20th International Conference
NUCLEAR ENERGY FOR NEW EUROPE 2011
Bovec /Slovenia /September 12-15

45 Years of TRIGA Mark II in Slovenia

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ABSTRACT

Since 1966 the TRIGA Mark II research reactor at Jožef Stefan Institute (JSI) in Ljubljana Slovenia has been playing an important role in developing nuclear technology and safety culture in Slovenia. In the 1970s-1980s the reactor was extensively used for production of radioactive isotopes. Since then the reactor has been mainly used for research and training. The utilisation of the reactor for training and research purposes is still increasing. Through the paper the reactor related activities and plans for the future are presented.

1 INTRODUCTION

The TRIGA Mark II research reactor at Jožef Stefan Institute (JSI) in Ljubljana Slovenia achieved first criticality on 31st May 1966 at 14:15. Since then the reactor has been playing important role in developing nuclear technology and safety culture in Slovenia. It is one of a few centres of modern technology in the country. Its international cooperation and reputation are important for promotion of JSI, Slovenian science and Slovenia in the world. The reactor has been mainly used for training and education of university students, future operators at Krško Nuclear power plant (NPP) as well as on-job training of staff working in public and private institutions, isotope production, neutron activation analysis, beam applications, neutron radiography, testing and development of a digital reactivity meter, verification of computer codes and nuclear data, comprising primarily criticality calculations and neutron flux distribution studies. In the past few years, it has been extensively used for irradiation of various components for the ATLAS detector in the European Organisation for Nuclear research (CERN). 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. There are several projects going on at JSI related to reactor and many more are planned.

In the first part of the paper activities that were intense in the past but have been in steady decline, i.e. production of isotopes and neutron radiography, are briefly presented. As nothing much has changed in the last ten years the statues is practically the same as in one of the past papers on TRIGA utilization [1].

The second part of the paper focuses on current and planned utilization of the TRIGA Mark II reactor at JSI, showing that even small reactors such as 250 kW TRIGA at JSI can still be used for various purposes and can significantly contribute to state of the art achievements in nuclear science and technology and other related fields. In addition current and planned activities to extend operation of the reactor at least until 2023 are presented.

2 PRODUCTION OF ISOTOPES

In the 1970s-1980s the reactor was extensively used for production of radioactive isotopes for medical purposes (^{18}F, ^{85m}Kr, ^{99m}Tc), industrial purposes (^{82}Br, ^{24}Na, ^{64}Zn, ^{131}I, ^{60}Co) and other activities. Due to relatively low neutron flux (10^{13} n/cm^{2}s in the central channel) the production was focused more on short lived isotopes. It is important to note that although isotopes for medical and industrial purposes are not produced anymore, knowledge and capabilities for their production still exist. Unfortunately the level of knowledge and experience steadily decreases as old staff members retire. After recent worldwide difficulties with ^{99m}Tc supply, the ideas of reviving the isotope production are becoming more and more realistic.

3 NEUTRON RADIOGRAPHY

Neutron radiographic facility was constructed in 1974 and improved in 1995. Problems studied in the past comprise neutron defectoscopy, study of basic imaging properties, image enhancement by sparking techniques, inspection of TRlGA fuel, applications in metallurgy and inspections in aviation and metal industries. Present activities to utilize thermaI column neutron radiographic facility are:

- Inspection of archaeological objects
- Quantitative measurements of moisture and hydrogenous matter in building material

Since 2001 the intensity of utilization of the neutron radiography has been in steady decrease. Last year however a research project on the measurements of water penetration through various types of concrete to be used in Slovenian low and medium level radioactive waste storage facility was successfully completed. Recently we started several discussions with Slovenian companies to use neutron radiography as a method to investigate their products.

