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Analysis of radiation environmental safety for China's Spallation Neutron Source (CSNS)

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Abstract The China Spallation Neutron Source (CSNS) is going to be located in Dalang Town, Dongguan City in the Guangdong Province. In this paper we report the results of the parameters related with environment safety based on experiential calculations and Monte Carlo simulations. The main project of the accelerator is an under ground construction. On top there is a 0.5 m concrete and 5.0 m soil covering for shielding, which can reduce the dose out of the tunnel's top down to 0.2 μSv/h. For the residents on the boundary of the CSNS, the dose produced by skyshine, which is caused by the penetrated radiation leaking from the top of the accelerator, is no more than 0.68 μSv/a. When CSNS is operating normally, the maximal annual effective dose due to the emission of gas from the tunnel is 2.40×10^{-3} mSv/a to the public adult, and 2.29×10^{-3} mSv/a to a child, both values are two orders of magnitude less than the limiting value for control and management. CSNS may give rise to an activation of the soil and groundwater in the nearest tunnels, where the main productions are ^{3}H, ^{7}Be, ^{22}Na, ^{54}Mn, etc. But the specific activity is less than the exempt specific activity in the national standard GB13376-92. So it is safe to say that the environmental impact caused by the activation of soil and groundwater is insignificant. To sum up, for CSNS, as a powerful neutron source device, driven by a high-energy high-current proton accelerator, a lot of potential factors affecting the environment exist. However, as long as effective shieldings for protection are adopted and strict rules are drafted, the environmental impact can be kept under control within the limits of the national standard.

Key words China Spallation Neutron Source, environmental safety, effective dose, specific activity

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1 Introduction

China Spallation Neutron Source (CSNS) is an advanced large-scaled experimental platform for the researches on the high-tech and academic forefront, and is a symbol of a state's comprehensive strength, including technological level and industrial level. CSNS is located in Shuiping Country, which is a village in Dongguan city, Guangdong province. CSNS is composed of a 130 MeV Linear accelerator of negative hydrogen, a 1.6 GeV fast cycle of the proton synchrotron, two beam transport lines, a target station, three spectrometers and other supporting facilities.

The core device of the CSNS is a proton accelerator. Beam loss occurs during the proton transport. The lost protons will hit the surrounding structural materials, which is similar to the process of protons hitting targets. Then nuclear reactions between the lost protons and the atoms of the materials will occur. That is, the protons enter the nuclei and then through a cascade of collisions with the nucleons of the nuclei, exchange energy, and release neutrons. This deceleration process is accompanied by gamma ray emission. According to the law of conservation of energy, these so-called cascade neutrons are high-energetic and mainly emitted in the forward direction. During this time period the system "bullet-target" is in an unbalanced state and then gradually transits to equilibrium. The remaining energy leads then to the evaporation of neutrons (evaporation neutrons),

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whose angular distributions is isotropic.

Because of the strong penetration capability of neutrons and gamma rays, we must consider the environmental problems when CSNS is operating: neutrons and gamma rays that penetrate the shielding will cause a direct radiation dose to human beings, and the neutrons that pass through the roof into the sky will cause an indirect radiation dose to the surrounding human beings because of skyshine (see chapter 3.3 for an explanation).

Neutrons will lead to an activation of the accelerator components, particularly in those places where the beam loss is more severe. As a result the maintenance personnel will be irradiated and some radioactive solid waste is produced.

Moreover, neutrons will also give rise to the activation of the air in the beam transition tunnel. The resulting products of this process are mainly ^{41}Ar, ^{11}C, ^{7}Be and ^{3}H etc. The cooling water will also be activated, where the main products are ^{7}Be and ^{3}H etc. These gaseous and liquid radioactive substances will affect the surroundings after emission. In addition, the neutrons penetrating the shielding at the bottom of the facility and going into the soil will activate the solid ground and the groundwater and probably affect the environment.

