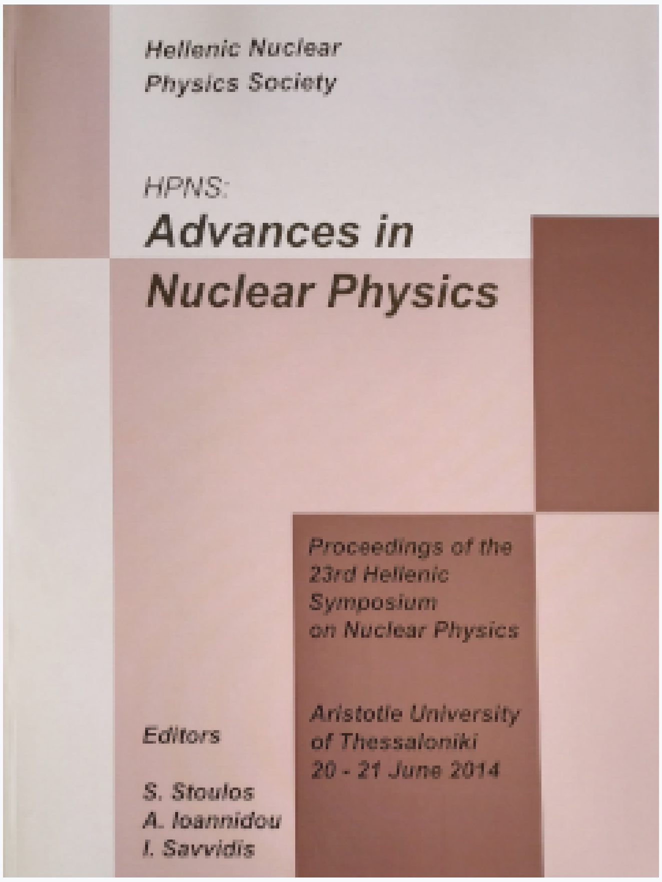
HNPS Advances in Nuclear Physics

Vol 22 (2014)

HNPS2014



Hellenic Nuclear Physics Society

HPNS: Advances in Nuclear Physics

Proceedings of the 23rd Hellenic Symposium on Nuclear Physics

Aristotle University of Thessaloniki 20 - 21 June 2014

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doi: 10.12681/hnps.1927

To cite this article:

Stamatelatos, I. E., Vasilopoulou, T., Batistoni, P., Conroy, S., Obryk, B., Popovichev, S., Syme, D. B., & EFDA JET contributors, the. (2019). Analysis of neutron streaming through penetrations in the JET biological shielding. *HNPS Advances in Nuclear Physics*, *22*, 34–39. https://doi.org/10.12681/hnps.1927

Analysis of neutron streaming through penetrations in the JET biological shielding *

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*** See the Appendix of F. Romanelli et al, Proceedings of the 24th IAEA Fusion Energy Conference 2012, San Diego, USA*

Abstract

In the present work neutron streaming through large ducts and labyrinths of the Joint European Torus (JET) biological shielding was evaluated. Neutron fluence and ambient dose equivalent were calculated along the total length of the ducts. Monte Carlo calculations using the MCNP code were performed for both Deuterium-Deuterium (D-D) and Deuterium-Tritium (D-T) toroidal plasma discharge sources. The results of the calculations were compared against measurements performed using thermoluminescence detectors. This work contributes to the operational radiation protection effort to minimize collective radiation dose to personnel at JET and, moreover, provides important information from JET experience that may assist in the optimization and validation of the radiation shielding design methodology used in future fusion plants, such as ITER and DEMO.

Keywords: Neutron streaming, Radiation shielding, Radiation protection, Fusion

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1. **Introduction**

The Joint European Torus (JET) is currently the largest tokamak in the world. The experiments and design studies performed by JET are consolidated to a large extent into the design of its successor ITER and the demonstration reactor DEMO. Among others, experiments are being carried out at JET aiming to validate in a real fusion environment the neutronics codes and nuclear data applied in ITER nuclear analyses. In particular, measurements and calculations of the neutron fluence through the penetrations of the JET shielding walls aim to assess the capability of numerical tools to accurately predict neutron transport along the long paths and the complex geometries characterizing the ITER biological shield.

