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Conceptual Design of Irradiation Facility with 6 MeV and 7 MeV Gamma Rays at the JSI TRIGA Mark II Research Reactor

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***Abstract*—Activated cooling water in nuclear facilities can present a significant r adiation s ource a round p rimary cooling system causing radiation damage to electrical components, increasing doses to personnel and in the case of fusion facilities additional heating to superconducting coils. As there are only few sources of gamma rays with energies in the range of 6 MeV and 7 MeV an irradiation system using activated cooling water as the source of energetic gamma rays is proposed at the Jožef Stefan Institute (JSI) TRIGA Mark II research reactor. Two different conceptual designs, one utilizing central irradiation channel and one utilizing radial piercing port for water activation, are presented and analysed in the paper. Despite an order of magnitude higher water activation in central channel compared to radial piercing port the ^{16}N decay rate in the irradiation facility is comparable between both design (order of 10^8 decays per second) due to longer transient time from central channel to irradiation facility. In the irradiation facility the expected biological dose rates due to the ^{16}N decay rate are in order of several mSv/h. From the results he conceptual design utilizing the radial piercing port currently presents the best option for the irradiation facility due to the simpler design of the irradiation loop, already present shielding of the loop and comparable number of ^{16}N decay rates to central channel.**

Keywords—**Activated cooling water, Monte Carlo, TRIGA, Irradiation facility.**

I. Introduction

Water is the cooling fluid i n m any fi ssion nu clear power plants, research reactors and it is also considered as a cooling fluid i n f usion r eactors. D uring t he c ooling o f t he reactor core in case of fission r eactors a nd b lankets i n c ase of fusion reactors the water is exposed to neutrons and becomes activated. The activation products in activated water are activated oxygen and hydrogen atoms, activated dissolved gases, corrosion products and water impurities. After irradiation the activated cooling water flows t hrough t he p rimary cooling circuit, commonly outside the primary biological shielding surrounding the reactor vessel, where the activated products decay and emit radiation. The emitted radiation may cause radiation damage to electrical components, increased doses to personnel working close to the cooling circuit and in the case of fusion facilities additional nuclear heating to various cold components such as superconducting coils cooled by liquid helium [1], [2].

There are several water activation products of which the most important are the ^{16}N due to high natural abundance of ^{16}O and the high energy of gamma rays (6.13 MeV and 7.11 MeV) and ^{17}N which emits neutrons with average energy of 0.88 MeV [3]. In case of fission reactors the water contribution to the total radiation field is usually negligible. The situation is however different for fusion devices such as ITER, where the dose-rate due to activated water is estimated to be several 100 Gy/h, exposing workers and sensitive equipment to high energy radiation [4]. Since most of today's gamma irradiations are performed by ^{137}Cs (0.662 MeV) or ^{60}Co (1.1732 MeV and 1.3325 MeV) sources, an irradiation facility with high energy gamma rays would enable rigorous testing of equipment and material samples to assess degradation.

As there are only few sources of gamma rays with energies in the range of 6 MeV and 7 MeV an irradiation system using activated cooling water as the source of energetic gamma rays is proposed at the Jožef Stefan Institute (JSI) TRIGA Mark II research reactor [5]. A conceptual design of such a facility consists of a closed water loop leading the water through one of the reactor's irradiation channels into a shielded irradiation facility outside the reactor core. The analysis of two different water activation loop irradiation systems was performed using the MCNP6 Monte Carlo particle transport code [6] and their usability as a source of high energy gamma rays was evaluated.

The paper is organized as follows. The principle of neutron

activation of water, the most important activated isotopes, the available nuclear data for neutron water activation and activation in the proposed activation loops at the JSI TRIGA reactor are presented in the first part of the paper. The second part of the paper presents the description of the two proposed water activation loops at the JSI TRIGA reactor. In the last part of the paper the analysis of the calculated results for both activation loops are presented. The proposed activation loops are comped by the water activity in the irradiation facility as the designs of both loop vary significantly. An analysis of the achievable water activity in the irradiation facility due to the water flow rate, reactor power and water retention time in the irradiation facility is also presented.

