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Radiation damage/activity calculation for CSNS target station

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A B S T R A C T

The radiation damages have been performed for Chinese spallation neutron source (CSNS) target center components that relies on Monte Carlo simulation code MCNPX. During the calculation, Bertini intranuclear cascade model, three level-density formulation GCCI, and multistage pre-equilibrium model MPM on which are provided within MCNPX are employed. We calculate the displacement per atom (DPA) and afterheat of the tungsten target, the stainless steel target vessel window and the aluminum alloy moderator vessel. As a hundred kW-level source, these spallation center components have the lifetime more than 5 year. We also give the activity for the T0 chopper of the beam line HIPD to get the primary data for making out a maintenance scenario.

1. Introduction

In recent years, the spallation neutron sources, driven by proton accelerators have aroused great interest in many fields of science and technology and matured into the indispensable tools in these fields [1]. The CSNS (Chinese spallation neutron source) project is a 100 kW-level spallation neutron source in its day one and now is under progress of close cooperation between Institute of Physics (IOP) and Institute of High Energy Physics (IHEP) [2]. When a proton beam with its energy 1.6 GeV bombarded a tungsten target, the highest cascade neutron on the forward direction will approach the energy of the incident proton beam. Thus spallation damage is largely nonelasitc, producing many new light particles (such as helium and hydrogen) and new heavier species in form of transmutation products, which will exacerbate the displacement rate [3].

In this paper, we calculate the displacement per atom for CSNS target station components including the tungsten target, the stainless steel SS316 target vessel and the aluminum alloy A6061 moderator vessel. These results provide the basic data to estimate the lifetime of these components. At the same time, we give the activity and afterheat of the target, which provide the basic data for the disposal design of the irradiated target. High Intensity Powder Diffractometer is one of the three instruments that will be built during day one in CSNS project. T0 chopper is used in this beam line to stop the fast neutrons but also flush gamma ray to reduce the background of neutron instrument. We also give the activity data for T0 chopper.

2. Damage energy and displacement cross sections for W, A6061 and SS316

The INC model in MCNPX provides damage energies delivered to the nuclei of target atoms per incident neutron or proton with its energy E. The damage energy cross section is obtained by

$$\sigma_{\text{damage}} = \frac{T_{\text{damage}}}{xN_v} \tag{1}$$

where T_{damage} is the mean damage energy per source particle, x is the target thickness, N_v is the atomic density of the target material. Fig. 1 gives the damage energy cross sections for W, A6061 and SS316 versus proton/neutron energy using Bertini physics model for neutron and proton energy higher than 20 MeV within MCNPX [4]. We choose three level-density formulation GCCI and multistage pre-equilibrium model on. Bertini intranuclear cascade (INC) model with the different level-density formulation and pre-equilibrium model option gives lower neutron induced damage energy cross section σ_{damage} than CEM2K INC model in the high energy range [3]. However, the contribution of the neutron flux in this range to the total flux is small; in this paper we do not consider the difference due to the cross section. For the neutron with its energy below 20 MeV, we use the cross section ENDF/B-VI. All protons are transported using Bertini INC model. According to the modified Kinchin–Pease model [5], the displacement cross section σ_d is given by

$$\sigma_{\text{displacement}} = \frac{\beta}{2T_d}\sigma_{\text{damage}} \tag{2}$$

where $\beta = 0.8$ deviation from a hard sphere, which compensates for forward scattering in the displacement cascade. T_d is the threshold displacement energy. For W, Al and SS316 T_d are 90, 27 and 40 eV, respectively. Factor of 2 means on average the

