ENVIRONMENTAL DOSE RATE ASSESSMENT OF ITER USING THE MONTE CARLO METHOD

by

Alireza KARIMIAN [1*], Amir BEHESHTI [2], Mohammadreza ABDI [3], and Iraj JABBARI [2]

[1]Department of Biomedical Engineering, Faculty of Engineering, University of Isfahan, Isfahan, Iran
[2]Department of Nuclear Engineering, Faculty of New Science and Technologies, University of Isfahan, Isfahan, Iran
[3]Department of Physics, Faculty of Science, University of Isfahan, Isfahan, Iran

Scientific paper
DOI: 10.2298/NTRP1401034K

Exposure to radiation is one of the main sources of risk to staff employed in reactor facilities. The staff of a tokamak is exposed to a wide range of neutrons and photons around the tokamak hall. The International Thermonuclear Experimental Reactor (ITER) is a nuclear fusion engineering project and the most advanced experimental tokamak in the world. From the radiobiological point of view, ITER dose rates assessment is particularly important. The aim of this study is the assessment of the amount of radiation in ITER during its normal operation in a radial direction from the plasma chamber to the tokamak hall. To achieve this goal, the ITER system and its components were simulated by the Monte Carlo method using the MCNPX 2.6.0 code. Furthermore, the equivalent dose rates of some radiosensitive organs of the human body were calculated by using the medical internal radiation dose phantom. Our study is based on the deuterium-tritium plasma burning by 14.1 MeV neutron production and also photon radiation due to neutron activation. As our results show, the total equivalent dose rate on the outside of the bioshield wall of the tokamak hall is about 1 mSv per year, which is less than the annual occupational dose rate limit during the normal operation of ITER. Also, equivalent dose rates of radiosensitive organs have shown that the maximum dose rate belongs to the kidney. The data may help calculate how long the staff can stay in such an environment, before the equivalent dose rates reach the whole-body dose limits.

Key words: tokamak, dose, radiation dose phanton, MCNPX 2.6.0 code

INTRODUCTION

In recent years, efforts have been made to determine and estimate the dosimetric data of staff employed in nuclear facilities and radiation treatment centers [1-3]. It is important to recognize that all nuclear facilities, in addition to having to abide by regulatory dose limits, are also required to set a program for maintaining prescribed occupational doses. These limits have resulted in prescribed doses considerably lower than the allowed annual limits for typical nuclear facility staff. The adopted average annual occupational effective dose limit recommended by the International Commission on Radiological Protection (ICRP) is 20 mSv per year [4].

Situated in the Cardache forest in France, International Thermonuclear Experimental Reactor (ITER) is the most advanced global experimental nuclear fusion engineering project involving a tokamak device. The machine is expected to achieve a Q-factor of 10, something that has not been achieved with the Joint European Torus (JET) tokamak or any previous fusion reactor. During normal operation, it produces a deuterium-tritium fusion power of 500 MW, with an injection of 50 MW of auxiliary power. It is predicted that the DT plasma will achieve a neutron flux in the range of about 10^{13} $cm^{-2}s^{-1}$ [5].

Superconducting coils are major components of the Cardache tokamak. Both toroidal and poloidal field coils magnetically confine, shape, and control the plasma inside the plasma toroidal vacuum vessel. This magnetic confinement system comprises toroidal field coils, a central solenoid, external poloidal field coils, and correction coils. Other components, such as blanket modules, divertor cassettes and port plugs are situated within the vacuum vessel. The tokamak hall is shielded by a 2 m thick bioshield wall made of removable specific concrete.

In the research done by Arione *et al*., [6], dose rate assessments for ITER have been calculated solely by considering the transport of emitted particles from the plasma. The produced delayed gamma radiation due to

* Corresponding author; e-mail: karimian@eng.ui.ac.ir

the equally important neutron activation of solid ITER structures has not been considered by Arione *et al*. Therefore, the aim of this research is the assessment of the amount of the equivalent dose rate behind the bioshield wall that the staff involved might receive during a normal operation of the ITER (taking into account neutrons, delayed gammas and photonuclear particle production inside the ITER). To achieve this, the ITER system and its components were simulated by the Monte Carlo method using the MCNPX 2.6.0 code. Also, in order to assess the equivalent dose rate of the staff, a medical internal radiation dose (MIRD) phantom with appropriate details was used in the simulation.

MATERIALS AND METHODS

At ITER, nuclear radiation during operation is mainly due to the neutrons of plasma interactions, *i. e.* prompt and delayed gammas generated by the radioactive nuclides during neutron irradiation. Therefore, to calculate the total dose rate, a coupled neutron and photon transport code is needed.