II. Water Activation

Due to neutron activation of oxygen isotopes in cooling water, the isotopes ^{16}N, ^{17}N and ^{19}O are produced. From the listed isotopes the most important isotope is ^{16}N which is produced via the ^{16}O(n,p)^{16}N reaction. Isotopes ^{17}N and ^{19}O are produced via the reactions ^{17}O(n,p)^{17}N and ^{18}O(n,γ)^{19}O [3].

Various high energy decay radiation types are emitted due to decay of activated isotopes in cooling water. As ^{16}N decays via decay path $^{16}\mathrm{N} \rightarrow {}^{16}\mathrm{O} + \beta^- + \gamma$, high energy gamma rays are emitted (6.13 MeV and 7.12 MeV) with half-life of 7.13 s. ^{17}N decays via decay path $^{17}\mathrm{N} \rightarrow {}^{16}\mathrm{O} + n + \beta^- + \gamma$ with average energy of 0.88 MeV and a half-life of 4.14 s. The emitted neutrons represent a neutron source outside the primary biological shielding and can activate components outside the primary circuit and produce neutron induced gamma rays. Activated isotope ^{19}O has a half-life of 26.9 s and decays via $^{19}\mathrm{O} \rightarrow {}^{19}\mathrm{F} + \beta^- + \gamma$ decay path and average gamma ray energy of 0.94 MeV.

The ^{16}O(n,p)^{16}N and ^{17}O(n,p)^{17}N reactions are threshold reactions with threshold energy at 10 MeV and 8 MeV respectively. The ^{18}O(n,γ)^{19}O reaction however takes places even at low incidents neutron energies. Fig. 1 displays the cross-section energy dependence for the above mentioned reactions. Due to threshold reactions the activation of water is expected to be higher in fusion reactors like ITER compared to fission reactors due to higher neutron energies (14 MeV neutrons from deuterium-tritium fusion).

The cross-sections the above mentioned water activation reactions vary significantly between the most common evaluated nuclear data libraries as ENDF/B-VIII.0 [3], JEFF-3.3 [7], FENDL-3.1b [8] and TENDL-2017 [9]. For the calculation of water activation presented in this paper only the ENDF/B-VIII.0 librarby was used while a detailed analysis of the cross-sections from different nuclear data libraries is presented in [4].

A closed loop irradiation facility using activated water as a high intensity, high energy gamma ray source is proposed at the JSI TRIGA research reactor. As the proposed system is still in the design phase the activation of water inside closed water loop systems needs to be calculated. The change of specific

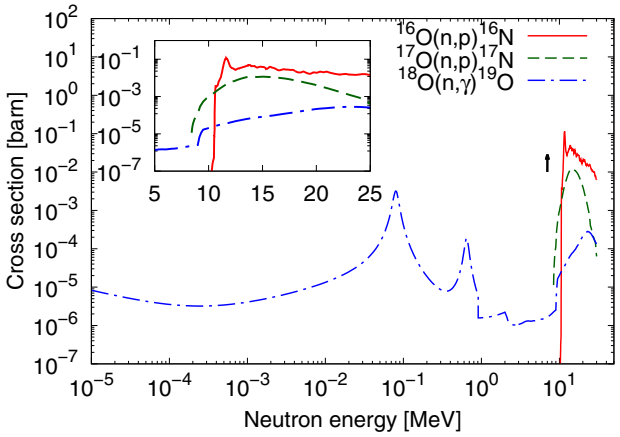

Fig. 1: Cross-section energy dependence for activation of oxygen nuclides taken from the JEFF-3.3 data library [7].

activity of a studied isotope in the water a is described using the equation [10]:

$$a(t) = R(1 - \mathrm{e}^{-\lambda t}), \tag{1}$$

where λ is a decay constant and R is an average reaction rate in region of interest of the studied isotope. However, the water in the loop system circulates and is exposed to the neutron flux in the reactor core for a short period of time, in the order of seconds. Thus the activity of the activated water at the inlet to the irradiation facility is described by equation [10]:

$$a_i = R\frac{1 - \mathrm{e}^{-\lambda t_i}}{1 - \mathrm{e}^{-\lambda T}}\mathrm{e}^{-\lambda t_f}, \tag{2}$$

where t_i is the exposure time in the reactor core, T is the total circulation time of the proposed closed water loop system and t_f is the transit time from the reactor core to the irradiation facility [10]. In order to calculate water activity, one most know the water flow rate, irradiation and cooling time, as well as water activation reaction rates inside the reactor core. In this paper we present water activation reaction rates inside the JSI TRIGA irradiation channels as calsulated using the MCNP code. [6].

