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Preliminary shielding analysis in support of the CSNS target station shutter neutron beam stop design*

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Abstract: The construction of China Spallation Neutron Source (CSNS) has been initiated in Dongguan, Guangdong, China. Thus a detailed radiation transport analysis of the shutter neutron beam stop is of vital importance. The analyses are performed using the coupled Monte Carlo and multi-dimensional discrete ordinates method. The target of calculations is to optimize the neutron beamline shielding design to guarantee personal safety and minimize cost. Successful elimination of the primary ray effects via the two-dimensional uncollided flux and the first collision source methodology is also illustrated. Two-dimensional dose distribution is calculated. The dose at the end of the neutron beam line is less than 2.5 μSv/h. The models have ensured that the doses received by the hall staff members are below the standard limit required.

Key words: neutron transport, spallation source shielding, discrete ordinates method

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1 Introduction

China Spallation Neutron Source (CSNS) [1, 2] complex is designed to provide multidisciplinary platforms for scientific research and applications for national institutions, universities and industries. Spallation, the process in which a heavy nucleus emits a large number of nucleons as a result of being hit by a high-energy particle, thus greatly reducing its atomic weight, has become an important technique for the production of high intensity neutron flux.

The baseline design of CSNS consists of an accelerator system capable of delivering a 1.6 GeV (25 Hz) proton beam with 100 kW of beam power into a single target station. The beam power has the capability of upgrade to 500 kW by raising the linac output energy and increasing the beam intensity. Tungsten is a proven target material for the CSNS design beam power. The position of the target is within a layered steel and concrete shield monolith which is approximately 12 m in diameter. There are 18 neutron beamlines viewing the moderators, nine on each side and equally spaced in angle. However, due to the limited project funds, only three day-one instruments are supported: a high-intensity diffractometer, a broad Q-range small angle diffractometer and a multi-purpose reflectometer. Each beamline has an independently operable shielding shutter controlled by the personnel and researchers. Each shutter is connected to a motor and drive shaft assembly located on top of the shielding monolith and designed to be raised and lowered in the vertical direction. The shutters are constructed with low carbon steel or stainless steel and contain a tungsten insert that blocks the neutron beamlines when the shutters are closed.

Calculations are being performed to optimize the beamline shielding design with the goal of minimizing the size of the shutter neutron beam stop, thereby

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reducing the costs and enhancing maintainability, as well as guaranteeing personal safety. A methodology of coupled Monte Carlo and multi-dimensional discrete ordinates methods has been utilized to perform the shielding analyses [3–5]. This work analyzed the shielding efficiency of the shutter neutron beam stop. The results of these calculations will provide an optimum design for the shutter and shutter neutron beam stop, so CSNS can be operated regardless of high dose rates resulting from the particles streaming through the neutron beamlines.

2 Methodology and cross section library

The radiation transport analysis is performed to optimize the efficiency of the CSNS shutter neutron beam stop for shielding the neutron beamline. It is very inefficient or difficult to simulate the whole radiation transport problem with a single scheme. Instead, we calculate the intermediate source terms defined at the moderator face using Monte Carlo simulations. Initially MCNPX [6] is used to calculate the leakage spectra off the moderators in a forward-directed 5.729° cone. The leakage spectra are used as a point source at the radial center of the entrance to the neutron beamline. Next, considering that this model is a long cylinder with 2 large void regions, thus susceptible to ray effects, this analysis emphasizes that the ray effects are to be eliminated. To mitigate the ray effects, GRTUNCL [7, 8] is used to calculate the uncollided flux and the first scattering source throughout the model. Then the two-dimensional discrete ordinates neutron/photon transport code DORT [9] using the first scattering source will complete the transport calculation. An upward biased quadrature pointing down the neutron beamline is used to eliminate ray effects once again. After DORT completes the transport of the first scattering source, the uncollided flux is added. Finally the dose at 10 m from the moderator face is calculated.

Figure 1 is a flow chart of this calculation sequence. The code NJOY [10] is used to produce a multi-group set library. The code TRANSX is used to pre-treat the MATXS file to a simple library which can be used by Sn codes, such as ANISN and DORT. The flow chart includes both the cross section library production and the radiation transport calculation.

