UTILIZATION AND APPLICATION OF THE SLOVENIAN TRIGA REACTOR

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Abstract

The Slovenian 250 kW TRIGA Mark II reactor operated by the Jožef Stefan Institute (JSI) has continuously operated since 1966. Since its commissioning it has played an important role in developing nuclear technology and safety culture in Slovenia. During the years the reactor has been utilized for training, research and isotope production. Education and training activities comprise regular experimental exercises for graduate and postgraduate students from several universities, training of reactor operators, courses organized by the JSI Nuclear Training Center, as well as visits for general population. International collaborations include participation in the three networks coordinated by the International Atomic Energy agency (IAEA): the East European Research Reactor Initiative, the Mediterranean Research reactor Network and the Advisory Safety Committee for Research Reactors in Eastern Europe. In addition, the reactor staff acts as IAEA external experts and train IAEA fellows upon request. Neutron activation analysis has represented one of the most important utilization of the reactor since its commissioning. Other research applications comprise irradiation of various materials, neutron radiography, verification and validation of computer codes and nuclear data, and development of a digital reactivity meter. In the 1970s and 1980s the reactor was extensively used for the production of radioactive isotopes, particularly ^{99m}Tc and ^{18}F. Although the production of medical and industrial isotopes discontinued, there are still some short-lived isotopes produced for mostly on-site users. Although the reactor is over forty years old, it still significantly contributes to new scientific achievements in nuclear science and to preservation of knowledge in nuclear energy.

1. INTRODUCTION

The 250 kW TRIGA Mark II research reactor of the Jožef Stefan Institute (JSI), Ljubljana, has been in operation since 1966. It achieved the first criticality on 31 May 1966 at 14:15. It is a light water reactor, with solid fuel elements in which zirconium hydride moderator is homogeneously distributed between 20% enriched uranium. The reactor core consists of about 70 fuel elements, yielding the maximum neutron flux in the central thimble of 10^{13} n cm^{-1} s^{-1}. A 40 position rotary specimen rack (located around the fuel elements), two pneumatic tube transfer rabbit systems, as well as central thimble and three extra positions in the core are used for irradiation of samples. Additional experimental facilities include two radial and two tangential beam tubes, a graphite thermal column and a thermalizing column.

In 1991 the reactor underwent major reconstruction, comprising installation of new grid plates, replacement of the control mechanisms and the control unit, modification of the spent fuel storage pool, etc. the reconstruction 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.

Since its commissioning the reactor has been playing an important role in developing nuclear technology and safety culture in Slovenia as is one of a few centers of modern technology in the country. Its international scientific cooperation and recognized reputation are important for promotion of JSI, the Slovenian science and Slovenia as a country in the world.

As the abbreviation TRIGA implies, the reactor has been mainly utilized (apart from "GA", abbreviation for the producer **G**eneral **A**tomics) for:

- **T**raining – education and training of university students, fellow trainees from abroad and future operators, as well as on-job training of staff working in public and private institutions;
- **R**esearch – neutron activation analysis (NAA), irradiation of various materials for research purposes, beam applications, neutron radiography, verification of computer codes and nuclear data (e.g., criticality calculations and neutron flux distribution studies), testing and development of a digital reactivity meter, etc;
- **I**sotopes – production of various isotopes intended for industrial, medical and research purposes.

The further sections are focused on more detailed explanation of the past, the present and the planned utilization and application of the Slovenian TRIGA reactor.

2. EDUCATION AND TRAINING

The vast majority of nuclear professionals in Slovenia started their career or attended practical courses at the TRIGA reactor, including all professors of nuclear engineering and reactor physics at the Ljubljana and Maribor Universities, directors and key personnel of the Nuclear Power Plant (NPP) Krško, the Slovenian Nuclear Safety Administration and the Agency for Radioactive Waste. The reactor is used in regular laboratory exercises for graduate and postgraduate students of physics and nuclear engineering at the Faculty of Mathematics and Physics, University of Ljubljana; the Faculty of Energy Technology, University of Maribor; and various courses for the University of Nova Gorica. All NPP Krško reactor operators and other technical staff attend training courses organized by the JSI Nuclear Training Center (NTC) located at the reactor site. In addition, on average more than 1,400 people visit the reactor yearly as part of building general knowledge on nuclear technology among population.

