

Estimation of Shutdown Dose Rate in Fusion Research Systems

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1. Introduction

Experimental fusion reactor systems such as KSTAR and ITER are under research and development stage for experimental demonstration. Therefore, they need an installation of detecting devices and a frequent visit of human personal.

After completion, the plasma may emit more than 10^{20} neutrons per second and last for a few seconds to several months. In this environment, the components and structures that make up the fusion reactor are highly activated by neutrons. These activated structures cause many problems; it is not allowed for the worker to enter inside for maintenance even after the shutdown.

The purpose of this study to calculate the radiation environment after shutdown in fusion system and finally We determine time and location which the workers can enter.

2. Calculation Model

It is desirable to consider the most conservative situation in the radiation environment simulation of the fusion reactor. Therefore, ITER with a fusion power of 500MW is selected as a reference model. MCNP6 and ENDF7 were used to model fusion system.

Each structure was modeled by referring to the ITER Design Report [1, 2]. The radial thickness and material composition is shown in the table below.

Table 1. Size (radial thickness) and material composition of each components

Component		Thickness (cm)	Material
Central Solenoid	Superconductor & insulator	80 - 90	Nb ₃ Sn + Incoloy908
	Support	90 - 180	SS316L(N)IG
Toroidal Field Coil	Wall Box	220 - 229.5	SS316L(N)IG
	Superconductor & insulator	229.5 - 310.5	Nb ₃ Sn + Incoloy908
	Wall Box	310.5 - 320	SS316L(N)IG
Vacuum Vessel	Wall Box	320 - 328.8	SS316L(N)IG
	Filling	328.8 - 350.5	SS316L + H ₂ O
	Wall Box	350.5 - 356.5	SS316L(N)IG
Blanket	Shield Bock	357 - 399	SS304B7 + H ₂ O
	Heat Sink	399 - 401	Copper
	First Wall	401 - 402	Beryllium
Plasma Chamber		402 - 853	Vacuum
Blanket	First Wall	853 - 854	Beryllium
	Heat Sink	854 - 856	Copper
	Shield Bock	856 - 898	SS304B7 + H ₂ O
Vacuum Vessel	Wall Box	898.5 - 904.5	SS316L(N)IG
	Filling	904.5 - 967.5	SS304B7 + H ₂ O
	Wall Box	967.5 - 975.5	SS316L(N)IG
Toroidal Field Coil	Wall Box	976 - 985.5	SS316L(N)IG
	Superconductor & insulator	1085.5 - 1165.5	Nb ₃ Sn + Incoloy908
	Wall Box	1165.5 - 1176	SS316L(N)IG
Cryostat	Wall	1400 - 1410	SS316L(N)IG
Bioshield	Wall	1455 - 1655	Concrete

We have big limitation to design in detail. So some details were omitted and Central Solenoid(CS), Poloidal Field Coil(PFC), Toroidal Field Coil(TFC), Blanket, Port Plug(PP) and Vacuum Vessel(VV) were modeled. Whole geometry is modeled as a 1/6 symmetric structure by applying reflective boundary condition as follows.

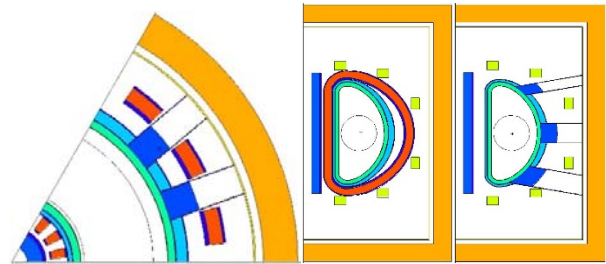


Figure 1. Modeling of Fusion System

3. Methodology

The structures are activated by the neutrons emitted from the plasma, and the activated structure returns to the stabilized state and emits gamma rays. This gamma ray has the most dominant influence on the radiation environment during operation and especially after shutdown.

However, MCNP itself can't calculate decay gamma ray source which is emitted from activated structure. So we apply the R2S method to calculate decay gamma source. In order to apply the R2S method more efficiently, our team combined the two codes to automate the calculation. The calculation procedure is as follows.

