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Analysis of Water Activation Loop at the JSI TRIGA Research Reactor

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ABSTRACT

A closed-water activation loop will be constructed at the Jožef Stefan Institute (JSI) research reactor TRIGA Mark II that will serve as a well-defined and stable 6 MeV - 7 MeV gamma-ray source. The main focus of this work is to analyse three different designs of the main irradiation part of the water activation loop, which is located inside the radial piercing port right next to the reactor core, in order to achieve the highest overall activity that can be obtained with a closed-water activation loop. These designs are in the following work referred as: "U-turn", "spiral" and "snail", representing the different complexity of the model, from a simple to an advanced shape. The results show that the most important parameter to achieve the highest activity is the effective water volume, where most of the water activation reactions occur. The effective water volume of the U-turn, spiral and snail designs are 1.13 l, 0.52 l and 2.72 l respectively. It turned out that at saturation value the snail design systematically outperformed U-turn and spiral designs by more than a factor of two for the main water activated isotopes (^{16}N, ^{17}N and ^{19}O). Furthermore, the effects of other parameters, e.g. reaction rate map, pressure drop, flow velocity profile, are practically negligible as they do not differ significantly between the analysed designs. Based on that, the snail configuration was chosen as the main candidate for the irradiation part and also for the observation part, which is located inside and outside the radial piercing port, respectively.

1 INTRODUCTION

Water as a primary coolant is used in the most fission reactors today and will also play an important role in the performance of fusion reactors. After being irradiated and activated, the cooling water flows through the cooling circuit, usually outside the primary biological shield surrounding the reactor vessel, and disperse the radioactivity throughout the plant. The threshold energy for the main water activation reaction, i.e. ^{16}O(n,p)^{16}N, is about 10 MeV. Thus, neutrons in fusion reactors leads to water activity that is 5 orders of magnitude higher than in fission reactors of similar power. Numerous computational analyses of the water activation process have been carried out for ITER [1] and DEMO [2]. However, the results are subject to uncertainties and are therefore of limited quality due to the lack of experimental nuclear data, inaccurate calculation methods/codes and experimental facilities to validate the methodology.

Against this background, a closed-water activation loop is being built at the Jožef Stefan Institute TRIGA Mark II (JSI TRIGA) research reactor [3], which will serve as a well-defined and stable 6 MeV - 7 MeV gamma-ray source. Such a high-energy radiation facility will allow various experiments based on water activation, e.g., shielding experiments using ITER relevant materials, investigation of the response of detectors to high-energy gamma rays, study of short-lived moving radiation sources, validation of computational codes/methods, etc.

The main of the work is to analyse different designs (from simple to more advanced shapes) of the main irradiation part of the water activation loop, i.e. part of the loop that is located inside the radial piercing port in close vicinity of the reactor core, where the majority of the water activation process takes place, with the aim of achieving the highest overall activity achievable by a closed-water activation loop. Since the moving activated water is a time- and location-dependent radiation source, detailed transport calculations should be coupled with CFD calculations. Similar conditions prevail in a water-cooled fission/fusion reactor. The most important design criteria of the irradiation part are the effective water volume, the reaction rate map and the hydraulic properties (pressure drop, flow velocity profile) based on different water flow rates. The analyses performed will provide important details for the final design of the entire closed-water loop, as the design/shape of the irradiation part directly affects the overall activity that can be achieved with such an irradiation facility.

The paper is structured as follows. In the first part of the paper, the principles of water activation and a description of the closed-water loop at JSI TRIGA reactor are presented. In the second part, three different designs of the irradiation part are analysed, covering both neutronic and hydraulic aspects.

