14 MeV neutron streaming calculations for JET-like maze entrance using TRIPOLI-4 Monte Carlo code

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For the future ITER (International Thermonuclear Experimental Reactor) operation needs, D-T fusion experiments named DTE2 will be conducted in 2019 at JET (Joint European Torus). During the DTE2 operations, 14 MeV fusion neutrons will be generated. One of the aims of the DTE2 neutronics experiments is to investigate the D-T neutron streaming along the penetrations of biological shield of the JET Torus Hall. The TRIPOLI-4 Monte-Carlo radiation transport code has been extensively used on radiation shielding analyses. The purpose of this study is to evaluate the variance reduction (VR) techniques of TRIPOLI-4 on the 14 MeV neutron streaming calculations for JET-like maze entrance. A JET-like torus hall building of 40 m x 40 m and a maze entrance of 11.8 m length in 5-section configuration of concrete were first modeled. The new developed VR method AMS (Adaptive Multilevel Splitting) was then presented and discussed. Using the single-step approach combined with AMS techniques, the TRIPOLI-4 calculations results including neutron flux and ambient dose equivalent maps, the VR performance, and the user-friendly AMS input of TRIPOLI-4 code were reported.

Keywords: 14 MeV Neutron Streaming, TRIPOLI-4 Monte Carlo Code, Variance Reduction, JET, Maze Entrance

1. Introduction

The International Thermonuclear Experimental Reactor (ITER) is currently under construction at Cadarache in southern France. The Joint European Torus (JET) is presently the largest tokamak in the world and the only one capable of using tritium. At JET, D-T fusion experiments will be conducted in 2019 (named DTE2) on addressing the future ITER needs and reducing the risks of ITER operations [1].

During the DTE2 operations, 14 MeV fusion neutrons will be generated. One of the aims of the DTE2 neutronics experiments is to investigate the Deuterium-Tritium (D-T) neutron streaming along the penetrations of biological shield of the JET Torus Hall.

Continuous-energy Monte Carlo (MC) neutron transport calculations and TLDs measurements were already performed by international teams for the previous Deuterium (D-D) neutron streaming benchmark experiments around the JET maze entrance [1-3].

Using two-step simulation approach, two different calculation ways were performed to decrease the variances of calculated neutron fluence and ambient dose equivalent. Both the MC-MC approach using a midway surface source [3] and the Deterministic-MC one [1] using deterministic generated weight windows produced overestimated results (C/E >> 1) in JET maze entrance zone.

The TRIPOLI-4 Monte-Carlo radiation transport code has been widely used on fission neutron shielding analyses [4]. To develop the TRIPOLI-4 application in ITER fusion neutronics, both experimental and computational benchmarks are being performed [5-6].

In this study, using single-step approach combined with AMS (adaptive multilevel splitting) variance reduction (VR) techniques [7] TRIPOLI-4 calculations were performed for a JET-like torus hall model and a maze entrance of 11.8 m length in order to investigate the D-T neutron streaming from the torus hall model. The neutron flux attenuation was calculated in the maze entrance configuration constructed with borated and ordinary concretes. The calculation results including neutron flux and ambient dose equivalent maps, the VR performance, and the user-friendly AMS VR input of TRIPOLI-4 code were reported.

2. JET-like torus hall and maze entrance

The JET torus hall and its south-west (SW) maze entrance configuration were reported in previous publications for the 2013–2014 JET campaigns [1-3]. Figure 1 shows the JET torus hall and the previous TLDs measurement locations for SW maze (A1-A7, and B8). Figure 2 presents the SW maze entrance configuration of JET torus hall and the calculation benchmark points (M1 - M6) in the 5-section maze tunnel.

From figures 1 and 2, a simplified JET-like torus hall building model of 40 m x 40 m was first prepared for this study. The thickness of the concrete wall was 2.5 m. The internal surfaces of the wall were covered by a layer of borated concrete of 0.3 m in thickness [3].