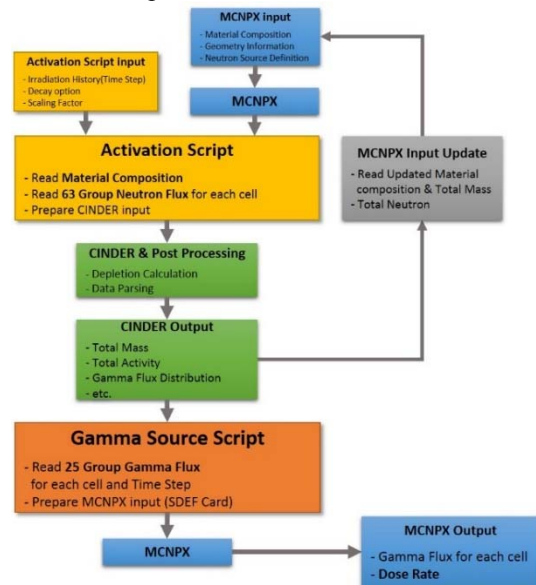


Figure 2. Calculation Procedure of R2S Method

1. The 63 group neutron flux for each cell is calculated using MCNP.
2. The activation script is used to read the information from the MCNP output and automatically generate the input of CINDER and perform the calculation.
3. The Gamma Source Script calls the 25-group decay gamma source for each cell calculated from the CINDER and creates an MCNP input. In this case, the input of MCNP is an input for calculation of dose through gamma ray transport calculation.
4. The gamma-ray transport calculations are performed through the inputs of the prepared MCNP, and finally the dose at a specific position is calculated.

3. Dose Rate Estimation in Fusion System

The dose calculations were performed focusing after the shutdown. It is not meaningful to calculate the equivalent dose during operation because the worker's access is limited. On the other hand, for the maintenance of the reactor after the shutdown, the worker's access should be considered. So, we calculated the inside of the port plug and the outer wall of the tokamak, which are the places where the workers firstly approach.

A spherical cell with a radius of 30 cm at a distance of 10 cm from the outer wall of the tokamak and in each port plug was defined as F4 tally of MCNP. Each location is labeled with a spelling and number as shown in Figure 4. Dose Conversion Factor(DCF) of ICRP74 was used to convert from flux to dose rate

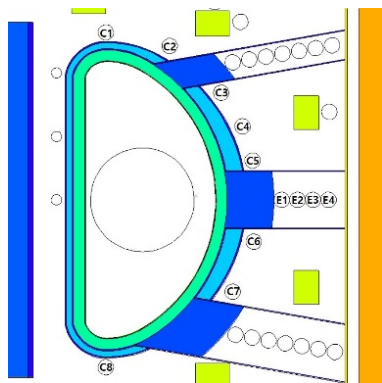


Figure 3. Tally Location in Fusion System

3.1 Irradiation Scenario

At present, ITER offers various operating scenarios for the activation analysis and dose estimation. In this paper, we apply the SA2 scenario, which is the most commonly used, and apply the operation stage with output of 500MW among various stages. In this operation step, the plasma output of 500 MW is maintained for 400 seconds and the cooling time of 3,920 seconds is repeated 17 times in total. The below table shows the duration of each operation step and the load and plasma power applied to the first wall.

Table 2. Irradiation scenario (ITER SA2 scenario)

Year	Duration	Wall load [MW/m ²]	Fusion Power [MW]	Repetition [times]
15 th	8 month	0	0	1
16 th & 17 th	16 month	0.065	41.65	1
18 th	8 month	0	0	1
19 th & 20 th	16 month	0.065	41.65	1
Aggressive	3920 sec	0	0	17
	400 sec	0.780	500	
	3920 sec	0	0	3
	400 sec	1.092	700	

3.2 Gamma Dose Rate Calculation

The gamma source was calculated from the activated structure by CINDER through R2S in Figure 2 and dose calculation was performed at the certain time after shutdown.

Due to the direct effect of the activated Diagnostic Shielding Module (DSM), the dose inside the port plug was higher than the tokamak outer wall, and the EPP dose was 3.60mSv/h immediately after shutdown. The dose limit of the worker is defined as 100uSv/h at 10 CFR, and ITER aims to enter the worker for maintenance and repair after 10⁶ seconds (~ 11 days). Despite conservative assumptions, As a result, the dose after 10⁶ sec is calculated as maximum 500uSv/h in EPP which is above 5 times higher than the maximum dose limit. it takes about cooling time of 100 days for the dose in EPP to drop to 100uSv/h after the reactor shutdown.

