

Advances in utilisation of the JSI TRIGA Mark II reactor

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Abstract. The TRIGA Mark II research reactor at the Jožef Stefan Institute (JSI) in Ljubljana Slovenia has been playing an important role in developing nuclear technology and safety culture in Slovenia. It has been extensively used mainly used for various applications, such as: irradiation of various samples, training and education, verification and validation of nuclear data and computer codes, testing and development of experimental equipment used for core physics tests at a nuclear power plant. The paper describes the latest advances in the utilisation of the JSI TRIGA Mark II reactor, that is new benchmark experiments, new pure gamma irradiation facility and new practical exercises.

Key Words: TRIGA, utilization, radiation hardness, benchmark.

1. Introduction

The TRIGA Mark II reactor at the Jožef Stefan Institute (JSI) is regularly used for Neutron activation analysis (NAA) in both instrumental (INAA) and radiochemical (RNAA) modes, radiation hardness studies, training of nuclear power plant (NPP) staff and education of university students, and for benchmark experiments for validation of computer codes and nuclear data. In the last 5 years the scientific level as well as the intensity of these activities has increased significantly.

The reactor has been extensively used for irradiation of various components to study radiation hardness for the ATLAS detector in the European Organisation for Nuclear research (CERN) and other accelerators under the Advanced European Infrastructures for Detectors and Accelerators (AIDA) framework, for ITER and for some companies producing radiation tolerant products. Due to very good characterization of the irradiation facilities the reactor has become a reference centre for neutron irradiation of detectors developed for the ATLAS experiment.

Due to large flexibility and well defined irradiation condition the irradiation facility has recently been developed, which allows irradiation in a well thermalized (99.8 % of total neutron flux is thermal) neutron flux. In collaboration with the Commissariat à l'énergie atomique et aux énergies alternatives / direction des applications militaires (CEA) CEA/DAM Ile de France the facility is used for performing neutron irradiation of materials used for control of non-proliferation in nuclear safeguards by using the Fission Track-Thermal Ionization Mass Spectrometry (FT-TIMS) method.

In 2010 a collaboration with CEA Cadarache Instrumentation, Sensors and Dosimetry Laboratory was established leading which lead to several experiments of benchmark quality; fission rate profile measurements, neutron dosimetry and spectra measurements, beta-effective measurements, gamma profile measurements, self-powered neutron and gamma measurements. These experiments were used for validation of computer codes and nuclear data and lead to better characterisation of irradiation conditions. In addition several CEA-developed detectors and data acquisition systems were tested within the collaboration.

In the field of education and training the reactor is used in regular laboratory exercises for graduate and post graduate students of physics and nuclear engineering at the Faculty of Mathematics and Physics, Ljubljana University and for training of operators at the JSI Nuclear training Centre. Since 2010 new advanced practical exercises for students and course attendees were designed and implemented; void reactivity coefficient measurements, the measurement of water activation, in-core flux mapping system, pulse mode operation, etc.

The purpose of the paper is to present the latest achievement in utilisation of the JSI TRIGA Mark II reactor.

2. Radiation Hardness studies

Since 2001 the reactor has been extensively used for irradiation of various materials with both neutrons and gamma rays. One of important activities is the testing of components for the ATLAS detector, composed of Si detectors for tracking particles in CERN (0[2]). The detector is intended to study proton-proton interactions at the Large Hadron Collider (LHC) at CERN. As the lattice damage within the detector introduced by heavy particles limits its use due to decreased performance, a program devoted to radiation resistance of Si detectors was established. For irradiating the samples in the TRIGA reactor, a dedicated relatively large “triangular” channel (6 cm in diameter) was constructed, allowing for testing radiation damage of full size Si detectors along with the associated electronics, at different temperatures by installing a heating/cooling module inside the channel. Due to well characterized irradiation channel the JSI TRIGA reactor has become an unofficial global reference center for such detectors irradiation. Furthermore, the reactor has been included into the AIDA II (Advanced European Infrastructures for Detectors and Accelerators) project [3] funded by the Horizon 2020 of the European Commission. About 2,000 samples of this kind are irradiated yearly for users such as CERN, DESY (German Electron Synchrotron) and KEK (High Energy Accelerator Research Organization, Japan), as well as for various universities and institutes. Major disadvantage of the triangular channel is limited size. Hence in May 2015 a project was initiated, within the AIDA II, to establish irradiation facility for larger samples, i.e. up to 15 cm in diameter. So called tangential channel passing the graphite reflector just next to the reactor core was chosen for this purpose. It features total neutron flux of $1.3 \text{ E}12 \text{ n/cm}^2\text{s}$ [4]. This modification will significantly expand irradiation capabilities and enable irradiation of complete systems instead of just individual electronic components.