In the present study, neutron streaming through the JET personnel entrance labyrinth was evaluated. Monte Carlo calculations using the MCNP code were performed in order to predict neutron fluence and ambient dose equivalent. Deuterium-Deuterium (D-D) and Deuterium-Tritium (D-T) toroidal plasma discharge sources were simulated. Baseline calculations were performed for the “as-built” concrete walls composition. Moreover, the sensitivity of the calculations on hydrogen and boron content in concrete was examined. The results of the calculations were compared against measurements performed by Obryk et al [1, 2] using thermoluminescence detectors (TLDs).

2. **Simulations**

The personnel entrance labyrinth is located at the South West (SW) corner of the JET Hall. Its geometry and dimensions are shown in Figure 1. The labyrinth configuration provides four right-angle turns. Its total length is 11.80 m and its height is 2.60 m. The labyrinth width varies between 0.90 and 1.10 m and therefore the labyrinth cross-sectional area ranges between 2.34 m^2 and 2.86 m^2. The thickness of the concrete wall is 2.50 m and its internal surface is covered by a layer of borated concrete (0.30 m in thickness). The densities of concrete and borated concrete are 2.43×10^3 $kg\cdot m^{-3}$ and 2.20×10^3 $kg\cdot m^{-3}$, respectively. The content of the "as-built" concretes in boron and hydrogen is shown in Table 1. More details on the "as-built" composition of concretes have been given by Stamatelatos et al [3].

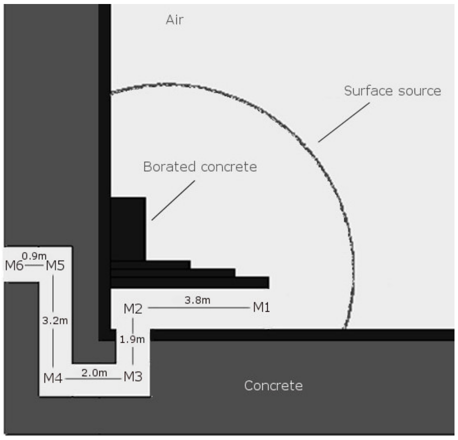

Fig. 1 Cross sectional view of the SW entrance labyrinth

Table 1. Concrete content in Boron and Hydrogen

Element or Isotope	Mass fraction (%)	
	Plain	Borated
B-10	0.0008	0.14
B-11	0.0032	0.56
H	0.56	0.20

Simulations were performed using Monte Carlo code MCNP-X (version 2.5.0) [4] and cross-section data obtained from JEFF 3.1.2 library [5]. A two-stage simulation approach was employed. At the first stage, a detailed model of the JET torus was used to produce a surface neutron source. The Surface Source Write file registered neutrons on a quarter-sphere with center at the SW Hall corner (1.0 m above the floor level) and a radius of 5.0 m (Fig. 1). At the second stage, the Surface Source Write file was used as Surface Source Read input file for the calculations along the labyrinth.

Neutron fluence was calculated using track length estimate tallies of neutron flux in spherical cells of 0.3 m in radius positioned along the maze at 1.0 m height above the floor level. Moreover, ambient dose equivalent, H*(10), was calculated folding neutron flux by ambient dose equivalent to neutron fluence conversion factors as a function of neutron energy [6]. Statistical uncertainties were kept below 10% for all tallies.

Calculations were performed for the "as-built" concrete composition. In addition, MCNP runs were performed to study the sensitivity of the calculations on changes in the hydrogen and boron content in concrete. Hydrogen content (by weight) in plain and borated concrete was altered from 0.41% to 0.71% and from 0.05% to 0.35%, respectively. Boron in borated concrete was altered from 0% to 5%. It is stressed that the density of plain and borated concrete was not changed in these runs and it was kept as in the "as-built" concrete composition.