2 WATER ACTIVATION LOOP AT JSI TRIGA REACTOR

2.1 Water activation process

The activation of water consists primarily of the activation of oxygen isotopes via the reactions $^{16}O(n,p)^{16}N$, $^{17}O(n,p)^{17}N$ and $^{18}O(n,\gamma)^{19}O$ [4], with negligible contribution from the activation of dissolved gases, corrosion products and additives. Activated N and O nuclides subsequently decay emitting different decay products (gamma rays and neutrons) with different energies. The reactions $^{16}O(n,p)^{16}N$ and $^{17}O(n,p)^{17}N$ are threshold reactions with energy thresholds of 10 MeV and 8 MeV, respectively, while the reaction $^{18}O(n,\gamma)^{19}O$ already occurs at thermal energies. It is important to note that the radioactivity of activated water is short-lived, on the order of seconds, so it presents a radiation source only during reactor operation. The half-life times of ^{16}N, ^{17}N and ^{19}O are 7.13 s, 4.14 s and 26.9 s, respectively.

The change in specific activity a (activity per unit volume) of a nuclide, which is the result of activation [5], is calculated as

$$a(t) = R\left(1 - e^{-\lambda t_{irr}}\right), \tag{1}$$

where λ is a decay constant of the studied isotope, R is an average reaction rate in the region of interest and t_{irr} is the irradiation time. After long exposure ($t_{irr} \rightarrow \infty$), the activity reaches the saturation value $a = R$. To consider transport of water through a pipe to the position of the detector or at any later time, i.e. the specific activity after a certain transport time t_{trans}, an additional decay term must be used as:

$$a(t) = R\left(1 - e^{-\lambda t_{irr}}\right)e^{-\lambda t_{trans}}. \tag{2}$$

Furthermore, in the case of the closed-loop system the specific activity increases after each loop. The new saturation value (equilibrium value) a_{sat} is defined as:

$$a_{sat}(t) = \frac{R(1-e^{-\lambda t_{irr}})e^{-\lambda t_{trans}}}{1-e^{-\lambda(T_{loop}+t_{irr})}} = \frac{R(1-e^{-\lambda t_{irr}})e^{-\lambda t_{trans}}}{1-e^{-\lambda T_{tot}}}, \tag{3}$$

where T_{loop} is the transport time through the remaining pipe system and T_{tot} is the total circulation time of the proposed closed-water loop system.

2.2 Closed-water loop at JSI TRIGA reactor

JSI TRIGA is a 250-kW light water pool-type research reactor cooled by natural convection. It has several irradiation channels in the core, i.e. in the outermost positions of the core with an additional channel in the central position of the reactor core, and three horizontal irradiation channels, i.e. two radial and one tangential, penetrating the concrete structure of the reactor. One of the radial ports ends at the outside of the graphite reflector, while the other, namely the radial piercing port, penetrates the graphite reflector and reaches the reactor core. The schematic representation of the JSI TRIGA reactor core with the irradiation channels is shown in Figure 1 (left) in a horizontal cross-section view. Based on previous analyses [6], the radial piercing port (shown in red in Figure 1) was selected as the main candidate for the installation of the closed-water loop due to the higher neutron flux, causing a higher activation rate of the water, and already present passive shielding of the surrounding concrete.

