TCV Tokamak Neutron Shielding Assessment and Upgrade

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ABSTRACT

The aim of this work was to estimate the reduction in neutron dose rates within the TCV building after adding a ceiling and installing a shielded door at the TCV hall entrance. The analysis was subdivided in to three tasks. This included a comparison of several different shielding materials at different thicknesses in the first task and the effect of existing gaps in the concrete walls in the second task. The material shielding task showed Shieldwerx SWX201 borated polyethylene was the best performing material closely followed by a laminate polyethylene/borated polyethylene material. The gap analysis showed that total dose from the gaps in the concrete walls was insignificant.

In the third and final task an upgraded MCNP model (reference model) was used for dose field calculations and dose rate calculations at specific locations around the TCV machine. Based on the reference model a basic shielding model was constructed with a ceiling and door plug made from polyethylene/Shieldwerx laminate material. The basic shielding design reduces the neutron dose at key locations up to a factor of 77 but does not provide sufficient shielding for key locations in the control room area. In future work, additional shielding will be added to the existing TCV hall walls to achieve a desired dose reduction factor of the order of 100 in the control room.

1 INTRODUCTION

The “Tokamak à configuration variable” or “Variable configuration tokamak” (TCV) \([1],[2]\) is a magnetic fusion research device located at the Swiss Plasma Center, EPFL. Its unusual rectangular vacuum vessel, 1.5 m high and 0.5 m wide is equipped with tightly fitted poloidal field coils that allow for a wide variety of plasma shapes to be investigated for properties such as energy confinement and magnetohydrodynamic stability.

Plasma electron heating up to ~3 MW is provided by gyrotrons operating in the range 80 GHz -120 GHz, while heating of the ions up to Ti~3 keV is presently achieved with a 25 keV - 30 keV, 1.4 MW neutral beam heating (NBH). A second NBH system operating at 50 keV - 60 keV is planned to enter operation early in 2021. When operating in deuterium (D), the NBH with a single 25 keV beam produces 2.45 MeV D-D neutrons at rates of several 10\(^{12}\) /s, depending on plasma conditions. Radiation exposure in the nearby control room currently meets strict safety limits (4 μSv/day), but can be exceeded within half a day of normal operation.
When operated together with the 2nd beam, also in Deuterium mode, neutron rates are predicted to increase by an order of magnitude, exceeding safety limits (unless hydrogen is used, which would be disadvantageous for ion heating experiments).

The insufficiency of the legacy neutron shielding for optimal deuterium operation of both NBH units motivated a design study for an upgraded shielding of TCV. Neutron transport simulations were performed to identify the main particle streaming pathways and scope out additional shielding to reduce the neutron and gamma doses to acceptable levels. The state-of-the-art hybrid (deterministic/stochastic) particle transport methodology was adopted. This combines the ADVANTG [3] code to determine efficient variance reduction parameters based on a rough deterministic transport simulation followed by a high-fidelity continuous energy stochastic particle transport simulation using MCNP [4].

The shielding analysis was performed in several steps. Initially, the most effective material for shielding was determined and the effect of gaps between shielding blocks quantified. Then, the existing TCV hall MCNP model was upgraded by inserting TCV’s major components including the toroidal and poloidal coils, vacuum vessel, support pillars and the wooden floors. Following simulations with the present shielding configuration, a basic shielding design was proposed and analysed using the hybrid transport methodology.

The first part of the paper includes a brief description of the computer codes used in the analysis. The second part describes the model used for testing the effectiveness of different shielding materials and the results obtained with this model. In the third part the effect of gaps on the total dose is presented. Finally, the reference MCNP model of the complete TCV building is described. Additionally, a basic shielding design is proposed and tested. The main results are summed up and discussed in the conclusion of the paper.

2 COMPUTER CODES

The main program used for neutron transport simulations was the Monte Carlo N-Particle (MCNP) program code version 5 1.6 [4] developed by the Los Alamos National Laboratory. This code has been validated on numerous benchmark experiments and is widely used in the particle transport community around the world. MCNP was compiled with the plasma neutron source subroutine provided by EPFL [5]. All neutron doses calculated with MCNP in this paper are H*10 ambient equivalent [6].