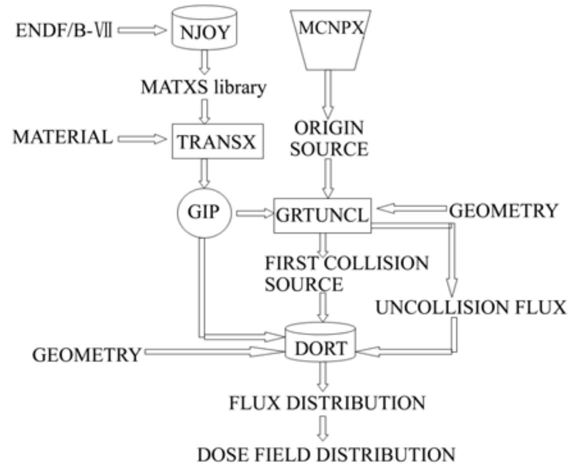

Fig. 1. The calculation flow diagram for shielding analyses.

All of these DORT and GRTUNCL calculations use the newly developed 150 MeV cross-section library HEST1.0. The library HEST1.0 verification has been finished [11]. The library contains altogether 301 energy groups, 81 high-energy neutron groups, 172 low-energy neutron groups and 48 photon groups. The library includes all the nuclides except manganese in materials such as low carbon steel and stainless steel 316.

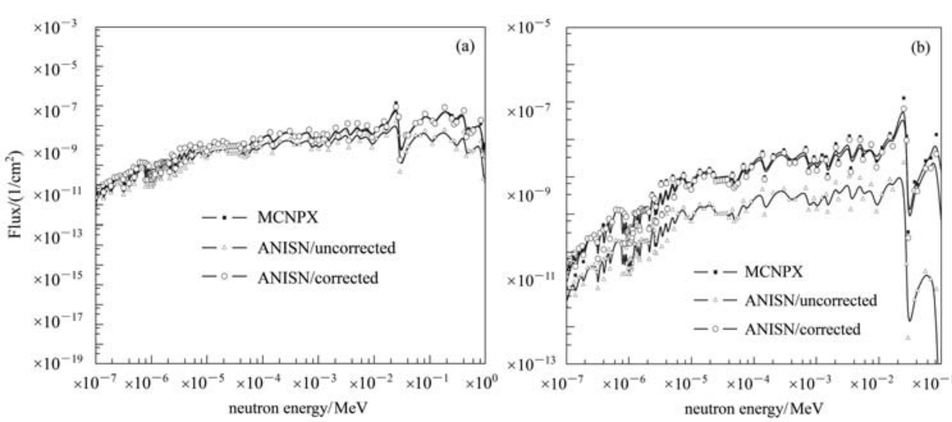

Fig. 2. The neutron fluxes calculated by MCNPX, ANISN/uncorrected cross section and ANISN/corrected cross section.

Figure 2 gives the comparison between MCNPX and one-dimensional discrete ordinates neutron/photon transport code ANISN in DOORS with the uncorrected and corrected cross sections. The neutron fluxes at the outer edge of the 1 m steel sphere with an isotropic 1 or 0.1 MeV neutron source in the center have been calculated. We find that the ANISN results agree well with the results by MCNPX calculation.

3 Geometric models

The CSNS shutter neutron beam stop and the neutron beamline, as shown in Fig. 3, extend 10 m from the moderator face. Table 1 lists the chemical composition of each of the materials.

In the actual engineering design, the neutron beamline and shutter neutron beam stop are rectangular parallelepipeds, but in this analysis they have been converted to a cylinder with area being conserved. The neutron beam stop models have a radius of 11 cm and the thickness of the low carbon steel is 104 cm. The neutron beam stop ranges from 250 cm to 450 cm of the moderator face. The core vessel insert placed in the neutron beamline between the shutter and moderators is 150 cm long. The inside radius of the core vessel insert is 5 cm and the outside radius is 11 cm. The core vessel insert is stainless steel 316. In this cylindrical model the left-hand side is treated as a reflected boundary condition. All other sides are treated as void boundary conditions.

