Study on induced radioactivity of China Spallation Neutron Source

WU Qing-Biao(吴青彪) WANG Qing-Bin(王庆斌)
WU Jing-Min(吴靖民) MA Zhong-Jian(马忠剑)
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

Abstract: China Spallation Neutron Source (CSNS) is the first High Energy Intense Proton Accelerator planned to be constructed in China during the State Eleventh Five-Year Plan period, whose induced radioactivity is very important for occupational disease hazard assessment and environmental impact assessment. Adopting the FLUKA code, the authors have constructed a cylinder-tunnel geometric model and a line-source sampling physical model, deduced proper formulas to calculate air activation, and analyzed various issues with regard to the activation of different tunnel parts. The results show that the environmental impact resulting from induced activation is negligible, whereas the residual radiation in the tunnels has a great influence on maintenance personnel, so strict measures should be adopted.

Key words: CSNS, radioactivity, FLUKA, dose, line-source

PACS: 07.89.+b, 28.41.Qb, 29.40.Wk **DOI:** 10.1088/1674-1137/35/6/017

1 Introduction

China Spallation Neutron Source (CSNS) is the first High Energy Intense Proton Accelerator (highest energy 1.6 GeV, current 125 μA) planned to be constructed in China during the State Eleventh Five-Year Plan period, whose induced radioactivity is very important for occupational disease hazard assessment and environmental impact assessment. In the process of beam acceleration and transport, some asynchronous protons will be lost in the surrounding materials (such as the beam pipe) and produce induced radioactivity by nuclear reactions. The induced radioactivity has bad effects, as follows. First, it harms the maintenance personnel by external irradiation as the personnel enter the tunnel and approach the activated components, or by internal irradiation as the personnel inhale activated air and tritium evaporated from cooling water. Second, it harms the public and environment in several ways, including activated air discharge to the surrounding environment, activated water infiltration through soil into underground water and then pollution of water sources and plant food.

On the basis of 1 W/m beam loss (maximal acceptable beam loss) and with the help of the FLUKA [1] code, this paper generally analyzes the induced radioactivity of CSNS by constructing a geometrical and physical model, and deducing the calculation formulas. Attention must be paid that if we take the great uncertainty of beam loss scenario, the following calculation results are conservative compared to future measurements within the range of several times, but it still gives a reasonable basis for assessment.

2 Model description

The CSNS tunnels include the following parts: Linear Accelerator (LINAC), Linear to Ring Beam Transport (LRBT), Rapid Cycling Synchrotron (RCS), and Ring to Target Beam Transport (RTBT). The beam loss rate along the tunnel beam line is designed to be 1 W/m, and the lost beam's energy includes 130 MeV (in LINAC and RTBT tunnel), 300 MeV (in RCS tunnel) and 1.6 GeV (in RTBT tunnel).

This paper picks the RTBT tunnel to analyze its activation, because it has the highest lost beam energy and the severest activation, and the other tunnels have similar results.

For simplicity, we constructed a cylinder-tunnel

Received 30 August 2010, Revised 19 October 2010

geometric model to represent the real rectangle-tunnel (see Fig. 1), whose length was 20 m (equal to the length of the straight linear part of the RCS). The inner radius and outer radius of the beam-pipe were 10 cm and 11 cm, respectively. From a safe and conservative point of view, we adopted 2 m as the tunnel inner radius, 50 cm as the concrete wall thickness, and 100 cm as the soil layer thickness [2]. The density of the soil was adopted as 1.9 g/cm^3, composed of dry soil with a density of 1.6 g/cm^3 and water with a volume of 30% in total. Substituting the soil with water and recalculating, we got the groundwater's activation results as well. To calculate the cooling water's activation, a hypothetical water pipe, made of iron and filled with cooling water, was placed parallel to the beam line. The water pipe was adopted as follows. Its axis was 22 cm away from the beam-pipe axis, and its inner radius and outer radius were 1 cm and 2 cm, respectively. By editing and compiling a user Fortran program–source.f, the lost protons were sampled along the beam-pipe linearly and uniformly, and hit the beam-pipe at a 10mrad emission angle (thus making the 1 cm thick beam-pipe equal to a 100 cm thick target for this situation). The sampling formulas were deduced as follows,