The Automated Variance Reduction Generator (ADVANTG) [3] hybrid code developed by Oak Ridge National Laboratory generates space and energy dependent weight-window bounds using 3D discrete ordinate solution, from the Denovo [7] solver. ADVANTG was used to determine variance reduction parameters for the reference and shielding model calculations. Most of the ADVANTG input parameters were left at their default values except for the geometrical mesh which was defined in such a way as to accurately describe all of the major components of the TCV model, including all of the walls and discontinuities. A global weighing option was used to determine effective variance reduction parameters for all voxels in the mesh tally.

Several programs were used for the modelling and visualization of the geometrical model including Rhinoceros 3D [8], GRASP [9] and VisIt [10].

3 MATERIAL TESTING

In order to perform several computational efficient calculations with a shielding model that is representative TCV, a simple spherical model was adopted. This was used to test for shielding properties of various candidate materials before they are included in the full model that is computationally far more demanding.
The material testing model is a spherical model which consists of three regions. The inner regions are air that contains a void (vacuum) area in the shape of the TCV plasma with a diameter of 230 cm. The air region is encapsulated by a shielding material region with a 70 cm thickness (outer diameter 370 cm). The third and final region surrounds the shielding material and is made from air. This is a simple spherical model, but the main dimensions such as the source shape and shielding thickness is representative of the actual TCV machine. The main dimensions and regions are shown in Figure 1. The left picture of Figure 1 represents the 3D model with one quarter of the sphere removed. The right picture is a 2D cross section of the model at the sphere centre. Colours represent different materials as is indicated in the figure.

Figure 1: Material testing MCNP geometry model. 3D model on the left, 2D cross section at sphere center on the right. Different colors represent different materials (Left picture: green air, blue shielding material; Right picture: blue air, red shielding material. No color is vacuum\(^1\)).

For the material testing scenarios and the calculations with the reference and basic shielding model, a neutron particle source was used that closely resembles the shape and the energy distribution of the DD neutrons originating from a TCV plasma. The MCNP plasma source subroutine produced neutrons with an energy distribution centred at 2.45 MeV.

Several materials were tested for their shielding properties: Ordinary concrete, TCV baryted concrete, M1 concrete, Shieldwerx 201 borated PE and a laminate material consisting of 10 cm of polyethylene and 10 cm Shieldwerx 201. The neutron dose was calculated as the ambient equivalent dose rate H\(^{*}\)10 [6] at different shield depths. Figure 2 gives the neutron dose for different materials at 10 cm and 20 cm. The total shield thickness in this case was 20 cm. The 1σ statistical uncertainty of simulations is negligible (below 1%). The connecting lines are there to guide the eye. While the Shieldwerx material performs best, the laminate material performs almost as well and was chosen for the basic shielding design concept presented in Section 5.

\(^1\) Material colours are different because of the different software used for visualization.
Figure 2: H*10 neutron ambient dose equivalent per source particle in dependence of shield thickness for a polyethylene laminate material and other relevant materials.

4 GAP ANALYSIS

The current TCV hall side walls are built from 50 cm thick stacked concrete blocks. The concrete blocks have slight imperfections causing on average 1 mm gaps between the vertical block separations. A gap analysis model was constructed using a lattice of blocks which are 1 m x 1 m and 50 cm thick. The array of blocks consists of 21 by 21 concrete blocks. The model includes an air region in front and behind the concrete blocks. This region is 11 m thick in front, representative of the TCV machine position in the hall. Figure 3. The left picture represents the ZX cross section at Y=0 cm, and the right is a XY cross section at Z=25 cm zoomed on one block. The right picture also clearly shows the air gap between the concrete blocks. Three different air gaps were modelled, 0 mm, 1 mm and 5 mm. The particle source is a 2.45 MeV neutron point source positioned at several locations, also shown in the left figure of Figure 3.

Figure 3: Gap analysis MCNP geometry model. ZX cross section at y=0 on the left, a close up of one concrete block with gaps (XY cross section at z=25 cm) on the right.

The results of the analysis are neutron fluxes and doses in the volume behind the concrete slab with a gap relative to gap-less. This quantity gives us the ratio of the total transmitted dose through the gap. The results show that the 1 mm gap scenario increases the doses by up to 5 %
which can be neglected. In the unrealistic case with the 5 mm gap the dose increases by almost 30% in the worst case scenario where the source faces the intersection of gaps directly. This value is still negligible compared to the dose reduction factors which the new shielding configuration aims towards i.e. a factor of 50-100.