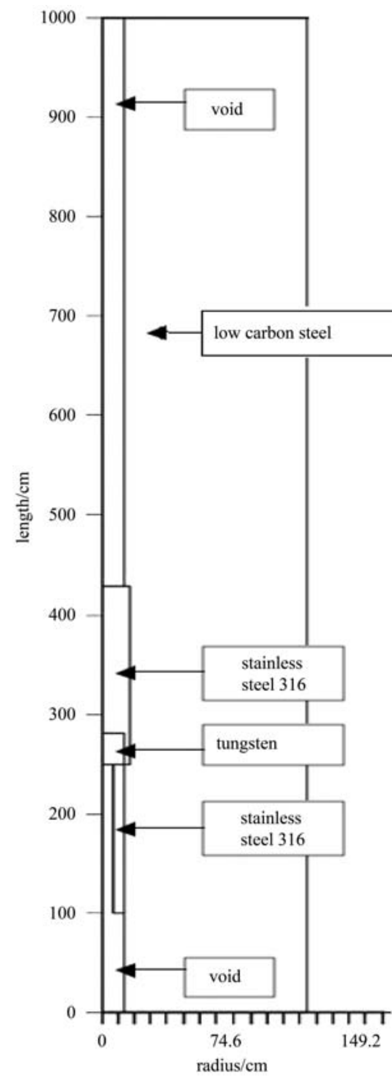

Fig. 3. The shutter neutron beam stop model.

Table 1. The material chemical compositions.

name	density/(g/cc)	chemical components/(wt. %)
stainless steel 316	8.03	iron (65.375%), chromium (17.0%),nickel (14.5%), manganese (2.0%), silicon (1.045%), carbon (0.08%)
low carbon steel	7.04	iron(99.1%), manganese(0.45%), silicon(0.25%),carbon(0.2%)
tungsten	19.3	tungsten (100%)

4 Shielding analysis

The first step in the analysis of the CSNS shutter neutron beam stop is to perform a parametric study. These parametric studies determine how much the low carbon steel surrounding the neutron beamline would be needed to consider it as an infinite reflector. Table 2 lists the thickness of the low carbon steel added around the neutron beamline, the dose at 6 m and the percent difference between the current dose and the previous dose. This calculation is used to determine how much the low carbon steel would need to be modeled around the neutron beamline, so as to get an accurate calculation of the dose 10 m from the moderator face. The current model adds about 100 cm steel around the neutron beamline, this result agrees with the SNS calculation that also adds about 100 cm steel [3].

Secondly, the shielding efficiency of the shutter neutron beam stop constructed with single material is analyzed. To date 4 models have been analyzed.

Table 2. The results of neutron beam stop parametric study.

thickness of low carbon steel/cm	dose at 6 m/(μSv/h)	percent difference(%)
30	20.67	N/A
50	24.72	19.58
70	26.29	6.33
90	26.61	1.23
110	26.62	0.05

The first was one of the current designs where the beam stop was completely constructed with stainless steel 316. The second model contained all stainless steel 316, like the first model, but the stainless steel 316 was extended to the largest possible radius but still within the structure of the shutter. The third model was the same as the second except the stainless steel 316 has been replaced by tungsten. The fourth model was the same as the second one but without the core vessel insert. The second model with isodose contours is shown in Fig. 4, this result basically agrees with the SNS shielding calculation [3]. The SNS reduced the dose of radiation by about 6 orders of magnitude with a 180 cm shield and in this paper the dose of radiation was rduced by nearly 7 orders of magnitude with the 200 cm shield. Table 3 lists the resulting dose at the end of the neutron beamline for each model.