In the last year the activities in the field of radiation hardness studies were expanded by collaboration with industrial partners. In collaboration with the Slovenian company Dito lighting [5] irradiation and testing of radiation hard LED lighting to be used in high radiation areas, such as particle accelerators, hot cell facilities, containment in nuclear power plants, etc was performed. First radiation hard product (High bay lamp) is to be released in November 2015. In addition new generation of cameras for radiation environments are developed in collaboration with the Swedish company ISEC [6], supplier of monitoring systems for facilities with ionizing radiation. During the research and development process of the above items it was decided to test them in mixed (neutron + gamma) and pure gamma field separately. Pure gamma irradiation was performed by using irradiated nuclear fuel as the gamma source and custom made submersible Al box (30 cm × 20 cm × 20 cm) for housing the electronic components under water. In such way, the irradiation of components can be performed online that is during their operation. The dose rate in such device is approx. 100 Gy/h. During the testing the accumulated dose is measured with RADFET (radiation sensing field-effect transistor) detectors, time dependent dose rate however is measured with gas flow ionization chamber.

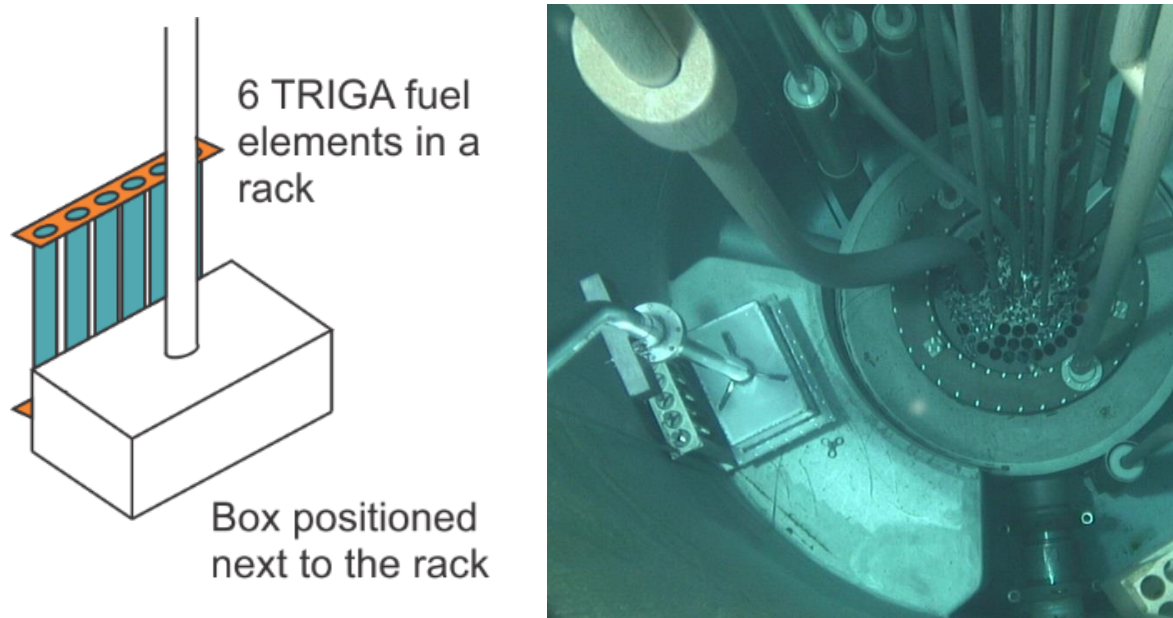


Figure 1: Gamma irradiation device at the JSI TRIGA reactor, schematic (left), photo (right).