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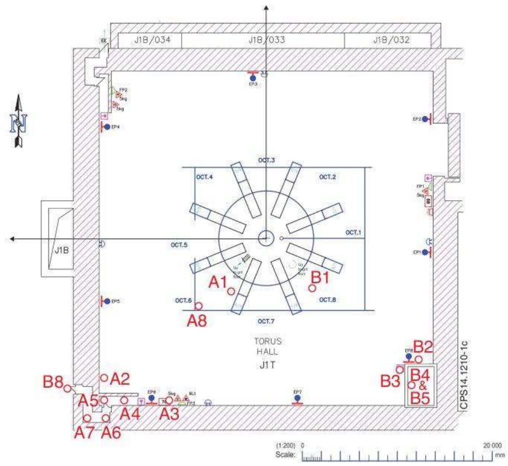

Fig. 1 JET Torus Hall (Dosimeters locations A1-A8 and B1-B8) (see Reference [2])

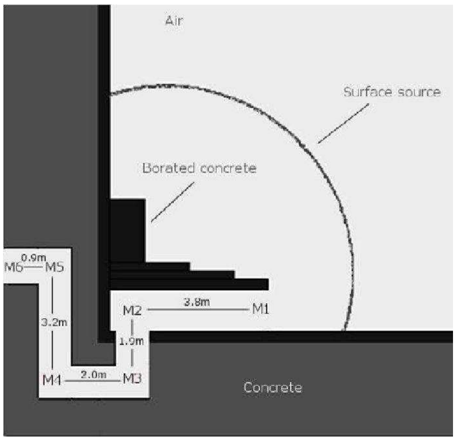

Fig. 2 Cross sectional view of the SW entrance maze of JET [2-3]

The SW maze configuration provides four right-angle turns. The total length of the maze is 11.8 m and its height is 2.6 m. The maze width varies between 0.9 and 1.1 m and therefore the cross-sectional area ranges between 2.34 m^2 and 2.86 m^2 [3]. To reduce the direct contribution of fusion neutron on the SW corner, several borated concrete shields were also installed. Their dimensions were reported in the Fig. 2 and 11 of Ref. [2]. The densities of ordinary concrete and borated concrete were 2.43 and 2.20 $g \cdot cm^{-3}$. Concrete compositions were defined in Ref. [2].

JET fusion device composed of several complicated components and eight sectors of TF magnets. This fusion machine was modeled in a simplified way in this work and placed in the center of the torus hall. According to the reference [2], the JET fusion device produces neutrons with an emission rate of 10^{16} n/s in D-D operations. The future D-T campaign (DTE2) has been estimated with a neutron emission rate of 10^{18} n/s and a total neutron yield up to 1.7×10^{21} neutrons.

Using the TRIPOLI-4 geometry package and the T4G display tool [8] Figures 3 and 4 show the simplified but JET-like geometry models for TRIPOLI-4 maze entrance neutron streaming calculations.

3. TRIPOLI-4 calculations

Previous investigations show that the JET fusion neutron streaming calculations in SW maze entrance is a challenging task [1-3]. Two-step simulation approach including MC-MC and Deterministic-MC methods was a must in order to decrease the variances of calculated neutron flux and dose. That is why in this work the VR techniques of TRIPOLI-4 were first evaluated.

The TRIPOLI-4 built-in variance reduction techniques such as implicit capture, particle splitting and Russian roulette were routinely involved in the shielding mode calculation but they are not sufficient for neutron deep penetration transport calculations of present case including thick borated shields and 5-section configuration of 11.8 m length concrete maze.

The TRIPOLI-4 traditional importance generator module INIPOND can be applied to improve the variance reduction performance [4]. Different options under INIPOND module are available. Generally the importance function of INIPOND is assumed to be factorized in space, energy, and angle variables, with a coupling between space and energy variables. A space mesh and an energy grid were separately defined for the initialization of the importance map by the code.

The adjustments of the importance map were performed from energy group to energy group by taking advantage of statistics on discrepancies between particle weights and reference weights given by the importance map, when particles slowing down in energy from group to group. The performance of associated variance reduction depends importantly on the input data prepared for INIPOND module. In this study due to the large size of JET-like torus hall and the thick shielding walls, the space and the energy meshes need to be adjusted in an iterative way in order to obtain an acceptable importance map. The performance of INIPOND in this work is similar to those of fission and D-T fusion neutron shielding calculations reported in previous studies [5, 9].

Recently a new developed variance reduction method named AMS was available in TRIPOLI-4 code [7]. This AMS method aims to duplicate the interesting particles of the simulation. Using the knowledge accumulated during the simulation itself this method for variance reduction determines on the fly which particle should be duplicated and at which point. According to the demo cases in [7], this method is suitable to study the neutron streaming calculations.

In this work the AMS method was utilized and investigated in detail because it is not only user-friendly with a convenient input preparation but also efficient. Table 1 shows the standard input of AMS module for the present work. As the distance between the JET fusion neutron source and the SW maze entrance is more than 20 m, the keyword “TARGET” of AMS input was first set in volume cell 702 (volume of interest), which corresponds to the third section of the 5-section maze configuration.