The goal of the proposed irradition facility is the utilization of energetic gamma rays from the decay of ^{16}N isotope. As the activity and gamma ray emission of ^{17}N and ^{19}O are negligible compared to activity of ^{16}N due to their low natural abundance the analysis of the water activation at the JSI TRIGA research reactor will focus only on the activation of isotope ^{16}O [4].

III. Activation Systems at JSI TRIGA Mark II

The Jožef Stefan Institute TRIGA Mark II research reactor is a light water pool type research reactor with maximum steady state power of 250 kW. The core is submerged into a 6.25 m high and 2 m wide aluminium pool filled with water. The reactor core consists of six concentric rings loaded with stainless steel clad cylindrical fuel rods and aluminium in-core irradiation channels. The fuel material is a homogeneous mixture of U-ZrH with 12 wt% of 20% enriched uranium.

The fuel rods are placed into two $1.9\,\mathrm{cm}$ thick aluminium supporting grids which serve for positioning of fuel elements, control road and addiational in-core experiemnts in concentric rings (A - F) The reactror power is controlled by four individually operated control rods named the safety (S), transient (T), compensating (C) and regulating (R) control rod. The first two are completely withdrawn during normal reactor operation, while the last two are inserted to an approximately equal level. The core is surrounded by a circular graphite reflector [11]. The irradiation channels are normally located in the outermost ring with one exception in the central position of the reactor core. There are also three horizontal channels, one tangential and two radial irradiation channels penetrating the concrete structure of the reactor. One of the radial channels penetrates the graphite reflector to the reactor core while the other ends on the outside of the graphite reflector. A schematic drawing of the reactor core, graphite reflector and irradiation positions is presented in Fig. 2.

Two different conceptual designs for the activated water irradiation facility are currently under consideration. The first concept utilizes the central channel while the second concept utilizes the radial piercing port for water activation (Fig. 2).

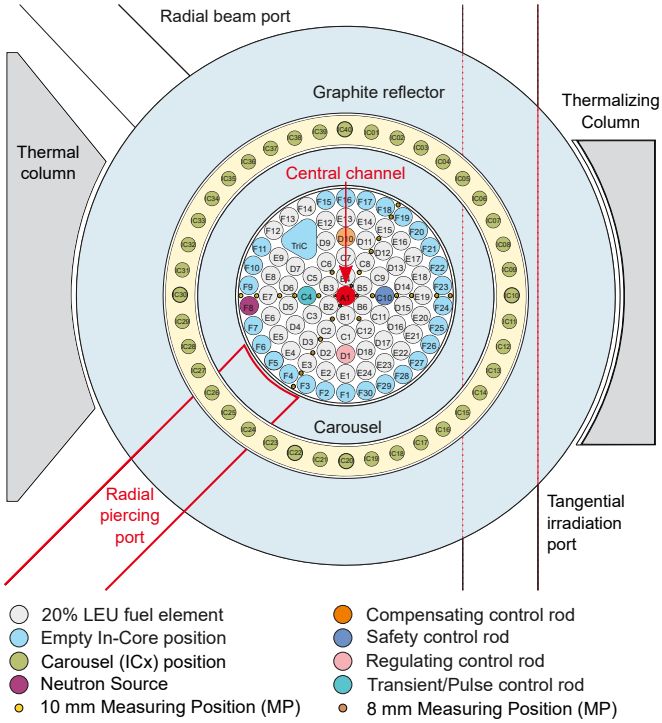

Fig. 2: Schematic drawing of the JSI TRIGA reactor core with marked irradiation channels under consideration for activated water irradiation facility.