Simulations were performed for D-D and D-T toroidal plasma sources. In both cases, the developed model took into consideration the actual distribution of the neutron source while all other parameters (geometry, materials and detector positions) were kept identical.

3. **Results and discussion**

3.1. Neutron fluence and ambient dose equivalent along the labyrinth

Figure 2 shows the MCNP predicted neutron energy spectrum at positions M1-M6 along the labyrinth for D-D and D-T JET plasma sources. Position M1 corresponds to the inner entrance of the labyrinth (mouth) and position M6 to the exit door.

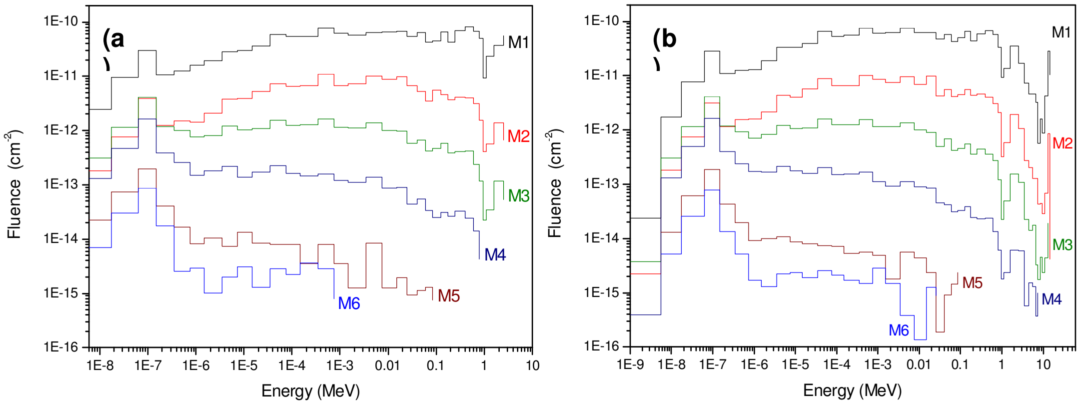

Fig. 2 Neutron energy spectrum at labyrinth positions M1-M6 for (a) D-D and (b) D-T plasma

Fig. 3 shows the calculated neutron fluence along the labyrinth as a function of the summed centerline distance (L) from the inner labyrinth entrance (mouth) to the exit door divided by the square root of the labyrinth cross-sectional area (A), for the D-D and D-T plasma sources. Neutron fluence is divided in three energy groups: "thermal" (E<0.5 eV), "epithermal" (0.5 eV<E<0.1 MeV) and "fast" (E>0.1 MeV). The total neutron fluence is also shown. It is noted that the results presented in Fig.3 were normalized per JET neutron. As it can be seen, the total neutron fluence is attenuated along the maze by about four orders of magnitude. In the first two sections of the labyrinth (M1-M2 & M2-M3) neutron fluence is dominated by epithermal neutrons. However, for $L/A^{0.5} \geq 4.5$ the thermal neutron group becomes the dominant one.

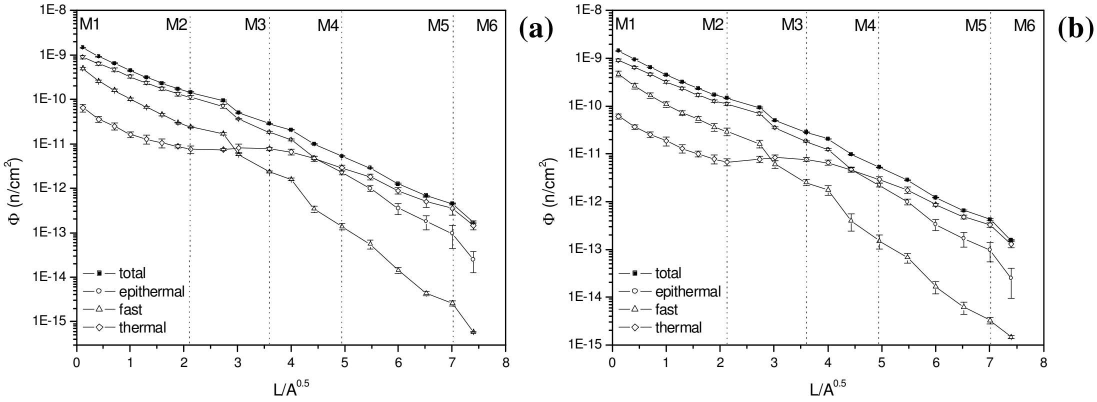

Fig. 3 Neutron fluence as a function of $L/A^{0.5}$ for (a) D-D plasma and (b) D-T plasma

