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Shielding analyses of the IFMIF test cell

Y. Chen [b,*], U. Fischer [a], S.P. Simakov [a], F. Wasastjerna [c]

[a] *Association FZK-Euratom, Forschungszentrum Karlsruhe, Institut fuer Reaktorsicherheit, P.O. Box 3640, 76021 Karlsruhe, Germany*
[b] *North China Electric Power University, Department of Nuclear Engineering, Dewai-Zhuxinzhuang, Beijing 102206, PR China*
[c] *Association Euratom-Tekes, VTT, P.O. Box 1604, FIN-02044 VTT, Finland*

Abstract

Full 3-D shielding calculations of the IFMIF test cell were performed using a computational scheme for coupled Monte Carlo/deterministic transport calculations that enables the use of a detailed geometry model of the test cell in the Monte Carlo calculation and is suitable, at the same time, to handle the deep penetration transport through the thick surrounding concrete walls. Calculations for the test cell cover, which includes numerous penetrations through which neutrons stream, were performed by the Monte Carlo method. The results demonstrate that the dose rate limit for work personnel access to the access/maintenance room can be safely met during IFMIF operation assuming the test modules are surrounded by a horseshoe shield and the back heavy concrete wall is no less than 250 cm thick. No work personnel access to the room above the cover will be permitted during IFMIF operation due to the strong neutron streaming through the cover penetrations.

1. Introduction

The IFMIF D-Li neutron source [1] will produce an intense, high-energy neutron field to provide the material irradiation conditions of a D–T fusion power reactor. With two deuteron beams of 125 mA each accelerated to 40 MeV deuteron energy, a neutron source intensity of $10^{17}\ s^{-1}$ will be achieved during full power operation. This will result in a maximum neutron flux density around $10^{15}\ cm^{-2}\ s^{-1}$ in the lithium target with a neutron spectrum extending up to 55 MeV. Accurate shielding calculations are required to assess the shielding performance of the test cell with the target, the test modules, reflectors and shield modules, the surrounding walls and the test cell cover to prove that the safety requirements can be met to allow for personnel access to the maintenance rooms during the operation of IFMIF.

Full 3-D shielding calculations of the IFMIF test cell were performed to this end using a recently developed computational scheme for coupled Monte Carlo/deterministic (S_N) transport calculations [2,3] that enables a description of a detailed geometric model of the test cell using the Monte Carlo approach and the handling of the deep-penetration problem of the thick shielding walls using a 3-D (deterministic) S_N method with a boundary source distribution as provided by the preceding Monte Carlo simulation. Shielding calculations for

* Corresponding author. Tel.: +86 10 51963350; fax: +86 10 80798618.
E-mail address: yxchen@ncepu.edu.cn (Y. Chen).

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the test cell cover, on the other hand, are complicated by a large number of penetrations through which neutrons will stream. Such problems are best handled by Monte Carlo calculations making use of different variance reduction techniques as available with the MCNP code [4].

The computational approaches for the shielding calculations are outlined and results are presented of flux and dose rate distributions in the maintenance and access rooms of the test cell.

2. Methodological approach

To accurately handle complicated shielding problems with complex geometry and large-scale bulk shields, a computational scheme for 3-D coupled Monte Carlo/deterministic (S_N) transport calculations has been recently developed and implemented [2,3]. The Monte Carlo approach to neutron transport problems is different from the S_N method. In the Monte Carlo approach, individual particles are simulated by tracking their life histories and recording events to obtain their average behaviour. In contrast, the S_N approach solves the Boltzmann transport equation using numerical methods. In order to couple these two different methods, a mapping approach to generate the S_N angular flux from Monte Carlo particle tracks has been developed and implemented. Fig. 1 shows the flowchart of the program system for the 3-D coupled scheme. This program is able to treat neutron, photon and coupled neutron/photon transport problems in both Cartesian (X, Y, Z) and Cylindrical (R, θ, Z) geometry.

