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CHARACTERIZATION OF MATERIALS USED FOR NEUTRON SPECTRA MODIFICATION

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Abstract

Monte Carlo Simulation is used to study the thickness-dependent neutron-spectral-modification after transport in different materials. A collection of significant materials is studied, for choosing of potential candidates in the construction and design of accelerator-based neutron irradiation system suitable for Boron Neutron Capture Therapy (BNCT).

Keywords : *Accelerator Based Neutron Capture Therapy,*
Monte Carlo Simulation, MCNP Code, ANISN Code.

INTRODUCTION

Boron Neutron capture therapy (BNCT) is a technique that was designed to selectively target high linear energy transfer (LET) heavy charged particle radiation to tumors at the cellular level. As the ^{10}B-containing pharmaceutical selectively localizes well in the tumor volume and then exposed to thermal neutrons, a higher radiation dose to the tumor relative to adjacent normal tissue would result. The thermal neutrons are highly captured by ^{10}B (cross section = 3840 barns) resulting in an energetic alpha particle back to back with a recoiling ^{7}Li ion (sharing 2.3 MeV) and travel less than 10 microns in tissue (comparable with cellular dimensions).

Two different neutron beams are commonly used in BNCT: thermal beams for which therapeutic benefit is limited to shallow depths, and epithermal beams where, with multiple beams, this effect may extend to 8 to 10 cm. In contrast to the epithermal beam, which shows a skin-sparing effect, the thermal flux falls off exponentially from the surface.

Both types of beams include contributions by fast, epithermal, and thermal neutrons, as well as gamma rays from the neutron source and from the capture and scattering of neutrons in the beam line structures. Since it is only the ‘boron dose’ that is the tumor-selective component, the remaining radiation components in the beam should be kept at a minimum. This constitutes an important challenge in beam design.

In addition to the above considerations of beam quality, the beam should also be sufficiently intense to ensure that treatment times remain within reasonable limits. The beam design objective is to deliver an epithermal neutron fluence within a reasonable treatment time and to produce the desired thermal neutron fluence at tumor depth with minimal other radiations present.

For the purposes of reporting beam intensity, the common definition for an epithermal energy range should be used, namely 0.5 eV to 10 keV [1]. It was found that all ideal neutron beams with energies in the range 4 eV-40 keV are capable of treating to the midline of the brain with therapeutic advantage. The optimal energy in terms of maximum "advantage depth" was found to be 10 keV under most conditions of beam size and phantom shape [2].

To reduce the superficial damage to the skin, thermal neutrons in the incident beam should be minimized. Also, because of the energy range of the gamma radiation and fast neutrons, it results in a non-selective dose to both tumor tissue and a large volume of healthy tissue. Hence it is desirable to remove as much gamma radiation and fast neutrons from the beam as possible. Spectrum shifting technique for neutron beam design moderates the fast neutrons down to an appropriate lower energy for BNCT.

In this study, a collection of significantly important materials is studied systematically in standard manner to investigate the efficiency of materials as reflector, filter, attenuator and/or moderator. It is to study the collective neutron behavior as a function of thickness, to classify materials according to there ability to modify the neutron beam (Energy, Intensity, directionality). It is a reference/preliminary study for our subsequent studies aiming to design a suitable irradiation system for BNCT using accelerator based neutron sources. As this study was issued as a first step toward design of a BNCT irradiation facility, therefore the characterization parameters were chosen to be compatible with the design criteria.

Therefore, the energy ranges for characterization of different neutron beam modifiers in this study will be : energies lower than 0.5 eV for thermal neutrons, energies from 0.5 eV to 10 keV for useful epithermal neutrons, 10 keV to 40 keV for acceptable epithermal neutrons and energies higher than 40 keV as fast neutrons.

METHOD

Problem Setup

The transport of unidirectional neutron beam from a point source in the Y-axis direction was calculated using both Monte Carlo and deterministic methods. Different neutron beam modifying materials was modeled in a simple geometric condition with a cylinder, of radius 1 meter and thickness ranging from 1 to 100 cm, parallel to Y-axis. The point source is located at the rear end of the cylinder at radius zero.

The neutron spectrum of the point source obtained from previously published experimental data of the ^{9}Be(p,n)^{7}Li reaction. The neutron yield of the ^{9}Be(p,n)^{7}Li reaction was determined in 0 direction as a function of neutron energy using the experimental measurements of Lone et al., with the data processed graphically [3,4].

The neutron spectra were exponentially extrapolated down to 10^{-9} MeV from the neutron detection threshold of 0.3 MeV [5,6].