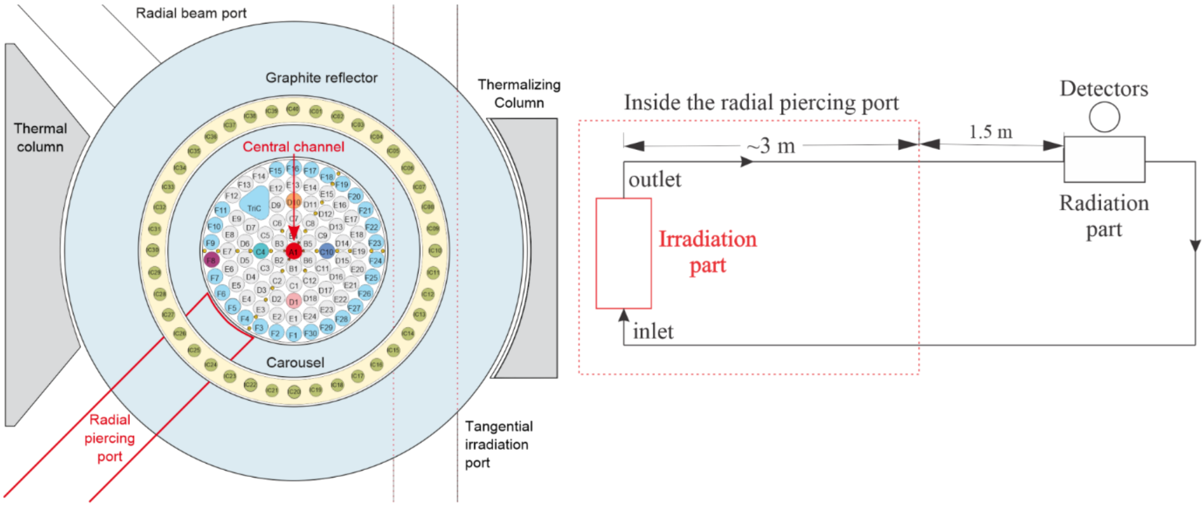

Figure 1: Schematic of the JSI TRIGA reactor core. Radial piercing port shown in red was chosen for the installation of the closed-water loop (left). Schematic of the closed-water loop with the irradiation part (U-turn, spiral, snail) shown in red (right); not to scale.

The basic concept of the closed-loop for water activation shown in Figure 1 (right) consists of a pipe loop that is partially inserted into the radial piercing port (dotted red line). The irradiation part of the loop, where the most of the water is activated, is located inside the radial piercing port in close proximity to the core. Narrow transport pipes containing the activated water will be led outside the port to the radiation part of the loop, located 150 cm from the entrance of the radial piercing port, around which various gamma and neutron detectors will be placed. The expected length of the transport part of the loop (total length of the loop excluding the irradiation part and the radiation part) will be about 12 m, of which 6 m is fixed due to the dimensions of the radial piercing port. All the necessary equipment, e.g. pump, flow metre, temperature/pressure detectors, cooling system, water filling system, etc., will be located outside the radial piercing port.

3 IRRADIATION PART OPTIMIZATION

The main goal of the proposed irradiation facility is to achieve the highest overall activity that can be achieved by such a closed-water activation loop. One of the crucial components is an irradiation part located inside the radial piercing port right next to the reactor core. The main focus of this work is to analyse different designs of the irradiation part to find the optimal shape based on several design criteria, i.e. effective water volume, reaction rate map, and hydraulics properties (pressure drop, flow velocity profile) based on different water flow rates. The main size constraints of the irradiation part are: the inner diameter of the radial piercing port of 15.4 cm and the length of 3.2 m; and a half-distance of the high-energy neutrons[1] in the water of 6.5 cm – 6.7 cm on average. The latter limits the total length of the irradiation part to an approximate length of 5 half-distances (about 34 cm).

With this in mind, 3 designs were analysed in detail; they are called: “U-turn”, “spiral” and “snail”, representing different complexity of the model, from a simple shape to a more complex one (see Figure 2). Each shape is optimised to maximise effective volume given the current complexity of the design. The U-turn design (Figure 2a) represents the simplest solution with a wide pipe and a single 180° curve that mitigates a U-turn. The spiral design (Figure 2b) uses a smaller pipe with several spiral turns that closely follow the shape of the sphere. This shape increases the length of the irradiation part and circulates the water closer to the reactor core. Last but not least, there is the snail shape design (Figure 2c), which uses 3-cylinder blocks and a vertical XZ wall that prevents axisymmetric water flow. To achieve a uniform flow rate throughout the snail, the size (diameter) of the cylinders has been chosen accordingly (to have a similar flow area). This advanced design is optimised to have a high volume of water that effectively fits into the cylindrical radial piercing port. The only exception is the central empty cylinder, which serves for the instruments[2], i.e. sensors and activation foils.

