Annals of Nuclear Energy 111 (2018) 407–440

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

# Evaluation of neutron flux and fission rate distributions inside the JSI TRIGA Mark II reactor using multiple in-core fission chambers

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ARTICLE INFO

*Article history:*
Received 21 April 2017
Received in revised form 4 August 2017
Accepted 10 August 2017

*Keywords:*
TRIGA research reactor
Fission chamber
MCNP
Multiple in-core detectors
Control rod movement
Neutron flux redistribution

ABSTRACT

Within the bilateral project between the CEA Cadarache and the Jožef Stefan Institute (JSI) a wide variety of measurements using multiple fission chambers simultaneously inside the reactor core were performed. The fission rate axial profiles were measured at different positions in the reactor core and at different control rod configurations. A relative comparison of the calculated fission rates using the MCNP code and the measured fission rates was performed. In general the agreement between the measurements and calculations is good, with the deviations within the uncertainties. For better observation and understanding of the neutron flux redistribution due to the control rod movement, the neutron flux and fission rate had been calculated through the entire reactor core for different control rod configurations. The detector position with minimum signal variations due to the regulating and compensating control rod movement during normal operation was determined. The minimum variation is optimal in case we want to reliably determine the reactor power without influence of the regulating and compensating control rod positions.



## 1. Introduction

The TRIGA Mark II reactor in Ljubljana (Snoj and Smodiš, 2011) is a 250 kW light-water, pool type research reactor cooled by natural convection. Similarly as other research reactors (Aghara and Charlton, 2006; Jonah et al., 2006; Merz et al., 2011), its primary purpose is education and training (Snoj et al., 2011a) of students and future reactor operators. The TRIGA research reactor in Ljubljana is also used for a wide variety of other activities, such as: verification and validation of nuclear data and computer codes (Snoj and Ravnik, 2008; Snoj et al., 2011b; Trkov et al., 2009) or irradiation of various samples (Kovačević et al., 2010). Due to the very well characterized neutron and gamma fields it is lately extensively used as source of neutrons and gammas for use in nuclear analytical techniques, e.g. neutron activation analysis (Radulović et al., 2013), irradiation of silicon detectors (Cindro et al., 2009; Kramberger et al., 2010), radiation damage studies of detector material and of reading electronics for the ATLAS detector in CERN (Kramberger et al., 2007) and irradiation of $SiO_2$ nano-materials for space applications (Huseynov et al., 2015a; Huseynov et al., 2015b; Huseynov et al., 2015).

This research was carried out within the collaboration between the CEA Cadarache and the Jožef Stefan Institute (JSI), to improve the accuracy of the current on-line power monitoring system at the JSI TRIGA reactor. In small research reactors such as TRIGA, the neutron flux profile inside the reactor core changes significantly in the axial and radial direction (Chiesa et al., 2015; Lin et al., 2006; Meftah et al., 2006; Stamatelatos et al., 2007; Štancar et al., 2012; Štancar et al., 2015; Žerovnik et al., 2015). The major effect of the neutron flux redistribution is due to the control rod movement. The neutron flux redistribution affects the power readings of a current ex-core power monitoring system (Štancar et al., 2017). In previous research (Kaiba et al., 2015) the evaluation of a single in-core fission chamber (FC) and a search of optimal detector position in individual measuring positions were performed. In this paper the previous research was upgraded by performing measurements with multiple in-core FCs simultaneously. Using multiple in-core detectors gives a possibility to average out the dependence of the detector signal on the control rod position (Žerovnik et al., 2014a). This paper presents measurements of full axial profiles that were performed at different control

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http://dx.doi.org/10.1016/j.anucene.2017.08.017
0306-4549/

rod positions. This enables extraction of a broad range of useful information, from axial neutron flux profiles to the evaluation of the neutron flux redistribution due to the control rod movement. In general measurements are in good agreement with the Monte Carlo neutron transport code MCNP calculations (Goorley et al., 2012). In further research the neutron flux and fission rate have been calculated across the entire reactor core using the MCNP code. In search for an optimal detector position inside the reactor core the change of the detector signal due to the control rod movement, represented by the $\chi^2$ value for the calculated neutron flux and fission rate, has been visualized.

The paper is structured as follows. In Section 2 the JSI TRIGA Mark II research reactor, computational model, fission chamber design and experimental set-up are described. In Section 3 different measurements and comparison with calculations are presented. The comparison of axial profiles at different radial positions and for different control rod configurations is presented. Within this section also the comparison of the detector signal at different axial and radial positions as a function of the control rod configuration is shown. In Section 4 the visualization of the calculated fission rate and the neutron flux profiles with calculated $\chi^2$ as a function of the FC position through the entire reactor core is represented.

## 2. JSI TRIGA reactor

The TRIGA Mark II reactor at the JSI is a 250 kW light-water, pool type research reactor, cooled by natural convection.

