Radiation Shielding Materials: Half-value layer determination for separate and simultaneous photon and neutron emissions by a ²⁵²Cf source

Z. Alizadeh Rahvar¹,², M. Ghorbani²*, M. Khosroabadi³, C. Knaup⁴

¹Cancer Research Center, Omid Hospital, Faculty of Medicine, Mashhad University of Medical Sciences, Mashhad, Iran
²Medical Physics Research Center, Mashhad University of Medical Sciences, Mashhad, Iran
³Faculty of Medicine, North Khorasan University of Medical Sciences, Bojnurd, Iran
⁴Comprehensive Cancer Centers of Nevada, Las Vegas, Nevada, USA

ABSTRACT

► *Technical note*

Corresponding authors:
Mahdi Ghorbani, Ph.D.,
E-mail:
mhdghorbani@gmail.com

Background: The present study aimed to determine half-value layers (HVL) of different materials with neutron, photon, and simultaneous neutron and photon emissions by a ²⁵²Cf source. MCNPX code was used for the simulation of the applicator tube (AT) ²⁵²Cf source and the attenuation materials. **Materials and methods:** The ²⁵²Cf source, a source collimator, a detector, a detector collimator, and HVL material were defined in the present study. HVL was determined for lead, concrete, water, polyethylene, and polyethylene mixtures with various concentrations of boric acid for separate neutron, separate photon, and simultaneous emissions of neutron and photon by the ²⁵²Cf source. **Results:** HVL values were tabulated for the aforementioned materials for separate neutron, separate photon, and for simultaneous neutron and photon emissions by the ²⁵²Cf source. Among the evaluated materials, polyethylene was the most adequate material for neutron shielding. **Conclusion:** The obtained HVL results for different materials could be used for shielding design around a ²⁵²Cf source. According to the comparison of lead with concrete, lead was a suitable material for shielding against the photons emission. On the other hand, concrete with a lower HVL value seemed to be superior for neutron shielding. The combination of several HVL layers of polyethylene and lead could result in proper shielding against neutron and photon. In simultaneous neutron and photon emissions, the emitted neutrons from the source generate secondary photons. The issue led to increase HVL, and could be considered in the protection and shielding against the source.

Keywords: *HVL, attenuation material, neutron emission, photon emission, ²⁵²Cf source.*

INTRODUCTION

As a radioactive material, californium-252 (²⁵²Cf) is used in a number of industrial applications and the boron neutron capture therapy (BNCT) and for brachytherapy [1-4]. Due to the aforementioned applications of ²⁵²Cf, it is important to protect against high energy neutrons and photons that are emitted by this radionuclide and introduction of new shielding materials.

Various studies have been conducted on shielding effects of different materials for protection against neutrons from ²⁵²Cf source [1, 5]. Few researchers have paid attention particularly to half-value layer (HVL) values for few shielding materials, but the secondary neutron contribution was neglected [1, 6]. HVL is defined as the thickness of material reducing the beam intensity to the half of the original value [7].

In the aforementioned previous studies, only the HVL against photons and neutrons of ^{252}Cf were determined for few materials. The past studies had not determined HVL for simultaneous neutrons and photons emissions of ^{252}Cf source. The evaluation of the past case is important because primary neutrons can generate secondary photons; and primary photons can generate secondary neutrons that affect the thickness of HVL. The present study aimed to obtain HVL for neutron-only, photon-only, simultaneous neutrons and photons emissions and the best material for radiation protection against ^{252}Cf source.

MATERIALS AND METHODS

In the present study, an applicator tube (AT) ^{252}Cf source (Oak Ridge National Laboratory (ORNL), Oak Ridge, USA) [8] model was simulated using MCNPX Monte Carlo code (version 2.6.0). It is noteworthy that the simulation of this source was validated in a research by the authors; and a validated program was used in the present study [9]. In this research a source, a source collimator, a detector, a detector collimator, and HVL materials were defined. Afterwards, HVLs were determined for lead, concrete, water, polyethylene, and polyethylene mixtures with various concentrations of boric acid for three emission modes using the ^{252}Cf source.

To this end, different thicknesses of the materials were defined in front of this source; and a scoring cell (detector) was placed beyond the attenuating layer; and fluency of particles was obtained before and after the presence of the attenuating layer using F4 tally. To prevent the leakage and scattered rays from reaching the detector, collimators were considered around the source and detector. The input Monte Carlo programs were run for sufficient numbers of particles, so that the fluency calculation uncertainty would be in an acceptable level for all cases. Finally, HVL of different materials were obtained and compared to select appropriate absorbing materials for three emission modes separately.