$$\text{position sample}\begin{cases} x = R_0\ \cos(2\pi\xi_1) \\ y = R_0\ \sin(2\pi\xi_1) \\ z = z_1 + \xi_2\cdot(z_2 - z_1) \end{cases},$$

$$\text{direction sample}\begin{cases} u = \sin\theta_0\cdot\cos(2\pi\xi_1) \\ v = \sin\theta_0\cdot\sin(2\pi\xi_1) \\ w = \cos\theta_0 \end{cases},$$

where (x, y, z) and (u, v, w) are the position coordinates and the direction cosines of the sampled particles, respectively; ξ_1 and ξ_2 are the two random numbers for sampling; R_0 is the radius of a supposed cylindrical surface for sampled particles; z_1 and z_2 are the z coordinates of the tunnel's two end planes; θ_0 is the emission angle of the sampled particles.

To calculate the activity and residual dose rate, we used some FLUKA input cards to set the running and shutting down mode of the accelerator, to record the residual dose rate and specific activity of all produced radioactive nuclides, which we normalized to per unit lost primary particle. Then we normalized it to 1 W/m by multiplying the total number of lost beam particles. Besides source.f, another user routine–usimbs.f was compiled, which, combined with the weight window set in input cards, reduced the computational time and improved the calculation accuracy.

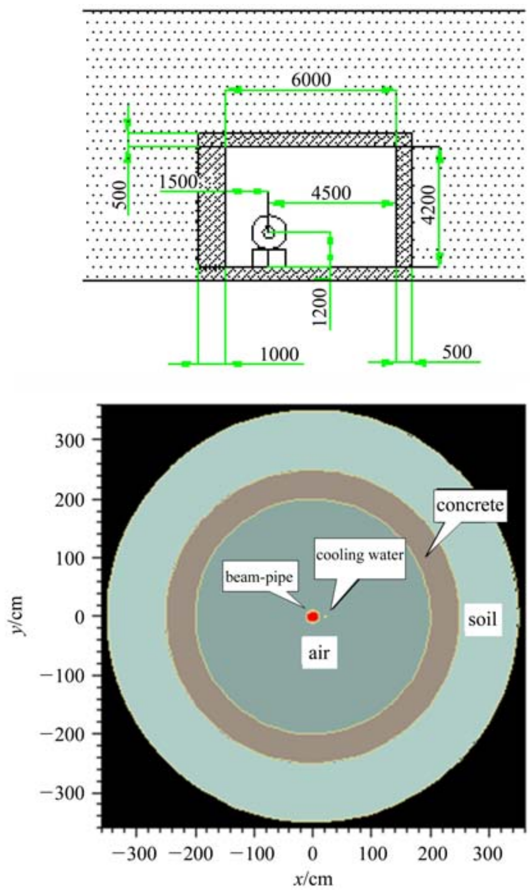

Fig. 1. The RCS tunnel and cylinder-tunnel geometric model.

3 Calculation method for air and water activation

3.1 Air activation calculation

During the accelerator running, in order to prevent the activated air from leaking out through the shielding gate and passageway, we have to ventilate the tunnel slowly to keep its air at negative pressure relative to the outside. After the accelerator was shut down, we waited half an hour for the activated air to decay (transition period), then ventilated the tunnel fast so as to avoid internal irradiation of the maintenance staff as they entered the tunnel. Taking the above factors into consideration, we must calculate the activity density and the total activity annually discharged to the environment in different ventilation conditions. Because the Monte Carlo code can only calculate the saturation activity at a static state (no ventilation), we deduced the following formulas for the ventilation state [3].