In the first conceptual design the higher neutron flux in the central channel compared to the radial piercing port will cause higher activation rate of water. The proposed water activation loop, located in the central irradiation position would consists of a long pipe with the same diameter as the central channel, split into two parts due to limited space in the reactor pool. The water would then be guided trough the reactor tank to the reactor platform, and back down to the ground floor, requiring a $15\,\mathrm{m}$ long connection. A schematic model of the proposed conceptual design is presented in Fig. 3. Due to long pipe connection between the reactor core and the irradiation facility the transit time t_f of such a device would be in the order of the $^{16}\mathrm{N}$ half-life ($\sim 8\,\mathrm{s}$) depending on the water flow rate. Additional complication due to the increased dose rates at the reactor platform and in the reactor hall during the operation of the loop would require additional shielding. The total length of pipe in the reactor core is estimated to be around $40\,\mathrm{cm}$ while the length from the reactor core to the irradiation facility is estimated to be around $15\,\mathrm{m}$ (Fig. 3).

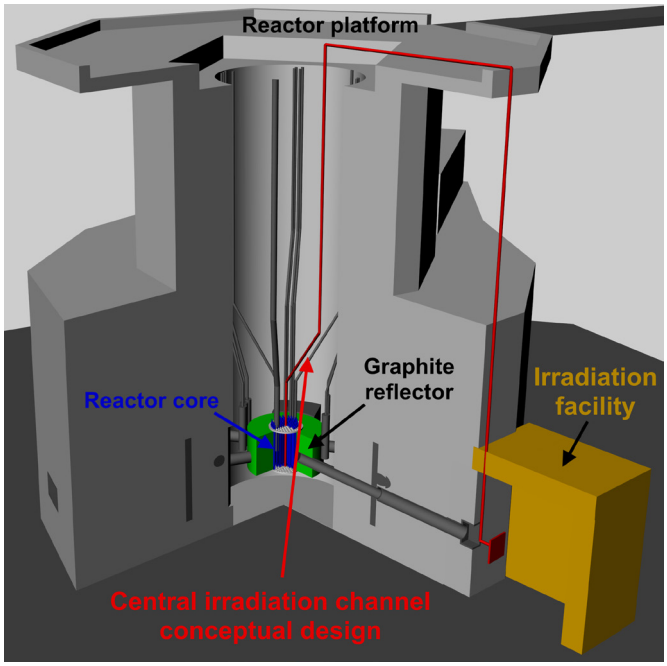

Fig. 3: Model of the proposed conceptual design for utilization of water activation in central irradiation channel.

In the second conceptual design the water is activated in the radial piercing port. Due to the port position adjacent to the reactor core the activation of the water will be lower compared to the central channel. To activate water in radial piercing port a pipe system will be inserted into the port with a large water cask at the end of the port to increase the exposure of the water to neutrons. However, unlike in the first design, the pipes with activated water will be guided outside of the port directly to the irradiation facility next to the port opening (the pipe length being around $3\,\mathrm{m}$) thus reducing the transport time. A schematic model of the proposed conceptual design is presented in Fig. 4. Another benefit of the radial piercing port is its position inside the concrete biological shielding which would provide shielding from activated water.

The summed properties of both proposed conceptual designs are presented in table I.

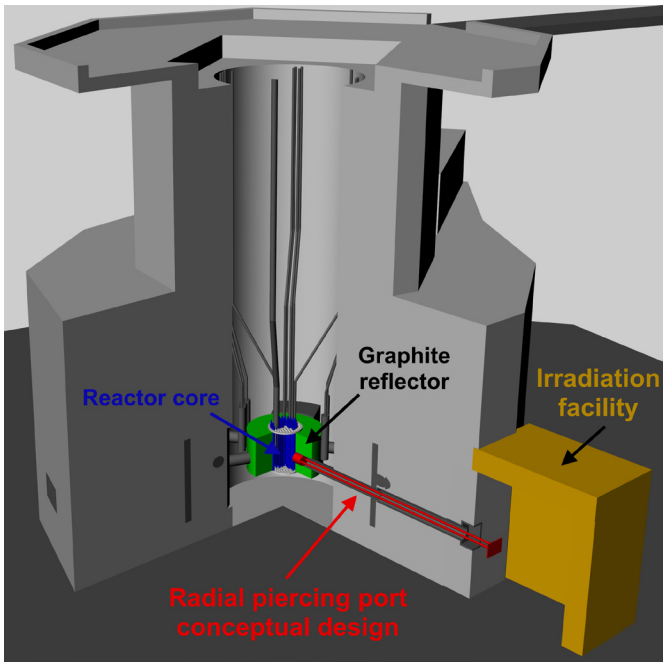

Fig. 4: Model of the proposed conceptual design for utilization of water activation in radial piercing port.

