Evaluation of neutron dose rates at the TCV tokamak facility

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Abstract

A detailed MCNP neutronics model of the building housing the TCV tokamak has been developed. Predicted dose rates have been compared to neutron dose measurements at 12 locations in the building, obtained during neutral beam injection into TCV plasmas. This work was motivated both by the necessity to understand neutron transport in a complex environment and to provide an adequate reference model of the building to which additional shielding can be added. The additional shielding is required because of an expected 5-10 fold increase of neutron doses by the addition of a second neutral beam source. The neutron source was estimated using the TRANSP code. Starting from a simple model, which left out or simplified many important structures, the model was iteratively refined. The discrepancies between the predicted and measured doses decreased significantly, down to less than a factor 2 for most of the locations calculated by the most detailed model. A factor 2 is believed to be within the combined errors resulting from uncertainties in the neutron source model, the detector calibration and the uncertainties stemming from the model itself.

1. Introduction

The Variable Configuration Tokamak (fr. *Tokamak à configuration variable*) or TCV is an experimental fusion research device in Lausanne, operated by the Swiss plasma center (SPC) at EPFL. So far, ion heating has been provided by one neutral beam heating (NBH) system (NBI1) operating between 25 keV and 30 keV with up to 1.2 MW power for up to 2 seconds. A second NBH system (NBI2) is being commissioned on site with injection energy in the 50 keV - 60 keV range. When both are operated in deuterium (D) the neutron production is calculated to increase by an order of magnitude [1]. Thus, much higher neutron doses are expected across the TCV facility, necessitating an upgrade of the existing radiation shielding.

The existing radiation protection consists of barite concrete walls [1], with a density of 3.4×10^3 kg/m^3, containing 50.8 % barium by weight. This shielding is insufficient already for the neutron rates obtained with the current neutral injector. In many cases NBI operation has

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to be stopped after 5 pulses because the daily neutron dose limit of 4 μSv is attained. To enable full power operation (30 pulses of 2 second duration per day, with both NBH systems) additional neutron shielding was designed with the help of the Monte Carlo N-Particle transport code (MCNP) [2] in 2019 [3] as the methodology has been used in the past to perform dose rates analysis on JET [4], ITER [5] and DEMO [6]. The first step was to improve, the basic computational model of the building in its current condition (TCV basic model)[2], before, additional shielding was added in order to guide the design of the physical shielding to be installed in 2023.

Neutron dose measurements were acquired in a series of reproducible TCV discharges heated by NBI1 with a LUPIN BF3 neutron REM dosimeter at 12 specified locations (Fig. 1), while another, the reference dosimeter, was kept at a fixed location (A in figure 1) in the control room. No measurement of neutron rates is available on TCV. The neutron source was calculated for a reference discharge using the beam heating by one injector and the plasma transport code TRANSP [7], based on the characteristics of the injector and plasma measurements such as the electron temperature and density. The ion temperature was obtained from ASTRA, another transport model [8]. For subsequent TCV pulses, the source was obtained by normalizing the reference source to the ratio of the corresponding measured dose to the dose measured for the reference discharge. Experience from JET, which is equipped with absolutely calibrated neutron rate measurements, shows that calculated neutron rates can significantly exceed the measured ones, even when a comprehensive range of diagnostics is available as input to the modeling codes [9]. We therefore expect uncertainties in the neutron source rate to be significant, probably no lower than 50 %. However the most important metric for assessing the merit of a particular model of the building is not the ratio of the measurements to predictions based on the neutron source from TRANSP, but the relative ratios of doses measured and calculated at different locations, which are not affected by the uncertainties of the neutron source.

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[2] In [3] this computational model is named "TCV reference model". To avoid confusion, we renamed it to "TCV basic model (2019)".
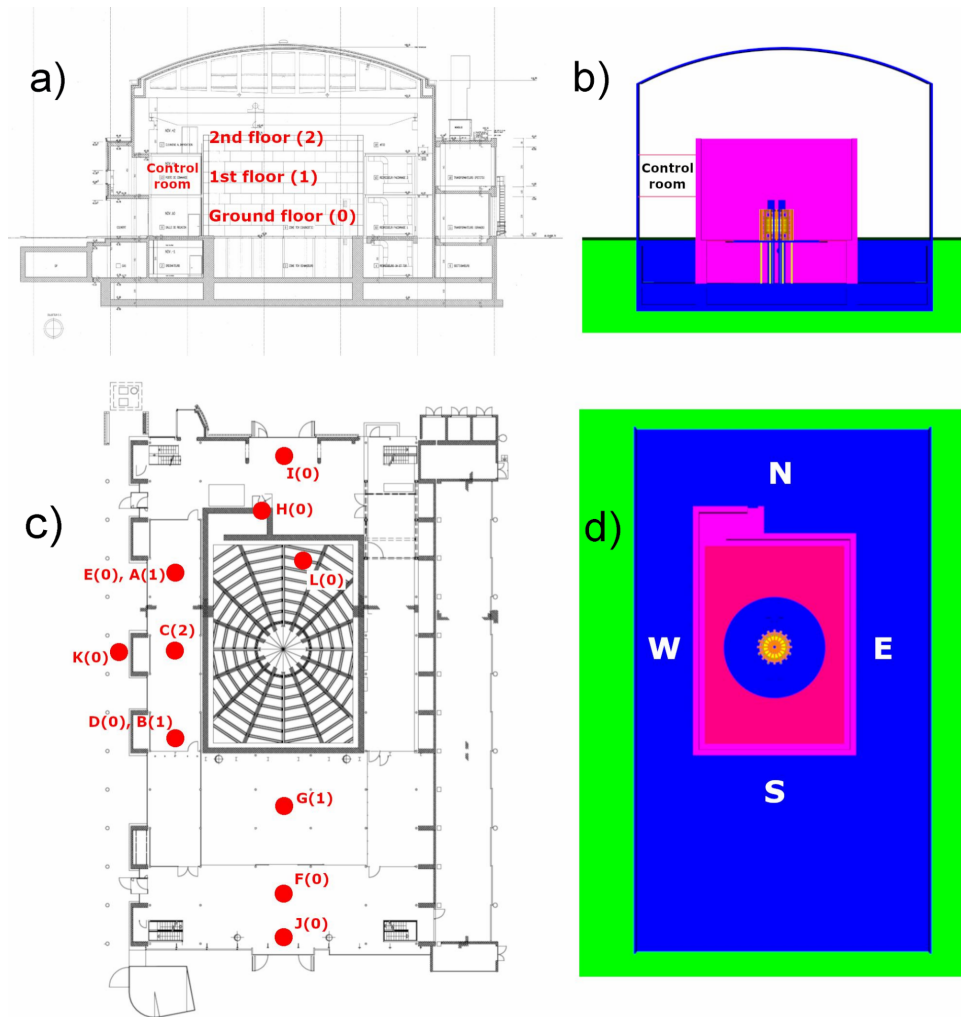
Fig. 1: In these MCNP computational model visualizations colors represent materials: blue is concrete, red is wood, yellow is stainless steel, orange is copper, magenta is heavy concrete. In this figure green is soil, whereas in later figures it also represents other materials. a) East-West engineering cross section of the TCV building in its current conditions. b) East-West cross section of TCV building in MCNP model. c) Horizontal cross section of the TCV building with dose measurement positions (identical with MCNP tally locations). The numbers in brackets indicate the floor levels of the tally locations. The TCV device is at the center of the TCV hall, on the web-like segmented dismountable ground floor. d) Horizontal cross section of MCNP model.

