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Computational validation of the fission rate distribution experimental benchmark at the JSI TRIGA Mark II research reactor using the Monte Carlo method

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ABSTRACT

A fission rate profile benchmark experiment has been performed at the Jožef Stefan Institute TRIGA Mark II reactor. The measurements were made using absolutely calibrated miniature fission chambers developed and manufactured by the Commissariat à l'Énergie Atomique et aux Énergies Alternatives. The aim of the paper is to describe the experimental set-up, fission rate measurements and to present the detailed Monte Carlo computational model of the TRIGA reactor, which was constructed with as used to compute absolute fission rate distributions in the core at a fixed control rod position, taking into account the detailed description of the experimental configuration. The paper focuses on the extensive evaluation of experimental and calculational uncertainties and biases following the International Reactor Physics Experiment Evaluation Project methodology. A comparison between the measured and computed absolute reaction rates concludes the paper, with the agreement being within one sigma standard uncertainty.

1. Introduction

The utilization of advanced Monte Carlo neutron transport codes for reactor core calculations has increased significantly in the past years, generating a need for their experimental verification through the use of evaluated benchmark experiments. At the Jožef Stefan Institute (JSI) Reactor Physics Department a detailed Monte Carlo geometric model of the TRIGA Mark II research reactor has been developed using the state-of-the-art Monte Carlo N-Particle Transport code (MCNP) (Goorley et al., 2014) The reactor model is used on a regular basis, providing a computational tool for the determination of crucial physical parameters of the reactor core such as the effective multiplication factor (Jeraj and Ravnik, 2010) neutron flux and reaction rate distributions (Snoj and Ravnik, 2006; Snoj et al., 2011; Radulović et al., 2014) reactor kinetic parameters (Snoj et al., 2010) and dose rate estimations. Moreover Monte Carlo calculations provide the computational support which is fundamental for an array of research activities, varying from design and optimisation of experimental campaigns, safety assessments of reactor modifications (Snoj and Ravnik, 2008) to evaluations of results, experimental uncertainties and biases.

The aim of the benchmark experiment, performed at the JSI TRIGA Mark II reactor, was to measure in-core fission rate distributions and perform an extensive evaluation of experimental and computational uncertainties. The results can then serve the purpose of validation of neutron transport codes, nuclear data to researchers worldwide. In the experiment specially designed miniature fission chambers developed by the Commissariat à l'Énergie Atomique et aux Énergies Alternatives (CEA) were used (Barbot et al., 2013). The fission chambers were inserted into the core of the TRIGA reactor by using aluminium guide tubes, which enabled accurate radial positioning of the fission chambers and measurement of axial fission rate profiles at multiple radial positions at a fixed control rod configuration. In the next step a Monte Carlo computational benchmark model of the reactor and the experiment configuration was constructed, which served the purpose of calculating the reaction rate distribution inside the core of the reactor and most importantly evaluating the experimental and computational uncertainties together with major benchmark model biases, following the meticulous IRPhEP (International Reactor Physics Experiment Evaluation Project) methodology. Detailed

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investigations into uncertainty sources like fuel composition, axial and radial positions of the fission chambers, core temperature effects and control rod position were made in addition to evaluating the effect of fuel burn-up and computational model geometric biases. A comparison of the measured and calculated fission rate profiles was made and a relatively good agreement between the two sets of data was found, with average relative discrepancies being within one sigma standard uncertainty.

The additional value of the benchmark experiment results and subsequent uncertainty analysis is in the fact that the fission rates, both measured and computed, are in absolute values. This means that the evaluation results can serve the purpose of testing and verifying the innovative design of the absolutely calibrated miniature fission chambers (Kaiba et al., 2015), as well as help validate the values of basic reactor parameters, such as the multiplication factor, power and neutron flux distribution etc. These are needed for the normalization of raw results of Monte Carlo neutron transport calculations (Žerovnik et al., 2014), and experiment methodologies (Štancar and Snoj, 2017). Experiments benchmarking absolute reaction rate values are scarce and are of high value for the reactor physics community. This was also recognized with the inclusion of the experiment into the International Reactor Physics Experiment Evaluation Project Handbook (Štancar et al., 2017), making it the first publicly available axial fission rate benchmark experiment with evaluated experimental uncertainties for TRIGA type reactors. Whilst the experiment was performed for a fixed position of the control rods, future investigations into the effect of control rod configuration on the neutron flux redistribution and ex-core power detector response will be made.