This study was based on the Monte Carlo method/ MCNPX 2.6.0 code (Monte Carlo All-Particle Transport Code). The advantage of this version of the MC method is its ability to trace the production and transport of delayed gamma rays. According to our results, certain nuclides such as Co, Mn, Mo, and Ni which comprise the components of SS316 and SS316L (tab. 1), have considerable cross-sections to produce delayed gammas. The data required to study delayed gamma calculations was taken from the CINDERGL library (delayed gamma data library) of the MCNPX.

The tokamak considered in this study is a complex and huge fusion reactor based on several last generation technologies. However, to simulate this system, the use of a model such as the one used in the previous study [6] is convenient. To ensure the reliability of particle transport mechanisms, special compositions and thicknesses of system materials were also applied.

In the present study, the ITER geometry used is similar to the ones mentioned in refs. [5, 6], meaning that the ITER system was simulated by using concentric finite cylinders. The said cylindrical surfaces have the same axial alignment and a height of 24 m. Each region between the two successive cylindrical surfaces was filled with the appropriate material in order to represent the different layers of each component along the radial reactor direction, as mentioned in [5]. A typical sample of a simulation for this geometric model has been shown in fig. 1. The system itself consists of a central solenoid (CS), blanket (BLK), vacuum vessel (VV), toroidal field coils (TC), cryostat (CRY), and a bioshield wall (BSD).

Some of these materials are composed of base metals or elements with a specific atomic or weight

Table1. Composition and thickness of the simulated tokamak [5, 7]

Structure		Thickness [cm]	Composition (% of volumes)
CS	Insert module	80-90	27% Nb_3Sn + 30% Incoloy 908 +30% SS316 + + 10% Resins + 3% Al_2O_3
	Superconductor and insulator	90-180	45% Nb_3Sn + 50% Incoloy 908 + 5% Al_2O_3
	Support	180-200	SS316
TC	Wall box	220-229.5	SS316
	Superconductor and insulator	229.5-310.5	45% Nb_3Sn + 50% Incoloy 908+ 5% Al_2O_3
	Wall box	310.5-320	SS316
VV	Wall	320-328.8	SS316
	Filling	328.8-350.5	84% SS316L + 16% H_2O
	Wall	350.5-356.5	SS316
BLK	Shield block	356.5-399	60% SS304 + 40% H_2O
	Waster heat	399-401	Copper
	First wall	401-402	Beryllium
PLASMA	–	402-853	Vacuum
BLK	First wall	853-854	Beryllium
	Waster heat	854-856	Copper
	Shield block	856-898	60% SS304 + 40% H_2O
VV	Wall	898-904.5	SS316
	Filling	904.5-967.5	84% SS316L + 16% H_2O
	Wall	967.5-975.5	SS316
TC	Wall box	975.5-985.5	SS316
	Superconductor and insulator	985.5-1065.5	45% Nb_3Sn + 50% Incoloy 908+ 5% Al_2O_3
	Wall box	1065.5-1075	SS316
CRY	Wall	1400-1410	SS304
BSD	Wall	1455-1655	Concrete

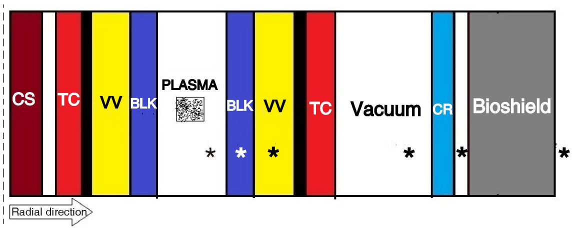

Figure 1. Typical view of the simulated tokamak geometric model. Stars show the locations of ring detector tallies

fraction. This was noticed in the simulation of the composition of materials used and equivalent density calculations. For instance, Incoloy 908 includes Fe, Ni, Cr, Nb, Al, Ti, Si, and C. Also, 70% of the resin weight is made of polystyrene, while the remaining weight fraction is made of polyethylene. All materials used, as well as their compositions, have been determined in tab. 1.

The composition of concrete used in this simulation has been studied in the previous research [8] and is considered to be an alternative for a specific shield of the fusion plant. In this study, the composition of concrete in the bioshield wall of ITER contains boron with a density of 0.1 g/cm^3.

In this simulation, a ring-shaped neutron source was used. Its cross-section is square and its height and width are 0.6 m, respectively. The position of the source was set at the central part of the plasma chamber. It emits neutrons isotropically and its spectrum is Gaussian, with a mean energy of 14.1 MeV. According to Wu and his team [9], despite this simplicity, the neutron flux density in the plasma chamber is acceptable.

