Radionuclide production and dose rate estimation during the commissioning of the W-Ta spallation target

Q Z Yu¹ and T J Liang¹

¹ Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China

qzyu@iphy.ac.cn

Abstract. China Spallation Neutron Source (CSNS) is intended to begin operation in 2018. CSNS is an accelerator-base multidisciplinary user facility. The pulsed neutrons are produced by a 1.6 GeV short-pulsed proton beam impinging on a W-Ta spallation target, at a beam power of 100 kW and a repetition rate of 25 Hz. 20 neutron beam lines are extracted for the neutron scattering and neutron irradiation research. During the commissioning and maintenance scenarios, the gamma rays induced from the W-Ta target can cause the dose threat to the personal and the environment. In this paper, the gamma dose rate distributions for the W-Ta spallation are calculated, based on the engineering model of the target-moderator-reflector system. The shipping cask is analyzed to satisfy the dose rate limit that less than 2 mSv/h at the surface of the shipping cask. All calculations are performed by the Monte carlo code MCNPX2.5 and the activation code CINDER’90.

1. Introduction

The China Spallation Neutron Source (CSNS), currently under construction in Dongguan, Guangdong Province, will use a 1.6 GeV proton beam of 100 kW power to produce neutrons in a tantalum (Ta)-cladded tungsten (W) target [1,2]. There are approximately 30 neutrons released per incident proton, resulting in a total neutron source of \(-1 \times 10^{16}\) n/s. 20 neutron beam lines are designed to export the produced neutrons for the experimental measurement [3,4]. But nonetheless, only a small fraction of these neutrons is successfully directed out of the target station. The major produced neutrons slow down and eventually get absorbed in the spallation target, the moderators, the reflectors and even in the biologic shielding, causing intense radiation damage and activation of these components [5-7]. Radiation damage caused by these produced neutrons, as well as that caused by the primary protons and the secondary produced particles, limits the life time of these components [8,9]. Some of these components such as the W-Ta spallation target and the moderators, need to be maintained or replaced regularly. Since these components are highly activated and can emit intensive decay gamma-rays, shipping casks used for transporting off-site of the damaged components are needed to ensure the personal safety. Once the radiation assessment for the maintenance scenarios of CSNS inner reflector plug was performed and analyzed [10]. The dose rate distributions and the shipping casks used to transport these activated components are also calculated and designed.

In this paper, we are aim to present the gamma dose rate distribution of the W-Ta spallation target irradiated by a high-energy proton accelerator. The thickness of the shipping cask used to transport the spallation target is calculated. The induced residual nuclei and the decay gamma rays are also analyzed. All these calculations are based on the target-moderator-reflector (TMR) engineering model.

2. Calculation code and method
To calculate the gamma dose rate and the shipping cask for the W-Ta spallation target, the Monte Carlo code MCNPX2.5 [11], the activation code CINDER’90 [12], the Activation Script and the Gamma-source Script [13] were used. The calculation sequence is illustrated as follows. Firstly, MCNPX2.5 is used to simulate the spallation reaction taken place in the TMR system. Bertini intranuclear cascade model coupled with Rutherford-Appleton Laboratory (RAL) evaporation-fission model was used to determine the spallation products for high energy interactions (E>20MeV). The evaluated nuclear data library ENDF-B/VI was used to calculate the low energy neutron (E<20MeV) fluxes in a 63 energy group structure. Secondly, the activation code CINDER’90, which solves the Bateman equations and deduces the time dependence of isotope buildup and decay, was used to calculate the activity, decay heat and induced gamma ray in a 25 energy group structure. Thirdly, an Activation Script provides the interface between MCNPX2.5 and CINDER’90, providing the residual gamma rays in the interested cells, corresponding to an irradiation time and a cooling time. And a Gamma Source Script was used to extract the induced gamma ray information as a new source file, including each cell number, intensity, spectrum, and space position. Lastly, MCNP4C was used to transport these induced gamma rays, for the gamma dose rate and shipping cask calculations that are aimed to perform in this paper.

3. Geometry of the 100 kW W-Ta target
The geometry models of the 100 kW CSNS W-Ta target and the TMR system are shown in Figure 1 (a) and (b), which are near to the engineering models [2]. This W-Ta spallation target is 17 cm wide, 7 cm high and 66.86 cm long. It consists of 11 W plates, each is surrounded by 0.3 mm thickness Ta claddings. The total length of the W plates is 67.1 cm, ensuring complete stopping of the 1.6 GeV protons in the target. There are 12 cooling water channels with 1.2 mm width between these W-Ta plates, which are used to remove the deposited nuclear heat in the spallation target. On the four sides of the W-Ta target, there are four water channels guiding the cooling water flows. SS316 steel with 1.0 cm thickness, is used as the target vessel. On the nose of the target, a 0.25 mm thickness Cr:Al₂O₃ luminescent coating is used to measure the incident proton beam profiles in real time.