Fig. 4 shows the MCNP calculated ambient dose equivalent, H*(10), along the labyrinth as a function of the parameter $L/A^{0.5}$ for the D-D and D-T sources. The results are normalized per JET neutron. In both cases the ambient dose equivalent is decreasing along the total length of the labyrinth. The comparable calculated H*(10) values at the labyrinth exit in D-D and D-T operation modes (per JET neutron) are attributed to the fact that neutrons entering the labyrinth have already been slowed down due to multiple interactions in the Torus and wall materials and their propagation along the labyrinth has become independent of their initial energy at the point of production (source).

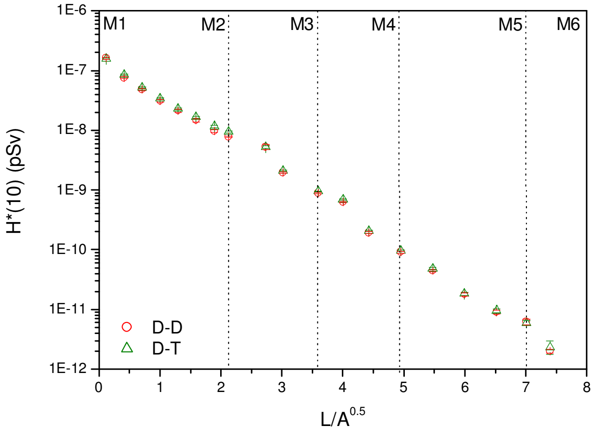

Fig. 4 Neutron *a*mbient dose equivalent, H*(10), as a function of $L/A^{0.5}$ for D-D and D-T sources

3.2 Effect of concrete composition

The ratio of H*(10) values calculated at the labyrinth exit for the tested concretes over the values calculated for the "as-built" concretes for the D-D plasma source is shown in Fig. 5. In this figure X-axis represents the alteration in hydrogen concentration in concrete in steps of 0.05% from the "as built" values. As it can be seen, a decrease in hydrogen concentration in both concretes by 0.05 % results in an increase of 25% in dose at the labyrinth exit. A similar result was also observed for the D-T source.

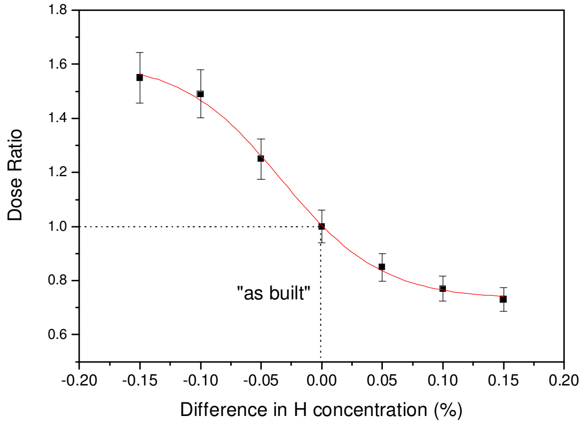

Fig.5 Predicted d centration in concrete for D-D

In Fig. 6, the neutron fluence at the labyrinth exit is plotted as a function of boron content in the surface concrete layer (of 30 cm in thickness) for the D-D and the D-T source. It can be seen that an increase in boron concentration in concrete from 0 to 1% resulted in a reduction in neutron fluence at the labyrinth exit by a factor of about 2. For a higher boron concentration the dose reduction at the labyrinth exit was small, since all slow neutrons were absorbed by the wall material.