2 Radiation protection and evaluation standard

When designing the CSNS protection, the PRC national standard Basic Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (GB18871-2002) [1] and The Rule for Radiation Protection of Particle Accelerators (GB5172-85) [2] are strictly obeyed. And the principle that “the workers and public ought to be irradiated safely, reasonable, feasible, and as light as possible” is also taken into consideration.

While protection for CSNS is designed and evaluated, the annual dose target and management dose target are determined in order to reduce the effect caused by the CSNS radiation to the environment. The target of the annual dose in the protection design is 5 mSv/a, and correspondingly the average effective dose rate designed for the shielding surface in the working place is less than 2.5 μSv/h. The dose management target for the staff is half of the present national standard, that is 10 mSv/a, and the designed annual dose target for the site boundary is less than 0.08 mSv.

3 Radiation sources analysis and shielding design

3.1 Beam loss and neutron yield

During operation of the CSNS accelerator (transporting and storing), beam loss is inevitable. The lost particles react with the components of the accelerator, such as beam tubes, magnets, collimators, beam dump and target stations, producing secondary particles-neutrons and gamma rays. Beam loss is the source of radiation and the starting point of the radiation shielding calculation.

For the CSNS the highest energy of the cascade neutrons, which are produced when high energy protons are hitting the targets, can be at the same level as the incident protons, that is, 1.6 GeV. Shielding for high energy neutrons is the main task in the shielding of high energy proton accelerators, because of the strong penetration capacity of high energy neutrons. The shielding design for high energy neutrons should also allow for the stopping of evaporation neutrons and gamma rays.

The neutron yield in a proton induced reaction depends on the energy of the incident protons and the material of the target. We have simulated the neutron spectrum induced by 1.6 GeV protons hitting a target of the 90 cm width using the Monte Carlo procedure FLUKA, as shown in Fig. 1. The integration of the neutron spectrum shows that for a total neutron yield of 1, a yield of cascade neutron of 0.5 is obtained, which is similar to the results of Ref. [1] and Ref. [2].

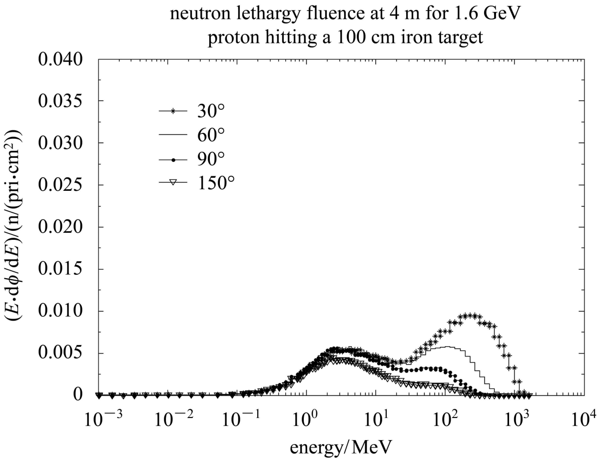

Fig. 1. Neutron spectra with different angles produced when high energy neutrons are hitting the target.

The physics design of the CSNS accelerator system provides the proton energy, the beam intensity, the beam loss power and material of the target for all the beam loss points. According to these parameters, the neutron and gamma ray source intensity at each beam loss point can be obtained.

3.2 The radiation dose out of the main shielding

Tesch's semi-empirical formula and the Moyer mode are the basic methods in the shielding calculation for a high energy proton accelerator. The Tesch Semi-empirical formula is suitable to the case that the energy of the incident protons is less than 1 GeV; while for the protons whose energy is larger than 1 GeV, the Moyer mode is used.

