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Original Article

Validating a simplified water-activation transport model using time-resolved reactor-pulse neutron measurements at KATANA

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ABSTRACT

KATANA is a water activation facility at the Jožef Stefan Institute TRIGA Mark II reactor in Ljubljana, Slovenia, developed to study water activation processes relevant for future fusion systems such as ITER. In this work, we validated a simplified activation-transport model of the KATANA loop using time-resolved neutron measurements during reactor pulse operation. A finite volume of water in the KATANA loop was irradiated during reactor pulses, and the subsequent decay of ^{17}N was tracked with a ^{3}He detector. For each reactor pulse two distinct activation peaks were observed, corresponding to successive passages of activated water, and showed excellent agreement with model predictions. The measurements enabled to determine loop parameters in particular the effective loop volume, which gave excellent agreement with the direct measurements. The presented validation provides a solid foundation for future experimental campaigns at the KATANA water activation facility, aimed at performing integral cross-section measurements of the ^{17}O(n, p)^{17}N reaction and advancing studies of activation phenomena relevant to fusion applications.

1. Introduction

Water is widely used as a coolant in nuclear fission and research reactors and is also to be used in future fusion reactors. Under fast neutron irradiation, water is mainly activated by nuclear reactions involving oxygen isotopes, in particular ^{16}O, ^{17}O and ^{18}O. This process poses an operational challenge in fusion devices where 14 MeV neutrons from D-T fusion reactions dominate. Due to higher neutron energies and flux levels, fusion systems are expected to produce significantly more intense ionizing radiation fields compared to fission reactors [1], requiring precise modeling and experimental validation of activation processes for licensing and safety assessments.

KATANA [2] is a water activation facility located in the Jožef Stefan Institute TRIGA Mark II (JSI TRIGA) reactor in Ljubljana, Slovenia [3]. Neutrons born from fission in the TRIGA reactor follow the typical ^{235}U fission spectrum, with a broad fast-energy distribution peaking at around 1 MeV and a high-energy tail extending to approximately 10 MeV, and an average energy of about 2 MeV [4]. Since its commissioning at the end of 2023, it has completed three experimental campaigns that have contributed to a better understanding of the water activation processes and their modeling, which are important in the context of research in nuclear fusion, in particular for the future operation of the ITER machine [5,6].

Recently several computational tools (FLUNED [7], RSTM [8], ActiFlow and GammaFlow [9]) have been developed for the characterization of the cooling system in ITER machine currently under construction in Cadarache, France, employing two primary methods: Computational Fluid Dynamics (CFD) in conjunction with neutronic simulations [10,11]. These methods enable accurate modeling of distributed radioactive sources, such as the cooling water in future fusion facilities: CFD resolves the detailed thermo-hydraulic conditions (temperature, pressure, flow, ...), while neutronic simulations predict neutron production and activation. As CFD is very computationally intensive, a hybrid strategy is applied: Full CFD is only applied in regions where complex mixing, geometries or turbulence critically influence the transport, while in the remaining sections the flow is modeled as water transport with a uniform velocity profile. The coupled models are usually validated using dose rate measurements at several locations around the source [9].

A KATANA water activation loop simulation model was developed based on a uniform water velocity profile. This paper presents its validation through measurements in reactor pulse mode at the JSI TRIGA reactor. During operation a limited volume of water in the inner irradiation part of the KATANA water activation loop is irradiated for a short time (<1 s). As the activated water circulates, it emits neutrons

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Table 1
Activation products of water [13]. The activation product that emits neutrons is shown in bold.

Reaction	$t_{1/2}$	Major decay products	Threshold energy	Natural abundance
^{16}O(n, p)^{16}N	7.13 s	γ: 6.13 MeV (67%) γ: 7.12 MeV (5%)	≈ 10 MeV	99.76%
^{17}O(n, p)^{17}N	**4.17 s**	**n: 0.38 MeV (35%)** **n: 1.17 MeV (53%)** **n: 1.70 MeV (7%)**	≈ 9 MeV	**0.04%**
^{18}O(n, γ)^{19}O	26.9 s	γ: 0.20 MeV (96%) γ: 1.36 MeV (50%)	<1 eV	0.2%

along the loop. Time-resolved measurements with neutron detectors make it possible to observe the passages of the activated water and provide information about the flow dynamics. The close agreement between the simulated KATANA neutron response and the measured detector signals — transit times, peak shapes and dispersion — confirms the validity of the simplified transport model.

