PRESENT SERVICES AT THE TRIGA MARK II REACTOR OF THE JSI

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1. INTRODUCTION

The 250 kW TRIGA Mark II research reactor of the Jožef Stefan Institute (JSI) has been in operation since 1966. The reactor went critical on 30 May 1966. It is a light water reactor, with solid fuel elements in which the zirconium hydride moderator is homogeneously distributed between enriched uranium. The reactor core consists of about 70 fuel elements, which are arranged in an annular lattice. A 40 position rotary specimen rack around the fuel elements, two pneumatic transfer rabbit systems, as well as a central thimble and three extra positions in the core are used for irradiation of samples. Other experimental facilities include two radial and two tangential beam tubes, a graphite thermal column and a thermalising column. In 1991 the reactor was almost completely reconstructed with new grid plates, control mechanisms and a control unit and modification of the spent fuel storage pool, among other improvements. The reconstruction additionally involved the installation of a pulse rod, so it can be operated also in a pulse mode. After the reconstruction, the core was loaded with fresh 20% enriched fuel elements, and in 1999 all spent fuel elements were shipped to the USA.

With a maximum neutron flux in the central thimble of 10^{13} $cm^{-2}s^{-1}$ and many sample irradiation positions, such a reactor may serve as an important research tool that is in many fields competitive with reactors in the higher flux region. In order to achieve efficient utilisation of the reactor, the choice of the equipment around the reactor has to be implemented to make optimum use of this flux. The acquisition and installation of the reactor has mainly been justified on the following grounds: to produce isotopes, to support basic and applied research in various fields and as a tool for training in the nuclear sciences. The reactor has been used to perform many experiments in solid state physics (elastic and inelastic neutron scattering), neutron dosimetry, neutron radiography, reactor physics including burn up measurements and calculations, boron neutron capture therapy and neutron activation analysis (NAA). Besides these, applied research around the reactor has been conducted, such as doping of silicon monocrystals, routine production of various radioactive isotopes for industry (^{60}Co, ^{65}Zn, ^{24}Na, ^{82}Br) and medical use (^{18}F, ^{99m}Tc, etc.) and other activities. However, part of the research programme such as neutron scattering, neutron dosimetry, gamma spectrometric examination of irradiated fuel and some other research fields which were active in the past were suspended in the mid-1980s. At present, the reactor is mainly being utilised for neutron activation analysis, irradiation of various samples, training and education, verification and validation of nuclear data and computer codes and testing and development of experimental equipment used for core physics tests at Krško Nuclear Power Plant (NPP). In 2010, the reactor operated 123 days. In the paper, all of the above mentioned activities are presented and briefly described together with references for further information.

The reactor is presently structured as a Reactor Infrastructure Centre (RIC), an organisational unit funded by the Slovenian Research Agency (SRA). This scheme provides for basic funding of reactor operation.

2. NEUTRON ACTIVATION ANALYSIS

Neutron activation analysis is a highly sensitive method for the accurate determination of elemental concentrations in a material. Its sensitivities are sufficient to measure certain elements at the nanogram level and below. The NAA method is based on the detection and measurement of characteristic gamma rays emitted from radioactive isotopes produced in the sample upon irradiation with neutrons. Most often samples with unknown elemental concentrations are irradiated with thermal neutrons in a nuclear reactor together with standard materials of known elemental concentrations. Neutrons are absorbed in the nuclei of constituent atoms, and later these nuclei emit radiation with energy and quantity characteristic of the particular elements. This emitted radiation is a 'fingerprint' of each element and the amount of radiation given off at certain energy is indicative of the amount of the element present in the sample. A comparison between specific activities induced in the standards and unknowns provides the basis for computation of elemental content in the sample. In this case, the relative standardisation of NAA is applied. Alternatively, elemental determinations without co-irradiated standards can also be performed using the so-called k_0 standardisation method of NAA, k_0–NAA [1]. By applying radiochemical NAA, where an element or group of elements to be determined is chemically separated either before or after neutron irradiation, detection limits may significantly improve, or even chemical specie of particular elements can be detected. Conversely, instrumental NAA (INAA), where the sample is measured without chemical processing, offers the possibility of simultaneous determination of many elements (typically more than 30), depending on their levels and sample matrix composition.

The samples at the TRIGA Mark II reactor of the JSI are loaded into the reactor and extracted after irradiation by pneumatic transfer systems. In Figure 1, pneumatic systems for long (i.e., hours) and short (i.e., seconds and minutes) irradiations are shown.

