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Calculations of radioactivity and afterheat in the components of the CSNS target station

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This paper shows the calculations of radioactivity and afterheat in the components of the China Spallation Neutron Source (CSNS) target station, with the Monte Carlo codes LAHET, MCNP4C and the multigroup code CINDER'90. These calculations provide essential data for the detailed design and maintenance of the CSNS target station.

Keywords: Monte Carlo codes, radioactivity, afterheat, CSNS target station
PACC: 2540S, 2875, 2820C

1. Introduction

The Chinese government initiated a conceptual design study for the China Spallation Neutron Source (CSNS) and approved the project recently. The first design stage consists of an accelerator system capable of delivering a 1.6 GeV proton beam with 100 kW beam power in a 0.5 μs pulse at a 25 Hz frequency to a target station. Three different moderators are selected to slow down the fast neutrons; they supply thermal neutrons to the 18 instruments for scientific research.

In the components of the CSNS target station, a large variety of isotopes is produced by spallation reactions and also those created by activation of the low energy neutron flux. A lot of them are radioactive and could be a source of concern for radioprotection.[1−3] Accurate calculations of radioactivity, afterheat and their time evolutions are important in terms of radioprotection, maintenance, remote handling and waste management. This paper presents such calculations and give brief discussions of the results. The calculation approach and geometric model are also described.

2. Geometric description of the CSNS target station

Figure 1 shows the geometry of the target station for calculation. Tungsten (W) material is used as the target, with a size of 13 cm×4 cm×40 cm. The target vessel is made of stainless steel (SS316), with a thickness of 0.5 cm for each side. The moderators are a coupled hydrogen moderator (CHM, 20 K, under the target), a decoupled and poisoned hydrogen moderator (DPHM, 20 K, above the target, upstream), and a decoupled water moderator (WM, 300 K, above the target, downstream), respectively. The vessels of the moderators are all constructed of aluminum alloy. Reflectors of heavy water (D_2O) cooled beryllium (Be, with a radius of 50 cm) and iron (Fe, with a radius of 100 cm) are placed around the moderators to reflect

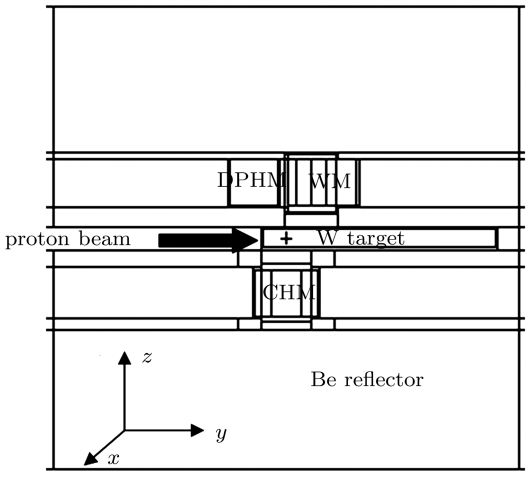


Fig.1. Vertical cut through target-moderator-reflector system of the CSNS target station.

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neutrons back into the moderators. The biological shield consists of an inner core of iron (with a radius of 5 m) and an outer layer of heavy concrete (with a radius of 1 m) to protect the personnel from radiation.

All calculations are based on a 1.6 GeV, 100 kW proton beam, with a Gaussian distribution of 8 cm and 2.67 cm full width at half maximum (FWHM) in x and z directions, respectively. The errors are below 5% in most of the calculations.

3. Calculations of radioactivity and afterheat

3.1. Brief introduction to the spallation reaction

Spallation refers to non-elastic nuclear interactions induced by high energy particles. When a high energy proton beam bombards heavy matter such as a W target, two stage processes of the spallation reaction take place. In the first stage an incident proton collides with an individual nucleon inside the nucleus and the struck nucleon causes further collisions, forming an intranuclear cascade. In this stage various secondary particles, protons, neutrons and pions are yielded. If the energies of these hadrons are approximately higher than 15 MeV, additional internuclear cascade proceeds by these hadrons. Those cascade processes leave excited nuclei. In the second stage the excited nuclei evaporate low-energy particles, including neutrons, protons, deuterons, tritons, ^{3}He, alpha and heavier particles. The remaining energy of the excited nuclei is released by gamma-ray emission. Residual nuclei are left after the spallation reactions, exhibiting a wide range of mass and charge number distributions, with different concentrations, life-times, decay styles and radioactivity.

3.2. Calculation approach of radioactivity and afterheat

The calculations of radioactivity and afterheat in the CSNS target station are performed in two steps. In the first step Monte Carlo codes LAHET[4] and MCNP4C[5] are used to estimate the radionuclides produced by high energy particles and to simulate the transport of neutrons and gamma rays below 20 MeV, respectively. The CINDER'90 code[6] is adopted in the second step to estimate the radioactivity and afterheat for different irradiation and cooling times. The performance scheme is shown in Fig.2.