In the practical application of the coupled scheme, a common surface is specified as a link between the Monte Carlo geometrical model and the S_N mesh model. The Monte Carlo particle tracks of interest crossing the common surface are stored in a surface source file. The contribution of each particle track to the S_N angular flux across the given surface element, energy group and direction is then evaluated based on the mapping

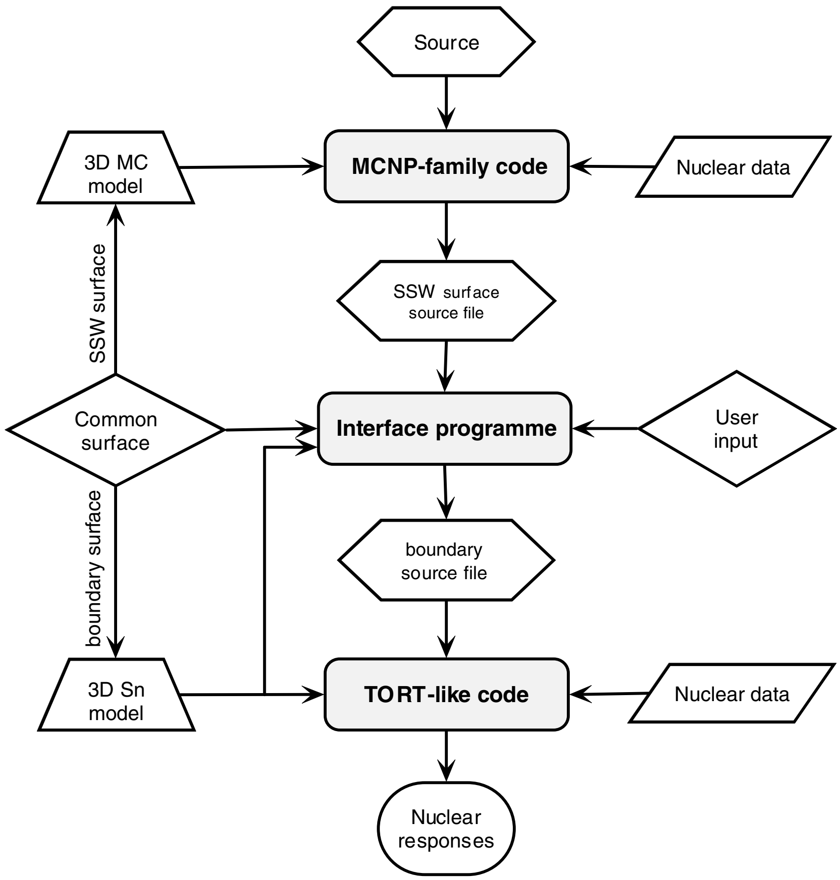

Fig. 1. Flow chart of the 3-D coupled Monte Carlo/deterministic computational scheme.

approach. The total angular boundary flux for each phase space element can be obtained by summing over contributions from all the effective Monte Carlo particle tracks, and then the boundary source for the S_N code can be generated and used by the 3-D S_N code.

In the shielding analyses, the code McDeLicious [5], an extension to MCNP with the capability of simulating the generation of D-Li source neutrons, is used for the Monte Carlo calculations along with high energy cross section data from the LANL150 (to 150 MeV) data library [6] and FZK/INPE (to 50 MeV) evaluated data files [7]. The well-known 3-D S_N code TORT [8] is used for the S_N calculations with Vitenea-IEF [9], an intermediate energy coupled 256-neutron and 49-gamma-ray multi-group cross section library provided by ENEA Bologna.

The calculation of the dose rate in the access cell above the test cell cover was performed by pure Monte Carlo calculations which are best suited to cope with the neutron streaming through the ducts of the cover. Russian Roulette and particle splitting with an optimised importance map were used for reducing the variance of the scored flux tallies.

3. Shielding calculations and results

The 3-D geometrical model used in the shielding calculations of this work is displayed in Fig. 2. This model includes two parts: the test cell and the access/maintenance room. Part of the test cell (the region with yellow color as shown in Fig. 2) is a 3-D MCNP model developed based on the up-to-date reference design of IFMIF. This model describes the detailed geometry of subsystems in the test cell such as the beam and target system, the lithium handling system, the high/medium/low flux test modules, the ceiling, the floor and the walls. The walls and floor are considered to consist of 3 m thick heavy concrete with a 3 cm thick steel liner on the inside. In addition, this model includes a horse-shoe-type shield around the test modules to reduce the radiation loading on the test cell walls.