3. Support to nuclear safeguards

In the framework of environmental monitoring control for non-proliferation in nuclear safeguards, CEA/DAM Ile de France has developed an ultra-sensitive analytical technique to detect traces of uranium and plutonium in micrometric particles. The FT-TIMS analysis [7] requires irradiation of the samples under well-thermalized neutron flux. The irradiations are currently performed at the Orphée reactor located in CEA Saclay (France).

The number of fission tracks left by a particle is directly linked to the number of fissile atoms and to the thermal fluence. A high thermal fluence, at least 10^{15} neutrons/cm², is required to detect submicron fissile particles. Moreover, the percentage of fast neutrons must be very low, in the range of 0.01 %. It has been observed that fast neutrons damage Lexan® and penalize the fission tracks observation. Consequently, particles can no longer be located and micromanipulated precisely. The last parameter concerns the irradiation channel dimensions. Particles from one swipe sample are deposited on 30 Lexan® disks and stacked inside a polyethylene rabbit tube, the dimensions of which are 13.3 cm × 3.3 cm. One rabbit tube thus contains the equivalent of two samples. Therefore the size of the irradiation position should be sufficient for at least one rabbit tube.

In collaboration with the CEA, an irradiation device in the TRIGA reactor was developed for the needs of CEA in terms of irradiation capacities for the FT-TIMS method. This development and design have been performed by using the combination of advanced methods

for Monte Carlo transport of neutrons and photons (e.g. MCNP) and experiments like foil activation analysis [8].

The irradiation device, filled with heavy water, was designed and optimized inside the Thermal Column and the additional moderation was placed inside the Elevated Piercing Port. The use of the device improves the ratio of thermal neutron flux to the sum of epithermal and fast neutron flux inside the Thermal Column Port by 390% and achieves the desired thermal neutron fluence of 1015 neutrons/cm² in irradiation time of 20 h.

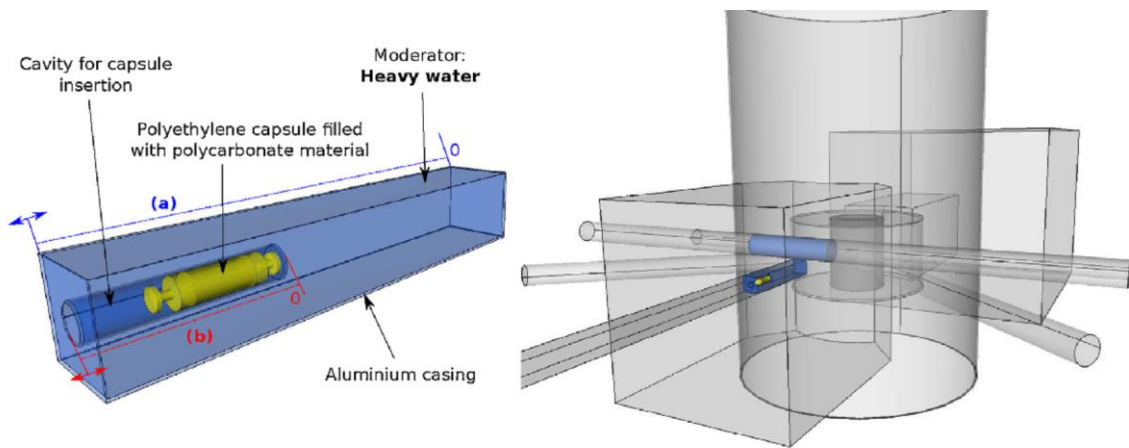


Figure 2: 3D model of the irradiation device filled with heavy water and with an opening for the polyethylene capsule that contains polycarbonate disks. The schematic drawing on the right shows the position of the irradiation device with respect to the reactor core [8].