4 RESEARCH

The research activities at the TRIGA reactor are performed mainly by tree research divisions and their partners:

- Reactor Physics Department
  - verification and validation of computer codes and nuclear data
  - testing and development of experimental equipment used for core physics tests at the Krško Nuclear Power Plant
  - neutron radiography
  - neutron activation studies
  - development of biodosimeters
- Department of Environmental Sciences
  - neutron activation analysis
  - production of trace elements
- Experimental Particle Physics Department
  - radiation hardness studies

In the continuation the above mentioned activities and main results are briefly presented.

4.1 Testing and development of digital reactivity meter

The JSI TRIGA Mark II reactor is used also for testing and development of a digital reactivity meter and associated computational methods which are then used 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 we test all equipments, go through all procedures, measure reactor core parameters (excess reactivity, control rod worth, reactor response to step reactivity insertion, etc) and prepare ourselves for the real start-up tests at the Krško NPP, which have to be completed in less than 14 hours. Hence a thorough preparation to the test is essential and could not be made without our TRIGA research reactor. It is important to note that the so called rod-in method for rod worth measurements was invented and first used at the JSI TRIGA reactor. This method reduced the time needed for control rod worth measurements from several days to a couple of hours.

4.2 Verification and validation of computer codes and nuclear data

The user of any computer code should not only know how the code works but has to be familiar also with the validity and the limitations of the code. Therefore one has to verify the code and the computational model by performing a comparison of the calculated results with benchmark experiments also called benchmarks. 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 by using the most advanced Monte Carlo neutron transport codes such as MCNP [8]. Criticality experiments performed in 1991 have been thoroughly evaluated and are included in the ICSBEP handbook [2], [3]. They present the world only 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 [4]. A series of pulse experiments are candidates for TRIGA kinetic parameters benchmark.

In 2010a bilateral project was started as part of the agreement between the French Commissariat à l'Energie Atomique et aux Energies Elternatives (CEA) and the Ministry of Higher Education, Science and Technology of Slovenia [5].The project involves the irradiation of CEA-developed neutron detectors in the JSI TRIGA Mark II reactor. The first objective of the project is to analyze and improve the power calibration process of the JSI TRIGA reactor (procedural improvement and uncertainty reduction) by using absolutely calibrated CEA fission chambers (FCs). The second objective is to use the TRIGA irradiation facilities to perform a test irradiation campaign of new activation dosimeters and neutron/gamma flux measurement devices recently developed by the CEA, which will help to improve the nuclear data for neutron dosimetry and spectrum characterisation. In addition the experiments will provide a unique opportunity to investigate the measurement to calculation ratios in a pool type reactor and validate the calculational tools and models used and developed at the JSI for neutron transport calculations in the TRIGA reactor.

In 2011 another joint project with CEA has started. In the frame of the project fission cells with superior characteristics will be inserted into the reactor for flux measurements. This will open possibilities for improvements on a number of fields, among others in the improved control rod worth measurements or determination of kinetic parameters. The latter will be measured experimentally and also calculated with Monte Carlo neutron transport code MCNP, which will give the possibility to use the results as a kinetic parameters benchmark.