During the previous few years, emphasis was on the development of procedures for speciation analysis, particularly for As and Hg, and on determination of some essential (e.g., I and Se) and toxic (As, Cd, Hg, U) elements, related with studies concerned with environmental protection, biomedicine, radioecology, nutrients in food, etc. [2, 3]. As NAA is recognised as having the potential of becoming a primary method of analysis, part of the work has been oriented towards collaboration with certifying organisations such as the National Institute of Standards and Technology (NIST), the Institute for Reference Materials and Measurements (IRMM) and the International Atomic Energy Agency (IAEA) in support of the characterisation of new reference materials. NAA, being one of the most sensitive methods for a number of elements, has been used for determination of elements at ultra trace levels in foodstuffs. Therefore, radiochemical procedures for determining elements such as As, Cd, Co, Cu, I, Mo, Ni, Sb, Se, Sn, Th, U and V in different foodstuffs have been developed [4-6]. NAA procedures include determination of radionuclides such as ^{129}I, ^{232}Th and ^{238}U in a variety of samples [7]. Nevertheless, the vast majority of samples, about 1000 per year, are analysed by k_0–INAA [8]. The method was accredited in 2009 according to the Slovenian Institute for Standardization (SIST) guideline EN ISO/IEC 17025:2005 for analyses of environmental samples.

Fig. 1. Pneumatic systems for long (left) and short (right) irradiations.

3. IRRADIATION OF SAMPLES

The TRIGA research reactor at JSI has been used for irradiation of various samples. During the previous few years, it has been extensively used for irradiation of various components for the ATLAS detector at the European Organisation for Nuclear Research (CERN) [9, 10]. The detector is intended to study proton-proton interactions at the Large Hadron Collider (LHC) at CERN. The detector is composed of Si detectors for tracking particles. However, lattice damage caused by heavy particles in those detectors limits their use due to decrease of performance. Consequently, a programme devoted to radiation resistance of silicon detectors was established, as it is possible to reach the fluence expected at the LHC within minutes. An irradiation site, a "triangular" channel, was constructed to allow testing radiation hardness of full-size detectors in the core of reactor. Furthermore, due to the relatively large "triangular" channel, the reactor enables irradiation of silicon detectors at different temperatures by installing a heating/cooling module inside the channel. Due to good characterization of the irradiation channels, the reactor has become a reference centre for neutron irradiation of detectors developed for the ATLAS experiment.

The reactor is used for irradiation of silicon detectors and related radiation damage studies:

— Irradiation of samples of detector material; and
— Irradiation of reading electronics.

Two projects have been initiated recently; the development and improvement of future fusion reactor materials and the development of bio-dosimeters. They both require a large number of irradiations under different conditions of neutron spectra and flux and subsequent gamma spectral analyses of the samples. Both activities together with results have been thoroughly presented and described in several conference papers [11–13]

4. TRAINING AND EDUCATION

Practically all nuclear professionals in Slovenia started their career or attended practical training courses at the TRIGA reactor, including all professors of nuclear engineering and reactor physics at Ljubljana and Maribor Universities, as well as directors and key personnel of the Krško NPP, the Slovenian Nuclear Safety Administration (SNSA) and the Agency for Radioactive Waste, ARAO. All Krško NPP reactor operators and other technical staff pass training courses at the TRIGA reactor (Figure 2). 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 at Ljubljana University. The reactor has been used in

several international training courses, the latest one being organised by the Eastern Europe Research Reactor Initiative [EERRI] [14].

Fig. 2.Training of reactor operators

Since 2009 the JSI TRIGA reactor has been equipped with a teleconference system (Figure 3), and two full high definition (HD) (1080×1920 pixels) digital cameras that represent the basis for installation of remote training capabilities. The two full HD cameras are installed above the core but can be submersed underwater also in a specially designed leak tight casing. Both cameras have 10x optical zoom, which allow the users to visually inspect the core or individual fuel elements. Both cameras can be operated from the control room, and the picture is also displayed there on a 132 cm full HD screen (Figure 4). These new features are extremely useful especially for observing the core during practical exercises such as critical experiments, where fuel elements are moved around and the source is withdrawn, and during void coefficient exercises, in which voids are inserted in different positions in the core and reactivity is measured. Experience shows that the new system enhances the understanding of the experiments and makes all practical exercises more attractive.

Fig. 3. Teleconference system.

Fig. 4.Top view of the reactor core as seen from the control room.

5. VERIFICATION AND VALIDATION OF COMPUTER CODES AND NUCLEAR DATA

The user of any computer code should fully understand how the code works, but should also be familiar with its validity and limitations. Consequently, the code and the computational model should be verified by performing comparisons between the calculated results and benchmark experiments. Moreover, one has to validate also the input data, usually the cross section data, used in the calculations.

Several well defined and carefully designed experiments have been performed at the TRIGA Mark II research reactor at JSI, in order to establish a set of benchmarks for TRIGA reactors. All of them have been thoroughly analyzed and the experimental uncertainties evaluated using the most advanced Monte Carlo neutron transport codes such as MCNP [15]. Criticality experiments performed in 1991 have been thoroughly evaluated and are included in the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook [16, 17]. They represent the reference case for criticality calculations with UZrH fuel. Recent measurements of neutron spectra and neutron flux distribution are candidates for becoming benchmark experiments for neutron spectra and neutron flux calculations in UZrH fuelled systems [18–20]. A series of pulse experiments performed are candidates for a TRIGA kinetic parameters benchmark [21–23]. In the following sections the main findings are briefly presented.

