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Monte Carlo simulation-based design for an electron-linear-accelerator-driven subcritical neutron multiplier for boron neutron capture therapy

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HIGHLIGHTS

- A subcritical neutron multiplier driven by an electron LINAC is designed for BNCT.
- The neutron multiplier is designed so as to ensure the safety of the treatment.
- Fuel configurations in the multiplier are examined to maximize the neutron beam.
- The neutron beam depends on an area per uranium fuel plate in the neutron multiplier.
- A LINAC with a 4.4 kW beam of 20 MeV electrons yields an enough neutron beam for BNCT.

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ABSTRACT

Fuel configurations for a subcritical neutron multiplier, which was embedded in a beam-shaping assembly and irradiated by electrons from a linear accelerator, were examined to maximize the production of the epithermal neutron flux for boron neutron capture therapy. The epithermal neutron flux at the treatment position increased as the area per uranium fuel plate increased and was estimated to be 2×10^9 cm^{-2} s^{-1} when the subcritical neutron multiplier was irradiated by a 4.4 kW (0.22 mA) beam of 20 MeV electrons.

1. Introduction

With the application of compact neutron sources to boron neutron capture therapy (BNCT), a BNCT system combined by a lithium target driven by a 56 kW (20 mA) beam of 2.8 MeV protons from a Dynamitron accelerator was developed (Forton et al., 2009), and an epithermal neutron beam from a beam-shaping assembly (BSA) equipped with a beryllium target driven by a 30-kW (1-mA) beam of 30-MeV protons from a compact cyclotron is in operation in Japan (Tanaka et al., 2009). Higher intensities for epithermal neutron fluxes than those of existing small accelerator-based neutron sources are desired for improving BNCT, although a higher beam power with a small accelerator would make heat removal from the compact target difficult. The BSA combined with a subcritical neutron multiplier (SNM) fueled by fissile materials to amplify the neutrons produced by the target may therefore be considered, since the SNM will be effective in dropping the beam power of a small accelerator.

A very high epithermal neutron flux for BNCT clinical trials, 4.3×10^9 cm^{-2} s^{-1}, had been attainable by a heavy-water-moderated subcritical assembly of nuclear fuel with an 83 kW thermal output combined by a research reactor with a 6-MW thermal output (Harling et al., 2002). An accelerator-driven SNM having a high safety rating may be also used as a compact source for BNCT in research-reactor institutes around the world, since such a system may be easier to build and maintain for certain institutes. Further, the radioactivity of fission products from a low-power SNM must be lower than those of the research reactors currently used for BNCT.

Photo-neutrons can be created by electrons as they strike targets of various materials at energies above the photo-neutron threshold which lies in the range of 6-MeV to 13-MeV for most materials, and uranium has the higher photo-neutron yield per second per kilowatt of incident beam power compared to other materials, *e.g.*, the higher photo-neutron yield at an electron energy of 34-MeV for a semi-infinite target of uranium (3.09×10^{12} s^{-1} kW^{-1}) compared to that of lead (1.60×10^{12} s^{-1} kW^{-1}) (Swanson, 1978). A photo-neutron source for BNCT pre-clinical research, in which a lead target is irradiated by 20-MeV electrons from a linear accelerator (LINAC) for medical uses, was investigated (Durisi et al., 2015); however, the intensity of an epithermal neutron flux from the photo-neutron source was insufficient for BNCT clinical trials. A water-moderated, uranium-plate-fueled SNM, a

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small area on the surface of which is irradiated by several tens of megaelectronvolt electrons from a LINAC, should efficiently produce and multiply neutrons, since the uranium fuel plates in the SNM predominantly produce photo-neutrons by Bremsstrahlung (γ, n) reactions and the photo-neutrons that are moderated by water can then efficiently produce fission. In this instance, the SNM fuel configuration including the number and dimensions of the fuel plates dominates not only the effective multiplication factor (k_{eff}) of the SNM with a BSA but also the photo-neutron creation per electron injection, and this would influence the neutron flux distribution in the BSA as well as the beam characteristics at the treatment position. Therefore, making a careful examination of the effects of the fuel configuration on the neutron flux in the BSA is needed to increase the epithermal neutron flux at the treatment position having beam characteristics appropriate for BNCT.

The present study is aimed at revealing a suitable fuel configuration for an SNM driven by a beam of 20-MeV electrons from a LINAC. For generating a high epithermal neutron flux at the treatment position, the k_{eff} governing the multiplication rate of neutrons needs to be close to unity. Further, for the advanced safety level required for treatment, the SNM with a BSA must have a negative moderator temperature coefficient of reactivity. In consideration of these requirements, various calculation models for an SNM fueled by uranium plates were designed using MCNPX (Pelowitz, 2008) including the number of fuel plates as a parameter, and the moderator to fuel ratio was determined so that the SNMs with a BSA could have the negative moderator temperature coefficient of reactivity. Moreover, these calculation models were designed so that the SNMs with a BSA could have the same multiplication rate of neutrons but the fuel configuration of the SNM could differ so as to exclude the effects of k_{eff} on the neutron flux. The neutron fluxes and beam characteristics of the various calculation models for the SNMs with a BSA, the design of which has followed in the article (Hiraga, 2015), were compared to identify the SNM fuel configurations suitable for BNCT.