The calculated doses exceed the measured doses for all detector positions[3] (Fig. 2). This indicates that simplistic modeling, which leaves out many of the components, should be improved. In the workshop, below the control room (point d), the calculated dose was 10 times higher than the measured dose. The relative ratios, which depend only on the neutronics model spanned a range up to factor 5 with respect to the measurement in the TCV hall (labeled l in figure 2). Clearly the model used for initial calculations, had to be improved for a more accurate neutron shield assessment.

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[3] Data from presentation "Radiation safety (with NBI), dose measurements (past and future)" by P. Blanchard and J. Dubray at SPC EPFL in June 2021.
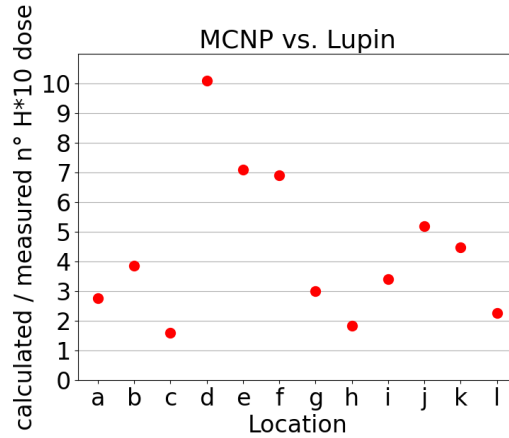
Fig. 2: Comparison of initial MCNP calculations to Lupin measurements at 12 locations.

The paper is organized as follows. In Section 2 the development of the TCV MCNP model is presented. The reference model represents the TCV facility as it was during the neutron dose measurement campaign with the Lupin BF3 dosimeter, described above. The shielded model, representing the geometry after the shielding update to the tokamak hall, was devised according to technical specifications[4]. These were dictated by the required neutron shielding effectiveness and engineering requirements. In Section 3 the MCNP computational results are presented. Based on the calculation results the engineering team modified the shielding model. After several iterations the following requirements were met:

1. Radiation safety requirements - sufficiently low neutron daily doses: a maximum daily dose of 4 µSv was set to comply with Swiss limits for the general public.
2. Ventilation requirements - ventilation of the reactor hall: During baking the vacuum vessel is heated, generating 100 kW of heat inside the reactor hall. The warm air must be exhausted through vents which still must provide sufficient neutron shielding.

2. Computational model development

Neutron transport calculations were performed with the Monte Carlo N-Particle transport code MCNP5-1.60 on the Skuta [10] cluster at Jožef Stefan Institute (JSI). The nuclear data used for the simulations were taken from the FENDL-3.1d nuclear data library [11]. Due to the effectiveness of the proposed neutron shield for the TCV tokamak, variance reduction weight windows, generated by the code ADVANTG were used to obtain results with low statistical uncertainty [12]. For dose comparison at the 12 assigned locations the optimization with the ADVANTG code was performed for all detector positions at the same time using the FW-CADIS method [13]. When evaluating the effectiveness of the neutron shielding the FW-CADIS method was implemented globally.

For MCNP codes the geometry of the computational model is described as a constructive solid geometry. 3D shapes are represented with cells with an assigned density and material, bounded by first-, second-, and fourth-degree user-defined surfaces [14]. These

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[4] Described by H. Weisen in "Specifications for MCNP calculations for the neutron shielding for TCV", unpublished document, April 2022.

split space into two regions. Cells are constructed by applying set operations (union and intersection) to these regions of one or more surfaces per cell.

For dose evaluation across the building many smaller items, such as railings, support beams etc. were neglected. Larger objects, far away from both the source and the detectors, such as the roof support trusses, were homogenized. Homogenization of materials and simplification of complex geometries makes it possible to construct a neutronics computational model for the reactor building.