The neutron spectrum is transformed from double differential yield to angular differential yield by integration over neutron energy, and is discretized into 29-energy group to be suitable for transport calculation. The total neutron yield obtained from integrating the Lone p-Be energy spectrum (from 10^{-9} to 19.2MeV) at 18 MeV bombarding proton energy is 2.77E+17 n/Sr./s/A.

Calculation Methods

The Monte Carlo code, MCNP, has been demonstrated to be very useful for the detailed design of a beam facility and gives excellent agreement with measured values of spectra and flux [1].

MCNP is a general purpose Monte Carlo code for calculating the time dependent continuous energy transport of neutron, photon and/or electrons. Independent probability distributions may be specified for the source variables of energy, time, and direction and for other parameters such as starting position within the geometry [7,8,9] .

Generally, the MCNP code is flexible and reliable code but has to be used very carefully in what constitutes the definition of the simulation conditions, such as geometrical, physical and tally definition, and in the interpretation of the output file.

In this study, MCNP code is used with the coupled neutron-photon transport mode to consider the additional gamma rays emitted from the interaction of neutrons with different materials.

RESULTS AND DISCUSSION

The results of transport of p(18)-Be neutron beam through different neutron modifying materials is divided into two main groups; the transmission and reflection properties. In each case, the behavior of neutron transported as well as the gamma produced will be reported.

The transported neutron intensities are reported as function of material thickness. The results for each material will be represented in two figures. The first figure (fig. a) will present the transmitted/reflected intensity relative to the incident neutron beam, while the second figure (fig. b) will present the transmitted/reflected intensity relative to the transmitted/reflected neutron beam. The first figure (fig. a) will characterize the exponential attenuation as well as relative rate of exponential attenuation of neutron beam and the build up of gamma radiation. The second figure (fig. b) will characterize relative percentage of each energy group and build up region of lower energy groups.

The neutron energies are divided into four groups, which were chosen from the BNCT beam design criteria. These groups are (1) Thermal neutrons range from 0 to 0.5eV, (2) Useful epithermal neutrons range from 0.5eV to 10 keV, (3) Acceptable epithermal neutrons range from 10 to 40 keV, (4) fast neutron range from 0.04 to 20 MeV.

Transmitted Neutrons Behaviour

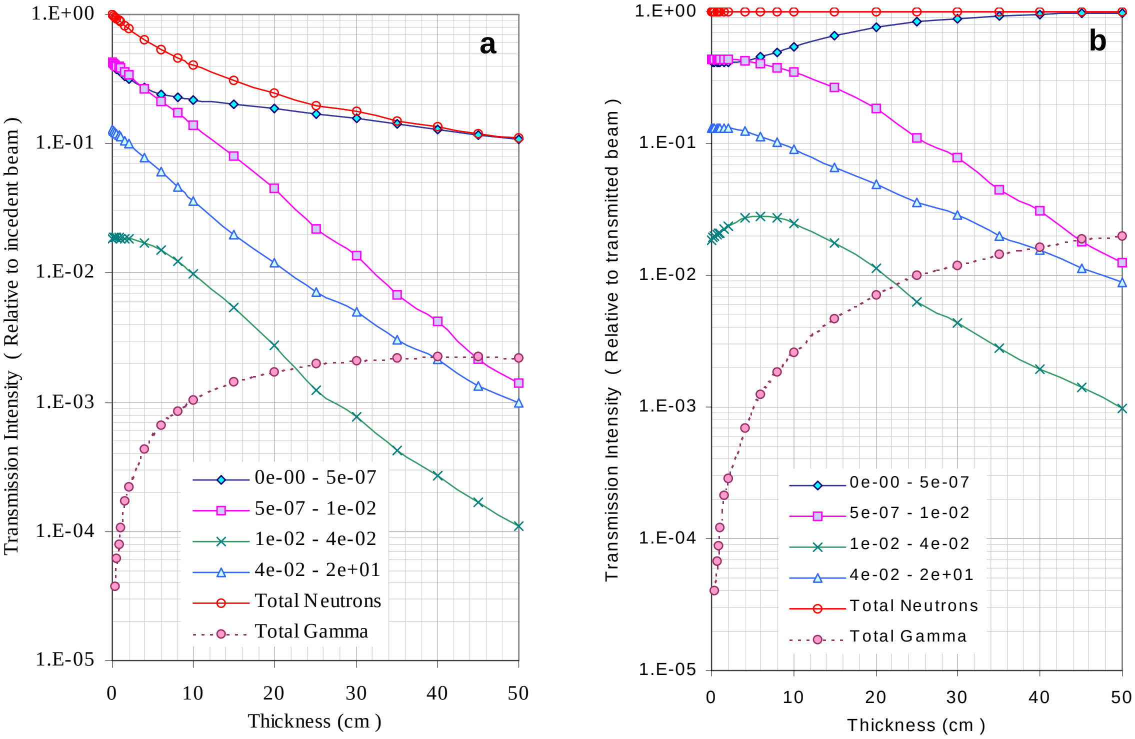

Figure 1. Neutron transmission through Heavy Water (D_2O)