The coupled hydrogen moderator (CHM) is arranged under the spallation target, while the decoupled water moderator (DWM) and the decoupled and poisoned hydrogen moderator (DPHM) are on the spallation target. Around the spallation target and the three moderators, a 27 cm in radius, 70 cm high beryllium (Be) cylinder is used as the inner reflector. Outside the Be reflector, a 47 cm in radius, 100 cm high iron (Fe) cylinder is used as the outer reflector. 3 cm thinkness aluminum is used as the container of the reflectors. Outside the Be/Fe reflectors is the biologic shielding. Although Fig. 1 (a) and (b) are the MCNPX models for the W-Ta spallation target and the TMR system, detailed geometries of each component can be seen, including the claddings, coatings, pipes, gaps, void spaces and so on.

![Fig. 1 MCNPX models for (a) W-Ta spallation target and (b) TMR system at CSNS.](image-url)
All calculations are based on a 1.6 GeV, 100 kW (3.9×10^{14} p/s), 25 Hz proton beam irradiation the W-Ta spallation target. The footprint of the proton beam profile is 16 cm width and 6 cm high, with double Gaussian distributions of 9.42 cm and 3.53 cm full width at half maximum (FWHM) in x and z directions. The target is irradiated with full proton beam power for 5 years (5000 h/y). After 7 days cooling by air, it will be taken to the hot cell for replacement, or transported by a shipping cask for maintenance. The acceptable dose rate at the surface of the shipping cask is limited to 2 mSv/h.

4. Calculation results

When high-energy proton beam irradiates a W-Ta target, intense spallation reaction takes place. Various high-energy particles (protons, neutrons, pions, etc.), low-energy particles (protons, neutrons, deuterons, tritons, 3He, alpha, etc.), and a wide range of residual nuclei are produced. The radioactive inventories and the induced gamma rays, will impact the personnel safety and the environment. The problems include when the W-Ta spallation target has to be maintained, transported, decommissioned and finally disposed. Detailed calculations and analyses about the residual nuclides, decay gamma rays, gamma dose rate distributions and shipping cask are shown below.

4.1 The residual nuclei

During the intense spallation process, a wide range of residual nuclei are produced in the W-Ta spallation target. The residual nuclei production rates in W plates, Ta claddings and SS316 containers are presented in Figure 2 (a), (b) and (c), respectively. The same color bars are used for the production rate comparisons. It can be seen that for each components, the produced residual nuclei cover from ^1H to the parent nucleus element. For an example, in the W plates, there are about 1500 nuclides produced during the spallation process. Some of the light nuclides with charge number less than 10, are produced via the evaporation process. A large number of medium nuclides with charge number between 30 and 50 are produced via the fission process. The high charge number nuclides, which are near the parents nuclides (Z=74), are produced during the cascades process. For the residual nuclides produced in Ta claddings and SS316 containers, their production mechanisms are similar, while the production rates are much lower than that in W plates.

Most of these residual nuclides are radioactive, releasing different energies of electrons, α, β particles and decay gamma rays, reaching their stable states eventually. Since the decay gamma rays are not charged but with high energies, it should be taken more attentions.

4.2 The induced gamma rays

![Fig. 2 (Color online) The produced residual nuclei in (a) W plates, (b) Ta claddings and (c) SS316 containers, as functions of residual charge number Z and residual neutron numbers N.](image)
As mentioned above, the produced residual nuclides in W-Ta spallation target are highly radioactive. These radio-nuclides can induce the decay gamma rays. We show here the decay gamma rays in the W plates as an example. Figure 3 (a) shows the gamma intensity in each W plate, corresponding to 5 years irradiation and 7 days cooling. It can be seen that the most intense gamma ray presented in the first W plate, reaching to ~8×10^{11} p/s/cm^3. The gamma intensity exceed ~10^{11} p/s/cm^3 for the 1~6 plates. It decreases rapidly along the target to ~8×10^{8} p/s/cm^3 at the last W plate. Figure 3(b) shows the induced gamma ray spectra in the 1, 4, 7, 10 W plates, respectively. The energy bin is according to the 25 energy-group that set in CINDER’90. It shows that most of the gamma rays are with energies less than 1 MeV, while a considerable portion has energy at several MeV. These high-energy gamma rays, can transport in the W-Ta spallation target to the outside region.

