Validation of the Neutron and Gamma Flux Distributions in the JSI TRIGA Reactor Core

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ABSTRACT

Within the framework of the collaboration between JSI and CEA Cadarache, a series of on-line neutron and gamma flux distribution measurements in the JSI TRIGA reactor core was performed. CEA manufactured fission and ionization chambers were used in this experiment. Axial gamma flux and fission rate distributions were measured in special measuring positions between fuel element in, above and below the reactor core.

The measurements were compared with the Monte Carlo calculations using the JSI TRIGA MCNP5 model. The fission chamber response function in pulse mode operation was compared with the calculated fission rates, while the ionization chamber response in current mode was (after background subtraction) compared to the calculated gamma fluxes. Due to almost equal sensitivities to gamma rays, the fission minus ionization chamber response in current mode was also compared to the calculated fission rates. In general, the agreement is very good which provides additional proof of the quality of the computational model. A new set of measurements with fission chambers operated in Campbell mode (fully selective response to neutrons) will be performed in 2014 and will also append the available measurement database.

Apart from the validation of the TRIGA computational model, the main purpose of the experimental campaign is to determine the fission chamber response as a function of control rod positioning, which will later serve as a basis for reactor thermal power measurements.
1 INTRODUCTION

The TRIGA Mark II research reactor at the Jožef Stefan Institute (JSI) is extensively used for various applications, such as training and education [1], verification and validation of nuclear data, computational methods and computer codes [2], testing and development of experimental equipment used for core physics tests at the Krško Nuclear Power Plant [3] and irradiation of various samples. The latter activity related mainly to using the reactor as source of neutrons for use in nuclear analytical techniques, e.g. neutron activation analysis (NAA) [4], and as source of neutrons and gamma rays for irradiation of silicon detectors [5] and related radiation damage studies of detector material and of reading electronics for the ATLAS detector in CERN.

Optimal performance of the studies is often sensitive to the intensity and the shape of the neutron spectra at the points of irradiation. Nowadays such tailoring is commonly done with advanced computer codes, such as MCNP [6]. However, the computational model in such calculations should be thoroughly verified and validated with experiments. The first validation of the TRIGA Mark II computational model in MCNP was done by comparing the calculated $k_{eff}$ with the criticality benchmark experiment performed in 1991 [7], later published in the ICSBEP handbook [8]. In order to expand the utilization of the JSI TRIGA computational model, the model was validated in MCNP for reaction rate distribution [2].

Since 2010 many experiments (neutron spectrum characterization, in-core flux mapping with $^{235}$U and $^{238}$U fission chambers, $\beta_{eff}$ measurements) have been performed in collaboration with CEA Cadarache. The purpose of these experiments was on one hand to test neutron measurement methods and equipment and on the other hand to use the measured data for verification and validation of the computational model.

The use of CEA developed miniature fission chambers (FC) [9] and JSI developed moving mechanism [10] (“FC positioning system”) allowed measuring axial and radial neutron flux profiles, or to be more exact, fission rate profiles, with a spatial resolution of 1 mm. In contrast to the above mentioned reaction rate measurements in irradiation channels, that give information on flux profile on a plane only, the advantage of such a system is that enables full 3D neutron profile characterization.

In addition to neutron flux measurements, measurements of the gamma fields were performed as well. The information on the intensity of the gamma field in the reactor is especially important for applications such as radiation hardness studies [5]. The fission chambers were operated in pulse mode as well as in current mode. Special attention was devoted to background determination, linearity tests and dead time corrections.

2 JSI TRIGA REACTOR

2.1 Description

The TRIGA research reactor at JSI is a 250 kW TRIGA Mark II reactor. It is a light water pool type reactor, cooled by natural convection. The reactor core is of annular configuration with diameter of 44.2 cm and active fuel height of 38.1 cm. As shown in Fig. 1, there are 90 positions in the reactor core available for fuel elements, control rods, irradiation channels, etc., including two larger openings in the D-E rings. In the metal grid above the reactor core, there are 26 additional small holes, i.e. measuring positions 8 mm and 10 mm in diameter, enabling access from above the core. For example, fission and ionization chambers can be inserted in any of these positions to measure the neutron or gamma flux at any axial position in (and above/below) the reactor core.