First, using Monte Carlo code, by setting a long running time of the accelerator (such as 30 years), we simulated the saturation activity (S_{sat}) of each radionuclide in the tunnel's air at static state. Then the instantaneous activity after any irradiation time (t_{i}) can be calculated as

$$S_{t_{\text{i}}} = S_{\text{sat}}(1-\text{e}^{-\lambda t_{\text{i}}}), \tag{1a}$$

where, λ is the radioactive decay constant. And the instantaneous activity after irradiation time (t_{i}) and cooling time (t_{c}) can be calculated as

$$S_{t_{\text{c}}} = S_{\text{sat}}(1-\text{e}^{-\lambda t_{\text{i}}})\text{e}^{-\lambda t_{\text{c}}}. \tag{1b}$$

Second, let us ignore the transition period (from the simple and conservative point of view), and suppose that the rate of ventilation during the irradiation period and cooling period is R_{i} and R_{c} (cm^3/s), respectively, and the air volume in the tunnel is V (cm^3). Now we need to introduce two more variables–effective loss constant λ_{lossi} and λ_{lossc}, to describe the effective loss rate of the radionuclide in the tunnel's air during irradiation period and cooling period, respectively. Then the decay constant in formula (1a) and (1b) should be replaced by λ_{lossi} and λ_{lossc} correspondingly,

$$\lambda_{\text{effi}} = \lambda_{\text{dec}} + \lambda_{\text{lossi}} = \lambda_{\text{dec}} + \frac{R_{\text{i}}}{V}, \tag{2a}$$

$$\lambda_{\text{effc}} = \lambda_{\text{dec}} + \lambda_{\text{lossc}} = \lambda_{\text{dec}} + \frac{R_{\text{c}}}{V}. \tag{2b}$$

So, the real (or dynamic) saturation activity will be reduced,

$$S_{(\text{reduced})} = S_{\text{sat}}\frac{\lambda_{\text{dec}}}{\lambda_{\text{effi}}}. \tag{3}$$

Substituting λ and S_{sat} in Formula (1a) and (1b) by (2a), (2b) and (3), the instantaneous activity in the ventilation state during the irradiation period and the cooling period can be written as

$$S_{t_{\text{i}}} = S_{(\text{reduced})}(1-\text{e}^{\lambda_{\text{effi}} t_{\text{i}}}), \tag{4a}$$

$$S_{t_{\text{c}}} = S_{(\text{reduced})}(1-\text{e}^{\lambda_{\text{effi}} t_{\text{i}}})\text{e}^{\lambda_{\text{effc}} t_{\text{c}}}. \tag{4b}$$

Finally, the total amount of activity Q_{i} and Q_{c} released to the environment during the irradiation period and cooling period can be calculated by integrating the instantaneous activity with time,

$$Q_{\text{i}} = \int_0^{t_{\text{i}}} S_{t_{\text{i}}} R_{\text{i}} \text{d}t = S_{\text{sat}}\frac{\lambda_{\text{dec}}}{\lambda_{\text{effi}}} R_{\text{i}}\left(t_{\text{i}} - \frac{1}{\lambda_{\text{effi}}}(1-\text{e}^{\lambda_{\text{effi}} t_{\text{i}}})\right), \tag{5a}$$

$$Q_{\text{c}} = \int_0^{t_{\text{c}}} S_{t_{\text{c}}} R_{\text{c}} \text{d}t = S_{\text{sat}}\frac{\lambda_{\text{dec}}}{\lambda_{\text{effi}}} R_{\text{c}}(1-\text{e}^{\lambda_{\text{effi}} t_{\text{i}}})\frac{(1-\text{e}^{\lambda_{\text{effc}} t_{\text{c}}})}{\lambda_{\text{effc}}}. \tag{5b}$$

3.2 Cooling water activation calculation

The real saturation activity of radionuclides in circulating cooling water can be calculated using the following formula [4],

$$S_{(\text{reduced})} = S_{\text{sat}} \times \frac{1-\text{e}^{\lambda t_{\text{V}}}}{1-\text{e}^{\lambda T}}, \tag{6}$$

where, t_{v} is the irradiation time and T is the one cycle period of cooling water. Other quantities have the same meanings, as mentioned above.