4.3 Neutron activation analysis

Soon after its commissioning, the reactor has been utilized for neutron activation analysis (NAA) [6]. Early applications were dedicated to development of radiochemical procedures for determining trace elements in the environment and in human health. Particular emphasis was devoted to studying the effects of the Idrija mining and milling activities onto the environment and man. Radiochemical NAA (RNAA) procedures for the determination of numerous elements were developed and successfully applied in characterizing Standard Reference Materials prepared by NBS, a predecessor of the National Institute of Standards and Technology (USA). Simultaneously, procedures for the determination of long-lived radionuclides by combination of NAA and other radiometric methods have been developed and applied. Along with the development of nuclear and gamma spectrometric equipment in late 1970s and early 1980s, instrumental NAA (INAA) has attracted more applications, gradually replacing the RNAA procedures, whenever applicable. Further decline in the application of RNAA occurred as consequence of introduction of other modern analytical techniques. In the late 1980s, the k_0- based NAA was introduced, gradually replacing the relative method of INAA, eventually resulting in its accreditation as a routine analytical tool in 2009 [7]. Currently, the k_0-NAA is used as primary analytical tool, along with the RNAA as a dedicated technique in cases where it prevails due to its advantages over the other analytical methods. During last years the emphasis in RNAA has been on the development of procedures for speciation analysis, particularly for As and Hg, and on determination of the concentration levels of some essential (Se and I) and toxic (Hg As, Cd, U) elements, in connection with the studies concerned with environmental protection, biomedicine, radioecology, assessment of nutrients in food, etc. The k_0- INAA, which is also accredited according to the ISO/IEC 17025 standard, is amply used for the analyses of reference materials, water, soil and air samples, as well as various bioindicators of environmental pollution. As part of broad international collaboration, analytical measurements for renowned reference materials producers such as BAM (Federal Institute for Materials Research and Testing), IAEA (International Atomic Energy Agency) and IRMM (Institute for Reference Materials and Measurements) are regularly performed.

4.4 Production of Hg isotopes

Biogeochemical cycle of mercury attracts much attention as various Hg chemical species are toxic compounds with ability to bioaccumulate and biomagnify throughout the food web. Usually, chemical determinations of Hg at low concentration levels are laborious and time-consuming, as special clean techniques are demanded to avoid potential contamination. Application of radioisotopes offers an alternative possibility of Hg measurements, reducing probability of contamination and enabling work at lower concentration levels. For this purpose, acidified water solution of ionic mercury (Hg^{2+}) enriched in isotope ^{196}Hg is irradiated in the central channel of the reactor, producing the gamma emitting (67 keV and 69 keV) radioactive tracer ^{197}Hg with half-life of 64.14 h. The relatively low gamma energies of the formed radioisotope and the simple gamma spectrometric measurement combined with advanced chemical speciation techniques make the tracer very useful for continuous investigations of biogeochemical transformations of mercury species.

4.5 Radiation hardness studies

The Experimental particle physics division at the JSI is a member of the ATLAS project. The ATLAS experiment is being constructed by 1850 collaborators. It, will study proton-proton interaction at the Large Hadron Collider (LHC) at the European Laboratory for Particle Physics CERN (Geneva). Our researchers are collaborating on development of the ATLAS inner detector which uses semiconductor detectors (Si) for tracking of particles [6], [9]. However, the lattice damage caused by heavy particles in these detectors limits their use due to decrease of performance. Fluences of the order of 10^{14} are expected during ten years of operation. Silicon detectors can not survive these high fluences unless special precautions are taken; therefore programme devoted to radiation hardness of silicon detectors was established at the TRIGA reactor in 2001. Due to relatively large “triangular” channel it enables the irradiation of silicon detectors together with the associated electronics at different temperatures by installing a heating/cooling module inside the channel. Due to good characterization of the irradiation channels the JSI TRIGA Mark II reactor has become an unofficial global reference centre for detector irradiation. The reactor has also been included into AIDA (Advanced European Infrastructures for Detectors at Accelerators) FP7 EU funded project [10]. Approximately 2000 samples per year are irradiated for users like CERN, DESY, KEK and various universities and institutes. It is interesting to note that with respect to radiation damage the JSI TRIGA reactor is mentioned in over 148 scientific papers in the journal of Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment.

5 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 Nuclear Power Plant (NPP) Krško, the Slovenian Nuclear Safety Administration and the Agency for Radioactive Waste. All NPP Krško reactor operators and other technical staff pass training courses on the TRIGA reactor; 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 University of Ljubljana, Faculty of energetic, University of Maribor and University of Nova Gorica. Practically all training courses are organised by the JSI Nuclear Training Centre (NTC). In addition more than 1400 people visit the JSI TRIGA reactor every year as part of their visit of the JSI reactor Centre.