In total there are four control rods (Fig. 1), however during normal operation only regulating (R) and compensating (C) rods are used while the pulse (P) and safety (S) rods are always completely...
withdrawn. As of 2014, the current excess reactivity is smaller than the integral worth of any control rod thus one control rod is sufficient to shut the reactor down.

![Diagram of reactor core positions](image-url)

**Figure 1:** Positions (A-F) in the reactor core including the small upper grid openings – measuring positions (MP) for in-core measurements.

### 2.2 Measurements

#### 2.2.1 Fission and ionization chamber design

The CEA manufactured miniature fission chambers (FC) were designed considering the operational constraints and the expected neutron flux in research reactors. CEA manufactured water-tight fission chambers with integrated mineral cable have a fissile deposit approximately 10 \( \mu \text{g} \) of 98.49 % enriched \(^{235}\text{U}\) [9]. FCs are nominally 3 mm in diameter and sensitive length approximately 4 mm. Mechanical parts are purchased from the PHOTONIS France SAS Company. Fissile deposits, detectors assembly and preliminary tests were performed in the CEA Cadarache facilities. The IC is mechanically identical to the FC but with no fissile coating [11].

Fission chambers are designed to be operated in the three possible modes: pulse, Campbell and current regarding the encountered neutron flux level and the associated signal acquisition system.

CEA manufactured fission chambers are all tested and absolutely calibrated in the MINERVE zero-power reactor at CEA Cadarache site. The used \(^{235}\text{U}\) reference FC is calibrated with an overall uncertainty of 1.4 %.

#### 2.2.2 Experimental setup

A FC was used to perform axial measurements (23 axial positions) of the fission rate along the complete core height at radial measurement positions MP5 and MP8 (Fig. 1). These measurements are used for verification and validation of our computational model as well.
The FCs were deployed into the reactor core by using a specially designed FC positioning system, composed of Al guide tubes, positioning system and data acquisition system. The axial positioning was ensured by an incremental system which measures the FC position relative to the reference position at the end of the guide tube. The accuracy of the FC positioning system was $\sim 0.1 \text{ mm}$ and the repeatability of the FC position was within 0.3 mm.

### 2.2.3 Measurements in the JSI TRIGA reactor core

When FCs are used in current mode, in addition to the contribution from (mostly thermal) neutrons the signal includes contributions of both prompt and delayed gamma flux. Most of the delayed gamma flux can be determined and later subtracted by performing zero-power measurements.

In pulse mode, the signals resulting from gammas are discriminated, enabling thus the measurement of neutrons almost exclusively. However, due to dead-time limitations, the FC may not operate in pulse mode at higher power levels. For the measurements in the centre of the core, the upper limit for using the pulse mode the reactor power is on the order of 1 kW.

An Ionization chamber (IC) with exactly the same geometry and material composition as the fission chamber has been used to determine also the prompt gamma response. The difference of the FC and IC signals should be sensitive only to neutrons. The problem of this combination is that it is required to perform the FC and IC measurements sequentially, which is not favourable for accurate online reactor power measurements, which is an objective, to which the present study serves as a basis. Due to their larger diameter, a possible location for online measurements with both FCs and ICs are the irradiation channels in the reactor core. For higher reactor powers the non-linear gamma contribution at a fixed position becomes negligible.

Because of (almost) symmetrical configuration of the core, the variations due to control rod movement in normal operation mode, when the compensating (C) and the regulating (R) rods are partially inserted, are the smallest in the central plane perpendicular to the R and C rods (Fig. 1). Measuring positions MP5 and MP8 have been chosen due to higher flux levels in the centre of the core.

All measurements were performed relative to the reactor online power monitoring signal $P$, which is performed using a compensating ionization chamber on the linear channel. For fixed positioning of the control rods, this signal is assumed to be reliable and is therefore taken as a reference. On the other hand, when comparing FC signals for different control rod positions, the power signal $P$ is corrected using MCNP calculated neutron flux redistribution factors [12].

### 2.3 Computational model

A detailed neutron spectrum and spatial flux distribution calculation has been performed using the Monte Carlo neutron transport code MCNP5 [6] and the ENDF/B-VII.0 [13] cross section library. A detailed 3D model of the JSI TRIGA reactor, has been developed in order to accurately calculate physical parameters of the TRIGA reactor. The main advantage of our computational model is that it has been thoroughly verified and validated with experiments.

