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CONCEPT OF AN ACCELERATOR-DRIVEN NEUTRON SOURCE FOR THE PRODUCTION OF ATMOSPHERIC RADIATIONS

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Abstract

At the Korea Multi-purpose Accelerator Complex (KOMAC) of Korea Atomic Energy Research Institute (KAERI), we are studying an accelerator-driven neutron source for the production of white neutron beams that resemble the atmospheric radiations on the earth. In the concept of the neutron source, high-energy neutrons are generated by using a 200-MeV proton beam on a heavy-metal target in a target station, which is consisted of a target, moderator, reflector, and biological shields, and a part of the high-energy neutrons are guided in a forward direction to make neutron beams with the atmospheric-like energy spectrum. The conceptual design has 6 more thermal-neutron beamlines at the separation of 30 degrees for the fundamental research on neutron science. Here, we present the concepts of the target station and basic parameters regarding the neutron source.

INTRODUCTION

The source of neutrons was mostly research reactors in the 20th century, part of them still play a key role as neutron science facilities. However a large fraction of the research reactors have been or will eventually be shut down, as a result, many capabilities are being lost as the number of neutron sources in the world decreases [1].

In the late 20th century, some national laboratories started the study of accelerator-driven neutron sources (ADNS) in order to substitute for reactor-driven neutron sources, and finally, the accelerator-driven system becomes the mainstream of neutron science facilities over the world (Fig. 1).

Figure 1: World-wide facilities that can produce neutrons and provide external users with irradiation or analysis services. There are more accelerator-driven neutron sources although only major facilities are shown in the picture.

At the Korea Multi-purpose Accelerator Complex (KOMAC) of Korea Atomic Energy Research Institute (KAERI), we are studying neutron sources based on the 100-MeV proton linear accelerator [2] and we have started planning for the construction of a new ADNS for neutron science. The potential users of the KOMAC neutron source include physicists, chemists and material scientists as well as semiconductor-device manufacturers, who belong to the major industry fields in Korea, therefore, it features an atmospheric-like neutron beam like in the ChipIR at ISIS of RAL and the ICE house at WNR of LANSCE besides thermal neutron beams. Here, we present the conceptual design of a target station for neutron production and its performance estimated in Monte Carlo simulations.

TARGET STATION

In the conceptual design of the KOMAC neutron source (Fig. 2), high-energy neutrons are produced by a 200-MeV proton beam on water-cooled tantalum targets. In a target assembly, 10 mm-thick rectangular-shaped tantalum plates are placed in a row to increase cooling efficiency. Three Ta plates after a proton beam window are sufficient to stop the incident proton beam because the range of 200-MeV protons in tantalum is 30.6 mm. Nevertheless, more Ta plates may be so inserted into the target assembly that high-energy primary neutrons from (p,xn) can make more secondary neutrons via (n,xn).

One of the applications of the neutron source is testing semiconductor devices for single-event effects induced by atmospheric neutrons, therefore, the part of the high-energy neutrons emitted in the forward direction are guided and extracted as atmospheric-like neutron beams through beam ports at 25 degrees without moderation. On the other hand, a room-temperature light-water moderator is placed above the targets to produce thermal neutrons, and the moderator is surrounded by a graphite reflector with a radius of 35 cm. The moderator is so placed at a higher level than the targets that the sample station at the end of thermal neutron beamlines does not look the targets. Thermal neutron beamlines are located at an interval of 30° from 60° with respect to the proton beam axis.

The target station employs a plug-socket concept in consideration of target replacement and maintenance like the second target station of the SNS at Oak Ridge National Laboratory (ORNL) [3]. The target assembly sits on a target trolley which can move to a pit for target maintenance. The whole reflector including the upper part of the shielding could be detached from the target station. The present design has only a light-water moderator in the heart of the graphite

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reflector, but the design might be modified to contain more or other types of moderators when necessary.