2.1 Reference model

The new reference computational model was built on a previous computational model of the TCV facility shown on figure 3 (created by Tim Eade at CCFE as described in [15] and last modified by Bor Kos at JSI for a project described in [3]). First, by adding simple rectangular shaped structures, described in a spreadsheet, then modifying the building structure according to technical drawings (Fig. 4). Because the computational results were still not close enough to measurements (section 3.1), additional structures were added which were observed on the virtual tour hosted by EPFL online [16]. These were also examined by the modeling team during an in person visit to the facility. Furthermore, large steel structures were added from an engineering CAD model of the tokamak and its support structures.
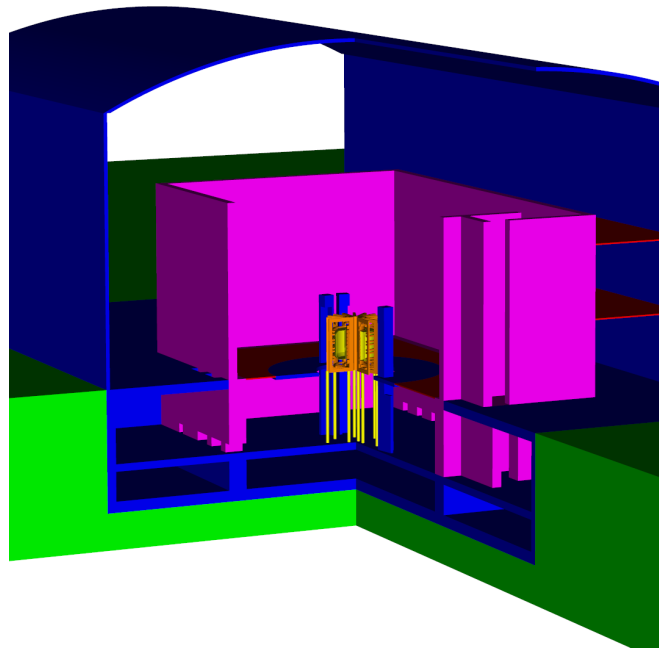

Fig. 3: Render of TCV basic model (2019). Slice at (+x, +y) quadrant is not displayed to show model interior.

A spreadsheet was provided, describing 49 objects inside the TCV building - system structures and components. Cabinets, instruments, desks as well as plasma heating components were approximated as boxes. Their attributes being location, dimensions, mass, orientation and approximated material composition. The geometric properties were converted into MCNP surfaces via a python script. Aluminum, stainless steel, wood and copper comprise these objects. A single object is composed of just one, or a half-half mixture of two materials.
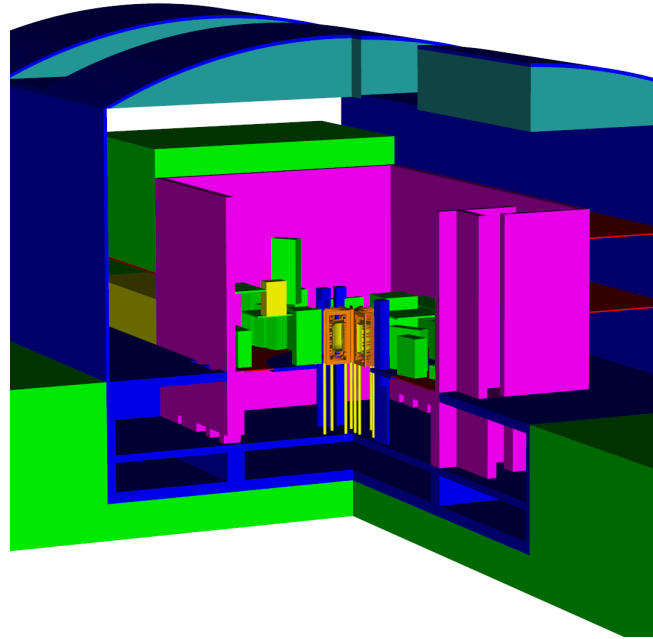
Fig. 4: Upgraded TCV basic model (2019). Roof has been modified and most system structures and components added.

In the initial model the roof has a domed shape, running continuously along the y-axis (north to south). To more accurately represent the roof, it has been split into 5 parts based on the original engineering drawings: 3 curved segments with a flat section in between each curved segment. The concrete trusses (Fig. 5) under each curved segment were approximated as a mixture of concrete, steel and air. Besides the concrete reinforcement, steel is also used to connect the trusses among each other in the form of large pipes. The amount of concrete and air was calculated from a simple CAD drawing constructed from the construction drawing. The amount of steel was calculated from the technical drawings. The mixture can be seen in table 1.
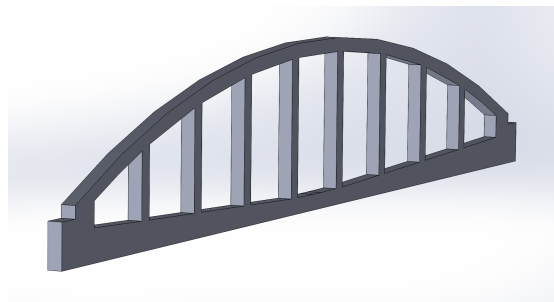

Fig. 5: Reinforced concrete roof truss, modeled in CAD. Used to calculate concrete to air ratio.

substance	Volumetric fraction	Density [g / cm^3]	Mass fraction
air	94.26 %	1.3e-3	0.77 %
concrete	5.675 %	2.4e+1	95.68 %
steel	0.065 %	7.8e+1	3.55 %

Table 1: Substances under curved roof segment.

Additional structures found in between the control room and the tokamak were roughly approximated and added into the model. These were seen on the TCV virtual tour. They are: a platform on the west wall and its steel supports, a steel air vent tube, a calorimeter and the epoxy bridge above the tokamak. A homogenous "fog", representing various cables, smaller instruments and structures, was added surrounding the tokamak. Sometimes called "scotch mist"[5], this "fog" has the same isotopic composition, but lower density as the one used in the Joint European Torus (JET) MCNP computational model (SC model in [17]).

Finally, large supporting structures for the vacuum vessel, coils and other tokamak components were added (Fig. 6). These were provided in a CAD model with more than 7000 solid bodies. For neutronics calculations, complex structures tend to be approximated as simpler shapes, but have to have an accurate mass and isotopic composition [18]. Therefore, the following steps were taken to model the supports in MCNP:

1. Axial symmetry was taken into account. The CAD model was cut into a quarter slice.
2. Parts were approximated with spheres and cylinders. Cylinders for long and narrow parts; spheres for the joints.
3. The volume of each unique component was calculated in CAD and used to correctly adjust the density of the simplified component (Table 2), to ensure the conservation of mass.
4. This simplified CAD model was then automatically imported into MCNP using SuperMC [19].
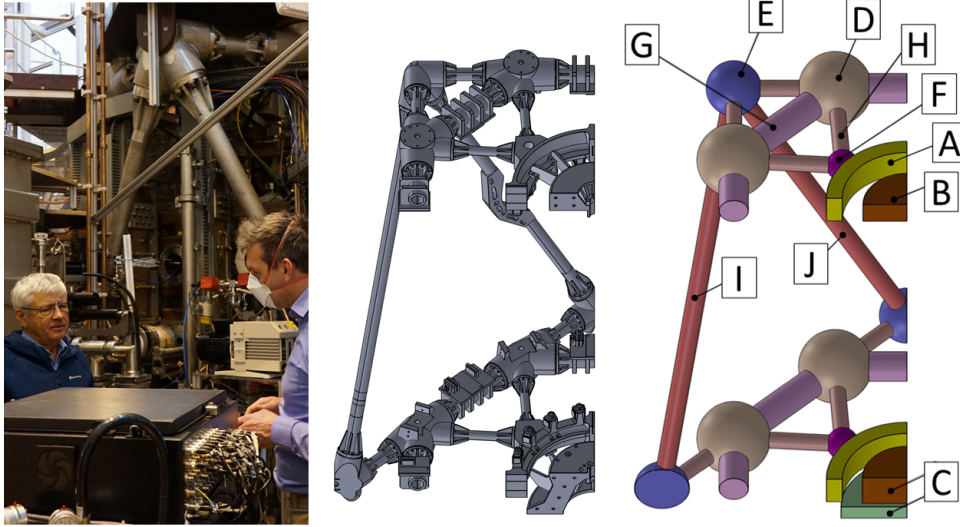

Fig. 6: Modeling of the steel tokamak supports. From left to right: picture of tokamak with visible support structures, a quarter slice of CAD model, a quarter slice of simplified CAD model (here, color distinguishes between components).

Component	A	B	C	D	E	F	G	H	I	J
Volume ratio: η	0.676	0.433	0.283	0.338	0.491	1.035	0.474	0.403	0.332	0.503
Simplified density: $\rho_S \ [g/cm^3]$	5.31	3.40	2.23	2.66	3.86	8.13	3.73	3.17	2.61	3.95

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[5] Scotch mist is a non-scientific term named after Brian Syme, head of the neutron diagnostic group at JET, who in 2012 suggested representing cables and other minor items around the machine with a homogenous mixture of low density. Brian Syme was Scottish and passed away in 2020.

Table 2: Calculating densities of simplified model components. A, B, C, etc. refer to labels on figure 6. Support structure is made of stainless steel with density $\rho_U = 7.84\ g/cm^3$. We calculate the volume ratio as $\eta = V_U/V_S$, where V_U and V_S are the volumes of the un-simplified and simplified components respectively. To ensure the conservation of mass the simplified component density is calculated as $\rho_S = \eta\,\rho_U$.

Empty space around the tokamak was assigned, into which this simplified model of support structures would be inserted as a MCNP feature called a universe - a specified volume into which larger structures or patterns may be filled. Some spheres of these simplified supports overlap with existing tokamak structures. Geometrically the universe feature elegantly resolves these overlaps. Since the simplified supports were cut by other reactor components their volume was reduced. To take this into account their volume was recalculated to ensure the conservation of mass. This volume calculation was performed stochastically with MCNP. All together, these tokamak support structures weigh 11 tons and are made from stainless steel.

This computational model was named TCV reference model (2022) and represents the state of the TCV facility from February 2021 to April 2021, when the Lupin dose measurements were performed. It can be seen on figure 7.
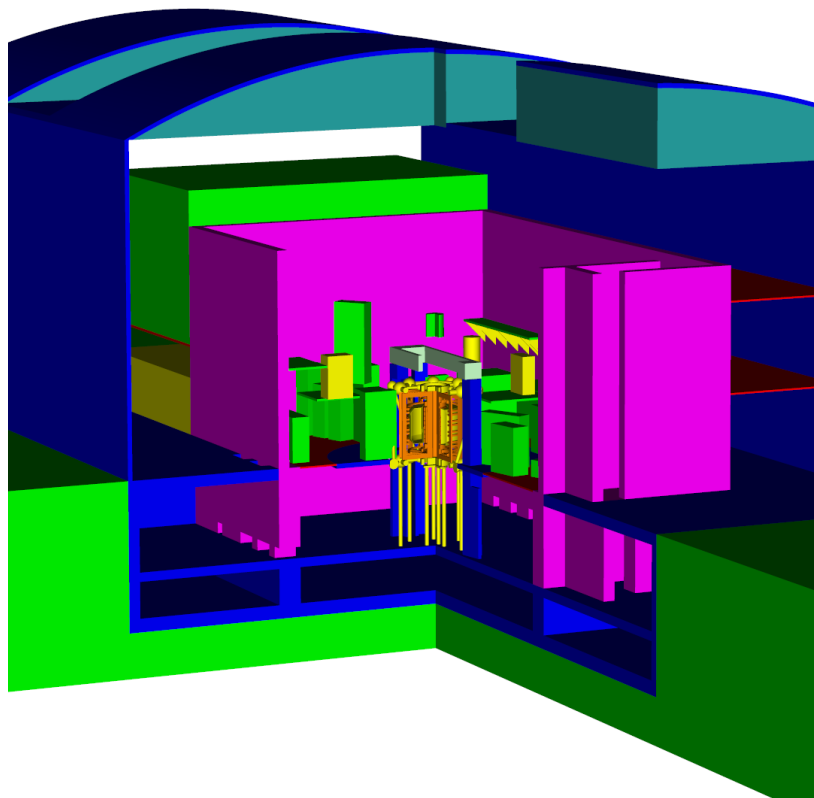

Fig. 7: Reference computational model of the TCV facility - TCV reference model (2022). More system structures and components were added. Homogeneous "fog" representing cables and small instruments isn't visible in this render.

2.2 Shielded model

The shielded model was built upon the reference model described in the previous section. Firstly, four objects were added south-west of the tokamak: the second NBH and 3

surrounding cabinets. These objects were added after the measurements were performed; hence they aren't present in the reference model.