4 Calculation results and analysis

4.1 Activation of beam-pipe

The exempt value for activation is pointed out in Appendix A of GB-18871 (Basic Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources): "if there are more than one kind of radionuclide, only if the sum of the ratio of activity (or specific activity) to its exempt value of each kind of the radionuclide was less than 1, it is exemptible". We can see from Table 1 that most of the radionuclides are long-lived radionuclides, and the half-life of about 90% of radionuclides is greater than 12 days. The sum of the ratio of specific activity to their exempt value is greater than 1000, so the beam-pipe is activated strongly.

4.2 Activation of concrete

The main radionuclides produced by concrete are ^{22}Na, ^{15}O, ^{18}F and ^{54}Mn. The half-life of about 46% radionuclide is greater than 12 days. Special attention must be paid to ^{22}Na and ^{24}Na, because both of them may dissolve into precipitation and then permeate into the ground water. The sum of the ratio of saturation specific activity to exempt specific activity is about 1.5, so the concrete is activated mildly.

4.3 Activation of soil and ground water

The main radionuclides produced by soil include ^{56}Mn, ^{24}Na, ^{22}Na, ^{54}Mn, ^{15}O, ^{18}F and ^{52}Mn. The sum of the ratio of saturation specific activity to exempt specific activity is about 0.66, which can be exempted according to GB 18871-2002.

The main radionuclides produced by ground water include ^{15}O, ^{7}Be, ^{3}H, ^{14}C, in which ^{15}O (with short half-life) and ^{14}C (with long half-life) have no influence on the environment. In fact, only ^{7}Be and ^{3}H need to be considered, but their saturation specific activities are far less than their exempt values and have little influence on the environment as well. Thus, we reached the conclusion that we adopted 50 cm as the

Table 1. Specific activity of beam-pipe in RTBT tunnel (radionuclide with saturation specific activity less than 10 times of its exempt value is not included here).

radionuclide	A	Z	$T_{1/2}$/s	saturation specific activity/(Bq/g)	saturation/exempt
F	18	9	6.59×10^{3}	1.39×10^{2}	1.39×10^{1}
Na	22	11	8.21×10^{7}	2.17×10^{2}	2.17×10^{1}
Na	24	11	5.39×10^{4}	1.54×10^{2}	1.54×10^{1}
Sc	46	21	7.24×10^{6}	7.64×10^{2}	7.64×10^{1}
V	48	23	1.38×10^{6}	2.26×10^{3}	2.26×10^{2}
Mn	51	25	2.77×10^{3}	6.66×10^{2}	6.66×10^{1}
Mn	52	25	4.83×10^{5}	1.77×10^{3}	1.77×10^{2}
Mn	54	25	2.70×10^{7}	7.59×10^{3}	7.59×10^{2}
Mn	56	25	9.28×10^{3}	1.15×10^{3}	1.15×10^{2}
Co	55	27	6.31×10^{4}	1.45×10^{2}	1.45×10^{1}
Co	56	27	6.68×10^{6}	3.54×10^{2}	3.54×10^{1}
sum			all-$T_{1/2}$	5.08×10^{4}	1.56×10^{3}
			$T_{1/2}$ >12 days	4.55×10^{4}	1.13×10^{3}

Table 2(a). Specific activity of soil in RTBT tunnel (only some important radionuclides are included).

