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Neutron measurements with activation foils around the JSI TRIGA water activation loop (KATANA)

J. Wlodarczyk[1], B. Bienkowska[1], E. Laszynska[2], D. Govekar[3], D. Kotnik[3], I. Lengar[3], X. Litaudon[4], J. Peric[3], V. Radulovic[3], L. Snoj[3,5], R. Villari[6]

[1] Institute of Plasma Physics and Laser Microfusion, 23 Hery Street, 01-497 Warsaw, Poland
[2] AGH University of Krakow, al. A. Mickiewicza 30, 30-059 Krakow, Poland
[3] Reactor Physics Department, Jozef Stefan Institute, Slovenia
[4] CEA, F-13108 St-Paul-Lez-Durance, France
[5] Faculty of Mathematics and Physics, University of Ljubljana, Slovenia
[6] ENEA, NUC Department, Via E. Fermi 45, 00044 Frascati, Rome, Italy

e-mail: jakub.wlodarczyk@ifpilm.pl

Abstract

As the primary coolant, water is used in most of today's fission reactors and is also one of the most promising coolants for future fusion reactors. During the cooling of the reactor in-vessel components, the water is exposed to the high-energy (E ~ 14 MeV) neutrons produced in the fusion D-T reactions. It is activated and produces radioactive nuclides that release 6 MeV – 7 MeV gamma rays and delayed neutrons (in the energy range 0.4 MeV – 1.7 MeV). The prediction of the dose rate field due to activated water is a complex task that requires the coupling of computational fluid dynamics (CFD), radiation transport and activation.

In order to study these phenomena and perform validation experiments, a water activation loop named KATANA was commissioned at the Jožef Stefan Institute (JSI) TRIGA Mark II reactor. This paper describes measurements to determine the neutron fluence due to delayed neutrons from ^{17}N using the neutron activation method. It is important to note that the cross section for the $^{17}O(n,p)^{17}N$ reaction has a significant uncertainty, hence such activation measurements can contribute to improving the nuclear data.

Prior to the experimental studies, a detailed pre-analysis using the FISPACT-II inventory code was conducted to determine the optimal activation monitors. Simulations have shown that, given the assumed neutron spectrum in the KATANA facility, In, Au, and Ni samples are the most suitable activation monitors. Given the relatively low expected neutron fluence in the KATANA facility, the use of massive activation foils (with masses of approximately 100 grams) was necessary. Subsequently, a series of irradiations were performed using selected activation foils. After irradiation, gamma spectrometry measurements were performed on the activation foils. The analysis of the obtained gamma spectra for the Au and In foils confirmed the presence of nuclides formed through neutron interactions. The indium foil provided the most reliable results, allowing for the determination of ^{115m}In activity.

Subsequently, MCNP simulations were performed to account for neutron production throughout the entire volume of water flowing through the loop. Simulations provided the expected neutron spectrum, which was then used to estimate the neutron fluence based on calculated reaction rates for ^{115m}In. The estimated neutron fluence at the KATANA water activation loop represents the final outcome of this study.

Aim of work

To assess the usefulness of neutron activation analysis (NAA) for detecting and quantifying neutrons at the KATANA facility:

- Assess the feasibility of detecting KATANA neutrons using neutron activation analysis.
- Select optimal activation samples for KATANA experiments.
- Provide the first estimation of the KATANA neutron emission rate based on NAA.
- Estimate the neutron fluence at sample positions using an MCNP model of the KATANA activation snail.

KATANA Water Activation Loop

- Well-defined and stable neutron source (Fig. 1).
- Oxygen activation produces ^{16}N, ^{17}N and ^{19}O.