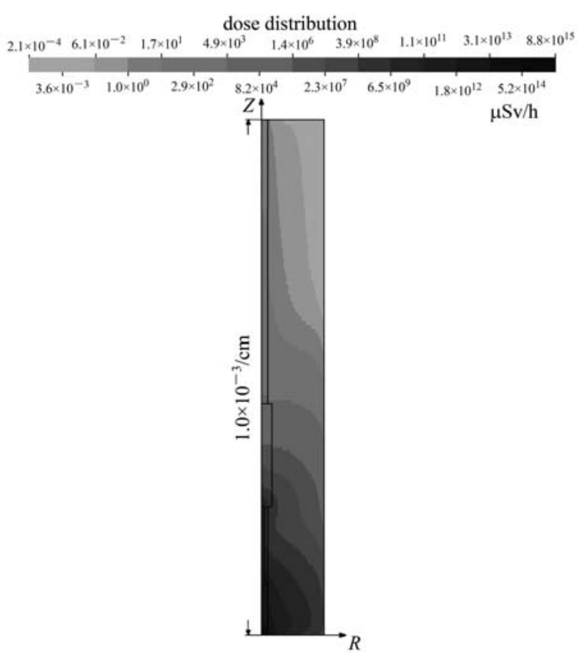

Fig. 4. The isodose contours of stainless steel 316 shutter neutron beam stop.

The results in Table 3 suggest that extending the radius of the shutter neutron beam stop can help reduce the dose at the end of the neutron beamline. The opening without the core vessel insert is bigger than the opening with the core vessel insert, with respect to the origin and it also increases the dose at the end of the neutron beamline to 4.781 μSv/h. This increment is proportional to the cross- sectional area of the beamline viewed by the point source. The material of tungsten demonstrates better shielding efficiency than the stainless steel 316. This result basically agrees with the SNS calculation.

Table 3. Various shutter neutron beam stop configurations and the dose 10 m from the moderator face.

shutter neutron beam stop configuration	dose 10 m from the moderator face
all SS316, radius 11 cm	4.1047 μSv/h
all SS316, radius 20 cm	3.9959 μSv/h
all tungsten, radius 20 cm	0.0264 μSv/h
all SS316, radius 20 cm without core vessel insert	4.7810 μSv/h

Thirdly, the shielding efficiency of different design of the shutter neutron beam stop is analyzed. Any neutron shield must be constructed so that higher energy neutrons are moderated as soon as possible and subsequently captured in order to remove neutrons significantly. In this section four shielding models have been evaluated. The details of multilayer shutter neutron beam stop configurations are shown in Table 4.

Table 4. Multilayer shutter neutron beam stop configurations.

shield configuration	layer	layer thickness/cm
model 1	tungsten	25
	steel	175
model 2	tungsten	50
	steel	150
model 3	tungsten	25
	steel	150
	tungsten	25
model 4	steel	150
	tungsten	50

One idea for establishing a suitable combination of materials for high shielding performance is investigated. It is obvious that the multilayer configuration offers a greater reduction in total neutron and photon dose. The reason is that the blocks of layers may yield approximately exponential attenuation of incoming flux at each block. We prefer to use as little tungsten as possible for the sake of reducing the construction expense and the dose at the end of the neutron beamline is less than 2.5 μSv/h. It is noted from Fig. 5 that 25 cm tungsten with 175 cm stainless steel satisfies the standard limit required. It is also interesting to know where the tungsten should be placed so that high shielding efficiency can be offered. The answer is obviously that the tungsten placed foreside can bring about the utmost shielding efficiency. This result basically agrees with that based on the Monte Carlo method [12].

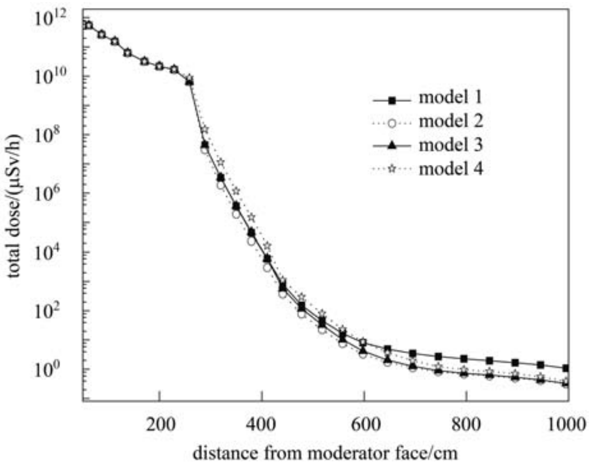

Fig. 5. The total dose axial distributions of four models.

5 Conclusions

Preliminary shielding calculations are being performed to optimize the beamline shielding layout of each CSNS beamline. A preferable shielding model has been obtained in the calculation and the dose at 10 m from the moderator face received by the hall staff members is below the standard limit required.

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