Nuclear Analyses for ITER NB System

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Abstract. Detailed nuclear analyses for the latest ITER NB system are required to ensure that the NB design conforms to the nuclear regulation for licensing. A variety of nuclear analyses started for ITER NB system including a tokamak building of ~ 50 m x 35 m x 20 m and outside the building by using a Monte Carlo code MCNP in 2009. MCNP geometry input data were successfully produced from simplified NB CAD data with the improved GEOMIT code, which automatically converts CAD data to MCNP geometry input data. We have performed calculations of the effective dose rates during DT operation and after shutdown, and activation of the NB components, etc. The effective dose rates satisfy the nuclear regulation with a few modifications of the shield design.

1. Introduction

In ITER, the effective dose rates at the non-controlled areas in the site and the site boundaries should be less than 80 μSv per month and 1 mSv per year, respectively, according to French regulations. In addition, the decay gamma-ray dose rates for workers at locations where hands-on maintenance must be below 100 μSv per hour in 12 days after DT operation shutdown. There are a lot of ports in the vacuum vessel of the Tokamak machine. The radiation shield plugs are installed in most of ports in order to reduce the radiation streaming through the ports. However the radiation shield plugs cannot be installed in the NB (Neutral Beam) injection ports, because neutral beams are required to be directly injected to the plasma. There are three HNB (Heating NB) ports and one DNB (Diagnostic NB) port, and there are large openings with about 130 cm in height and 60 cm in width in these ports. The effective dose rates increase due to the radiation streaming through the NBI ports. The radiation shield design for the NB ports is one of the most critical concerns in the shield design of ITER.

The NB system is composed of front components, injectors and high voltage transmission lines, etc. The front components are composed of the fast shutter, bellows and exit scraper, etc. The injectors are composed of magnetic field coil, opening door, passive magnetic shield, injector vessel, neutralizer, calorimeter, residual ion dump, ion source and bushing, etc. The front components and the injectors exist in the first and second floors of the building, and the high voltage transmission lines exist in the third floor. Although the NB system exists outside the bio-shield, DT neutrons generated in the plasma directly penetrate through the NB ports with large opening, and the radiation fluxes around the NB system increase. In addition, an outside concrete wall in the third floor has four large openings for the NB transmission lines, and the effective dose rates outside the Tokamak building increase.

Detailed nuclear analyses for the latest ITER NB system are required to ensure that NB design conforms to the nuclear regulation for licensing. A variety of nuclear analyses started for ITER NB system including a tokamak building of ~ 50 m x 35 m x 20 m and outside the building in 2009. The NB system and the tokamak building are very complicated, and the shielding analyses for such complicated and large structure had not been performed in the previous studies. The Monte Carlo calculation code MCNP5.14 [2] was adopted to evaluate the radiation dose rates with high accuracy, because the calculation geometry can be exactly modelled in this code. However it is practically impossible to make geometry input data for the MCNP calculation of the NB system and the building manually. Thus we have developed the conversion program from the CAD data to the MCNP geometry input data, GEOMIT [1]. By using MCNP and the detailed calculation geometry input data created by GEOMIT, we performed neutron and prompt gamma-ray transport calculations during DT operation. In addition, we performed decay gamma-ray transport calculations after shutdown. We performed activation calculation of the components in the NB system, and evaluated the gamma-ray dose rates from transport cask containing activated NB components. In this paper, we mention effective dose rate distribution outside Tokamak building, shutdown dose rate inside Tokamak building and effective gamma dose rates from transport cask with activated NB component.

