

Assessment of the gamma and neutron dose field around the closed-water activation loop at the JSI TRIGA reactor

Domen Kotnik^{1,2,*}, Luka Snoj^{1,2}, and Igor Lengar¹

¹Reactor Physics Department, Jožef Stefan Institute, Slovenia

²Faculty of mathematics and physics, University of Ljubljana, Slovenia

(*) domen.kotnik@ijs.si

Abstract — A closed-water activation loop is being built at the Jožef Stefan Institute TRIGA reactor in Slovenia to serve as a well-defined and stable source of high-energy gamma rays and neutrons. The radial piercing port, which penetrates the graphite reflector and touching the reactor core was chosen for the installation of the closed-water loop due to the high neutron flux and favourable shielding conditions of the surrounding concrete bioshield. The main objective of this work is to assess the neutron and gamma dose field outside the port to obtain important details for the final design of the inner part of the irradiation facility and to assess the background noise for the detectors. The main part of the work consists of the design of the shielding plugs and the construction of a detailed MCNP model of the whole irradiation facility. The dose field calculations were performed with a two-step hybrid transport approach using ADVANTG for variance reduction and MCNP for particle transport. Such deep penetration and shielding calculations are challenging and computationally intensive. The results showed that the dose rate using shielding plugs is more than 7 orders of magnitude lower compared to an empty open port. To reduce the computational uncertainty, further optimisation of the ADVANTG input is essential. The final design of the shielding plugs is described. Additional lead shielding blocks will be added outside the port afterwards if needed.

Keywords — TRIGA, water activation, MCNP, ADVANTG.

I. INTRODUCTION

The cooling water in a fusion reactor is crucial to the performance of the reactor, but as a source of radiation it is still poorly understood. In fusion reactors, activated water is one of the main sources of radiation during operation, resulting in radiation exposure to personnel and equipment. The threshold energy for the main water activation reaction, i.e. $^{16}\text{O}(n,p)^{16}\text{N}$, is about 10.5 MeV. Neutrons in fusion reactors lead to water activity that is 5 orders of magnitude higher than in fission reactors of similar power [1]. Numerous computational analyses of the water activation process have been performed for ITER and DEMO. However, the results are subject to uncertainties and are therefore of poor quality due to the lack of experimental nuclear data, inaccurate computational

methods/codes and experimental facilities to validate the methodology experimentally, specifically considering time- and spatial dependent radiation sources (such as the flow of activated water in the cooling system [2]). Consequently, the calculated dose rates are subject to larger uncertainties.

On this basis, a closed-water activation loop is currently being built at the Jožef Stefan Institute (JSI) TRIGA Mark II reactor in Slovenia, which will serve also as a well-defined and stable 6 MeV – 7 MeV gamma-ray and 0.4 MeV - 1.2 MeV neutron source. Such a high-energy and well-characterised irradiation facility, i.e. a closed-water activation loop, will enable to perform benchmark experiments based on water activation to be performed, e.g. shielding experiments using ITER relevant materials, investigation of the response of detectors to high-energy gamma radiation, investigation of short-lived moving radiation sources, etc., and will also serve as a benchmark facility for the validation of computational methods and computer codes for the modelling of time- and spatial-dependent radiation sources. Currently, basic water activation experiments are already routinely performed for educational purposes at the JSI TRIGA reactor, using a simplified open water loop on the reactor platform. Even with such a simplified experimental setup, the main peaks of ^{16}N can be observed with a High Purity Germanium (HPGe) detector [3].

An important part of the overall irradiation facility is to ensure adequate protection from gamma rays and neutrons originating from the reactor core through the RPP and from the activated water of the closed-water loop. It is necessary to ensure that dose rates in the reactor hall are sufficiently low during operation of the reactor at full power (250 kW) and that personnel are not exposed to high radiation doses, as are the detectors (background noise) that will be located around the water activation loop. The influence of the reactor core and the influence of the water activation can be considered separately.

The aim of this work is to build a detailed MCNP model and to assess the neutron and gamma dose field outside the Radial Piercing Port (RPP), considering only the contribution of the reactor operation. In this way, the efficiency of the proposed main shielding inside the RPP, i.e. the neutron and gamma shielding plugs, is assessed.