2. Water activation

The most important nuclear reactions involved in the process of water activation are ^{16}O(n, p)^{16}N, ^{17}O(n, p)^{17}N and ^{18}O(n, γ)^{19}O. The importance arises from the abundance of oxygen isotopes and their sufficient cross-sections to produce the primary activation products, making them the main contributors to induced activity in cooling water. The activated water serves as a time dependent radiation source that emits radiation during and shortly after reactor operation. The radioactivity of the activated water consists mainly of high-energy gamma rays and neutrons. In water activation, the reaction with ^{16}O has been the most studied in fission research due to its high natural occurrence (99.7%) and a significant activation cross-section, which indicates a higher probability of interaction with neutrons compared to other oxygen isotope reactions [12].

The emission of neutrons after the decay of ^{17}N is particularly important for fusion applications, as the D-T fusion neutron spectrum has more intense fast component compared to spectra in fission systems, which leads to a higher degree of activation. Neutrons with energies above 9 MeV are required for the ^{17}O(n, p)^{17}N reaction. The radioisotope ^{17}N, which decays with a short half-life (4.17 s), emits high-energy neutrons (see Table 1) [14]. In this article, the emitted neutrons from the decay of ^{17}N are used to characterize the water loop and to validate the simulation results.

In the present work, neutrons from ^{17}N decay were used as the primary observable for validation. The short half-life of ^{17}N ensures that essentially only the decays that occur while the activated volume of water is within the measurement volume contribute to the recorded signal, thus strongly constraining the reaction spatially and temporally. In addition, the total emitted neutron intensity is low compared to the γ field, which further suppresses contributions from activities outside the measurement volume. The reactor pulse provides a clear time reference: the prompt burst of reactor neutrons appears as a clearly identifiable peak in the detector signal and allows precise synchronization. After the reactor pulse, the neutron background is minimal, resulting in a high signal-to-background ratio that is well suited for the extraction of transit times and comparison of the simplified water activation transport model [14].

3. Reactor pulse operation

The JSI TRIGA research reactor features a pneumatic system that enables operation in pulse mode by rapidly ejecting the transient control rod. This rapid ejection immediately puts the reactor into a prompt supercritical state, which triggers an exponential increase in power. As the fuel temperature follows the power, the negative temperature coefficient of reactivity of the TRIGA fuel leads to a strong negative feedback that rapidly reduces reactivity. This self-limiting mechanism immediately stabilizes the reactor, leading to a rapid drop in power and a transition to a new steady state. Depending on the level of inserted reactivity and the configuration of the reactor core, the peak power during a pulse can be between 1 MW and 1 GW. Nevertheless, the total energy released is relatively low, typically only a few megajoules, which is due to the extremely short pulse duration of around 50 ms [3, 15,16].

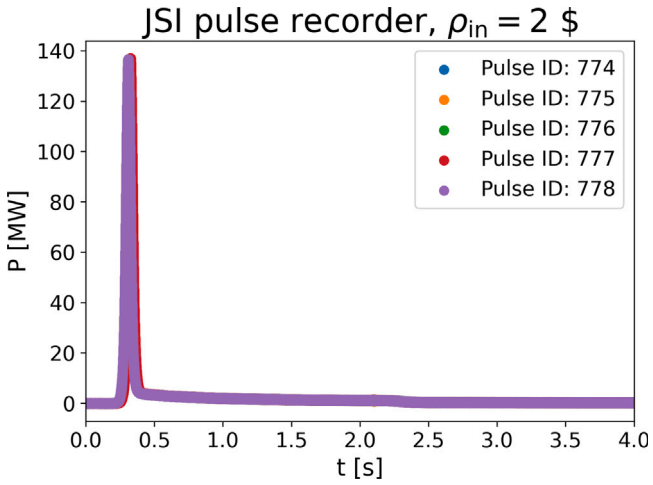

Fig. 1. TRIGA pulse signals measured with JSI pulse recorder (October 24, 2024).

Table 2
Pulse parameters measured with JSI pulse recorder [18].