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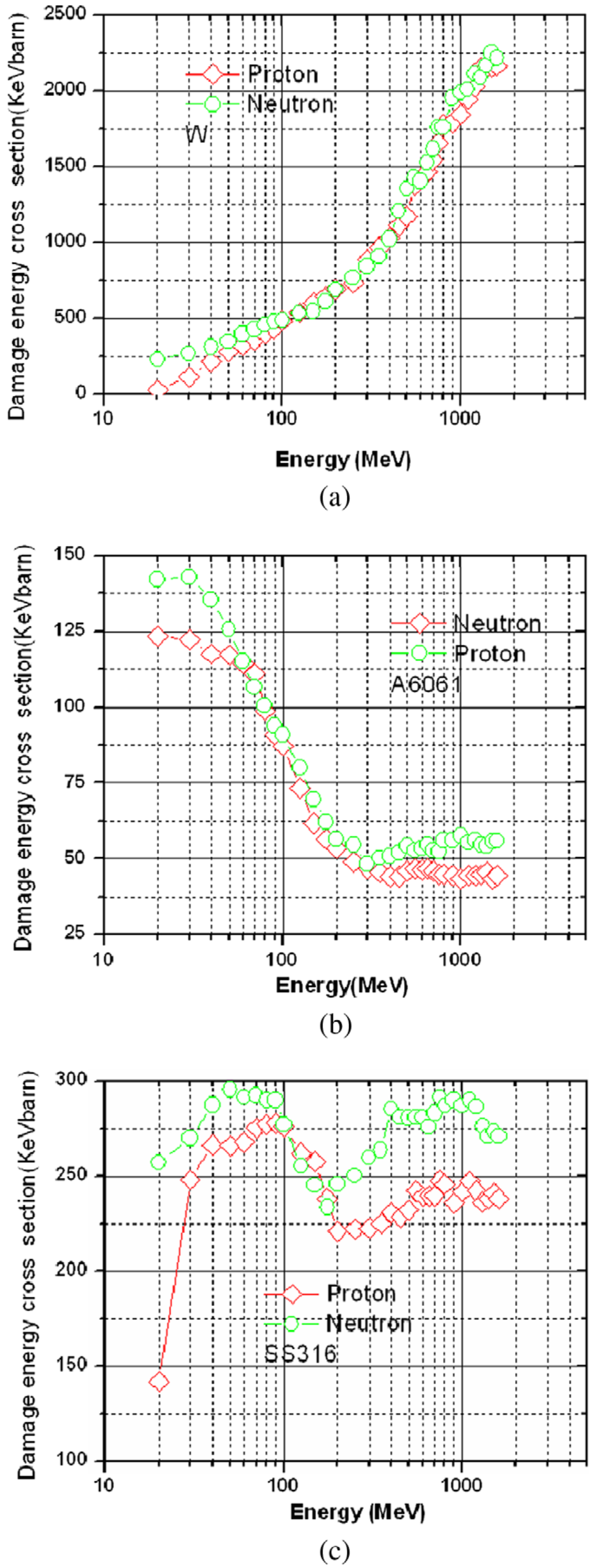


Fig. 1. Proton/neutron induced damage energy cross sections by Bertini physics model within MCNPX (20 MeV < E < 1600 MeV) (a) W; (b) A6061; and (c) SS316.

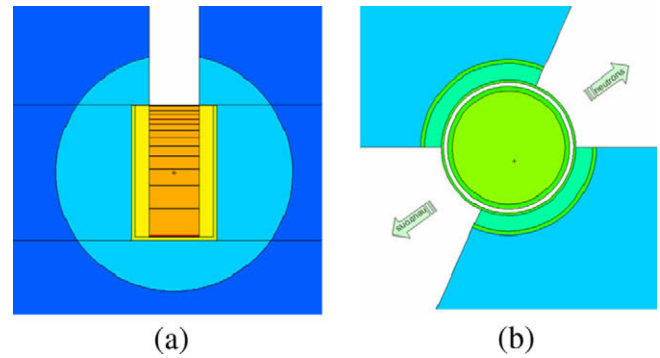


Fig. 2. MCNPX calculation model (a) the tungsten target; and (b) the coupled hydrogen moderator.

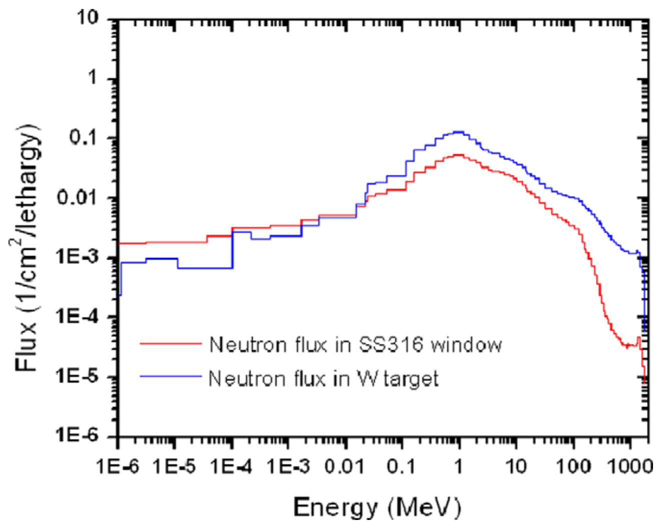


Fig. 3. The neutron fluxes at W target and SS316 vessel window.