Power monitoring is performed with five independent neutron detectors covering the entire operational range from start up in mW range to pulse mode operation up to 1 GW. They are called start-up, linear, logarithmic, safety and pulse channel (see Fig. 1). Start-up channel contains a fission counter, linear and logarithmic channel have compensated ionisation chambers, while safety and pulse channel contain uncompensated ionisation chambers. These detectors are located outside the reactor core and enable continuous neutron flux measurements. The ex-core detectors can be used to determine the reactor power with 2% uncertainty (Štancar et al., 2017). The detectors are placed on the bottom of aluminium tube-like instrumentation chambers, approximately from 23.3 cm to 44.4 cm above the core mid plane. The instrumentation chamber is 67.3 cm high and has an outer diameter of 11.4 cm. The reactor core configuration with the ex-core detector channels is shown in Fig. 1.

The reactor core has a diameter of 44.2 cm and active fuel height of 38.1 cm. There are 91 positions inside the reactor core available for positioning of fuel elements, control rods, irradiation channels, etc. and are shown in Fig. 1. Miniature FCs can be located in the additional 26 holes in the metal grid above the reactor core. These measuring positions (MP) enable measurements of the neutron flux in any axial position and have different diameters (10 mm and 8 mm).

There are 4 control rods inside the reactor core. In normal operation only regulating (R) and compensating (C) control rods are partially inserted and pulse (P) and safety (S) control rods are always fully withdrawn. R, C and S control rods consist of two parts. The lower part contains fuel, while the upper part contains a strong neutron absorber $B_4C$. When control rods are inserted, the upper part with neutron absorber is inside at the active fuel height and the opposite when rod is withdrawn. Pulse control rod features an air follower instead of the fuel follower in the lower part. Relation between the rod steps and actual position in the core (in cm) (Merljak, 2013) are presented in Table 1.

### 2.1. Computational model

Calculations were performed with the Monte Carlo neutron transport code MCNP6 (Goorley et al., 2012) and the nuclear data library used in the calculations was ENDF/B-VII.1 (Chadwick et al., 2011). A full 3D JSI TRIGA reactor model used in calculations is based on the criticality benchmark model (Jeraj and Ravnik, 1999) which is thoroughly described in the International Handbook of Evaluated Criticality Safety Benchmark Experiments (ICSBEP, 2009). Our computational model has been expanded, verified and validated by many experiments for different calculations: the effective multiplication factor $k_{eff}$ (Ravnik and Jeraj, 2003),

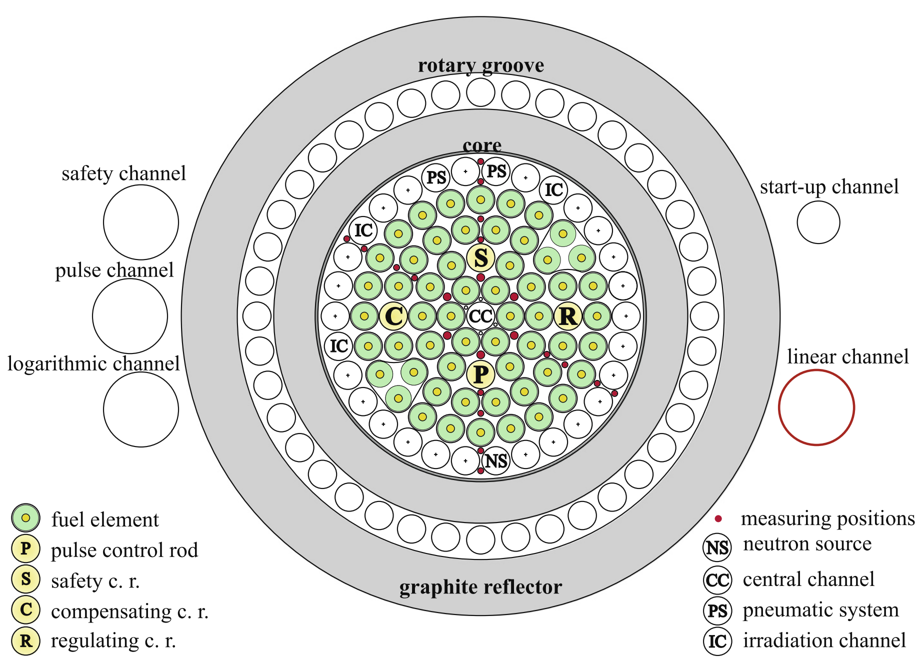


**Fig. 1.** Reactor core configuration with current neutron detector locations: safety, pulse, logarithmic, start-up and linear channel. Control rods are denoted as safety (S), pulse (P), compensating (C) and regulating (R). Measuring positions inside reactor core are presented with red dots. (Figure was contributed by Žiga Štancar from Jožef Stefan Institute. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)