2.1. International collaborations and activities

The reactor has been involved in many international training courses, mostly organized by the NTC and the IAEA. The institute actively participates in three international collaborations coordinated by the IAEA: (1) the East European Research Reactor Initiative (EERRI), (2) the Mediterranean Research Reactor Network (MRRN) and (3) the Advisory Safety Committee for Research Reactors in Eastern Europe (EURASC). The EERRI, established in 1998, organizes regular training courses on utilization of research reactors for educational purposes; so far, four training courses were organized with the fifth one planned in November 2011 [1]. The training is usually organized as a six weeks course implemented at research reactors in four countries, one of them being the Slovenian TRIGA. Within the MRRN, the JSI acts as a coordinator for Nuclear Education and Training [2].

2.2. Advanced educational tools

The reactor lecture room is equipped with a teleconference system and two full high definition (HD) (1080 x 1920 pixel) digital cameras allowing for installation of remote training capabilities. One camera with a 10 x optical zoom is installed a few cm under the water level, allowing the users to visually inspect the core or individual fuel elements. The camera can be operated from the control room and the picture is also displayed on a 132 cm full HD screen. This feature is extremely useful for observing the core at practical exercises such as a critical experiment, where fuel elements are moved around and a source is withdrawn, and at a void coefficient exercise where voids are inserted in different positions in the core and reactivity is measured. Experience shows that the system enhances understanding of the experiments and makes all practical exercises more attractive to trainees.

FIG. 1. EERRI training course participants in the control room.

The development of fast and relatively inexpensive computer clusters enabled the development and use of powerful computer codes for neutron transport (such as Monte Carlo transport codes) and 3D visualization of large amounts of data in real time. By combining those codes and visualizing reactor physics data such as neutron flux and power distribution, a powerful tool for obtaining a rapid insight into the characteristics of a reactor was developed. With the use of advanced software for 3D visualization one may create and present neutron flux and power distribution in a very attractive way. One may observe axial, radial or any other views of the neutron flux and power distribution in a nuclear reactor and literally "walk" through the reactor core and observe the changes in neutron flux and power throughout the different components of the reactor core. As humans tend to remember things better if they can see them and visualize the processes, the new presentation of the reactor and neutron transport parameters represent an outstanding educational tool for the future generation of nuclear power plant operators, nuclear engineers and other experts involved in nuclear technology. The JSI TRIGA reactor was the first reactor in the world on where those methods were applied and tested. Moreover, the 3D visualization tools for presentation of the reactor parameters have already become a standard tool at the NTC and EERRI courses.