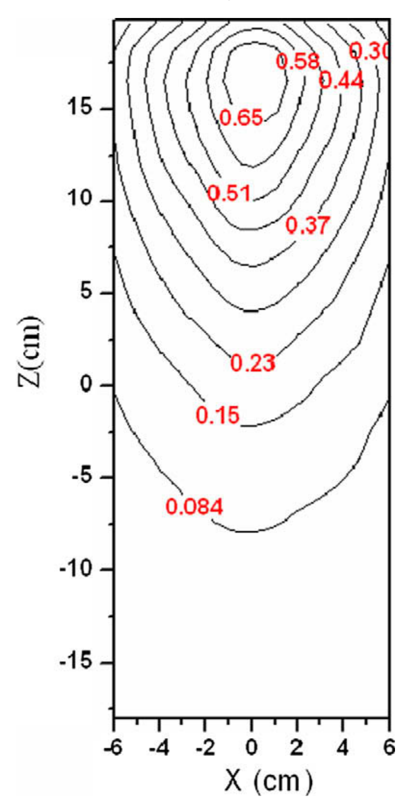


Fig. 4. The displacement distribution of tungsten target from neutrons.

PKA (Primary Knocked-on Atom) energy is shared equally between two atoms after the first collision.

3. Displacements per atom (DPA) for CSNS target, target vessel and moderator vessel

The CSNS target station includes the tungsten target, three moderators including a coupled hydrogen moderator, a decoupled water moderator and decoupled poison hydrogen moderator, and beryllium reflector. The dimension of the target is 400 mm-thick, 150 mm-wide and 60 mm-height. There are twelve 1.5 mm-thick heavy water channels between the target plates. The width of pipe in/out is 50 mm. The thickness of the SS316 target vessel is 10 mm except its window. The thickness of the window is lessened to 2 mm for avoiding neutrons absorption and reducing thermal stress. We choose the volume coupled hydrogen moderator for higher intensity of cold neutrons. The diameter and height of the coupled hydrogen moderator is 150 and 100 mm, respectively. Its A6061 vessel is 5 mm thick. The diameter of Be reflector is 700 mm. For para-hydrogen moderator, we use the different thick water as its pre-moderator. Fig. 2 gives the calculation model. The energy of the proton beam is 1.6 GeV and the profile is Gaussian with FWHM 90 and 35 mm in wide and height, respectively. All calculations are made for the proton beam power 100 kW and 5000 h (one operating year).