5 BASIC SHIELDING MODEL

The idea behind the reference model was to construct a more realistic model, including the major components of the machine, absent in the original MCNP model [11]. The components were chosen based on their probable effect on the dose values i.e. massive and high-density components. The following elements were included in the model: TCV vessel (1 cm stainless steel), Main magnetic coils (copper), Steel support bars, Concrete support pillars, TCV hall floor (concrete and wooden) and Wooden floor between ground level and control room. Most of the dimensions of the additional components were provided from a large TCV CAD model. This was simplified using Rhinoceros 3D [8] and converted to MCNP format geometry using GRASP [9]. The reference model is presented on the left of Figure 4.

The basic shielding model is based on the reference model. A laminate of two materials was chosen for the shielding of the ceiling of the TCV hall and for the door plug. The laminate is modelled as a 20 cm thick layer of pure polyethylene with a 5 cm coating of Shieldwerx SWX201. Additionally, the TCV hall side walls were lowered to 8 m. The model is presented in on the right of Figure 4. Note that the colour of some material has changed compared to the reference model namely the dark red colour now represents the polyethylene while the lime green indicates the borated polyethylene.

Figure 4: Reference MCNP model (left), basic shielding MCNP model (right). Side view cut at y=0 cm of the complete TCV building.

Neutron doses were calculated using these two models on a global mesh tally and at specific locations around the tokamak hall. The results are normalized to a 1 s plasma pulse with a neutron emission of 4×10^{13}. The dose maps calculated with the reference model (Figure 5) and basic shielding model (Figure 6) are given in mSv/s at y=0 cross section plane through the tokamak centre.
Figure 5: H*10 neutron dose rate color and contour map in mSv/s at slice y=0 cm calculated using the reference MCNP model. Axis dimensions are in centimeters.

Figure 6: H*10 neutron dose rate color and contour map in mSv/s at slice y=0 cm calculated using the basic shielding MCNP model. Axis dimensions are in centimeters.
From the global mesh tally results one can clearly see the reduction of the dose above the laminate shielding ceiling. A similar effect is seen when looking at the doses behind the door plug. To quantify the dose reduction, doses were also calculated at specific locations around the tokamak hall with both models. These, Figure 7, are as follows (coordinates are given in meters with respect to the plasma centre):

A. Control room, North half (operating team area), (-9.5; 6; 3.7)
B. Control room, South half, (-9.5; -9; 3.7)
C. Second floor, West side, 2 m from wall, at 1 m above floor level, (-9.5; 0; 7.6)
D. TCV hall at position, (2; 8; -0.4)

![Figure 7: Specific tally locations in the reference model at three different locations.](image)

The absolute neutron dose values for both models and the ratio of the two are given in Table 1. The reduction factor at locations A) and B) (control room) is not sufficient. Additional shielding is required on the TCV outside walls.

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6 CONCLUSION

The analysis presented in the paper covered in three subtasks. Firstly, several candidates for shielding materials were tested. This showed that pure polyethylene performs as well as a borated combination were able to sufficiently reduce the H*10 neutron ambient equivalent dose. The borated plastics only reduce the thermal peak that does not significantly contribute to the overall H*10 ambient equivalent dose and could be removed.

Secondly, the effect of gaps between concrete blocks on the total neutron dose was determined. The analysis showed that with a 1 mm gap the increase of the neutron dose behind
the concrete block is in the worst-case scenario 5% compared with the gap-less scenario. An unrealistic 5 mm gap scenario increase the dose by 30%. These results show that the gaps do not contribute significantly to the total when sufficiently behind the concrete block wall.

Finally, an upgraded MCNP model of the TCV building – the reference model – was used for baseline calculations of the neutron dose rates in and around the TCV building. The baseline results were used for comparison and assessment of the efficiency of the proposed basic shielding model which included a ceiling and door plug constructed from the laminate material identified as the best shielding option in the first subtask.

The reduction of the doses using the basic shielding model above the roof and behind the door are clearly seen from the dose maps. A dose tally at locations around the TCV hall show that reduction factor at location a) and b) (control room) is insufficient reaching only a value of 4.7 and 9.9 respectively. A reduction factor of 77 at location c) tells us that the shielding provided by the roof for location c) is very effective, however locations which are close to the walls aren’t sufficiently shielded by this configuration. Additional shielding is thus needed on the TCV hall side walls. Such a shielding scenario will be the topic of future analyses.

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REFERENCES