The parameters of the emission spectrum were adjusted by MCNPX through the choice of special source probability functions. For this purpose, a Gaussian fusion energy spectrum was used. The said spectrum is shown in eq. 1. By choosing the appropriate values for parameters a and b (a = –0.01, b = –1), according to calculations done by MCNPX 2.6.0 and using eq. 1, the D-T fusion energy for plasma temperature was calculated to equal an average energy of 10 keV

$$P(E) = Ce^{-\left(\frac{E-b}{a}\right)^2} \tag{1}$$

Various types of neutrons and photons around the tokamak hall constitute the main source of the staff absorbed dose. In this research, to classify the neutrons in various bins of energy, meaning fast, epithermal, and thermal neutron fluxes, the TECDOC 1223 was used. According to this, the following energy group subdivisions have been used: fast group, $E_n > 10$ keV; epithermal group, 1 eV $\le E_n \le$ 10 keV; and, thermal group, $E_n < 1$ eV [10]. However, the total neutron flux density was calculated in this research, too.

In order to calculate staff organ doses, a MIRD-MIT phantom [11] simulating the human head and torso was used. Over 60 cells were employed to measure the equivalent dose rates of specific organs during the normal operation of the tokamak. The MIRD-MIT body phantom used represents a human male, as shown in fig. 2. He is comprised of the MCAT phantom plus testes, thyroid, legs, bladder, and intestines. Equivalent dose rates have been calculated for some important organs such as the head, brain, thyroid, liver, kidneys, testes, lungs, and skin.

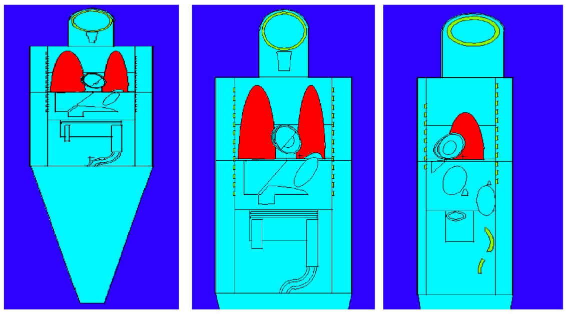

Figure 2. Three views of the MIRD-MIT phantom used

Because ITER is rotationally symmetric in relation to the co-ordinate axis, in this study, the total dose rate and neutron flux density were calculated by a ring detector tally. Ring detectors can be used in most axial symmetry geometries, because a ring detector enhances the efficiency of point detectors concerning problems rotationally symmetric to the co-ordinate axis [12]. A geometry-splitting/Russian-roulette variance reduction method was also used to reduce the errors. A weighting factor equal to 10 was used in the variance reduction technique applied in our study. By using these methods, relative errors in the vicinity of the bioshield were reduced to 3%, a value acceptable by international standards. Also, radiation dose rates were calculated using the flux-to-dose conversion factors (DE/DF cards) based on ICRP-21 reports [13].

All computations have been performed on a 320 core cluster consisting of 5 nodes of quad Opteron CPU running at 2.2 GHz, each equipped with a 128 GB memory. The MCNPX code was executed in a parallel mode and all calculations of 10^9 source-particle histories were also studied. The Fusion Evaluated Nuclear Data Library (FENDL 3.0), taken from the IAEA Nuclear Data Services, was used for all MCNPX calculations in this study.

RESULTS AND DISCUSSION

Neutron flux density and dose rates were calculated in all cylindrical surface zones along the radial direction of the machine, from the plasma chamber to the outer surface of the bioshield, by ring detectors. The results are presented in tabs. 2 and 3.

Table 2. Neutron flux densities from plasma chamber to bioshield wall

Component	Position [cm]	Neutron flux density [$cm^{-2}s^{-1}$]
Plasma chamber	602	4.132E+13*
BLK-shield block	875	1.691E+12
VV-filling	935	5.100E+09
Vacuum	1200	9.604E+07
Inside bioshield	1432	4.520E+07
Outside bioshield	1660	1.859E+02

*Note 4.132E+13 read as 4.132 10^{13}

Table 3. Total equivalent dose rates from plasma chamber to bioshield wall

Component	Position [cm]	Total equivalent dose rates [Sv/h]
Plasma chamber	602	6.228E+04*
BLK-shield block	875	3.825E+04
VV-filling	935	5.742E+01
Vacuum	1200	9.067E-03
Inside the bioshield	1432	8.264E-03
Outside the bioshield	1660	1.8786E-06

*Note: 6.228E+04 read as 6.228 10^4

As shown in tabs. 2 and 3, depending on the position, both the neutron flux densities and total equivalent dose rates (neutron and photon dose) are reduced on the way from the plasma chamber toward the bioshield wall.