Tesch's semi-empirical formula for a point source is given by:

$$H=H_{\mathrm{casc}}\cdot J\cdot\exp\left(-\mathrm{d}/\lambda\left(\frac{\pi}{2},\ E_{\mathrm{p}}\right)\right)\cdot\frac{1}{r^2}(\mathrm{Sv/s}).$$

Tesch's semi-empirical formula for a line source is given by:

$$H=\frac{\mathrm{d}J}{\mathrm{d}L}\cdot 2H_{\mathrm{casc}}\cdot\frac{1}{r}\cdot\exp\left(-\frac{\mathrm{d}}{0.89\lambda\left(\frac{\pi}{2},\ E_{\mathrm{p}}\right)}\right)(\mathrm{Sv/s}).$$

The Moyer mode is given by:

$$H=J\cdot H_1\left(E_{\mathrm{p}}\right)\cdot r^{-2}\cdot\exp\left(-\mathrm{d}/\lambda\left(\frac{\pi}{2},\ E_{\mathrm{p}}\right)\right)(\mathrm{Sv/s}),$$

with

$$H_1\left(E_{\mathrm{p}}\right)=H_0\left(E_{\mathrm{p}}\right)\cdot\exp\left(-\frac{\pi}{2}b\right).$$

Here,

H_{casc} is the neutron equivalent dose caused by one incident proton at a point 1m away from the target (Sv·m^2).

r is the distance to the source (m).

d is the thickness of the shielding (g/cm^2).

J is the incoming proton flux on the target (proton/s).

E_{p} is the energy of the proton (GeV).

$H_1(E_{\mathrm{p}})$ is a parameter determined by the energy of the protons and the shielding materials (Sv·m^2/proton).

$H_0(E_{\mathrm{p}})$ is the equivalent dose at a point 1m away from the target without shielding (Sv·m^2/proton).

B is a parameter (1/radian).

θ is the angle between the beam direction and the line that connects the source point and the calculating point (radian).

$\mathrm{d}J/\mathrm{d}L$ is the beam loss rate per unit length (proton/m/s).

$\lambda(\pi/2,\ E_{\mathrm{p}})$ is the attenuation length of the protons in the material.

According to the target specification of the shielding design, using the shielding calculating formula and the beam loss assumption given by the physics design, we can get the radiation dose rate out of each shielding at every point of the accelerator under a variety of conditions. The calculation results are list in Table 1 as follows.

After penetrating the shielding, the neutrons and gamma rays produced when the accelerator is operating. They may cause a maximal annual of dose 0.46 mSv/a(assuming that a worker operates 2000 h per year) to the staff, except the workers in the neutron hall. The neutron hall is the place where the neutron beam is extracted from the accelerator for the purpose of scientific experiments, so the dose rate

Table 1. Required shield thickness and the dose rate for the accelerator.

position	distance from beam line/cm	shielding thickness/cm		dose rate/(μSv/h)
		concrete	soil	
LEBT	530	50	250	3.14×10^{-10}
RFQ	530	50	250	3.20×10^{-8}
MEBT-chopper	530	50	250	1.29×10^{-7}
DTL1	530	50	250	3.04×10^{-9}
DTL2	530	50	250	3.30×10^{-6}
DTL3	530	50	250	3.79×10^{-4}
DTL4	530	50	250	6.11×10^{-3}
DTL5	530	50	250	6.08×10^{-2}
DTL6	530	50	250	2.03×10^{-1}
DTL7	530	50	250	5.80×10^{-1}
LRBT	580	50	300	1.03×10^{-1}
LRBT collimator	580	50	300	2.06
injection region	850	50	500	4.04×10^{-3}
RCS	850	50	500	2.09×10^{-1}
extraction region	950	150	500	2.74
REBT	950	150	500	2.74×10^{-1}

Table 2. Annual dose rate caused by Skyshine (01#, 09#, 19#, 27# stand for the number of the environmental monitor site at the CSNS boundary).