4. Benchmark experiments

A number of well-defined and carefully designed experiments have been performed aimed at establishing a set of benchmarks for the TRIGA reactors. The performed experiments have been thoroughly analyzed and the experimental uncertainties evaluated using the most advanced Monte Carlo neutron transport codes such as MCNP, the Monte Carlo N-Particle Transport Code [9]. The criticality experiments carried out in 1991 have been thoroughly evaluated and are now included in the International Criticality Safety Benchmark Evaluation Project (ICSBEP) handbook [10]. They present the world-unique reference case for criticality calculations with the UZrH fuel.

In 2010 a collaboration was established between the CEA and the JSI. Since then several experiments of benchmark quality have been performed such as: axial fission rate (²³⁵U and

^{238}U) profiles [11], axial Au (n,g) rate profiles [12], gamma field in the core [13] [14], core kinetic parameters [15]. It is interesting to note that reaction rate profiles measurements were performed in relative and on absolute scale, hence they can be used for validation of normalization methods [16]. In addition fission rate axial profiles have been measured at various control rod position [17] thus providing benchmark experiment for validation of neutron flux redistribution effects. Some examples are given below.

In 2016 we plan to perform on-line neutron spectrum measurements by simultaneously using three fission chambers with different fissile deposits (U, Pu, Np) and under different neutron absorbers (B,Cd, Gd). In 2017 we plan to perform detailed gamma field characterization in and outside the reactor core at different power levels, from zero to full power. The measurements will be performed with ionization chambers, TLD and OSL dosimeters, gamma calorimeters, RADFETs. These measurements will serve for validation of gamma ray production codes, such as FISPACT.

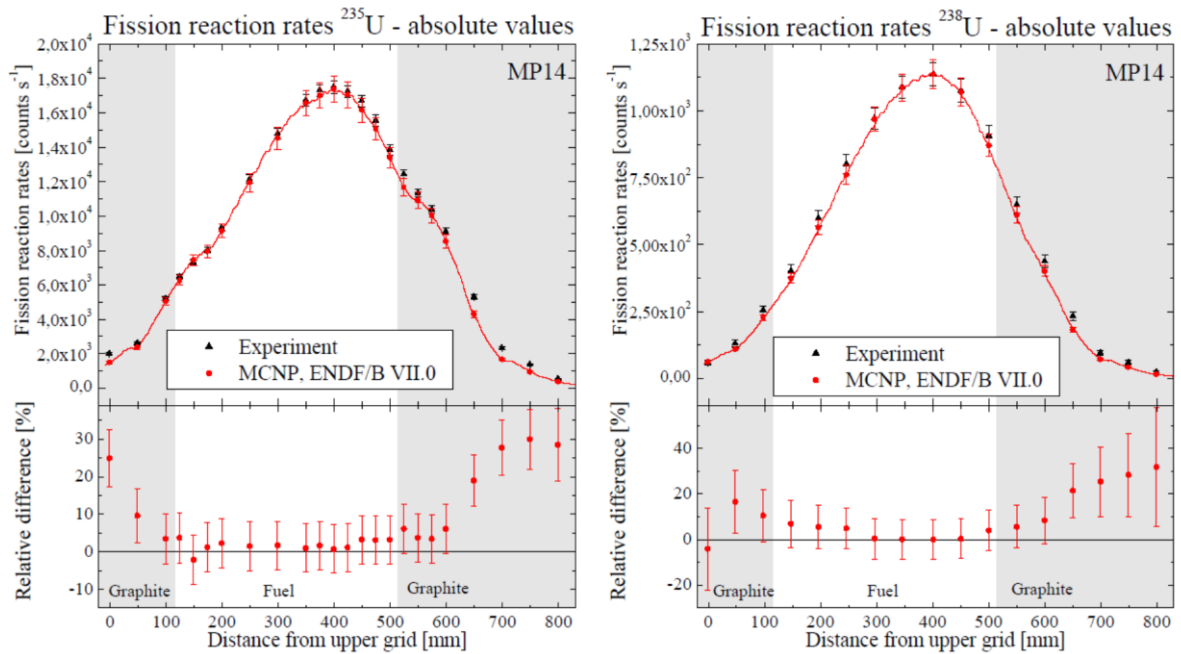


Figure 3: Comparison and relative discrepancies between the measured and calculated axial profiles of fission reaction rates with estimated uncertainties for the ^{235}U (left) and ^{238}U (right) fission chamber at measuring position 14 in the reactor core [11].

