Gamma-heating and gamma flux measurements in the JSI TRIGA reactor, results and prospects

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***Abstract*—The neutron field of various irradiation positions of the TRIGA Mark II reactor of the Jožef Stefan Institute has been thoroughly characterized by neutron activation dosimetry and miniature fission chambers techniques. In order to have a fully validated calculation scheme to analyze and plan experiments, the gamma field also has to be experimentally validated. The 10-year long collaboration between CEA and JSI is a perfect framework to carry out such a study, and measurements of the gamma field started in late 2016. Several measurement techniques were investigated in in-core and ex-core positions.**

On-line measurements were carried out using miniature ionization chambers manufactured by the CEA and PTW Farmer ionization chambers. Positional dependence was studied, showing a decrease in the delayed gamma contribution to the total gamma flux with increasing distance from the reactor core center.

To characterize the gamma dose in the core, as well as in the periphery, thermo- and optically stimulated luminescent detectors were tested. These detectors are commonly used at CEA to measure the gamma dose in a given material in order to study the nuclear heating in various core elements (control rod, baffle, structural material). Different filters were used in order to assess an integrated dose ranging from a few Gy up to several kGy. The feasibility of such measurements demonstrates the complementarity between measurements with dosimetry and ionization chambers from low to very high gamma-dose environment, such as in material testing reactors.

***Index Terms*—CaF_2, gamma flux, ionization chamber, LiF, TRIGA, TLD**

I. Introduction

THE ability of a research reactor to perform precise irradiations (for electronic components, biological samples, sensors,…) lies with its neutron and gamma fields characterization. In steady state operating mode, the neutron field of various irradiation positions of the TRIGA Mark II reactor of the Jožef Stefan Institute has already been measured by means of neutron activation dosimetry and miniature fission chambers techniques [1]-[3].

In a reactor core, gamma rays can be emitted promptly after a reaction (from fission or capture for instance), or after a certain time, which can range from seconds to years or more (activation or fission products decay). From the radiation safety point of view, as well as for irradiation purposes, it is mandatory to characterize these contributions, especially shortly after reactor shutdown. Thus, a comprehensive gamma characterization campaign has been carried out, within the framework of the 10-year old JSI-CEA collaboration agreement on nuclear instrumentation [4]. The work presented here deals with the gamma measurements performed in late 2016 and 2017. The delayed gamma contribution importance has already been pointed out [5][6], and this study will bring new data to characterize this component in the TRIGA reactor. Complementary to his study, the dose rate was assessed with dosimetry techniques.

The JSI TRIGA Mark II reactor is a pool type reactor with maximum steady state power of 250 kW. The core has 91 available positions in a concentric configuration for U-ZrH fuel elements, irradiation positions and control rod positions (Fig. 1). In between these positions, there are also positions with diameter of 10 mm, 8 mm and 6 mm, arranged along two lines across the reactor core, used for miniature detectors (Fig. 2).

The first part of the paper describes the measurements techniques used, while the results are discussed in the second part.

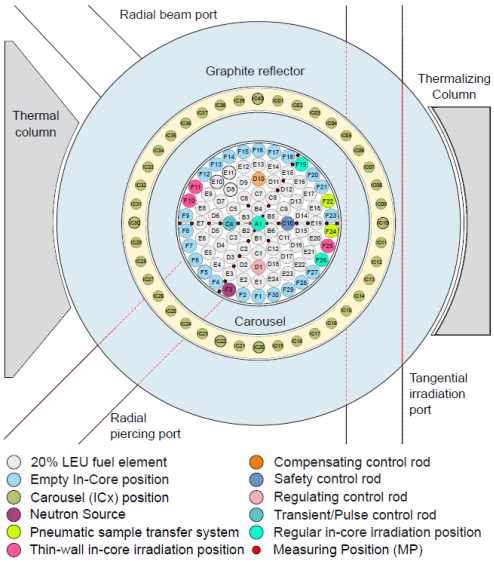

Fig. 1. Core configuration during the measurement campaign.