TABLE I: Tabulated data of both proposed conceptual designs for water activation at the JSI TRIGA reactor.

	Central channel	Radial piercing port
Pipe radius [cm]	1.12	1.50
Pipe length [m] (one direction)	15	3
Irradiation time [s] (flow rate = 0.5 l/s)	0.82	2.74
Irradiation time [s] (flow rate = 1 l/s)	0.41	1.37
Transit time [s] (flow rate = 0.5 l/s)	11.76	4.24
Transit time [s] (flow rate = 1 l/s)	5.88	2.12

IV. Conceptual Design Analysis

To calculate the reaction rates for activation of isotope ^{16}O at the JSI TRIGA reactor the water in irradiation channels in the detailed MCNP model was divided in smaller sections to thoroughly analyse both proposed conceptual designs. For the calculation of the reaction rates the ENDF/B-VIII.0 [3] library was used as it is the most up-to-date nuclear data library and there are no significant differences in the cross-section between nuclear data libraries. In the case of water activation in the central channel the highest water activation is in the middle of the active fuel as presented in Fig. 5 due to highest neutron flux. From Fig. 5 it is also visible that the water activation is higher in the bottom half of the reactor core. This is due to position of the control rods as two of the control rods are completely withdrawn while two are withdrawn to approximately same hight at the middle of the reactor core.

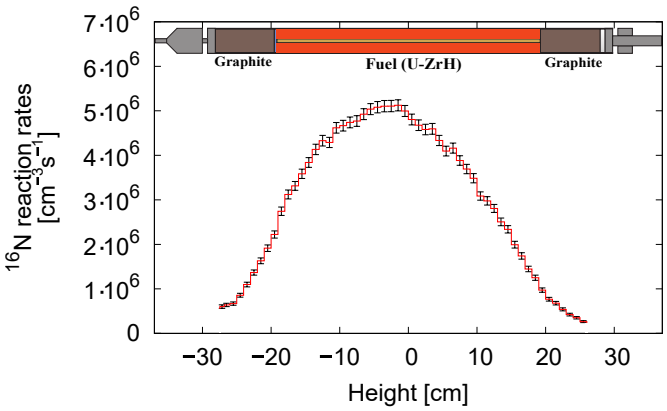

Fig. 5: Reaction rates for water activation in central irradiation channel normalized to reactor full power. The shift of the reaction rates to lower half of the reactor core is due to the position of control rods as two of them were withdrawn to half of the reactor core hight.

In case of water activation in the radial piercing port the reaction rates were calculated at different distanced from the core center and the results are presented in Fig. 6. The highest reaction rates are closest to the reactor core and falls with distance from the reactor core, at 10 cm distance from the core in the port the reaction rates are five times lower compared to the end of the port. By comparison of water reaction rates in central channel (Fig. 5) and radial piercing port (Fig. 6) the reaction rates are on average an order of magnitude higher in the central channel compared to the radial piercing port.

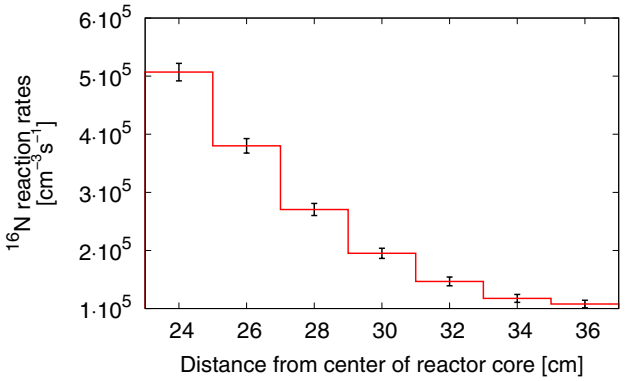

Fig. 6: Reaction rates for water activation in radial piercing port normalized to reactor full power. For the calculations the radial piercing port was filled with water for accurate representation of the proposed design.

