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Neutronics analysis of uranium compounds spallation target using Monte Carlo simulation

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A B S T R A C T

In this paper, we investigated the neutronics performance of uranium carbide (UC), uranium nitride (UN) and uranium dioxide (UO2) monolith targets and granular targets by using GPU-based Monte Carlo particle transport program (GMT). Effects of the target thickness and diameter on leaked neutron yield of monolith targets irradiated by 1 GeV protons were studied; the leaked neutron yield and neutron spectra for the dense granular uranium compounds and UC-kernel TRISO type targets were presented. Results show that, with an optimal dimension $\phi 25 \times 50$ cm, uranium compounds target can produce 40% more leaked neutron yield than the tungsten target. Results also show that by 1 GeV protons incident on, our designed carbon and SiC layers coated UC-kernel TRISO type pellets target with about 70% kernel volume fraction can produce about 30% more leaked neutron yield than the granular tungsten target in their optimal diameters.

1. Introduction

In recent years, accelerator-driven systems have been widely developed for scientific research, industrial and medical applications (Cho, 6043; Bowman et al., 1992; Mason et al., 2005; Angelone et al., 2002; Zavorka et al., 2015). One of an important application is the accelerator-driven sub-critical system (ADS), which is proposed to produce high flux neutrons to transmute long-lived radioactive nuclei of spent fuel. In order to attain high enough neutron flux, MW-scale proton accelerator is demanded for the transmutation demonstration and an at least 10 MW beam power is required for the industrial scale transmutation (Abderrahim et al., 2010).

At present, there are mainly two kinds of spallation targets in the world, the solid target and the heavy-liquid-metal (HLM) target. For the traditional solid target (Schnberger, 1993), the heat removal is carried out mainly by the heat conduction between the target material and the convection cooling fluid. Consequently, the potential to increase the target power is significantly limited, and some new target modules have been proposed for higher power accelerator, such as plate target in ISIS and CSNS (Nunomiya et al., 2001; Yin et al., 2011), rod target in SINQ Blau et al., 2009, rotating target design in SNS (McManamy et al., 2010), which is devoted to enlarge the surface of target with cooling fluid and then improving the target power. Concerning the liquid corrosion and the chemical toxicity of the HLM target (McManamy et al., 2001; Ikeda, 2005; Bauer et al., 2001), the target operation system is very complex and costly. In addition to those targets, a gravity-driven Dense Granular flow Target (DGT) has been proposed for Chinese ADS (Yang et al., 2015). The DGT with an optimal target diameter can produce the same maximum neutrons per proton as the monolith target does, and flowing target pellets can bring the thermal power out of the beam irradiation region, thus can significantly improve the target power. Gravity and mechanical hoisting plant can provide motives to transfer the target pellets in a loop movement. Therefore, the DGT can broaden the choices of material for the spallation target.

In this paper, we aim to investigate the neutronics performance of UC, UN and UO2 materials for monolith target, granular target and TRISO type mixture pellets target. The effects of the target diameter and thickness on the leaked neutron yield are examined for monolith target. The effects of the target diameter and mixture ratio of TRISO type pellets on the laterally leaked neutron yield and the laterally leakage neutron spectra are investigated. The average gas production of TRISO-type pellets target and tungsten pellets target in a loop system is also calculated and discussed.

2. Materials and methods

Generally, tungsten is deemed to be one of the most ideal target material due to its suitable physical properties and relative high neutron yield. Despite the fact that the neutron yield of ^{238}U is remarkably higher than that of the tungsten (Hashemi-Nezhad et al., 2011; Feghhi

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Table 1
Some properties of the materials discussed in the investigation (Benjamin, 1983).

Materials	W	^{238}U	UC	UN	UO2
Molar mass (g/mol)	183.84	238.03	250.04	252.04	270.03
Density (g/cm^3)	19.25	19.1	13.63	14.32	10.97
Melting point (K)	3695	1405	2620	3108	3138
thermal conductivity [w/(cm K)]	1.73	0.275	0.25	0.16	0.06

et al., 2014), the melting point of the former is rather low and the irradiation stability is not optimal. To enhance neutron yields of the spallation target, we studied the neutronics performance of the UC, UN and UO2 targets which have relatively high melting points (in the range of 2500 ~ 3000 K) and have already been widely adopted in nuclear engineering designs. Other advantages of those uranium compounds are as follows: (1) As non-fissile elements, carbon, nitrogen and oxygen elements have very low thermal neutron capture cross-section; (2) Those uranium compounds have good irradiation stability to keep size and shape stable under long time irradiation; (3) The problems induced by anisotropy can be avoided by their isotropic properties. Table 1 lists some representative properties of these materials.

In this article, the calculations of the spallation reaction are performed using the GPU-based Monte Carlo particle transport program (GMT) (Cai et al., 2016), which uses the Intra-nuclear Cascade of Liege (INCL) model (Boudard et al, 2002) and the ABLA evaporation/fission model (Junghans et al., 1998). Results obtained by the INCL_ABLA with transport code agree well with the experimental results in a wide range of observed variables (Boudard et al, 2002). When neutron energy is below 20 MeV, the evaluated data library ENDF/B-VII.1 (Chadwick et al., 2011) is used for accurate simulation for low energy neutron transportation. INCL_ABLA model predicted neutron production and mass distributions of ^{238}U fission products also have demonstrated a good agreement with the experimental data (Malyshkin et al., 2012). Concerning a Monte Carlo particle transport simulation, the delta-tracking method has been used as an optional technology (Woodcock et al., 1965), which is more powerful in simulations of complex geometries and more efficient to simulate the particle transport in huge number pellets target than the commonly used ray-tracking approach (Lux and Koblinger, 1991).