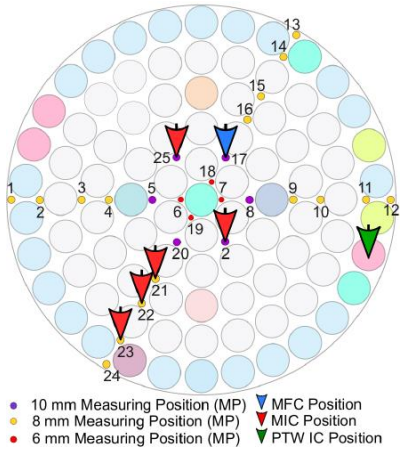

Fig. 2. Measurement positions inside the TRIGA core.

II. Measurement techniques

In this section, we describe the sensors that were used during the measurement campaign, as well as their main characteristics.

A. Ionization chambers

We used two types of ionization chambers. The first one, developed by CEA, labeled as MIC (Miniature Ionization Chamber), is a 3-mm diameter and 55-mm long sensor, sealed at the end of a mineral cable. The second one is a commercial PTW Farmer® Ionization Chamber Type 30010, labelled PTW IC (30-mm long sensitive length, 16-mm diameter). These detectors are devoted to gamma radiation detection.

To monitor the irradiations we used a Miniature Fission Chamber (MFC), of same geometry as the MIC, but with a fissile coating of a few micrograms of ^{235}U on the anode, to have a very high sensitivity to thermal neutrons.

B. Optically stimulated luminescent detectors and thermoluminescent detectors

1) Characteristics

To assess gamma doses ranging from a few Gy up to kGy we used thermo-luminescent detectors (TLDs). These detectors were inserted in 2-mm thick aluminium cylinders to ensure the charged particle equilibrium. Two types of TLD were used: TLD400 (CaF_2:Mn) and TLD700 (^{7}LiF:Mg,Ti) obtained from ThermoFisher Scientific. The dose reader is a Harshaw model 3500, which can heat a single TLD up to 400 °C. The readout process for the TLD400 is the following: pre-heating at 150 °C for 5 s, then heating up to 350 °C at a 10 °C.s^{-1} rate and maintaining this temperature for 30 s. For TLD700, the read out consists of a pre-heating at 140 °C for 10 s, then heating up to 280 °C at a rate of 15 °C.s^{-1} and maintaining the temperature at 280 °C for 23 s [7]. Prior to each irradiation, the residual dose in the detectors is annealed (1 h at 400 °C + 2 h at 100 °C).

In order to avoid the saturation of the photomultiplier tube while reading dosimeters with integrated doses higher than a few Gy, we used neutral optical filters of various efficiencies: 10%, 1% and 0.1% (corresponding to the fraction of the transmitted radiation).

For the background doses in the different positions, nanoDots optically stimulated luminescent detectors (OSLDs) from Landauer were also used. The integrated dose is read thanks to light stimulation of the detector. The read out process is non-destructive, and the detector cannot be annealed afterwards. They are only used for the small dose range since the detector itself saturates after a dose of a few Gy.

2) Calibration

The relation between the charge integrated in the detector (in nC) and the dose is determined by calibration measurements in a reference gamma field. For doses below 2 Gy (measurements without filters), the calibration was carried out at CEA Cadarache at the radiation protection division. The high dose calibration (with filters) was performed at CEA Saclay on the PAGURE and POSEIDON ^{60}Co irradiators, in which the dose rate can reach several kGy.h^{-1}.

III. Results

Several steady state power levels were investigated with reactor power ranging from 50 W to 250 kW. After reactor shutdown by rapid control rod insertion (SCRAM) the delayed contribution was also measured with MIC, MFC and TLDs. The methodology to distinguish the delayed and prompt gamma component from MIC and MFC measurements is described in [8]. To assess the delayed contribution with TLDs, they were inserted at different times after a SCRAM, in the central channel.

The MFC was inserted in the MP17 position, the reference gamma detector PTW IC was into the F25 position, into an irradiation channel. To assess the gamma flux dependence against the distance to the core centre, the MIC was moved in different measuring positions (Fig. 1).

We measured the dose with TLD in the central channel A1, the peripheral position F26 and in the IC40 position of the carousel, inside the graphite reflector.