Geometry of ^{252}Cf source

The ORNL-made AT ^{252}Cf type consists of an active core, a primary capsule and a secondary capsule. The active core component is a cylinder of Pd: Cf_2O_3 ceramic metal [10]. More details of this source model can be found in previous studies [10, 11]. The specifications of ^{252}Cf including half-life, yield, energy, and dose rate can be considered in a study by Kang et al.[1] Fig. 1 shows the geometric arrangement of this source.

Validation of ^{252}Cf source simulation

The present study used the ^{252}Cf source simulation program that was validated in a previous study by Khosroabadi *et al.* [9] and here -in a summary of validation of the source simulation is presented. MCNPX (version 2.6.0) simulation code [12] was used to simulate the AT ^{252}Cf source. Dosimetric parameters of the source were determined according to the presented formalism in the updated American Association of Physicists in Medicine (AAPM) task group No. 43 report [13]. The obtained data was compared with the published results of other studies on this source model [14-16]. Finally, the source simulation was validated based on this comparison; and the dosimetric results were consistent with other studies.

HVL determination for neutron emission mode

Maxwellian fission distribution was used for neutron emission by the ^{252}Cf source in order to determine HVL. Based on this distribution, the spectrum of emitted neutrons by ^{252}Cf has an average energy of 2.1 MeV, and the most probable energy of 0.7 MeV [14]. Figure 1 shows the HVL determination set-up. For the neutron emission, collimator layers were made of polyethylene, cadmium, polyethylene, lead, lead, cadmium and paraffin for part numbers of 1-7 respectively (figure 1). Collimator materials were selected to absorb scattered particles and prevent them from being counted by the detector [5, 17].

Table 1 presents the compositions and mass densities of these materials as well as HVL materials and they were calculated by the authors according to the table of isotopic masses

382

and natural abundances [5, 10, 18] This information is necessary and can be repeated by other researchers. The source collimator tube (layer no. 1) has a length of 130 cm. The thicknesses of layers 2-7 were 0.2 cm, 35 cm, 12 cm, 5 cm, 0.1 cm and 5 cm, respectively. The gas detector was defined as a cylinder with 0.5 cm radius and 1.2 cm height. The detector contained air in the simulations.

For determination of HVL for each material, the particle fluence (primary fluence) was first scored in the detector without the presence of any HVL material on the beam's path. The thickness of each material was then changed with 1 mm intervals, and the thickness at which the particle fluence had the half of the primary fluence, was calculated. The second digit of HVL value was calculated by interpolation. The neutron spectrum of ^{252}Cf radionuclide was defined in the source's active core. The neutrons were transported and F4 tally was scored. No energy cut-off was defined for neutrons. Each input program was run for 10^8 particles, and the maximum type A uncertainty was 2.77%. It should be noted that the output of MCNP is per source particle, not per number of transported particles. The HVL of neutron was determined for water, lead, concrete, polyethylene, and polyethylene mixture at various concentrations (15%, 25% and 35% weights) of boric acid.

HVL determination for photon emission mode

The same method of neutron emission mode was used for the HVL determination for the separate photon cases with differences under which all materials of collimators were made of lead. The photon spectrum of ^{252}Cf radionuclide was defined in the source's active core [19]. The photons and electrons (due to the production of secondary photons) were transported, and F4 tally was scored for photons in the detector cell. The energy cut-off was 10 keV for the separate photon cases. Each input program was run for 2×10^8 particles, and the maximum type A uncertainty was 3.22%. The HVL was determined for lead and concrete.

HVL determination for simultaneous neutron and photon emission mode

The same method of neutron emission mode was used for the HVL determination for the simultaneous neutron and photon emission mode with differences under which all materials of the collimators layers were made of lead. The neutron and photon spectra of the ^{252}Cf radionuclide were defined in the active core. Neutrons, photons, and electrons were transported. F4 tally was scored. The energy cut-off of zero, 10 keV and 10 keV were considered for neutrons, photons and electrons, respectively. Two input programs were run for 4×10^8 and 2×10^8 particles for neutron and photon, respectively. In the first program of the simultaneous neutron and photon emission, the fluency was scored only for neutron. The fluence was scored only for photons in the second program. The maximum type A uncertainties were 3.77% and 3.65%, respectively, in the HVL determination for neutrons and photons. The HVL was determined for both lead and concrete for neutrons and photons scoring, separately.