2. Calculation Method

Radiation transport calculations were performed with MCNP5.14 and Fusion Evaluated Nuclear Data Library FENDL-2.1 [3]. Activation calculations were performed with the activation calculation code ACT-4 [4]. A special “Direct 1-step Monte Carlo” method [5] was adopted for shutdown dose rate calculations. The activation calculations were carried out based on the SA2 operation scenario specified by ITER organization for ITER nuclear analyses [6]. Table I shows the SA2 operation scenario. We used the automatic conversion code GEOMIT to make MCNP geometry input data from CAD data. For these analyses, GEOMIT was improved as follows; (1) The conversion performance from CAD data to MCMP geometry input data was drastically enhanced. The CAD solid data of the NB system could be fully converted to the MCNP solid cell data. (2) The void cells in MCNP input data were generated by subtracting the solid cell data from simple rectangular void cells. In order to drastically reduce the memory size in MCNP calculations to suitable one to our computer, we represented the void cells without the complement function “#” in MCNP by using only surface function.

We produced the MCNP geometry input data by using the CAD data of the latest NB system supplied from ITER Organization. The CAD data are produced for fabrication, and therefore they are too detailed and had many extra parts such as small bolts unnecessary for the nuclear

TABLE I: SA2 OPERATION SCENARIO.

Duration	2 y	10 y	0.667 y	1.325 y	3920 s	400 s	3920 s	400 s
Neutron wall loading (MW/m^2)	0.003	0.0231	0	0.0465	0	0.56	0	0.784
Fusion power (MW)	2.68	20.6	0	41.5	0	500	0	700
Repetition	once				17 times		3 times	

analysis. In addition, the spline functions were used in the CAD data, but they cannot be represented in MCNP. In order to solve these problems, we simplified the CAD data to be able to apply them to the nuclear analyses. Figure 1 shows a 3D view of the simplified NB system CAD data including the tokamak building, which is composed of 2213 solids. The CAD data was loaded to GEOMIT and was successfully converted to MCNP geometry input data after void generation in short time. Figure 2 shows a horizontal cross-sectional view of the created MCNP geometry data around the NB system in the first floor. Figure 3 shows a vertical cross-sectional view of MCNP geometry data along the dotted line A-A' in Fig. 2. Four point neutron sources were set in the front components as shown in Fig. 2, and they were prepared taking into account the neutron current from the plasma [7]. The neutron current was estimated by the MCNP calculation with the 80-degree ITER Tokamak NBI sector model (based on A-lite model which was the reference model for ITER nuclear analyses prepared by ITER Organization [8]). The neutron fluxes at the injector inlet by the point neutron source used in this study agreed well with those by A-lite [7]. It takes huge and unrealistic calculation time to perform MCNP calculation with the model combined to NB system model and A-lite. In order to drastically shorten the calculation time, the MCNP calculations were done with the sole NB system model. As a result, we could get the calculation results with adequate accuracy. In order to check the geometrical error, we performed a test calculation. From the test calculation results, it could be confirmed that there were no lost particles. This demonstrated that there were no geometry errors in the MCNP input data. The detailed calculation methods for each calculation are mentioned in the following sections.

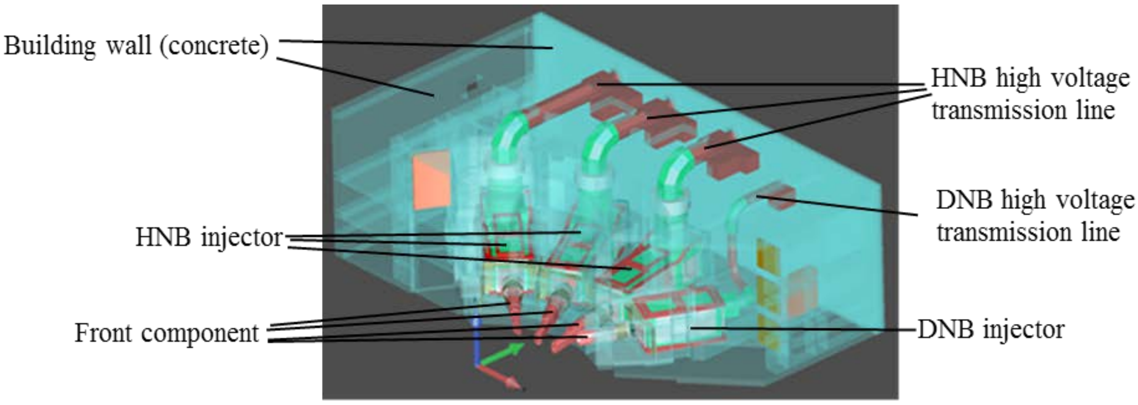

FIG. 1. 3D view of simplified NB system CAD data including tokamak building.