A. Gamma flux characterization

Regarding the gamma flux dependence to the position inside the core, we observed a clear decrease of the delayed contribution, linear with the distance to the core center (Fig. 3) [8]. Measurements carried out so far showed that the delayed contribution, estimated after 10 minutes of irradiation, obeys the following equation:

$$\text{Delayed } \gamma \text{ fraction} = -6.25 \times 10^{-3}.r + 0.314 \quad (1)$$

r being the distance (in centimeters) from the core center. This seems to originate from the environment of the measurement, since central measuring positions are surrounded by more fuel elements than the peripheral ones. The delayed contribution ranges roughly from 20 % (periphery) up to 30 % (inner position) of the total gamma flux after 10 minutes of reactor operation.

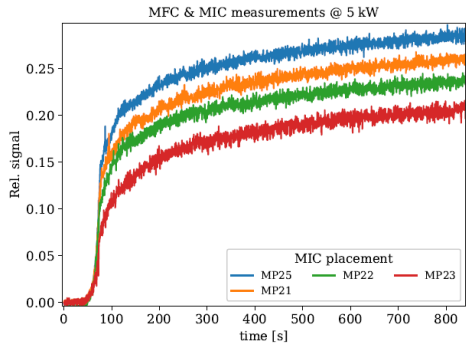

Fig. 3. Delayed gamma contribution measured with the MIC at 5 kW with regard to the position.

B. *Gamma dose measurements*

The absolute doses measured by TLD400 and OSLDs are presented in Tab. I. The uncertainties (given at 1σ) correspond to the maximum between the standard uncertainty propagation and the discrepancy between detectors. The irradiations at higher power levels than 4 kW are not presented here since they show incoherent results, as the measured dose rate was lower than during the low power irradiations. For the background measurements in F26 and IC40, there is a good agreement between TLDs and OSLDs.

TABLE I
ABSOLUTE DOSE MEASUREMENTS IN ALUMINUM (GY)

Pos.	Detector	Background 3.5min		200W 20min		4 kW 10min	
A1	TLD400	33	1.6%	131	13.1%	1146	2.0%
F26	TLD400	9	9.9%	36	10.1%	336	5.3%
	OSLD	8	1.1%	-	-	-	-
IC40	TLD400	1.2	5.6%	7	8.0%	80	2.5%
	OSLD	1.0	4.9%	-	-	-	-

The total prompt gamma air KERMA (Kinetic Energy Released per unit MAss) has been calculated in various core positions in [9]. By adding to the prompt component a delayed contribution, calculated as:

$$K_{\gamma,\mathrm{tot}} = \frac{1}{1-\text{Delayed }\gamma\text{ fraction}} K_{\gamma,\mathrm{prompt}} \qquad (2)$$

one can estimate a total gamma air KERMA rate in the dosimeter positions, per unit power. The delayed γ fraction is evaluated from Eq. (1). Results are presented in Tab. II. Measurement uncertainties are defined here as the standard deviation between the averaged dose rates of the two irradiations (around 10%). The uncertainties can be quite large (especially for the KERMA calculation in the core periphery), but there is an overall good agreement between calculations and measurements.

Precise modeling of the detectors as well as their surroundings could improve the comparison, as well as taking into account the neutron contribution in the integrated dose. Some correction factors should also be applied to the measured dose, that are not yet implemented.

TABLE II
COMPARISON OF CALCULATED AND MEASURED TOTAL GAMMA AIR KERMA ($GY.KW^{-1}.MIN^{-1}$)

Pos.	Calculation				Measurement	
	Kγ,prompt	Delayed fraction[1]	Kγ,tot	Unc.	Kγ,tot	Unc.
A1	19.6	31%	28.6	5.8	30.7	2.9
F26	5.6	19%	6.9	1.7	8.7	0.4
IC40	1.1	11%	1.9	1.2	1.9	0.2

[1]Delayed fraction uncertainty: 15%

C. *Delayed contribution*

The delayed gamma contribution was assessed after a 4 kW irradiation. TLDs were inserted at different times after SCRAM and spent different amount of time in the core (Tab. III).