3. Results and discussion

3.1. Leaked neutron yields of monolith targets

In this part, we investigated the effects of the target diameters and the target thickness on neutron leakage yield of the cylindrical monolith targets of tungsten, uranium and the three uranium compounds materials mentioned above. The proton beam energy is adopted as 1.0 GeV and beam spot is annular distribution with diameter as 10 cm. Firstly, we investigated the effects of target diameters on leaked neutron yield from the surface of the cylindrical targets, with a fixed target length 60 cm. The results are shown in Fig. 1. It is obvious that the leaked neutron yield is increasing with the growth of the target diameter, and reaches a peak when the target diameter is about 20 cm (25 cm) for tungsten target (uranium and uranium compounds target).

Secondly, we fixed the tungsten target diameter as 20 cm, uranium and uranium compounds target diameter as 25 cm to investigate the effect of target thickness on leaked neutron yield, the results are shown in Fig. 2. From the plots, it can be seen that neutron leakage yield is increasing rapidly up to maximum at about 30 cm for tungsten and uranium target, and at about 50 cm for UC, UN and UO2, this is mainly due to the higher density of tungsten and uranium target. As the thickness grows larger, the neutron leakage yield keeps stable, this is because of the competition of spallation reaction, (n, xn) and (n, fission) reactions with neutron capture reaction. From these results, the optimal dimension is 20 × 50 cm for tungsten target and about 25 × 50 cm for uranium and uranium compounds targets for 1 GeV protons irradiation. Table 2 gives the neutron leakage yield from the three sides of the cylinder in the optimal size of those surveyed targets, the total neutron leakage yield of the uranium target is the highest, next are UC, UN and UO2 targets. Tungsten target produces the lowest neutron leakage yield, and UC, UN, UO2 material targets can produce 64.8%, 57.4%, 40.2% respectively higher neutron leakage yield than tungsten target with their corresponding optimal target dimensions. Therefore, using uranium compounds targets is a very effective option for the spallation target to improve the leaked neutron yield.

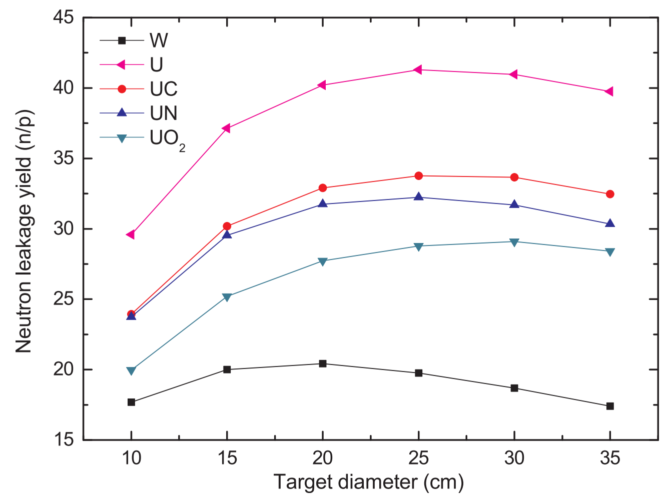

Fig. 1. Neutron leakage yield from different materials as a function of target diameter, with the target thickness fixed as 60 cm.

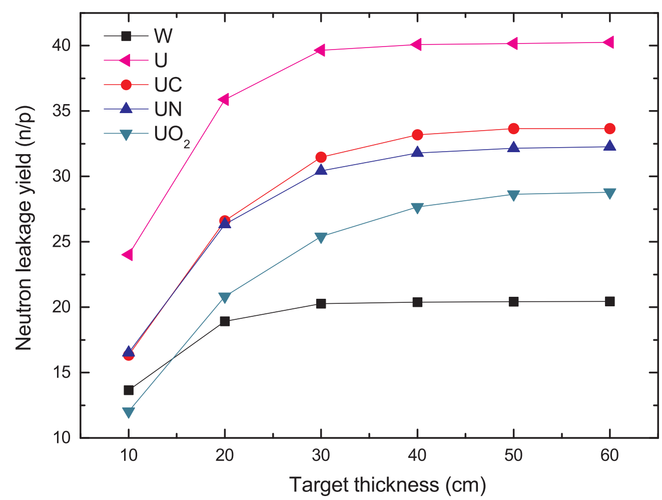

Fig. 2. Comparison of neutron leakage yield in effect of target thickness, with the diameter of tungsten target fixed as 20 cm and other targets as 25 cm.

Table 2
Neutron leakage from the three sides of different targets in their corresponding optimal sizes.

Target material	Optimal size	Leaked (n/p)	Side (n/p)	Forward (n/p)	Backward (n/p)	Side/ leaked (%)
W	20*50	20.43	15.09	0.042	5.300	73.9
UC	25*50	33.66	25.13	0.486	8.046	74.6
UN	25*50	32.16	23.66	0.377	8.123	73.6
UO2	25*50	28.64	21.83	0.694	6.118	76.2
U	25*50	40.16	28.14	0.227	11.790	70.0