The paper is structured as follows: Section 2 presents a

description of the JSI irradiation facility focusing on the inner part of the closed- water activation loop and Section 3 presents the analysis performed, focusing on the computational methods and tools, the creation of the detailed MCNP model and the dose rate calculations.

II. CLOSED-WATER ACTIVATION LOOP AT JSI TRIGA

The JSI TRIGA is a pool-type reactor operated by natural convection with a thermal output of 250 kW [4]. A special feature of this reactor is its ability to reach briefly a power of 1 GW for a few milliseconds in pulsed mode [5]. The reactor core contains several irradiation channels, including vertical channels at the edge of the core and three channels embedded in the core. In addition, there are three horizontal irradiation channels – two radial and one tangential – that penetrate the concrete bioshield of the reactor. One of the radial ports ends outside the graphite reflector, while the other, called the Radial Piercing Port (RPP), also penetrates the graphite reflector and practically reaches the reactor core. A visual representation of the JSI TRIGA reactor core with its irradiation channels can be seen in a horizontal cross-section in Fig. 1 in a horizontal cross-section view. Previous assessments [6] led to the choice of the RPP (highlighted in red) for the installation of a closed-water loop due to the high neutron flux and the favourable shielding conditions of the surrounding reactor concrete bioshield.

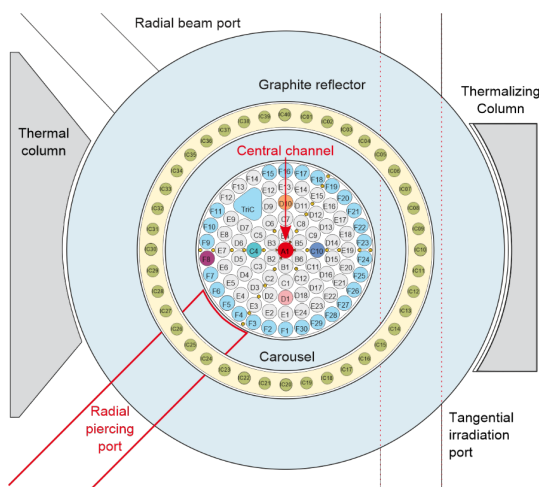


Fig. 1. Horizontal cross-section of the JSI TRIGA reactor core with the irradiation channels. The RPP shown in red was chosen for the installation of the closed-water loop.

The central idea behind the proposed closed- water activation loop system, highlighted in red in Fig. 2, is to set up a pipe loop that is inserted into the RPP. This conceptual framework consists of three key components: first, the "inner activation part," which is located inside the RPP in close proximity to the reactor core. This is where most of the water activation process takes place. Secondly, the "transport pipes" are responsible for transporting the activated water to the "outer observation part" of the circuit. Around this outer part is a series of advanced gamma and neutron detectors, i.e. HPGe, LaBr, TLD and He-3 detectors. The expected length of the transport segment of the loop (including the entire circuit pathway, but excluding the inner activation and outer observation parts) is estimated to be

about 12 m. However, due to the constraints imposed by the fixed dimensions of the RPP, approximately 6 metres of this length is predetermined.

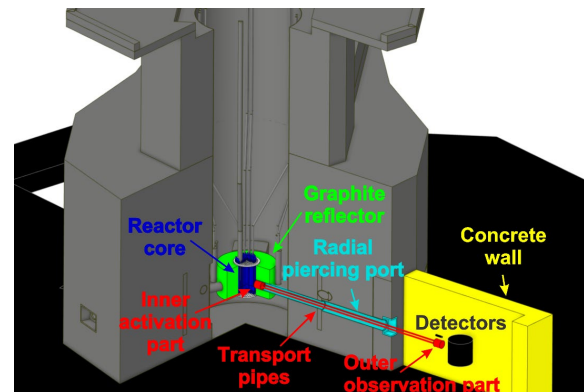


Fig. 2. Conceptual design of the JSI TRIGA closed-water activation loop, which consist of three main components, i.e. the inner activation part, the transport pipes and the outer observation part, using the RPP.