Pulse ID	P_{peak} [MW]	FWHM [s]	E_{rel} [MWs]
774	133 ± 0.5	$0.039 \pm 5 \times 10^{-4}$	5.8 ± 0.1
775	135 ± 0.5	$0.039 \pm 5 \times 10^{-4}$	5.9 ± 0.1
776	136 ± 0.5	$0.039 \pm 5 \times 10^{-4}$	5.9 ± 0.1
777	137 ± 0.5	$0.039 \pm 5 \times 10^{-4}$	5.9 ± 0.1
778	137 ± 0.5	$0.039 \pm 5 \times 10^{-4}$	5.9 ± 0.1

The power signal of the reactor during the pulse is measured with a dedicated pulse measurement channel in the TRIGA instrumentation, which is equipped with an uncompensated ionization chamber. The measured signal for the pulses fired during the experiment with an inserted reactivity of 2 $ is shown in Fig. 1. In reactor kinetics, the reactivity ρ is dimensionless, generally defined as $\rho = (k_{\text{eff}} - 1)/k_{\text{eff}}$. The "dollar" ($) is a practical unit obtained by normalizing ρ to the effective fraction of delayed neutrons β_{eff}: by definition $1\ \$ \equiv \beta_{\text{eff}}$. A reactivity expressed in dollars is therefore $\rho[\$] = \rho/\beta_{\text{eff}}$. This convention is particularly useful for pulse experiments, as the prompt-critical threshold is $\rho = \beta_{\text{eff}}$ (i.e. 1 $) [17].

Table 2 lists the most important pulse parameters: peak power (P_{peak}), full width at half maximum ($FWHM$), and energy released (E_{rel}). These values vary only slightly between individual measurements, indicating that the pulse properties are almost identical and that the water was irradiated under comparable conditions [15].

The repeatability of the pulse height was evaluated to account for possible variations between individual pulses. Although the measured pulse characteristics exhibit consistent behavior, small fluctuations in peak power are unavoidable due to the transient-rod actuation mechanism [3]. Analysis of the five pulses used in this experiment yielded a relative standard deviation of 1.24% in the peak power. To conservatively account for this effect in the uncertainty analysis, a 2 % (1σ) repeatability uncertainty was adopted. The distribution of the measured peak powers, together with this uncertainty range, is shown in Fig. 2.

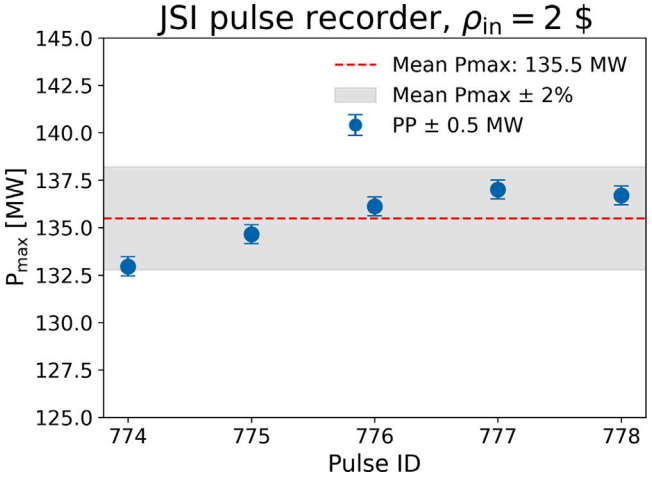

Fig. 2. Measured peak powers of the five TRIGA pulses used in the experiment, recorded with the JSI pulse recorder on October 24, 2024. The data demonstrate the high repeatability of the pulse height; the shaded region indicates the applied 2% (1σ) uncertainty adopted for the repeatability assessment.

4. KATANA water activation facility

The KATANA water activation facility is a water activation loop in the JSI TRIGA reactor hall, which provides a source of high-energy gamma rays and neutrons in the energy range from 0.3 MeV to 1.2 MeV. It was developed to support experimental studies of water activation processes. Designed for flexibility, the facility can be used for numerous research applications, including the calibration of radiation detectors and dosimeters, shielding experiments, the validation of simulation codes for fusion cooling systems and the measurement of integral cross sections [2,19,20].

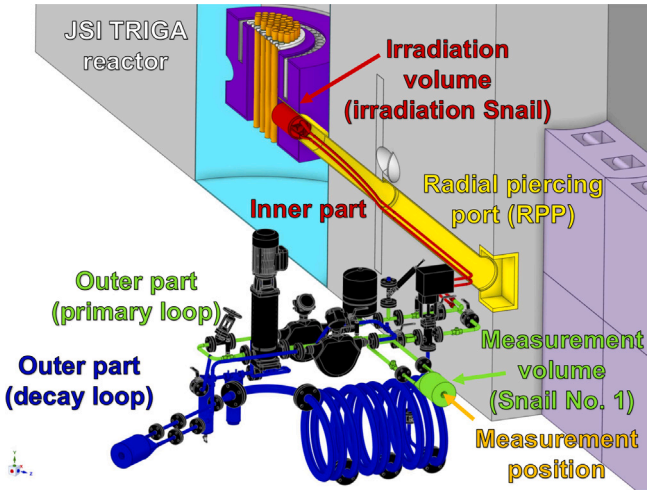

Fig. 3. KATANA water activation loop model.