The mesh model for TORT calculations includes the front wall and the access/maintenance room. The ceiling, vertical wall and the floor of the access/maintenance room are 0.5 m, 0.5 m and 1.0 m thick ordinary concrete (except the front wall), respectively. In order to employ a detailed mesh model with a fine energy group structure, high order of scattering anisotropy representation and angular quadrature set and making full use of the available computer resources, the mesh model was further divided into two parts: the front wall and the access/maintenance room. The mesh grids for the front wall and the room are $(63 \times 52 \times 60)$ and $(62 \times 44 \times 82)$ in X, Y, Z geometry, respectively. The code TORSET [8] was used for the splicing and bootstrapping from the part of the front wall

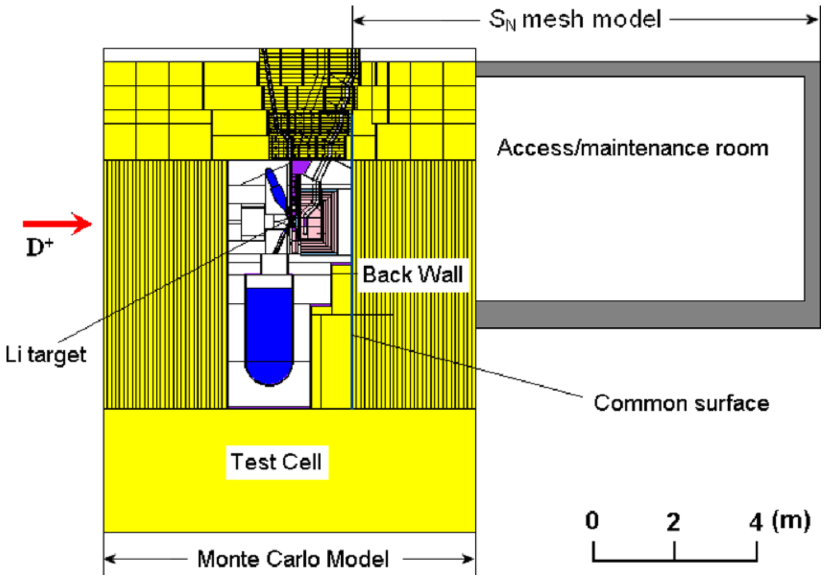

Fig. 2. Geometrical model of the IFMIF Test cell and access/maintenance room.

to the access/maintenance room in the TORT solution. In this application, the inner surface (see Fig. 2) of the front wall was specified as the common surface for scoring the Monte Carlo particle tracks and acting as boundary for TORT source input. The thick concrete walls were included in the model for Monte Carlo simulation in order to take the albedo effect into account.

The 3-D neutron and photon flux distributions in the back wall and access/maintenance room were calculated using the approach described above. The dose rates were then obtained by multiplying the neutron/photon fluxes by flux-to-dose rate conversion factors [10]. In the TORT calculations, a S_8 angular quadrature set, a P_3 Legendre series approximation of the scattering kernel and the 256-neutron and 49-photon energy group structure were used.

Fig. 3 shows the peak dose rates across the back wall and the access/maintenance room. Two cases are considered, one with and one without a horseshoe shield around the test modules. The horseshoe shield consists of 40 cm thick slabs made of the efficient shield material tungsten carbide (WC) at 80% of the normal mass density. The results show that the neutron radiation dominates the dose rate in both cases. At the front of the back wall, the dose rate in the case without a horseshoe is almost 24 times higher than that with the horseshoe. The dose rate attenuates more than nine orders of magnitude across the back wall with the horseshoe shield and more than 8 orders without the horseshoe. At the rear of the back wall the dose rate with the horse-

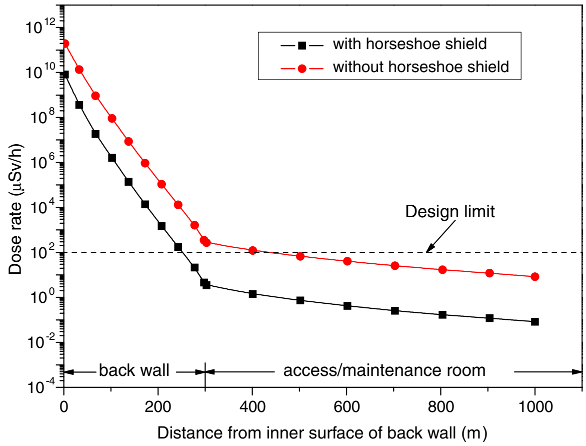

Fig. 3. Profiles of the total dose rate as function of the distance from the inner surface of the back wall.