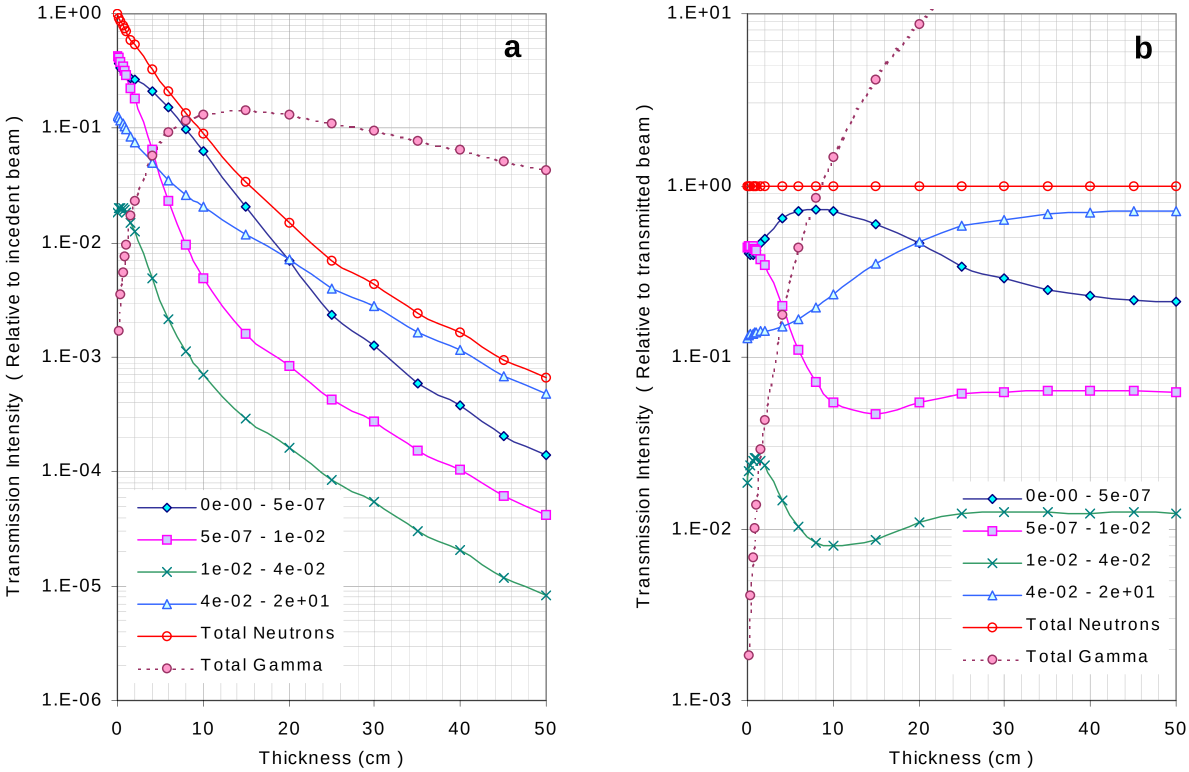

Figure 2. Neutron transmission through Water (H_2O)