3. RESEARCH

3.1. Neutron activation analysis (NAA)

NAA is a powerful tool for the determination of over 70 elements in a variety of matrices (geological, environmental, biological, industrial, etc. samples) at broad concentration ranges (from about 10^{-10} g g^{-1} to virtually 10^{0} g g^{-1}). The reactor has been utilized for NAA soon after its commissioning in 1966 [3]. The early applications were concerned with the determination of trace elements in biosphere and biological materials with focus on the environment around the mercury mine and distillation plant located at the city of Idrija. Radiochemical procedures, largely based on solvent extraction, ion exchange and volatilization processes, were developed for the determination of essential and toxic elements such as As, Cd, Co, Cu, I, Mn, Mo, Ni, Sb, Se, Sn, Th, U, V and Zn. Simultaneously, long-term collaboration with international organizations producing reference materials including International Atomic Energy Agency (IAEA) has been established. Along with the development of nuclear and gamma spectrometric equipment in late 1970s and early 1980s, instrumental NAA (INAA) has attracted more and more applications, gradually replacing the radiochemical NAA, RNAA. Further decline in the application of RNAA had occurred as a consequence of introducing less manpower-demanding modern and competitive analytical techniques. Finally, in late 1980s a semi-empirical the k_0- based NAA [4] was introduced, gradually replacing the relative method of INAA, eventually resulting in its accreditation according to the ISO/IEC 17025 standard in 2009, as a routine analytical tool for the analysis of environment and samples from the environment, foodstuffs, feedstuffs and biological samples. Nevertheless, RNAA is still used where being competitive, e.g., in speciation of As in biomedical studies, and in studying some essential (Se, I) and toxic (As, Cd, Hg, U) elements in environmental protection, biomedicine, nutrition and radioecology. A dedicated RNAA procedure for the determination of ^{129}I in environmental samples has been recently developed [5]. The k_0- NAA is amply used for the analysis of environmental samples including bioindicators, as well as for new materials and industrial samples. About 1,000 samples per year are analyzed by this method [6]. As part of broad international collaboration analytical measurements for the IAEA and other renowned reference materials producers such as BAM (Federal Institute for Materials Research and Testing) and IRMM (Institute for Reference Materials and Measurements) are regularly performed.

3.2. Irradiation of various materials

During the last years, the reactor has been extensively used for irradiation of various components for the ATLAS detector, composed of Si detectors for tracking particles, in the European Organization for Nuclear Research (CERN) [7, 8]. 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 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 (**A**dvanced European **I**nfrastructures for **D**etectors and **A**ccelerators) project funded by the Seventh Framework Programme (FP7) 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 Reserarch Organization, Japan), as well as for various universities and institutes.

Further examples of irradiating various materials for research purposes include:

— Irradiation of thermoluminescent detectors (TLDs) and biodosimeters in mixed neutron/gamma radiation fields for population dosimetry purposes [9];
— Irradiation of potential future first wall and breeder blanket structural materials for the planned fusion reactor [10, 11].

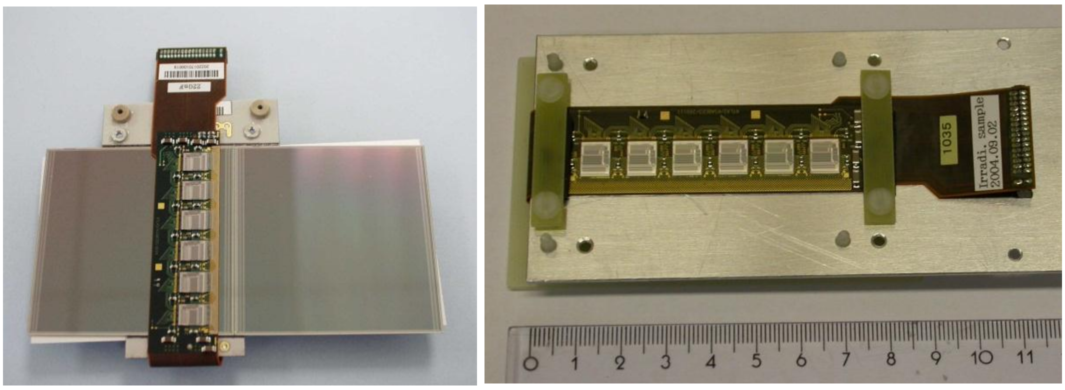

FIG. 2. Module of strip detectors: dimensions: 6×12 cm; 2 x 768 strips, 80 µm between strips (left). Reading electronics ready for irradiation (right).

3.3. Neutron radiography

A neutron radiographic facility was constructed in 1974 and upgraded in 1995. Problems studied in the past comprised neutron defectoscopy, studies of basic imaging properties, image enhancement by sparking techniques, inspection of the TRIGA fuel, applications in metallurgy and inspections in metal industry. More recent activities have involved a thermal column neutron radiographic facility in inspecting of archaeological objects and quantitative measurements of moisture in building materials. Among others, a project on water penetration through various types of concrete to be used in the planned Slovenian low and medium level radioactive waste storage was performed.