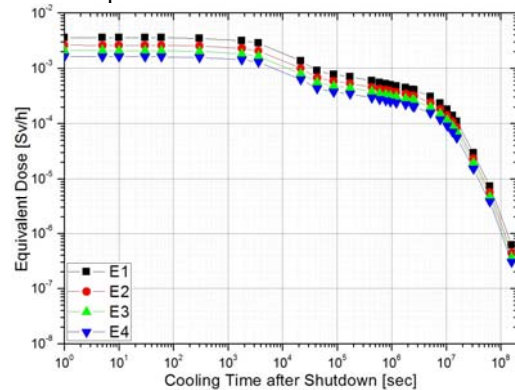


Figure 4. Dose Rate in EPP according to the time

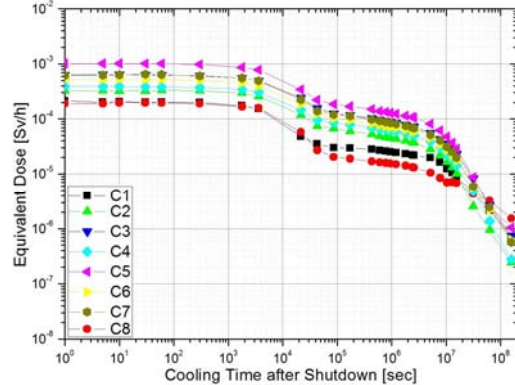


Figure 5. Dose Rate outside the Tokamak outer wall according to the time

3.3 Radiation Mapping

Tecplot was used to visualize mesh data of MCNP.

The calculation results for the overall radiation environment in the fusion system are as follows. In each figure, the left is the TFC plane and the right is the port plug plane.

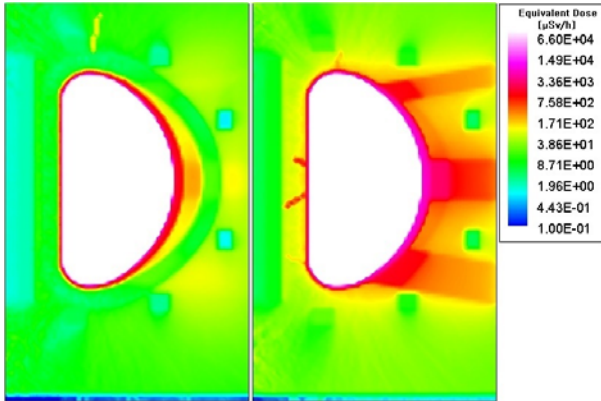


Figure 6. Gamma Dose Mapping(Distribution) Immediately after shutdown (left: TFC plane, right: Port Plug plane)

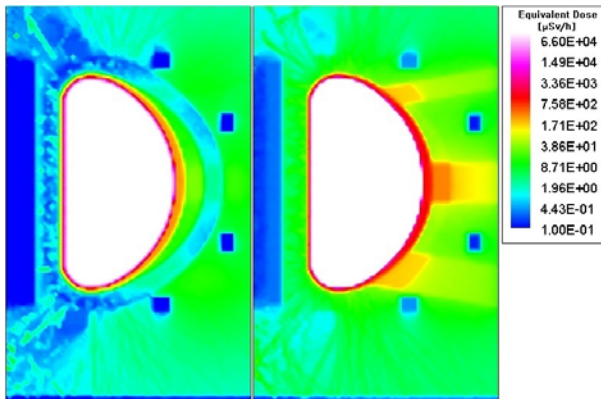


Figure 7 Gamma Dose Mapping(Distribution) 10^6 sec after shutdown (left: TFC plane, right: Port Plug plane)

As shown in the figure, due to the activation of DSM and the outer wall of port plug, inside of all port plugs have relatively high dose than outside. Because of the partial shielding effect of TFC and PFC, after 10^6 seconds, the space excluding the port plug is lower than the dose limit.

4. Conclusion

ITER was chosen as the reference model for MCNP6 simulation for dose calculation. The R2S methodology was used to calculate the radiation environment of the fusion system after shutdown.

Due to the activation of the DSM, a relatively high dose rate was showed in the port plug which is considered to be frequently accessed by the worker because the diagnostics is located.

Despite conservative assumptions, it seems impossible to access to the port plug because it exceeded the dose

limit even after 10^6 seconds which is recommendation of ITER. It is considered that a cooling time of about 100 days or more is required for entering.

The space outside the tokamak showed a dose lower than the dose limit after 10^6 seconds due to the partial shielding effect of other structures. However, additional shielding is desirable.

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