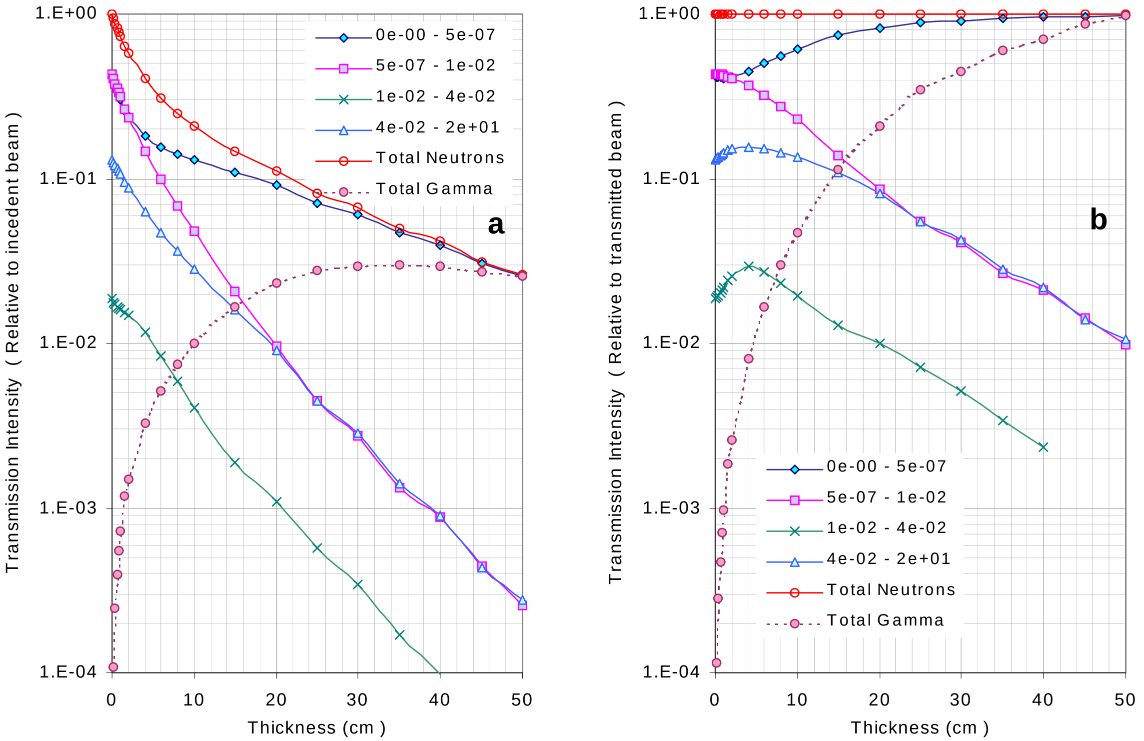

Figure 3. Neutron transmission through Beryllium (Be)

Figure **1.a** shows that gamma photons, produced by the neutron capture by D_2O nuclei, increase till saturation at 35 cm. Also, it shows that the rate of attenuation of thermal neutrons group is less than other groups, which expressed as relative increase in the thermal component of the transmitted neutron beam (figure **1.b**). Figure **1.b** reveals that the neutron range from 10 to 40 keV builds up till its maximum value at 6 cm then it exhibits exponential attenuation behavior. Therefore, 6 cm of D_2O represents the build up equilibrium thickness for the 10-40 keV energy group. It represents balance between neutron build up due to thermalization of higher energy neutrons (parameterized by elastic scatter cross-section and energy loss per collision) and neutron losses due to thermalization and capture reactions (parameterized by elastic scattering and capture cross-sections). This implies that 6 cm is the best operating thickness for D_2O, and after that there are dangerous increase in relative thermal as well as gamma components with exponential attenuation of all other components.

Figure **2.a** indicates that H_2O is a very efficient moderator for shielding purpose, as H_2O exhibits attenuation rate higher than exponential. This is due to the high absorption and elastic-scatter cross-sections as well as the highest energy loss per collision for hydrogen. Figure **2.b** shows that the build up equilibrium thickness of thermal energy group is about 8 cm, while it is about 1 cm for the 10-40 keV energy group. Also, there are depletion equilibria at 10 cm for the 10-40 keV and 15 cm for the 0.5eV-10 keV energy groups. These interesting depletion equilibria as well as the saturation build up of the fast neutron group may be explained by considering that fast neutron group has smaller elastic-scatter and higher absorption cross-sections and hence smaller rate of neutron shift from this group to lower energy groups.