For the calculations presented in this paper, the fission and ionization chambers have not been modelled explicitly since it has been assumed that the impact on the signal due to the neutron interactions with the fission chamber and its guide tube is independent of FC position. Previously, the perturbation of the thermal neutron flux due to FC and guide tube has been estimated to be of the order of 2% [12]. Self-shielding in the active part of the fission chamber is negligible.
3 RESULTS

3.1 Power range determination of the fission chamber

One of the objectives of this investigation is also the determination of the power ranges, where the signal from the fission chamber is accurate and reliable. In future, reactor power measurements with multiple fission chambers positioned at different locations in the reactor core, are considered [14]. Using an optimized system with multiple detectors, the accuracy of the online power monitoring system can be significantly improved compared to the existing system, in which a single ex-core large compensating ionization chamber is used. Secondly, the multiple-detector system could be used for multiple-point-reactor kinetics studies. With these far-lying objectives in view, the detector responses in both current mode (also applicable to ionization chamber) and pulse mode were studied.

3.1.1 Current mode

In current mode, the operation power range of the FC is limited by the (non-linear) contribution of delayed gammas. In order to determine the lower limit, linearity of the FC response in current mode has been studied. The FC response has been measured in measuring position MP26 approximately in the centre of the active fuel height. There is almost perfect linearity of the signal down to around 10 W under the condition of well-known zero-power background contribution.

Consequently the current mode may be used from about 10 W in combination of background determination before start-up under the condition that the reactor did not operate at high power (above \( \sim 10 \text{ kW} \)) in the last couple of 10s of hours. In case the reactor recently operated at higher power, the current mode is completely reliable only above \( \sim 1 \text{ kW} \).

3.1.2 Pulse mode

In pulse mode, the operation power range of the FC is limited on the lower side by count rate and statistics requirements, and on the upper side by the electronics setup performances (dead-time, etc.).

The approximate count rate of the FC in the centre of the measuring position MP8 is 260 s\(^{-1}\)W\(^{-1}\). For example, if the target accuracy of the recorded number of counts is 1 % or a counting time of 1 s, the lower operation limit for FCs is approximately 40 W. For lower power levels, more sensitive fission chambers with higher fissile material mass would have to be used.

Fig. 2 (left side) shows the response of the FC (in count rate \( C \)) in pulse mode as a function of reactor power. In the centre of the measuring position MP8 (similarly for MP5) the deviation from linearity becomes significant at around 20 W. The dead-time corrected count rate \( C_{\text{corr}} \) can be expressed as

\[
C_{\text{corr}} = \frac{C}{1 - t_{DT} C},
\]

where \( t_{DT} \) is the dead-time of the electronics and \( C \) is the measured count rate.

Assuming proportionality of the corrected count rate \( C_{\text{corr}} \) to the reactor power \( P \), the dead-time corrected function has been fitted (Fig. 2 - left side) to the data; and the fitted dead-time of the electronic setup was \( t_{DT} = 4.69 \mu s \pm 0.04 \mu s \). The uncertainty of the dead-time has been obtained by random sampling of the measured count rate within their uncertainties assuming Poisson statistics and performing non-linear fit of \( t_{DT} \) for each sample.

However, at higher power levels the signal starts to significantly deviate even from the standard dead-time corrected function (Fig. 2 - left side). We assume that at higher count rates the pulses start...
to superpose, i.e. they are piling up which results in the inability of the system to take into account new coming pulses during this extended dead-time. This can also be interpreted as an “effective dead-time” increase at higher power levels (above $\sim 1 \text{ kW}$).

By applying the dead-time correction, the count rate linearity is extended to significantly higher powers (Fig. 2 - right side). The linearity of the dead-time corrected count rate is within $\sim 1\%$ up to 300 W.