The facility features a closed water activation system that can be divided into three main parts: the inner part, the outer part and the control panel. The inner part is located in the Radial Piercing Port (RPP) of the JSI TRIGA reactor, where neutron-induced radioisotopes are generated in water (shown in Fig. 3). The activated water then flows through pipes into the outer part, which is located inside the concrete shielding next to the RPP. The outer part can be divided into two circuits connected by a three-way valve: the primary loop (short, in green) and the delay loop (long, in blue). In the experiments presented here, only the primary loop was used due to the short half-life of the radionuclide of interest. The activated water is monitored in the outer measurement volume, a 3D-printed aluminium cylindrical capsule with internal baffles, referred to as Outer Snail No. 1, before being recirculated into the inner section. The control panel is located behind the concrete shielding [2].

4.1. Experimental setup

The experiments with neutrons from the decay of ^{17}N were performed on September 24, 2024 with a reactor core configuration #253. During the experiments single ^{3}He detector with CAEN DAQ system was used positioned in the central experimental position inside the outer measurement volume, i.e. Snail No. 1, as shown on Fig. 4.

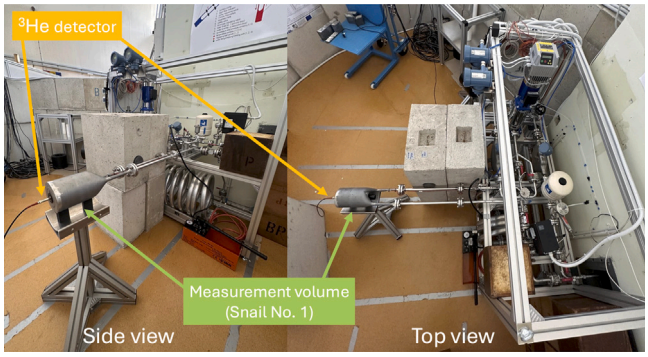

Fig. 4. Experimental setup: outer Snail No. 1 of the KATANA water activation loop, ^{3}He detector in the central experimental position.

During the experiments, the KATANA water activation facility was operated in the primary closed water loop configuration (short loop) at a constant water flow. Prior to the experiments, it was determined that the neutron background signal due to the operation of the reactor is negligible (less than 0.1 counts per second).

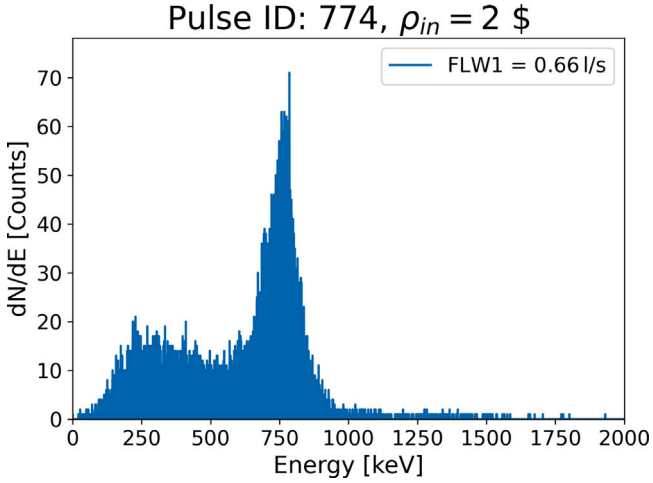

Fig. 5. ^{3}He pulse height spectra measured during pulse number 774 in the measurement volume with KATANA at a constant flow rate of 0.66 l/s (October 24, 2024).

The count rates of the ^{3}He detector are calculated from the measured signal spectra by taking into account the whole spectra associated with the ^{3}He(n,p)^{3}H reaction and dividing by the measurement time. The signal spectra from the neutron detector is presented in Fig. 5. Simplified water activation model was used to calculate the ^{17}N activity within the outer observation Snail No. 1.