TABLE III
CHARACTERISTICS OF THE DELAYED MEASUREMENTS WITH TLDS

Time of insertion after SCRAM	Integration duration
2 seconds	2 minutes
5.5 minutes	5 minutes
16 minutes	10 minutes
32 minutes	137 minutes

On the top plot of Fig. 4, one can see that the difference between MFC and MIC signal after SCRAM is related to the delayed neutrons. The decaying behavior of the TLD400 dose rate agrees with the one of the MIC. The bottom plot of Fig. 4 displays plots of relative MIC and TLD signals. The relative MIC signal is obtained by dividing the MIC signal with the constant value just before the reactor SCRAM. The TLD relative signal is obtained by normalizing the TLD values to the MIC signal averaged on the TLD time of integration, either on the first TLD measurement (red squares) or the second one (black triangles):

$$\dot{D}_{\mathrm{norm},i} = \frac{\dot{D}_i}{\dot{D}_{1\text{ or }2}} \frac{1}{T_i} \int I(t)\mathrm{d}t \qquad (3)$$

where $\dot{D}_i$ is the TLD dose rate measurement i, $I(t)$ the MIC signal, T_i the time of integration of measurement i.

The relative signals of the MIC current and dose rates determined with TLD after a reactor SCRAM are seen to match one another very well, within 10% in both cases, except for the last point. The latter indeed shows a very high uncertainty linked to the discrepancy between TLDs. In addition, the MIC signal appears to be very noisy for current below 1 nA, leading to a more difficult analysis. The slight difference between the two normalization is attributable to the partial sensitivity of the TLDs to the neutron field, more specifically delayed neutrons, still present shortly after a reactor SCRAM. At around $t = 2$ min after SCRAM, the delayed neutron contribution seems to be negligible compared to the delayed gamma one. Nevertheless, the neutron sensitivity of TLD400 should be taken into account in order to have a more consistent comparison against the MIC data.

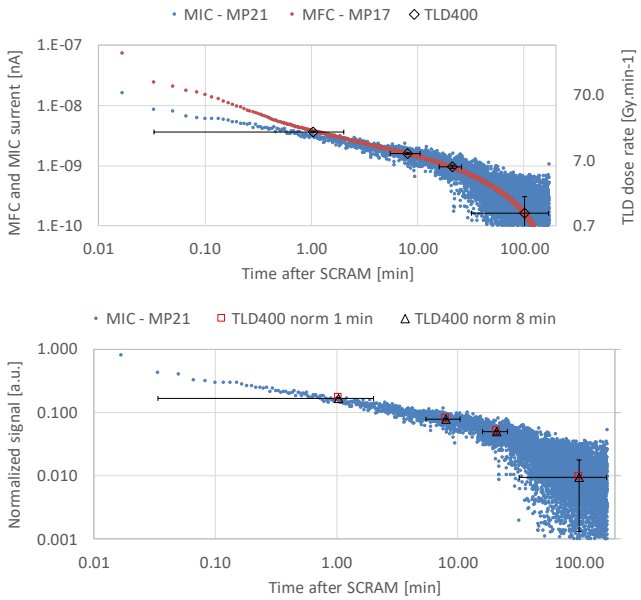

Fig. 4. Gamma and neutron signals decay after SCRAM. Top: MIC and MFC currents (left axis) compared to dose rates in the TLD400 (right axis). Bottom: comparison of the normalized MIC current and dose rates. Time uncertainties correspond to the time of dose integration for TLDs.

IV. Conclusion and outlooks

This study aimed at comparing measurements and calculations of dose rates in different irradiation positions of the JSI TRIGA reactor. Given the low number of measurements in each position, the preliminary analysis shows a qualitatively good agreement. This work should be continued by taking into account different correction factors for the measurement analysis, and by an additional effort in the experiment modeling. The TLD700 results are not presented since their readout protocol was not suited for such high integrated dose levels. Further study on the TLD700 readout protocol are to be performed, based on work on reading procedures for high dose measurement with LiF:Mg,Cu,P detectors [10]-[12].

This study emphasizes the complementarity between in-line and off-line techniques, and the interest of using TLDs for in-core dose monitoring due to their measurement range spanning over several orders of magnitude.

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