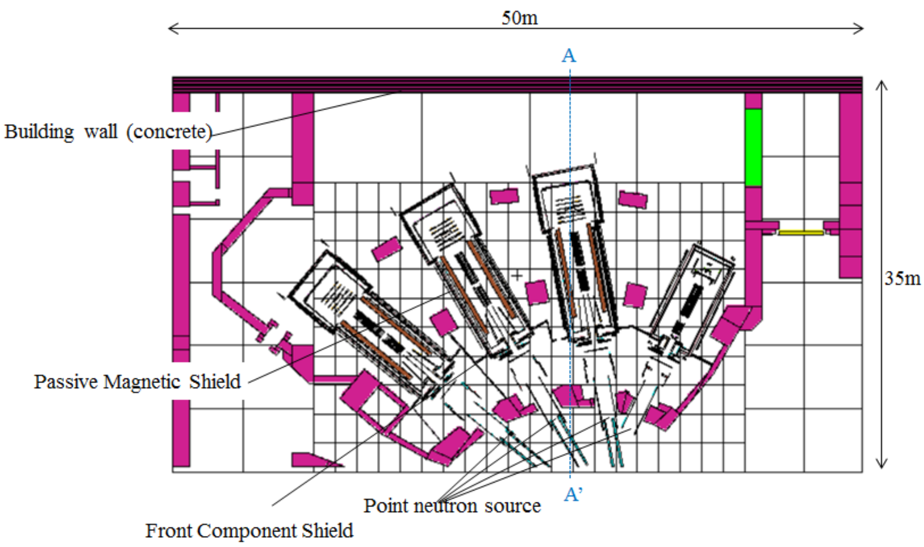

FIG. 2. Horizontal cross-sectional view of MCNP geometry around the NB system in the first floor.

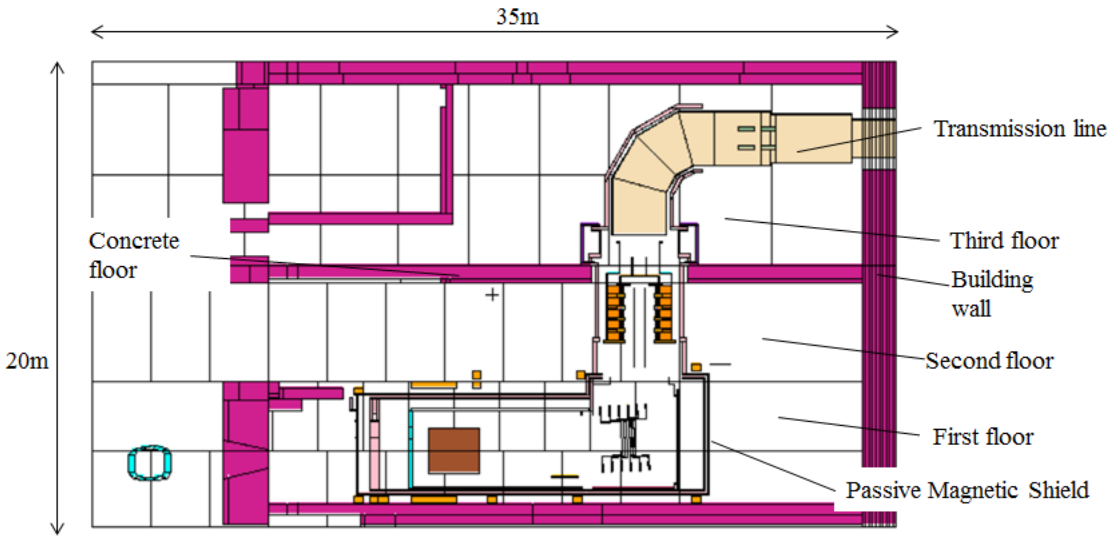

FIG. 3. Vertical cross-sectional view of MCNP geometry along the dotted line A-A' shown in Fig.2.