4.3 Gamma dose rate distribution and shipping cask

Although the self-shielding effect in the W-Ta target, the high-energy gamma rays can penetrate the target itself to the out region, causing the gamma dose rate threat to the personal and the environment. A shipping cask is needed to shield the target during its maintenance or transportation. Figure 4 (a) is a MCNP4C geometry model of a Pb shipping cask for the W-Ta spallation target. A 2 cm air layer near the target is designed for the engineering consideration. It means that the Pb layer in calculation model, each Pb layer is set as 2 cm thickness, for the use of the variance reduction of the gamma rays. Figure 4 (b) is the gamma dose rate map for the W-Ta spallation target, in the x-y plane at z=0. It can be seen that in the W-Ta target, the most intense dose rate can reach ~10^6 mSv/h. At the surface of the target, the dose rate is ~10^5 mSv/h. This means that the induced gamma rays emitted from the activated W-Ta spallation target, can cause serious radiation threat to the surroundings. The shielding effect of Pb cask is needed during its close range operation. We can see the dose rate varies distinctly in the Pb layers. At the surface of the Pb cask, the dose rate decreases to 1.0 mSv/h.
For better analyzing the gamma dose rate distribution and the needed Pb thickness, we calculate the dose rate along x, y and z directions. Figure 5(a) shows the dose rate along x axis, at y from -8.95 cm to -6.65 cm (the thickness of the first W plate) and z=0. Figure 5 (b) shows the dose rate along y axis, at x from -5 cm to 5 cm and y from -8.95 cm to -6.65 cm. It can be seen that the dose rate in the W-Ta spallation target is higher than 1.0×10^6 mSv/h. The dose rate decreases exponentially in the Pb cask. Results show that at both x directions, 19.0 cm thickness of Pb is needed to decrease dose rate to 2 mSv/h at the surface of the Pb cask. At y direction, the dose rate variations in the W-Ta target can be seen. In front part of the spallation target, the dose rate exceeds 1.0×10^6 mSv/h. While at the back of the target, it is about 1.0×10^5 mSv/h. This causes the asymmetric dose rate distributions and different Pb shielding thickness. Calculation shows that 19 cm thickness Pb layer is needed in front of the target (-y direction), while 15.4 cm Pb layer is required at the backend of the target (+y direction). At both z directions, the dose rate distributions are symmetric. 21 cm thickness Pb is needed to satisfy the dose rate limitation. By calculating the dose rate distributions, the dimensions of a shipping cask can be determined.

5. Conclusion
The CSNS facility is intended to be operation in 2018. Due to the W-Ta spallation target is the most activated components in the target station, its commissioning is essential for the progress of the whole project.
Calculations have been carried out to determine the gamma dose rate around the W-Ta spallation target, which was irradiated by a 1.6 GeV proton beam with 100 kW beam power. Due to the intense spallation reactions, various particles and radio-nuclides are produced. The decay gamma rays induced from the radioactive inventories, can transport out of the W-Ta target itself, resulting the dose rate distributions around the target. It shows that the dose rate can reach ~10^6 mSv/h in the center of the W-Ta spallation target. At the surface of the target, the dose rate is at the level of ~10^5 mSv/h. Such kind of dose rate can cause a serious threat to the personnel during the close operation of the activated target. It also means that after a long time irradiation of the W-Ta spallation target, a shipping cask is needed to decrease the dose level to the safety range. Calculation shows that 19 cm thickness Pb shipping cask is needed to decrease the dose rate to 2 mSv/h limitation at the surface. These results and analysis are essential for the commissioning of the W-Ta spallation target.

**Acknowledgement**
This work was supported by the National Science Foundation of China (Grant Nos. 11575289 and 11174358).

**References**
[1] http://csns.ihep.ac.cn/english/index.htm.
[2] Wei J, Chen H S, Chen Y W., et al., China Spallation Neutron Source: design, R&D, and outlook, Nucl. Instr. Meth. Phys. Res., A 600 (2009) 10.
[3] Wang F W, Liang T J., Yin W, Yu Q Z, et al., Physical design of target station and neutron instruments for China Spallation Neutron Source, Sci. Chin. Phys. Mech. Astron. 56 (2013) 2410.
[4] Yu Q Z, Yin W, Liang T J, A physical design of a neutron irradiation spectrometer at CSNS facility, 11th International Topical Meeting on Nuclear Applications of Accelerators, AccApp (2013)55-59
[5] Yu Q Z, Liang T J and Yin W, Activity and radiation protection studies for the W-Ta target of CSNS, Radiat. Prot. Dosimetry, 136 (2009) 216–221.
[6] Yin W, Liang T R, Shen F, Wang S L, Yu Q Z and Liang T J, Shielding calculation for CSNS target station, Progress in Nuclear Science and Technology, 4(2014) 210.
[7] Yu Q Z, Liang T J, Yin W and Yan Q W, Induced radioactivity in components of CSNS target station, PSI Proceedings, (2009) 164.
[8] Yu Q Z, Yin W, Liang T J, Calculation and analysis of DPA in the main components of CSNS target station, Acta Phys. Sin. 60 (2011) 052501-8.
[9] Yin W, Yu Q Z, Lu Y L, Wang S L, Tong J F and Liang T J, The expected radiation damage of CSNS target, J. Nucl. Mater., 39 (2012) 431.
[10] Yu Q Z, Hu Z L, Zhou B, et al., The radiation assessment for the maintenance scenarios of CSNS inner reflector plug, Progress in Nuclear Science and Technology, 4 (2014) 376-379.
[11] MCNP/MCNPX CCC-730, Monte Carlo N-Particle Transport Code System Including MCNPX 2.5.0 and Data libraries, (2006).
[12] Wilson W B, England T R and Van R K A, Status of CINDER’90 Codes and Dat, LA-UR-99-316, Los Alamos National Laboratory, (1999).
[13] Gallmeier F X, Wilson W L, Wohlmuther M, et al., An environment using nuclear inventory codes in combination with the radiation transport code MCNPX for accelerator activation problems, AccApp07, Pocatello Idaho, 2007, 207.