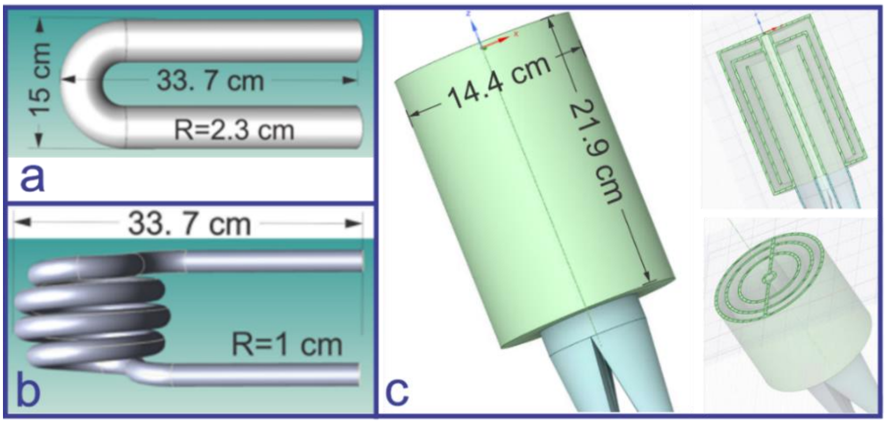

Figure 2: Three different designs of the irradiation part based on the degree of complexity: a) “U-turn”, b) “spiral”, and c) “snail”.

3.1 Activity calculation

In the following analysis, the simplified activity calculation is presented. The main difference between the three irradiation concepts is the shape and consequently the effective water volume in immediate vicinity of the reactor core where the water activation process

[1] Above the threshold energy for the main water activation reactions: 8 MeV and 10 MeV.

[2] The instrumentational pipe is not visible in the U-turn and spiral because installation is less complicated as there is much more free space around it.

occurs. The effective water volume of the U-turn, spiral and snail is 1.13 l, 0.52 l and 2.72 l, respectively. Furthermore, the different designs also affect the reaction rate (RR) map due to the self-shielding effect. The simplified activity calculation (see Eq. 3) consisted of several steps and included both stochastic simulation and an analytical approach in a further step. It should be noted that a conventional approach was used and computational fluid dynamic (CFD) calculations were not considered at this stage. First, the detailed RR map for each design was calculated with a two-step hybrid transport method using MCNP code [7] for particle transport and the deterministic code ADVANTG [8] for variance reduction. For simpler calculation in a further step, all models were divided into smaller volume elements and an average RR was calculated along these elements. The RR results for three designs (U-turn, spiral and snail) and for three main isotopes (^{16}N, ^{17}N and ^{19}O) are shown in Figure 3. Similar dependencies are observed in all cases: The number of peaks coincides with the number of turns included in the model; higher values indicate that a certain volume element is closer to the reactor core; and RR values for ^{16}N are on average 6-12 times higher than for ^{19}O and 14000 times higher than for ^{17}N.