	01#		09#		19#		27#	
source term	distance/ m	dose rate/ (μSv/a)	distance/ m	dose rate/ (μSv/a)	distance/ m	dose rate/ (μSv/a)	distance/ m	dose rate/ (μSv/a)
LEBT	640	0.00	630	0.00	190	0.00	250	0.00
RFQ	610	2.28×10^{-10}	600	2.43×10^{-10}	200	6.03×10^{-9}	260	3.20×10^{-9}
MEBT-chopper	590	1.04×10^{-9}	560	1.26×10^{-9}	210	2.17×10^{-8}	270	1.17×10^{-8}
DTL1	530	3.62×10^{-11}	510	4.14×10^{-11}	240	$3.72\ \times10^{-10}$	300	2.09×10^{-10}
DTL2	530	3.94×10^{-8}	510	4.50×10^{-8}	240	4.04×10^{-7}	300	2.27×10^{-7}
DTL3	530	4.52×10^{-6}	510	5.17×10^{-6}	240	4.63×10^{-5}	300	2.61×10^{-5}
DTL4	530	7.29×10^{-5}	510	8.33×10^{-5}	240	7.48×10^{-4}	300	4.20×10^{-4}
DTL5	530	9.45×10^{-4}	510	1.06×10^{-3}	240	7.59×10^{-3}	300	4.49×10^{-3}
DTL6	530	3.16×10^{-3}	510	3.56×10^{-3}	240	2.54×10^{-2}	300	1.50×10^{-2}
DTL7	530	9.02×10^{-3}	510	1.01×10^{-2}	240	7.25×10^{-2}	300	4.28×10^{-2}
LRBT	490	2.43×10^{-3}	440	3.32×10^{-3}	280	1.08×10^{-2}	350	6.18×10^{-3}
injection region	510	1.82×10^{-4}	410	3.41×10^{-4}	260	1.08×10^{-3}	400	3.65×10^{-4}
RCS	480	1.19×10^{-2}	380	2.22×10^{-2}	300	3.97×10^{-2}	430	1.60×10^{-2}
extraction region	450	2.42×10^{-1}	330	5.18×10^{-1}	340	4.83×10^{-1}	460	2.28×10^{-1}
RTBT	380	3.70×10^{-2}	370	3.94×10^{-2}	390	3.47×10^{-2}	400	3.26×10^{-2}
sum		3.06×10^{-1}		5.98×10^{-1}		6.75×10^{-1}		3.46×10^{-1}

there is comparatively higher. In order to take into account this, the design of a T0 Rotor (which is a round iron plate with 1 m thickness), an additional ferroconcrete gallery and an additional shielding to spectrometer are used. All these measures can ensure that the radiation dose rate is less than 2.5 μSv/h in the hall.

3.3 The radiation dose produced by skyshine

The neutrons and gamma rays produced in the target and accelerator can penetrate through the roof into the sky. Some of these neutrons and gamma rays may be reflected down to the ground because of scattering by the atmospheric molecules and atoms. This process is called Skyshine. The public around the border of the facility may be irradiated.

In the calculation of Skyshine, the Stapleton semi-empirical formulas are used, which are

$$H(r)=\frac{a\cdot\exp\left(-\dfrac{r}{\lambda(E_{\rm c})}\right)}{(b+r)^2}\cdot Q,$$

$$Q=\frac{{\rm d}^2}{g}\cdot H(d,t)\cdot\varOmega,$$

$$\varOmega=2\pi(1-\cos\theta).$$

Here

A is a coefficient, which is $2\times10^{-15}{\rm m}^2\cdot{\rm Sv}$.

B is a coefficient (40 m).

R is the horizontal distance from the calculating point to the source point(m).

$\lambda(Ec)$: is the attenuation length corresponding to cut-off energy(m).

$E_{\rm c}$ is the cut-off energy.

Q is the number of neutrons penetrating ground surface (here means the outside of the ceiling)(n/h).

D is the distance from source point to ground surface (m).

G is the conversion factor between dose and fluence (Sv·m^2).

$H(d,\ t)$ is the dose rate on the ground surface (Sv/h).

T is the thickness of shielding (m).

$\varOmega$ is the solid angle of the radiation source.

In the shielding design of the accelerator's main part and target, Skyshine affects the environment only slightly if the shielding is thick enough. The results are listed in the Table 2, which shows that the neutrons and gamma rays which penetrate the shielding can cause a maximal dose of as much as 0.68 μSv/a to the public. This value is by two orders less than the given boundary value of 0.08 mSv/a.