However, the intensity of utilizing the neutron radiography has been in steady decrease since 2001. Therefore, a systematic market survey has recently been initiated aimed at offering the available neutron radiography facility to Slovenian companies for investigating their products.

3.4. Verification and validation of computer codes and nuclear data

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 by using the most advanced Monte Carlo neutron transport codes such as MCNP, the Monte Carlo N-Particle Transport Code [7]. 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 [12, 13]. They present the world-unique reference case for criticality calculations with the UZrH fuel. The recent measurements of neutron spectra and neutron flux distribution are candidates for becoming the benchmark experiments in calculations in UZrH fuelled systems [14]. A series of pulse experiments is candidate for a TRIGA kinetic parameters benchmark.

Recently, a project involving irradiation of neutron detectors developed at the French Alternative Energies and Atomic Energy Commission (CEA) has been started as part of an agreement between CEA and the Slovenian Ministry of higher education, science and technology [15]. The first project objective is to analyze and improve the power calibration process of the JSI TRIGA reactor (procedural improvement and uncertainty reduction) by applying absolutely calibrated CEA fission chambers. The second objective is to apply the TRIGA irradiation facilities for irradiation campaign of new activation dosimeters and neutron/gamma flux measurement devices recently developed by the CEA, which will help improve the nuclear data for neutron dosimetry and spectrum calibration. The planned experiments will provide a unique opportunity to compare measurement and calculation results for a pool type reactor and thus help validate the calculation tools and models developed and used at the JSI for neutron transport calculations in the TRIGA reactor.

Another joint project with CEA has been initiated this year. The project foresees insertion of fission cells with superior characteristics into the reactor for neutron flux measurements. The planned experiments will hopefully open possibilities for further refinements such as improved control rod worth measurements or determination of kinetic parameters. The latter parameters will also be calculated with the MCNP thus giving the possibility of using the results as a kinetic parameters benchmark.

3.5. Development and testing of a digital reactivity meter

A digital reactivity meter and associated computational tools were developed and tested at the JSI TRIGA reactor to be applied for performing core physics tests at the Krško nuclear power plant (NPP). Every year before the planned start-up test in the NPP, the experimental equipment is tested by measuring the TRIGA reactor core parameters (the excess reactivity, the control rod worth, the reactor response to step reactivity insertion, etc.) and all practical procedures are reviewed and amended, if needed. A very thorough preparation step is essential as the real on-site start-up test at the Krško NPP should then be completed in less than 14 hours. As part of the procedure, the so called rod-in method for the rod worth measurements was invented and first introduced at the JSI TRIGA reactor. This method reduced the time needed for the control rod worth measurements from several days to a couple of hours.

4. PRODUCTION OF ISOTOPES

In the past, in particular in 1970s – 1980s, the reactor was extensively used for the production of radioactive isotopes for medical purposes (^{18}F, ^{85m}Kr, ^{99m}Tc), industrial use (^{82}Br, ^{60}Co, ^{131}I, ^{24}Na, ^{64}Zn) and other activities. Due to relatively low neutron flux (10^{13} cm^{-2} s^{-1} in the central channel) the production was focused more on short lived isotopes.

Technetium was obtained from ^{99}Mo, which was produced by irradiation of natural isotopic composition ^{98}Mo. A dedicated apparatus for routine production of ^{99m}Tc from low specific activity ^{99}Mo was developed and further refined as a semi-automatic extraction system [16, 17]. The production was based on irradiation of 80-85 g of MoO_3 (four weeks in a flux of 4 x 10^{12} n cm^{-2} s^{-1} and finally 48 hours in a flux of 1 x 10^{13} n cm^{-2} s^{-1}), dissolution of the irradiated product in NaOH and subsequent solvent extraction of ^{99m}Tc with methyl ethyl ketone (MEK). After evaporation of MEK, the product was dissolved in sterile physiological solution in the form of $Na^{99m}TcO_4$ and delivered to customers. The described procedure allowed for a daily production of 50-70 GBq of ^{99m}Tc with specific activity of about 4.8 GBq mL^{-1}.