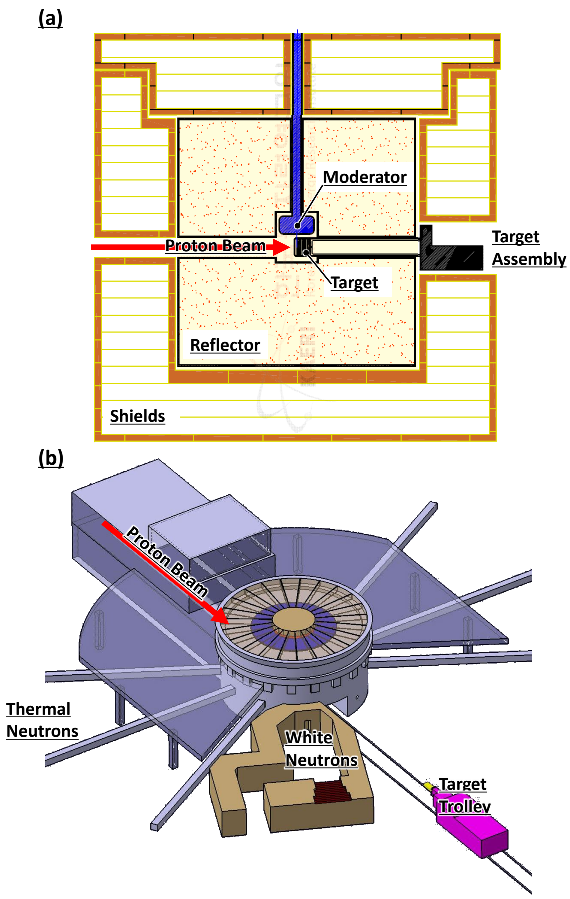

Figure 2: (a) The conceptual interior of the target station composed of heavy-metal targets, light-water moderator, graphite reflector, and concrete shielding. (b) The present exterior design of the target station has one white neutron beam line and experimental hall, and 6 thermal neutron beam lines.

NEUTRON CHARACTERISTICS

The neutron-beam characteristics at 25° and 60° beam ports were calculated with MCNP6.2 [4]. Complicated geometries were converted into Monte Carlo input codes with the help of SuperMC [5, 6]. At the incident proton energy of 200 MeV, the neutron yield is estimated to be around 1.5 n/p, giving the neutron-source intensity of 4.7×10^{13} n/s/kW. Calculated neutron energy spectra in the neutron beam lines are shown in Fig. 3. In the Fig. 3(a), the analytic model for describing the energy spectrum of atmospheric neutrons in New York City [7] is employed. At the 25° beam port, the flux of high-energy neutrons above 10 MeV is 2.2×10^6 n/cm^2/kW while the total neutron flux is 7.9×10^6 n/cm^2/kW. On the other hand, the thermal neutron flux at the beam port at an angle of 60° is 9.5×10^5 n/cm^2/kW while the total neutron flux is 2.2×10^6 n/cm^2/kW.

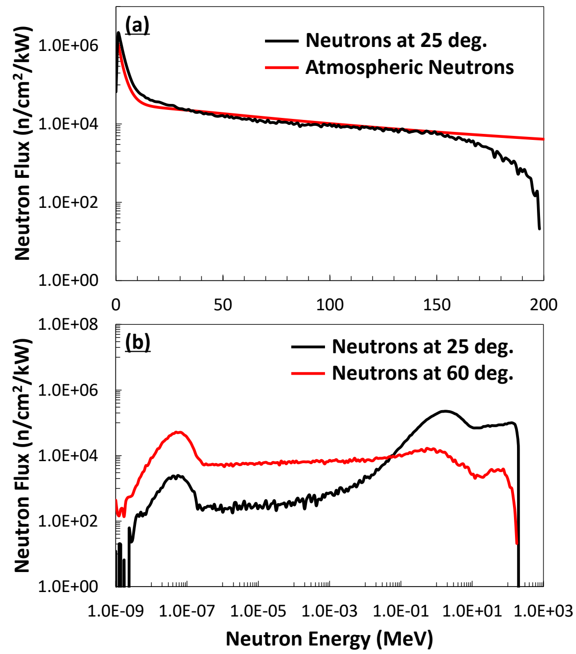

Figure 3: (a) Neutron energy spectrum at the 25° beam port in comparison with the reference atmospheric neutron spectrum in Ref. [7], and (b) neutron energy spectra at 25° and 60° beam ports on a logarithmic scale.

SHIELDING AND ACTIVATION ANALYSIS

Calculations concerning shielding and activation analysis were conducted with MCNP6.2 and PHITS3.23 [8]. The goal of the shielding calculations was finding the minimum radius of concrete shielding to achieve surface neutron dose rate of 12.5 µSv/hr when a 20-kW 200-MeV proton beam bombards the Ta targets. In this endeavour, neutron dose rates in beam-on-target condition were estimated as a function of the radius of the cylindrical shielding (Fig. 4(a)). A neutron tally was placed at the surface of the shielding, and ANSI/ANS-6.1.1 flux-to-dose conversion factors were invoked in for dose-rate calculations (Fig. 4(a)). The number of histories to achieve relative error of 10% at a 4-meter shielding was 2×10^{11}, and an one-meter increment of the shielding required roughly 20 times more histories for the same relative error. Because of huge computing time with thick shielding, dose rates beyond 4 meters were extrapolated from the trend between 0.5 and 4 meters. With the 6-meter shielding, the surface neutron dose rate was 12.7 µSv/hr, which is close to the goal but not sufficiently small considering the relative and systematic errors in the calculations. The shielding material was the ordinary concrete with mass density of 2.3 g/cm^3 [9], therefore it is possible to introduce heavier concrete or heavy-metal layers in the shielding structure to reinforce shielding capability. With the ordinary concrete shielding, the target station weighs 2 ktons.