It is important to note that all necessary equipment, including essential elements such as pumps, flow metres, temperature and pressure sensors, cooling systems and mechanisms for refilling water, are located outside of the RPP. To effectively control radiation exposure inside the reactor hall, an additional 90 cm thick concrete wall will surround the entire irradiation facility [7]. It serves as a physical barrier and separates the experimental area from the rest of the reactor hall. In addition, it serves the dual purpose of reducing the contribution of dose rate from the reactor core and, most importantly, providing sufficient protection from high-energy gamma radiation from the activated water. The largest contribution is due to the outer observation part with its large volume of water compared to the narrow transport pipes.

A. Inner part of the closed-water loop

The inner set-up of the closed- water loop consists of the inner activation part, the narrow transport pipes and the appropriate shielding, i.e. gamma and neutron shielding plugs. The proposed design is shown in Fig. 3. The major size constraint of the whole setup is the RPP itself, which consists of two parts, an inner narrow part (length 150.3 cm and diameter 15.4 cm) and an outer wider part (length 151.5 cm and diameter 20.5 cm). The final design of the inner activation part was chosen based on a previous optimisation analysis [8] and includes a complex snail-shape design, with the highest effective water volume, which achieved the highest activities of the main water-activated isotopes (^{16}N , ^{17}N and ^{19}O) with respect to other candidate designs. The complex designed snail was fully 3D printed with aluminium. As a result, the cylindrical snail shape with a diameter of 14.8 cm and a length of 21.9 cm with 3 mm thick aluminium walls has an effective water volume of ~ 3 l.

The primary gamma-shielding plug consists of a 5 mm thick aluminium shell and is filled with (from left to right in Fig. 3) 19.2 mm thick Boral plates to minimise material degradation by neutrons, ~ 56 cm of concrete, ~ 62 cm mixture of concrete and lead shot, and a subsequent 12 cm long stainless-steel part (SS), which has three wheels for easier insertion into the RPP and a

cavity for mounting a handling tool. The neutron shielding plug, located behind the gamma shield, is made of borated polyethylene (BP). The BP plug, with a boron mass fraction of 5 % enables much more effective shielding against neutrons than the previous wooden plug because it contains the isotope ^{10}B , which has a very large absorption cross-section for thermal neutrons. Similar to the gamma plug, a 19.2 mm thick Boral plate is placed in front of it.

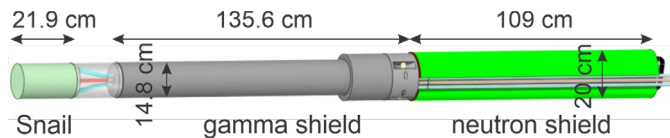


Fig. 3. Scheme of the inner set-up of the closed-water activation loop located inside of the RPP at the JSI TRIGA reactor consisting of three main components, i.e. inner activation part (snail), aluminium-concrete gamma shielding plug and the neutron shielding plug made of borated polyethylene. The water inlet and outlet tubes are shown in blue and the central hollow instrumental tube in red.

In addition, three pipes lead from the snail through the aforementioned shielding plugs: an inlet and an outlet pipe for the water circuit (shown in blue in Fig. 3) and a central hollow instrumental pipe (shown in red) for the insertion of detectors and cables during reactor operation, e.g. a fission cell for measuring the neutron flux inside the snail (inner activation part) to monitor reactor power or using activation foils to determine the neutron spectrum along the snail. The above tubes are also embedded in the concrete plug and bent to minimise the streaming of direct (non-scattered) neutrons and gamma rays from the reactor core.

III. CALCULATIONS

One of the most important components of the irradiation facility with closed-water activation loop as a whole is to ensure adequate shielding for the personnel and instruments (detectors). For this reason, an assessment of the neutron and gamma dose field outside the RPP has been performed, excluding the contribution of the activated water in the whole circuit at this stage. In this way, the shielding efficiency of the proposed inner set-up is assessed.

