An Optimization of Shielding Design for Compact-Fusion Neutron Sources

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1. Introduction

The Compact-Fusion Neutron Source (C-FNS) is widely used in various industrial and research area such as neutron activation analysis, neutron radiography, neutron capture therapy, and so on [1-2]. Also, for easier and wider applications of C-FNS, a need for more compact and even portable design is being increased. To achieve a goal of C-FNS design considering its compactness, optimization of neutron and gamma shielding is essential.

In this study, an optimized shielding design for deuterium-deuterium (D-D) C-FNS was performed based on the well-known MCNP6 code [3].

2. Design Target and Model

2.1 Design Target

In many applications of the neutron source, usage of thermal neutron is more efficient than fast neutron while D-D C-FNS produce 2.5 MeV fast neutrons. Hence one of the design targets is a maximization of "thermal neutron flux level" by adopting appropriate neutron moderator.

The other design target is a minimization of shielding and moderator size as mentioned in the introduction section.

For worker dose limit, 5 μSv/hr is used according to the recommendation of ICRP-60.

2.2 Approximated Model for Conceptual Design

In this paper, the 2.5 MeV neutron from D-D fusion reaction is approximated as isotropic, and 1-D spherical model with 10^{11} n/sec source as shown in Fig. 1 is used.

The neutron source is born at the center of the spherical model, and the target neutron flux region is assumed from r=4cm to r=5cm. Then this region is surrounded by a 50-cm-thickness moderator region and 150-cm-thickness region.

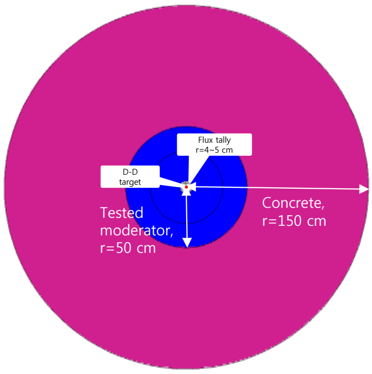

Fig. 1. Approximated 1-D spherical model for conceptual design

3. Moderator Analysis for 10^{11} n/sec Source

3.1 Moderator material

Figure 2 shows thermal (<0.1 eV) neutron fluxes at considered region for various moderator materials suggested in references [4] and [5]. Because of the Be-9(n,2n)Be-8 reaction which has about 1.8 MeV threshold energy, beryllium shows the best thermal neutron flux. Since the source neutron energy is 2.5 MeV, other materials which have higher threshold energy than 2.5 MeV in (n,2n) reaction did not show considerable moderation effect.

Although the beryllium showed best results, the chemical property of the beryllium induces alternative difficulty in C-FNS design. Hence the polyethylene is selected as a moderator material.

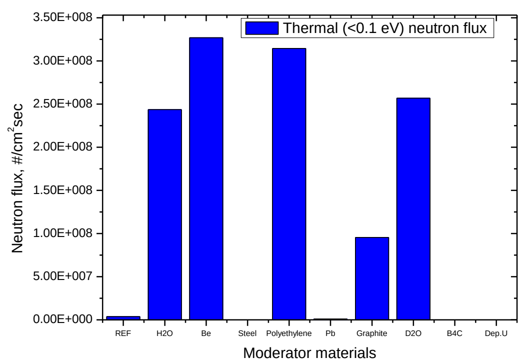

Fig. 2. Thermal neutron fluxes for various moderators

3.2 Thickness of Moderator

Figure 3 shows thermal (<0.1 eV) neutron fluxes at considered region according to the polyethylene moderator thickness. It is easy to find that 15 cm-thickness polyethylene shows converged thermal neutron flux strength.

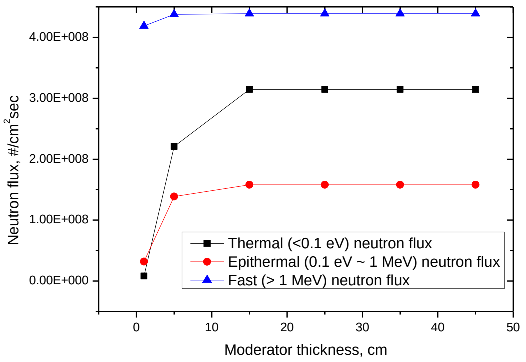

Fig. 3. Thermal neutron fluxes according to the thickness of the polyethylene moderator

3. Shield Analysis for 10^{11} n/sec Source

3.1 Shield Materials

For shielding design model, 15 cm-thickness polyethylene moderator was adopted as concluded in the previous section. Figures 4 and 5 show neutron and photon dose rate distributions for various shield materials.