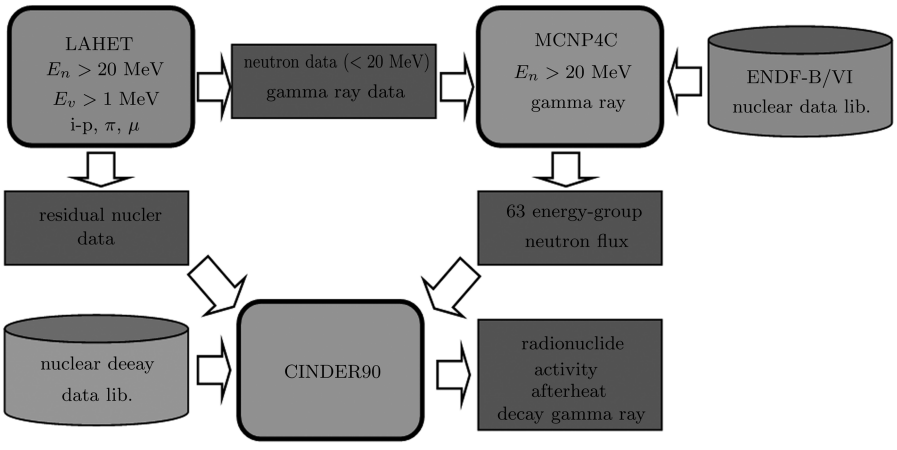


Fig.2. Flow diagram of radioactivity and afterheat calculation procedure.

3.3. Radioactivity in the components of the CSNS target station

When bombarded by a proton beam with an energy of 1.6 GeV, spallation reactions take place not only in the W target, but also in other components such as the target vessel, the moderators, the Be/Fe reflectors and so on. Table 1 lists the radioactivity of some components in the CSNS target station after 5 years of irradiation (5000 full power operating per year). The cooling times correspond to 1 day, 3 days, 7 days, 1 month and 1 year, respectively. It shows that the W target is the highest contributor to the total radioactivity of the target station. Detailed calculations of the W target are also performed.

Table 1. Radioactivity decay in components of the CSNS target station after 5 years of irradiation.

the components	1 day	3 days	7 days	30 days	1 year
W target	2.5383×10^{15}	2.3779×10^{15}	2.0858×10^{15}	8.1599×10^{14}	1.463×10^{14}
target vessel	3.7573×10^{13}	3.5964×10^{13}	3.3925×10^{13}	2.8068×10^{13}	1.325×10^{13}
CHM vessels	3.0462×10^{12}	8.5775×10^{11}	3.1365×10^{11}	3.032×10^{11}	2.3532×10^{11}
DPHM vessels	7.5808×10^{11}	6.2596×10^{11}	5.7083×10^{11}	4.8413×10^{11}	2.8728×10^{11}
WM vessel	7.8121×10^{11}	6.6204×10^{11}	5.9354×10^{11}	4.7671×10^{11}	2.6488×10^{11}
Be reflector	2.6167×10^{13}	2.5988×10^{13}	2.5663×10^{13}	2.4095×10^{13}	1.8850×10^{13}
Fe reflector	3.6453×10^{14}	3.4985×10^{14}	3.3061×10^{14}	2.7548×10^{14}	1.2862×10^{14}

3.4. The radioactivity in the W target

Figure 3 shows the time evolutions of the radioactivity in the W target, with a proton beam power of 100 kW. It can be seen in Fig.3(a) that the radioactivity is 1.47×10^{14} Bq for the first 1 second irradiation time, and increases to 5.95×10^{14} Bq and 1.1×10^{15} Bq for 1 hour and 1 day irradiation, respectively. The rapid buildup of the radioactivity indicates that short life-time nuclides are the main contributors to the total radioactivity. It reaches 2×10^{15} Bq for one year of irradiation and 2.73×10^{15} Bq for ten years of irradiation. The nearly saturated state indicates that there exist long life-time nuclides with low radioactivity in the W target.

The decay behaviour of the radioactivity of the total and some nuclides in the W target after one year of irradiation is shown in Fig.3(b). The total radioactivity for 1 year of irradiation decreases to 6.26×10^{14} Bq, 1.3×10^{14} Bq, and 4.56×10^{12} Bq for cooling times of one week, one year and ten years, respectively. Typical radioactive nuclides such as W181, W178, Ta178, Fe55, Mn54 and Cr51 with intensive radioactivity and Mn53 with long life-times are also shown. All these radioactivity data provide important parameters for the design and maintenance of the CSNS target station.