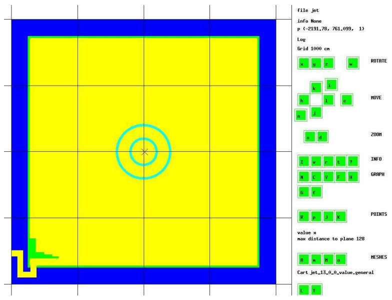

Fig. 3 TRIPOLI-4 model of the JET-like torus hall. (X-Y cross sectional view, Grid: 10 m x 10 m, Concrete in deep blue, Air in yellow, and Borated concrete in green).

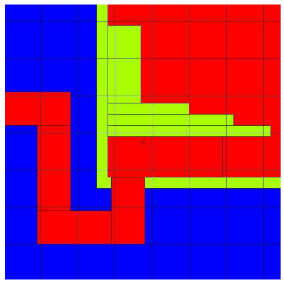

Fig. 4 TRIPOLI-4 model of the JET-like entrance maze. (X-Y cross sectional view, Grid: 1 m x 1 m, Concrete in deep blue color, Air in red, and Borated concrete in green).

The "TOWARDS POINT (X, Y, Z)." means the reference detector point in target volume. With keyword TOWARDS, the importance is 1/d, which causes the particles to be attracted to (X, Y, Z). That means that for all sampling points within the fusion source and from the collision sites, the importance is inversely proportional to the distance "d" to the maze entrance. In the maze, the importance increases from the first section of the maze entrance.

In this way, it is helpful to guide the simulated particles traveling toward the maze SW corner. The "IMPORTANCE" keyword allows to define the spatial importance functions and/or the traditional INIPOND options of TRIPOLI-4 code.

Table 1 TRIPOLI-4 input of AMS variance reduction module for neutron streaming calculations of JET-like entrance maze

```
AMS                                    // Adaptive Multilevel Splitting

  TARGET LIST 1  702                   // Target volume cell name

  RESAMPLE_COLLISION    1   // Optimization I

  IMPORTANCE  NEUTRON   // Particle type
                  TOWARDS  POINT -1865.  -1855.    0.
                                        // Reference point in target cell
 END_IMPORTANCE

END_AMS
```

The performance of the AMS method and its options used in this study was presented in Table 2. To evaluate the performance of VR techniques, the FOM (Figure of Merit) index is utilized. The FOM index is defined as $1/(\sigma^2 * t)$, where σ is the standard deviation of the calculated result and t is the calculation time. It is clear that the basic AMS spatial importance function was already powerful in present neutron streaming case. Other AMS options were also investigated and presented in Table 2. They can slightly improve or degrade the FOM. The "Monitoring 0" option of TRIPOLI-4 was helpful to improve the fast neutron FOM and it was already shown in previous study [9]. The collision resampling option was activated so as to improve FOM values for both A7 and M6 positions (see Fig. 1 and 2). That means it performs particle splitting after and before collisions (otherwise only after collisions).

The CROSS_SPLIT option is to get a more precise estimation of the importance of a particle during its transport through the geometry. Remove it can degrade the FOM in A7 but improve that in M6 where the slow neutrons contribute more. The "SPLIT" option adjusts the level of splitting, clearly it is not necessary here when collision resampling option activates.

In conclusion, the AMS VR method is easier for users and its performance is generally better than that of traditional INIPOND one for present study.

Table 2: TRIPOLI-4 variance reduction performance in FOM index using AMS options for neutron ambient dose equivalent calculations of JET-like entrance maze (H*(10) at SW reference points A7 and M6 - see Fig. 1, 2 and Table 1)

FOM	A7	M6
(1) TRIPOLI-4 Reference run	1	0.6
(2) (1) + AMS Point attractor	684	977
(3) (2) + Monitoring 0	760	920
(4) (2) + RESAMPLE_COLLISIONS 1	815	1403
(5) (4) + CROSS_SPLIT 0	496	1568
(6) (4) + SPLIT 0.05	768	1094

4. Calculation results

The main calculation results of this study were presented in graphic maps based on the numerical results of neutron flux and ambient dose equivalent H*(10) in 3D meshes. The normalization of calculation results was performed to one single D-T fusion source neutron per second. Figures 5 and 6 present the TRIPOLI-4 calculated ambient dose equivalent maps for neutron. Figures 7 and 8 show the fast (G1, E > 0.1 MeV) and thermal (G3, E < 0.5 eV) neutron flux maps. Using the TRIPOLI-4 mesh-tally option and the T4G display tool, they are helpful to perform the analysis of radiation shielding design for the JET-like torus hall and the SW maze entrance.