radionuclide	A	Z	$T_{1/2}$/s	saturation specific activity/(Bq/g)	saturation/exempt
H	3	1	3.89×10^{8}	2.44	2.44×10^{-6}
Be	7	4	4.60×10^{6}	5.78×10^{-1}	5.78×10^{-4}
O	15	8	1.22×10^{2}	4.40	4.40×10^{-2}
F	18	9	6.59×10^{3}	2.52×10^{-1}	2.52×10^{-2}
Na	22	11	8.21×10^{7}	9.82×10^{-1}	9.82×10^{-2}
Na	24	11	5.39×10^{4}	1.12	1.12×10^{-1}
Mn	52	25	4.83×10^{5}	1.00×10^{-1}	1.00×10^{-2}
Mn	54	25	2.70×10^{7}	7.83×10^{-1}	7.83×10^{-2}
Mn	56	25	9.28×10^{3}	2.76	2.76×10^{-1}
Fe	55	26	8.61×10^{7}	2.24	2.24×10^{-4}
sum			all-$T_{1/2}$	1.75×10^{1}	6.65×10^{-1}
			$T_{1/2}$ >12 days	8.02	3.19×10^{-1}

Table 2(b). Specific activity of underground water in the RTBT tunnel.

radionuclide	A	Z	$T_{1/2}$/s	saturation specific activity/(Bq/g)	saturation/exempt
H	3	1	3.89×10^{8}	3.31	3.31×10^{-6}
Be	7	4	4.60×10^{6}	9.46×10^{-1}	9.46×10^{-4}
C	14	6	1.81×10^{11}	2.83×10^{-2}	2.83×10^{-6}
O	15	8	1.22×10^{2}	9.67	9.67×10^{-2}
sum			all-$T_{1/2}$	1.40×10^{1}	9.77×10^{-2}
			$T_{1/2}$ >12 days	4.28	9.52×10^{-4}

concrete wall thickness in the main tunnel shielding, which can meet the needs of not making the soil and the ground water activated out of limit.

In addition, the ratio of total saturation activity of the soil (30% water excluded) to that of the ground water can be figured out as

$$S_{\rm soil}/S_{\rm water}=5.24.$$

The result agrees with IAEA-NO.283 report, which concludes that the total activity of the soil is about 5–10 times greater than that of the water [5]. This is a reliable basis for checking the calculation results.

4.4 Air activation analysis

The air activation results are shown in Fig. 2 and

Table 3, from which we conclude the following:

(1) The dynamic saturation activity of the long-lived radionuclide is about several orders of magnitude less than its static saturation activity, such as ^{3}H, ^{7}Be, whose half-life is far greater than the ventilation period (400 minute); whereas for those short-lived radionuclide whose half-life is far less than the ventilation period, the dynamic saturation activity is almost the same as its static saturation activity.

(2) It's common sense that we can believe that a radionuclide reaches its saturation state when the irradiation time is greater than 10 times its half-life. The dynamic half-life is less than 6.6 hours for all of the radionuclides in the ventilation situation, so it is acceptable that all of the radionuclides reach their saturation states as long as the irradiation time is greater than 66 hours.

(3) During the period of accelerator overhaul, after machine shutdown, there's half an hour (transition period) before ventilating fast. All of the radionuclides in air can be evacuated in one hour, so there is no need to consider the effect of the internal irradiation on the maintenance personnel.

(4) The total amount of radioactivity released to the environment after machine shutdown (Q_c) is about 3 orders of magnitude less than that during the running period (Q_i), so it is negligible.

(5) The main radionuclides that may harm the environment are ^{15}O (produced by (n, 2n) reaction of ^{16}O), ^{41}Ar (produced by (n, γ) reaction of ^{40}Ar), and ^{38}Cl, ^{3}H, ^{7}Be, ^{11}C, ^{13}N, etc, which are products of spallation reaction products reacting with N or O in air. The dynamic saturation specific activity of all of these nuclides is far less than their exempt value except ^{15}O, but the half-life of ^{15}O is only 2 minutes, so it will decay fast and can therefore also be neglected.