It is interesting that the polyethylene shows best performance in neutron shielding and worst performance in photon shielding while the lead shows worst performance in neutron shielding and best performance in photon shielding (up to 100cm-shieidng-thickness). Since photon (or gamma) is generated by the (n,γ) reaction, the worse performance in photon shielding is induced by the not-shielded-neutrons in lead shield case.

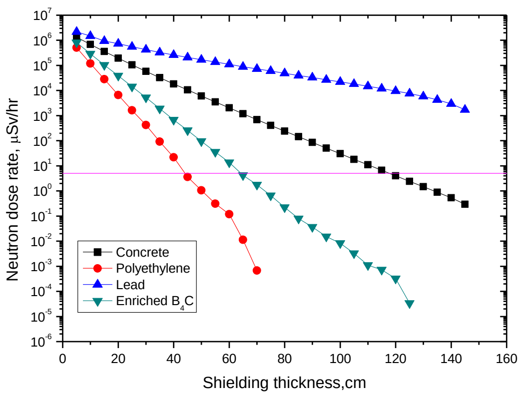

Fig. 4. Neutron dose rates for various shield materials

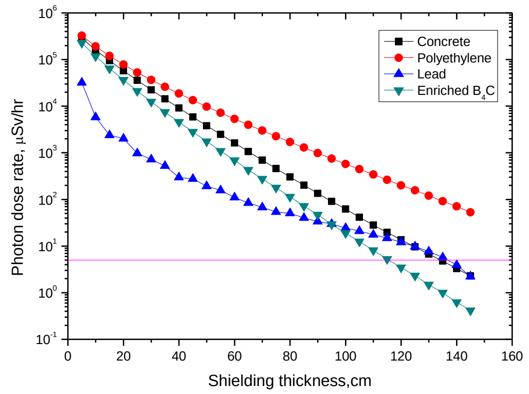

Fig. 5. Photon dose rates for various shield materials

Consequently, we can choose the polyethylene as a neutron shield and the lead as a photon shield. Fig.6 shows total dose rate of combined the polyethylene and the lead shields. In Fig. 6, remained region after polyethylene is filled by the lead shield.

We can obtain that the smallest size of shield for 10^{11} n/sec source case is a combination of 45cm-thickness polyethylene and 20cm-thickness lead.

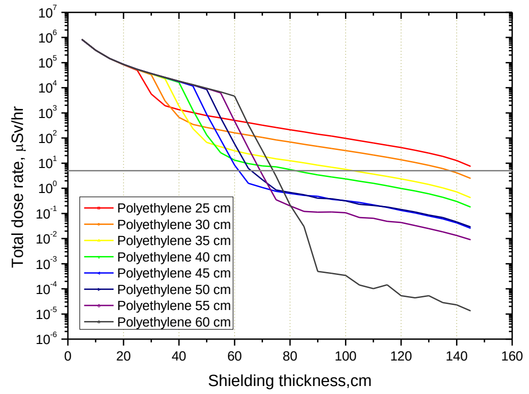

Fig. 6. Total dose rates for combination of polyethylene and lead

4. Shield Analysis for Various Source Strength

Based on the previous results, we can derive required minimum shield thickness for various D-D source strengths as shown in Fig. 6. It is noted that the 15cm-thickness moderator is still considered inside of shield.

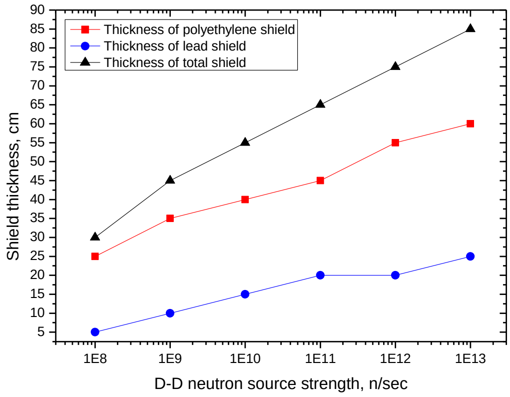

Fig. 6. Minimum shield thickness for various D-D neutron sources

3. Conclusions

In this paper, optimized moderator and shield design was suggested based on a simple 1-D spherical model. The 15cm-thickness polyethylene moderator was suggested with 45cm-thickness polyethylene neutron shield and 20cm-thickness lead photon shield for 10^{11} D-D neutron source.

In addition, minimum shield thickness was also evaluated for the various strength of D-D neutron sources.

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