Neutron and photon equivalent dose rates along the radial way after passing the bioshield wall are shown in fig. 3. Both equivalent dose rate curves have a downward trend from the center to the outer layers. Depending on its position and specific materials used, the slope of curves varies. In fig. 3, it can be seen that the photon equivalent dose rate is greater than the neutron equivalent dose rate after the bioshield wall. The exact figures for neutron and photon equivalent dose rates after the bioshield wall are 5.89 10^{-7} Sv/h and 1.11 10^{-6} Sv/h, respectively. Therefore, the photon dose rate in this region is about two times greater than the neutron dose rate, due to the existence of boron in the concrete mixture (2.9% weight fraction) and the production of gamma rays according to eq. 2 [14]

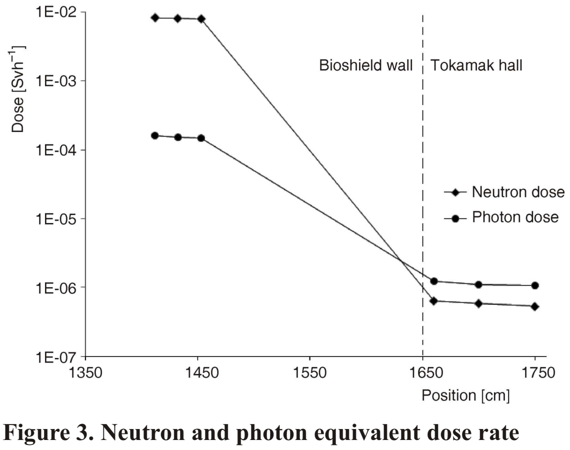

Figure 3. Neutron and photon equivalent dose rate values along the bioshield wall toward the tokamak hall

$$^{10}\mathrm{B} \quad n_{\mathrm{thermal}} \quad {}^{7}\mathrm{Li}(0.84\ \mathrm{MeV})$$
$$\alpha(1.47\ \mathrm{MeV}) \quad \gamma(0.48\ \mathrm{MeV}) \qquad (2)$$

Furthermore, in fig. 3, equivalent dose rates of photons and neutrons in the tokamak hall seem constant and slow to reduce. This is due to the diminishing values of equivalent dose rates in this region which have remained within the range of background values.

Table 4 shows the total equivalent dose rates of some radiosensitive organs such as the testes, thyroid and brain of the human body. These data have been calculated by a MIRD phantom.

Table 4. Total equivalent dose rates of some radiosensitive organs

Organ name	Total equivalent dose rate [Svh^{-1}]	Organ name	Total equivalent dose rate [Svh^{-1}]
Head	6.7032E-07*	Liver	9.6040E-07
Brain	1.2024E-07	Kidney	1.0608E-6
Thyroid	4.0964E-07	Testes	8.7906E-07
Lung	5.1450E-07	Skin	1.8889E-07

*Note: 6.7032E-07 read as 6.7032 10^{-7}

CONCLUSIONS

In this research, the total dose rates of neutrons and photons in various positions of the ITER, from the plasma chamber toward the outside of the bioshield wall, have been calculated. Furthermore, dose rates received by radiosensitive organs of the ITER staff while in the tokamak hall were also calculated. To our knowledge, no assessments of radiation dose rates in multiple and discrete locations of the body have been done up to now. By performing this simulation, it is possible to estimate how long before the body absorbs high-risk levels of radiation the staff may remain in such high-risk environments.

It should be noticed that the contributions due to the presence of slits between blanket modules and the various holes in the cryostat and bioshield were not considered in our calculations. These simplifications decrease the actual values of dose rates that would be obtained if they were taken into account. In the presence of slits and holes, by passing more radioactive particles from these ports and holes, their dose rate values would have increased. The bioshield wall causes a reduction of an order of 4 on the total dose rates, as presented in tab. 3. As demonstrated in fig. 3, photon dose rates are dominant (about two times higher) in relation to neutron dose rates after the bioshield wall, due to the high boron concentration in the concrete. Our results also show that the environmental equivalent dose rate level near the outside of the bioshield wall of the tokamak hall seems constant and amounts to about 1 mSv per year, less than the limit set for the annual occupational dose rate during normal operation of the ITER.

AUTHOR CONTRIBUTIONS

The idea and work plan for the research are to be attributed to A. Karimian. The Monte Carlo simulation and processing of data were done by A. Beheshti, under the supervision and advisory of A. Karimian, M. Abdi, and I. Jabbari. The manuscript, including figures, tables and text were prepared and written by A. Karimian and A. Beheshti.