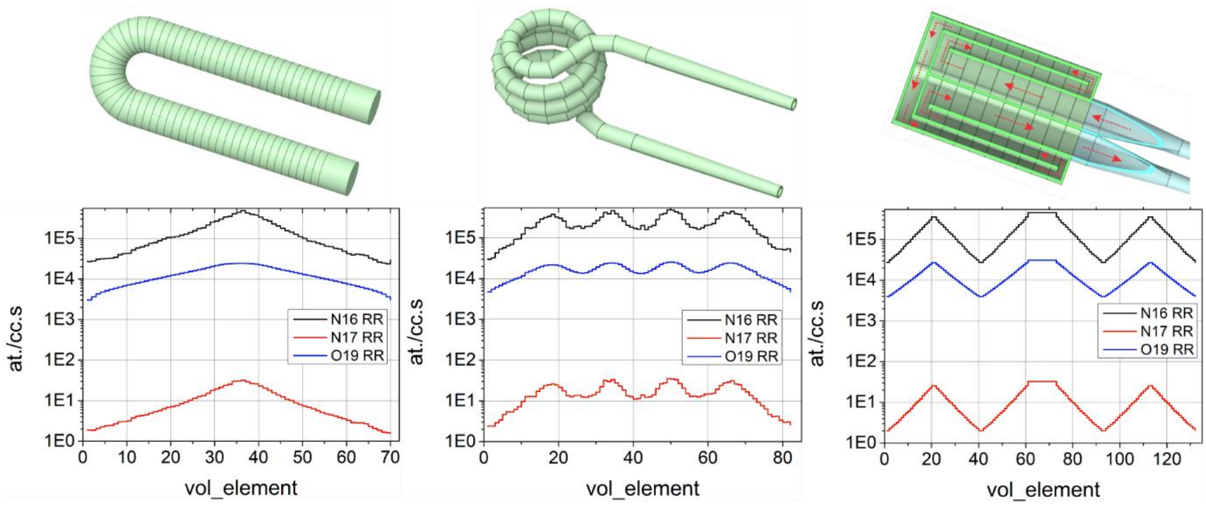

Figure 3: Reaction rate values (atoms per cubic centimetre per second) for the tree main activated isotopes (^{16}N, ^{17}N and ^{19}O) as a function of volume element (position) for three different irradiation designs; U-turn: left, spiral: middle and snail: right.

In the second step, the specific activity in each volume element was calculated analytically for each activated major isotope based on Eq. 1. At constant flow rate, a higher water volume leads directly to a longer irradiation time and consequently to a higher specific activity. In the next step, based on Eq. 2, a specific activity was calculated for each volume element based on the transport time[3] needed to get to the end part of the model. By summing up all contributions, the total specific activity (Bq/l) at the outlet was determined for each model. In addition, to properly account for a closed-loop contribution, the values were multiplied by the build-up factor $\frac{1}{1-e^{-\lambda(T_{loop}+t_{irr})}}$ (see Eq. 3). To have consisted comparison, the same remaining closed-loop configuration was used for all three cases, i.e. the same transport time was used in the entire remaining pipe system (T_{loop}), which comprises 12 m transport pipes (volume 1.36 l) and an arbitrary radiation part[4] (volume 2.72 l) (Figure 1 right). However, the build-up factor is

[3] The transport time for any volume element is equal to the total irradiation time of all volume elements after it.

[4] The volume of the arbitrary radiation part is equal to the volume of the snail design – irradiation part.

different for each design, as the irradiation time t_{irr} is directly related to the volume of water inside the respective design. The ratios of t_{irr}/T_{loop} for U-turn, spiral and snail are 28 %, 13 % and 67 %, respectively, with a lower ratio resulting in a larger build-up factor. In the third final step, to obtain the activity inside of the radiation part [Bq], the specific activity in the end part of the model [Bq/l] is first transported to the radiation part ($e^{-\lambda t_{trans}}$ in Eq. 3) and then multiplied by the factor of $\left(1 - e^{-\lambda t_{rad}}\right)\frac{\Phi}{\lambda}$, where t_{rad} is the time spent by the activated water in the radiation part and Φ is the water flow rate. The final quantity represents the number of decays per second [Bq] of ^{16}N, ^{17}N and ^{19}O within the radiation part using a closed-water loop. The results for three designs (U-turn, spiral and snail) and for three main activated isotopes (^{16}N, ^{17}N and ^{19}O) are shown in Figure 4 for different water flow rates. A general dependence can be observed for all scenarios. At low flow rates, the activity values increase strongly with increasing flow rate. At some point, roughly at 0.4 l/s, a saturation value is practically reached and the contribution of a higher flow rate becomes negligible. It turned out that at a saturation value, the snail design systematically outperformed U-turn and spiral designs for more than 2 times. The decisive parameter is the effective activated water volume. A significant difference between U-turn and spiral is only noticeable for ^{19}O in favour of U-turn (32 %).