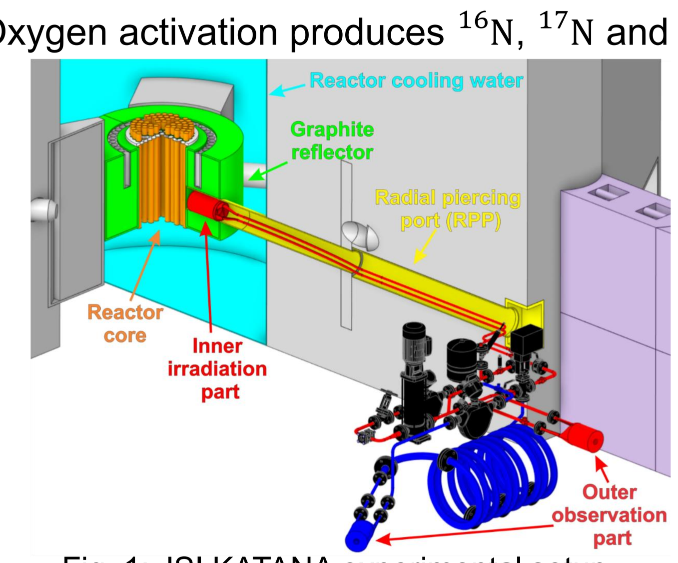

Fig. 1: JSI KATANA experimental setup.

JSI webpage: katana.ijs.si

Experiment

1. Selected activation foils (In, Ni, and Au) were placed inside and outside the activation snail (Fig. 2) and irradiated by neutrons from ^{17}N decay.
2. Gamma-spectrometry measurements were conducted using an HPGe detector.
3. The activity of the selected nuclides was derived.

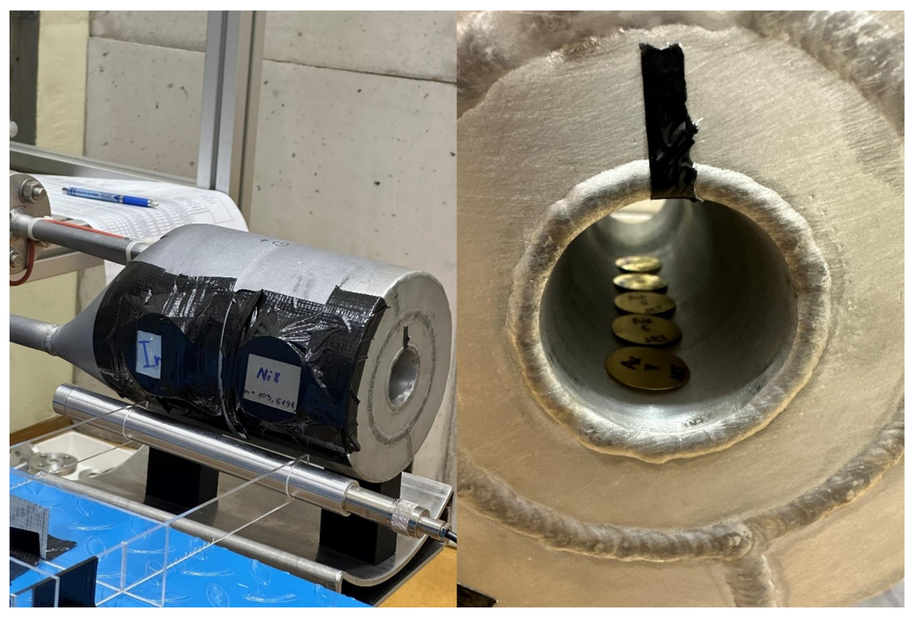

Fig. 2: Irradiation geometry.

Results

Neutron detection at the KATANA facility:

- Indium foils showed clear evidence of neutron activation, with the production of ^{115m}In and ^{116m}In.
- Nickel and gold foils yielded no useful data, as no activation products were observed in the gamma energy spectrum.

KATANA neutron emission estimation:

- Based on the measured activity of ^{115m}In, the experimental reaction rate (RR_{exp}) was derived:

$$RR_{exp} = \frac{A \cdot A_{rel}}{m \cdot f_i \cdot N_{AV} \cdot (1 - \exp(-\lambda t_{irr}))},$$

where:
A – measured ^{115m}In activity (Bq),
A_{rel} – the atomic mass of the target nucleus $(g \cdot mol^{-1})$,
m – mass of irradiated sample (g),
f_i – abundance of ^{115}In in the sample,
N_{AV} – the Avogadro constant (mol^{-1}),
λ – decay constant (s^{-1}),
t_{irr} – irradiation time (s).