Figure 1. The geometric arrangement of the ^{252}Cf source, source collimator and detector collimator. The figure is not into a real scale.
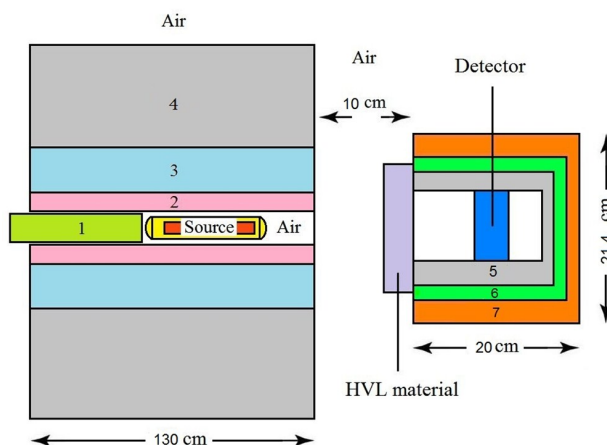
Int. J. Radiat. Res., Vol. 18 No. 2, April 2020

383

Table 1. Compositions and densities of the applied materials in the present study based on the setup in Figure 1.

| Material	Composition		Density (g/cm^3)
	Element	Weight fraction	
Active core	Pd	0.49	12.00
	Cf_2O_3	0.51	
Primary and secondary capsules	Pt	0.9	21.51
	Ir	0.1	
Air	C	0.000124	0.00120479
	N	0.755267	
	O	0.231781	
	Ar	0.012827	
Cadmium	Cd	1.0	8.65
Polyethylene	H	0.143711	0.94
	C	0.856289	
Lead	Pb	1.0	11.35
Paraffin wax	H	0.148605	0.93
	C	0.851395	
Water	H	0.111894	1.00
	O	0.888106	
Polyethylene and 15% weight boric acid	$(C_2H_4)_n$	0.85	0.86
	H_3BO_3	0.15	
Polyethylene and 25% weight boric acid	$(C_2H_4)_n$	0.75	0.88
	H_3BO_3	0.25	
Polyethylene and 35% weight boric acid	$(C_2H_4)_n$	0.65	0.92
	H_3BO_3	0.35	
Concrete	H	0.010000	2.3
	C	0.001000	
	O	0.529107	
	Na	0.016000	
	Mg	0.002000	
	Al	0.033872	
	Si	0.337021	
	K	0.013000	
	Ca	0.044000	
	Fe	0.014000	

RESULTS

Table 2 presents HVL values for the ^{252}Cf source for various materials and four emission modes. As it is presented in table 2 and figure 2, comparisons of HVL values for various materials and four emission modes, the minimum HVL of neutrons and photons emission modes belong to polyethylene and lead, respectively. For simultaneous neutron and photon emission modes, the minimum HVL values belong to concrete and lead when neutron and photon were scored, respectively. The maximum HVL value belongs to concrete (HVL=5.03 cm) for simultaneous neutron and photon emissions mode when photon was scored.

Table 2. HVL values for various materials for neutrons, photons, and spontaneous neutron and photon emissions by ^{252}Cf source in the present study.

Type of source particle	Type of particle for HVL calculation	Material	HVL (cm)- Present study	HVL (cm)- Zarezadeh [5]	Difference (%)
Separate neutron	Neutron	Water	2.16		
		Lead	3.35		
		Concrete	3.03		
		Polyethylene	1.85	1.8	2.0
		Polyethylene and 15% weight boric acid	1.90	1.2	37.0
		Polyethylene and 25% weight boric acid	1.95	1.4	28.0
		Polyethylene and 35% weight boric acid	2.03	1.4	31.0
Separate photon	Photon	Lead	0.77		
		Concrete	4.80		
Simultaneous neutron and photon	Neutron	Lead	3.45		
		Concrete	2.80		
Simultaneous neutron and photon	Photon	Lead	0.82		
		Concrete	5.03		
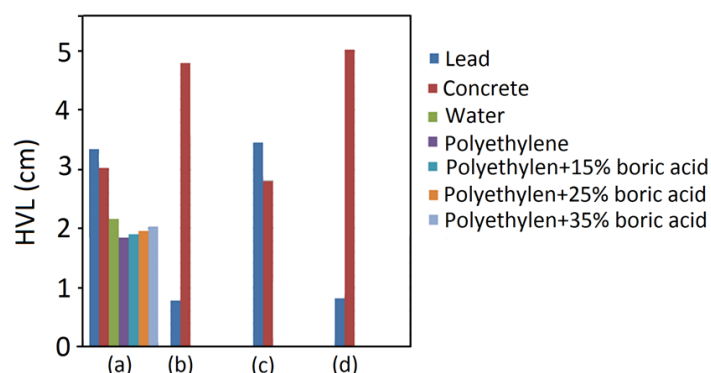
Figure 2. HVL values for various materials and four emission modes: separate neutron emission **(a)**, separate photon emission **(b)**, simultaneous neutron and photon emission when neutron is scored **(c)** and simultaneous neutron and photon emission when photon is scored **(d)**.