3. Effective dose rate distribution outside Tokamak building

We performed neutron and prompt gamma-ray transport calculations during DT operation, and evaluated effective dose rate distribution outside Tokamak building. Figure 4 shows the map outside the Tokamak building. The effective dose rates in the north area outside Tokamak building increase due to neutrons and gamma-rays from the NB systems. The bold blue dashed line in Fig. 4 shows the boundary (130 m from the Tokamak building north wall) between the electric power area for the NB system, which will be a controlled area, and the office area. At this boundary, the effective dose rate should be less than 80 μSv/month. In addition, the effective dose rates at the north site boundary, which is about 350 m far from the Tokamak building north wall, should be less than French regulation of 1 mSv per year. The effective dose rate outside Tokamak building due to neutrons and gamma-rays passing through the concrete wall in the first and second floors are much larger than that in the third floor. On the other hand, an outside concrete wall in the third floor has four large openings with about 2 m in diameter for the NB transmission lines, though there are no openings in the first and second floors. The effective dose rate outside Tokamak building increases due to the radiation streaming through the openings. Two factors should be considered for the effective dose rates outside the Tokamak building as follows; (1) The radiation passing through the concrete wall in the first and second floors, (2) The radiation streaming through the opening in the third floor. Calculations were separately performed for the above two factors, because of easier calculation treatment. The calculation geometries on the third floor were deleted in the calculation (1). The whole model was used in the calculation (2), where neutron and photon importance just behind the outer concrete wall in the first and second floors were set to 0 in order to eliminate neutrons and photons passing through the outer concrete wall in the first and second floors. Calculation time was drastically saved, and the effective dose rates outside the Tokamak building due to the radiation streaming through the opening in the third floor were effectively evaluated with adequate accuracy.

In the calculation (1), we calculated the effective dose rate outside the Tokamak building for outer concrete all of 2.1 m in thickness. The effective dose rate at these boundaries is inserted to Fig. 4. It is expected that the effective dose can satisfy French regulation if considering ITER operation duty factor and calculation safety factor. For the calculation (2), the additional shields around the openings for the transmission lines at the outer wall concrete and the floor concrete at the third floor are assumed in order to reduce dose rates outside the building. With these shields it was found that the effective dose rate at the boundary satisfies French regulation even if including the dose rate from the first and second floors. The effective dose rate at the site boundary at 350 m far from the Tokamak building can fully satisfy French regulation, 1mSv per year.