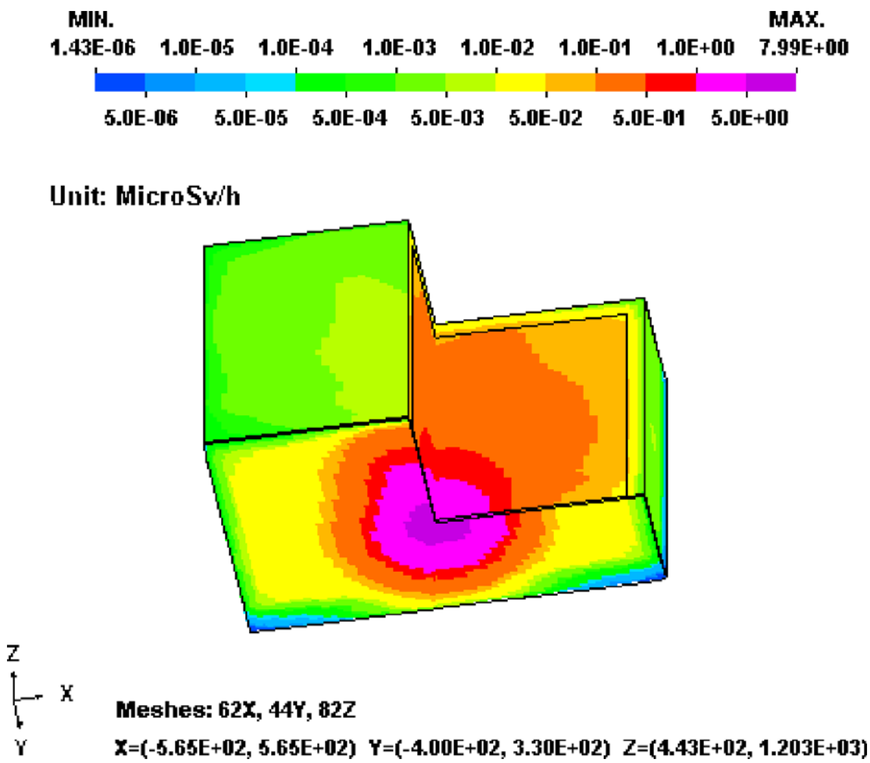

Fig. 4. Dose rate distribution in the access/maintenance room with horseshoe shield.

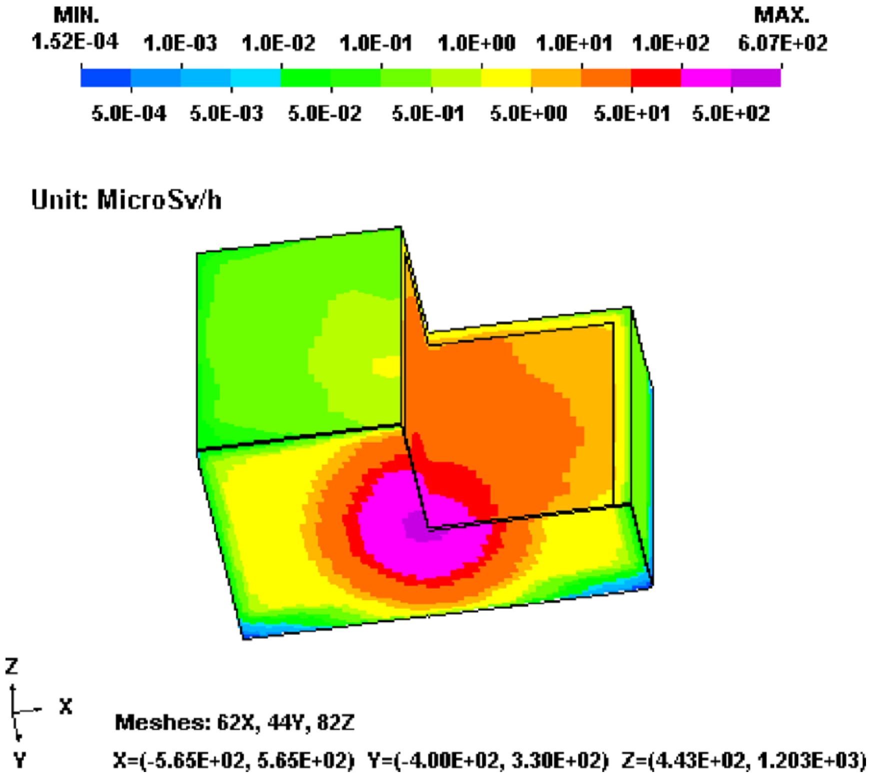

Fig. 5. Dose rate distribution in the access/maintenance room without horseshoe shield.