So far, radiation protection was provided by the walls, made of barite concrete blocks. To ensure better neutron protection, required due to upgrades to the plasma heating, additional shields in the form of polyethylene (PE) panels are planned [1]. A crucial step in designing such shields is modeling and simulating their effectiveness. These panels flank the walls of the reactor hall and comprise the ceiling which covers it. The entrance into the reactor hall would be equipped with a sliding door made of the same panels. Testing would be done to determine with which method the basement holes should be closed. Later an air vent would be designed to comply with fire safety regulations and tokamak hall airflow requirements.

The first phase of shield design was intended to eliminate all direct paths of the neutrons escaping the reactor hall. Based on our analyses [1], a neutron escaping the reactor hall should have to penetrate at least:

- 100 cm of heavy concrete, or
- 50 cm of heavy concrete and 20 cm of PE, or
- 35 cm of PE.

Ideally the inside wall should be covered with PE. Unfortunately some hard to move objects are placed against the walls. At these places patches of PE were added on the outside in the model. As far as neutron attenuation is concerned, it makes almost no difference whether the additional PE is at the inside or at the outside. However, a major disadvantage of having PE on the outside is that gammas, produced by neutron capture, can reach human occupied zones unimpeded. (In the final engineering design all PE shielding is placed inside the walls). Sliding doors made of PE will be used to block radiation from escaping through basement and reactor hall entrances. Air vents are necessary for adequate ventilation of the TCV hall and were initially designed as a set of 20 simple holes in the PE ceiling (Fig. 8). They led to neutrons streaming towards the building roof, from where a significant fraction were scattered back down, leading to unacceptably high doses (section 3.2 and figure 14). The 20 hole air vent design was abandoned and replaced by the dog leg design (Fig. 8).
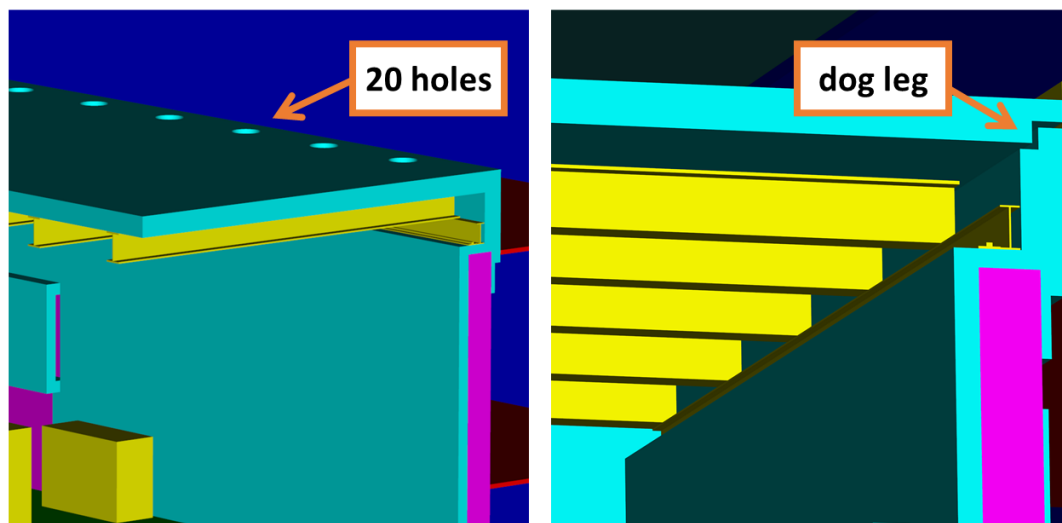

Fig. 8: Air vent designs. Left: 20 hole design, right: dog leg design. Yellow is stainless steel, magenta is heavy concrete, turquoise is polyethylene.

The walls in the building basement are made of 100 cm thick TCV concrete. These walls have 27 penetrations, with apertures ranging from 0.24 m^2 to 0.65 m^2, that would need to be plugged. Three different variations were tested (Fig. 9):

A. A 40 cm PE panel placed flush with the inside wall surface.
B. Two 20 cm PE panels. One flush with the inside, the other with the outside wall surface.
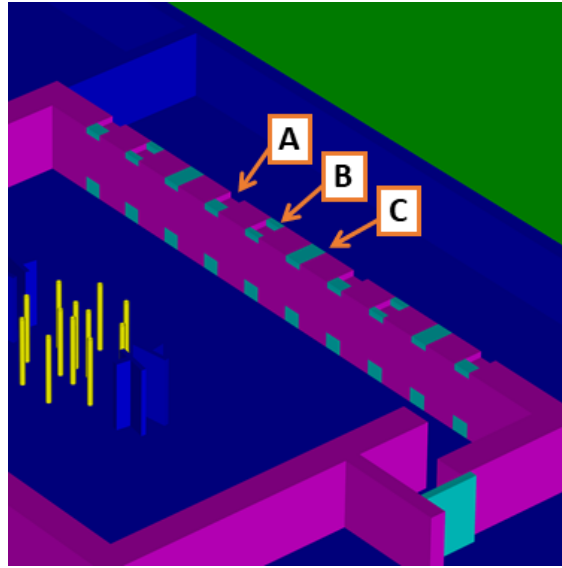C. PE beads would fill the hole with a packing ratio of 60 %.

Fig. 9: Render of PE plugs in building basement. Slice is horizontal, 320 cm below tokamak center. The C variant has 60 % the density of normal PE, which is not visible in this render.