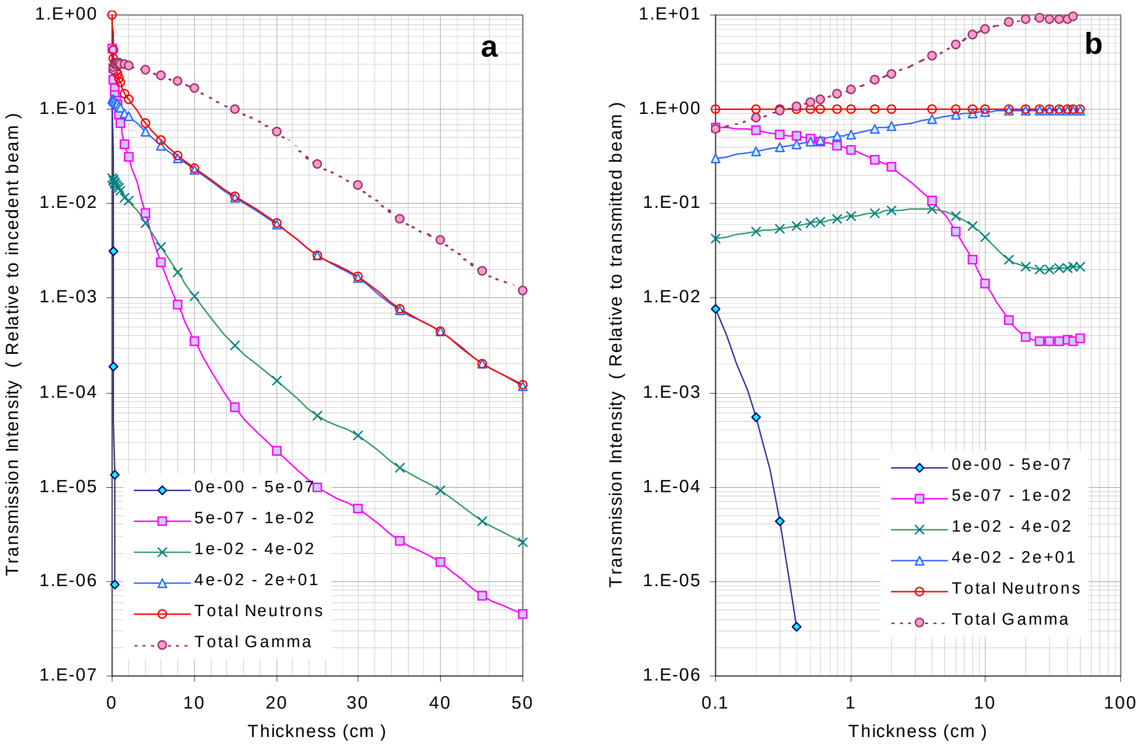

Figure 4. Neutron transmission through Boron (B)

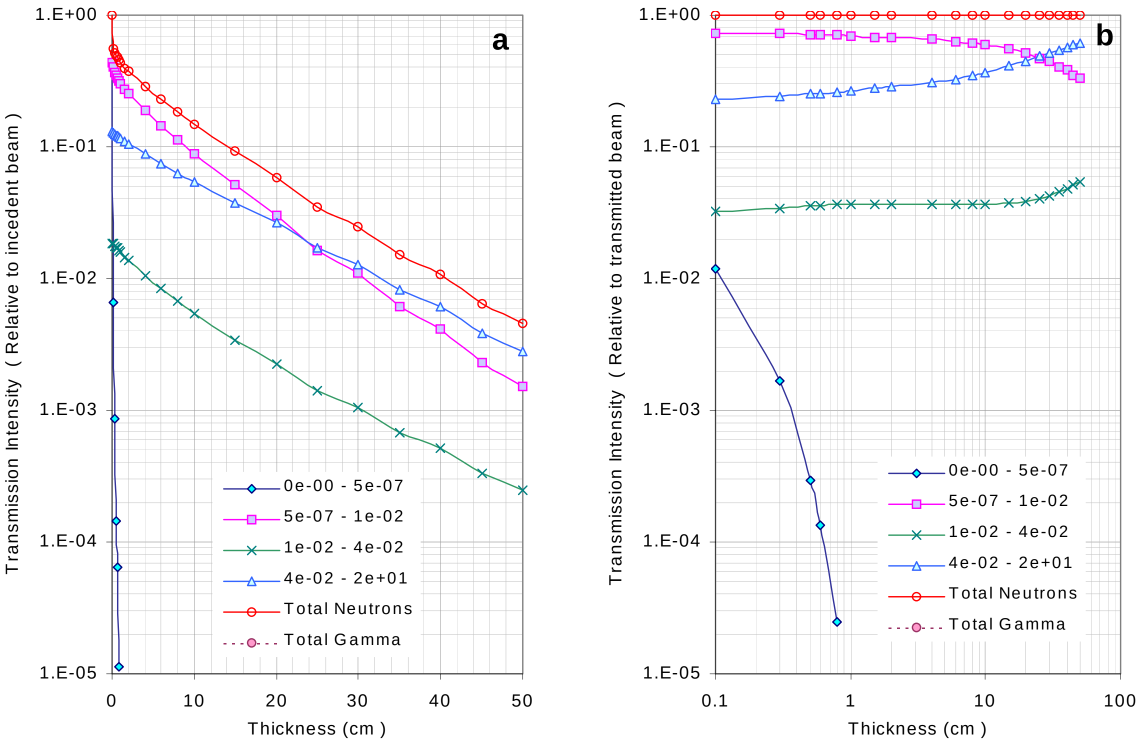

Figure 5. Neutron transmission through Cadmium (Cd)

Figure **2.b** also illustrates that the gamma component of transported beam exceeds 100% of the transmitted neutron beam at about 9 cm of H_2O.