To compare viability of both conceptual designs for different experiments utilizing high energy gamma rays the ^{16}N decay rate in the irradiation facility was calculated and compared. The design of the water activation loop allows for the water

activity to be controlled by two independent systems - reactor power and water flow rate. However, as the dependency of the ^{16}N decay rate on the reactor power is linear while for the water flow rate it is asymptotic, full reactor power was assumed in all calculations and only water flow rate was varied for analysis of both conceptual designs. The water flow rate was varied for several $0.1\,\mathrm{l/s}$ to several $\mathrm{l/s}$ as this flow rates are achievable in the proposed conceptual designs. In all cases a $4\,\mathrm{s}$ time was assumed in the irradiation facility to produce high energy gamma rays. The results are presented in Fig. 7.

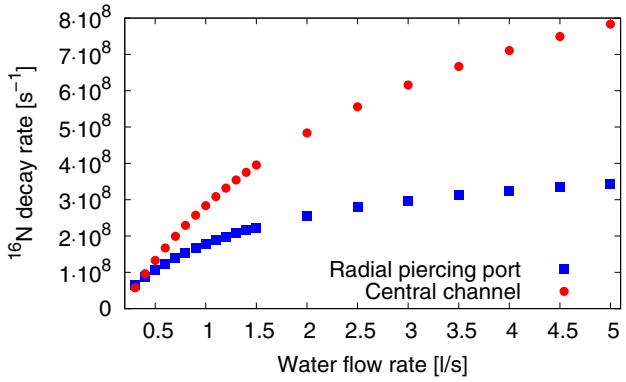

Fig. 7: ^{16}N decay rate dependence on the water flow rate at reactor full power.

For flow rates below $0.5\,\mathrm{l/s}$ the ^{16}N decay rate in the irradiation facility is higher for water activated in the radial piercing port despite an order of magnitude higher activation in the central channel. This is due to the long transient times (in the order of ^{16}N half-life) in the conceptual design utilizing the central channel. However, at higher flow rates, above $1\,\mathrm{l/s}$, the ^{16}N decay rates are higher in conceptual design utilizing central channel as the transient time becomes shorter.

For both proposed conceptual designs the maximal flow rate is estimated to be around $1\,\mathrm{l/s}$ due to the pipe sizes. At this flow rate the ^{16}N decay rate in the conceptual design utilizing the central channel is expected to be around $3{\cdot}10^8$ s^{-1}, which is only by a factor two higher compared to the conceptual design utilizing radial piercing port despite an order of magnitude higher activation in the reactor core.

The uncertainty of the water flow rate is the higher contributor to the uncertainty in the ^{16}N decay rate in the irradiation facility as the power of the reactor can be kept constant by the reactor automated systems. Due to this effect the conceptual design utilizing the radial piercing port has an advantage compared to the conceptual design utilizing the central channel. A small change in the water flow rate has a small effect in the ^{16}N decay rate in the irradiation facility due to this region of flow rate being in the saturated part of the ^{16}N decay rate curve, while for the conceptual design utilizing the central channel a small change in water flow rate can change the ^{16}N decay rate significantly, as the ^{16}N decay rate curve is still in the ascending part.

A. *Irradiation facility*

Different experiments utilizing activated water as a source of high energy gamma rays are going to be performed in an irradiation facility to minimize background radiation and shield the reactor hall during operation of water loop. Currently the irradiation facility is considered to be a closed room, $2\,\mathrm{m}$ high and $3\,\mathrm{m}$ long and wide. The shielding of the facility will be achieved by $30\,\mathrm{cm}$ thick high density concrete blocks. A schematic model of the propose irradiation facility is presented in Fig. 8.

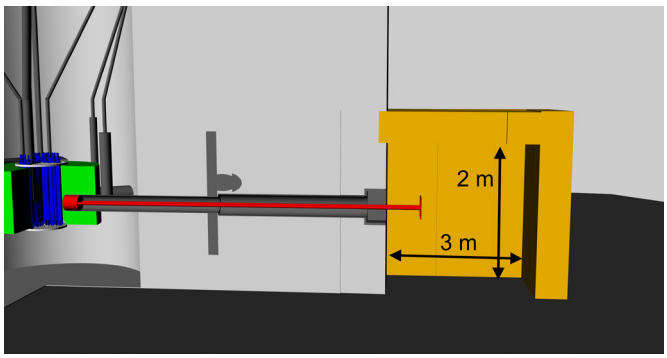

Fig. 8: Conceptual design of the irradiation facility for experiments utilizing high energy gamma rays from activated water decay. The depicted conceptual design utilizes the radial piercing port for water activation.