DISCUSSION AND CONCLUSION

For Neutron emission mode, (table 2 and figure 2), the maximum HVL value belongs to lead while polyethylene is the most adequate material for neutron emission mode among the evaluated materials. Due to the addition of boric acid, the inclusion of boric acid simultaneously reduces the percentage of polyethylene in the material, and increases HVL value against neutrons. Since boron captures thermal neutrons, this effect may be due to the fact that fast neutrons have greater contribution to the

neutron emission by ^{252}Cf. In this regard, evaluation of effect of adding other capture agents such as ^{157}Gd to polyethylene on HVL may be attractive.

Water is also similar to polyethylene. The advantage of water is its availability and low cost. In emergency situations for neutron protection, a ^{252}Cf source can be put in a water container.

For Photon emission mode, based on the obtained results in the present study, the minimum HVL value belongs to lead (HVL=0.77 cm) for photon emission mode, according to

Int. J. Radiat. Res., Vol. 18 No. 2, April 2020

385

evaluation of lead and concrete. In comparison, for neutron emission mode in the lead and concrete evaluation, concrete with a lower HVL value seems to be superior for neutron shielding. Therefore, since the density of lead (11.35 g/cm³) is higher than concrete (2.3 g/cm³), lead occupied less space than concrete in terms of volume. In summary, lead is a good absorber of photons of ²⁵²Cf and this is accounted as its advantage if the cost consideration is not taken into account. It can be concluded that a combination of several HVL layers of polyethylene and lead can result in proper shielding against neutron and photon for a ²⁵²Cf source.

For simultaneous neutron and photon emission mode, as it is presented in table 2 and figure 2, the minimum HVL value belongs to concrete and lead when neutron and photon were scored, respectively. In this mode, the HVL of photons were higher than HVL of photons in separate photon emission modes for both lead and concrete. However, it should be noted that the differences are minor. This effect suggests that neutrons, which are emitted from the source, generate secondary photons; and this issue could be considered in protection and shielding against this source. A similar effect is not seen for HVL of neutrons for lead and concrete materials.

Based on the data presented in table 2 and figure 2, a comparison between HVL values can be performed. In summary, the minimum and maximum HVL for separate neutron emission mode belong to polyethylene (HVL=1.85 cm) and lead (HVL=3.35 cm), respectively. The minimum and maximum HVL for separate photon emission mode belong to lead (HVL=0.77 cm) and concrete (HVL=4.80 cm), respectively. The HVLs for the simultaneous neutron and photon mode when neutron is scored for concrete and lead are 2.80 cm and 3.45 cm, respectively. The HVLs for the simultaneous neutron and photon mode when photon is scored for lead and concrete are 0.82 cm and 5.03 cm, respectively.

In a study by Zarezadeh [5], HVL was determined for neutron emission of ²⁵²Cf source by experimental measurement of different mixtures of polyethylene and boric acid. In this study, the data related to polyethylene is in good agreement with the HVL data for polyethylene in table 2. In the case of mixture of polyethylene and boric acid, higher HVL values are observed in the present study due to the increased weight percentage of boric acid, while a decreasing HVL was seen in the study by Zarezadeh. Since relatively similar geometries were used in these two studies, these differences could be related to the uncertainties in the Monte Carlo or experimental measurements.

The results of the present study and those reported by Da Silva and Crispim[6] cannot be compared because there are some differences between the methods of the present study and the research by Da Silva and Crispim [6] in terms of the final evaluated quantities, the types of materials, and the type of presentation of the results (table versus curves).

The present study offer basic practical information about the selection of neutron and photon shielding materials for fuel transport casks, nuclear reactor panel design and the use of ²⁵²Cf source in neutron brachytherapy and BNCT [1]. According to the conducted studies on the HVL for neutrons and photons of ²⁵²Cf source, such types of materials have not been considered for shielding evaluations. HVL for photons of this source has not been evaluated yet. It can be concluded that different materials can have advantages and disadvantages in terms of HVL thickness, cost, construction, and space occupation.