Figures **3.a** and **3.b** clarify that neutron transport behavior through beryllium almost is the same as D_2O with 4 cm build up equilibrium thickness for the 10-40 keV energy group and slightly higher rate of attenuation of all energy groups and higher rate of gamma production. One exception can be noted that the fast energy group has build up equilibrium at 4 cm of beryllium, which could be attributed to the balance between neutron build up due to (n, 2n) reaction and neutron losses due to thermalization and capture reactions.

Figures **4** and **5** manifest that boron and cadmium are characterized by sharp decrease in the thermal neutron component and build up of fast neutron components, which is an expected behavior as response to the very high absorption cross section in that thermal energy region. Boron exhibits *1/v* dependence in the absorption cross-section, where v is the neutron velocity, while cadmium exhibits high absorption cross-section till a resonance at 0.4 eV followed by drop in fast neutron region.

However, boron seems to be more efficient thermal neutron filter, only 3 cm boron could reduce thermal components to 10^{-5} of incident beam, while 8 cm cadmium is needed to get the same value. It may be attributed to the higher thermalization efficiency of boron (boron mass = 5 and cadmium mass = 48) which accelerates neutron removal through shifting neutrons to lower energy regions that have higher absorption cross-section.

Reflected Neutrons Behaviour

Increasing beam intensity is achieved by surrounding the beam with an appropriate reflector and tapering it from a wide to a narrow aperture. Suitable reflector materials for this are those with high scattering cross section and high atomic mass (resulting in little energy loss). Generally all materials exhibit same reflection saturation behavior with different saturation thickness.

It could be concluded from figures **6** and **7** that natural iron and lead exhibits same neutron reflection behavior, with generally lower absolute reflected intensity for all neutron groups and higher rate of gamma production. It is due to higher neutron absorption and photon production cross-sections of iron and higher photon interaction cross section of lead.

Both iron and lead show build up equilibria (at 1 cm for lead and at 0.5 cm for iron) of the gamma component that coincides with depletion equilibria of the 10-40 keV neutron group. The 10-40 keV neutron group lies in the resonance region of both iron and cadmium, which causes increased production of gamma rays. The produced photons are balanced with the high photon interaction cross-section of lead and iron.

Iron has saturation thickness of 4 cm for thermal group, 10 cm for epithermal group and 45 cm for other groups, while lead has 25 cm for thermal group, 35 cm for fast group, and about 50 cm for other neutron groups.

Figure **8** illustrates that beryllium has build up equilibrium at thickness ranging from 2 to 4 cm for fast and 10-40 keV energy groups, which is attributed to its multiplication efficiency through (n, 2n) reaction. Beryllium has saturation thickness of 35 cm for thermal group, 15 cm for epithermal group and 10 cm for other groups.