4 Analysis of the environmental safety

4.1 Air activation and emission

4.1.1 Emission of airborne radioactive effluent produced by air activation

The high energy protons running in the CSNS accelerator will produce secondary neutrons and gamma rays because of beam loss which hits the walls of the pipeline. The secondary rays will activate the air in the transmission tunnel [3]. The cascade neutrons will react with the N and O in the air, producing ^{3}H, ^{7}Be, ^{11}C and ^{13}N, and the evaporation neutron will react with ^{16}O via the (n, 2n) process leading to ^{15}O. Thermal neutrons will react with ^{14}N by the (n, p) process leading to ^{14}C [4], and react with ^{40}Ar producing ^{41}Ar by means of the (n, γ) reaction. The radioactive nuclides produced in these reaction processes are the main sources of the radioactivity in the air in the accelerator tunnel. There are also some nuclides whose half-life is less than 1 minute, caused by spallation and thermal neutron capture reaction, such as ^{14}O, ^{19}O, ^{10}C, ^{16}N and ^{17}N etc. The effect of these nuclides turned out to be insignificant when we analyzed the situation during the accelerator operation. Also the effect to the workers in the accelerator tunnel after the facility is turned off, is marginal. So they can be ignored.

The CSNS will work about 6000 hours each year. The tunnel is ventilated during the accelerator operation. Applying the transfer rules to the activated product's producing and removing, we deduce the radioactive activity that be emitted to the environment every year as

$$Q_i = A\left[t_0 + \frac{1}{\lambda_i + F/V}\left(\mathrm{e}^{-(\lambda_i+F/V)t_0} - 1\right)\right],$$

$$A = \frac{F\lambda_i\sigma\phi\rho A_0 f_n f_m}{(\lambda_i + F/V)G}.$$

Here

Q_i is the activity of nuclide i which is emitted to the environment every year (Bq/a).

$\phi(r)$ is the neutron fluence rate at the point r (n/(cm^2·s)).

σ is the activation crosssection of the parent nuclide which produces the nuclide i (cm^2).

λ_i is the decay constant of nuclide i (s^{-1}).

ρ is the air density(0.001293g/cm^3).

A_0 is Avogadro's constant(6.022×10^{23}/mol).

f_m is the natural abundance of the parent nuclide.

f_n is the weight percentage of the parent nuclide in air.

G is the parent nuclide's molar mass (g/mol).

t_0 is the working time of the accelerator(s).

F is the ventilation velocity in the tunnel(cm^3/s).

V is the volume of the tunnel (cm^3).

The calculation results show that the main elements emitted to the environment by the CSNS every year are ^{11}C, ^{13}N, ^{15}O, ^{41}Ar with an activity of 5.22×10^{12}Bq, 6.50×10^{12}Bq, 6.36×10^{12}Bq and 1.63×10^{10}Bq, respectively [5].

4.1.2 Radiation dose to the public caused by the emission of airborne radioactivity

Considering the weather conditions in the place where the CSNS is located and the components and emissions of the airborne radioactivity under normal conditions as the source term, the radiation dose to the public caused by it can be obtained. The results tell us that the adult may receive a maximum individual annual effective dose of 2.4×10^{-3} mSv/a, while for a child it is 2.29×10^{-3} mSv/a. From this about 93.8% is coming from external air immersions; 4.73% comes from inhalation, 1.46% comes from external ground deposition, and 0.01% comes from agricultural products. The main nuclei are ^{11}C, ^{13}N, ^{15}O [6].

4.2 Activation of the cooling water in the facility

During the operation of the CSNS, some parts and apparatuses need to be cooled with cooling water. While circulating, the cooling water will be activated through the irradiation by secondary neutrons produced when the device is working. The radioactive nuclei in the cooling water originate mainly from the spallation reaction between high energy neutrons and ^{16}O in water [7]. The main nuclei, their half-lives and reaction crosssections in the spallation reactions are shown in Table 3.