![Figure 2: Measured fission chamber count rate $C$ as a function of reactor power $P$ (black points) with fitted dead-time corrected response function (line) on the left side and on the right side with dead-time corrected count rate $C_{\text{corr}}$ (red) as a function of reactor power $P$ (points) and corresponding fitted dead-time corrected and linear response functions (dashed and solid line, respectively). FC located in measuring position MP8 slightly above the centre of the active fuel height (301.8 mm above the lowest axial point).](image)

3.2 Gamma background at zero power

When the reactor was in shutdown condition, the axial distribution of the gamma background has been measured in position MP5 using both the fission and ionization chambers. In such state, the response of the FC and IC was expected to be equal in first approximation due to the negligible contribution of the neutrons and the same geometry of both detectors. Indeed the shape of the axial distributions is practically equal, however slightly shifted. The difference in “zero current” of approximately 0.1 nA is presumably due to a different current offset (i.e. different leaking currents) between the two detectors due to different insulating resistances ($1.6 \text{T}\Omega$ for FC and $28 \text{T}\Omega$ for IC).

Due to equal sensitivity to photons, the pure sensitivity of the FC to neutrons can be estimated by subtracting the response of the IC from the measured FC response and taking into account the “zero current” correction. The measured “zero current” is approximately 0.13 nA.

3.3 Axial gamma and neutron flux distributions

MCNP is capable of simulating the transport of prompt gamma rays, only. The axial distribution of the delayed gamma ray flux (originating from the decays of fission and activation products) is different, however it roughly follows the same (cosine) shape. Therefore, at higher power levels (above 10 kW) the total gamma distribution (measured by IC) becomes similar to the prompt gamma
distribution (MCNP calculated) even though the delayed gamma contribution remains in the order of a few %. This effect is shown in Fig. 3.

Figure 3: Comparison of the calculated (solid curve) axial prompt gamma flux distribution with the measured total gamma flux distributions at different reactor power levels (dashed and dotted curves). Measuring position MP5. All distributions are normalized to the variance-weighted average over the total axial range.

Axial distributions of the fission reaction rates were measured using CEA manufactured fission chambers at the measuring positions MP5 and MP8 in the JSI TRIGA reactor core in current and pulse mode.

Fig. 4 shows the axial fission rate distribution in measuring positions MP5 and MP8 for fully withdrawn compensating rod and regulating rod at the critical position (around step 580). The axial distribution in current mode (at 100 W) systematically deviates from the calculated axial distribution due to the contribution of the gamma rays which are not taken into account in the simulation. The agreement between the calculated and measured distributions in pulse mode is generally relatively good, especially taking into account the age of the JSI TRIGA reactor and relatively scarce information on reactor geometry and material composition. This result further validates the computational model and will serve as a basis for further applications such as the characterization of the neutron and gamma fields thermal column and dry chamber which can be used for neutron irradiation of larger objects and will improve the overall utilization of the reactor.

In the next step, the sensitivity of the fission chamber response to control rod movement will be determined (both experimentally and by simulation) and the feasibility of installation of a more accurate online power monitoring system will be studied.

4 CONCLUSIONS

Linearity of the CEA manufactured miniature fission chamber response has been confirmed in the current and pulse mode, and suitable power intervals in the chosen measurement positions of the JSI TRIGA reactor core have been determined. Neutron and gamma flux distributions have been determined in the JSI TRIGA reactor core. The measured axial gamma field and fission rate
Figure 4: Relative $^{235}\text{U}$ fission rates as a function of axial position $z$ of the fission chamber in measuring positions MP5 (left) and MP8 (right). In MP5, the measurements were performed both in current and pulse mode of the fission chamber. The discrepancy of the current mode is due to a significant contribution of photons to the measured current. All distributions are normalized to the variance-weighted average over the total axial range.

...distributions have been compared with MCNP calculated distributions. In general, the agreement is very good providing additional validation of the existing Monte Carlo model of the TRIGA reactor.

An online power monitoring system using multiple in-core fission chambers, which have been studied in this work, is considered at the JSI TRIGA reactor. In order to achieve this goal, the response of the detectors as a function of control rod movement will be studied in immediate future in the frame a new bilateral collaboration project with CEA Cadarache. Simultaneous measurements with multiple identical fission chambers will be performed using a CEA recently developed FC acquisition system operating simultaneously in pulse and Campbell mode over a wide reactor power range [15]. Finally, the system will be adapted and constructed for routine operation in the JSI TRIGA reactor.

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