5. Education and training

Since the 1990s the Jožef Stefan Institute (JSI) TRIGA reactor has been extensively used for performing training in experimental reactor physics for students at Slovenian Universities, for NPP operators as well as for international training courses such as the EERRI course [18]. IN 2012, after the fission rate profile measurements with CEA, the system was slightly simplified

in order to use it for practically exercises for trainees and students. In addition we upgraded some of the existing and introduced some new exercises [19].

The pulse mode operation exercise was upgraded by installation of new data acquisition system. The critical experiment exercise was improved by adding a new detector inside the reactor core and changing the data acquisition system. Now neutron population is monitored with two independent fission chambers on different locations. In the past the void reactivity coefficient exercise was performed by inserting Al tube into various positions in the reactor core and measuring the corresponding reactivity changes. In order to make the exercise more realistic, a pneumatic system for generating air bubbles just below the core was installed. The aim of the exercise is to measure reactivity changes versus flow rate and air bubble position (Figure 5). The second new exercise was measurement of water activation. In this exercise special system which pumps the water through the core at a constant flow rate to the reactor platform, where the water activity is measured was installed. The purpose of the exercise is to measure the ^{16}N and ^{19}O gamma line intensity and dose rate versus reactor power. The third new exercise, named in core flux mapping, was performed by measuring the axial fission rate distribution at various radial positions in the core. The CEA – developed mini fission chambers and a special home developed system for moving the fission chamber in axial direction and measuring the count rate versus fission chamber position was used. Majority of the exercises are now controlled and monitored by using LabVIEW user interface on personal computer or laptop.