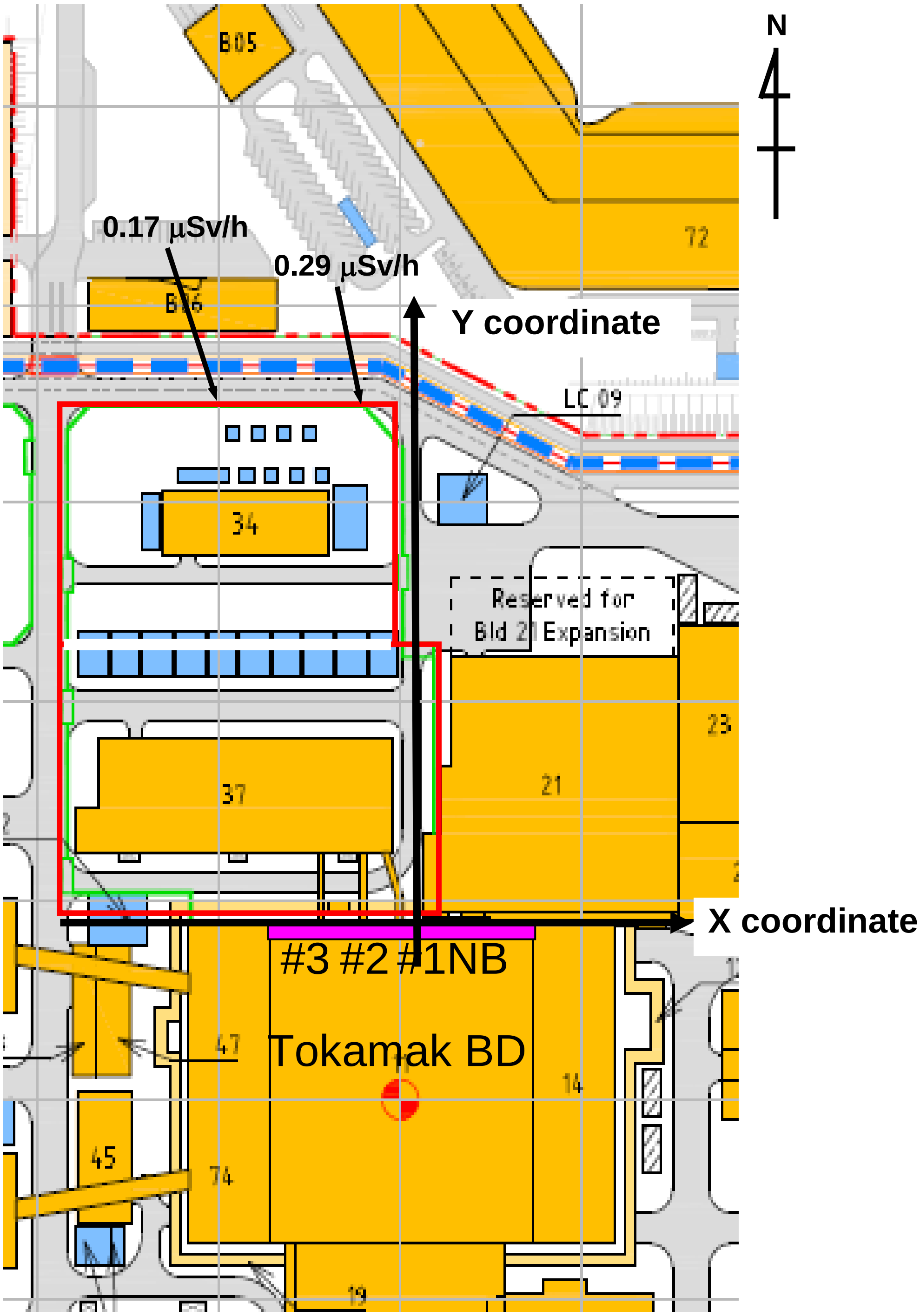

FIG. 4. Evaluation point on effective dose rate outside Tokamak building.