The anhydrous ^{18}F-HF was also produced by irradiation of $^{6}Li_2CO_3$ [18]. The formation of ^{18}F is based on a two step nuclear reaction: ^{6}Li (n, α) ^{3}H and ^{16}O (^{3}H, n) ^{18}F. A mixture of 5 g Li_2CO_3 of natural isotopic composition and 1 g of 95.6 % ^{6}Li enriched Li_2CO_3 was irradiated in a neutron flux of 1 x 10^{13} n cm^{-2} s^{-1} for 6 hours. The irradiated Li_2CO_3 was then dissolved in sulfuric (VI) acid and the solution subsequently distilled into tetraethylammonium fluoride. The ^{18}F-HF produced was used to exchange some fluorine atoms in tetraethylammonium fluoride, which was the reagent used in the synthesis of ^{18}F-3-deoxy-D-glucose. The activity of 3-^{18}FDG was 150 to 220 MBq.

The isotopes for medical and industrial purposes are not produced anymore. Consequently, knowledge and capabilities for their production still exist although the level of the knowledge and experience steadily decrease as old staff members retire. Nevertheless, short-lived radioactive isotopes are still produced for on-site users, mostly in developing new

NAA procedures and studying biogeochemical processes involving environmental contaminants. An interesting application involves production of ^{197}Hg ($T_{1/2}$ = 64.1 h) by irradiating ionic mercury enriched in ^{196}Hg. The relatively low gamma energies (67 keV and 69 keV) of the formed radioisotope and the simple gamma spectrometric measurement combined with advanced chemical speciation techniques make the trace very useful for studying biogeochemical transformations of mercury species.

5. OPERATING EXPERIENCE

The reactor has been operation without any extended unplanned shutdown. However, the annual operating time in has decreased from about 1,600 to approximately 650 hours during the last decade, mainly due to reduced funding of projects related to reactor physics and increased complexity of experiments (especially benchmark experiments), which demand careful planning and thorough subsequent analyses of the performed experiments. Typically, planning and designing of an in-core flux measurements may take one year, with additional one year being spent for analyzing and correctly interpreting the measurements results.

The high safety requirements imposed by the Slovenian Nuclear Safety Administration (SNSA) requires virtually the same safety and quality standards for research reactors as required for nuclear power plants as legislation for the two types of facilities is almost the same since 2009, with some not well defined graded approach for the former ones.

During past few years the TRIGA reactor has undergone a number of major renovation works such as upgrading of reactor ventilation system, replacement of entrance doors, and renovation of power supply, fire protection and physical protection systems. Presently, the program of periodic safety review is in progress.

6. FINAL REMARKS – CONCLUSIONS

The Slovenian TRIGA reactor has been playing an important role in developing nuclear technology and safety culture in Slovenia as one of few centers of modern technology in the country. Its broad international cooperation and reputation are of big importance for the promotion of JSI, the Slovenian science as well as Slovenia as a country in the world. Apart from the activities given in the sections above, the highly qualified and skilled reactor staff supervise refueling in the Krško NPP, participate in the Ecological Laboratory with a Mobile Unit (radiological emergency preparedness), assist in radiological demanding works inside and outside JSI, assist in quality assurance audits within JSI, assist in radiation safety at work, participate in IAEA missions as external experts and perform many other demanding activities.

A small and relatively old research reactor having rather low neutron flux may even nowadays efficiently support both fundamental and applied research in various fields of science, and significantly contribute to preservation of knowledge on nuclear energy.

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