2. Calculation models and methods

Fig. 1 shows an axial section of the BSA with an SNM fueled by two uranium plates. The SNM has a 0.5-cm-thick Zr vessel and is embedded in the rectangular parallelepiped Be reflector. The incident electron beam deposits all energy on the 5 × 5 cm target portion of the vessel. This part may be designated as a photon generating target, since the Bremsstrahlung X-rays with energies more than 6-MeV are mainly produced in the target portion of the vessel. It was assumed that the target portion of the vessel is cooled by water flow in the SNM. The U plates in the SNM may be called neutron generating targets, since photo-neutrons mainly occur in the U plates in the SNM. The Bremsstrahlung X-ray creation and photo-neutron creation was calculated in a Monte Carlo simulation assuming an area of 5 × 5 cm on the surface of the Zr vessel was uniformly irradiated by a collimated beam of 20 MeV electrons. Further, the material and thickness of the target portion of the vessel of an SNM was examined to increase the epithermal neutron flux at the treatment position.

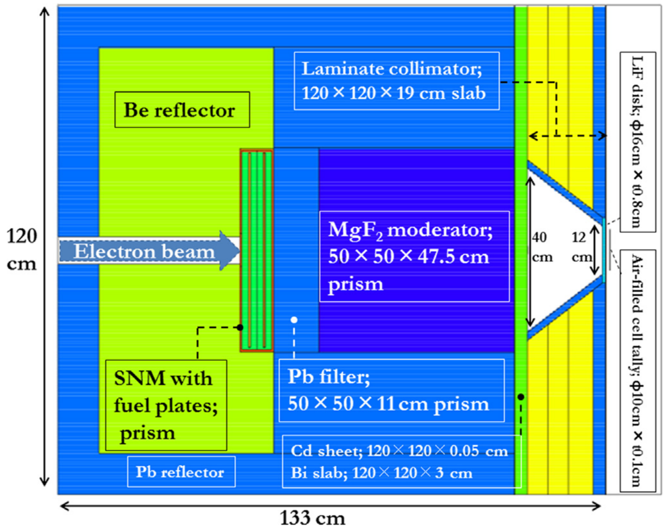

Fig. 1. Axial section of a BSA with an SNM.

In the SNM, the square U plates with a thickness of 0.392 cm in Zr jackets with a thickness of 0.04 cm interlaminated with water zones are stacked along the beam axis. The thickness of 0.392 cm for U plates was decided based on a fuel design for research reactors. The fuel is enriched to 19.8% to miniaturize the SNM. The number of fuel plates (N_f) in the SNM was varied in five steps (2, 3, 5, 7, and 9) to alter the total thickness of the fuel plates as the neutron generating target. For each value of N_f, the area per fuel plate and the thickness per water zone were determined by iterative calculations with MCNPX so that the k_{eff} of the SNMs with a BSA reached 0.992 which is close to unity for high neutron multiplication. The values of k_{eff} were estimated by the KCODE criticality calculations using MCNPX. Moreover, the thickness per water zone was determined so that the SNMs with a BSA could have the negative moderator temperature coefficient of reactivity (Graves, 1979).

Other components embedded in the rectangular parallelepiped Pb reflector are the Pb filter prism for reducing γ-rays in the radiation from the SNM and the MgF_2 moderator prism for neutron filtration. Further, a 0.05-cm-thick Cd sheet to absorb thermal neutrons was sandwiched between the SNM and the Pb filter to reduce the prompt γ-rays at the treatment position from (n, γ) reactions in the components downstream of the SNM. The laminate collimator consisted of a 16-cm-thick polyethylene slab containing LiF for capturing neutrons and a 3-cm-thick Pb slab for scattering prompt γ-rays from (n, γ) reactions in the polyethylene slab. A 0.05-cm-thick Cd sheet for absorption of thermal neutrons and a 3-cm-thick Bi slab for reducing γ-rays from the neutron beam were sandwiched between the MgF_2 moderator and the laminate collimator. A 16-cm-diameter 0.8-cm-thick LiF disk was placed on the aperture of the laminate collimator to drop the thermal neutrons at the treatment position. The treatment position, on which a 10-cm-diameter 0.1-cm-thick air-filled cell tally for calculating the neutron and photon flux is placed, is on the beam axis and 1 cm distant from the aperture of the laminate collimator.

The sizes of the Pb filter (50 × 50 × 11 cm), MgF_2 moderator (50 × 50 × 47.5 cm), and laminate collimator (120 × 120 × 19 cm) were determined previously (Hiraga, 2015) so that a BSA model with these components could produce an epithermal neutron flux at the treatment position that was not only of the greatest intensity but also almost met the recommended beam characteristics given by the International Atomic Energy Agency (International Atomic Energy Agency, 2001). Further, some of the SNM design parameters for the previous study are identical to those of the present study, including a k_{eff} of 0.992 and a fuel enrichment of 19.8%, and therefore, characteristics of the radiation from the SNM for the previous study may be similar to those of the present study. Thus the sizes of these components for the previous study are also adopted in the present study. Moreover, it was assumed that the sizes of these components do not depend on the primary neutron source that is based on the ^{9}Be (p, n) reaction for the previous study and the photo-neutron reaction for the present study, since the beam characteristics at the treatment position will be dominated by the SNM, not by the primary neutron source.

3. Results and discussions

3.1. Design for SNM

For each value of N_f, the thickness per water zone was determined on the basis of the dependence of k_{eff} on the ratio of hydrogen atoms to uranium atoms (N^H/N^U), which is shown in Fig. 2 for N_f = 2 and 7 for