2. The Slovenian TRIGA Mark II research reactor

The JSI TRIGA Mark II reactor is a pool type light water research reactor, with a maximum steady state power of 250 kW. The core is submerged into a 6.25 m high and 2 m wide aluminium pool filled with water and has an annular configuration. It consists of six concentric rings, where cylindrical fuel rods with stainless steel cladding are positioned. The fuel material is a homogeneous mixture of U-ZrH with 12 wt% of 20% enriched uranium. The core itself is composed of two 1.9 cm thick aluminium supporting grids in which holes of different diameters are drilled. These serve the purpose of positioning the fuel elements, control rods and additional in-core experiments. In total there are 91 locations for fuel elements and additional 26 smaller holes, 9 of which were used for the insertion of the fission chambers. A schematic top view of the upper support grid of the reactor together with a photograph of the core are shown in Fig. 1. The core is surrounded by an annular graphite reflector which contains the rotary specimen rack. On the outside of the graphite reflector five ex-core nuclear channels are positioned, which consist of neutron and gamma detectors utilized for reactor thermal power measurement. Each of the five channels has an individual power measuring interval based on the sensitivity of the detector. At steady-state reactor operation the power is commonly determined using the linear channel, which is denoted with a red circle in Fig. 1. The nuclear detectors are periodically calibrated with a recently developed calorimetric calibration method using electrical heaters (Štancar and Snoj, 2017), which enables a thermal power estimation with 2% uncertainty.

3. Miniature fission chambers and experiment configuration

The aim of the experiment was to measure fission rate distributions in the core of the TRIGA reactor, therefore the type of the detector to be used was chosen on the basis of several operational

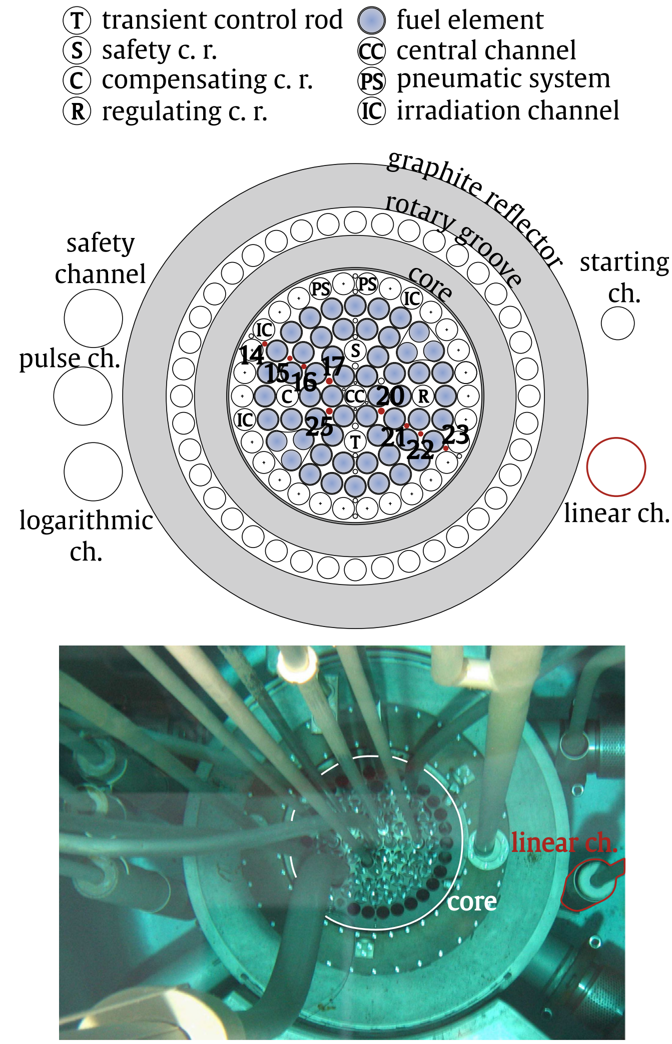

Fig. 1. Schematic top view and a photograph of the reactor upper support grid with denoted fuel elements, control rods and measuring positions used for in-core fission chamber insertion.

constraints and expected neutron flux. The identified detector was a watertight miniature fission chamber (FC) connected to an integrated mineral cable, which was designed, manufactured and absolutely calibrated by CEA (Barbot et al., 2013). The detectors structure material was made of stainless steel, with Al_2O_3 acting as an electric insulator. The fission chambers were filled with a gaseous mixture of argon and nitrogen. They had a cylindrical shape with a 3 mm diameter which can be seen in Fig. 2. In the experiment two different fission chambers were used, which differed in the type and amount of fissionable material deposited on the walls of the active part – one with a fissionable coating composed mainly of ^{235}U and the other of ^{238}U. The material composition of each of the two types of fission chambers is presented in Table 1.

The signal at the output of the detector, resulting in current pulses, can be processed in several modes, depending on the measured fission rates (proportional to neutron flux). The fission chambers can thus operate in *pulse mode* at low fission rates, i.e. when individual pulses can be separated, *fluctuation (Campbell) mode* at intermediate fission rates, i.e. when pulses are starting to overlap (useful signal is the variance of the current) and the *current mode* at high fission rates, i.e. when pulses are piled up (useful signal is the average of the current). These modes allow the FCs to operate over a wide neutron flux range from 10^5 neutrons cm^{-2} s^{-1} to