefore the total cross section of Cf-252 neutrons is $\Sigma_t = \frac{ln2}{HVL} = 0.142 \; cm^{-1}$.

The shielding geometry has rectangular shape consisting of paraffin blocks.

Thickness of paraffin layer

When general materials are considered for shielding the interactions which have a significant effect on the transport are important.

Such an interaction is referred to as a removal process. Certainly all non-elastic processes such as (n, p) and (n, n') reactions are removal processes. Elastic scattering with sufficiently large angle may also contribute to removal. Following a removal interaction the neutron is then treated as commencing the moderation process as described by a form of age-diffusion theory. A removal cross section $\Sigma_R[cm^{-1}]$ is defined operationally by determining the attenuation in neutron flux measured in a moderating medium produced by the interposition of a thickness of the material in question. The removal cross section may also be a thought of as given by

$$\Sigma_R = \Sigma_{ne} + f\Sigma_e$$

where Σ_{ne} is the non-elastic cross section, Σ_e is the elastic scattering with suffiRciently large angle. It is found in practice generally that the removal cross section is approximately 3/4 of the total cross section [4], thus

$$\Sigma_R = \frac{4}{3}\Sigma_t = 0.1065\ cm^{-1}$$

It is possible to employ a simplistic exponential equation similar to that used monoenergetic photons in order to calculate the shielding. The dose-equivalent rate $\dot{H}_0$ at a distance r [cm] from a point source with a neutron emission rate of S $[neutrons/s]$ is given by [2]

$$\dot{H}_0 = \frac{S\ q}{4\pi R^2}$$

where $\frac{S}{4\pi R^2}$ is the neutron emission rate in an spheric surface ($S = 2.314334 \times 10^6\ neutrons/s$) and q is the equivalent dose per unit of neutron fluence rate. Using the values of [2] for the average energy of $\bar{E} = 2.1\ MeV$, about 18 $neutrons/cm^2 \cdot s$ give a dose equivalent rate of 0.025 $\frac{\mu Sv}{h}$ at 1m. Therefore we have

$$q = \frac{0.025\ mSv \cdot h^{-1}}{18\ cm^{-2}s^{-1}}$$

and the equivalent dose without shielding at 1 meter is:

$$\dot{H}_0 = \frac{2.314334 \times 10^6 neutrons \cdot s^{-1}}{4\pi R^2}\frac{0.025\ mSv \cdot h^{-1}}{18\ neutrons \cdot cm^{-2}s^{-1}} = 26\frac{\mu Sv}{h}$$

Using a shield of thickness T outside of the source described above, the dose equivalent rate $\dot{H}$ is given by [2]:

$$\dot{H} = \dot{H}_0 B e^{-\Sigma_R T}$$

where B is a buildup factor usually assumed to be 5 and $\Sigma_R = 0.1065\ cm^{-1}$ is the removal cross section. Since our goal is $\dot{H} = 1\ \mu Sv/h$, thus

$$T = \frac{1}{\Sigma_R} ln\left(\frac{\dot{H}_0 B}{H}\right) = \frac{1}{0.1065} ln\left(\frac{26\ \mu Sv/h \cdot 5}{1\ \mu Sv/h}\right)$$

and the thickness of the paraffin is:

$$T = 45.7\ cm$$

Second Layer: Lead

As the fast neutrons get thermalised in the medium, there is a high probability of thermal neutron capture reactions of $^1H(n,\gamma)^2H$ in paraffin, emitting secondary gamma ray of energy:

$$E^*_{N(A+1)} \approx [m_n + m(N(A)) - m(N(A+1))]c^2$$

where n is the neutron incident and N is the nucleus. Here we have approximate the kinetic energy to cero. The energy of the secondary gamma rays is:

$$E^*_{H(2)} \approx [1.008665 + 1.007825 - 2.014101]c^2 \cdot 931.49\ MeV/c^2 = 2.22 MeV$$

There is a low probability of thermal neutron capture reactions $^{12}C(n,\gamma)^{13}C$ in paraffin, with energy of:

$$E^*_{C(13)} \approx [1.008665 + 12.000000 - 13.003355]c^2 \cdot 931.49\ MeV/c^2 = 4.95\ MeV$$

The results are according to the values reported by [2] [4] for hydrogen 2.223 MeV and for carbon 4.95 MeV. These secondary high energy photons have to be shield with a second layer. Another

[2]Taken from http://www.nndc.bnl.gov/capgam/byn/page001.html at September 2014

option to avoid the second layer is to incorporate boro into the shield of paraffin because boro has a large cross section for neutron absorption and only emits a low energy captura gamma ray ($\sim$ 700 keV). To calculate the shield for the photons, the following basic equation is used

$$\dot{H} = \dot{H}_0 e^{-(\mu x)}$$

where $\mu = 0.484\ cm^{-1}$ is the linear attenuation coefficient of lead for photons of 5 MeV [3] , $\dot{H}_0$ is the dose rate without shield, which we can assume is $\dot{H}_0 = 1.36\ \mu Sv/h$ at 1 meter for the emission of primary gammas and $\dot{H} = 1\ \mu Sv/h$ at 30 cm is the goal of the shielding. Thus

$$x = \frac{1}{0.484} ln(1.36) \frac{1}{(0.3)^2}$$
$$x = 7.05\ cm$$

Conclusions

The combination of thickness of 45.7 cm of paraffin with 7.05 cm of lead permits the meet the safety requirement to the planned dose limit outside of shielding 1 $\mu Sv/h$. Currently we are developing a simulated validation of the theoretical results presented here. Our principal goal is to test the segmented shielding consisting of a paraffin wax and a layer of lead. To do that we already started to write a set of codes using the Geant4 tools. We hope to show that comparison soon. These results will provide the correct parameters to build up an appropriate shielding.

References

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