A. Computational methods and tools

The calculations for the assessment of neutron and gamma dose rates were performed using MCNP6 v2.0, while the variance reduction parameters, more specifically the weight window (WW) parameters, were prepared using ADVANTG [10]. The use of a variance reduction technique is essential as deep penetration/shielding calculations are challenging and extremely computationally intensive. This two-step hybrid transport approach was chosen because large speedups in terms of computational time (more than a factor of 1000) were observed for a variety of shielding and radiation geometries compared to analogue MCNP calculations [11-15]. Due to the ADVANTG limitation, a fixed SDEF source based on a kcode calculation was prepared. A deterministic ADVANTG calculation used a 27n19g nuclear cross-section library, a variable geometric mesh with $13.7 \cdot 10^6$ voxels that varied in size depending on the geometry, i.e. finer mesh in the areas of the

reactor core and RPP (a few centimetres) and coarser mesh in the surroundings (from several centimetres to one metre), a P_3 scattering- angle expansion and an S_4 angular approximation.

The ANSYS SpaceClaim programme [16] was used to create CAD models of the entire closed-water activation loop. It allowed detailed modelling and easier 3D visualisation.

In addition, the open code GEOUNED [17] was used to convert the models from CAD to MCNP input files. This step was essential to conserve as much details as possible, which is otherwise practically impossible to achieve manually.

B. Computational model

The computational model for the MCNP calculation was created in several steps. In the first step, the detailed CAD model, shown in Fig. 3, was simplified because some surfaces, e.g. splines, torus, extruded, rotated, etc., are not supported in MCNP. Specifically, 2 spline, 30 torus and 115 extruded/rotated surfaces were manually simplified as planes, cylinders, cones or spheres. In the second step, the GEOUNED code was used to convert the simplified CAD model, shown in Fig. 4a, into an MCNP input file. In general, the conversion was smooth, with less than 3 cells requiring subsequent manual correction. To avoid errors during the conversion, complex cells were preferably split into smaller simpler geometries, i.e. the most problematic parts were curved pipes and the area around them (Fig. 4b).

Last but not least, the generated MCNP input file of the entire inner set-up of the closed-water activation loop was implemented into the detailed MCNP input of the JSI TRIGA reactor considering the current core configuration #244 (Fig. 4c).

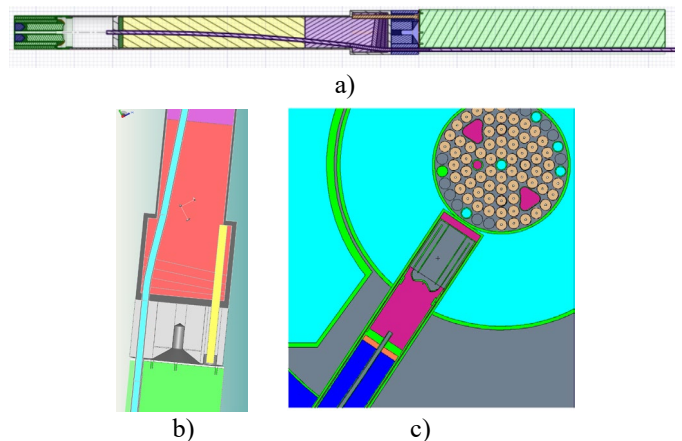


Fig. 4. a) Simplified CAD model of the inner set-up of the closed-water activation loop. b) Detailed MCNP model generated with the GEOUNED code. c) Final computational model.

C. Dose rate calculations

Neutron and gamma dose rate values were calculated as ambient dose equivalent $H^*(10)$ using NCRP-38 [18] and ICRP-21 flux- to- dose- rate conversion factors, respectively. The measurement position (MP) was chosen at the entrance of the RPP (outer boundary of the reactor bioshield), about 320 cm from the centre of the reactor core. The overall efficiency of the proposed shielding plugs was assessed by comparing the dose rate values at the MP with the entire inner set-up of the

closed-water loop and without it (empty RPP). In both scenarios, the reactor was considered at full power (250 kW).