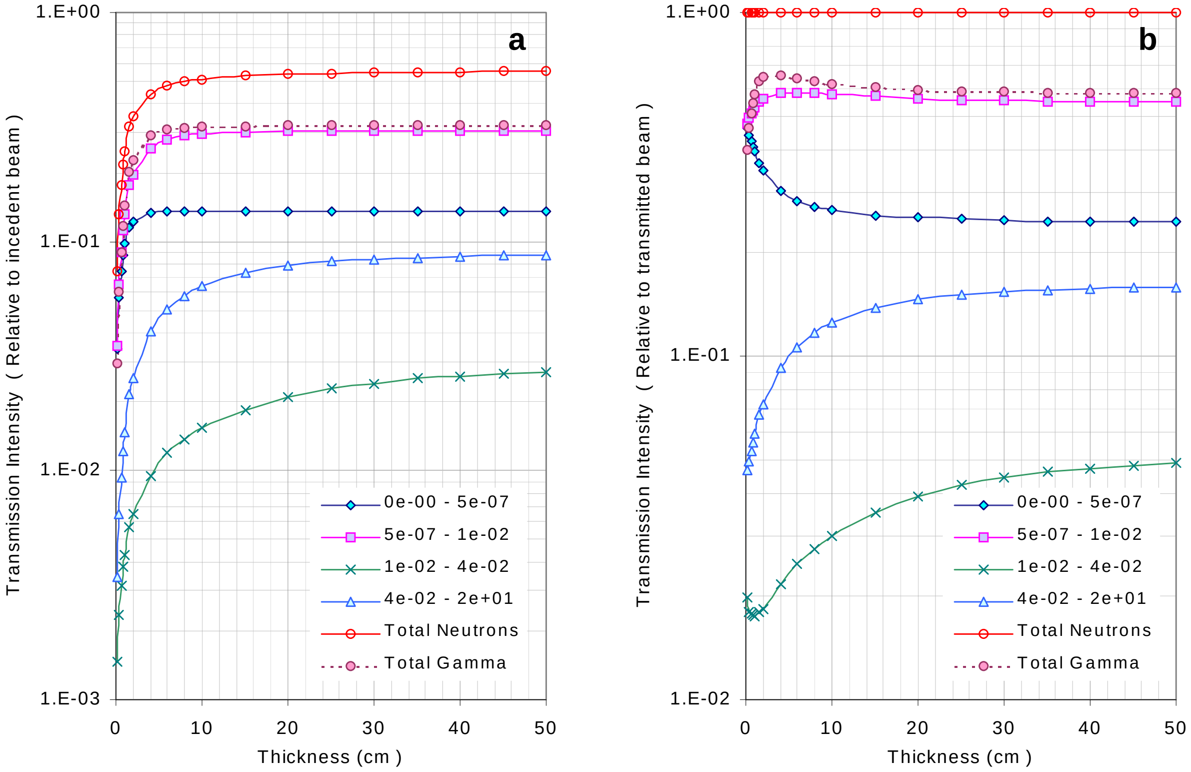

Figure 6. Radiation reflection due to neutron transmission through Iron

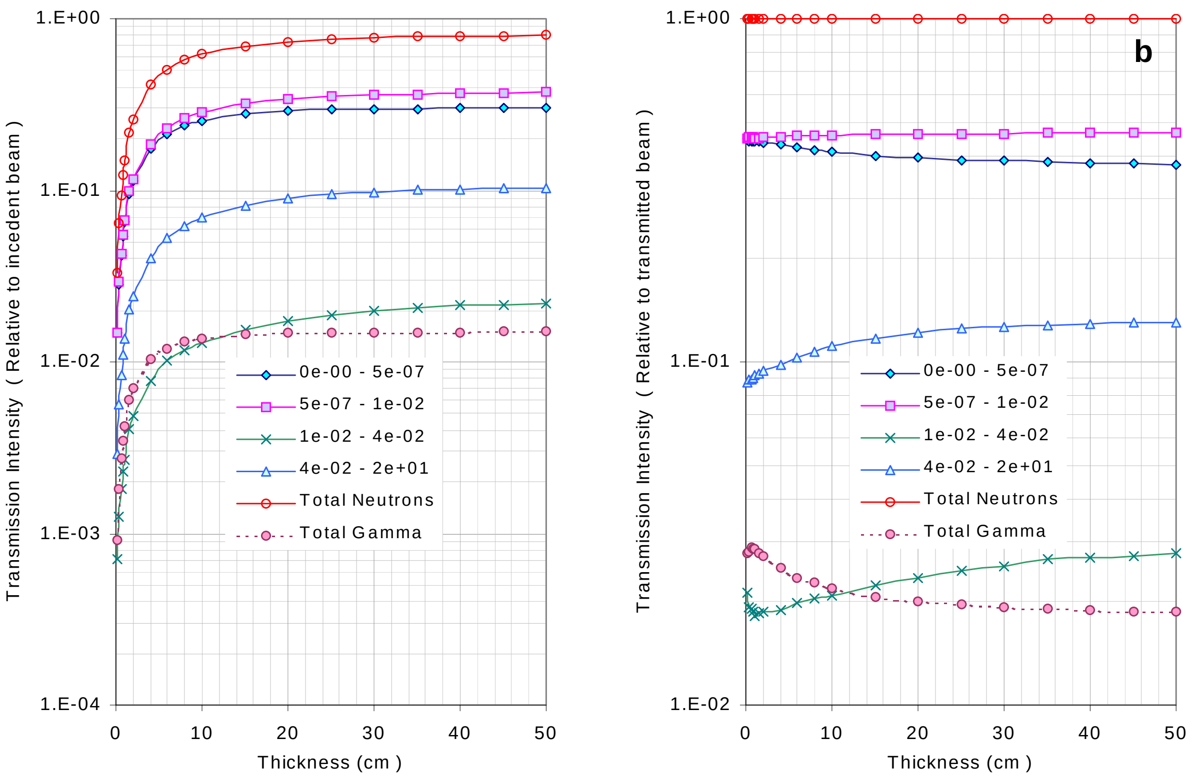

Figure 7. Radiation reflection due to neutron transmission through Lead

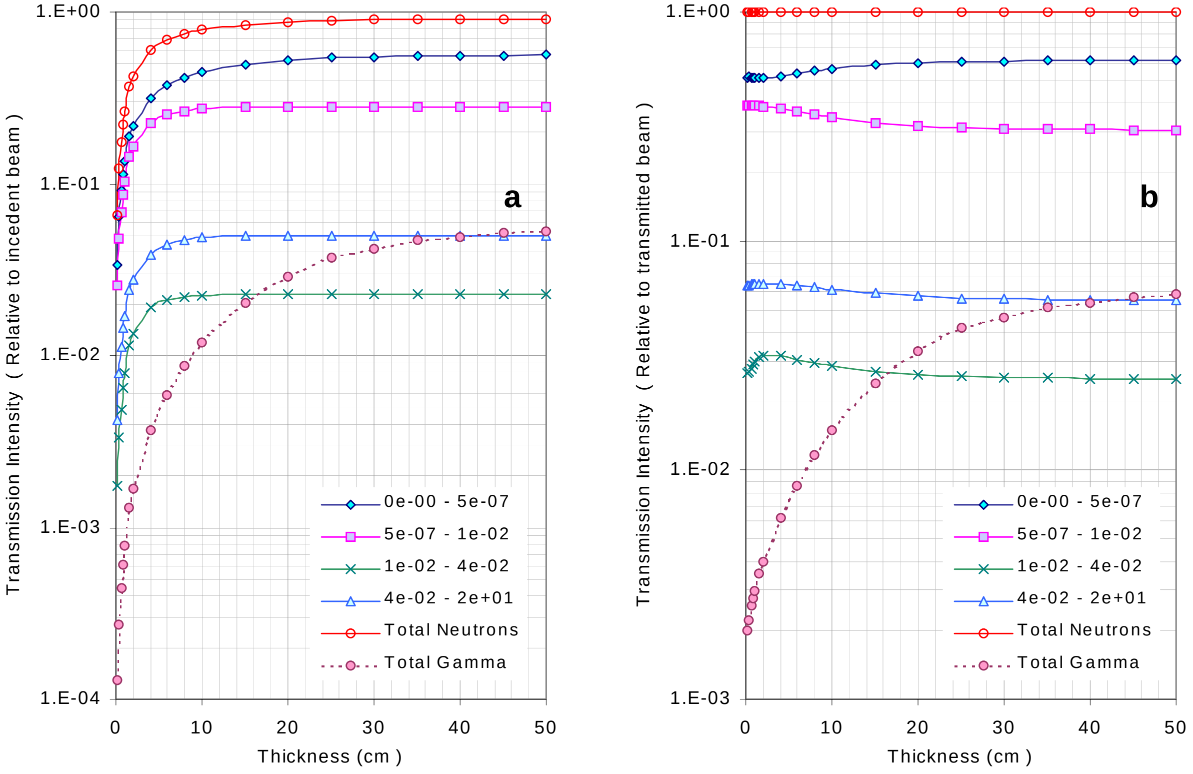

Figure 8. Radiation reflection due to neutron transmission through Beryllium

CONCLUSION

H_2O can not be used as moderator for epithermal beam design because of intense photon field and neutron attenuation properties.

D_2O should not be used beyond 6 cm thickness and Be should not used beyond 4 cm thickness. 6 cm D_2O and 4 cm Be almost has same neutron transport properties with higher photon field in case of Be. Multi-layer moderator of successive layers of D_2O and Be may be very efficient, considering that material thickness should be changed with neutron spectrum change and that the front layer should be D2O to reduce photon dose to the patient.

Boron is a very good filter especially for thermal neutron, but as 1/v cross section materials it may deplete the lower energy part of the epithermal neutron spectrum. Cd produces a high-energy (7-8 MeV) capture gamma ray, which is difficult to control. However, boron produces very intense photon field (468 keV) that exceeds 100% of transmitted neutron field after 3 mm of boron.

Lead has higher reflected beam intensity and has lower photon contamination than iron. However, lead has higher thermal neutron contamination. May be a lead reflector with a thin layer of thermal neutron filter will be very efficient.

Beryllium dons not exhibit good reflection properties due to its high thermal and gamma components in the reflected beam. However, it may be used with small thickness (2 - 4 cm) behind the neutron source, because its multiplication properties.

ACKNOWLEDGMENT

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