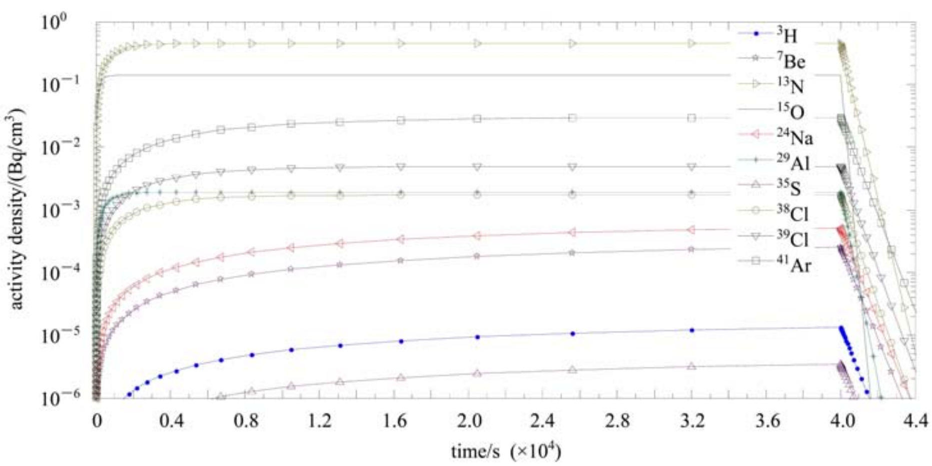

Fig. 2. Relation between activity density and time of main radionuclides in air of RTBT tunnel in ventilation state.

Professor Liu Yuanzhong, Tsinghua University, adopted traditional analysis formulas (using the energy spectrum multiplied by the activation cross section to determine the activity), and the neutron spectrum provided by the authors, roughly took 70%, 29% and 1% as the percentage for evaporation neutron, cascade neutron and thermal neutron, figured out the annual discharge amount of radionuclides of air in CSNS tunnels [6]. By comparison, our results agreed with Professor Liu's, and the latter are more conservative.

4.5 Cooling water activation results

We determined the saturation activity density of cooling water from Formula (6), as listed in Table 4. If the half-life and saturation activity density are considered comprehensively, the main radionuclides produced are ^{7}Be and ^{3}H. The cooling water is a closed–circuit circulation system: the water can only be discharged into a special gathering tank during the device overhaul period, and then be put into the cooling system for reuse after the overhaul. As long as the leakage of the cooling water is small, its hazard to the environment can be neglected.

4.6 Residual dose rate and cooling time

Figure 3 shows the relationship between the residual dose rate and the cooling time in the RTBT tunnel after 100 years' running. The literature [7] gives a figure that shows the space distribution curves of the residual dose rate after 30 years' continuous running and 4 hours' cooling by using the

MCNP+HETC+ORIHET routines and point-source model to calculate the different energy parts of the LINAC tunnel of the American Spallation Neutron Source (SNS). Converting to the same conditions using Formula (7) [8], our calculation results of the residual dose rate agree well with the literature [7]. As the calculation in the literature [7] agrees well with the corresponding measurement results [9], we can say that our calculation will agree with our future measurements as well. More than that, our line-source sampling physical model displays a more realistic space distribution of radiation field than obtained by the point-source model. From Fig. 3, we conclude:

Table 3. Saturation activity density and total activity annually released to the environment from the air of the RTBT tunnel.