ACKNOWLEDGMENTS

Conflicts of interest: *Declared none.*

386

Int. J. Radiat. Res., Vol. 18 No. 2, April 2020

REFERENCES

1. Kang HY, Park CJ, Seo KS, Yoon JS (2008) Evaluation of neutron shielding effects on various materials by using a Cf-252 source. *J Korean Phys Soc* **52:** 1744-1747.

2. Gong C, Tang X, Fatemi S, Yu H, Shao W, Shu D, Geng C (2018) A Monte Carlo study of SPECT in boron neutron capture therapy for a heterogeneous human phantom. *Int J Radiat Res,* **16**: 33-43.

3. IAEA. Current status of neutron capture therapy, International Atomic Energy Agency, IAEA-TECDOC-1223, 2001, Vienna, Austria

4. Wang Q, Li T, Liu H, Jia X, Liu B, Wan X, Lang J (2014) The safety and usefulness of neutron brachytherapy and external beam radiation in the treatment of patients with gastroesophageal junction adenocarcinoma with or without chemotherapy. *Radiat Oncol, 9: 1-7.*

5. Zarezadeh M (2013) The preparation of polyethylene and mineral material composites, and experimental and theoretical (using MCNP code) verification of their characteristics for neutron beam attenuation. *J Sci Engin, 1: 95-101.*

6. Da Silva A and Crispim V (2001) Shielding design studies for a neutron irradiator system based on a ^{252}Cf source. *Radiat Prot Dosimetry, 95:* 333-8.

7. Yue NJ (2008). Energy spectrum based calculation of the half and the tenth value layers for brachytherapy sources using a semi-empirical parametrized mass attenuation coefficient formulism. *Med Phys, 35: 2286-93.*

8. ORNL Invention Disclosure No. 1289, under CRADA contract with Isotron, 2002.

9. Khosroabadi M, Ghorbani M, Rahmani F, Knaup C (2014) Neutron capture therapy: a comparison between dose enhancement of various agents, nanoparticles and chemotherapy drugs. *Australas Phys Eng Sci Med, 37: 541-9.*

10. Hwang KC, Lai PD, Chiang CS, Wang PJ, Yuan CJ (2010) Neutron capture nuclei-containing carbon nanoparticles for destruction of cancer cells. *Biomaterials, 31: 8419-25.*

11. Rivard MJ, Wierzbicki JG, Van den Heuvel F, Martin RC, McMahon RR (1999) Clinical brachytherapy with neutron emitting ^{252}Cf sources and adherence to AAPM TG-43 dosimetry protocol. *Med Phys, 26: 87-96.*

12. Pelowitz D. (2008) MCNPX user's manual, version 2.6.0, LA-CP-07-1473. Los Alamos National Laboratory.

13. Rivard MJ, Coursey BM, DeWerd LA, Hanson WF, Huq MS, Ibbott GS, Mitch MG, Nath R, Williamson JF (2004) Update of AAPM task group No. 43 report: a revised AAPM protocol for brachytherapy dose calculations. *Med Phys, 31: 633-74.*

14. Melhus CS, Rivard MJ, Kirk BL, Leal LC, editors (2005) Clinical brachytherapy dosimetry parameters and mixed-field dosimetry for a high dose rate Cf-252 brachytherapy source. American Nuclear Society Topical Meeting in Monte Carlo, Chattanooga.

15. Krishnaswamy V (1972) Calculated depth dose tables for californium-252 sources in tissue. *Phys Med Biol, 17: 56-63.*

16. Colvett R, Rossi H, Krishnaswamy V (1972) Dose distributions around a californium-252 needle. *Phys Med Biol, 17: 356-364.*

17. Chung WC, Ro TI, Kim G, Lee S, Igashira M, Ohsaki T (2007) Measurement of the keV-neutron capture cross-sections and capture γ-Ray spectra of ^{155}Gd and ^{157}Gd. *J Korean Phys Soc, 50: 409-16.*

18. National Institute of Standards and Technology, Available at: http://physics.nist.gov/cgi-bin/Star/compos.pl?matno=001

19. Kelm RS. In-water neutron and gamma dose determination for a new Cf-252 brachytherapy source. M. Sc. Thesis in Mechanical Engineering, 2009, http://smartech.gatech.edu/bitstream/1853/28121/1/kelm_robert_s_200905_mast.pdf., Accessed Sept 2, 2013, Georgia Institute of Technology.

Int. J. Radiat. Res., Vol. 18 No. 2, April 2020

387