shoe shield is ~5 μSv/h, which is well below the design limit of 100 μSv/h for work personnel access. Without the horseshoe shield, the dose rate at the rear of the back wall is about 350 μSv/h, thus exceeding the radiation design limit. Figs. 4 and 5 show the three-dimensional dose rate distributions in the access/maintenance room with and without the horseshoe shield, respectively. The results demonstrate that the required dose rate limit for work personnel access to the access/maintenance room can be safely met during IFMIF operation assuming the test modules are surrounded by a WC horseshoe shield. Furthermore, the thickness of the back wall, made of heavy concrete, could be reduced to about 250 cm.

For the calculation of the dose rate in the access cell above the test cell cover, the first results were obtained for fast neutrons with energies above 0.1 MeV. However, this demonstrates that the dose rate limit for work personnel access in this room will be exceeded during operation. Fig. 6 shows a vertical cut of the Monte Carlo test cell model with the enlarged test cell cover section which includes a variety of penetrations and ducts. The fast neutron dose rate averaged over the upper surface of the thicker

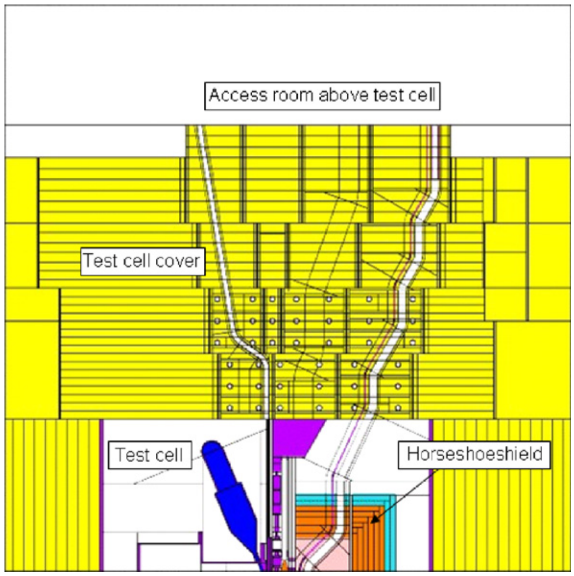

Fig. 6. Vertical cut of test cell model used for Monte Carlo streaming/shielding calculations of test cell cover showing 2 out of 43 ducts.

part in the center of the cover was found to be close to 4000 μSv/h, with a peak of about 9000 μSv/h. These values apply in the absence of a horseshoe shield around the test modules. If such a shield is present, the average and maximum values are reduced to about 900 and 2000 μSv/h, respectively.

4. Conclusions

Full 3-D shielding calculations of the IFMIF test cell have been performed to evaluate the dose rate distributions in the neighboring rooms of the test cell during operation using a recently developed 3-D coupled Monte Carlo/Deterministic (S_N) computation scheme. This approach enables the use of a detailed geometry model of the test cell in the Monte Carlo calculation along with a proper representation of the D-Li neutron source through the use of the McDeLicious code while the deep penetration transport through the thick concrete walls surrounding the test cell is described by means of 3-D S_N calculations with the TORT code. To handle the neutron streaming problem of the upper test cell cover, pure Monte Carlo calculations were performed using the importance sampling technique for the variance reduction available with MCNP.

The results demonstrate that the required dose rate limit for work personnel access to the access/maintenance room adjacent to the test cell can be safely met during IFMIF operation assuming the test modules are surrounded by a WC horseshoe shield and the test cell is made enclosed by a heavy concrete wall with a thickness of at least 250 cm. No work personnel access to the room above the test cell cover will be permitted during IFMIF operation due to the strong neutron streaming through the cover penetrations and ducts.

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