The final design, which included all the abovementioned shielding improvements complied with neutron dose rate limits and fire safety regulations, can be seen in figure 10.
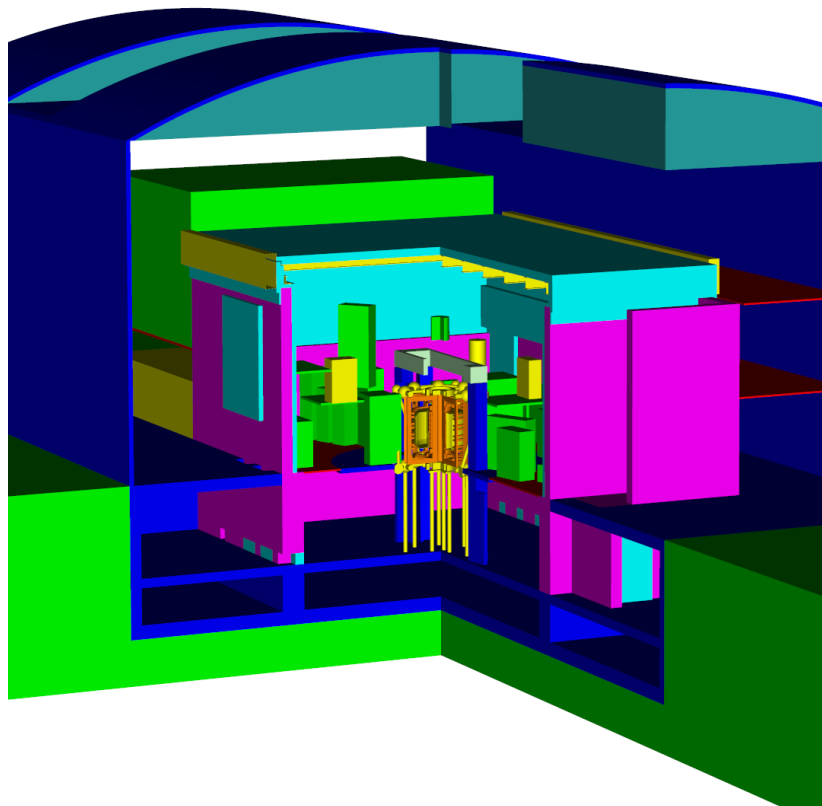

Fig. 10: Neutron shielded model of the TCV facility.

2.3 Comparison of computational models

A comparison of the computational models is presented in table 3 and in figure 11.

feature	basic (2019)	upgraded basic	reference (2022)	shielded (2022)
Building and environment	✓	✓	✓	✓
Heavy concrete walls	✓	✓	✓	✓
Vacuum vessel, mag. coils, pillars	✓	✓	✓	✓
Segmented roof		✓	✓	✓
System structures and components		✓	✓	✓
Homogenous fog around tokamak			✓	✓
Epoxy bridge			✓	✓
Steel tokamak supports			✓	✓
Polyethylene shielding				✓

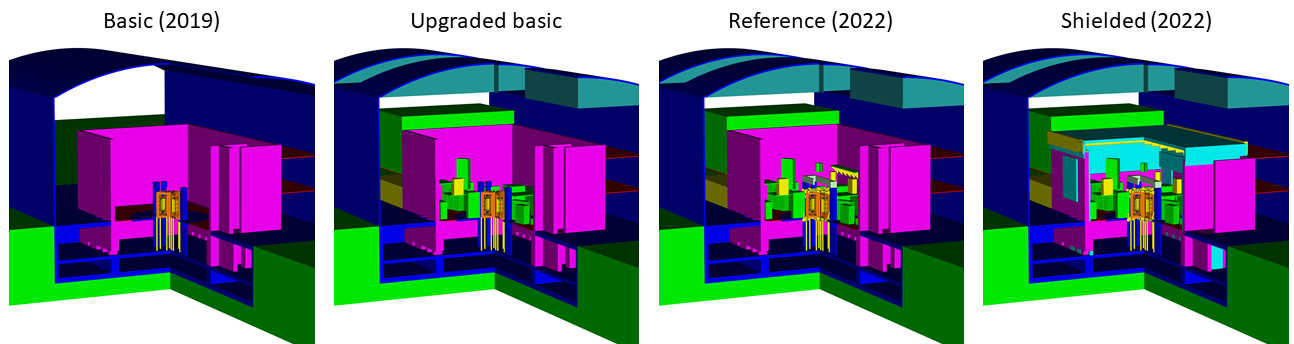Table 3: Features of TCV computational models for MCNP.

Fig. 11: Renders of TCV computational models for MCNP.

3. Results

3.1 Reference model results

The accuracy of the computational model is evaluated by the calculation to measurement ratio (C/E). A decent improvement would mean the C/E is close to 1 at all locations.

After adding system structures and components and modifying the roof, the calculated doses were closer to the measured ones, compared to the basic model. To evaluate the effect of the first modifications, a simple sensitivity study was performed on system structures and

components: firstly, all the densities were doubled, then multiplied by ten. The multiplication of densities had a positive effect on most locations - for most locations the C/E decreased towards 1. As is seen on figure 12, at some locations the C/E still remains high or hasn't moved towards 1. These locations have to be addressed. More specifically: there are still objects missing in the computational model, which in reality absorb or reflect neutrons coming to these locations. These are cabinets and workbenches in the workshop and large air ducts in the control room. After the sensitivity study, all densities in the computational model were returned to normal values, approximating the densities of real system structures and components at the TCV facility.
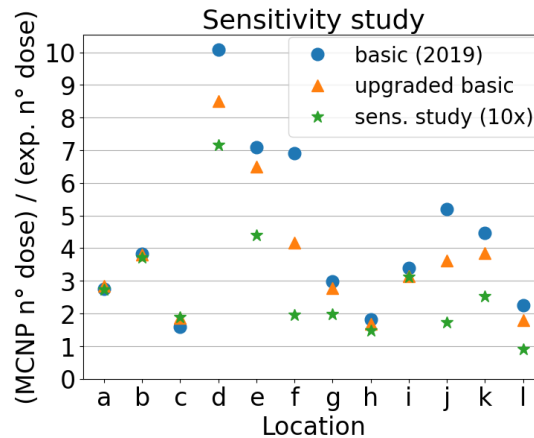

Fig. 12: Sensitivity study was performed on the upgraded basic model. Locations 'a', 'b' and 'h' affected less than others. Locations 'c' and 'i' are negatively affected by 10x normal density of system structures and components.

To determine the origin of neutrons towards locations with the highest C/E, cell flagging was utilized. I.e., all neutrons which pass through certain building structures were counted. Thus, it was obtained that 25 % of neutrons, detected in the workshop below the control room, back-scatter off the building roof, passing through the control room.