4.2. Experiment simulation

The KATANA water activation loop is simulated using a conventional analytical approach. The simulation model consists of uniform volume elements with a volume of 21.65 cm^3, which are divided into four parts: the irradiation region (inner irradiation Snail), the observation region (outer Snail No. 1) and two transport regions (pipes and pump). The volumes of water are transported through the simulated circuit and the specific activity ($A'_{t+\Delta t}$) of each volume element is calculated after each time step (Δt) as follows

$$A'_{t+\Delta t} = A'_t \, e^{-\lambda \Delta t} + R(1 - e^{-\lambda \Delta t}), \tag{1}$$

where A'_t is the specific activity of the analyzed isotope in the volume at time t, λ is a decay constant of the isotope and R is the average reaction rate of the isotope in the region of interest. R can be further expressed as

$$R = C(t) \int \Phi(E)\sigma(E)N \, dE, \tag{2}$$

where $C(t)$ is the reactor power coefficient, Φ is the neutron flux, σ is the microscopic cross-section of the nuclear reaction, and N is the atomic number density of the parent nuclide [2]. The reaction rate R is non-zero only within the irradiation volume, named the irradiation Snail, as shown in Fig. 3. The irradiation scenario is determined by the reactor power coefficient C as follows

$$C(t) = \frac{P_{pulse}(t)}{P_{full}}, \tag{3}$$

where $P_{pulse}(t)$ is the measured reactor power during the experiment and P_{full}=250 kW is the reactor power at which the neutron flux is calculated with the JSI TRIGA MCNP model [21,22]. The volume is transported in discrete steps, each of which occurs at regular intervals Δt. The time step Δt is calculated based on the volumetric flow rate.

The uncertainties in the results of the simplified model are calculated by combining contributions from uncertainties in the nuclear data, statistical uncertainties associated with Monte Carlo transport calculations and the averaging of the calculated reaction rates within the irradiation volume.

5. Results

The principle of the experiment is based on the activation and transport of radionuclides in a closed-loop system. A defined volume of water is irradiated with neutrons, whereby the irradiation time is significantly shorter than the residence time of the water in the irradiation volume. After activation, the water, which contains short-lived radionuclides, is transported through the circuit, with the decay of these nuclides generating a measurable signal in the downstream detector. By analyzing the time-dependent evolution of the signal, which reflects both the decay kinetics and the flow dynamics, the response of the system can be compared with the simulated one.

The temporal evolution of the reactor power, the neutron detector signal and the simulated ^{17}N activity during reactor pulse No. 774 with a KATANA flow rate of 0.66 l/s is shown in Fig. 6. The reactor power measured by JSI TRIGA pulse recorder is shown as a green line, and it can be seen from the graph that a high reactor pulse occurred at the beginning of the experiment and the reactor was in a shutdown state afterward. The ^{3}He count rate, shown by red markers and error bars, rises promptly during the reactor pulse ($t \approx 0.5$ s) due to prompt neutrons scattering off the ceiling of the reactor hall and streaming out of the reactor through the radial piercing port. After a delay of about 1 s, the neutron signal from water activation is observed ($t \approx 1.5$ s), forming the first activation signal as the highly activated water package enters the outer measurement Snail. The first peak of the water activation signal occurs after approximately 5 s. The signal then returns to zero as the activated water flows back into the irradiation volume, and reappears after less than 20 s with the second water activation peak.

The simulated average of the ^{17}N activity in measurement Snail (blue line) agrees well with the measured signal within the uncertainties, confirming the representativeness of the simple KATANA simulation model for this system. By comparing the modeled KATANA ^{17}N activity with the measured neutron signal increase of the first water activation peak, it becomes clear that different parts of the water are activated to different degrees depending on their position within the irradiation Snail during the nuclear reactor pulse. This spatial non-uniformity in the activation, which is preserved in the measurements and agrees with the model predictions, indicates that the flow between the inner irradiation Snail and the outer measurement one can be presented with a uniform velocity profile.

The temporal agreement of the two peak values of water activation observed in both the simulated and measured signals shows that the volume defined in the KATANA water activation model accurately reflects the actual system volume. This agreement confirms the geometric and fluidic assumptions of the model and provides a solid basis for determining the system volume directly from the neutron signal of the activated water.

5.1. System volume measurement

When the KATANA water activation facility was commissioned in 2023, the total system volume of the KATANA water activation loop was determined by a combination of direct measurement and CAD model analysis. These measurements resulted in an effective total system volume of 12.8 ± 0.15 litres [23].

The pulsed reactor operation, the stable flow rate of the KATANA water activation loop and the measurable neutron signal from the ^{17}N decay provide a method to measure the system volume by measuring the time difference between the two water activation signal peaks associated with the passage of the activated water packet through the measurement volume. The position of the first peak is determined by applying the moving average filter to the measurement data. On the other hand, based on the shape of the second peak, a Gaussian function can be fitted to the measurement data to determine the position of the maximum. The measured data and the calculated positions of the water activation peaks are shown in Fig. 7 for three different flow rates.