5.1 International courses

The reactor has been used in several international training courses, mostly organises by the NTC and the IAEA. In order to enhance utilisation of research reactors for educational purposes we established a coalition between Austria, Czech Republic, Hungary in the field of international trainings and education. The coalition is formalised within the Eastern European Research Reactor Initiative (EERRI), which was established with the support of the IAEA in 2008 [12]. Since then we carried out four training courses for participants from Member States each one lasting for six weeks. The fifth course is planned for November 2011.

5.2 Advanced education tools

Since 2009 the JSI TRIGA reactor has been equipped with teleconference system, and two full high definition (HD) (1080 × 1920 pixel) digital cameras which represent the basis for installation of remote training capabilities. The full HD camera is installed a few cm under the water level in a specially designed leak tight casing. It features also 10 × optical zoom, which allow 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 there on a 132 cm big full HD screen. This new features are extremely useful especially for observing the core at practical exercises such as critical experiment, where fuel elements are moved around and the source is withdrawn and at void coefficient exercise, in which voids are inserted in different positions in the core and reactivity is measured. Our experience shows that the new system enhances the understanding of the experiments and makes all practical exercises more attractive.

The development of fast and relatively cheap computer clusters enabled the development and usage 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 these codes and visualizing reactor physics data, such as neutron flux and power distribution, we created a powerful tool for gaining rapid insight into the characteristics of a reactor. With the use of advanced software for 3D visualization (e.g. Amira [1], Voxler [2], etc.) one can create and present neutron flux and power distribution in a revolutionary way never seen before. One can 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.

Most of the people remember things better if they can see them and visualize the processes. Therefore the new representation of the reactor and neutron transport parameters is certainly 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 which these methods were applied and tested. Moreover using 3D visualization tools for presentation of reactor parameters has already become a standard tool at the NTC and EERRI courses.

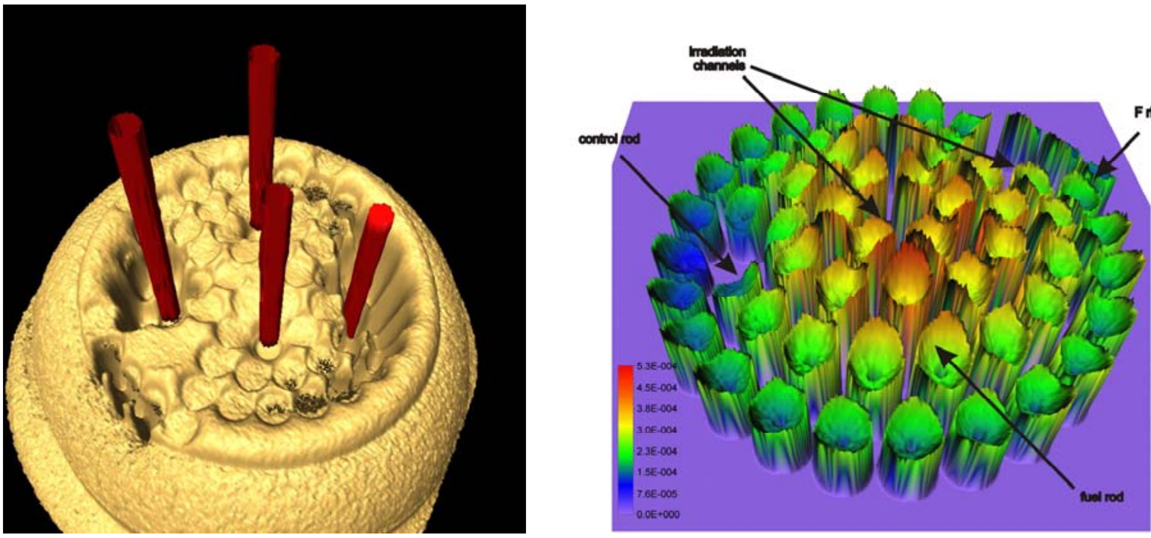

Figure 1**,** Left: Thermal flux distribution in TRIGA reactor presented in isosurface mode (yellow) and control rods (red).right: Radial power density distribution (rel. units) in JSI TRIGA Mark II core 189.