After adding more system structures and components and more importantly: the homogeneous "fog" surrounding the tokamak, the calculated dose rates rapidly approached a C/E ratio of 1, as can be seen on figure 13.
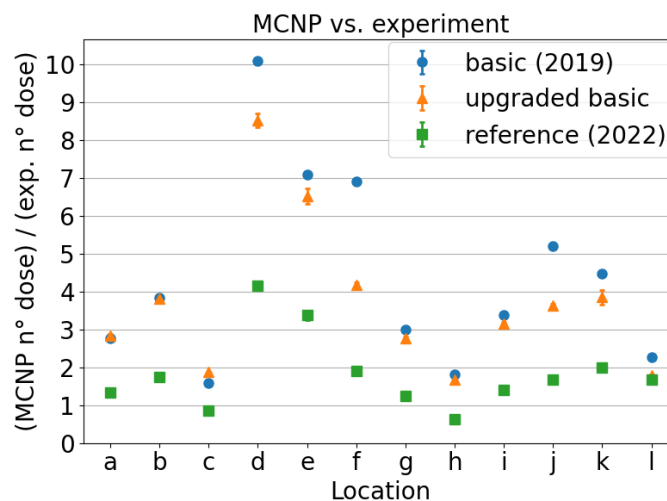
Fig. 13: TCV reference model (2022) results are much closer to measurements. Locations 'd' and 'e' still deviate the most from measurements. Error bars represent one sigma uncertainty.

The uncertainty of a dose calculated with MCNP stems from 3 main contributions: statistical uncertainty $\sigma_s = \sqrt{N}$, where N is the number of detected particles in a tally, nuclear data uncertainty and the computational model uncertainty. The only contribution which is given by the MCNP code itself is the statistical uncertainty. Nuclear data uncertainty as well as model uncertainty require dedicated codes and methods and their evaluation is beyond the scope of this paper. Hence only statistical uncertainty is provided in the paper. Modeling uncertainty was estimated by performing sensitivity studies described in this section. Uncertainty in measured dose was considered as statistical uncertainty due to the finite number of detected particles in the following way. The flux calculated from MCNP was normalized by the C/E ratio to calculate the estimated measured flux ϕ_{EM} at the Lupin detector. Considering the detector cross-section A the number of detected neutrons was calculated as $N = \phi_{EM}A$. In this approach we assumed the detector to have the same energy response as is modeled in MCNP (ICRP-74 H*10) and that the simulated neutron spectrum is accurate. With this approach we calculate the number of detected neutrons to be between 7E+3 and 2E+7, depending on the measurement location and direction of incoming neutrons (because of its cylindrical shape the BF3 detector has a non-isotropic response). Because of the detector geometry, we assumed most neutrons enter the detector from the side. Thus, we estimate the dose per pulse measurement relative one sigma statistical uncertainty to be between 0.02 % and 0.42 %, depending on the measurement location. The uncertainty of the C/E ratio is a combination of measurements and calculational statistical uncertainties. The one sigma uncertainty is displayed with error bars on figure 13. It can be seen that the discrepancy between measurements and calculations is still much larger than the statistical one sigma uncertainty. This is most probably due to the 3d model geometric uncertainty. As was stated in the introduction, the 50 % relative uncertainty in absolute source strength as calculated by TRANSP is irrelevant here. The MCNP calculations are consistent whereas the measurements are scattered and later normalized to the reference probe in the control room.

Figure 13 shows that all but two of the reference model predictions, including the source calculated by TRANSP, are now within a factor 2 of the measurement. The range of ratios with respect to position 'l' span a range up to 4. The two locations with the largest differences, 'd' and 'e', are both ground level rooms, which were modeled as being empty, although they include a large amount of workshop and laboratory equipment. There, the measurements were performed behind sheet metal cabinets. In the control room there are large air vents which would reflect some of the neutrons back-scattered off the building roof. Both the cabinets and air vents have not yet been modeled in MCNP. These missing objects and structures outside the control room are suspected to be the main cause of the remaining differences between calculated and measured doses.

Despite these differences, the computational model TCV reference model (2022) was deemed sufficiently accurate to serve as a basis for the shielded model. The aim of the shielding project is to achieve a reduction of dose rates by two orders of magnitude in the most exposed human occupied locations, with respect to the current situation. The reduction depends primarily on the locally added shielding and hence is expected not to be very sensitive to inaccuracies of the reference model.

3.2 Shielded model results

Results from the shielded model simulations were evaluated based on how much of the TCV facility can be left unrestricted i.e., has a neutron dose rate lower than 4 µSv / day at full tokamak operation. Different designs were tested and if necessary, modified.

Neutron H*10 dose rate fields are shown on figure 14. We can see that the "dog leg" design has substantially lower dose rates outside the reactor hall. Even though the "20 hole" design streams neutrons upwards, away from habitable spaces, they back-scatter off the building roof. This design would necessitate additional shielding material. The easier-to-implement and more effective "dog leg" design was chosen.
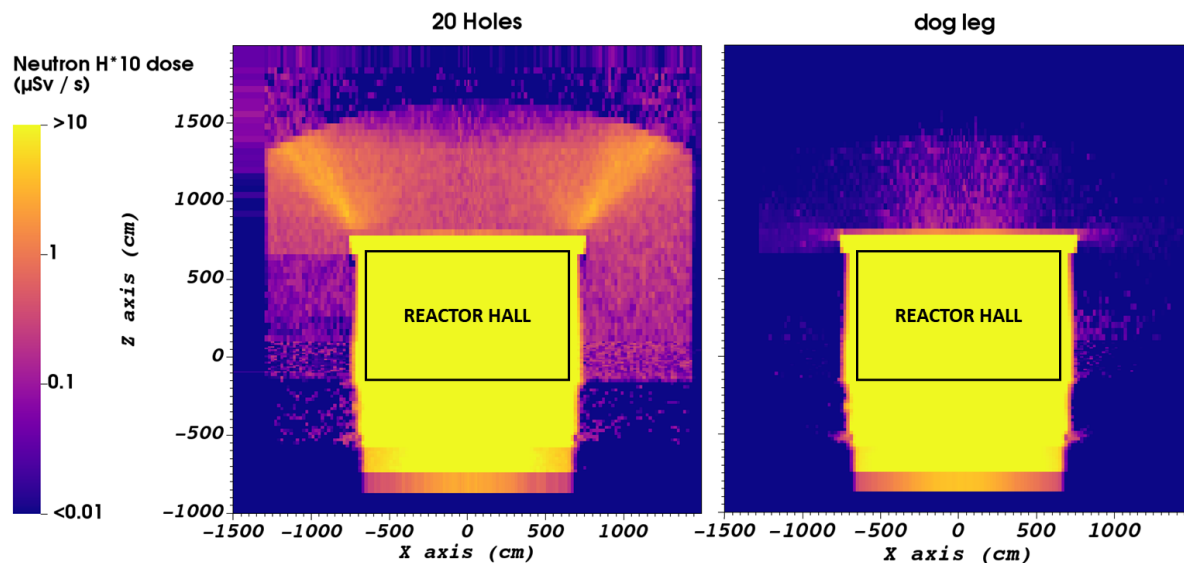