Table 3. Spallation product of ^{16}O.

nuclei	half-life	cross section*/mb
^{10}C	19 s	very small
^{14}O	71 s	5
^{15}O	2.03 min	60
^{13}N	10 min	10
^{11}C	20.39 min	20
^{7}Be	53.28 d	10
^{3}H	12.33 y	30

From the table we see that all nuclei, except ^{7}Be and ^{3}H, are short-lived. These short-lived nuclei will decay completely before they are set free into the air. Therefore their effect on the environment is negligible.

According to the operating condition of the CSNS, the cooling water in the facility flows in a closed circuit and will not be set free during operation. In the calculation we assume that after a long time working (as long as 6000 hours), the device will be shut down for 2760 hours. After working many years the radioactive concentration in the cooling water becomes saturated. According to the above situation and the document of Ref. [8], we can deduce the radioactive saturation concentration of the cooling water in the device to:

$$C_i = \sigma\phi\cdot\frac{\rho A_0 f_n f_m}{G}\cdot\frac{1-\mathrm{e}^{-\lambda T_0}}{1-\mathrm{e}^{-\lambda\tau}}\cdot\frac{1-\mathrm{e}^{-\lambda t_V}}{1-\mathrm{e}^{-\lambda T}}. \qquad (1)$$

Here

C_i is the density of nuclei i in the cooling water (Bq/cm^3).

σ is the activation corsssection of the parent nuclei (cm^2).

$\phi(r)$ is the flux of neutrons that enter the cooling water at the point r (n/(cm^2·s)).

ρ is the density of water (g/cm^3).

A_0 is Avogadro's constant(6.022×10^{23}/mol).

f_m is the weight percentage of the parent nuclei in water.

G is the molar mass of the parent nuclei (g/mol).

T_0 is the time during which the accelerator is working (s).

τ is the circulating period between two beams(s).

t_V is the time when the cooling water pass the target hall(s).

T is the period of the cooling water circulation(s).

λ is the time constant of the activated nuclei (s^{-1}).

There are 7 cooling water systems for the devices in the CSNS. According to Eq. (1) we can get the activity of ^{7}Be and ^{3}H in each system. The values are listed in Table 4. In the calculation the ratio of cascade neutrons is 30%.

It should be mentioned here that an Ion exchange resin purification device is used, which is able to purify ^{7}Be. Because the purification of ^{7}Be is not taken into consideration in the calculation, the result of ^{7}Be is comparatively conservative.

4.3 Activation of the soil and groundwater

The particles penetrating the tunnel walls of the accelerator will give rise to the activation of the soil and groundwater around the tunnel. The kinds of nuclei being produced depend on the geological conditions of the site. We can calculate the activation of the soil and groundwater around the tunnel with the FLUKA procedure [9]. According to the results, we can see that the maximal specific activity of the soil activated is very low, and the most severe activated place is the soil and groundwater near the shielding around the high energy transport line tunnel. The maximal specific activity of ^{3}H in the soil is 2.44 Bq/g, while in the groundwater it is 3.31 Bq/g, followed by ^{7}Be, ^{22}Na and ^{54}Mn. The exempt specific activity of the low-level solid waste in the PRC national standard GB13367-92 is listed in Table 5 as follows.

Table 4. The activity of ^{7}Be and ^{3}H of the cooling water system in each device.

name of system		density of the radioactivity in the cooling water/(Bq/cm^3)	
		^{7}Be	^{3}H
DTL drift tube		3.23×10^1	5.63×10^2
RCS magnet		5.26×10^0	9.16×10^2
RF cavity		1.14×10^1	1.99×10^2
collimator		2.47×10^4	4.30×10^5
target station	cooling heavy water	1.61×10^5	2.80×10^6
	common cooling water	4.84×10^4	8.43×10^5

Table 5. The exempt specific activity of low-level solid waste.