6 OPERATING EXPERIENCE

The reactor has been operating without any extended undesired shutdowns. Annual operating time in the last decade has decreased from 1600 to approx. 650 hours. The decrease in operation time is mainly due to reduced financing in the field of experimental reactor physics and increased complexity of experiments (especially benchmark experiments) which demand careful planning and thorough after experiment analysis. For example, it took us one year to plan and design the in-core flux measurements. The measurements will be performed in two weeks, later it will take us another year to analyze in correctly interpret the results.

The reactor is regularly visited, inspected and supervised by the Slovenian Nuclear Safety Administration (SNSA), by inspectors and other staff from the International Atomic Energy Agency, and by EURATOM inspectors. The reactor has practically the same safety and quality standard as required for the nuclear power plant operation. Since 2009 the legislation for the nuclear power plants and research reactors is practically the same.

In the past few years the reactor has gone trough major renovation works and many more are planned. For example we completely renovated the reactor ventilation system, changed the entrance door, now we are in the middle of the projects on renovating the reactor power supply system, installing new fire protection system, installing new system for physical protection. In the near future we will buy new reactor instrumentation and improve physical protection of the whole reactor site.

In 2011 the major efforts were put into preparation of the programme of the periodic safety review, which is now waiting for approval by the SNSA.

7 OTHER ROLES OF TRIGA REACTOR

The reactor has been playing important role in developing nuclear technology and safety culture in Slovenia. It is one of a few centres of modern technology in the country. Its international cooperation and reputation are important for promotion of JSI, Slovenian science and Slovenia in the world.

In addition due to specific knowledge our operators do many different jobs not directly connected to the reactor:

- supervision of refuelling in Krško NPP
- cooperation in The Ecological Laboratory with a Mobile Unit
- assistance in radiologically demanding works inside and outside JSI
- assistance in quality assurance audits inside JSI
- assistance in occupational safety

The radiation protection team has long-term practical experience with all aspects of radiation protection of a research reactor. Due to their expertise the team members are often invited on different missions as IAEA experts. They also performed radiation measurements during the two recent shipments of spent fuel that was sent to from Hungary and Serbia via Slovenia to Russia.

Due to high level of safety culture and long-term experience with quality assurance (QA) the TRIGA reactor personnel provides assistance in this field and constantly raises the safety culture and QA levels at the JSI and among its partners.

8 FUTURE PLANS

In the short-term future the most important activities will be preparation of the long-term strategy of reactor operation and decommissioning and performing the periodic safety review, which will identify potential ageing problems.

We will certainly continue with existing activities in the field of research and expand our activities in the field of reactor physics experiments and benchmarks and in the field of irradiation of samples under well defined conditions.

Together with the Nuclear Training Centre we plan to become important global centre for nuclear training and education.

In 2010 Slovenian Ministry of Higher Education, Science and Technology prepared the national strategy of the research infrastructure 2010-2020. In the strategy it is written that the TRIGA reactor will receive 20 million EUR for complete refurbishment + additional 1 million EUR per year for maintenance and staff. This would enable reactor to operate at least until 2040, when Krško NPP will be shutdown, if the current operating licenses is prolonged. In this scenario the last generation of the Krško NPP operators would be trained at the TRIGA reactor. The reavctor would then be closed and decommissioned. During decommissioning of the TRIGA reactor, people involved would get operational and theoretical experience, which could later be used in decommissioning the Krško NPP. In addition a company could be established that would provide services and practical training on decommissioning worldwide.

It is expected that by 2040 the TRIGA reactor might have no more than 100 irradiated fuel elements, weighing about 400 kg. As this would be less than 1/1000 of all spent fuel from the Krško NPP, disposing the TRIGA fuel together with the spent fuel from the Krško NPP would not make any significant effect on the total budget of the spent fuel disposal in Slovenia.

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