radionuclide	A	Z	$T_{1/2}$/s	$S_{\rm sat}$/ (Bq/cm^3)	$S_{\rm (reduced)}$/ (Bq/cm^3)	$S_{\rm (reduced)}$/ $S_{\rm (exempt)}$	$Q_{\rm i}$/(Bq/a)	$Q_{\rm c}$/Bq
H	3	1	3.89×10^{8}	3.85×10^{-1}	1.65×10^{-5}	1.34×10^{-8}	5.31×10^{7}	5.87×10^{4}
Be	7	4	4.60×10^{6}	8.75×10^{-2}	3.15×10^{-4}	2.57×10^{-4}	1.01×10^{9}	1.12×10^{6}
C	14	6	1.81×10^{11}	2.07×10^{-1}	1.90×10^{-8}	1.55×10^{-9}	6.11×10^{4}	6.76×10^{1}
O	15	8	1.22×10^{2}	1.40×10^{-1}	1.39×10^{-1}	1.14	4.47×10^{11}	1.13×10^{8}
Na	24	11	5.39×10^{4}	2.44×10^{-3}	5.75×10^{-4}	4.69×10^{-2}	1.85×10^{9}	2.03×10^{6}
S	35	16	7.56×10^{6}	1.95×10^{-3}	4.28×10^{-6}	3.49×10^{-8}	1.38×10^{7}	1.52×10^{4}
Cl	38	17	2.23×10^{3}	1.95×10^{-3}	1.72×10^{-3}	1.40×10^{-1}	5.54×10^{9}	5.16×10^{6}
Ar	41	18	6.56×10^{3}	4.13×10^{-2}	2.96×10^{-2}	2.42×10^{-1}	9.52×10^{10}	9.94×10^{7}
sum			all-$T_{1/2}$	1.66	0.939	1.565	3.02×10^{12}	1.48×10^{9}
			$T_{1/2}>10^4$ s	0.687	9.10×10^{-4}	4.72×10^{-2}	2.93×10^{9}	3.23×10^{6}

Table 4. Saturation activity density of cooling water in CSNS main systems.

radionuclide	A	Z	$T_{1/2}$/s	$S_{\rm (reduced)}$/(Bq/cm^3)		
				DTL-drift tube	RCS-magnet	RFQ-high frequency cavity
H	3	1	3.89×10^{8}	1.56	1.61×10^{2}	2.56×10^{1}
Be	7	4	4.60×10^{6}	1.49×10^{-1}	2.12×10^{1}	6.32
C	14	6	1.81×10^{11}	1.78×10^{-2}	2.86	5.83×10^{-1}
N	16	7	7.13	7.45	1.03×10^{3}	1.17×10^{2}
O	15	8	1.22×10^{2}	4.42	7.98×10^{2}	1.23×10^{2}

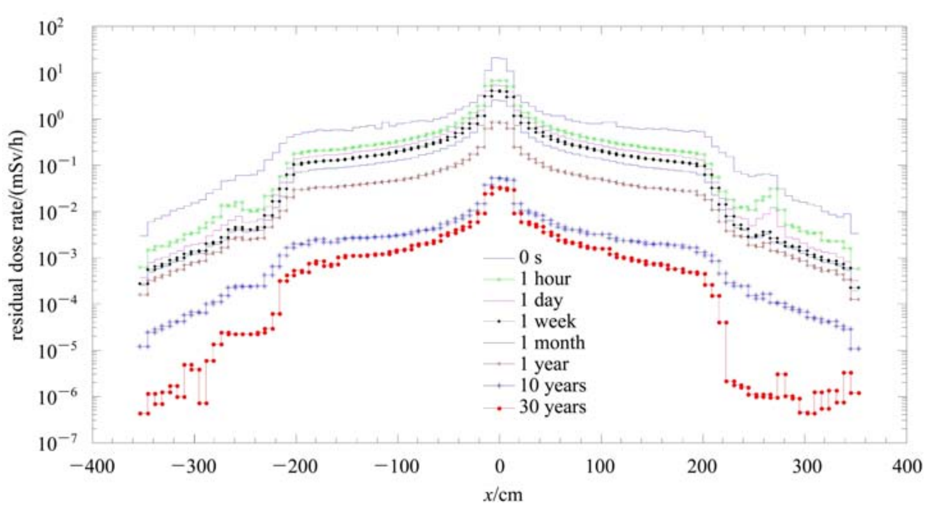

Fig. 3. Relationship between the residual dose rate and the cooling time in the RTBT tunnel after 100 years' continuous irradiation.

(1) The residual dose rate is dominated by the activation of the beam-pipe (and magnets). The concrete activation contributes less than 2% of the total residual dose rate.