nuclei group	nuclei	exempt specific activity/(Bq/g)
high energy β-γ emitter	^{24}Na, ^{60}Co, ^{137}Cs	0.1–1.0
other β-γ emitter	^{54}Mn, ^{106}Ru, ^{131}I	1.0–10^2
α emitter	^{239}Pu, ^{241}Am	0.1–1.0
carbon	^{14}C	10^2–10^3
short-lived β emitter	^{32}P, ^{32}S, ^{35}Ca	10^3–10^4

Comparing the results obtained with FLUKA to the exempt specific activity of the low-level solid waste as listed in Table 5, we find that the specific activity of radioactive nuclei, produced by the activation of soil and groundwater in the CSNS, is less (or far less) than the exempt specific activity. We can conclude that the effect of activation of the soil and groundwater is trifle.

The specific activity of ^{24}Na in the soil near the high energy transport line tunnel given by FLUKA is 1.12 Bq/g. But this is the result at the spot with maximal level of activation. Because of the shielding effect of the soil, the activity in the other soil and groundwater is less than 1.12 Bq/g. That is to say, the specific activity of ^{24}Na is less than 1.0 Bq/g, so the request in GB13367-92 can be met.

4.4 The disposal of radioactive solid waste

Our calculations show that among the activities of the devices and various parts of the CSNS, the activity of parts of the target station is the most important one. The total induced radioactive activity of each part in target station can reach as much as 6.8×10^{15} Bq after operating one year continuously. And after 10 years the total activity will be 7.2×10^{15} Bq, about 90% of which accumulated in the target station and the target container, 4% in the Be reflector, 4% in the Fe reflector, and 2% in the structure material of the other parts.

The activation level in the other parts is not very high. The specific activity is approximately $\sim10^4$ Bq/g.

After operating for a long time, the core parts in the He container of the target station will be activated severely. In order to maintain and replace these parts quickly and conveniently, the core parts are assembled on a track vehicle. This track vehicle can carry the core parts from target station to the maintenance area behind the station, or in the opposite direction. The core parts will be maintained and replaced in the maintenance area. There are remote manipulators, semi-automatic master-slave manipulators, remote controlled cameras, and remote controlled cranes, etc. The remote maintenance personnel can be able to control the manipulators to maintain the core parts outside of the shielding of the maintenance area, whose shielding is made from concrete with a width of 1.2 m. The calculation results show that when the core activated parts are in the maintenance area, the dose out of the shielding is less than 2.5 μSv/h. Also they can cut, enfold and reduce the size of the replaced activated devices and pipelines in the maintenance area by remote operation. Then these activated parts are sent into the storerooms in the basement under the maintenance area. In some storerooms, there are target storage wells, which are used to store the replaced high activated target. Independent cooling loops, used to remove the heat of the activated target when they are stored, exist inside the storage wells. The total area of the storerooms is 5×10 m^2.

The ion-exchange resin in the cooling loops needs to be exchanged periodically. The replaced resin is kept in the low-level radwaste storeroom, which is located near the cooling water system. The area of this storeroom is 10×10 m^2.

According to the results of the analysis and calculations of chapter 4.2, the main radioactive nuclei in the cooling water are ^{7}Be and ^{3}H. So, the main radioactive nuclei in the replaced resin are ^{7}Be. As the result of Table 3 shows, the density of ^{7}Be in the cooling water is not high and the half-life of ^{7}Be is about 53.28 d. Therefore the replaced ion-exchange resin is sent to the low-level radwaste storeroom and decreases the radioactive activity by the decaying method. If we keep it for 10 half-life periods, which, for ^{7}Be, is 532.8 d, the activity will be reduced by about 3 orders. The average radioactive activity of the waste resin will be measured before it is sent away. If the data is less than the exempt value, the resin can be considered as a non-radioactive waste, however, while if the data is still higher than the exempt value, the resin can be still kept in radwaste storeroom or sent to the city radioactive waste base.