4. Shutdown dose rate inside Tokamak building

In order to avoid poor spatial resolution problem in the traditional 2-step calculation process of shutdown dose rate, namely neutron transport during reactor operation and photon transport after shutdown, ITER project developed a special technique so called "Direct 1-step Monte Carlo" for shutdown dose rate calculation. Some modifications are necessary for the both of the MCNP code and nuclear data file to implement "1-stepMonte Carlo". MCNP program on the gamma-ray generation was modified to recognize that "important reaction" has occurred, which emits influential decay photons to the dose rate after shutdown. Prompt secondary photon spectrum caused by these important reactions was replaced with decay photon spectrum from the product of such important reactions. In this study, the Direct 1-step Monte Carlo calculation was conducted for the following reactions; $^{59}Co(n,\gamma)^{60}Co$, $^{50}Cr(n,\gamma)^{51}Cr$, $^{52}Cr(n,2n)^{51}Cr$, $^{63}Cu(n,\gamma)^{64}Cu$, $^{54}Fe(n,p)^{54}Mn$, $^{56}Fe(n,p)^{56}Mn$, $^{57}Fe(n,n'p)^{56}Mn$, $^{58}Fe(n,\gamma)^{59}Fe$, $^{55}Mn(n,\gamma)^{56}Mn$, $^{58}Ni(n,p)^{58}Co$, $^{60}Ni(n,p)^{60}Co$, $^{61}Ni(n,n'p)^{60}Co$, $^{62}Ni(n,\alpha)^{59}Fe$, $^{186}W(n,\gamma)^{187}W$, $^{181}Ta(n,\gamma)^{182}Ta$, $^{93}Nb(n,2n)^{92m}Nb$. Only these nuclides contribute to the effective dose rates at 10^6 s after shutdown. Figure 5 shows the horizontal cross-sectional view of MCNP geometry in the third floor and the calculation results on the shutdown dose rates in some points around the transmission lines in the third floor. They can fully satisfy the design limit of 100 microSv/h.