The calculation of the system volume is based on

$$V = FLW1 \cdot \Delta t, \tag{4}$$

where V is the system volume, $FLW1$ is the measured flow rate in the KATANA water activation loop and Δt is the circulation time of the activated water. The circulation time is calculated as

$$\Delta t = t_2 - t_1, \tag{5}$$

where t_1 is the time of the first water activation peak and t_2 is the time of the second water activation peak.

Table 3
System volume measurements.

FLW1 [l/s]	Δt [s]	V [l]
0.66 ± 0.001	19.40 ± 0.05	12.80 ± 0.04
0.60 ± 0.001	21.30 ± 0.06	12.78 ± 0.04
0.50 ± 0.001	25.60 ± 0.08	12.80 ± 0.05
Direct		12.80 ± 0.15

The system volumes measured at different flow rates and presented in Table 3 are consistent within the uncertainties. Furthermore, the system volume determined with the neutron approach agrees with the direct measurement within the uncertainties. This volumetric characterization of the KATANA water activation loop forms the basis for a more accurate representation in newly developed calculation tools [8,24].

In future water-cooled fusion systems, this method could be used to monitor volume changes in cooling circuits due to the deposition of corrosion products and activation layers on the inner surfaces of the pipes during operation.

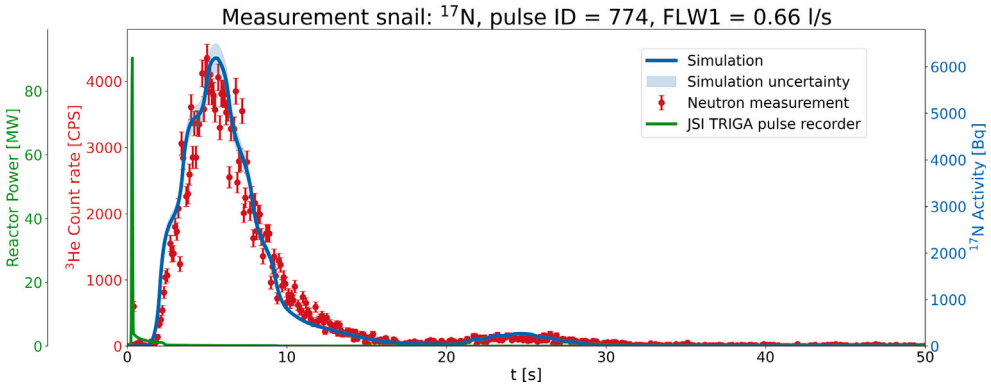

Fig. 6. Combined ^{3}He signal measured during pulse No. 774 in the center of measurement Snail No. 1 (red), reactor power (green) and simulated ^{17}N activity (blue) with its associated uncertainty band (light blue), recorded with KATANA at a constant flow rate of 0.66 l/s on October 24, 2024.

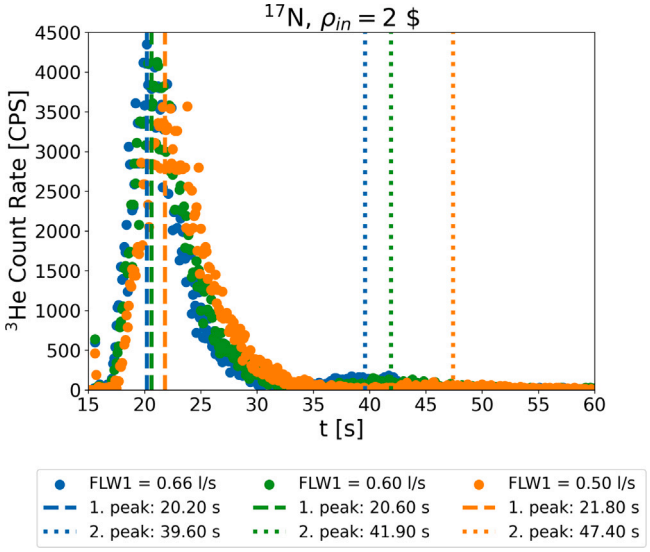

Fig. 7. Time-resolved ^{3}He detector response after activation of ^{17}O during reactor pulses with inserted reactivity of 2 $ at different KATANA flow rates (FLW1). The dashed vertical lines indicate the first passage of the activated water volume through the measurement volume. The dotted vertical lines indicate the second passage of the activated water volume. The experiment was conducted on October 24, 2024.