5 Summary

Our calculations are based on experiential equations and Monte Carlo simulation, and showed that during the accelerator operation the personnel (except the workers in the neutron hall), will receive a maximal dose of 0.46 mSv/a due to the neutrons and gamma rays penetrating the shielding. This is based on the assumption of 2000 h working time per year. Since the neutron hall is the place where the beam is guided out to the experiments, the corresponding dose there is somewhat higher. In order to take into account this, the design of a T0 Rotor (which is a round iron plate with 1 m thickness), an additional ferroconcrete gallery and an additional shielding to the spectrometer are used. All these measures can ensure that the radiation dose rate is less than 2.5 μSv/h in the hall. So the scientists experimenting in the neutron hall will receive an irradiation dose of no more than 5 mSv/a (assuming that a scientist works 2000 h every year as well). Even if the radiation dose rate, somewhere in the neutron hall, is higher according to the actual monitoring result, we will use some local shielding to reduce the dose rate to ensure it is less than 2.5 μSv/h everywhere in the hall.

With respect to the device maintenance workers, the increase of the operating distance and a strict control of the working time can ensure that the dose which the staff gets every year is less than 10 mSv/a, which is the dose limit for the CSNS.

The maximal dose to the public due to the neutrons and gamma rays penetrating the shielding is 0.68 μSv/a, 2 orders of magnitude less than the project limit.

The air in the beam tunnel will be activated because of neutron irradiation. The calculations show that the total activity of the airborne radioactivity is 1.18×10^{13} Bq every year. The main nuclei are ^{13}N, ^{11}C, ^{15}O and ^{41}Ar. Public adults may receives a maximal dose of 2.40×10^{-3} mSv/a, while for a children it will be 2.29×10^{-3} mSv/a. These values are 2 orders of magnitude less than the limit of 0.1 mSv/a mentioned in chapter 4.1. The critical path is air immersion, and the critical nuclei are ^{11}C and ^{13}N.

The radioactive wastewater is produced by the activation of the cooling water in the device. The main radioactive nuclei in the cooling water of each system in the device are ^{7}Be and ^{3}H. Their density in the cooling water system of the collimator and the target station is little higher than in the other cooling systems, where it is very low.

The device cooling water system is a closed circuit, opened only for empty during the maintenance (this is contrast to the cooling water in the collimator and the target station cooling water system which is never opened even during the maintenance of the device). The activated water is kept temporarily in the collection tank for radioactive waste water of the CSNS, together with the waste water that has leaked out of the cooling water system (roughly 0.5 m^{3}). The collection tank has to be discharged under a strict management. The waste water will be sampled and monitored before discharging. The allowed mount of discharged wastewater, each time and every month, is strictly ruled by the GB18871-2002 (Rule.8.6.2), and the water will be guided into the drainage network of Dongguan City together with the domestic and industrial waste water.

The activation of the soil and groundwater is very low. The specific activity of the soil and groundwater from the device is less (or far less) than the exempt specific activity of low-level solid waste given in GB13367-92. So we conclude that the activation of the soil and groundwater affects the environment only insignificantly.

The activated parts, the wasted target, and the wasted resin replaced from the cooling water system are the main solid radioactive wastes of the device. The method to deal with these wastes is to send them temporarily into the storeroom in the tunnel. The room has an area of about 5 m×10 m and can keep the waste for 30 years. Then the waste will be sent to the city radioactive waste base or solid waste disposal for further processing.

There are mainly two kinds of possible accidents in the CSNS. One is that workers enter, by mistake, the room of the operating device or the beam tunnel, which can cause personnel excessive exposure; the other is the occurrence of an accidental power-off, which leads to an accidental beam loss that causes instantaneously a high neutron and gamma ray intensity somewhere. For the former, there is a strict and reliable interlock system to prevent this kind of accident happening. For the latter, because the design of the device is very conservative and this kind of accident just produces an instantaneous dose, there is no affect to the environment.

We can conclude that, according to the experiential calculations and the M-C simulations, the CSNS will be safe to the environment and the request of the PRC national standard is fully met. But as a basic scientific research center, it is very important that all the results in this paper should be verified by experiment. The measurement results will be published after the project being constructed.

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