To asses the biological dose rates (H*(10) ambient dose equivalent) and air kerma in the proposed irradiation facility, a MCNP model was constructed. The source of gamma rays was modelled as an isotropic plane as it is currently considered as the best source for uniform activity with the use of activated water. The room in the model was filled with air and the biological dose rates and air kerma were calculated at different distances from the source. To calculate the biological dose rates from gamma rays flux-to-dose conversion factors from the standard ICRP-21 [12] were used while the air kerma was calculated using the energy deposited in the air due to gamma rays. The results for conceptual design utilizing radial piercing port for water activation at full reactor power and water flow rate of $1\,\mathrm{l/s}$ are presented in Fig. 9. The biological dose rates close to the source are in the order of several $\mathrm{mSv/h}$ and air kerma is in the order of several $\mathrm{mGy/h}$ while these values fall significantly at greater distance from the source. At $1\,\mathrm{m}$ distance from the source the biological dose rates are in the order of $0.1\,\mathrm{mSv/h}$ and air kerma $0.1\,\mathrm{mGy/h}$. For the conceptual design utilizing central channel for water activation the biological dose rates and air kerma are higher by around a factor of two at reactor full power and water flow rate of $1\,\mathrm{l/s}$ due to higher ^{16}N decay rate.

These preliminary calculations on water activation rates, ^{16}N decay rates, biological dose rates and air kerma serve as a basis for design of the proposed water activation irradiation facility.

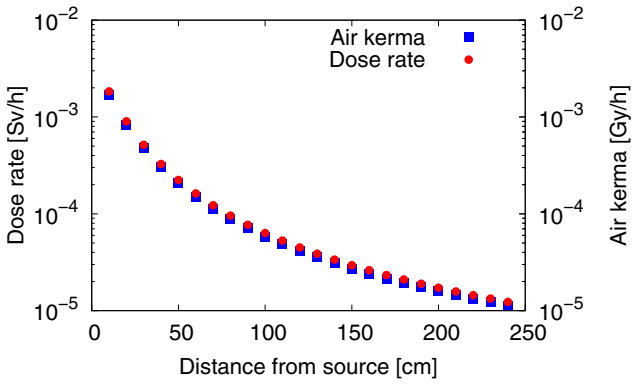

Fig. 9: Calculated biological dose rate and air kerma due to gamma rays in the proposed irradiation facility utilizing activated water as a source of high energy gamma rays. The values represent results for conceptual design utilizing radial piercing port at reactor full power and $1\,\mathrm{l/s}$ flow rate.

V. Conclusion

In the paper two concepts to utilize activated water for characterization of detector responses and shielding at high energy gamma rays at the JSI TRIGA reactor are presented. The first conceptual design utilizes the central channel for water activation while the second concept utilizes the radial piercing port for water activation. Using the Monte Carlo code MCNP the water activation in both conceptual designs was calculated. In the first conceptual design the water activation is an order of magnitude higher than in the second, however the transit time is longer by a factor of around 3. Also, the first conceptual design would require thick shielding of the water pipe in order to keep the reactor hall accessible.

The water activation results were used to obtain the ^{16}N decay rates in the irradiation facility for comparison. Despite an order of magnitude higher activation of water in the central channel the ^{16}N decay rate in the irradiation facility is just short of two times higher compared to conceptual design utilizing the radial piercing port at reactor full power and water flow rate of $1\,\mathrm{l/s}$, which is in the order of several 10^8 decays per second. However, for water flow rates below $0.5\,\mathrm{l/s}$ the ^{16}N decay rates from water activated in radial piercing port are higher compared to central channel due to longer transient times. In the irradiation facility water activity will produce biological dose rates in the order of $2\,\mathrm{mSv/h}$ to $4\,\mathrm{mSv/h}$ depending on the water flow rate, reactor power and which conceptual design is used for water activation.

The conceptual design utilizing the radial piercing port currently presents the best option for the irradiation facility due to the simpler design of the irradiation loop, already present shielding of the loop and comparable ^{16}N decay rates in the irradiation facility. Since the water activation is in saturation in the proposed design small changes in water flow rate will small effect on ^{16}N decay rate in the irradiation facility compared to the conceptual design utilizing central channel.

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