The results of the neutron and gamma dose rate calculations, with a relative statistical uncertainty of 1 sigma, are shown in Fig. 5 at the entrance of the RPP for different scenarios. The results for the reference scenario, the empty RPP, are very large, i.e. ~ 400 Sv/h for neutrons and ~ 13 Sv/h for gamma rays. Of course, this scenario cannot be reproduced experimentally, but it shows that any shielding used in the RPP should reduce the dose rate by several orders of magnitude. Specifically, the dose rate limitation in the reactor hall is $10 \mu\text{Sv/h}$ and up to several mSv/h within the experimental area. Considering the proposed inner set-up of the closed-water activation loop, the dose rate values decrease significantly. In particular, they amount to $\sim 82 \mu\text{Sv/h}$ for neutrons and $\sim 11 \mu\text{Sv/h}$ for gammas. The absolute values are quite promising, but should be considered with caution as they are currently of lower quality due to the high ($\sim 40\%$) statistical uncertainty even when using a variance reduction technique. We would like to point out that such deep penetration/shielding calculations are extremely computationally intensive and the analogue MCNP calculation did not yield any result at all. The statistical uncertainty could be reduced by generating more effective WW. Further work on optimising the ADVANTG parameters is essential.

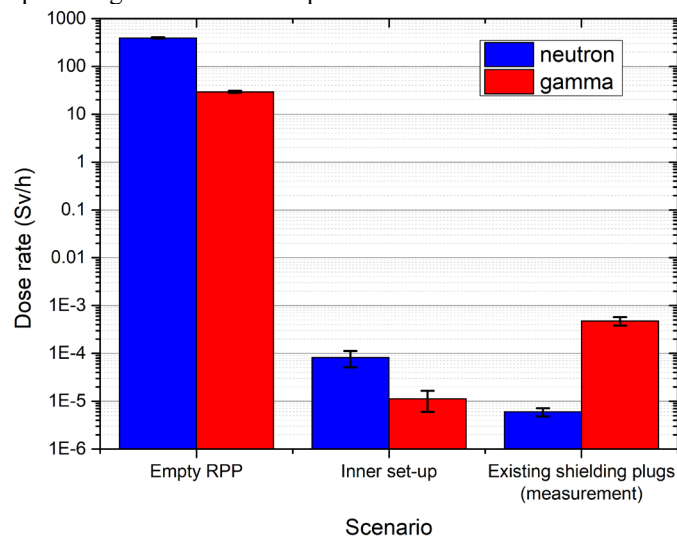


Fig. 5. Neutron and gamma dose rate values at the entrance of the RPP for empty RPP and inserted inner set-up of the closed-water loop. Due to the lower quality of the latter, experimental results of using similar existing shielding plugs are also shown for orientation.

To provide a more tangible comparison of the shielding effectiveness of the proposed design of the inner set-up, the experimental values of using similar existing shielding plugs are also shown in the graph. Existing shielding plugs currently used inside the RPP were the basis for developing new plugs for the inner set-up of the closed-water loop. Although a difference of more than an order of magnitude can be observed, the experimental results are only indicative. However, they indicate promising shielding properties of the proposed new shielding plugs. The most important comparison will be the experimental validation after the whole set-up is built and tested.

IV. CONCLUSIONS

A unique irradiation facility for high-energy gamma rays (6 MeV – 7 MeV) and neutrons (0.4 MeV - 1.2 MeV) is being built at the research reactor JSI TRIGA in Slovenia, using a closed-water loop for experiments based on water activation. The main focus of this work was to build detailed MCNP model and to assess the neutron and gamma dose rate outside the radial piercing port of the closed-water activation loop, with particular emphasis on the shielding efficiency of the proposed inner set-up that is inserted inside of the port. In this way, the efficiency of the proposed main shielding inside the port, i.e. the neutron and gamma shielding plugs, is assessed.

It turned out that the GEOUNED code is very useful for converting CAD models into MCNP input files. This step was essential to obtain as much detail as possible, which is otherwise practically impossible to do manually.

The results show that the dose rate using shielding plugs is more than 7 orders of magnitude lower than for a empty open port and in good agreement with the experimental results of existing similar shielding plugs. While the calculated dose rate values appear promising, they are currently subject to high statistical uncertainties. The deep penetration/shielding calculations are extremely computationally intensive and the analogue MCNP calculation gave no result at all. Further optimisation of the ADVANTG input parameters is foreseen to optimise the weight windows and thus improve the accuracy of the results.

The proposed design of the shielding plugs and the whole internal set-up of the closed-water loop has been confirmed. The most important confirmation will be the experimental validation after the whole set-up is built and tested. After that, any additional lead shielding blocks will be placed outside the port if needed. The commissioning of the entire irradiation facility and first experiments are scheduled by the end of the year.

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