Energetic primary and secondary particles can produce various radioactive isotopes along their flight paths, especially the Ta targets are the most hot components in the target station. The total radioactivity and the activity

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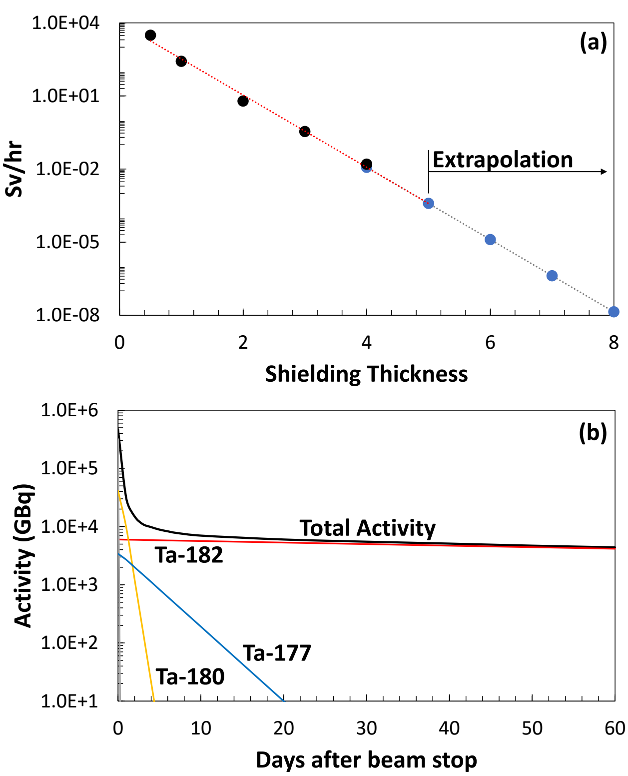

Figure 4: (a) Surface neutron dose rates at zero degrees as a function of the radius of the cylindrical shield. Dose rates up to 4 meters were calculated then values at thicker shields were extrapolated from the trend. (b) Radioactivity of Ta discs with respect to time after beam stop due to radioactive isotopes produced by proton- and neutron-induced reactions in the targets. See texts for details.

of individual isotopes are shown in Fig. 4(b) as a function of elapsed time after the shut down of the proton beam. After the 24-hour irradiation of a 20-kW proton beam, the total radioactivity of the targets is expected to be around 12,700 Ci (= 4.7×10^5 GBq). Dominant isotopes contributing to the total radioactivity are mostly Ta isotopes, ^{174,177,180,182,182m}Ta, and other nearby nuclides such as Lu, Hf, and W. Radioactivity right after the beam stop is dominated by ^{182m}Ta [$T_{1/2}$ = 283 ms], which is produced by (n,γ) in the targets. Because of the half-life, the number of ^{182m}Ta rapidly decreases, then ^{180}Ta [$T_{1/2}$ = 8.154 h] dominates the target radioactivity until the activity of the ^{180}Ta falls below that of the ^{182}Ta [$T_{1/2}$ = 114.74 d]. Although ^{177}Ta [$T_{1/2}$ = 56.56 h] has longer half life than ^{180}Ta, ^{177}Ta does not contribute significantly to the total radioactivity. In the above irradiation condition, it is found that ^{182}Ta is the main source of the target activity after a day of cooling time with the initial activity of A_0 = 162 Ci (= 6.0×10^3 GBq).

CONCLUSION

We presented the conceptual design of the neutron target station, and its performances estimated based on Monte Carlo simulations. The target station is composed of Ta targets, light-water moderator, graphite reflector inside the thick concrete shielding, providing the integrated flux of atmospheric-like high-energy neutrons and thermal neutrons in the order of 10^6 n/cm^2/kW. The shielding calculations for a 20-kW proton beam imply that the target station requires massive shielding for the surface neutron dose rates of 12.5 µSv/hr, and the results of activation analysis intimate that remote handling system is necessary for target exchange and maintenance. The present picture of the target station is an initial sketch of the neutron facility at KOMAC so only the major issues were discussed in the manuscript. Many other components missing in the sketch need to be included in the future design, and it needs further extensive reviews in the aspects of science, technology, and economy for the successful planning and construction.

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