Journal of Nuclear Materials 431 (2012) 39–43

Contents lists available at SciVerse ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

The expected radiation damage of CSNS target

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ARTICLE INFO

Article history:
Available online 13 November 2011

ABSTRACT

The radiation damage to the tungsten target and its SS316 vessel for Chinese Spallation Neutron Source (CSNS) has been estimated with a Monte-Carlo simulation code MCNPX2.5.0. We compare the effects on the radiation damage due to two different proton beam profiles: a uniform distribution and a Gaussian distribution. We also discuss the dependence of the radiation damage estimation on different physics models. The results show the peak displacement productions in vessel and the fourth target plate are 2.5 and 5.5 dpa/y, respectively, under a Gaussian proton beam. The peak helium productions in the vessel and the fourth target are 305 and 353 appm/y, respectively, under the same proton beam. Based on these results and the allowable dpa values we have estimated the lifetime of the tungsten target and its vessel.
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1. Introduction

The Chinese Spallation Neutron Source (CSNS) project is a 100 kW-level spallation neutron source with a proton energy of 1.6 GeV [1,2] on day one. When the facility is operating, the tungsten target and its stainless steel vessel are the most heavily exposed components to the high-energy particle flux and therefore their radiation damage is very severe. It is important to evaluate the radiation damage induced by high-energy protons and neutrons, which gives the basic data to assess the lifetime of the materials. These analyses are required to determine the frequency of remote handling for target and its vessel, the potential site contamination and costs.

Radiation damage energy is the energy transferred through nuclear interactions to the target nuclei. The spallation-induced radiation damage is mainly due to the displacements of the particles from the lattice. At the same time, the non-elastic reactions, which produce many new light particles and also new heavier species [3].

In order to quantify the target damage due to the proton and neutron irradiation we considered the following quantities: (i) nuclear heating due to proton, neutron and gamma interactions with the nuclides; (ii) radiation damage in terms of displacements per atom (dpa); (iii) helium and hydrogen production.

In this paper, we focus on calculating the second and the third quantity for the CSNS target and its vessel with MCNPX 2.5.0 [4]. The target material is tungsten (density = 19.3 g/cm^3) and the material of its vessel is stainless steel SS316 (density = 8.0 g/cm^3) with composition of Si 1 wt%, Mn 2 wt%, Cr 15 wt%, Ni 12 wt%, Mo 2.5 wt% and Fe 67.5 wt%. On the base of the results we estimate the lifetime for these components.

2. Displacement and gas production cross sections

The cross sections of displacement per atom and gas production are often different due to the use of various physics models and codes. In this paper, the physics models and the tabular nuclear data used for calculating the cross sections of tungsten and stainless steel are given in Table 1.

The displacement production and gas production cross sections are obtained by calculating the damage energy, the helium and the hydrogen production in a thin target bombarded by a proton/neutron beam at high energies. At low energies, the standard ENDF/B-VI and LA150n format provides the reaction identifiers for damage energy cross section, ^{1}H, ^{2}H, ^{3}H, ^{3}He, and ^{4}He production cross section as 444, 203, 204, 205, 206, and 207, respectively. In this paper, for En < 150 MeV, we use MCNPX tally 4 F4 capability along with tally multiplier card FM to extract the neutron-induced damage and gas production cross sections [4]. And for En > 150 MeV, we use HTAPE3X and XSEX3 to analyze the history file produced by MCNPX to obtain these cross sections [4]. We run 10^6 histories for each cross section calculation. The displacement production cross section depends on the damage energy and on the energy required to displace an atom from its lattice position E_d. Since the damage energy is shared equally between two atoms after the first collision, the displacement cross section is defined as [5]

$$\sigma_{displacement} = \frac{\beta}{2E_d}\sigma_{damage}, \quad (1)$$

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doi:10.1016/j.jnucmat.2011.11.025

Table 1
The physics models and the tabular nuclear date used for cross sections calculations.

Material	Particle	Energy range $E < 20$ MeV	Energy range $20 < E < 150$ MeV	Energy range $E > 150$ MeV
Tungsten	Neutron	ENDF/B-VI	LA150n	CEM2K
	Proton	LA150h	LA150h	CEM2K
SS316	Neutron	ENDF/B-VI	LA150n	Bertini/Juelich/MPM on
	Proton	LA150h	LA150h	Bertini/Juelich/MPM on

where $\beta = 0.8$ deviation from a hard sphere, which compensates for forward scattering in the displacement cascade. E_d is the threshold displacement energy, for W and SS316 this values are 90, 40 eV, respectively.

Fig. 1 gives the damage energy and gas production cross section σ_{damage}, σ_{Helium} and $\sigma_{Hydrogen}$ of SS316 and tungsten. These results agree well with Lu's results in Refs. [3,6].