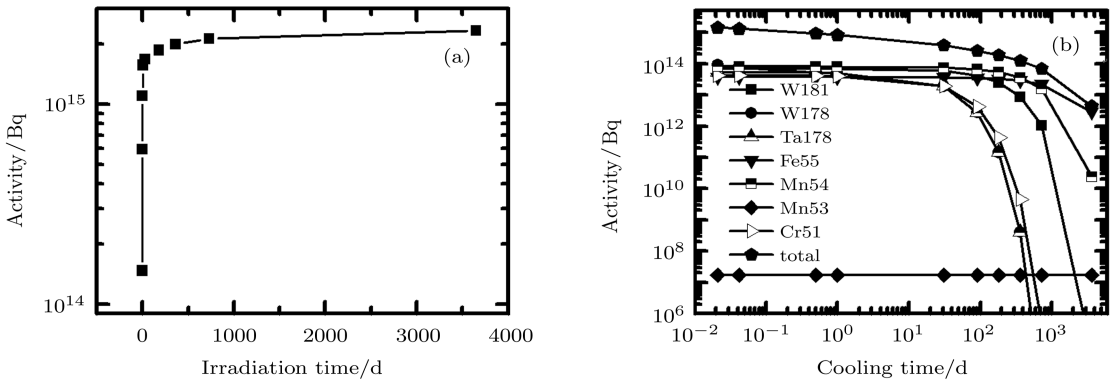


Fig.3. (a) The buildup behaviour of the radioactivity in the W target. (b) The decay behaviour of the raidoactivity in the W target after one year of irradiation.

3.5. The afterheat in the W target

Figure 4 shows the time evolutions of the afterheat in the W target. It can be seen in Fig.4(a) that the afterheat has a rapid buildup during the initial irradiation time then increases slowly. The afterheat reaches its quasi-saturation value of 160 W after 1 year of irradiation. Figure 4(b) shows the afterheat decay in the W target during the cooling time, after 1 year of irradiation. One can see that the afterheat decreases rapidly during the initial cooling time. The

behaviours of rapid buildup during the initial irradiation time and rapid decay during the initial cooling time imply again that the produced radionuclides are mainly short life-time nuclides. Long life-time nuclides maintain the slow changes of the afterheat. The calculated results imply that the additional coolant of the target should be considered to remove the afterheat for its normal operation.

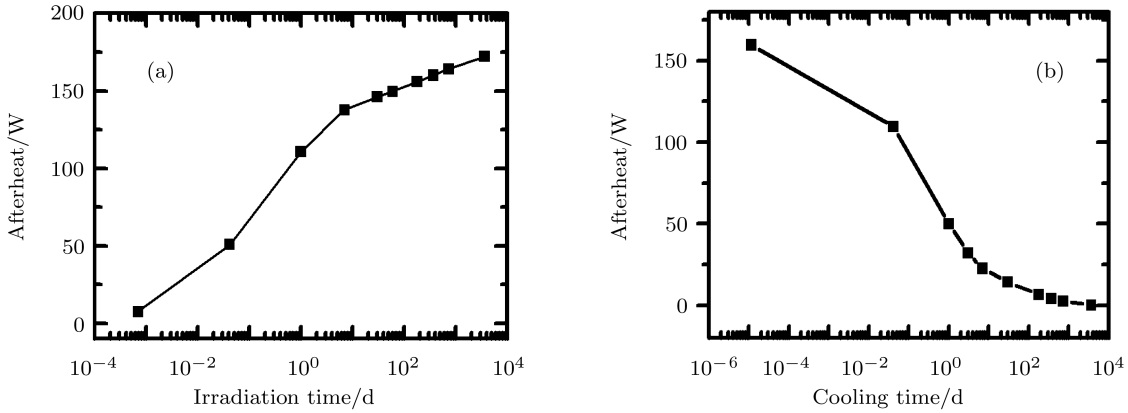


Fig.4. (a) Afterheat buildup of the W target during the irradiation time. (b) Afterheat decay of the W target during the cooling time after 1 year of irradiation.

4. Summary

Radiation transport and neutronics have been carried out for the CSNS target station during the conceptual design stage, with an incident proton beam of 1.6 GeV energy and 100 kW power. The calculations of radioactivity and afterheat in the components of the CSNS target station have been performed with the Monte Carlo codes LAHET MCNP4C, and the multigroup code CINDER'90. The total radioactivity and afterheat reach 2×10^{15} Bq and 160 W for one year of irradiation, respectively. Results show that the W target is the highest contributor to the total radioactivity of the target station. It also implies that additional coolant should be considered to remove the afterheat produced in the target for its normal operation. These calculations provide essential data for the design and maintenance of the CSNS target station.

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