REFERENCES

[1] Sadat-Eshkevar, S. M., Karimian, A., Mirzaee, M., Assessment of Personnel Absorbed Dose in Production of Medical Radioisotopes by Cyclotron, *Journal of Radiation Protection Dosimetry, 147* (2011), 1, pp. 250-253

[2] Sandri, S., Di Pace, L., Collective Dose at ITER Feat, *Fusion Engineering and Design, 63-63* (2002), pp.199-203

[3] Mossadegh, N., *et al.*, Experimental Simulation of Personnel Dosimetry in Production of Medical Radioisotopes by Research Reactor, *Journal of Radiation Protection Dosimetry, 147* (2011), 2, pp. 267-271

[4] Harrison, J. D., Streffer, C., The ICRP Protection Quantities, Equivalent and Effective Dose: Their Basis and Application, *Journal of Radiation Protection Dosimetry, 127* (2007), 1, pp. 12-18

[5] ***, ITER Final Design Report, *Nuclear Fusion, 39* (1999), 12, pp. 2137-2627

[6] Arione, A., *et al.*, Flux and Dose Rate Evaluation of Iter System Using MCNP5, *Brazilian Journal of Physics, 40* (2010), 1, pp. 58-62

[7] Hu, H., *et al.*, Benchmarking of SNAM with the ITER 3-D Model, *Fusion Engineering and Design, 82* (2007), 24, pp. 2867-2871

[8] Khripunovl, V., Santoro, R., Khater, H., Profit from Borating Concrete in the ITER Biological Shield, *Proceedings*, 17th IEEE/NPSS Symposium on Fusion Engineering, October 6-9, San Diego, Cal., USA, 1997, pp. 991-994

[9] Wu, Y., FDS Team, CAD-Based Interface Programs for Fusion Neutron Transport Simulation, *Fusion Engineering and Design, 84* (2009), 11, pp. 1987-1992

[10] ***, Current Status of Neutron Capture Therapy, IAEA-TECDOC-1223, International Atomic Energy Agency, 2001, pp. 13-19

[11] Xu, X. G., Eckerman, K. F., Handbook of Anatomical Models for Radiation Dosimetry, Taylor and Francis Group, 2010

[12] Pelowitz, D. B., MCNPXTM User's Manual Version 2.6.0, 2008

[13] Briesmeister, J. F., MCNPTM-A General Monte Carlo N-Particle Transport Code Version 4C, 2000

[14] Davis, A., Radiation Shielding of Fusion Systems, Ph. D. thesis University of Birmingham, 2010

Received on February 22, 2013
Accepted on March 17, 2014

Алиреза КАРИМИЈАН, Амир БЕХЕШТИ, Мохамадреза АБДИ, Ирај ЏАБАРИ

ПРОЦЕНА ЈАЧИНЕ ДОЗЕ У ОКОЛИНИ ИТЕР ПОСТРОЈЕЊА МОНТЕ КАРЛО МЕТОДОМ

Излагање зрачењу један је од главних извора ризика за особље запослено у реакторским постројењима. Особље токамака изложено је широком опсегу неутрона и фотона око токамак хола. Међународни термонуклерни експериментални реактор (ИТЕР) представља инжењерски пројекат фузионог реактора и најнапреднији експериментални токамак у свету. Са радиобиолошког становишта посебно је значајна процена јачине дозе ИТЕРА-а. Циљ овог рада је процена количине зрачења у ИТЕР-у током нормалног режима рада у радијалном правцу, од плазма коморе ка токамак хали. Да би остварили овај циљ, ИТЕР систем и његове компоненте симулиране су Монте Карло методом помоћу MCNPX 2.6.0 кода. Потом, јачина еквивалентне дозе неких радиосензитивних органа људског тела израчуната је коришћењем MIRD фантома. Наше проучавање засновано је на деутеријум-трицијум плазма сагоревању и производњи неутрона енергије од 14.1 MeV, као и на фотонском зрачењу услед неутронске активације. Као што наши резултати показују, укупна годишња еквивалентна доза са спољне стране биолошког штита токамак хале износи око 1 mSv, што је мање од границе годишње дозе за професионална лица током нормалног режима рада ИТЕР-а. Такође, јачина еквивалентне дозе радиосензитивних органа показала је да је највећа јачина дозе у бубрезима. Подаци могу помоћи при прорачуну колико дуго запослени могу остати у околини постројења пре него што се достигне вредност границе дозе за цело тело.

Кључне речи: токамак, доза, дозни фантом, MCNP 2.6.0 програм