3. The evaluation of radiation damage of the CSNS target

The particles transport analysis for the CSNS target and its vessel is performed using the geometrical layout shown in Fig. 2. The target is composed of a set of tungsten plates of 130 mm (width) by 50 mm (height). These plates have different thicknesses as determined by the previous thermal hydraulic analysis of the target. There are 1.5-mm-thick heavy water channels between these target plates. The thickness of the target vessel is 10 mm, but for its window the thickness is 2 mm mainly for reducing thermal stress.

The most severe damage is located at the front five target plates and the target vessel window because they are the most heavily bombarded by the proton beam. The radiation damage is a combined effect of proton and neutron fluxes. After considering that the fourth target plate has the highest neutron flux and high proton flux, we calculate the damage quantities of the fourth target plate and the target vessel window. For understanding the effect of the proton beam intensity on the radiation damage of the target and its vessel, we consider two proton beam profiles. One is uniform with 120 mm in width and 40 mm at height. The other is a Gaussian with a horizontal full width half maximum (FWHM) of 66 mm and a vertical FWHM of 22 mm. Here we use small tally areas of 5×5 mm^2 at the center of the target vessel window and the fourth target plate to estimate the maximum damage of the vessel and the target. Fig. 3 gives the proton intensity distribution at the vessel window under these two proton beam profiles.

Fig. 4 shows the neutron and proton flux spectra at the vessel window and the fourth target plate bombarded by the uniform and Gaussian proton beams. Here we notice that the proton fluxes are strongly dominated by the high-energy incident protons. We calculate the displacement and gas production by folding the neutron and proton fluxes into the radiation damage cross sections. These calculations assume a proton beam power of 100 kW and 5000 h in one operating year. The results show the maximum displacement productions at the vessel and the fourth target plate are 2.5 and 5.5 dpa/y, respectively, under the Gaussian proton beam and are 1.3 and 2.2 dpa/y, respectively, under the uniform proton beam. The maximum helium productions at the vessel and the fourth target are 305 and 353 appm/y, respectively, under the Gaussian proton beam and are 105 and 123 appm/y, respectively, under the uniform proton beam. The ratio of the helium production to the displacement production for SS316 vessel is 80 appm/dpa under the uniform proton beam and that is 122 appm/dpa under the Gaussian proton beam. The ratio of the helium production to the displacement production for tungsten is 56 appm/dpa under the uniform proton beam and 64 ammp/dpa under the Gaussian proton beam. The maximum hydrogen production in the vessel and the fourth target are 1115 and 2141 appm/y, respectively, under the Gaussian proton beam and are 337 and 768 appm/y, respectively, under the uniform proton beam. The high amounts of helium and hydrogen result in swelling and degradation in ductility of the material.

4. Discussions

We have calculated the radiation damage quantities for the 100 kW-level CSNS target and its vessel. We notice that the current displacement production of the target is somewhat higher than our previous results (see Ref. [7]). In Ref. [7], the maximum displacement production is 1.48 dpa/y for the target compared to 2.2 dpa/y in this paper. The discrepancy mainly comes from the choice of the tally area and the physics model in calculating the cross sections. In this paper we use a much smaller tally area at the center of the fourth target plate. The damage energy cross sections calculated by CEM2 K are generally higher than those by Bertini-GCCI physics model in Ref. [7]. The cut-off energy from the intranuclear cascade in CEM2K is sufficiently low rather than 7 MeV as in Bertini model [6]. Fig. 5 compares the damage energy cross sections calculated by the two physics models. As mentioned above, the proton fluxes are strongly dominated by the high-energy incident protons whose energy is around 1–1.6 GeV. Thus when we use the damage energy cross section calculated by CEM2K, the displacement production induced by proton will be much higher. These two factors result in 30% higher displacement production for the target in the current calculation.

For estimation of the lifetime of the target and its vessel, it is very important to determine the allowable displacement for tungsten and SS316. It is difficult to determine the allowable displacement since we do not have any experimental data under CSNS condition. Los Alamos Neutron Science Center (LANSCE) had measured the tensile properties of annealed 304L, 316LN, 316L after these stainless steel were irradiated to a maximum dose of 12 dpa at temperatures ranging from 30 to 120 °C [8]. LANSCE also had made the compression tests of the tungsten rod after it was irradiated up to 23.3 dpa at temperatures ranging from 50 to 270 °C [9]. These results show an increase in tensile strength and a reduction in ductility of the materials after irradiated by high-energy proton beams. These data can be used in the structural design for our target and vessel. If we consider the allowable displacement for tungsten is 23.3 dpa and the allowable displacement production for SS316 is 10 dpa based on the above experimental results, the lifetimes of the target and its vessel are about 4–5 years under a Gaussian proton beam. For a Gaussian-type proton beam, it is also important to find the peak damage of the vessel window and the target, which strongly depends on the proton beam profile. This conclusion means we need pay attention to the following factors in our initial design: (1) the appropriate choice of the radiation damage cross sections; (2) the proton beam profile, especially peak intensity; (3) the appropriate choice of the allowable displacement rate of the materials under the operation condition of the target. These three factors have a very important effect on the lifetime estimation of the components.

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