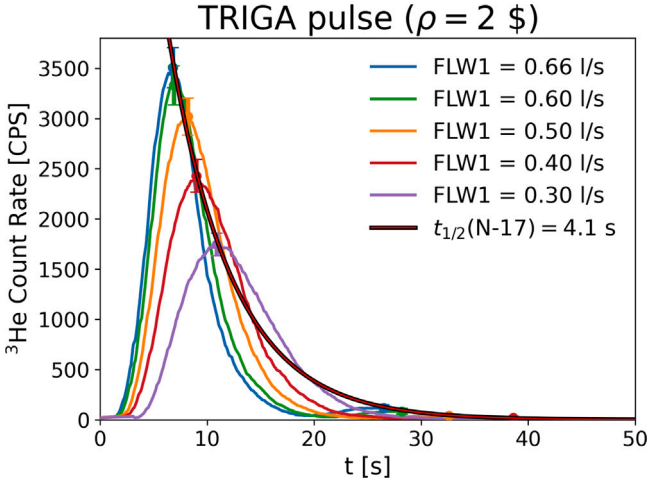

Fig. 8. Time-resolved ^{3}He detector behavior after activation of ^{17}O during reactor pulses with inserted reactivity of 2 $ at different KATANA flow rates (FLW1). The measured signal was filtered with a moving average filter (MAF) with a window size of 30 samples [25]. The measured maxima of the neutron signals are plotted with an error bar with one sigma uncertainty. The black and red lines represent the exponential decay of ^{17}N with a measured half-life in this experiment. The experiment was performed on October 24, 2024.

5.2. ^{17}N half life measurement

The operation of the KATANA water activation loop at different flow rates under the same pulse irradiation scenario of the JSI TRIGA research reactor results in the activated water reaching the measurement volume with different time delays. The inserted reactivity during the pulse experiments was 2 $. The activated water follows an exponential decay according to the relationship $A = A_0 e^{-\lambda t}$, where $A(t)$ is the activity at time t, A_0 is the activity after the reactor pulse, and λ is the decay constant. The measured signals are synchronized in time with the neutron signal peak recorded during the pulse, as shown in Fig. 6.

The KATANA water activation loop is a closed system, and assuming a uniform flow profile, the maxima in the neutron signal indicate when the activated water passes through the measurement position. The temporal neutron response of the KATANA water activation loop to the reactor pulse for different flow rates is shown in Fig. 8. The measured maxima in the neutron signal correspond to the observation of the same volume of water with different time delays with respect to the irradiation. By measuring the height of the signal, a point on an exponential decay curve is obtained.

The neutron signals have been transformed by applying the natural logarithm to facilitate linearization and are shown in Fig. 9. This converts the exponential decay into a linear form, with the slope of the linear fit k representing the decay constant $-\lambda$. The half-life of ^{17}N is determined from the decay constant as follows

$$t_{1/2} = \frac{\ln(2)}{\lambda}. \tag{6}$$

From the linear fit presented with red and black line ($k = -0.169\ (1 \pm 0.021)\ ln(CPS)/s$; $n = 9.30\ (1 \pm 0.009)\ ln(CPS)$), the half-life of the measured signal was calculated

$$t_{1/2} = 4.1\ \text{s} \pm 0.3\ \text{s}.$$

The half-life determined for ^{17}N agrees with earlier measurements [14,26]. However, the uncertainty of the result is relatively high due to limitations in the experimental setup and the type of measurement.

The uncertainty of the measured ^{17}N half-life result from the combination of uncertainties in the experimental system presented in Section 5.3 and the linear fit applied to the measured data. The main source of uncertainty is the statistical uncertainty due to the low count rate of the neutron detector. In the future, the knowledge gained from this experiment will help in the development of more precise

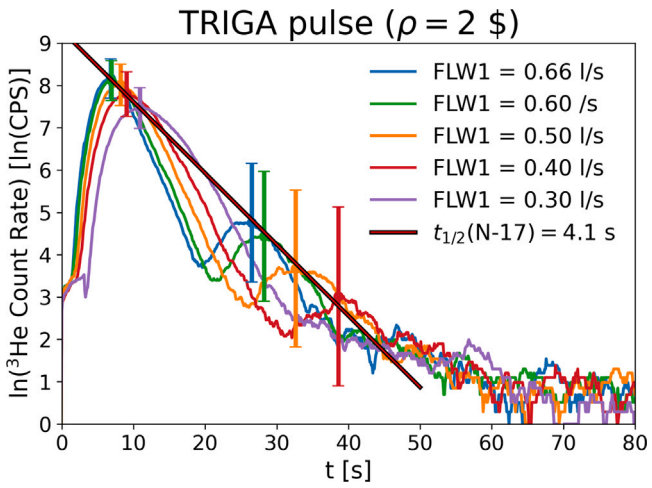

Fig. 9. Time-resolved ^{3}He detector behavior after activation of ^{17}O during reactor pulses with inserted reactivity of 2 \$ at different KATANA flow rates (FLW1). The measured signal was filtered with a moving average filter (MAF) with a window size of 30 samples [25]. The measured maxima of the neutron signals are plotted with an error bar with one sigma uncertainty. The black and red lines represent the exponential decay of ^{17}N with a measured half-life in this experiment. The experiment was performed on October 24, 2024.