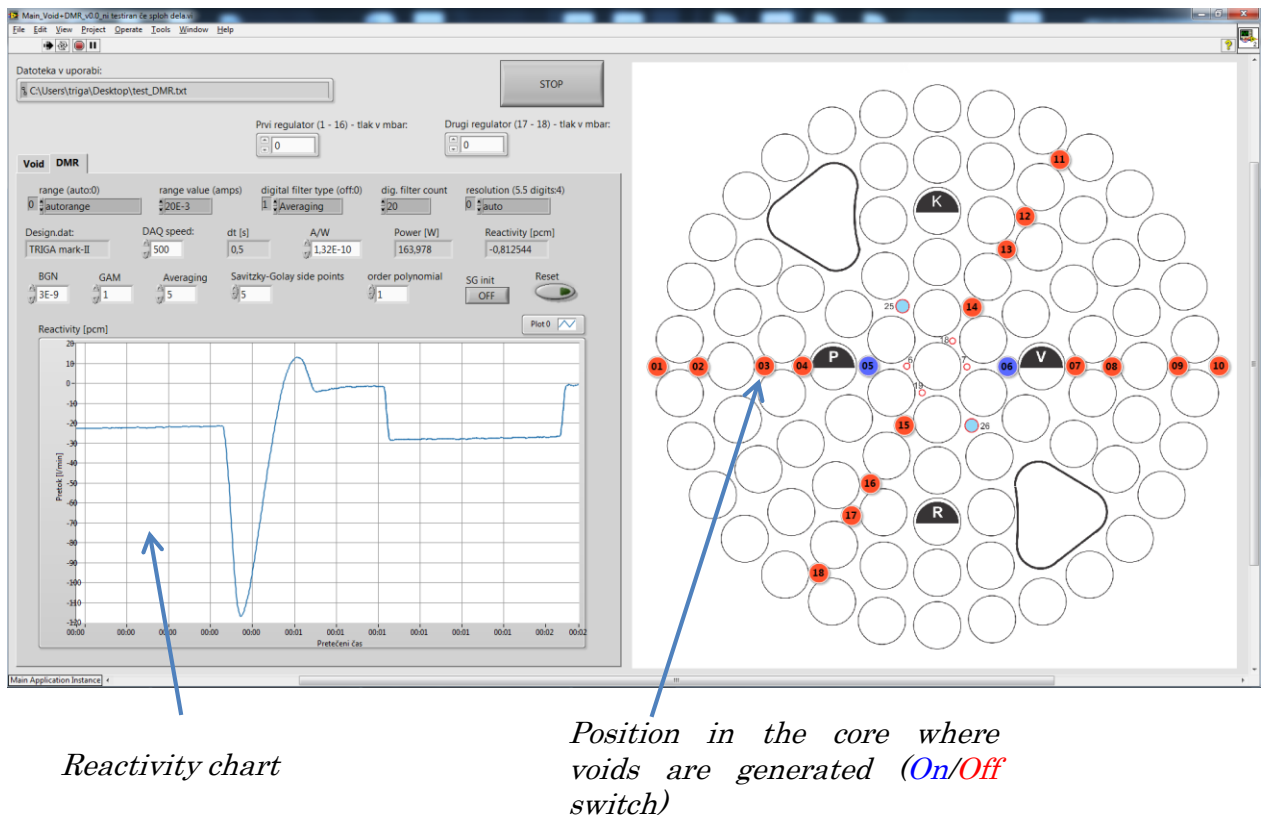


Figure 4: User interface of LabVIEW program developed to control voids generation and reactivity measurement. On the left there are reactivity measurements and on the right there is core scheme of our TRIGA reactor with positions where voids can be generated. By pressing on red circles one can turn on or off voids generation on that position. Airflow measurement tab is hidden on this picture.

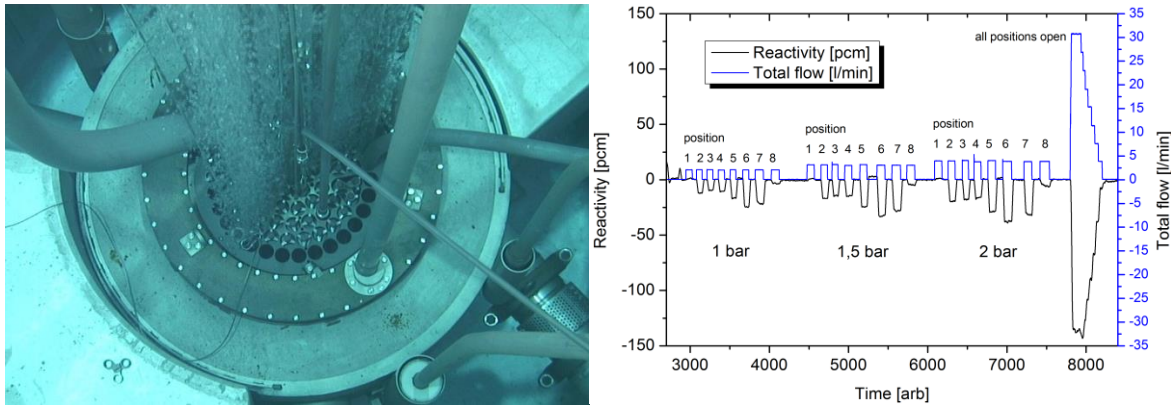


Figure 5: Simulation of water boiling in nuclear reactor (left) . Air is fed just under the core where air bubbles (voids) are generated. Here air bubbles are generated across the reactor core. Reactivity changes at different flow rates and different void positions (right). Voids were triggered one after another on different positions across the reactor core. This was repeated 3 times at different flow rates and at the end voids were produced on all positions together and then switched off one by one.

6. Conclusion

The JSI TRIGA Mark II is a good example of a relatively small research reactor having a rather low neutron flux that can support a variety of high-level research and developments activities as well as education and training at a very high level. Recent and current experimental programs performed with various nuclear instrumentation in the JSI TRIGA reactor have improved its measurements capacity and its intrinsic physical parameters and uncertainties (kinetic parameters, spatial flux and reaction rate distributions, power level...). Completed with a fully validated calculation scheme, these experimental data set allows considering this small and relatively old research reactor, having rather low neutron flux ($\sim 10^{12}$ n/cm²s), as, even nowadays, able to efficiently support both fundamental and applied research. The JSI TRIGA reactor can significantly contribute to the development of new methods and knowledge in reactor physics as well as in radiation hardness studies.

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