- Experimental reaction rates (RR_{exp}) were compared with MCNP-calculated reaction rates (RR_{MCNP}), obtained using the KATANA MCNP model (Fig. 3), to estimate the neutron emission rate ($S = \frac{RR_{exp}}{RR_{MCNP}}$) (Tab. 1).

Tab 1: Calculated and experimental reaction rates and the resulting neutron emission rate from the activation snail water.

Sample name	RR_{exp} (s^{-1})	RR_{MCNP} (reactions per n)	S (s^{-1})
In 1	$(10.00 \pm 1.12) \cdot 10^{-24}$	$(3.0155 \pm 0.0015) \cdot 10^{-29}$	$(3.33 \pm 0.37) \cdot 10^{5}$
In 2	$(4.69 \pm 1.23) \cdot 10^{-24}$	$(3.0255 \pm 0.0015) \cdot 10^{-29}$	$(1.55 \pm 0.40) \cdot 10^{5}$
In 3	$(7.52 \pm 0.81) \cdot 10^{-24}$	$(3.0313 \pm 0.0012) \cdot 10^{-29}$	$(2.48 \pm 0.27) \cdot 10^{5}$
In 5	$(2.69 \pm 0.93) \cdot 10^{-24}$	$(2.9346 \pm 0.0017) \cdot 10^{-29}$	$(0.92 \pm 0.32) \cdot 10^{5}$
In 6	$(7.04 \pm 0.47) \cdot 10^{-24}$	$(2.9000 \pm 0.0015) \cdot 10^{-29}$	$(2.43 \pm 0.16) \cdot 10^{5}$

KATANA neutron fluence estimation

- The neutron fluence at the KATANA facility (Tab. 2) was derived by combining the experimental reaction rates with the MCNP-calculated neutron fluence energy spectrum in the selected activation samples (Fig. 4):

$$\phi = RR_{exp} \cdot t_{irr} \cdot \left(\frac{\sum_{i=1}^{709} \varphi(E_i) \cdot \sigma(E_i)}{\sum_{i=1}^{709} \varphi(E_i)}\right)^{-1} = S \cdot t_{irr} \cdot \sum_{i=1}^{709} \varphi(E_i),$$

where:
$\varphi(E)$ – the MCNP-calculated neutron fluence energy spectrum in the selected activation samples,
$\sigma(E)$ - $^{115}In\,(n,n')^{115m}In$ cross-section for given neutron energy E.

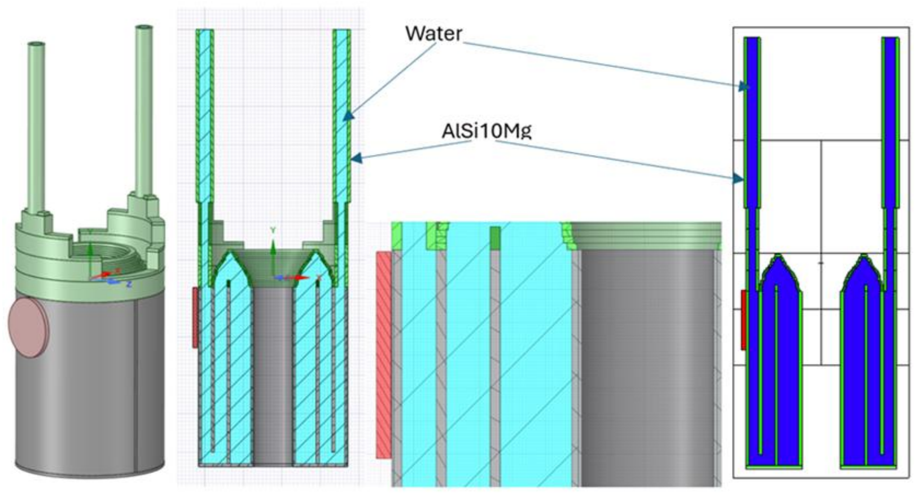

Fig. 3: MCNP model of the KATANA activation snail geometry.