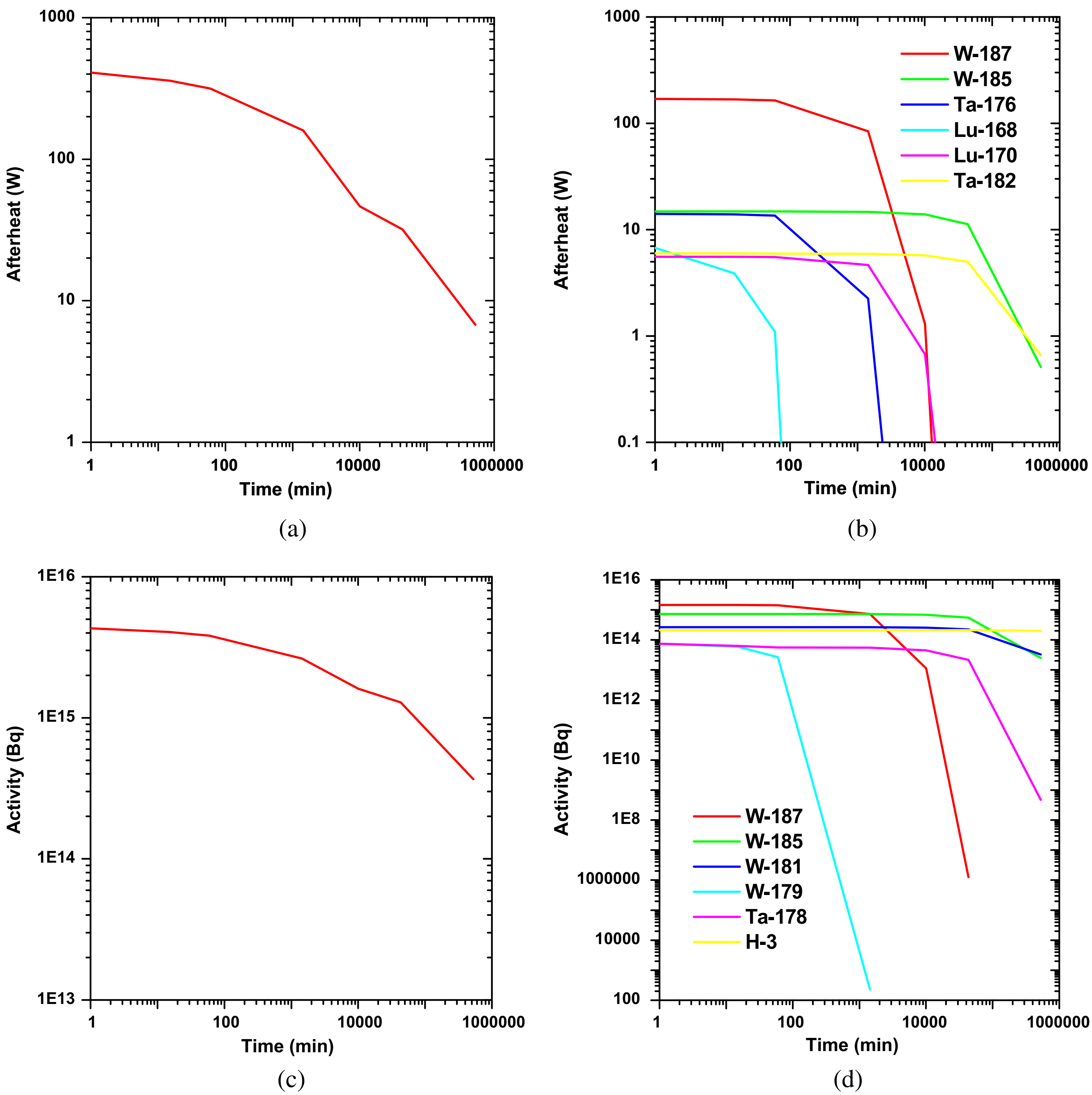
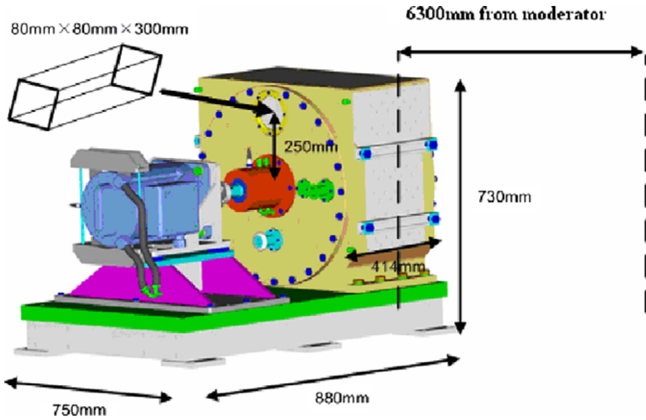
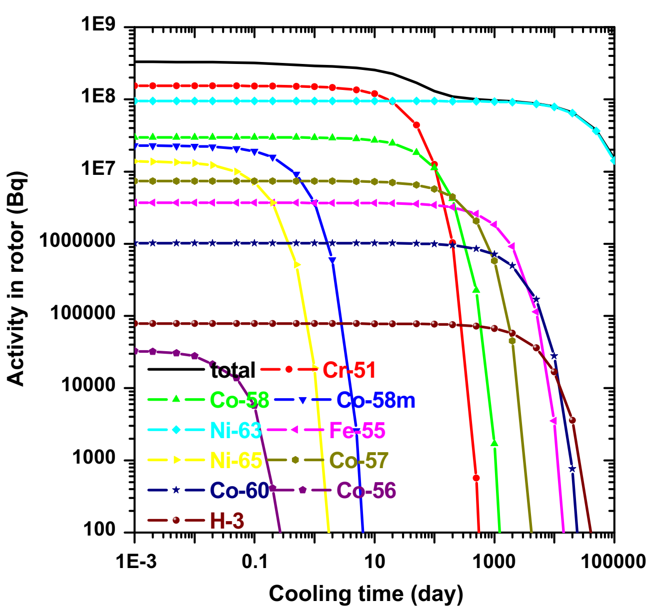