(2) The residual dose rate attenuates with the distance away from the beam axis, basically obeying inversely the proportional relationship.

(3) The relationship between the total residual dose rate and time can be written approximately as follows according to the literature [8],

$$D(T,t)=aGI\ \ln\left(\frac{T+t}{t}\right)\propto\ \ln\left(\frac{T+t}{t}\right). \qquad (7)$$

Where $D(T,\ t)$ is the residual dose rate after irradiation time T and cooling time t, a, G, I are constants. Using the results of Fig. 3 and Formula (7), we obtained, after 100 days' irradiation and 4 hours' cooling, the residual dose rates at the place of 30 cm away from beam-pipe surface are −0.51 mSv/h (LINAC and LRBT tunnel), 0.70 mSv/h (RCS tunnel), 0.38 mSv/h (RTBT tunnel). All of these values are less than 1 mSv/h, and match the regulations adopted by SNS: the maintenance personnel can get into the tunnel only when the residual dose rate is below 1 mSv/h [10].

According to the operating experiences of other spallation neutron sources, the working time of maintenance personnel in the tunnel is approximately 3 hours per year. If we take conservatively 1mSv/h as the residual dose rate in the tunnel during the overhaul period, this will bring about 3 mSv per year to CSNS maintenance personnel.

(4) After the accelerator shutdown, the residual dose rate in the tunnel will drop to 1/2 one hour later, to 1/3 one week later, then fall very slowly–for the reason that the residual dose rate is determined by the activation of the beam-pipe (and magnet), and most radionuclides produced by beam-pipe activation are long-lived. Therfore, if the worker needs to overhaul in the tunnel and the job is urgent, it's no use waiting too long.

5 Conclusion

Adopting the FLUKA code, we first constructed a cylinder-tunnel geometric model and a line-source sampling physical model. Then we deduced some proper formulas to calculate air activation in the ventilation state. At last, according to the 1W/m beam lost power and lost beam's energies of different tunnels, we calculated and analyzed various issues on activation of the beam-pipe, air, soil, ground water and cooling water, including activity and its density of the main radionuclides, annual amount of radionuclides discharged to the environment from activated air, residual dose rates changing with time, etc. The results show that the environmental impact resulting from induced activation is negligible, whereas the residual radiation in the tunnels has a great influence on maintenance personnel, so strict measures should be adopted. The calculation results are the fundamental basis for occupational disease hazard assessment and environmental impact assessment.

References

1 www.fluka.org

2 Rokni S, LIU J C, Roesler S. Initial Estimates of the Activation Concentration of the Soil and Groundwater Around the NLC Beam Delivery System Tunnel. SLAC RP Note, 2000, RP-00-04: 2–3

3 Thomas Ralph H et al. NCRP Report No.144, 2003. 148–149

4 Jaeger R G et al. Engineering Compendium on Radiation Shielding, VolumeIII, Shielding Design and Engineering. New York: Springer-Verlag, Berlin, Heidelberg, 1970. 263–268

5 Thomas R, Stevenson G R. IAEA Technical Report No.283, 1988. Chapter **6**: 26–27

6 LIU Yuan-Zhong et al. CSNS Environmental Impact Assessment Report. Tsinghua University: Institute of High Energy Physics, 2007. 29–32 (in Chinese)

7 SANTORO R T, BARNES Y Y. Spallation Neutron Source Radiation Shielding Issues. ORLN. 2008. 3–4

8 Patterson H W, Thomas R H. Accelerator Health Physics: (in Chinese), translated by XI Hui-Chang, WANG Yi-Ming, DU De-Lin et al. Beijing: Atomic Energy Press, 1983. 289–290

9 http://www.ornl.gov/∼webworks/cppr/y2001/pres/113280.pdf

10 WEI J, Abell D, Beebe-Wang J et al. Low-Loss Design for the High-Intensity Accumulator Ring of the Spallation Neutron Source. Physical Review Special Topics-Accelerators and Beams, 2000, **3**: 13–13