5.1. Criticality calculations

In order to verify and validate the calculations of the multiplication factor in a TRIGA reactor, the TRIGA criticality benchmark from the ICSBEP Handbook was used [16]. The benchmark experiments were performed as part of the start up test after reconstruction and upgrading in 1991. All core components (top and bottom grid plates, fuel, control rods, irradiation channels), with the exception of the graphite reflector around the core, were replaced with new ones in the process. The experiments in steady state operation were performed with completely fresh fuel, including instrument elements containing thermocouples and fuelled followers of control rods, in a compact and uniform core. All elements including the fuelled

followers of control rods were of the same type, with no non-fuel components in the critical core configuration, at well controlled operating conditions. The benchmark experiment was performed with standard commercial TRIGA fuel elements of 20% enrichment and 12 wt.% uranium concentration in UZrH.

Two realistic benchmark core configurations, denoted as core 132 and core 133 were examined [16]. The benchmark k_{eff} values together with the measurement uncertainties and the calculated values, calculated with MCNP version 5.1.40, of k_{eff} are presented in Table 1.

TABLE 1. BENCHMARK MODEL KEFF AND CALCULATED VALUES OF THE BENCHMARK KEFF USING DIFFERENT CROSS-SECTION LIBRARIES

Cross section set Case ↓	Benchmark model k_{eff}	ENDF/B-VI.8	ENDF/B-VII	JEFF 3.1
Core 132	1.0006±0.0056	1.0001±0.0001	1.0059±0.0001	1.0019±0.0001
Core 133	1.0046±0.0056	1.0048±0.0001	1.0107±0.0001	1.0063±0.0001

It was found that the benchmark k_{eff} can be reproduced well with MCNP code, indicating that the computational model describes the reactor geometry and material properties sufficiently for performing criticality calculations. However, the calculated values of k_{eff} strongly depend on the cross section library used in calculations. Therefore, further emphasis should be put on improvement of nuclear data libraries in the future.

5.2. Neutron flux distribution

The second step in the process of computational model validation is the validation of spatial neutron flux distribution. The process involves activation experiments to validate the calculated results. The measured activities are compared with the calculated ones to validate the calculated spatial distribution of the fast and thermal plus epithermal neutron fluxes, thus proving that no important geometrical features of the structural components are omitted from the model.

The verification of neutron flux distribution was performed by comparing the calculated and measured $^{27}Al(n,\alpha)^{24}Na$ and $^{197}Au(n,\gamma)^{198}Au$ reaction rates in several irradiation channels located in the core centre, at the core periphery and in the graphite reflector surrounding the core. The results have been thoroughly discussed and presented in several papers and reports [18–20]. It was observed that the applied computational model very well describes the neutron flux and reaction rate distribution in the reactor core. At the core periphery however, the accuracy of the epithermal and thermal neutron flux distribution and attenuation is decreased, mainly due to a lack of information about the material properties of the graphite reflector surrounding the core.

Since our computational model properly describes the reactor core, it can be used for calculations of reactor core parameters such as power distribution, power peaking factors [24], effective delayed neutron fraction and prompt neutron lifetime [25]. Moreover, now that a very good computational model of the JSI TRIGA Mark II research reactor was developed, it can be further utilised to support various activities such as validation of self-shielding factors [26, 27].

6. TESTING AND DEVELOPMENT OF A DIGITAL REACTIVITY METER

The JSI TRIGA Mark II reactor has been used for testing and development of a digital reactivity meter and associated computational methods that have been then applied for performing core physics tests at the Krško NPP. All experimental equipment and computer codes were developed and tested at the JSI TRIGA Mark II reactor. Every year before the start up test of the NPP, all the equipment is tested, the procedures crosschecked and reactor core parameters measured (e.g., excess reactivity, control rod worth, reactor response to step reactivity insertion, etc.). Eventually the real start up tests are performed, which must be completed in less than 14 hours.

7. CONCLUSIONS

It has been shown that a small and relatively old research reactor having rather low neutron flux may still support a variety of valuable endeavours for both fundamental and applied research. When considering the activities presented, one should have in mind that for maintaining appropriate nuclear and radiation safety for the given reactor technology, the availability of highly qualified staff is of key importance. Furthermore, even a small research reactor may play an important role in educating young scientists who will eventually take responsibilities in a nuclear power programme. The knowledge and expertise acquired during their years at the TRIGA Mark II reactor proved to be invaluable to the staff trained at the Reactor Centre of the JSI as they became involved in performing safety assessments, start up tests, core design calculations and other activities important for the Krško NPP and SNSA.

It can be concluded that although the reactor is over 40 years old, it still significantly contributes to new scientific achievements in nuclear science and to preservation of knowledge on nuclear energy.

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