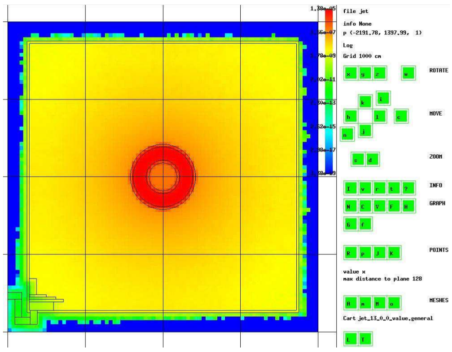

Fig. 5. TRIPOLI-4 calculated ambient dose equivalent map for neutrons in the JET-like Torus Hall and the entrance maze.

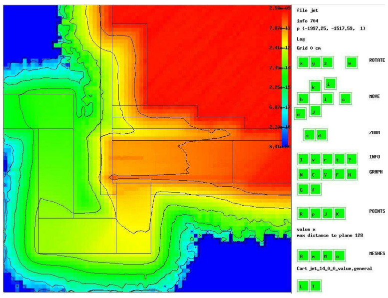

Fig. 6. TRIPOLI-4 calculated ambient dose equivalent map for neutrons and iso-dose rates curves around the JET-like maze entrance. (X-Y cross sectional view).

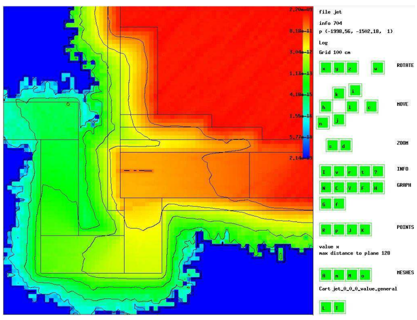

Fig. 7. TRIPOLI-4 calculated fast neutron (G1 > 0.1 MeV) flux map and iso-flux curves of the JET-like maze entrance.

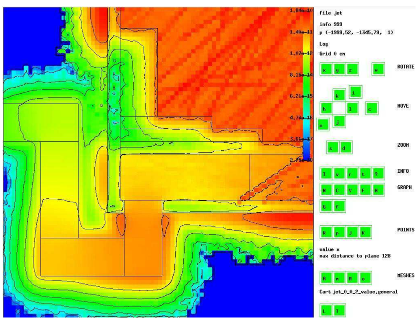

Fig. 8. TRIPOLI-4 calculated thermal neutron (G3 < 0.5 eV) flux map and iso-flux curves of the JET-like maze entrance.

G1 and G3 neutron flux maps have different flux images in sections 2 and 3 of SW maze entrance. Different gradients in 5-section streaming tunnel and concrete walls were also observed from G1 and G3 maps. Borated concrete installed in the SW corner of torus hall is efficient to reduce the neutron flux (see Figures 6-8). Fast neutron flux attenuates regularly along with the 11.8 m length maze. Peaks of thermal flux observed in G3 map appeared in sections 2 and 3. That means the concrete and borated concrete shielding walls play a role of moderator to slow-down the D-T fusion neutrons. And the water moderator contend in concrete is a key factor of calculation uncertainties [9-10].

Table 3 presents the TRIPOLI-4 calculated neutron flux and ambient dose equivalent (H*(10) from ICRP 74) results for six benchmark points from M1 to M6 (see Fig. 2). Their attenuation from M1 to M6 has a similar trend comparing with those in references [1-3].

Table 3. TRIPOLI-4 calculated neutron flux (n/s. cm**2) and ambient dose equivalent H*(10) (μSv/h) in JET-like maze entrance (normalized to single D-T source neutron per second)

	Neutron flux*	Ambient dose equivalent*
M1+	4.49E-9	1.42E-9
M2	3.21E-10	5.75E-11
M3	5.26E-11	4.93E-12
M4	9.68E-12	5.41E-13
M5	7.47E-13	3.64E-14
M6	1.44E-13	6.40E-15

* Uncertainty < 1%, + See Fig. 2

5. Conclusions

Using the new developed and user-friendly AMS variance reduction options of TRIPOLI-4, the D-T fusion neutron streaming calculations for a JET-like maze entrance were successfully performed by a single-step Monte Carlo radiation transport approach.

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