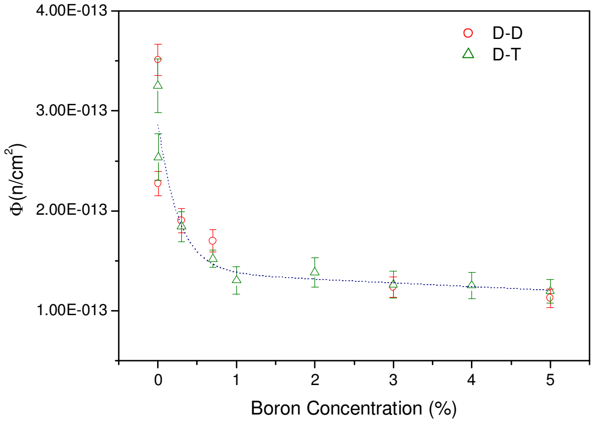

Fig.6 MCNP calculated neutron fluence at the labyrinth exit as a function of boron concentration in concrete for D-D and D-T plasma sources

4. Comparison against measurements

The results of the calculations were compared against measurements using TLDs. Sets of MCP-N and MCP-7 type TLDs were positioned within cylindrical polyethylene moderators in several locations in the JET Hall including the labyrinth region. The detector irradiation was carried out during JET C31 experimental campaign in D-D operation mode. The experimental procedure and detector calibration has been described in detail by Obryk et al [1, 2]. Table 2 shows the comparison of the calculated and measured neutron fluence at three positions in the labyrinth region. Detector A3 was positioned near the labyrinth mouth, detector A4 was in the middle of labyrinth section M1-M2 and detector A5 was at section M2-M3. The experimental values shown in Table 2 were obtained from MCP-N type detectors positioned in vertically oriented rectangular holders within the moderator cylinders. Calculations were normalized per 2.38 × 10^{18} neutrons produced at the source during the experimental campaign.

Table 2: Comparison of calculated and measured neutron fluence at three labyrinth positions (with their % relative errors)

Detector	Fluence (cm^{-2} n^{-1})		C/E ratio
	Calculated	Experimental	
A3	1.68E+09 (4.8)	1.03E+09 (12.7)	1.62 (13.6)
A4	9.63E+08 (4.1)	3.86E+08 (18.0)	2.49 (18.4)
A5	5.64E+07 (8.8)	2.01E+07 (17.7)	2.81 (19.8)

As it can be seen from Table 2, a systematic overestimation of the calculations over the measurements is observed. The observed discrepancy in C/E ratios was mainly attributed to approximations in the model geometry. In particular, although the JET tokamak and the labyrinth configurations were described to sufficient details in the MCNP model, the diagnostic systems, heating systems and various equipments surrounding the machine were not accurately described in the model and a homogeneous material zone was used instead. These components have an attenuation effect on neutron fluence that is not adequately described by the model and therefore calculations overestimated the neutron fluence results. However, taking into consideration the overall complexity of the modeled configuration the C/E ratios found in this study should be considered as a satisfactory agreement.

5. Conclusions

Monte Carlo calculations using the MCNP code were performed in order to predict neutron fluence and ambient dose equivalent along the JET entrance labyrinth for both D-D and D-T sources. Furthermore, the sensitivity of the calculations on changes in the hydrogen and boron content in concrete was evaluated. The results of the simulations showed that neutron streaming simulations through the JET labyrinth depend on the exact knowledge of the labyrinth geometry and wall composition and is practically independent of the source neutron spectrum. Moreover, the calculations were compared against measurements performed using TLDs and the C/E ratios were found to be in the range of 1.5 – 3. This difference was attributed to limitations in the complex geometry modeled. The results of this work support the operational radiation protection effort to minimize collective radiation dose to personnel at JET and provide important information from JET experience that may assist in the optimization and validation of the radiation shielding design methodology used for ITER and DEMO. Further work will be directed towards model refinement and improving measurement and computational statistics.

Acknowledgements

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement (EFDA) under JET Fusion Technology task JW13-FT-5.48. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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