measurements to reduce the uncertainty in the determination of the half-life.

5.3. Origins of uncertainty

The uncertainties in the simplified activation model result from the combination of several independent sources. These include the uncertainties in the nuclear data associated with the cross-section data used for neutron-induced reactions, the statistical uncertainties in the Monte Carlo transport simulations and the uncertainties in the measurement of the reactor power during pulse operation. In addition, the averaging of the calculated reaction rates over the discretized irradiation volume leads to further uncertainties.

The uncertainty in the ^{3}He detector count rates results primarily from statistical fluctuations in the measured counts, which follow Poisson statistics. The second most significant contribution is due to the repeatability of the reactor pulses, introducing an additional systematic uncertainty in the delivered neutron flux between individual irradiations. In addition, uncertainties in the KATANA flow rate and the pulse power measurement of the JSI TRIGA reactor affect the neutron flux at the irradiation position and, consequently, the activity of the water prior to detection. The inaccuracy of pulse repeatability, reactor power, and flow rate accuracy contribute to the overall measurement uncertainty of ~6% [2,27].

6. Conclusions

This study demonstrated a neutron-based method to characterize the KATANA water activation loop using the JSI TRIGA reactor in pulsed mode. The unique ability of the TRIGA reactor to deliver pulses enabled the activation of a well-defined volume of water within the KATANA loop, while the short half-life of ^{17}N allowed time-resolved neutron measurements with high temporal sensitivity.

The experimental results showed excellent agreement with the developed analytical model of the water activation process and confirmed the reliability of the simplified activation and transport representation under controlled flow conditions. The volume of the KATANA loop was determined from the measured time difference between the activation peaks and was in agreement with direct measurements.

The simulation model is derived under the assumption of a uniform flow profile. This assumption is valid for well-developed laminar flows and for turbulent flows where mixing results in negligible velocity gradients. Under conditions where significant velocity stratification, recirculation zones, or strong shear layers exist, the assumption no longer holds. Therefore, the applicability of the present model is limited to flow regimes where the velocity distribution remains approximately uniform.

In addition, the half-life of ^{17}N was determined from the decay of the neutron signal, yielding a value of 4.1 ± 0.3 s, which agrees with literature data and confirms the potential of the method for radionuclide decay measurements in circulating systems.

The demonstrated approach enables monitoring of system volumes and flow dynamics, which is crucial for accurate prediction of activation products and dose rates in the cooling circuits of future fusion reactors. In practical devices such as ITER, the methodology developed and validated at KATANA can serve as an experimental benchmark and as a diagnostic principle. At the design and licensing stage, the KATANA data provide integral constraints for tuning and validating coupled neutronic – thermo-hydraulic tools (e.g. FLUNED, RSTM, ActiFlow, GammaFlow) used to predict activity transport and dose rates in ITER cooling circuits. During plant operation and surveillance, the same principle could be implemented in dedicated monitoring branches or bypass loops to determine the effective system volume and residence time distribution of the coolant by analyzing time resolved activation signals following power transients. Deviations from the expected transit times or peak shapes would indicate changes in loop inventory or flow conditions, for example, due to partial blockages, gas ingress, or progressive deposition of activation layers.

Future work will focus on extending the method to long-term monitoring of system changes, reducing measurement uncertainties by optimizing detector configurations and applying the methodology to investigate corrosion and activation layer deposition effects in operational fusion-related systems. In parallel, dedicated experiments and coupled thermo-hydraulic–neutronic analyses will be performed to quantify the impact of non-uniform and transient flow conditions on the activation–transport behavior, with the aim of refining or extending the current empirical model beyond the uniform-flow regime.

CRediT authorship contribution statement

Julijan Peric: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Domen Kotnik:** Visualization, Validation, Resources, Investigation, Conceptualization. **Domen Govekar:** Writing – review & editing, Resources. **Luka Snoj:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Vladimir Radulović:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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