Fig. 5. The afterheat and activity of the tungsten target for cooling 1 year. (a) The total afterheat; (b) the contribution to the afterheat from the different nuclide; (c) the total activity; and (d) the contribution to the activity from the different nuclide.



(a)



(b)

Fig. 6. (a) The sketch of the T0 chopper of HIPD and (b) the activity of the T0 chopper blade.

The average displacements per atom can be obtained by folding the neutron flux (see Fig. 3) into the displacement cross section (Fig. 1). As an example, we give the displacement distribution of the centre part of the target from neutrons (see Fig. 4) based on an operating year of 5000 h. The maximum DPA strongly depends on the proton profile and its corresponding inject area. According to the calculation of the neutron and proton fluxes for the target, target vessel and the moderator vessel, we estimate the maximum DPA of these components are in the fourth target plate, the target vessel window and the center of the bottom of the pre-moderator vessel. The maximum DPA from neutrons and protons for the target, the target vessel window and the moderator vessel are 1.48 dpa, 1.5 dpa/year; and 0.8 dpa/year, respectively. We compare the results with that for SNS target vessel nose. When normalized to 100 kW the maximum DPA is 1.8 dpa/year in Ref. [3] which is larger than our results 1.5 dpa/year. We consider this discrepancy partly comes from the different physics model in MCNPX, and partly comes from the different calculation model and the proton beam parameters including energy and profile.

4. Activity of the target and T0 chopper

Activity of the target is due to spallation reaction which generally leaves the struck nucleus in an excited state. Further radioactivity can be produced by the secondary particles released in the spallation reaction and by the evaporation neutrons that are emitted as the excited nucleus release its excess energy. It is important for get the activity and afterheat of the activated material which will determine the CSNS facility radioactive waste, remote handling/maintenance requirements and potential site contamination. The total activity and afterheat of the target are calculated for cooling down 1 year after continuous 5 year irradiated. Here MCNPX is used to calculate the neutron fluxes and production rates. Then these results are used for the next radionuclide inventory calculations by CINDER90 code. The afterheat of the target descends to a low value that is about 7 W when cooling down 1 year. However, due to the long half-life nuclide ^{3}H and ^{185}W, the activity of the target is still above 10^{14} Bq (see Fig. 5).

High Intensity Powder Diffractometer is one of the three instruments that will be built during day one in CSNS project. In HIPD, T0 chopper is used to stop the fast neutrons and flush gamma ray to reduce the background of neutron instrument. Its motor drive has a certain lifetime. So activation of a T0 chopper is estimated to get a basic data for making out a maintenance scenario. It is assumed that the chopper was located at 6.3 m from the water moderator, the thickness of the chopper blade is 30 cm and the material is inconel 750. The dominant radioactive nuclides are produced by the ^{50}Cr$(n,\gamma)^{51}$Cr, ^{62}Ni$(n,\gamma)^{63}$Ni reaction and Fig. 6 shows that the total activity after cooling down 10 days is about 10^{8} Bq.

5. Conclusions

We have calculated the displacements per atom of the target, the target vessel and the moderator vessel. The result shows that the maximum displacement of these components is 1.5 dpa based on the proton beam power 100 kW and one operation year. We will compare the results with the other models such as CEM2K/MPM off/LA150. The afterheat of the target will drop to 7 W after cooling down 1 year. But due to the long half-life nuclide ^{3}H and ^{185}W, the activity is still above 10^{14} Bq. This value will be much higher when we consider the Ta cladding. T0 chopper is used for stopping the fast neutrons and flush the gamma ray in many instruments. The activity of the chopper mainly comes from the (n,γ) reaction. The activity of the chopper blade after cooling down 10 days will decrease to 10^{8} Bq.

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