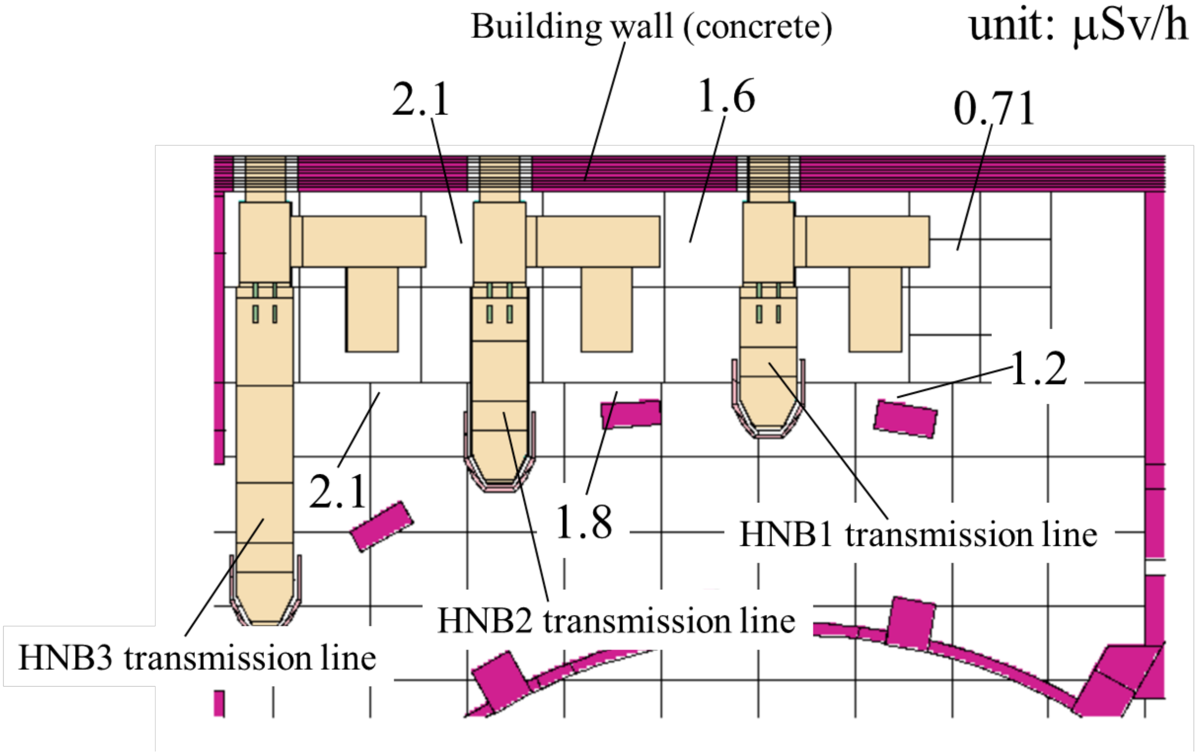

FIG. 5. Shutdown dose rate in the third floor

5. Effective gamma dose rates from transport cask with activated NB component

The calculation procedure consists of three parts; a) neutron spectra calculation (neutron transport calculation), b) gamma spectra calculation (activation calculation), c) effective gamma dose rate calculation (gamma transport calculation). First we calculated average neutron spectra (175 groups) in NB main components with the MCNP code during DT constant operation. Next an energy spectrum (42 groups) of gammas emitted from each NB component activated with neutrons at 10^6 seconds after shutdown was deduced with the ACT4 code and the above neutron spectra. Finally effective gamma dose rates from a transport cask, in which only one activated NB component was installed, were estimated with the MCNP code. The calculation geometry is a simple sphere model, and it is composed of an iron shell cask of 3.3 m in inner diameter and a 50 cm thick concrete shell wall. The sphere gamma source of 3 m in diameter was uniformly distributed inside the iron cask. Figure 6 shows the effective gamma dose rate from activated fast shutter in case of the iron cask of 29 cm in thickness. Figure 7 shows the effective gamma dose from activated fast shutter at 30 cm from the cask as a function of the cask thickness. It was found that the effective dose rates in the case of 27 and 29 cm thick casks were less than 25 μSv/h at 30 cm from the outer surface of the iron cask and were less than 0.1 μSv/h outside the concrete wall of 50 cm in thickness.

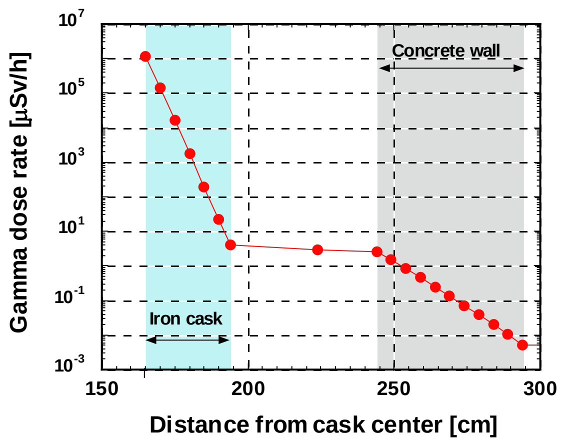

FIG. 6. Effective gamma dose rate from activated fast shutter in case of iron cask of 29 cm in thickness

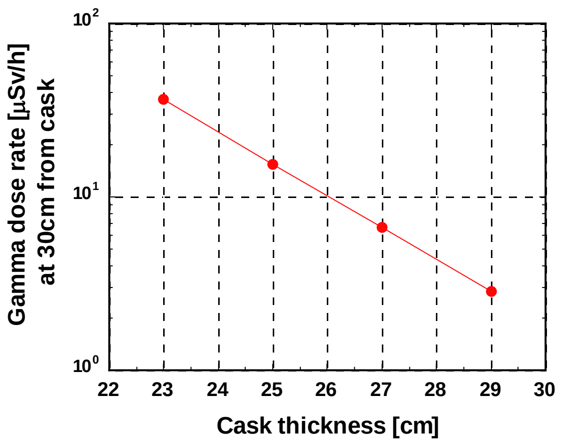

FIG. 7. Effective gamma dose rates at 30cm from cask.

6. Summary

We have performed ITER NB nuclear analyses since 2009. We drastically modified the automatic conversion code GEOMIT from CAD data to MCNP geometry input data, and could successfully convert the very complicated and large CAD data on the latest NB system and tokamak building to MCNP geometry input data. By using the detailed MCNP model converted from NB CAD data, a variety of nuclear analyses were performed for ITER NB system including a tokamak building of ~ 50 m x 35 m x 20 m and outside the building. From the calculation results, we evaluated the detailed effective dose rates during DT operation and after shutdown, and activation of the NB components, etc. The effective dose rates satisfy the nuclear regulation for licensing with a few modifications of the shield design.

Acknowledgments

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