Fig. 14: Neutron H*10 dose rate fields. Cuts at y = 0 (East-West). Comparison of air vent designs.

We can evaluate different basement plug variations (Fig. 9) by the attenuation ratio. That is, the ratio of dose rates on the inside versus the outside of the plug. When averaged over all the plugged holes we can see that variation C, the hole filled with PE beads, performs best (Fig. 15). Besides providing the best neutron shielding it's also the most flexible, since the beads can be filled around existing cables and pipes.
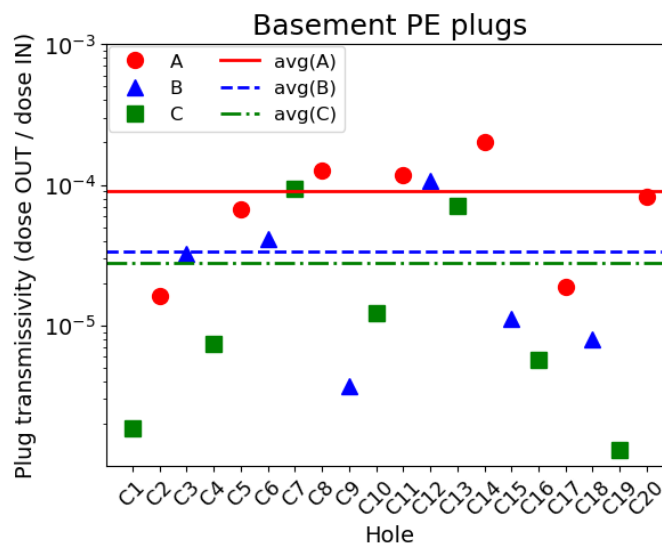
Fig. 15: Reduction in dose rates on the inside versus the outside of the basement holes. A, B, C refer to the designs in section 2.2.

Results of the final neutron shielded model can be seen on (Fig. 16). Calculated dose rates inside the control room have been decreased by 2000 times. For 30 TCV pulses per day the neutron dose inside the control room is expected to be 0.5 µSv, well below the 4 µSv limit. After this study, an assessment of prompt gamma radiation by neutron capture in PE triggered a further modification of the shielding model, the most important of which is the addition of a 20 cm parapet wall made of TCV concrete at level 2, described in [1].
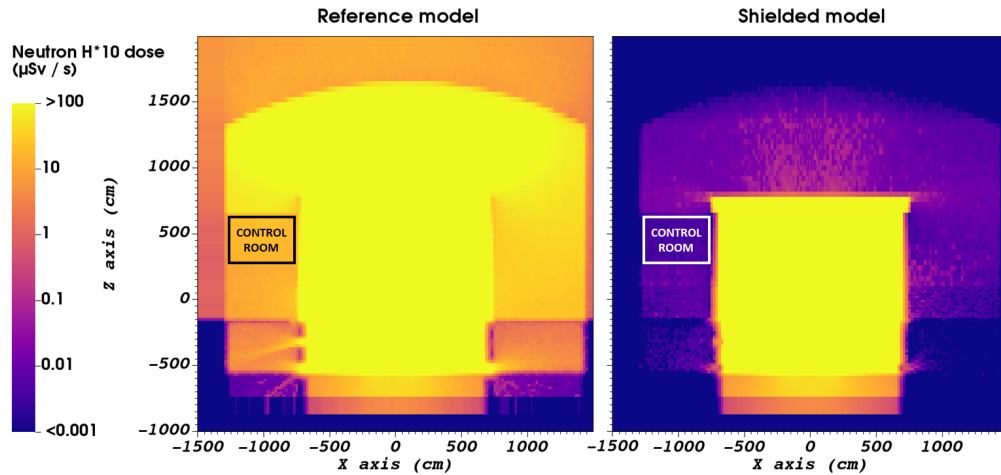

Fig. 16: Neutron H*10 dose rate field. Cut at y = 0. Comparison of reference (unshielded) model to shielded model.

4. Conclusion

The homogenization of system structures and components as well as building structures, enabled rapid model development and faster simulations. This approach resulted in the most accurate neutronics model of the TCV facility so far. Though there still are deviations from the measurements, this model serves as a good base for neutron shielding calculations. And if need be, can easily be improved in the future. The calculated dose rates tend to be higher anyway, resulting in the planned shielding being over dimensioned.

All comparisons between measurements and calculations in this work have been performed with neutron H*10 doses. A more fundamental physical quantity such as reaction rate would be better suited for validation purposes. In the absence of other fusion relevant experiments, the experiments presented in this paper, together with evaluated uncertainties, can serve as benchmark experiments and guidance for validating neutron transport codes for fusion reactors.

In the process of improving the neutronics model we found systems structures and components containing large amounts of light nuclei to be the most important. Especially, when on the neutron path towards the detector. Back-scattering of neutrons from the roof represents a significant contribution (~25 %) to the neutron dose in the control room. The remaining discrepancies between simulations and measurements are assumed to stem from the lack of smaller objects outside the reactor hall in the detector's proximity, which may have influenced the measured dose.

After polythene shields have been installed, neutron and gamma ray measurements will be performed in order to experimentally validate the calculations performed in this work.

Acknowledgement

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