Tab 2: Neutron Fluence Estimation at the KATANA facility

Sample name	ϕ (cm^{-2})
In 1	$(2.21 \pm 0.25) \cdot 10^{6}$
In 2	$(2.07 \pm 0.54) \cdot 10^{6}$
In 3	$(5.00 \pm 0.54) \cdot 10^{6}$
In 5	$(2.02 \pm 0.70) \cdot 10^{6}$
In 6	$(1.63 \pm 0.11) \cdot 10^{7}$

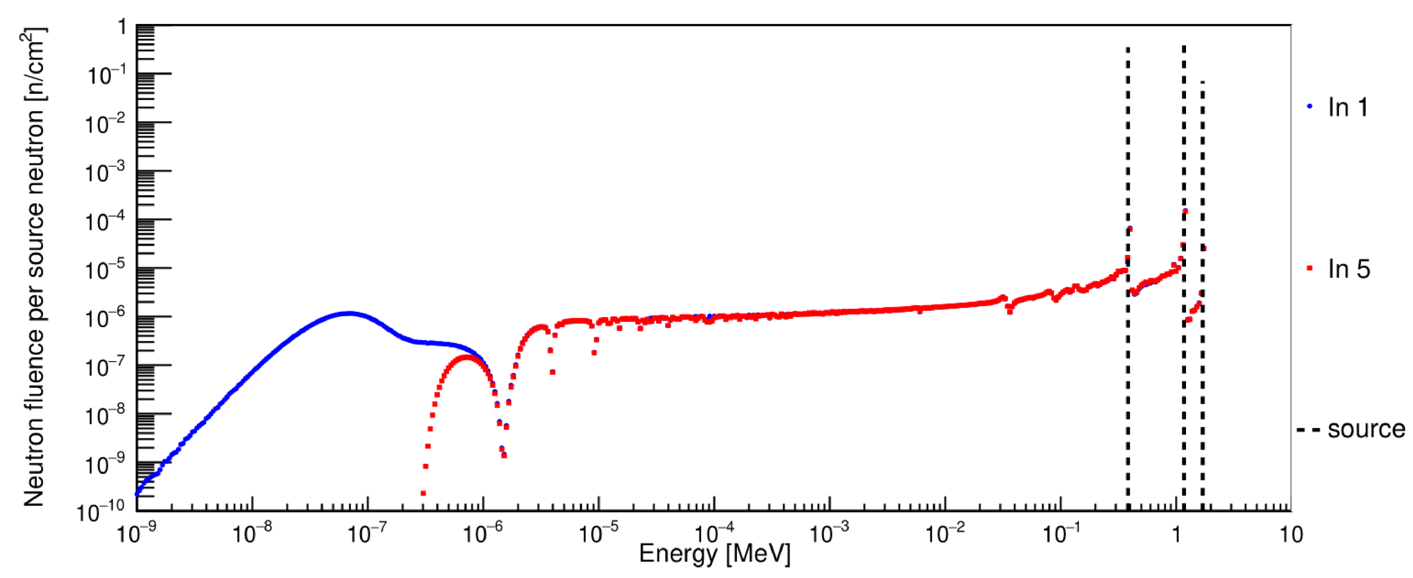

Fig. 4: The MCNP-calculated neutron fluence energy spectrum in the selected activation samples.

Conclusions

1. Neutron activation analysis is suitable for neutron measurements at the KATANA facility.
2. Indium activation samples proved effective as neutron monitors at the KATANA facility.
3. The ratio of experimental reaction rates (RR_{exp}) to MCNP-calculated reaction rates (RR_{MCNP}) enables estimation of the KATANA neutron emission rate.
4. Using the experimental reaction rates together with the MCNP-calculated neutron fluence energy spectrum for the selected activation samples, the neutron fluence at the sample location was determined.

Jožef Stefan Institute
Ljubljana, Slovenia

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