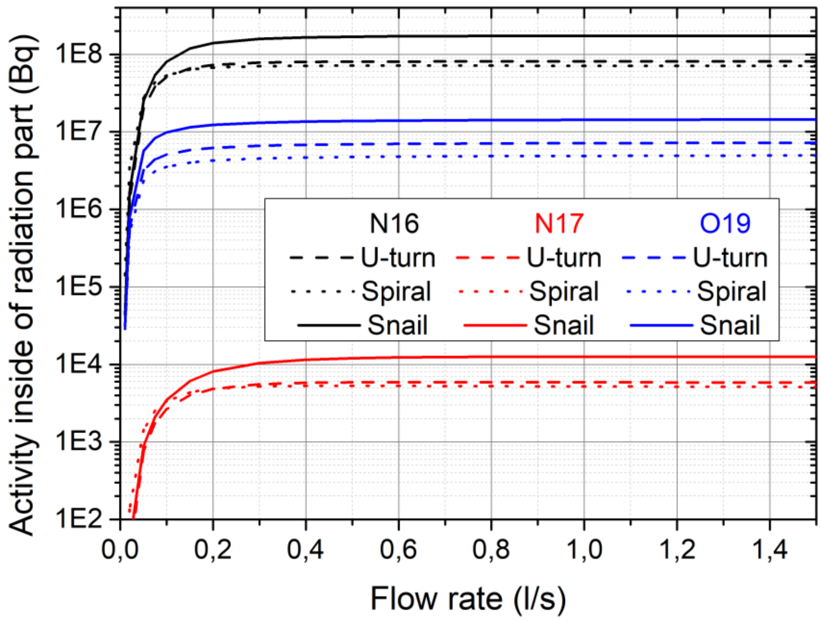

Figure 4: Activity values within the radiation part (Bq) for the three main water-activated isotopes (^{16}N, ^{17}N and ^{19}O) in dependence on the water flow rate using closed-water loop and three different irradiation designs: U-turn, spiral and snail.

Furthermore, the activity values of ^{16}N, ^{17}N and ^{19}O at the saturation point for the snail design are approximately 1.7E8 Bq, 1.2E4 Bq and 1.4E7 Bq, respectively. Higher values are preferable for easier measurement. It turned out that the main parameter for the large discrepancies between them is the reaction rate for water activation reactions and the natural abundance of oxygen isotopes. Similar dependencies were also observed in Figure 3.

3.2 Hydraulic properties

Last but not least, analyses of various hydraulic properties, i.e. pressure drop and flow profile of water velocity in dependence on the flow rate, were carried out for three main irradiation designs. Computational fluid dynamic (CFD) calculations and post-processing were performed using ANSYS Fluent package [9]. It was found out that the pressure drop inside is relatively small[5] and slightly different between the irradiation designs, however, its contribution to the total pressure drop of the whole closed-water loop is less than 2%. The main contribution is due to narrow transport pipes and other installed equipment, e.g. Coriolis flow metres, valves, etc. In light of this, the pressure drop is not a relevant parameter on the basis of which the optimal design of the irradiation part is chosen. However, it plays the important role in the selection of the optimum water flow rate, as it increases greatly at higher flow rates.

The outcome of the water velocity flow profile in different irradiation designs is similar to the pressure drop analysis. The flow rate in the U-turn and spiral is slightly more uniform than in the snail due to simpler design without multiple 180° turns. However, the snail design performed relatively well, with a negligible number of stagnation points or vortexes (an example with at flow rate of 1 l/s can be seen in Figure 5). The greatest effect on the water profile within the irradiation part is the water profile at the inlet part. By using a suitable connection part that allows a smooth water transition from the narrow transport pipe to the irradiation part, a relatively good uniform water profile can be achieved in all analysed irradiation designs. Further CFD analysis is essential to optimise the final closed-loop design, especially to determine the optimal size of the transport pipes and the connecting part to the irradiation/radiation part of the loop.

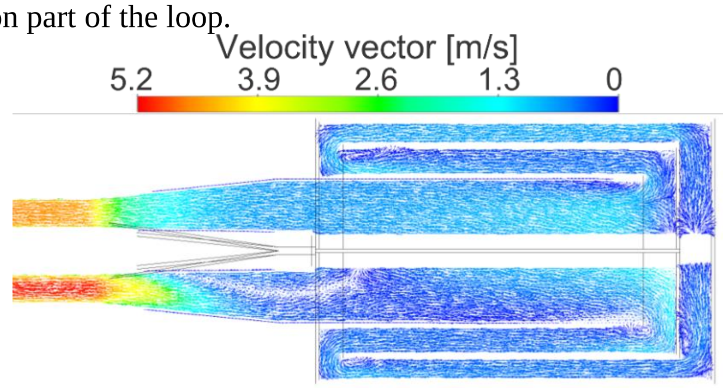

Figure 5: Water velocity profile within the snail design at a flow rate of 1 l/s.

4 CONCLUSION

The problem of water activation is currently dealing with a number of shortcomings: large discrepancies and inconsistencies between nuclear data libraries, lack of calculational tools/methods for dose rate calculations and, most importantly, lack of experimental facilities with high-energy gamma-ray sources for shielding experiments around activated water. A unique irradiation facility for 6 MeV – 7 MeV is being constructed at the JSI TRIGA research reactor, which includes a closed-loop for water activation. In order to achieve the highest total activity that can be obtained with a closed-water activation loop, three different designs of the main irradiation part, which is located inside the radial piercing port right next to the reactor core, were analysed. These designs were referred as: “U-turn”, “spiral” and “snail”, representing different complexity of the model, from a simple shape to an advanced one. The main design criteria for the irradiation part were the effective water volume, reaction rate map, and hydraulic properties (pressure drop, flow velocity profile) based on different water flow rates. To have consisted comparison the same remaining closed-loop configuration was used

[5] Less than 5000 Pa at a flow rate of 0.5 l/s along the complex snail configuration, which has the highest pressure drop.

for all three cases, i.e. 12 m transport pipes and an arbitrary radiation part located outside the radial piercing port.

The results show that the most important parameter for obtaining the highest activity is the effective water volume of the irradiation part located in close proximity of the reactor core, where most of the water activation reactions (n, p) and (n, γ) on oxygen isotopes occur. Specifically, the effective water volume of the U-turn, spiral and snail designs is 1.13 l, 0.52 l and 2.72 l, respectively. It was found out that at a saturation value (which is achieved at a flow rate of 0.4 l/s – 0.5 l/s), the snail design systematically outperforms the U-turn and spiral designs by more than a factor of two for main water-activated isotopes (^{16}N, ^{17}N and ^{19}O). A notable difference between U-turn and spiral is only found for ^{19}O in favour of the U-turn (32 %). Furthermore, the effects of other parameters, e.g. reaction rate map, pressure drop, flow velocity profile, etc., are practically negligible as they do not differ significantly between the analysed designs. Based on that, the snail configuration was chosen as the main candidate for the irradiation part.

Due to its large effective volume, the snail design was also chosen for the observation part, which is located outside the radial piercing port and around which various gamma and neutron detectors are to be mounted. Higher activity values are preferable for easier measurement. It should be noted that a conventional approach was used for the activity calculation and CFD calculations were not considered at this stage. Further CFD analyses coupled with neutronics (reaction rate maps) will be essential for optimising the final closed-loop design and for the calculation of gamma dose field around the water-activation loop.

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